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VOLUME XX No. 1

DOMINION OBSERVATORY ROCKBURST RESEARCH 1938 - 1945

BY

ERNEST A. HODGSON

EDMOND CLOUTIER, C.M.G., O.A., D.S.P.
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PREFACE

A long series of rockburst studies, beginning late in 1938 and continuing through to October 31, 1945, was carried out at the request of Lake Shore Mines, Kirkland Lake, Ontario, by the Surveys and Engineering Branch of the (then) Department of Mines and Resources, Ottawa, operating through the Dominion Observatory. The direction of this research was assigned to Dr. E. A. Hodgson, then Chief of the Seismological Division of the Observatory.

Reports covering the progress of this work (22 in all) were prepared for limited distribution to serve as memoranda for Lake Shore Mines, the Department, and the Observatory. About fifty copies of each were mimeographed and bound, pamphlet style, and requests from various sources soon exhausted the supply. The continued demand for copies, and a growing opinion that a permanent record in printed form should be made available, has led to the decision that these reports should be edited and printed.

DOMINION OBSERVATORY ROCKBURST RESEARCH 1938-1945

by

Ernest A. Hodgson

Introduction

The first inquiry from Lake Shore Mines Limited was received on December 28, 1938. A severe rockburst had occurred the previous night at 10.50. C.E. McKnight, the company's Safety Director, inquired if any record had appeared on the Observatory seismographs to indicate that an earthquake had occurred at the time of the burst and, if so, whether it might have been the cause.

The vertical Benioff seismograph had produced a record lasting about three minutes that showed well-defined phases. It was quite evident that this was a record of the rockburst, and that there had been no general seismic activity that might have been the triggering cause of the burst.

The writer went to Kirkland Lake to consult with the mine officials and to obtain data regarding the rockburst. During the visit, E.W. Todd, Mine Superintendent, proposed that a seismograph station be established at the mine at company expense both as to initial cost and maintenance, but under direction of the Observatory. This proposal was accepted by the Department and steps were taken to secure instruments suitable for the conditions peculiar to the location. It took some months to decide on the best types and to have them manufactured, but the last items were received at Ottawa on October 31. After some weeks of testing, they were installed at the site selected by the writer, and the station came into operation on December 19, 1939.

Mr. Todd then proposed that rockburst research should be undertaken in the mine itself. This also received Departmental approval, and it was arranged that the general direction of the work should be assigned to the writer; a resident operator was secured in the person of Zack E. Gibbs, of San Marino, Cal.

In the meantime, Mr. Todd had resigned as Superintendent and Mr. A.E. Blomfield had been appointed to that office. The program continued to operate under the above conditions for about two years except that, from time to time, the company engaged part-time assistants for Gibbs. In June 1941, Frank Hallick was engaged as assistant on a full-time basis.

In 1942, the writer was assigned to full-time participation in the program, to be responsible for the work as a whole and to take over the underground studies. Hallick was to assist Gibbs in the maintenance of equipment and was to carry on the underground program in the writer's absence. This arrangement continued until the agreement with Lake Shore was terminated in 1945, when underground research was discontinued. Shortly thereafter, the surface seismograph was transferred to Hallick's property at Kirkland Lake, a vault was constructed, and a full complement of instruments of modern type and high sensitivity was installed. A first-class seismological station has been operated there since that time.

Further research programs, utilizing rockbursts as energy sources of precisely known location, accurately timed by the Kirkland Lake seismographs, were carried out during the next three or four years by John H. Hodgson and his associates. The data so obtained have enabled him to draw up improved travel-time curves for short epicentral distances and to determine surface structure over the Canadian Shield. These results have been reported by him in detail in a series of papers (see bibliography).

The seismograph installation at Kirkland Lake is today one of the fully equipped and regularly operating stations of the network operated by the Seismological Division of the Dominion Observatory.

Summary Sketch of Original Rockburst Reports

Brief summaries of the original twenty-two reports are given below. Alphabetic designations (A to W inclusive, omitting I) are here employed in preference to numbers, with a view to simplifying the references to sub-headings in the complete, but revised, reports forming the body of this publication.

Report A

Dec. 27, 1938 to Jan. 18, 1940

The report first outlines the events leading up to the establishment of a seismograph station at Lake Shore Mines. Then follows a discussion of a correlation between a list of rockbursts (1938-1939) as furnished by Lake Shore with the corresponding seismograph records at Ottawa, Shawinigan Falls, and Seven Falls. Comparison is also given, with reproduction of the records obtained at Ottawa, of the registration of the rockburst of Dec. 27, 1938 with a quarry explosion of 45,000 lb. of dynamite near New Haven, Connecticut.

The report then deals with the selection of seismograph and radio equipment, the testing of equipment at Ottawa, the choice of site and preparation of recording room, observation routine, and analysis of records from Dec. 19, 1939 to Jan. 18, 1940.

The report notes Mr. Todd's proposal that an underground rockburst research program be established at Lake Shore Mines, and outlines a series of recommendations in that connection for the consideration of the company.

Report B

Jan. 18, 1940 to April 15, 1940

As those conducting the underground research knew little of mining in general, most of this report is devoted to a description of conditions at Lake Shore.

The last part of Report B describes the equipment and procedure during the first two months of the new underground program.

Report C

April 15, 1940 to Aug. 15, 1940

The report describes the construction and equipping of an electronics laboratory and machine shop at Lake Shore.

Improvements to the surface seismograph are noted as having been completed. A new mine (underground) seismograph, designed and constructed by Gibbs, is reported in operation.

The question of the possible difference in vibration frequency between bursts and blasts is suggested as a possible study, and plans to that end are outlined. Other lines of inquiry discussed are: supersonic vibrations (suggested by the writer in 1923 as an index of pressure and a means of prediction of earthquakes): strain gauges (one constructed by Gibbs is shown); temperature variation measurements; systematic correlation of mine and seismological data.

The collaboration between the Lake Shore research group and that of The International Nickel Company of Canada Limited, at Sudbury was reported in some detail.

Report D

This report deals solely with the program with the surface seismograph. It describes the steps taken to ensure, as nearly as possible, complete time coverage of burst and earthquake recording. It details the procedure for fixing responsibility for any lapse; this is considered important as a means of maintaining efficient operation.

Report E

Aug. 15, 1940 to April 15, 1941

The report deals with progress for the period indicated. Two chief items of interest are an account of experiments with a bore-hole closure gauge (microgauge) designed by

V.E. Hollinsworth of the Observatory staff and a record, through a burst, made by the strain gauge described in Report C.

The report also describes experiments with seismic survey equipment for the purpose of measuring vibration frequencies and velocities in the mine. These yielded few data, and none of much value in burst prediction.

The reason for the attempt to distinguish differences in vibration frequencies as between bursts and blasts was that if such differences could be shown to exist it might be possible to design a filter for the mine seismograph that would transmit bursts more strongly than blasts. Some slight frequency differences were indicated by the seismic survey equipment and by oscilloscope experiments, and a filter was designed and built by Gibbs for the mine seismograph, but the results were disappointing.

Report F

This report describes experiments with the microgauge carried out on typical Lake Shore mine rock at the Mines Branch, Ottawa.

Report G

The report covers the recording of the surface seismograph for 1941. In addition to the text describing the operational modifications, and the tabular matter as given in Report D, 1940, the following tables are included: larger rockbursts located and listed by Lake Shore Mines and rockbursts recorded on the surface seismograph.

Report H

Ten of the larger rockbursts recorded on the Benioff seismograph at Ottawa were studied as a group to determine the velocity of elastic waves and the structure of the earth's crust in the vicinity of Ottawa. Each of these bursts was precisely located in the Lake Shore mine. Two had been accurately timed at Kirkland Lake by the surface seismograph. This paper initiated the research in velocities and in surface structure carried out over several years by John Hodgson and his associates.

Report J

April 15, 1941 to June 30, 1942

Experiments in the mine with the microgauge are briefly reported. Modifications of the mine and surface seismograph are discussed. A severe rockburst that occurred on July 30, 1941 is dealt with at some length.

Steps had been taken to study supersonic vibrations as indicators of increasing rock pressure. Some equipment had been assembled and experiments had begun when the work of Dr. Leonard Obert, of the U.S. Bureau of Mines, was brought to the attention of the Kirkland Lake group. This report outlines the steps that led to the use of Obert recorders for the supersonic vibration studies.

Report K

July 1, 1942 to Dec. 31, 1942

The report reviews the difficulties overcome, outlines the underground program in progress, and describes the layout of test holes from which records were being obtained by means of Obert recorders. It includes a number of conclusions and recommendations.

The report concludes with data on test holes assigned to rockburst research (their location, history, condition, etc.).

Report L

Jan. 1, 1943 to March 31, 1943

A heavy rockburst on January 29, 1943 occurred in the section of the mine in which the recorders were operating. The effects of this burst and a discussion of the records are given, with photographic illustrations. This burst furnished the best evidence of the fact that subaudible snapping (designated 'microseismims') gives warning of a burst. It also shows the limitations in the application of the method in a mine such as Lake Shore.

An extensive list of recommendations shows the trend of the program, and a complete tabulation of data from all test holes is given for the period. A list of rockbursts registered in January includes 61 for which the observations are tabulated.

Report M

April 1, 1943 to Jan. 31, 1944

The first part of this report is devoted to a revision of theories and deductions and to a series of recommendations. The further development of the research program is detailed. The routine of calibrating the equipment is described, the listening procedure outlined and the data obtained during the period are given in detail. The rockbursts occurring from April 1943 to January 1944 inclusive are listed.

Report N

A short bibliography of rockburst literature listing 58 items. It serves as the source of most of the publications listed in the bibliography at the end of this publication. The additional items cover only the later research program on rockbursts carried out by the Dominion Observatory through its Division of Seismology.

Report O

Feb. 1944 to June 1945

After reporting progress on the regular underground program, this report outlines a new intensive program carried out in a section of the mine considered particularly liable to bursts. Seventeen holes were spaced at 30-ft. intervals on each side of a section of drift, the holes being staggered so that there was one every 15 ft. Recordings were taken from nine holes in a planned order, each recording lasting a little over 5 minutes. One hole of the nine, designated as a monitoring comparison, recorded three times in the hour. The recording was carried on for 3 hours in the afternoon when mining activity was at a minimum, and for 3 hours in the 'graveyard' shift, when no mining was in progress. The strips of recorder tape were mounted in sequence and photographed each day. These photographs, with brief notes calling attention to features of interest, were published as reports P to V.

Report W

This report covers experiments of the College Park, Md., laboratory of the United States Bureau of Mines. Specimens of Lake Shore rock were cut into small samples and subjected to increasing pressure in a hydraulic press. A geophone unit attached to the specimen under test recorded on a regular Obert instrument.

The object of the experiments was to test the validity of the contention that high pressures on a rock specimen produce high-pitched, subaudible vibrations (microseismims), and that these microseismims offer a means of determining when the rock under pressure has reached the limit of its strength and is about to burst.

The experiments were undertaken at the request of the National Research Council of Canada, and were carried out by three Canadians (Hodgson, seismologist; Langford, mining engineer; Bailey, electronics engineer).

Report A

Surface Seismograph Installation

1939

o

A-1 Correlation of Rockburst and the Ottawa Seismograms

On December 27, 1938, at about 10:50 p.m., E.S.T., a severe rockburst occurred at Lake Shore Mines. It was decided that the writer should go to Kirkland Lake to learn what he could of the burst. While there, he made various attempts to determine the exact time of the burst, but was unable to do so.

The burst was slightly above the 2700-ft. level. About 160 ft. of drift was affected, 98 ft. being closed solidly. Broken rock resulting from a burst is coated with a fine white dust, indicating that part of the rock disintegrated at the instant of release from strain. Rock broken by blasting does not exhibit this dust coating.

Examination of the seismograms at Ottawa established the fact that no earthquake occurred at the time of the burst, and it must therefore be considered as being the sole cause of the record. The mechanism of the release of energy is exactly the same whether the storage of that energy was due to natural causes or to the mining operations. Moreover, the energy release in a severe burst is very great.

Lake Shore Mines furnished a list of the larger rockbursts that had occurred up to that of December 27, 1938. On checking these at Ottawa, the following report was sent to mine officials under date of January 11, 1939.

"You will note that the records of two instruments were checked -- the short-period vertical Benioff at Ottawa and the short-period horizontal Wood-Anderson at Shawinigan Falls. The Ottawa Benioff was not in operation previous to April 5, 1937. It was then run experimentally for a couple of months or so, the recording being sometimes interrupted to permit changes in the set-up. For this reason we have no records to check bursts numbered 1-5. The instrument was temporarily out of commission for Nos. 16 and 17 (July 19 and September 9, 1938).

"The net result of the check-up is that the only record obtained at Ottawa is that of December 27 last. Those recorded at Shawinigan Falls are those of January 5, 1937, July 19, 1938, and December 27, 1938. Presumably, the first two of these would have recorded at Ottawa had the Benioff been in operation at the time."

Requests for seismograms were sent out to those seismograph stations within a radius of 600 miles of Kirkland Lake at which short-period seismographs were operating during the period covered by the tabulation of rockbursts. None of these bursts were recorded except that for December 27, 1938, which was just visible as a trace on the Weston, Mass., short-period Benioff record. The arcual (computed) distance from Kirkland Lake to Weston is 580 miles.

Subsequent to December 1938 and through 1939, the larger rockbursts occurring at Lake Shore were reported to Ottawa (see list p.). Eight bursts were reported from Lake Shore Mines and recorded with phase differentiation at Ottawa.

A-2 Initial Discussions and Correspondence

In January 1939, E.W. Todd, of Lake Shore Mines, discussed with the writer the possibility of establishing a seismograph station at Kirkland Lake. The company undertook to finance the establishment of such a station and to purchase the equipment, also to provide quarters, electricity, water services, and daily attendance on condition that the Observatory would supervise the selection of instruments and their installation, would supply photographic paper and developer, and would provide such technical assistance as might be required. The Observatory was also to analyse the records and issue regular reports to the company; the seismograms were to become the property of the Observatory.

The Observatory stressed the point that the establishment of a single seismograph at Kirkland Lake would be of considerable scientific value but that, so far as rockburst prediction was concerned, the instrument could only be expected to record their times of occurrence and their relative intensities. This is specifically set forth in a letter from Mr. Stewart to Mr. Todd under date of January 11, 1939, which at the same time tabulated the various requirements that would have to be met by a seismograph operating under the exacting conditions obtaining at Kirkland Lake. The unusual amount of ground disturbance due to traffic and heavy machinery, together with the presence of power transmission lines, made it problematical whether any type of seismograph then available could be used to advantage. It was quite possible that if the sensitivity were made high enough to record the bursts, the local surface disturbance would vitiate the record. It was also evident that some means of readily adjusting the sensitivity would be essential.

In a letter to Mr. Stewart, dated January 14, Mr. Todd confirmed the verbal agreement and acknowledged the limitations outlined from Ottawa.

A-3 Selection of Seismograph and Radio Equipment

Correspondence was immediately initiated by the Observatory with those seismologists best qualified by experience to advise on the selection of an instrument; and the results were submitted to Mr. Todd on April 14. In his reply, dated April 17, 1939, Mr. Todd guaranteed to meet the cost of the equipment and of installation and maintenance.

Under date of April 25, the necessary authorization was given by the Department. A proposal was made by Mr. Stewart, under date of March 6, that the company should reimburse the Department for the cost of the seismograph and radio equipment, the whole to become and remain the property of the Department, and to be left at Lake Shore as long as required. The authority from the Department included a guarantee to leave the instruments at the mine 'at least 10 years, or longer if conditions so require'. This arrangement was agreed to by Mr. Todd in a letter dated May 8, 1939.

The equipment ordered consisted of the following:

1 Special Rockburst Recorder
1 Type SE-400-P Vibration Detector
1 Special Recording Camera from the Heiland Research Corporation.

and

1 National Standard HRO Receiver (2.5 volt)
4 Sets of Coils 1.7 m.c. to 30 m.c.
1 Speaker for above Receiver
1 Power Supply Unit (110 v., 25 cycles)
1 Set of Coils 100 k.c. to 200 k.c.
2 Sets of Coils 900 k.c. to 2,000 k.c. from the Canadian Marconi Company.

The initial radio equipment was received at Ottawa about July 8, 1939. It was tested under various conditions and by different operators throughout the summer and fall. The seismograph was received at the Observatory on October 31, 1939.

A-4 Testing and Installation of Equipment

On testing the equipment at Ottawa, it was found that certain alterations and adjustments to the seismograph were necessary, and this delayed the installation at Lake Shore. However, the instruments were placed in operation on December 19.

The site for the station, chosen by the writer, was below the gymnasium of the building used as living quarters by Lake Shore staff members: its relation to the mine is shown in Figure 5. An anteroom 5' x 7' housed the radio and time-recording equipment, and also acted as a light trap for the adjoining seismograph room. The latter (11' x 12', less a corner 3' x 5' -- Figure 6) housed the seismograph and a developing bench, with the necessary cupboard space. The emplacement of the seismograph is shown in Figure 7.

A-5 Observational Routine

On arrival at the station, usually about 12:30 p.m., the operator tuned in Station NAA (Arlington), adjusting the relay to give as clear reception as possible, and closing the knife switch on the relay at about 12:55, so that the beats up to and including the long note at 1 p.m. were recorded. If the work had to be done at another time of day, the operator tried to pick up the Observatory continuous signals (CHU): if these were not sharp enough to operate the relay, the signals were recorded by means of a telegraph key.

The record sheet was then changed, and the mechanism for driving the drum wound up. The sheet removed was developed, and the time breaks and other data entered in soft pencil; the completed sheet was then forwarded to Ottawa.

A-6 Further Rockburst Research Proposed

When the seismograph installation had been completed at Lake Shore, Mr. Todd suggested the possibility of further research on rockbursts. It seemed possible that a rockburst in any given section of the mine might be predicted, and the following possibilities were suggested:

(a) If a sensitive seismometer were installed in the area under observation and were to record continuously, the chronological pattern of the heavy rumbling noises preceding a burst might be learned by experience and serve as a basis for predicting later bursts.

(b) If the pick-up used were a sensitive microphone with its amplifier provided with a wave trap to cut out the rumbling, it was believed that high-pitch (perhaps ultrasonic) crackling might be found to precede bursts, in a chronological pattern that would have to be learned by experience.

(c) The velocity of sound in rock increases with the pressure, and it is possible to measure such velocities over short distances with the necessary precision to indicate changes in velocity due to increasing pressure. The velocity at bursting conditions has been found experimentally in the laboratory. If velocities were frequently measured at the suspected point in the mine, the approach to critical conditions could be observed.

(d) It is possible that continuous registration of temperature creep, by means of thermo-couples and amplifiers, might yield some indication, by its time pattern, of the approach of a burst.

(e) The use of strain meters to produce continuous records of the displacements in suspected areas might prove worth while.

(f) Reference marks could be installed at known faults in the mine. The separation of these could be measured at regular intervals, and would serve to indicate the activity along these faults.

Mr. Todd proposed that such research be carried on under the supervision of the writer, who was asked to suggest the name of a qualified man who might be employed by the company to take charge of the actual operations at Kirkland Lake. He suggested Zack E. Gibbs, of San Marino, Cal., who was engaged as of January 27, 1940.

The project was approved by the Department on January 12, 1940, and steps were taken to plan such studies as were possible with the limited equipment immediately available. Most of this was designed and built at the Observatory.

Appendix Section

A-7 Location Data for Rockburst of December 27, 1938

1. Geographical coordinates of centre point of No. 3 Shaft:

   N. 48°08'56.95" W. 80°02'42.72"

2. Azimuth and Distance from above point to centre of burst:

   N. 80°58'36" E. Distance: 213.8 ft.

3. Elevation of No. 3 Shaft Collar = 1051.0 ft. (Sea-level datum).
4. Distance below collar of No. 3 Shaft to point nearest the centre of the burst: 2,683 ft.

The readings for the Ottawa record of the rockburst are as follows:

H = 11:49.9 p.m., E.S.T.	S^* = 11:51:50
P_n = 11:50:52	F = 11:53.5
P^* = 11:51:01	$\triangle$ = 415 km. (258 mi.)
S_n = 11:51:37	

These readings are based on Joliat's Tables for nearby earthquakes. These evidently need revision, for conditions between Kirkland Lake and Ottawa at any rate, for the computed arcual distance between these places is 279 miles.

A-8 Correlation of larger rockbursts at Lake Shore Mines with seismograms at Ottawa and Shawinigan Falls March 20, 1936, to December 27, 1938
Short-period, vertical Benioff, Ottawa, Ont.

1. Mar. 20'36	3:25 p.m.	No records available
2. Dec. 3'36	9:45 a.m.	No records available
3. Dec. 16'36	3:25 p.m.	No records available
4. Jan. 5'37	7:30 p.m.	No records available
5. Apr. 27'37	2:40 p.m.	No records available
6. June 13'37	6:30 a.m.	No trace found

7. June 16'37	11:00 p.m.	Questionable trace at 9:59:45 (might be the burst if K-L time as given were Daylight Saving, as is probable)
8. Aug. 14'37	10:20 p.m.	No time breaks on the record Various faint traces, but not definite at 9:20± (or 10:20±)
9. Sept. 4'37	11:20 p.m.	No time breaks on the record. Various faint traces but not definite at 10:20± (or 11:20±)
10. Nov. 26'37	10:15 p.m.	Possible faint traces at 10:15 but clock beats and heavy microseisms prevent certainty
11. Dec. 24'37	5:00 a.m.	Microseisms and clock beats; no certainty of traces.
12. Apr. 6'38	3:15 a.m.	Very heavy microseisms; no trace
13. May 11'38	9:15 p.m.	Very heavy microseisms; no trace
14. May 20'38	12:45 p.m.	Microseisms present; no trace at 11:45 a.m. ± or 12:45 p.m. ± 11:45 p.m.± or 12:45 a.m.±(May 21) but sharp "local" type at 1:45:22 p.m., May 20. However, two others much the same at 11:03:23 a.m. May 20 and at 3:03 p.m., May 20
15. July 4'38	3:30 p.m.	Microseisms present; no trace
16. July 19'38	7:19 a.m.	No record available
17. Sept. 9'38	6:40 a.m.	No record available
18. Oct. 2'38	2:30 a.m.	Small microseisms; no trace
19. Oct. 14'38	2:40 a.m.	Small microseisms; no trace
20. Nov. 17'38	9:10 a.m.	Gear trouble and microseisms; no trace
21. Dec. 27'38	11:50 p.m.	Well recorded, begins at 11:50:52 and continues for a little more than two minutes

Short-period, Vertical Wood-Anderson, Shawinigan Falls, Que.

Of the 21 rockbursts reported above no trace was found at Shawinigan Falls, except for the following:

4.	Jan. 5'37	7:30 p.m.	Fairly good record beginning at 7:30:17 and continuing for about one minute
16.	July 19'38	7:19 a.m.	Trace at 7:28 a.m., continuing slightly less than a minute; not legible
18.	Oct. 2'38	2:30 a.m.	Faint traces, possibly due to the burst; quite illegible
21.	Dec. 27'38	11:50 p.m.	Trace at 11:52:09, continuing for about a minute; illegible

All records to which Daylight Saving time might have applied in the report from the mine were examined also an hour earlier than the time given. No traces other than those listed above were found.

A-9 Rockbursts at Lake Shore Mines, Dec. 28'38 to Dec. 18'39

The first section of each entry below gives the report as received from Lake Shore Mines. The times given in this first section are approximate only. The latter section shows the nature of the reception at Ottawa, with full readings of those tremors which were registered.

1. Feb. 7 1:25 p.m. Felt at Lake Shore, but no damage in Lake Shore Mines and none reported from adjoining properties.

Ottawa readings:

H = 1:25:26.6	e = 1:27:15.5
eP_n? = 1:26:25	e = 1:27:23
e = 1:27:02	F = 1:27.8
eS_n? = 1:27:10	Δ = 415 km. (258 mi.)

2. Feb. 19 4:02 p.m. Medium intensity.

Ottawa:

A single faint trace 4:06:25 to 4:07:05; may be due to other causes

3. Mar. 11 — 8:14 p.m. — Very heavy, disturbed large section of the mine covering a vertical distance of 500 ft. and a horizontal distance of 400 ft.; centred at 686 ft. S 80° 14' E from the centre of No. 3 Shaft at a vertical depth of between 3450 ft. and 3575 ft.

2 killed

Ottawa readings:

H = 8:14:11:.6
P_n = 8:15:10
P* = 8:15:18
S_n = 8:15:55
S* = 8:16:06.5
F = 8:17
Δ = 415 km. (258 mi.)

4. Mar. 26 — 4:50 a.m. — Heavy burst; location of apparent centre from No. 3 Shaft is 604 ft. S 26° 50' W.

Ottawa readings:

Ottawa records show light traces only from 5:08:01 to 5:10.5; may be due to other causes

5. Mar. 28 — 1:07 p.m. — Location of apparent centre from No. 3 Shaft is 936 ft. S 86°00' E.

Ottawa readings:

H = 1:09.0 p.m.
i(P*) = 1:10:40
i(S_n) = 1:11:17
i(S*) = 1:11:30
i = 1:11:33.5
F = 1:11.8
Δ = 445 km. (276 mi.)

6. Apr. 30 — 4:03 p.m. — Severe rocking motion; some slight trace in mine but not sufficient to account for surface tremors; no damage.

Ottawa and Shawinigan Falls got no trace

7. Aug. 31 — 2:50 a.m., 3:00 a.m., 3:04 a.m. — Three tremors, the first of medium intensity, the second heavy, and the third medium. These were followed by more tremors. Approximate centre of disturbance from No. 3 Shaft was 600 ft. in a direction S 80° E at depth 3575 ft.

Ottawa readings:

H = 2:51:59 a.m.
P_n = 2:52:57
P* = 2:53:05
S_n = 2:53:42
i = 2:53:55
i = 2:53:58
F = 2:55
Δ = 415 km. (258 mi.)

$H = 3:02:00$ a.m. $i = 3:03:58$
$P_n = 3:02:59$ $i = 3:04:00$
$P^* = 3:03:07$ $F = 3:06$
$i = 3:03:50$ $\Delta = 415$ km. (258 mi.)

There was no trace of the third disturbance, but the second shock was recorded as more severe than the first.

8. Sept. 2 2:40 a.m. These shocks were each of medium intensity; they originated at about the same locality as those of Aug. 31, but approximately 300 ft. deeper.

Ottawa readings:
$H = 1:44:55$ p.m. $i = 1:46:52$
$P_n = 1:45:53$ $F = 1:48$
$i = 1:46:02$ $\Delta = 415$ km. (258 mi.)
$S_n = 1:46:38$

No trace of the first of the above bursts was found on the records at Ottawa

9. Sept. 19 10:45 p.m. 11:25 p.m. Each of these bursts was of heavy intensity; they were followed by some fifteen smaller bursts, not sufficiently severe to register at Ottawa. The bursts occurred between the 1400 and 2500 ft. levels.

Ottawa readings:
$H = 10:54:44.5$ p.m. $iS^* = 10:56:46$
$iP_n = 10:55:46$ $iS_g = 10:57:00$
$iP^* = 10:55:55$ $F = 11:07$
$iS_n = 10:56:33.5$ $\Delta = 440$ km. (275 mi.)
$i = 11:08:10$ $i = 11:09:0$
$i = 11:08:47$ $F = 11:11$

It is just possible that an earthquake, represented by the first set of readings above, occurred somewhat north of Kirkland Lake, and that the rockbursts were set off at the mine as a consequence of the disturbance.

All times given in the section just completed (A-9) are given in Eastern Standard Time.

A-10 Explanation of index abbreviations in Table 1

1. Dates are recorded as: Day : Month
e.g. 19 : 12 indicates December 19.

2. Value of the time signal is given by a number in the scale 0 to 3, with the following signification:

   3 = excellent   1 = doubtful

   2 = fair   0 = lacking altogether

3. Time correction: + means clock slow
   - means clock fast.

4. The amount of time correction is given in seconds and is followed by the hour (on the 24-hour system beginning at midnight) nearest to which the correction was obtained. It is not underlined if the correction was obtained on the first day of the record. If it was obtained on the second day it is underlined, thus:
   + 110^s : $\underline{13}$ means that the clock was found to be 100 sec. slow at 1 p.m. (the normal time for taking time signals) on the second day of the record.

5. In the remarks column the following letters indicate comments most likely to be frequently used:

   B = Blasting at Lake Shore
   BT, BW = Blasting at Teck-Hughes or Wright-Hargreaves
   C = Charging equipment interference
   F = Finger marks on record
   S = Stain from developer on record
   R$^{\pm}$ = Rate of driving clock was accelerated or retarded; indicated by sign after the R
   G = Interference from games or dancing in the gymnasium
   Is = Recording light too strong
   Iw = Recording light too weak
   Iv = Light variable owing to voltage fluctuation
   a, b, c, etc. = Index letters to footnotes to tabulation, given at botton of sheet on which they occur.
   () = Brackets on any letter denote that the fault reported is relatively small
   $\underline{B}$, $\underline{R}$, $\underline{H}$ = at the end of the remarks line for each entry indicate the name of the operator responsible for the given date

Table 1 as given in this publication is the second of two given in the original report. It is given here to show the methods used to secure continuous and efficient service. There is no longer anything to be gained by presenting all such material in the present publication.

Table 1

KIRKLAND LAKE SEISMOGRAM RECORD

January, 1940.

No.	Rec'd	On		Off		Time Correction		Bursts	Quakes	Remarks	
		Time	Date	Time	Date	Value	Amount				
18	5:1	12:44 p. m.	1:1	11 a. m. ca.	2:1	1	+ 59. 5 :13	-	-	Batteries ran down; record fails after 11 a. m.	R
19	13:1	12:41 p. m.	2:1	1:02 p. m.	3:1	2	+51. 5 :13	1?	-	S, (Iw), B, BT. Light out 3:02 to 3:55 p. m., Jan. 2	B
20	"	1:07 p. m.	3:1	1:16 p. m.	4:1	3	+ 46. 5 :13	1?	-	(Iw), B, BT.	B
21	"	1:22 p. m.	4:1	1:05 p. m.	5:1	0	-	-	-	Clutch not completely engaged; no record.	B
22	"	1:10 p. m.	5:1	11:25 a. m.	6:1	1	+ 44. 5 :14	2?	-	B, (G), Iw.	B
23	"	11:31 a. m.	6:1	1:02 p. m.	7:1	3	+ 37. 5 :13	1+?	-	B,C, (G), a. Very good light spot intensity.	?
24	"	1:06 p. m.	7:1	1:03 p. m.	8:1	3	+ 33. :13	1?	-	Is, C, B, G.	?
25	"	1:09 p. m.	8:1	1:03 p. m.	9:1	3	+ 30. :13	2?	-	(Is), B, BT. Very nice rate on clock drive.	B
26	"	1:09 p. m.	9:1	1:01 p. m.	10:1	1	+ 26. 5 :13	4?	-	B, G, BT.	B
27	23:1	1:06 p. m.	10:1	1:02 p. m.	11:1	3	+ 23. :13	3?	-	B. Effective light spot intensity.	?
28	"	1:06 p. m.	11:1	1:05 p. m.	12:1	-	-	-	-	No record; clutch out; breaking in a new man.	B
29	"	1:09 p. m.	12:1	12:40 p. m.	13:1	1	+ 20. 5 :14	1?	-	G,B,C. CHU time signal.	B
30	"	12:47 p. m.	13:1	12:32 p. m.	14:1	1	+ 17. :13	-	-	B, G, Is (corrected after 1:47 p. m.), b.	A+R
31	"	12:37 p. m.	14:1	1:02 p. m.	15:1	2	+ 10. 5 :13	1?	-	Iw, (C). Second of two time comparisons used.	B
32	"	1:08 p. m.	15:1	1:03 p. m.	16:1	3	+ 7. :13	1?	-	S, Is, B, (G). Well-marked blasting; No. 4 Shaft.	B
33	"	1:09 p. m.	16:1	1:09 p. m.	17:1	3	+ 4. :13	1?	-	C, B, G. Bubble blank due to developing (small)	B
34	"	1:13 p. m.	17:1	1:04 p. m.	18:1	3	+ 0 :13	1+2?	-	F, B, c. Change to 12-volt charger.	B

a Small but well-marked burst at 5:09:50 a. m., Jan. 7.
b Dance and card party in gym. evening of Jan. 13.
c Fairly well-marked burst at 10:17:43 p. m., Jan. 17. Was "not located in the mine".

Report B

Initial Mine Research

January 18 to April 15, 1940

°

B-1 Geology of Kirkland Lake Area and Lake Shore Mines

According to Robson (2), "the productive veins of the Kirland Lake district lie within a belt of metamorphosed tuff, conglomerate and greywacke, which occupies a synclinal trough in the old Keewatin basement". In the vicinity of Kirkland Lake, numerous granitic offshoots, chiefly syenitic types, have intruded the older sedimentary rocks in an area north of the central axis of the syncline. The intrusions occur in the form of dykes and small bosses, which together make up the greater part of the ore zone. This syncline is about 2 miles wide in the vicinity of Kirkland Lake and extends for about 100 miles in a direction roughly east-west.

The orebodies at Lake Shore were deposited in pre-ore overthrust fault zones, the faults being caused by pressure from the southwest. There are two main veins, the No. 1, or south vein, and the No. 2, or north vein. They lie roughly parallel and about 400 ft. apart at the surface. No. 2 vein is 2,800 ft. long from boundary to boundary of the Lake Shore property. The outcrop of the veins has a strike roughly N60°E. The dip varies, according to Adamson (8) "from about 75° to the south, down to the 1200-ft. level, to approximately 87°, also to the south, for 1,800 ft. below this horizon". There are also several important diagonal veins. The plan of these veins at the 3075-ft. level is shown in Figure 8.

The orebodies are thus subsequently mineralized pre-ore overthrust faults. These faults were caused by pressure from the southwest.

The mine has been developed from a series of shafts on a line running at approximately right angles to the veins, at about the centre of Lake Shore property. It is to be noted that, when the mine was first opened, only the south or No. 1 vein was visible on the surface, the north or No. 2 vein being concealed beneath Kirkland Lake, which has since been filled by tailings from the mine.

There is an important difference between the east and west sections of the mine. From a point roughly 200 ft. west of the line of shafts to the eastern boundary of Lake Shore property there lies a porphyry mass that has not been invaded by other intrusives. It has, however, been subjected to post-ore cross-faulting of considerable magnitude. The displacement of both veins at the extreme east end of the property is 600 ft., the eastward continuance of the veins being thrown up into the Wright-Hargreaves property. To the west, the intrusives are in smaller masses, tongue-shaped in horizontal section. Post-ore cross-faulting is here less pronounced. There are, however, a goodly number of these cross faults joining the two chief veins; these are clearly due to tension. As between the two principal veins, cross-faulting is more pronounced on No. 1. A large pre-ore diabase dyke occurs near the western boundary of the property.

In addition to the post-ore cross-faulting, strike faults are encountered although, with few exceptions, the displacement along them is not great. These dip at a lower angle than the principal veins (as little as 30°) and have a strike slightly more to the north. Tension cracks were developed in some parts of the footwall of the south vein, and thus provided channels in which ore was deposited. Their presence in any part of the development results in increased width of drift and stope.

The north vein is much the more productive of the two larger ore zones. This is due to the fact that it is much more crushed than is the south vein. At various horizons, branching vein structure has resulted in the formation of parallel orebodies. High-grade orebodies as much as 70 ft. in width are found in this vein, particularly in the fractured zone at its junction with the diagonal vein. Because of the more widespread fracturing of the rocks in the west end of the mine, this section has, in general, larger ore shoots than has the east end. A model of the north vein has been constructed, covering the section from the 3075-ft. level to the 4075-ft. level, on a scale of 20 ft. to one inch. Important ore shoots were found in both the south and diagonal veins towards the east end of the property.

The principal fact to note, from the standpoint of rockburst study, regarding the geology of Lake Shore is that the north vein, particularly in the west half of the mine, is much more crushed and fractured than the south. The vein-fracture pattern is made up of several parallel fractures with diagonal breaks joining them, resulting in the formation of roughly diamond-shaped blocks. This structure persists not only in the larger masses, but throughout the blocks of these masses, and is apparent in both cross-section and in plan. A well-developed system of jointing results in weak walls, particularly in the north vein, where crushing has been more pronounced. When the ore is mined, especially if the rock is porphyry, small angular blocks are formed along the walls and, if unsupported by backfill or timber, the sloughing will extend for quite a distance into the walls of the orebody. When the walls are predominantly basic syenite, larger lenticular slabs are formed. They are bounded by smooth surfaces coated with chlorite and other secondary minerals, resulting in treacherous stope walls that require careful attention. In general, the Lake Shore rocks are hard and brittle. The jointing and the numerous contacts of various types of rocks, notably in the west end of the mine, are features that tend to result in the building up of stresses that are released by rockbursts of various types.

B-2 Development

By the term 'development' is meant the work done in a mine to provide access to the stopes or working faces of the orebody and to permit the transportation or ore, waste, fill, and other materials. The development at Lake Shore Mines will be discussed briefly in order that an index may be placed on record to serve in the case of later references to various mine locations. With regard to nomenclature, it is to be noted that serial numbers indicate the chronological order of development; for example, No. 1 and No. 2 veins as previously noted. Shafts Nos. 1 to 6 were sunk in that order. A drift is indicated by a preceding number of one or two digits as required, to indicate the level, followed by a two-digit number indicating the order of development and followed again by E or W, showing the direction of the drive, e.g. drift 3908W refers to a drift on the 3950-ft. level, it being the eighth drift to be opened on that level, and indicates that it was drifted in a westerly direction.

(1) Shafts and Hoists:

The six shafts at Lake Shore Mines lie roughly on a line that runs at right angles to the veins at about the centre of the property. No. 1 goes to a depth of 4,500 ft. in two stages; the first from the surface to 2,200 ft. and the second offset at the 2000-ft. level, where the hoist is located.

No. 2 is inclined at 18°, extending to the 200-ft. level from what was once a peninsula on the north side of Kirkland Lake. Railway terminals are adjacent to this shaft. A timber-framing plant, timber storage yard, and timber-treating plant are located at its entrance. The fire hazard is thus kept far from the mine proper and the passage of timber and other construction materials into the mine is facilitated.

No. 3 drops from the surface to 4,000 ft. in one stage. Because of the proximity of this shaft to the north vein zone, a portion of the orebody had to be left in place. There was thus a great deal of valuable ore tied up in the shaft pillar and the crushed nature of the rock made the use of the shaft a serious hazard. It has therefore been abandoned for hoisting purposes and is now used as the main upcast airway for ventilating the mine.

No. 5 also begins at the surface and drops to 4,000 ft. in one stage. It was sunk 70 ft. through mill tailings dumped in what was formerly Kirkland Lake, and in spite of the location the water seal is so effective that no water of any consequence enters the mine. There is, in fact, very little seepage anywhere in the mine. Lake Shore may be classed as a dry mine, but the mine air is very moist and in many places the walls are wet. The Geodetic Survey has tiedin the collar of No. 5 shaft as being 1051.03 ft. above sea level.

Shafts 4 and 6 extend from the 3950-ft. level to locations in lower horizons of the mine. Shaft No. 6 is temporarily bottomed (as of 1940) at 4750 ft. while No. 4 is being extended below the 5325-ft. level (1940).

For the purposes of this article it is sufficient to note here that:

(a) The line of shafts lies roughly N30°W, as shown in Figure 8. The entrance to No. 5 shaft lies farther to the north, along a line from No. 1 to No. 3 and a little west. It is 125 ft. north and 250 ft. west of the collar of No. 3 shaft. It is thus 80 ft. in the footwall of the north vein on the 200-ft. level and 600 ft. in the foot-wall on the 3950-ft. level.

(b) The hoisting machinery is on the surface in the case of No. 5 shaft, and at the 3575 and 3825-ft. levels in the case of No. 6 shaft.

(c) No. 5 shaft is about 17 x 13.5 ft. in cross-section and is divised into five compartments. The largest of these accommodates the main hoist, which can carry a load of 45,000 lb., and the others carry two smaller hoists, ladders between levels, electric cables, and pipes for air and water.

Stations are cut in the shaft wall at set vertical intervals. From these stations, cross-cuts are run back to meet the two veins. At the intersection of a cross-cut with a vein, drifts are run east and west along the orebody to the boundaries of the property.

Down to 2200 ft., the levels were run at 200-ft. intervals, and below that at 125-ft. intervals. The levels below 2200 ft. were thus run at 2325, 2450, 2575 ft. and so on. No level designation carries the hundred digit 1 or 6.

The drifts were given 4-digit designations, the first two being the hundreds digits of the level and the last two being reserved to indicate the chronological order in which the drift was developed on that level. The letters E and W were added to indicate the direction from the cross-cut. Thus the first drift to be run west on the 2825-ft. level is designated the 2801W drift. A digit following the letter indicates the section. Section intervals are 100 ft., and the number 2801W-8 therefore indicates a section 800 feet west on drift 2801W.

It is natural, then, in referring to a level, to indicate it in even hundreds, e.g. to call the 4075-ft. level the '4000-ft. level'. It must be remembered, however, that the separation in vertical distance between any pair of adjacent levels below 2200 ft. is always 125 feet. Thus the difference in elevation between the '4000-ft. level' and the '4200-ft. level' (the latter properly so called) is 125 ft., not 200 ft., as might be expected.

Throughout this publication, both the true and the conventional level designations are used indiscriminately.

The hoists make regular trips at shift change hours, but at other times operate irregularly, moving ore, waste, and supplies. They can therefore be relied on for transportation at change hours only, although the hoist man can sometimes arrange for travel between levels at other times.

B-3 Mining Procedure at Lake Shore Mines

Practically all mining at Lake Shore is overhead. In the upper levels, shrinkage stoping and stull stoping were used; but, as the mine was developed to deeper levels, the horizontal cut-and-fill methods came into use. There are some shrinkage stopes in the upper levels from which the shrinkage ore has not as yet been removed (1940).

As time went on and the mine was developed below the 2000-ft. level, rockbursts became more frequent and more severe, and square-set rill stoping was adopted. At the present time experiments are being carried on with horizontal cement plugs immediately over the lower drift. Such cement plugs are the full width and length of the stope and 8 ft. deep. In some cases they are reinforced with tension cables and iron rods. Such plugs will, it is hoped, relieve some of the pressure on the stope walls until the ore has been mined out (Figures 47, 58 and 62).

In the west end of the mine, the veins were not mined out for a distance of 100 ft. from the cross-cuts. About the centre of the west end, another section of vein 100 ft. wide was left. These sections are referred to respectively as the shaft pillar and the west pillar (see Figure 8). Raises at the boundary and at the sides of these pillars provided four working faces or stopes, which could be carried forward away from the pillars until they met in the centre.

B-4 Rockbursts in the Kirkland Lake Region

Informative papers on this subject have been published by: Christian (5), Robertson (6), and Robson *et al*. (7). Valuable contributions to the same subject are given in earlier papers by Robson(2) and Weldon(3). These are listed in Section B-6. Some of the points brought out in the papers referring to Lake Shore Mines are noted below:

The governing factors affecting the incidence and severity of rockbursts are:
- Type of rock and its properties;
- Depth of workings, other conditions being equal;
- Dip of the orebody and rock structure;
- Mining methods and speed of operation.

It has been found that:
- Bursting occurs in many instances at the time of, or closely following, blasting;
- Complete extraction of ore is desirable, and the leaving of small pillars*, whether of ore or waste, is to be avoided, so that a gradual and uniform subsidence of the hangingwall may take place;

* The term 'pillar' is used rather loosely to indicate any body of rock or ore with more or less definite, if sometimes only partly visible, physical boundaries (air-rock, air-ore, ore-rock). For example, a section of waste rock between two branches of a drift is a pillar. In Figure 8, we have, in plan, a section of ore 100 ft. long (which is, in elevation, at least 1000 ft.) of varying thickness and cut entirely through at every drift, yet this mass of ore is called the West Pillar. If the ore in any drift in this West Pillar is capable of taking pressure vertically, horizontally, or obliquely, it is itself a pillar. If a stope is mined out from below until a thin section only remains below the floor of the next drift above, it is referred to as a sill pillar or a floor pillar.

Horizontal pillars are a menace and should be avoided or else removed as soon as possible;
Mining out a remnant from two directions is not good practice, regardless of the form of the triangle established;
Steep rills avoid the formation of horizontal remnants and hence are least susceptible to bursts;
Long rills extending from level to level and advancing in the direction of unmined ground are less susceptible to bursts than those mining out a remnant;
The method of mining vertical cuts in short sections is useful in particluarly heavy ground, but costs are higher;
Bursts at either side do not transfer through the shaft pillar, nor, in most cases, do they occur close to it;
No bursts have occurred in the vertical pillars formed by the Tech-Hughes boundary line and the diabase dike.

Rockburst types may be listed as:
Strain bursts, affecting the face of workings only;
Pillar bursts, where a volume of rock bursts in a more or less localized part of the mine;
Crush bursts, where larger sections of the mine burst and settle.

The mechanism by which, it is supposed, the large stresses are built up is known as doming. As a section of ore is taken out of a stope, the rock in the wall, with or without partial support of crib and fill, is called upon to hold open the workings. The face of the rock is generally in the crushed region of the vein and has little strength. The stress is supported by the rock behind, which acts as an arch or dome,spreading the stress to the pillar edges. As the workings increase in size, the dome changes in dimension and the stress per unit area on the pillar increases. If this stress exceeds the bursting strength of the pillar, a rockburst results. Doming takes place in the hangingwall at lesser depths than in the footwall.

In the upper part of the mine, there was some displacement of the veins along a strike fault which gave a displacement to the south of as much as 90 ft. in the case of the most prominent strike fault. In this area therefore, the upper workings are over a solid base in the footwall of the vein. The doming caused by the upper workings is thus not carried on downward to the lower levels. This type of fault does not extend below the 1600-ft. level.

The location of rockbursts in the various workings at Lake Shore Mines is given by Robson et al. (7). Some of the larger bursts are described and their effect on timbering and on the circular steel sets is noted.

The prevention of rockbursts has depended in the past, and must continue to depend in the future, on careful mining technique, particularly in the matter of speed. At Lake Shore, to reduce the hazard, two eight-hour shifts only are worked--from 7 a.m. to 3 p.m. and from 7 p.m. to 3 a.m. All major blasting is restricted to the off-shift periods, when only a few workmen are in the mine. The blasts are fired electrically from the shaft station, the stopes being fired in order, beginning with those farthest out.

B-5 Adaptation of Research Program to Mine Conditions

In the foregoing, care has been taken to include all observed data that would affect the design of the research equipment or the planning of the program. All equipment will have to be designed for the conditions found in the mine. Some of these are noted below:

(1) Equipment will have to be operated in very moist air, but little or no special precautions need be taken against dust.

(2) Operational noises and electrical disturbances in the vicinity of the cross-cuts that may affect recorders are likely to be caused by: hoists, charging stations, hoist machinery, ventilating fans, ore and waste discharges, fill runs, crushers, annunciator and telephone systems, locomotives and trucks with ore and supply loads, water pumps, and chute blasts to loosen ore.

(3) Operational noises and electrical disturbances in the drift regions that must be considered may be caused by: drilling, discharges of ore from chutes in the stopes, discharge of fill into stopes, transportation equipment, water pumps, popshots for timbering and placing drills and blasting.

(4) Equipment must be made in units that can be lifted by one man and loaded into trucks so as to clear all timbering and permit of unloading at its destination.

(5) Locations for seismic equipment, which will be placed for the most part in the west end of the mine, must be on solid rock. This will mean scaling into the walls and providing cement-lined recesses for the units, which must therefore be as compact as possible. Equipment must be so placed as not to obstruct traffic through the drifts.

(6) Locations should not be in the west pillar, but as close to it as possible in the drifts.

(7) As shaft travel is time-consuming, projects should be planned to require as little as possible.

(8) As the shaft provides ready access to all levels, the problem of installing electric cables would be mainly one of expense, should it be decided to set up a surface recording system.

(9). As the only electric service in the stopes is for blasting purposes, equipment should be battery-equipped as far as possible.

(10) To avoid using mine trucks, a light service truck that can be lifted from the track should be provided.

(11) The uniform temperature conditions do not present a problem for seismic equipment and the situation is favourable to studies on temperature effects within the pillars due to changing pressure.

(12) Since all workings are interconnected, it should be possible to record with seismometer and microbarograph at the same location and obtain some indication of the position of a burst from the time interval between the elastic wave through the rock and the shock wave through the air.

B-6 References for Preceding Sections of Report B

1. Todd, E.W. Kirkland Lake gold area. Ontario Department of Mines, Vol. 37, Part 2, Toronto, 1928.
2. Robson, W.T. Lake Shore geology. The Canadian Mining and Metallurgical Bulletin, No. 287, Montreal, March, 1936.
3. Weldon, Leslie S. Mining methods and practices at Lake Shore, Ibid.
4. Dougherty, E.V. Some geological features of Kolar, Porcupine, and Kirkland Lake. Economic Geology, Vol. 34, No. 6, Lancaster, September-October, 1939.
5. Christian, J.D. Rockbursts at Teck-Hughes. The Canadian Mining and Metallurgical Bulletin, No. 331, Montreal, November, 1939.
6. Robertson, A.F. Rockbursts at Wright-Hargreaves, Ibid., No. 332, December, 1939.
7. Robson, W.T., J.C. Adamson and W.E. Selnes. Rockbursts at Lake Shore Mines. Ibid., No. 333, January, 1940. (Excellent rockburst bibliography appended).
8. Adamson, John C. Construction and equipment of No. 5 shaft at Lake Shore Mines Limited. Canadian Mining Journal, Vol 61, No. 1, Gardenvale, January, 1940.

B-7 Initial Program Planned and Equipment Provided

The aim of the March program was to determine the nature and occurrence of mine noises that might, by their chronological pattern, indicate that a pillar was in danger of bursting. As nothing was known as to the vibration frequency of such noises, two frequency ranges in detectors were required. A Heiland geophone covering the frequency range from about 20 cycles to 75 cycles (see Figure 18 for interior construction) and, for the higher frequencies, a Brush crystal detector (Type DP-1) ranging from about 1 cycle to a little over 5000 cycles, were purchased.

The amplifier for use with the above detectors was built by Hollinsworth for another purpose, but was made available through the courtesy of the Dominion Astronomer and Mr. Hollinsworth. The amplifier was designed to have a linear amplification over the combined range of both detectors, but had not been tested and modified when it was taken over for this work.

The recorder was built at the Observatory under the direction of Hollinsworth and according to his design. It records with ink on ordinary paper. For details of the pen see Figures 19 and 20. The pen is mounted at right angles to the axis of a Milne-Shaw recording drum, which uses a sheet of paper about 10 by 19.5 inches, travelling at 8 mm./min. To mark time, an alarm clock was fitted with a minute contact operating a relay through two

No. 6 dry cells. The relay, in turn, supplied current from a single No. 6 dry cell, through a rheostat, to the loud-speaker unit of the pen. The rheostat permitted the amplitude of the time marks to be adjusted. A small copper oxide rectifier between the amplifier and the speaker unit of the pen was arranged so that all mine noises were recorded by a downward mark of the pen. The time marking device was arranged to move the pen upwards to mark the minutes. The recording assembly is shown in Figure 20.

The recording unit and amplifier were mounted in a wooden case, the latter in the lower part and the recorder in the upper. Holes in the shelf allowed the heat from two 40-watt lamps to reach the recorder. This was found to be ample protection against the dampness of the mine.

As set up in Section 8W of 2901W, the crystal detector was suspended on the drift wall. The rock was spalled at all points in the vicinity, so the detector did not rest on solid rock. For this same set-up the Heiland geophone was set firmly wedged on loose rock on the face of the drift. More solid conditions were available in the second set-upin 3908 (south drift). These are shown in Figure 21.

B-8 Recording Program as Implemented

(1) Mine Seismograph

The equipment was received at Lake Shore early on Monday, March 11, and was immediately set up and tested. The instruments were set in place and connected at a location in the unused south drift about 90 ft. east of cross-section 2909 on Tuesday.

The installation began operating on Wednesday, using the Heiland geophone, but, as a result either of faulty adjustment or dampness, the recording pen lost contact soon after operations began and the ink dried in the pen, with the result that no data were recorded for the period March 13-14. On March 17 the Heiland geophone was replaced by a crystal detector, and good 24-hour records were obtained for the next three days.

On the 20th, the installation was moved to the east end of 3908W, where good records were obtained up to the 26th--the date of the report. The detector was first attached to a post resting on service pipes running along the floor of the drift, but it was pointed out that these pipes carried tremors resulting from normal mine operations, so on the 25th the supporting wires were fastened to the rock (Figure 21).

Each day, the records were compared with the mine captains' reports showing the amounts of explosive used and the nature of the rock blasted. Special reports on the positions and times of all popshots for timbering were also received and, for one day, a report on the movements of electric trains in the vicinity of the west pillar on the 3950-ft. level. Full 24-hr. runs were obtained regularly except for the first two days, when the pen ran dry. The record for March 19-20 is shown in Figure 17.

(2) Surface Seismograph

The surface seismograph was completely overhauled and the timing circuit was arranged to operate from a dry cell instead of from the battery supplying the light source. This eliminated any possible interference by the charging generator. The efficiency of the surface installation was greatly enhanced and served as a valuable check on the mine seismograph.

As it was sometimes impossible to receive time signals, even from NAA, the aerial was taken down and re-wired, the dimensions being changed. The long wire was cut and three insulators were inserted at intervals of 66 ft. From the middle insulator an ordinary lamp cord was run to the receiving set. Each conductor of the lamp cord was soldered to one 66-ft. length of the antenna. When connected to the receiver as a 'half-wave doublet', this antenna gave excellent reception of CHU on 3330 Kc. and reduced the static. By changing the method of attaching the feeders to the receiver, the antenna may be used as a simple capacitive antenna. Knife switches were mounted on the wall of the radio room to facilitate the change. Operating as an ordinary antenna, the signals from NAA were better than before, owing mainly to a better signal-to-noise ratio obtained with the effectively shorter antenna.

B-9 Deductions from Data Obtained

Observed results of the short recording program carried out with the mine seismograph follow:

(1) All blasting and all reported bursts in the region of the west pillar appeared to have been recorded by the mine seismograph.

(2) The crystal detector was more sensitive for both the blasts and for the few small strain bursts experienced during the experimental runs.

(3) There seemed to be no record of any noises in the mine other than those due to mine operations and to the strain bursts reported. A few other shocks seemed to have recorded in the same way as strain bursts and appeared on the charts of both mine and surface seismographs. These were probably due to small strain bursts not located by the miners.

(4) No mine noises, as distinct from strain bursts were reported in the vicinity of the west pillar since recording began. The mine was not 'talking' or 'cracking'.

(5) Dumping of ore or waste rock through the chutes was not recorded except at the set-up in 3908W where the chutes were very close and the recording was affected by the improper attachment of the detector wires.

(6) The seismograph, when in 2901W, picked up small blasts from greater distances than when in 3908W.

(7) The seismograph seemed to pick up small blasts from greater distances below it than above, indicating that the energy of a blast travels more freely upward than downward; e.g. when in 2901W it recorded small blasts in the 5300 cross-cut with equal or greater amplitudes than when in 3908W.

(8) Rock drills did not affect the seismograph, even when operating quite close by, e.g. in the stope above 3908W.

(9) Locomotives and trains, even when loaded, did not record unless passing very closely. Detailed reports of locomotive operation were obtained for one day only.

(10) Strain bursts gave no warnings that can be detected on the slow time scale of the recording drum (paper speed 8 mm./min.).

(11) Experience indicated that the detector (crystal or geophone type) should be installed on solid rock, with no direct connection to timbering, piping, electric services, or tracks.

B-10 Limitations of Equipment

It will be clear from the foregoing that the assembly had to be improvised at short notice, with no definite knowledge of the frequency characteristics that were to be measured, and it seems certain that even if some of the recorded offsets were due to mine noises as distinct from operational ones, it could not give a clear picture of mine noises alone.

If, therefore, the investigation was to continue new equipment would be required. The two detectors would cover a frequency range to 5,000 cycles, but a third unit to extend the frequency range to at least 10,000 cycles would have to be added. It would also be necessary to build an amplifier that would filter out operational noises and record mine noises only. This phase of the problem is discussed later.

The investigation generally had proved well worth while, showing the general noise level in the mine and demonstrating the feasibility of operating delicate detectors underground. It was, however, clear that for a regular program a new type of recorder would have to be developed.

B-11 Instrumental Criteria for New Recorder

(1) Listening Post Equipment:

Listening post equipment should have a variable-speed recording unit so that it may be speeded up at those times of the day when it is desired to get a clear record of the nature and frequency characteristics of certain noises. The amplifier should be equipped with filters that would enable the operator to confine the record to those sections of the frequency spectrum that it may seem desirable to explore. Equipment that meets these criteria was available commercially, and it therefore seemed better to make a selection of the various commercial units and then build them into a coordinated whole, than to attempt to build an outfit from the ground up.

The coordinated equipment should have a portable recording unit, operating on A.C. or batteries, that would record with ink on sprocket-driven paper charts at any desired speed:

(a) all noises, as to amplitudes
(b) the amplitude of noises of segregated bands of specified frequency, or
(c) the frequencies of all noises, regardless of amplitude, therby identifying the type of sound and, probably, its source.

It would be desirable to perfect a single unit at first: it would then be possible to locate all the recorders in the office building on the surface. The only difficulty in such an arrangement would probably be the expense of providing shielded cable connections from the various detectors to the central recording station. The advantages of such an arrangement are obvious, but it could not be recommended until all experimenting with a single recording device had been satisfactorily completed.

(2) Time-recording Devices:

The most serious instrumental difficulty in carrying out a research program on seismic velocities would be in securing time-measuring devices of the necessary sensitivity and precision. The total time for a seismic wave to travel 1000 ft. in a pillar would probably be about .05 sec. The shortest distance of travel involved in the program would be about 100 ft. which would involve a travel time of .005 sec. Variations in total time, which would be the quantity required for burst prediction purposes, would thus be about .0001 sec. To do this, clear and accurately timed lines would have to be photographically recorded at intervals of .001 sec.

(3) Strain Meters:

If strain meters were to be used in the drifts, it would be very desirable first to study closely the extensive work previously done in this field.

The meters would have to be installed at numerous points, and it would be necessary for readings to be taken regularly and frequently, and for the results to be kept tabulated right up to date.

In some cases, the variation in dimensions of the pillar itself could be taken with a constant tension device suggested by Gibbs, provided it were possible to drill a hole completely through the pillar from stope to stope and from drift to drift. Such a procedure would be very informative. It could probably be used to advantage in small pillars.

B-12 Laboratory Facilities Required

For a continuing research program facilities would have to be provided at the outset for an electronics laboratory. Such a laboratory should be light-tight, ventilated, and provided with hot and cold water, A.C. and D.C. power supply, compressed air, and gas. An oscilloscope, frequency standards, etc. would be needed, as well as the necessary measuring devices, tools, and supplies.

B-13 Interim Program Proposed

The interim program described below would require a year or more of experimenting until suitable equipment for measuring the various physical properties of the rock in the mine was developed. It might, perhaps, evolve the chronological pattern of the physical phenomena, significant for the purpose of rockburst prediction. Whether it did or not the necessary pattern of routine observation would then be indicated and an established routine program could be planned.

Five distinct types of investigation are recommended. The details of providing for each of these (from the point of view of the difficulties involved) have been treated in sections B-13 and B-14. The present section sketches briefly the proposed method of attack in each case and the equipment required.

(1) Listening Post:

If a single listening post only is planned, it should be a portable type that could be set up at various points. Battery-operated equipment is indicated.

(2) Velocity Measurements:

The west pillar is at least 1000 ft. in height, measured along the dip of the veins. If a seismic prospecting outfit were obtained, the recording unit could be set up in some convenient position in a drift midway of the pillar and cables run up and down to several geophone pickups sealed in suitable positions at various heights in the pillar walls. Arrangements might then be made for a five-minute stoppage daily at some convenient time for observational purposes.

At this time, a shot of approximately one stick of dynamite would be fired at a selected point in the pillar. A wire would have been run previously from the recording unit to the firing point. This wire would be left in place from day to day to record the instant of discharge. The camera would run through about 30 inches of paper per second, recording the arriving tremors in full detail.

Such a record would show to .0001 sec. the travel time from the shot point to each of the geophones and would thus give the times for several paths through the pillar. By firing at several points, the number and position of the travel paths could be increased for each firing position. The geophone would remain in position, the recording unit would be sealed and left ready for operation, and the lines to each firing poistion would be left in place.

The shifting of stress from one part of the pillar to another as mining progressed would reveal itself in the relative movements of the plotted travel times for the various paths. Such a composite graph would be most informative.

(3) Strain Meters:

It was proposed to place these in numerous positions in drifts throughout the west pillar region and also, if possible, in some of the smaller pillars, as well as in the east side of the mine. They would be set in place permanently and read at frequent intervals.

(4) Thermometric Measurements:

It was considered that instruments for this purpose could best be built by Gibbs and installed by him at no cost except for supplies. One or two experimental stations would suffice for the duration of the proposed interim program.

(5) Fault Markers:

It would involve very little expense for the construction and installation of devices for measuring the amplitude and direction of slow displacements along the plane of all major faults exposed in drifts. These would be designed to involve a minimum of servicing. Some thought was given to this form of research and several designs for such markers were discussed.

Fault markers should be installed in the east end of the mine also, where faulting is more marked and, presumably, more active. The tabulated results would be obtained at a minimum of expense and trouble and should prove most informative. It was recommended that the installation and servicing of such markers be included in any continuing program adopted. The expense, other than overhead, would be purely nominal.

Note: In all the above, except as noted, it was proposed to confine the investigations to the west pillar, where conditions were more simple in that there were fewer faults. The pillar, too, was smaller, and was changing more rapidly as mining progressed.

B-14 Conclusions

The five forms of investigation proposed above, if carried on simultaneously, would give a comprehensive picture of the tectonic conditions in the mine. No such concerted attack on the problem of rockbursts had ever been attempted in Canada, so far as the writers were aware. Indeed, until quite recently, electronics was not sufficiently advanced to allow such

work to be carried out.

The data obtained from this interim program would be of ever-increasing value. It was considered that the ultimate goal of rockburst prediction was more nearly possible than had been thought and that the proposed program was a reasonable method of procedure towards that end. Its adoption as a coordinated whole was recommended.

Report C

Initiation of Interim Program
April 15 to August 15, 1940

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Two reports dealing with the seismic research program being carried out in collaboration with Lake Shore Mines have already been presented, covering the work up to the middle of April, 1940. The present memorandum is designed to bring the detailed account to August 15.

C-1 Report of Progress, April 15 - August 15, 1940

At the date of the second report, Gibbs was just returning to Kirkland Lake, after two weeks spent at Ottawa in building an amplifier. It was expected that the surface seismograph would be ready to ship to Kirkland Lake in two or three weeks. In the meantime, the seismograph constructed by Hollinsworth and used in the mine during March was to be continued in operation at the surface station at the mine in order that the program of accurately timing the bursts might not be interrupted.

The electronics laboratory was completed about April 20: it was located in the Accommodation Building as had been recommended. The only current available was 25-cycle.

Recording by the surface seismograph began July 2-3 and was practically continuous for the remainder of the period.

The Hollinsworth seismograph, held on surface until July 2, was returned to Ottawa. In the meantime, Gibbs completed a new mine seismograph, building an amplifier and related equipment and using a commercial Esterline-Angus recorder. After a period of testing and adjustment on the surface, this seismograph was placed in a specially prepared position on the 2950-ft. level on June 10 at the point first occupied during the March experiments by the Hollinsworth instrument.

As was the case with the Hollinsworth seismograph, the records on the new instrument were confused by man-made noises: blasting, tramming,etc. It was believed that in many cases the blasts initiated bursts. If so, many of the offsets at blasting time were probably due to small bursts. During the relatively quiet off-shift periods, the recorded disturbances were few, and were almost certainly due to small strain bursts.

It was considered that a seismograph that would not register mine noises but would record bursts was needed. Such an instrument could be built if the frequencies of the vibrations at the time of a burst differed from those resulting from man-made noises. If the frequency ranges were known, filters could be constructed to pass only that part of the spectrum desired. Much time was spent in an endeavour to determine these frequencies, but without success. This problem had to be solved before further work could be efficiently carried on.

Rockburst research was initiated by The International Nickel Co. of Canada Ltd. at its Frood mine in December 1938, under the general superintendence of R.D. Parker, General Superintendent, Mining and Smelting Division, and Dr. Arthur B. Yates, Chief Geologist. Close collaboration was arranged between those working at the Frood mine and the group at Lake Shore. Data were exchanged on amplifiers, etc. and complementing programs were arranged. In the case of one rather costly project (determination of vibration frequencies) the experiments were planned to be done in both mines, the overhead cost of equipment being shared. Steps were taken to calibrate the seismometers and amplifiers used, so that the records might be compared qualitatively.

On June 11, Messrs, Parker, Yates, and Shenon visited Lake Shore Mines for a conference on geophysical methods of studying the rockburst problem. It was arranged that such visits should be interchanged from time to time, and on July 30-31, Gibbs and the writer visited the Frood mine for a conference on a continuing program.

The Ontario Mine Operators Association appointed a special committee on rockbursts with R.D. Parker as Chairman. The committee arranged for a visit by G.K. Morrison of the Nundydroog Mines, Mysore State, India, an authority on rockbursts, which he had studied in India, South Africa, and Canada. In the course of this visit, the writer had the benefit of several long conversations with Mr. Morrison.

A report on the rockburst research at Lake Shore was presented by the writer at the Annual Meeting of the Royal Society of Canada at London, Ontario, on May 20. At that time, Prof. E.S. Moore of the Department of Geology, University of Toronto, made available to the research program data from a series of tests on the strength of various samples of Lake Shore rock, studied under his direction some years ago at Toronto by C. Godefroy. He stated that he would be glad to try to arrange any cooperation with his Department that might be desired. The work had, however, not proceeded far enough to permit the formulation of definite problems that could be presented for solution with the aid of the University's trained personnel and special equipment. Similar offers were received from the Department of Physics of the same University. It seemed likely that, as the work proceeded, special problems would arise that could be submitted to such organizations with advantage.

E.W. Todd resigned as Superintendent at Lake Shore Mines on June 22, and his successor, A.L. Blomfield, Managing Director of Lake Shore, indicated that the program of rockburst research was to continue.

A memorandum presented to Mr. Blomfield on August 6 suggested that the detailed geological studies made in the mine after all bursts be made immediately available to the rockburst investigators. At the same time it was recommended that an assistant be appointed to help Gibbs. It was decided to engage an geologist, Howard M. Butterfield, to take care of the geological side of the work and to collaborate with Gibbs.

C-2 Alterations to the Surface Seismograph

The clockwork drive of the surface seismograph, adopted to render the instrument independent of power interruptions, had proved not entirely satisfactory, and further trouble arose from the deterioration of the two mirrors used in the light track. It was therefore decided to send the instrument to Ottawa to have a synchronous motor drive installed in place of the clockwork drive, to have it fitted with change gears permitting speeds of 30 to 60 mm./min., and to have the optical system re-designed so as to eliminate the mirrors and prism. In its absence, the Hollinsworth seismograph, designed for underground use, was brought to the surface. As this instrument has a paper speed of 9 mm./min. only, the timing was not as accurate, but the recording of blasts and bursts was excellent.

Specifications for the motor, ordered from the Bodine Electric Co. of Chicago, called for Type KYC-22RC 110v., 25-cycle, 1500:1 reduction, 1 r.p.m. While awaiting delivery, the optical system was changed. A new type of lamp suggested by Gibbs was found to give excellent results. This was a precision lamp used in large quantities by the motion picture industry, known as a pre-focused photo-exciter 4A, 8.5v., and available at a cost of only 50 cents. Replacement merely required the removal of the old lamp and insertion of the new, without any of the delicate adjustments necessitated by the former type. It proved so satisfactory that it was adopted as standard equipment at all Canadian seismograph stations. The new system, designed and made in the Observatory machine shop, eliminated the prism and mirrors, thus increasing available light.

The new optical system on the Kirkland Lake instrument located the lamp at the rear of the recorder case. The power supply was furnished through a Thordarson transformer from the 110v., 25-cycle service. The light beam traversed a series of baffles in a light-tight metal case to the galvanometer, which was mounted on a weighted base independent of the case. After reflection by the galvanometer mirror, the beam passed through a cylindrical lens mounted in a hole cut in the rear of the old case. The focused point of light fell on the rear of the drum.

Work on the gear system, designed to give paper speeds of 30 or 60 mm./min., began as soon as the motor was received, and the machine was shipped to Kirkland Lake on June 27. Installation was completed by July 2, and the instrument has functioned practically continuously since. The only modification found necessary was a slight adjustment in the lighting system designed to reduce the intensity of the recording spot except when a burst is in progress, when the light is brought up to full strength.

As the optic axis of the new system was only about .6 as long as the one it replaced, the magnification was proportionately reduced. However, experience shows that this is not a disadvantage, as all bursts record on the new system.

The Heiland Research Corporation supplied the design of a battery-operated amplifier, and such an amplifier was constructed by Gibbs. It proved quite satisfactory except that it shorted the timing impulse to the galvanometer so that all the time marks were lost. Pending the design of a semaphore timer to be placed in the light path in lieu of the impulse to the galvanometer, the use of the amplifier was discontinued.

The power source at Lake Shore Mines since April 30, 1940 has been the Hydro system. The frequency control has been excellent, as the sample record shows; the interruptions have been few and of short duration. Of course, when such interruptions did occur, the timing of bursts ceased. Except for this drawback, the modified equipment proved much more satisfactory than the former design. It should be said, however, that the difficulties experienced with the first set-up did not arise from any defects in manufacture, but from the specifications, which stipulated that the apparatus was to be designed so as to be unaffected by interruptions in the power supply.

C-3 Construction of the Electronics Laboratory

Work on the electronics laboratory began on April 11, and although all the work had not yet been done, Gibbs was able to move into it on May 15. It was felt that some of the more expensive testing instruments came under the classification of instruments for scientific purposes as regards customs regulations, as they would be of no use to Lake Shore Mines except for the rockbursts research. Accordingly, these were purchased by the Dominion Observatory with the understanding that Lake Shore Mines would reimburse the expenditures incurred, and that the instruments would remain at Lake Shore for at least 10 years, or longer if circumstances should so require. A list of the equipment, ordered from General Radio Co., Cambridge Mass., follows:

Two Variacs (200-CMH)
and one each of the following:
Impedance Bridge (650-A)
Beat Frequency Oscillator (713-BM)
Output Power Meter (583-A)
Microvolter (546-A)
Sound Level Meter (759-A)
Sound Analyser (760-A)

The best frequency oscillator was designed for 25-cycle current: the other equipment was battery operated. All instruments were received at Lake Shore Mines on August 15.

C-4 Experimental Work to August 15

The experimental work for the period covered by this report was as follows:

(a) Design and construction of a strain gauge;

(b) Design, construction, and tests of a mine seismograph;

(c) Frequency tests in the mine.

(1) Strain Gauge:

The strain gauge constructed by Gibbs consisted of a heavy brass cylinder with an internal diameter of one inch, closed at one end by a piston working through a packed sleeve. The other end opened into a glass tube at right angles to the brass cylinder. The ratio of cylinder area to tube area was 12:1. This was expected to give sufficient magnification. The liquid proposed for use in the gauge was a coloured light oil. The gauge (Figure 22) was not set up in the mine as it lacked a recording system.

Steps were taken to design and construct ten recording gauges to be operated in the mine at strategic points to be selected by the geological department.

(2) Mine Seismograph:

A mine seismograph designed and constructed by Gibbs was in practically continuous operation on the 2950-ft. level from June 10 to date. The design of this seismograph depended on the solution of a series of problems here discussed briefly:

(a) Power Supply Frequency:

The frequency of the power supply at Lake Shore Mines is 25-cycle. Nearly all commercial testing equipment required for the laboratory is designed for 60-cycle. It was a question whether equipment should be selected and designed for 25-cycle or whether converters should be used to change the supply to 60-cycle. It was finally decided to adapt all equipment to either 25-cycle or to battery eperation.

(b) Seismograph Design:

The pick-ups for this instrument were the Heiland geophone and the DP-1 Brush vibration detector purchased by Lake Shore Mines for use in the March experiments. The recorder selected was a commercial 5-milliampere Esterline-Angus meter. This instrument uses a paper chart run normally at 3 in. per hour, but capable of a variety of speeds for experimental purposes. Registration is by means of ink, using a special pen.

The power pack and amplifier were built by Gibbs. Tests of this instrument on the surface showed that voltage fluctuations affected the over-all magnification to an extent that precluded intercomparability of the records. A voltage regulator was therefore designed and built by Gibbs, and gave excellent results.

The amplifier and meter were originally used with the DP-1 pick-up. The combination worked quite well until about the end of June when it suddenly failed. Examination showed that moisture had affected the cyrstal of the DP-1, so the unit was returned to the manufacturers to be repaired.

With the DP-1 out of commission, the Heiland geophone was installed, but the results were not satisfactory. The amplification was much too low, and the geophone and amplifier were not impedance-matched. A matching transformer (Hammond No. 910) was tried with excellent results. The available gain of the amplifier was now more than adequate and, in fact, when used to the full, brought in mine noises to an extent that seriously affected the record. This arrangement continued to date, the installation being on the 2950-ft. level, where a special pier was constructed on solid rock for the pick-up location. The power pack, amplifier, and Esterline-Angus meter are housed in a special steel box as shown in Figure 24 (the meter itself being just out of the picture on the right). Figure 25 shows the entire outfit as set up in the drift, and Figure 26 a typical record.

The records showed clearly that small bursts probably occurred during blasting and that they certainly occurred at intervals during off-shift hours. Even comparatively large bursts did not go off scale on this seismometer. The gain was linear for about half the full scale and then diminished rapidly. For example, bursts marked as such were perhaps tenfold as severe as the heaviest bursts occurring during blasting time.

Experiments at the Frood mine gave some promising results. All bursts occurring there were plotted on an empirical vertical scale designed to show integrated total intensity, with a horizontal time scale. The resulting curve, extending over some months, shows a distinctive pattern after and before large bursts. If the records could have been cleared of all mine noise records and confined to bursts alone, this pattern would probably have become sufficiently distinct to permit approximate prediction of large bursts. Clarifying the record would have been possible if the vibration frequencies of blasts and bursts differed materially. It was suggested at Frood that the frequency of bursts was from 20-40 cycles, and that of blasts from 40-80 cycles, but it seems doubtful if the evidence given by the experimental data is sufficient to warrant this conclusion.

(c) Frequency Problems;

With a view to determining the frequency of bursts, a head set and an oscilloscope were arranged in multiple at the same amplifier output. It was thus possible to hear and see the oscilloscope record and, at the same time, the record of the Esterline-Angus meter. The results were too uncertain to be of any value. Attempts to use photographic paper to record the oscilloscope picture were not successful. It was hoped that the seismic prospecting apparatus might enable the operators to solve this problem of vibration frequencies.

C-5 Plans for the Immediate Future

In addition to the proposed strain gauge program, plans for the immediate future called for a new set-up of the mine seismograph for the vibration frequency tests, and for experiments to determine whether supersonic vibrations (very high frequency and low energy level) occur before a burst and reveal by their presence the approach to bursting conditions in a rock under pressure. These may be outlined as follows:

(a) New Location for Mine Seismograph:

An excellent location for the mine seismograph was found in a long cross-cut on the 3075-ft. level. This cross-cut ran north from the drift on No. 2 vein for about half a mile. It was an exploratory working, no longer in use. It was planned to instal the seismograph there as soon as Gibbs could build an amplifier that could be operated on batteries, there being no power supply in the cross-cut. The seismograph station was at a point on the west wall of the drift about half-way between the junction of 3053W drift and the indicated Lake Shore boundary.

(b) Velocity Tests:

Authority having been given to lease a seismic prospecting outfit from Dr. L.D. Leet, tests with it were planned for Lake Shore and one of the mines of International Nickel, which was sharing the expense of this part of the investigation. The tests were aimed at finding the velocity of transmission of the elastic waves for both bursts and blasts. Variations in this velocity over certain selected paths were also to be studied. The instruments would also make it possible to determine the vibration frequencies of both bursts and blasts.

(c) High-frequency (ultra-sonic) Vibrations:

It seemed possible that bursts might be preceded by frequency vibrations that would, if they could be recorded, furnish a means of burst prediction (see No. 47, bibliography). It was planned to begin studies along these lines as soon as possible. To this end, two high-frequency Brush pick-ups were purchased: these are known as the VP-1 and VP-2. With suitable filters and matching transformers they were to be used with the equipment set up in the long cross-cut on the 3075-ft. level.

C-6 Yates-Shenon Memorandum on Lake Shore Conference

The conference on rockburst research, held at Lake Shore Mines on June 11, 1940, was mentioned in section C-1. A summary of the discussion follows:

Library:

A complete bibliography of papers and reports covering rockburst and allied subjects has been compiled and libraries of rockburst literature are being assembled by the Ontario Mine Operators Association at Toronto and at some of the mines.

Investigations:

Critical parts of mine workings have been mapped in great detail to determine the disposition of rock types, faults, and joints in an endeavour to determine if there is any correlation between these structural features and the locations of rockbursts. It has been found that, in general, rockbursts are confined to the more brittle or friable rocks and that major structural features influence their location; for example, intersections of vein or fracture systems, major irregularities in orebody outlines, close spacing or parallel orebodies, and the presence of many closely spaced joints and fractures. The object of this work is to furnish data that will aid in planning of mining methods and proper mining sequence to control, as far as possible, the occurrence and severity of rockbursts.

Engineering and geological records of rockbursts have been kept for a number of years as a basis for statistical analysis, which has led to a better understanding of the contributing causes of the phenomena. Charts, plans, and sections showing the location, time, frequency of occurrence, extent of damage, relative intensity, and sequence of bursting have been prepared. From these data an understanding of the space relationship of bursts to the physical condition of the mine as a whole may be obtained. Study of such data also aids in the determination of critical areas.

Many attempts have been made by means of various micrometer bars, extentiometers, and gauges to measure small movements within the walls of various mine workings to ascertain if there are indications of movement within the elastic limit of the rocks that might indicate areas within which unusual stresses are being built up to produce rockbursts. Thus far it has been found that slabbing along the walls and differential movement along small joints vitiate results. Some work has been done and further work has been planned to determine temperature changes in areas known to be undergoing increasing pressure, in the belief that the rate of temperature increase may give a measure of the accumulating stresses that cause rockbursts and thus furnish a basis for predicting their occurrence.

Apparatus has been constructed and installed in several places in two mines for the purpose of recording vibrations within the rock structure set up by stress releases. The immediate object of the work is to relate these vibrations to subsequent rockbursts and to attempt to give adequate warning of the forthcoming bursts. Enlightening data have been obtained with reference to the time pattern of the minor readjustments preceding major movement and it is hoped that eventually results will be consistent enough for reliance to be placed on their interpretation. A specially designed seismograph has been purchased and put into continuous operation in coordination with the Dominion Observatory of the Department of Mines and Resources. Dr. E.A. Hodgson, Dominion Seismologist, is working in close cooperation with the technicians employed by the mines for this special purpose and is devoting considerable time and energy to the problem.

A very well-equipped laboratory supervised by specially trained scientists has been set up to develop and construct instruments for use in this investigation. New types of extremely sensitive electronic apparatus, much of it especially designed and constructed, have been applied to the problem, and while it is too early to cite specific examples, sufficient encouragement has been attained in the short time in which these methods have been in use to hold out the promise of valuable contributions to the safety of deep mining operations.

Report D

Surface Seismograph Records

Dec. 19'39 - Dec. 31'40

This report discusses the records made in the course of the regular surface recording from December 19, 1939, when the work began, to the end of 1940. A comprehensive summary is first given, followed by a discussion of the data under various headings. A tabular record of the entire set of individual seismograms, prepared in accordance with the initial form as given in Report A, Table 1, completes the report.

D-1 Summary Discussion

The maintenance of a surface seismograph at Lake Shore Mines could serve only two purposes: to furnish data for an accurate determination of the velocity of propagation of elastic waves in the upper surface layers and to provide a complete record of the rockburst activity over a period of years and determine whether it is growing or not. The former is of considerable value from a purely scientific point of view.

To accomplish this velocity determination it was necessary that the absolute time of all large bursts be known to within a half second, or less if possible. Any interruption to the seismograph or its auxiliary time equipment might mean the loss of data for the obtaining of which opportunities are so rare. Moreover, the chronometer correction must be obtained accurately and regularly. All adjustments affecting the chronometer and its rate should be immediately noted in detail on the back of the corresponding seismogram. Only in this way can a complete and accurate time correction be obtained.

To accomplish the second purpose, studies of rockburst incidence, there must be prompt, regular, and careful correlation with the seismograms of data from the underground superintendent's office.

Except for lost time, the surface seismograph recorded all bursts of even moderate intensity with a timing error which was, in general, $\pm$ .5 sec. and seldom if ever greater than $\pm$ 1.0 sec. No burst of moderate intensity seems to have occurred during any lost-time period, and certainly no burst large enough to have served for a velocity determination. Finally, it must be recorded that no velocity determination has been made, as yet, in more than a year of recording. As for the complete tabulation of all bursts and their relative magnitudes as experienced at the surface station, the service fell far short of the possibilities. Interruptionsdue to required modifications of equipment were past, and the sensitivity seemed adequate. Although it was not as high for Series III as for Series I, the recording seemed to be a better indication of burst activity with less disturbance from adjacent conditions in the gymnasium, etc. The records for 1941 would be much improved with a daily sensitivity test and daily correlation of data; the first of these was planned for the near future.

D-2 Lost Time

One of the chief reasons for installing and maintaining the surface seismograph was to determine accurately the speed of propagation of the elastic waves in the upper part of the earth's crust for the path from Kirkland Lake to Ottawa. To do this, the Kirkland Lake instrument must be operating at the moment when a burst of sufficient magnitude to register at distant seismographs occurs. To be of any value, the record must carry regular chronometer minute marks and the correction for these must be known.

If such a burst occurred at a moment when any one of the above conditions failed, the opportunity for obtaining a velocity measurement would be lost. It was therefore important to reduce servicing stoppages to the absolute minimum. The time required to change the seismograph sheets varies from a few seconds to several minutes, and was necessarily designated as lost time.

There were other causes of lost time that were in some cases unavoidable and in others must be classed as due to the carelessness of the operator. These causes have been listed in the legend section of the table, the actual time lost on account of these various causes being indexed in the body of the table. All entries are to the nearest minute.

Where the chronometer signals were not, for any reason, shown on the record, the time was irretrievably lost and the fact was therefore included in the tabulation. This was especially serious when the cause was failure to wind the chronometer. In such circumstances, the time without signals was lost and the chronometer rate also was usually affected.

Time lost for the period of this report ($378^d\ 12^h\ 25^m$) amounted to 33509 min. (23^d $06^h\ 29^m$) or 6.14 per cent. It was hoped that this lost time could be brought down to at most 2.5 per cent for 1941 (see section G-2).

D-3 Chronometer Corrections

Time comparisons between the chronometer and radio signals were made usually once a day, though there were a few periods in which the comparisons were somewhat irregular. In general, the comparisons were good, most of them being automatically recorded on the seismograms. During the interim period of Series II (April 1 to July 2), automatic recording was not attempted, as the paper speed of the mine seismograph was then only 8 mm./min. For the time of this series, the comparisons were made by eye-and-ear method, a single signal being put on the seismogram by means of the telegraph key. The correction, as estimated by looking at the second-hand of the chronometer while listening to the radio signal, was also kept as a desk memorandum.

In preparing this report, the chronometer corrections were obtained from the records or from desk memoranda. They were plotted on cross-section paper to a scale of .1 in. = 1 sec. correction and for the other coordinate 1 in. = 1 day. Through these plotted points, the graph for the chronometer correction, as determined from the observational data, was plotted to give the rate graph. All out standing deviations from the plotted graph were re-examined on the records.

The corrections as read from the graph were given to tenths of seconds. In using them, one may interpolate to the required epoch and obtain a correction expressed to tenths of seconds. This permits the exercise of a certain amount of judgment when scaling the time of an event and applying the correction, but the final result should never be quoted to a closer approximation than half a second.

D-4 Distribution of Bursts

Merely to approximate a statistical study of the surface-recorded rockbursts for the period of this report, it would be necessary to have the sensitivity of the seismograph the same throughout or to secure data permitting a comparison; these conditions did not apply. The sensitivity was roughly the same throughout each of the three series: 19/12/1939-31/3/1940 with the original Heiland equipment; April 1 to July 2, 1940 with the mine seismograph on surface; July 3 to Dec. 31, 1940 with the modified Heiland equipment. Inter-comparison of the sensitivity for the three series cannot be made and it is not certain that the sensitivity was the same throughout any given series. Indeed, in the case of Series I it is certain that the sensitivity was falling off after the middle of February. It is to be noted, however, that at no time (except when the gain was inadvertently set at zero, which time is included in the lost time tabulation) was the instrument so lacking in sensitivity that a moderately severe burst would not have been registered.

To overcome this difficulty, it was proposed to provide a simple and uniform mechanical test to be applied to the seismograph each day as a matter of routine. This would show, in some degree at least, the comparative sensitivity of the equipment from day to day.

Another condition that had to be met before the records could be used to show comparative burst acitivity from month to month was that of routine and regular correlation of underground data as to blasting and other activity with the surface records. Unless this was done promptly and regularly, questions of interpretation would arise when the records were read which could not then be answered.

The reports of bursts for the period of this report may be tabulated on the following basis. In line A are listed bursts sufficiently severe to have a marked duration period (two seconds or more). In line B are listed those less severe, but that could be certainly identified as bursts. In line C are those that were recorded with a notation as to the lack of certainty that they really were bursts.

December 1939 to December 1940

	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
A	0	1	4	0	0	0	0	0	2	0	3	3	1
B	2	5	2	16	18	5	4	17	24	40	12	24	14
C	4	57	27	28	2	0	0	17	17	18	29	19	21

For proper appreciation, this tabulation should be studied in the light of the following notes:

(a) Line A shows 14 fairly large bursts, each of a duration of 2 sec. or more. This is a minumum list; had all records been registered on the original Heiland equipment or even on the final modified Heiland seismograph, the number of larger bursts showing such a duration would undoubtedly have been larger. It should be noted that not a single entry appears in line A for the months April to June, inclusive, when only the mine seismograph with ink registration and low paper speed was in service.

(b) Where the classification was not carefully done, the number of bursts shown in line C probably includes some that should have appeared in line B.

(c) The entries for Series III were determined with the modified Heiland equipment at, presumably, the same sensitivity. While light spot conditions varied and the lost time was not uniform in those months, the conditions were nevertheless more nearly uniform and continuous. The number of records identified as bursts varies from 15 to 40 per month. During this period the scanning of the records at Ottawa was done fairly uniformly, all being read in order without interruption. The number of entries in the three lines combined varies from 34 to 58 per month.

(d) For the last half of 1940, the number of larger bursts ranged from zero to 3 per month and none of these were sufficiently severe to register at Ottawa. The large burst in line A for December occurred on December 28 and at a time when the Benioff at Ottawa was dismantled for adjustment. It was not registered on the short-period instrument at Shawinigan Falls. Previous experience showed that a burst registering at Ottawa also registered at Shawinigan Falls on a slightly smaller scale. It may be inferred that if the burst had registered at Ottawa the amplitude would have been so small as to have precluded the possibility of making a velocity determination.

D-5 Suggestions for Improvement of Service

(a) The operator should avoid as far as possible the causes of lost time as noted in 1940, and detailed in section D-6.

(b) Sheets should be replaced on the drum with a minimum loss of time, even though adjustments may be found necessary on developing the sheet just removed. It is better to use an extra sheet than to have the equipment out of use for even a short time.

(c) When a record covers only an hour or so between two regular sheets, but does so adequately, it should be included in the records sent in evidence of coverage.

(d) Correlation of sheets with mine data should be noted promptly and regularly, and all offsets on the record should be explained or marked as due to unknown causes.

(e) Records should be sent to Ottawa regularly once a week.

(f) Sheets should be time-annotated as soon as they are dry.

(g) The initials of the operator (or operators) responsible for each sheet should be noted on it.

(h) All adjustments of the chronometer should be noted on the seismograms. These should be sufficient to enable the chronometer corrections to be determined for the entire record time. If time comparisons were plotted regularly by the operator on a large-scale graph, they would tend to be more accurate, and any changes in rate would show up at a time when the operator might be able to determine the reason.

(i) Notice should be sent to Ottawa at least one month before the stock of seismograph paper would need replenishing and at least two months before new developer or fixer would be needed.

(j) It should be borne in mind that any sheet being developed may contain important data that will require copying for use in a report.

D-6 Lost Time Tabulation

In this tabulation, the nearest number of minutes required to change the seismograph sheets each day is entered first, in the appropriate intersection of column and line. Following, in the adjacent compartment for the same day and month, appears the number of minutes lost during that calendar day from various causes as indicated by lower-case letters having reference to the causes listed below. The total and percentage loss for each month are tabulated in the last two spaces respectively of the columns concerned.

a Adjustments made at record-changing time
b Light inadvertently turned out
c Sensitivity dial set at zero
d Record destroyed in developing
e Chronometer signals failed
f Batteries ran down
g Clutch on lateral drive not set in
h Clock drum stopped
i Experimenting with equipment
j Power supply at mine changed to a new system
k Ink supply failed (mine seismograph on surface)
m No record received at Ottawa (no explanation)
n Pen balance out (pen off paper for some time)
p Too overexposed to give clear record.
q Severe electrical storm; power off repeatedly
r Seismograph being demonstrated to visitors
s Overlap on adjacent small sheets lost in crack
t Chronometer ran down for lack of winding
u Record not changed in time; over-run
v Light spot too weak to record

Total Lost Time	Percentage Lost Time
33509 min.	6.14 per cent
$23^d\ 06^h\ 29^m$	

*

Note:

The original of Report D gave the lost time tabulation as Table I. It is repeated here in full to permit comparison of efficiency of operation of the surface seismograph for 1940, here reported, and for 1941, as given in Report G of this publication.

*

Table 1

	Dec.		Jan.		Feb.		Mar.		Apr.		May		June		July		Aug.		Sep.		Oct.		Nov.		Dec.	
																									D	
1			4		2		3		8		3		2		3		3		2			833g	1		6	566m
2				185bf	2		4		2		2		3		0		13		2		2	668g	1		1	293ms
3			5		2		6		4		3		2		2			150a	1		1			20a	1	45s
4				644g	14		5		4			1032h	2		1		2		3		2		2		7	39s
5				791g	2		4		5		3		2		0		4		3		1		1		1	133ms
6			6		5		5		3		3		2		0		2		3		1			435g	1	
7			5		8		3		3		1		2	162n	2		4			20a	2			1044g	2	
8			6		2		2	410f	7		1		3		2		5		1		5		2		1	
9			13		2			780f	5		3		2		2		1			31a	2		1		1	
10			5		1			327ah	4		1		1		2		1		2		2		0		1	
11				658g	3		7	744h	4			716k	?		1		3		2		3		1		1	
12				791g	3			1217h	3			922k	3		2		1		2		2		1		1	
13			8		6		4		3		1		2	90h	2		5		2		2		1		2	
14			5		2		3		4		0		2		2			31a		34a	2		1		1	
15			6		3		5		3		1		2		1		16		4		3		1		0	
16			5		3		2		3		2		3		1		4		2		2			88u		11u
17			4		2		3		5		3		2	96n	1		2		2		2		1		1	
18			3		5		4			658c	4		2		2		1		2		2		1		1	
19	7	44a	6		2			52a		784c	4		1		8		1		2		2		1		1	
20	4	825abc	5		7		2		3			392u	6			671c	1		2		2		2		1	
21	8		7		4		2		3		3			43k		1410c	13		1		1		0		3	
22		765d	6		4		3		3		2			62a		577v	1			26a	2		1		1	
23		671d	3		3		3		2		3		1			1213v	1		3		2		0		1	
24	6		6		3		2		4		1		2			782p	2		2		2		2		2	
25		646e		547h	8		4		3		2		2		4	137q	1		3		2		1		2	136t
26		721e	8		4		4			223i		415m	1		1	617h	1			39a	18		2		3	
27	14		5		5		3		1			1396m	2			505h	1		1			38u	7	76m	2	
28	6		2		6		3		2		3	295k	3		1	191h	1			878g	2		5		3	
29	4		10		6			239h	2		2		2		3		1			487g	2		24		2	
30	7			1356bf			3		2		2		2		2		1		1	11r	2		12	107m	2	
31	6		3					44a		414j	0				2		1				11				1	
T		3734		5108		119		3902		2174		5221		512		6150		274		1574		1623		1842		1276
P		20.7		11.4		0.3		8.7		5.0		11.7		1.2		13.8		0.6		3.6		3.6		4.3		2.9

Report E

Leet Seismograph, Microgauge, and Strain Gauge Results
August 15, 1940, to April 15, 1941

o

The present report deals with the studies made during the period that has been designated the Interim Program. It presents the results obtained with the Leet seismograph, which was operated at the Frood mine and at Lake Shore, together with the tests made with the Hollinsworth microgauge, and the results obtained from the strain gauge designed and constructed by Gibbs. The last-named was operated in 3001W drift, Sec. 8 from early September, 1940, until a burst on April 8, 1941 wrecked the location and destroyed the gauge. Daily readings of the strain gauge are shown graphically in Figure 34, and discussed in Section E-7.

E-1 Progress Report

At the closing date of Report C, a memorandum had just been presented to Lake Shore Mines recommending among other things the leasing of a seismic prospecting outfit from Dr. L. Don Leet of Harvard University, for the purpose of determining the frequencies of the elastic vibrations in the rock, as generated by bursts, blasts, or other mine noises.

In the meantime, Gibbs constructed a battery-operated amplifier for the mine seismograph, to be used in a long exploratory cross-cut on the 3075-ft. level, running north from the mine proper for more than half a mile. The remote end of this long-disused cross-cut was not supplied with electric current.

The amplifier was completed and installed in the cross-cut (designated 3052 X-C) on August 29. The hydraulic gauge previously constructed was installed in 3001W drift. The routine operation of these and of the surface seismograph was assigned to Butterfield, the new assistant in the rockburst program (see Sec. C-1).

The Leet equipment was tested and installed, and on September 30 was placed in operation. R.G.D. Morrison of Nundydroog Mines, Mysore, India, who had been engaged by the Mining Association to investigate the rockburst situation, was present on this occasion, also Messrs. Yates and Shenon of International Nickel, Professor George B. Langford, head of the Department of Mining Geology, University of Toronto, Mr. Robson of Lake Shore, Gibbs, and the writer. The records were discussed the following day, after which the group dispersed.

It was planned to ship the equipment to Sudbury for experiments in the Frood mine early in October. The cost of leasing and installing the Leet equipment was borne by the two companies.

The Frood experiments were carried out by Gibbs over the period October 8-24. The frequency investigations were carried out at two locations, one on the 2000-ft. and the other on the 2800-ft. level. Considerable difficulty was experienced owing to moisture and acid-charged ground water affecting the equipment, to the practically constant interruptions by mine noises, and to stray electric currents affecting the galvanometers. Good frequency records were obtanied after some difficulty, but experiments to obtain rough values of the speed of propagation of the elastic waves through the rock could not be carried out without extensive modification of the equipment. As the instruments were leased, this was out of the question, and the Leet apparatus was returned to Lake Shore Mines on October 25.

Experiments to determine frequency were resumed at Kirkland Lake by Gibbs, assisted by O.E. Andrew of the Lake Shore staff, who had been appointed to assist in this work after Butterfield left Lake Shore early in October. Frequency studies were made again in 3052 cross-cut and also on the 2950-ft. level in a specially prepared location in 2920W cross-cut, close to the west pillar. As the ground was loose, special timbering and lagging were necessary.

The experiments at Lake Shore and Frood showed definitely that:

(a) Blasting always generated vibrations in the frequency range of about 40-60 c.p.s.
(b) Some blasts had, superposed on the above low frequency, a higher order of from 200-400 c.p.s.
(c) The few cases where strain bursts alone registered were found to show frequencies in the higher range only.
(d) Other mine noises (trimming, hoists, crushers, etc.) generated frequencies of less than 100 c.p.s.

To determine whether the high frequencies could have been due to some characteristic of the equipment, extensive experiments were carried out at Lake Shore. A geophone was subjected to various frequencies controlled by an oscillator and to amplitudes that were kept within appropriate limits. It was found that no high frequencies registered on the seismograms when the geophone was subjected to low frequencies, and that it recorded the high frequencies faithfully as to period, but at a much lower amplification than for the low frequencies.

It was concluded that:

(a) Blasts generate rock vibrations with a frequency of 40-60 c.p.s.
(b) Other mine noises generate frequencies of less than 100 c.p.s.
(c) Bursts generate frequencies of 200-400 c.p.s.
(d) Blasts in strained rock induce the low frequency and often also release energy that causes the high frequency characteristic of bursts.
(e) The discrepency in amplitude of recorded low and high frequencies is due to the non-linear amplification of the equipment. The energy in the burst frequency is relatively greater than the records indicate.
(f) The high frequencies attenuate with distance much more than the low.

Some attempts were made to determine sound velocities in the rock at Lake Shore but, as at Frood, the difficulties were too great to be surmounted in the limited time available with the leased equipment. Experiments were concluded at Lake Shore on November 19 and the equipment was returned to Harvard.

Filters that would suppress oscillations up to 200 c.p.s. but give good amplification for higher frequencies were finally secured, and were given an exhaustive series of tests. It was found necessary to change the terminal impedance of the filters from 250,000 ohms to 20,000 ohms. Under the new conditions, the cut-off was sharp to 200 cycles and the amplification beyond that frequency was reasonably flat to nearly 5000 c.p.s.

The mine seismograph, equipped with the filter, was set up in the rear of a safety shelter on the 4200-ft. level, where it was operated for some days early in March. This location was not only at considerable depth, but was also in strained ground and close to extensive mining operations. An observer sat beside it several days during blasting time, watching the record while listening to the blasts. It was found that:

(a) Not all the blasts registered.
(b) Most of the heavy ones were recorded.
(c) No records of bursts alone occurred during the observation period.
(d) Some disturbances, presumably strain bursts, were registered at other than blasting times, and these were usually registered on the surface seismograph also.

It was concluded tentatively that:

(a) Some of the larger blasts or those nearer the equipment were able to pass the filter simply because of their magnitude.
(b) Considering the location and its nature, it was probable that most of the blasts released inherent strains in the rock and so generated both high and low frequencies.

On March 15, it was decided to remove the mine seismograph to the surface for the following test. It was set up alongside the surface seismograph and operated first without the filter. Tests were to be made, setting the gain so that both instruments would record with about the same amplitude; the records would thus show both blasts and bursts. The filter was then to be installed on the mine seismograph and the gain stepped up the amount known to be necessary to care for the reduction of amplification due to the filter. The records should then differ if the filter were effective in eliminating blasts in unstrained rock. As many blasts occur in the upper levels of the mine and so, probably, do not release strain, it was confidently expected that the records from the two seismographs would differentiate between bursts (or blasts releasing strain) and blasts not associated with strain.

It was found difficult to get the two instruments to record the same with the filter removed. Tests were finally run on the two geophones to see if they were comparable as pick-ups, and these indicated they were not. Investigation disclosed a friction in the surface geophone. When this was eliminated, the two geophones gave practically the same result under varying tests.

In the intervals between the trial runs, the Leet seismograms were sorted and indexed, those showing no records being discarded. There were hundreds of feet of these obtained at Lake Shore and Frood. Several bursts were recorded, but the bulk of the seismograms had to be discarded.

The time-marking device of the surface seismograph consisted, up to this time, of a shunt which sent a small current through the recording galvanometer for two seconds at the end of each minute. A semaphore arm for eclipsing the light for the timing interval had been constructed at Ottawa. This was installed in such a way that its eclipsing edge divided the recording spot at its zero position. The screen on the lens was removed. The zero position of the spot was set well to the left of the cylindrical lens as viewed from the front of the recording box. The offsets were thus all to the right (downward on the sheet) but could use the full width of the lens instead of only half as before. The time impulse shifted the semaphore to the left, making a mark upwards. The time marks were thus on the opposite side of the record line from the recorded burst and blast offsets.

The changes in the optical system required many adjustments to the surface seismograph equipment. The comparisons between mine seismograph and surface seismograph were hardly begun when, on March 23, Hollinsworth arrived with his hicrogauge and equipment. The comparison experiments were postponed indefinitely while part of the mine seismograph was taken over for use in the microgauge experiments.

<u>Microgauge and Strain Gauge Tests</u>

Hollinsworth had been experimenting during the late summer of 1940 with an electric gauge for rapid testing of machined parts. The device is very sensitive, showing a deflection of about a quarter of an inch on the meter for a movement of 10^{-5} inches at the gauge. It was suggested that such a gauge might yield valuable information if designed to be placed deep in a diamond drill hole run into a pillar to reach the pressure zone of a dome.

The gauge, redesigned by Hollinsworth with this object in view, was the subject of experiments by him at Ottawa from early November to the middle of March. At Ottawa the power supply is 60 cycles and the voltage fluctuations were not severe. The gauge was made quite stable for experiments at Ottawa.

The power supply at Lake Shore was 25 cycles and the voltage fluctuations severe. Moreover, there was no certainty that the bore hole, only 1.5 in. in diameter, would be deformed appreciably by pressure. For these reasons it was felt that experiments should be carried out at the mine.

The equipment was set up in the laboratory at Lake Shore on March 24. A block of rock about as large as a football had a standard diamond drill hole bored in it. It was found that pressure on the rock with the hand alone would deform the bore hole sufficiently to cause a marked deflection on the meter. Pressure in the direction of the line of contacts of the gauge indicated a shortening of that axis of the hole; pressure at right angles showed the same axis to lengthen. There was no longer any doubt that the bore hole might be deformed by comparatively slight changes in pressure.

The change to 25 cycles necessitated changes in the gauge. Experiments were run in the laboratory for several days. While these were in progress Gibbs arranged equipment, utilizing the Esterline-Angus meter of the mine seismograph for recording the meter readings continuously. A special horizontal diamond drill hole 20 ft. deep was made in the rock at the observing station in the rear of the safety shelter on the 4200-ft. level. The device was taken into the mine and no difficulty was experienced in clamping the gauge at any desired depth in the hole, but the voltage fluctuation was found to be unusually severe.

A special supply line was run to the station in an effort to avoid the circuits most affected, but the trouble was still much too great to permit the operation of the gauge. After more than a week of experiment, it was decided that a commercial voltage regulator would be required. Enquiry showed that this would cost about $200 and could not be promised for less than five weeks after order. For the gauge to operate continuously an extra Esterline-Angus recorder was also needed, or the mine seismograph routine would be interrupted. This would cost upwards of $300. It also would require several weeks for delivery.

On being advised of the situation, Mr. Blomfield at once authorized the purchase of the two instruments. It was agreed that the gauge should remain at Lake Shore and that Gibbs should experiment with it in the laboratory with a view to achieving the necessary constant power supply and to ironing out other difficulties connected with continuous registration. A second gauge was to be made at Ottawa to be used by Hollinsworth for obtaining pressure-strain curves of large samples of rock, bored at the mine and supplied for these experiments. The blocks, after being sawn into regular form and lapped, would be subjected to pressures applied by a hydraulic press and carried to the point of failure of the specimens.

Three specimen rocks, two of syenite and one of porphyry, were received at Ottawa about the middle of April, to be sawn and lapped at the Bureau of Geology and Topography and tested at the Bureau of Mines.

It was planned to resume underground work at Lake Shore as soon as the equipment was ready, and it was expected to produce interesting data of a local character. Steps were also taken towards developing equipment for detecting and recording supersonic vibrations in pillars. This line of investigatoin also was considered most promising and might yield data of a local character, since the short wavelength of the vibrations would result in their rapid attenuation with distance.

The hydraulic strain gauge, described in section C-5, was installed in section 8 of 3001W drift on September 1, 1940. Deep holes were drilled on opposite sides of the drift, in which thrust rods were set with the gauge between them. Thus the convergence (or divergence) of the walls behind the loose rock was made the subject of study.

Daily readings obtained from this gauge are shown in Figure 34. It will be noted that, after a period of about two weeks during which, it may be presumed, the lost motion in the connections was being taken up by convergence, the graph drops down from the broken line drawn at an angle of approximately 38° with the axis of abscissae and rises again to meet that line at the time of the large burst on January 19, 1941. This burst was close to the gauge, affecting among other places the adjacent section 7 of 3001W drift. It may be argued with some reason that the broken line represents the average rate of convergence of the drift and that, when the actual convergence rate was less, strain was building up, leading toward another burst in the vicinity. Some other bursts, more distant from the gauge but still in the same general area, are shown to have little or no effect on the displacement of the graph from the average line.

The graph falls again after the January burst to the last reading on April 7. On April 8, there occurred a large burst that involved section 8 of 3001W drift, and the gauge was buried in fallen rock.

E-2 Experiments at Lake Shore Mines with Leet Equipment

After two days of assembling and testing in the laboratory, the seismograph was installed on the 3075-ft. level a little north of the Lake Shore boundary, as shown on Figure 27. Three of the galvanometer tracks were used for pick-ups: an SSC geophone, the spare Heiland geophone, and the Brush crystal detector. The natural frequencies of these were, respectively: 38 c.p.s., 20 c.p.s., and 1-5000 c.p.s.

The spare geophone line was used for signalling by means of small currents sent through its galvanometer. A telegraph key was used by one observer to note, by deflections of the signal record line, the occurrence of certain observed noises regarding which notes were made by another. It was found difficult to make the closing of the key sufficiently short to give a definitive signal. After the first few experiment periods the method was abandoned.

The experiments were carried out during blasting time. In a few cases only, the air wave penetrated to the observation point and registered, especially on the line from the crystal pick-up. The frequency of such waves was very low, about 20 c.p.s. (see Figure 29e) and the amplitude high.

All the blasts registered with frequencies of from 40 to 60 c.p.s., but in some cases frequencies of from 200 to 400 c.p.s. were registered. These higher frequencies occurred sometimes right at the beginning of the shorter frequency series, sometimes from .08 to .11 sec. before, and also right at the beginning. In a few cases, a high frequency registration occurred when there was no blasting; in others, the frequency characteristic of blasting had no high frequency imposed on its initial swings. The low frequency usually decreased slightly after the first few swings.

Samples of records made in Lake Shore Mines during this period are given in Figures 29 and 30. The description of these is as follows:

29a Record No. 47 (LS)
Small burst with no blast frequency. Some interference from 50-cycle tuning fork.

29b Record No. 82(F)
Burst superposed on blast.

29c Record No. 21(LS)
High frequency .10 sec. before blast frequency and also at the beginning of the blast.

29d Record No. 42(LS)
Same as Figure 29c except that the lag of blast frequency is only .08 sec.

29e Record No. 38(LS)
Air wave from earlier blast, with high frequency preceding a blast by .10 sec.

29f Record No. 75 (F)
Blast showing high frequency missing. Note lag of successive records owing to spacing of pick-ups.

30a Record No. 94(F)
Showing effects due to tramming.

30b Record No. 111(F)
Showing effects due to the crusher.

30c Record No. 87(F)
Showing effect of pulling chutes.

30dd Record No. 86(F)
Showing effect of a drill in a nearby stope.

30e Record No. 140(LS)
Record made by impressing disturbance on geophone of 2 c.p.s.

30f Record No. 146(LS)
Record made by impressing disturbance on geophone of 54 c.p.s.

E-3 Experiments at Frood Mine with Leet Equipment

The observations were discontinued at Lake Shore after about a week. The equipment was taken to Sudbury, and experiments began at the Frood mine on October 9 and continued until October 24. The first set-up was made in a special observing room on the 2800-ft. level which had been converted from a powder magazine to a seismograph station. This room was adjacent to a travelled cross-cut, and there was considerable disturbance from passing trams and electric locomotives. Stray electric currents affected the galvanometer circuits and acid-charged water tended to short the cable.

Small strain bursts are relatively frequent in the Frood mine, and it was expected that good records would be obtained of a burst, showing its vibration frequency. The disturbances were so great, however, that daytime observing was abandoned. Conditions at night were much better, and some good records were obtained at this first location.

It was decided to attempt some velocity measurements while the equipment was in a section of the mine best suited for such investigations. Blasts could be set off about 2000 ft. distant and the development drifts provided a convenient path for the connecting cables.

Experience showed that the equipment could not be used for this work without considerable modification: this was out of the question, as the instruments were on lease. The only velocity value obtained was 12,120 ft./sec. This is of the order to be expected, but the doubtful values of the basic data render it quite uncertain. The velocity determinations were made difficult by electrical interference on the connecting cables and by the difficulty experienced in getting sufficient energy from the blasts without throwing down a prohibitive quantity of muck. One blast of three sticks at 2000 ft. brought down about 10 tons of muck into the drift and failed to register on the geophones.

Attempts to continue velocity experiments were finally halted when the acid-charged water in the drift attacked the cables and necessitated a complete overhaul of the outfit. It was decided to move to the 2000-ft. level, where a set-up was made between manways 27.25 and 27.75 in a narrow travelway about 30 ft. above the drift. The geophones were placed on solid rock and set with plaster of paris.

Interference here was much less. There were many more small strain bursts in the immediate vicinity, and numerous good records of both blasts and bursts were obtained. The average low frequency obtained from all the Frood blast records was 60 c.p.s. The average for the high frequency was 272. The average for the frequency of vibration of small, known, isolated strain bursts was 223 c.p.s.

E-4 Testing Experiments with Leet Equipment

The very definite recording of two groups of frequencies raised the question as to whether the higher values might not be due to some resonance characteristic of the equipment. The arguments against such a conclusion were: (a) pick-ups of different natural frequencies recorded, and rapid movements at essentially the same frequency, though with different amplitudes: (b) at times the high frequencies occurred when no blasting was recorded, while at other times blasting frequencies alone registered. (c) the character of the records, made with the same equipment but in different mines, differed somewhat in the frequency values and also in the relative positions of the two frequencies. Experiments impressing various known frequencies on the equipment were carried out, and in every case the recording showed the same frequency as that impressed on the pick-up. Two samples of such records are shown as Figures 30e and 30f, the first being in the nature of a series of sharp impulses, and the second approximating the average blast frequency.

E-5 Final Experiments at Lake Shore with Leet Equipment

The final experiments at Lake Shore Mines were designed to secure records made during blasting time, velocity records, records of typical disturbances, and records made in off-shift periods.

The blasting time records were made on the 2975-ft. level in a specially constructed shelter in 2920W, and also in the long cross-cut, 3052W, where the equipment was simply wheeled into place on a small mine car. The results agreed entirely with those reported in the preceding sections.

Attempts at velocity records were made on the 1000-ft. level and also on the 4000-ft. level. The same difficulties were encountered as at Frood, and no records of any value were obtained.

Records made of typical mine noises (see Figure 30) due to tramming, drilling, chute-pulling, etc. were similar to those obtained at the Frood mine. In no case were mine noises of frequencies higher than those of blasting, except those caused by the drill. Here the frequency was of the order of 250 c.p.s. Drilling did not register, either on the Leet equipment or the mine seismograph, unless it was taking place very near the set-up, usually in the adjacent stope.

Making records in off-shift periods was a little like trying to secure a moving picture of a street accident by repeatedly taking short shots of a busy corner. The operator entered the mine soon after blasting time, when small strain bursts are most common, and ran sections of record paper at intervals. Notes were made for each section as to what noises were heard and at about what part of the record. Several small strain bursts were registered in this way and one rather severe one at a little distance. The frequencies obtained from these were always high. The method was adopted as an off-chance means of obtaining useful data and using up the remainder of the photographic paper before the lease period expired. It entailed a great deal of work in developing the many feet of paper, scanning it in connection with the notes, and picking out the few useful sections.

The Leet seismograph was shipped back to Harvard on October 25.

E-6 Filter Designed for Mine Seismograph

Accepting the deduction from the experiments outlined above, that there is a wide difference in the frequency range of blasts and bursts, it became desirable to secure for use with the mine seismograph a filter that would reject pure blast frequency and accept that of bursts, either alone or relaased by blasting.

The design and construction of these filters was referred to General Radio Corporation of Cambridge, Mass. Because of the pressure of defence work, they were unable to supply the filters without very considerable delay. However, they kindly furnished the specifications for their construction, and the filters were made, with very little delay, by the Hammond Manufacturing Co. of Guelph, Ont. On being tested they were found to require some modification of their terminal impedances. When these were corrected they gave a very satisfactory cut-off to a little below 200 c.p.s.

The mine seismograph operated from about February 25 with this filter in circuit. It was tested at various positions in the mine and was found to reduce the number of registrations of blasts; at some locations, however, it passed so many that it was difficult to believe that such a large percentage of blasts could be coupled with induced bursts.

Experiments carried somewhat beyond the time range of this report have finally shown that, when the seismograph with its filter was located in the 3052 cross-cut, it recorded all the known strain bursts very definitely, and only about 5 per cent of the blasting, when set at 2.5 decibels attenuation.

The record from the mine seismograph under these circumstances showed all bursts of any importance, and so few of the blasts that it is safe to conclude that these registered blasts were accompanied by a release of strain. The location was at the extreme end of the 3052 cross-cut, and the record under these conditions may be taken as a measure of the release of strain in the mine.

E-7 Record of the Hydraulic Strain Gauge

The hydraulic strain gauge, designed and constructed at Lake Shore by Gibbs, was installed early in September 1940 in 3001W drift, section 8, a particularly unstable part of the workings.

The gauge consisted of a heavy brass cylinder with an internal diameter of about an inch. This was closed at one end by a piston working through a packed sleeve. The other end opened into a glass tube at right angles to the brass cylinder. The ratio of areas of internal cross-sections of the cylinder and tube was found to be 12:1. The liquid used was a coloured oil.

Two holes were drilled opposite to each other in the walls of the drift to a depth of about six feet — well within the spalled surface. Into these were thrust two iron rods that transmitted the pressure of the walls to the cylinder and piston.

The daily readings of the gauge are shown graphically in Figure 34; the gauge itself is shown in Figure 22. The various numbers written above the graph indicate bursts that occurred near the strain gauge. The location of these in the order in which they occurred is given below. The letter 'C' after a burst number indicates a crush type. The time of each is roughly indicated by the position of the dot associated with each number on the time scale of the graph.

No.	Cross-cut or Drift	Sec.	Rock Fall in Tons	Class
221C	3301W :	10-1	10	Light
223C	3001W :	10	10	Light
224C	2801W :		*	Medium
"	2819X :		*	"
"	2918X :		*	"
"	2901W :		*	"
225C	3301W :	10-1	10	Medium
230C	3301W :	8	45	Light
"	3301W :		10	"
231C	3401W :		5	Light
"	3413X :		1	"
"	3401W :		20	"
288S	3001W :	10	5	Light
236C	2901W :	9	20	Medium
"	2901W :		50	"
"	3001W :	7	10	"
237C	3001W :		80	Light
238C	3401W :		*	Medium
"	3501W :		100	"
"	3701W :		12	"
"	3701W :	14	5	"
240C	3202W :		25	Heavy
"	3301W :		200	"
"	3301W :	10-1	8	"
"	3401W :		20	"
"	3401W :	9	30	"
241C	3301W :		40	Heavy
"	3202W :		50	"
"	3301W :		35	"
"	3301W :	7-2	30	"

* Damage confined to timbering.

It should be noted that some 'light' bursts displace more muck (broken rock) than do those designated as 'medium'. For example, 225C is marked medium, but displaced only 10 tons, while 237C, a light burst, displaced 80. That is to say, the intensity of the burst is not measured by the amount of rock thrown down, but by the general evidence of violence, including the shock as noted by the miners underground and on the surface.

It may be assumed that, after a period during which the closure was taking up lost motion in the gauge set-up, the broken line on the graph shows the average closure on the gauge. Where the actual closure fell away from the average, it was brought back by a large burst (236C). The light burst of early November (230C) was two levels below the drift in which the gauge was set, and apparently caused a slight return to the average. The medium bursts of mid-October (224C, 225C) were in the vicinity, one above and the other below the gauge location, and appear to have caused the graph to trend upward from the average slope. On the other hand, the light burst of early February (237C) had no apparent effect.

The graph, after late January, was below the average line. On April 7, 1941, the date of the last reading of the gauge, the tread was still downward from the broken line. On April 8, a large burst involved section 8 of 3001W drift, the location of the gauge. The gauge was buried in the muck and was not recovered until some weeks later.

Though this series of observations was neither long enough, nor repeated in a sufficient number of places, to warrant definite conclusions, the results seemed to indicate that the closure is variable, that it may be detected by such a gauge, and that a slowing up in closure indicates the building up of pressure that creates conditions favourable to a burst in the region under investigation.

Report F

Microgauge Experiments at Ottawa

May-June 1941

These experiments were arranged by Hollinsworth, who collaborated throughout the entire range of the experiments and assisted in the preparation of the data for this report.

The experiments were undertaken to determine the behaviour of drilled specimens of Lake Shore rock under pressure. It was realized that the conditions for rock in place could not be duplicated. At depth, rock pressure is pseudo-hydrostatic. Even when excavations have been made, only a part of the surface of a pillar is exposed. In the laboratory, with the time and means available, it was possible to employ unilateral pressure only. However, it was felt that the experiments should be attempted, in the hope that some leading ideas might emerge on testing with a microgauge the deformation of a diamond drill hole in a prepared specimen of mine rock as the pressure was gradually increased to the bursting point.

F-1 Preparation of Specimen Rocks

One specimen of porphyry and two of syenite, each with a 1.5-in. diamond drill hole, were supplied in the form of rough blocks weighing upwards of 75 lb. each. The porphyry specimen showed some signs of jointing; the others seemed quite solid. It is very difficult to secure solid specimens of this size at Lake Shore. The syenites are designated S_1 and S_2: the porphyry specimen is indicated throughout this report by the symbol P.

Each block was sawn into a cube of about 5-inch sides, so that the drill hole lay symmetrically along the line joining the centre points of two opposite sides. Two opposing planes parallel to the axis of the drill hole were selected and lapped to smooth surfaces.

Arrangements were made to use the Bureau of Mines (now the Mines Branch) hydraulic testing press. The prepared specimens were checked on being received and as specimen S_2 was found to be not as well surfaced as the others it was capped for the pressure tests.

As prepared for the tests, the specimens had the following areas on the faces to be subjected to pressure: P, 21.0 sq. in.; S_1, 20.3 sq. in.; S_2, 26.6 sq. in.

The drill hole effectively reduced these areas by an amount equal to its projection on the pressure plane. The areas sustaining pressure thus became: P, 14.2 sq. in.; S_1, 13.8 sq. in.; S_2, 19.1 sq. in.

F-2 Preliminary Crushing Strength Tests

In order that the crushing strength of the rock might be known approximately, permitting removal of the gauge shortly before the specimens were likely to burst, cylinders two inches in diameter and two inches long were cut with a core drill from some of the larger pieces sawn from the large syenite rock to reduce it to regular form. These test cylinders, three in all, were carefully capped and then crushed in the press. The pressures at which the test cylinders broke were: 37,800, 38,800, and 32,200 pounds per square inch.

F-3 Behaviour of Specimens under Pressure

The behaviour of all three specimens under pressure was substantially the same. Up to about 250,000 lb., depending on the specimen, the difference in pressure for a unit of compression was, within the errors of observation, apparently constant. That is to say, the diameter of the drill hole that was perpendicular to the plates of the press shortened linearly as the pressure increased.

At about 250,000 lb., the pump control being left unchanged in its setting, the pressure dial would show a falling off in pressure, sometimes accompanied by a cracking noise, while at the same time the milliammeter pointer moved rapidly in a positive direction, showing that the hole was closing. The specimen was yielding, compressing the hole and reducing the pressure between the plates of the press in spite of the steady slow pumping in of oil.

These observations were qualitative only. The amount by which the block as a whole yielded and the amount by which the diameter of the hole was reduced could not be measured. Indeed, at the first sign of such a reversal of pressure, the gauge was unclamped as quickly as possible. In no case was the gauge injured by this yielding, initially sudden and followed by a gradually attenuating diminution.

After the pressure dial again began to move positively, with the controls as they were, the gauge was reclamped and a unit compression reading taken. The initial reading was sometimes as low as 400 lb., but the second and successive readings, as the pressure was gradually raised some thousands of pounds, were of normal value, showing that the rock was, apparently, as strong as before.

At a higher value another sudden yield occurred, and the above cycle was repeated. In some cases as many as four yield points were passed before the pressure was so near the probable bursting value, as indicated by the test experiments with the cylindrical samples, that the gauge had to be removed from the hole. Throughout all the regular compression, including the yield points, the hole was never compressed so much that the available adjustment on the jacking device of the gauge would not permit its ready removal. This available range was about .02 in., and the total yield of the hole was thus of the order of .01 in. This is of no particular importance except for the indication that the design of the clamping device was satisfactory for conditions likely to occur in practice in the mine.

Figure 39 indicates the course of the experiments as described above. The position of the yield points, the loss in pressure at each, and the final bursting pressure are taken from the test of specimen S_1. The slope of the compression is of the same approximate value for all the specimens. The amounts and rates by which the compression increased during the yield periods are not known; hence the dotted lines in these sections of the graph.

F-4 Observations on Figure 39

This graph indicates, qualitatively rather than quantitatively, the behaviour of the small syenite specimen S_1. The series of determinations of the differences in pressure for a unit of compression inidcated that the variation was linear. The slope selected for the unbroken lines of uptrend is quite arbitrary. It was approximate ly uniform, however, throughout the experiment.

At 150,000 lb., a tension crack opened above the centre of the hole. In spite of a continued slow input of oil to the press, the pressure fell, indicating that the block, and therefore the hole, was yielding. The amount of the pressure-fall and that of compression not being known, the slope of the broken, down-trending lines was not determined. This slope was arbitrarily chosen. It may not have been uniform for any one instance and many have differed for different parts of the graph. The specimen yielded several times in this 150,000-lb. region, but terminal pressure values were not defined. Hence the faint terminations made in drawing the otherwise solid lines.

The block yielded several times in about the same pressure range, and in each case resumed its former strength. This strength was then maintained from little over 160,000 to about 270,000 lb. At this point several cracks opened, with temporary resumption of strength in the intervals.

The experiment was discontinued during the lunch hour, the pressure being left on at 272,000 lb. What change occurred in compression is not known, but, on resuming the experiment, the press dial read 266,000 lb.

A series of yield points followed, after which the rock again became, apparently, as strong as before. At 350,000 lb. the gauge was removed from the hole and the control valve set to slowly build up pressure.

At 364,000 lb., the pointer on the press dial wavered, stopped, and then began to move in reverse quite rapidly. As it reached 340,000 lb., the specimen broke with great violence. It then appeared as in Figures 36 and 37. Note the multiple fine lines of shear in otherwise solid wedges, as shown in Figure 37.

F-5 Character of the Specimens after Yielding

After the porphyry specimen had been subjected to pressures up to 130,000 lb. it suddenly yielded but did not burst (Figure 38). It was removed from the press and taken to the Observatory to be examined. The jointing due to pressure is quite marked and a spalled line along the inside of the hole is clearly shown. The block, however, was evidently quite strong for, on being returned to the press, it showed about the same resistance up to 257,000 lb., when it again yielded. It then recovered its normal strength and withstood increasing pressure. It finally burst at 294,000 lb.

The porphyry specimen was not as strong as the syenites, but this was, in part at least, owing to the fact that it was visibly jointed. One of these joints opened as a slab was cut from the rough block.

The large syenite specimen, S_2, was capped and the plates of the press were oiled to reduce lateral friction. The other specimens were left dry. In every case, a piece of cardboard was used above and below, between the block and the plates of the press. Prior to 510,000 lb. pressure, the specimen had yielded only once. It snapped at 505,000 lb., and the pointer on the press dial fell to 462,000 lb. before the specimen again resumed its normal resistance to compression. At 510,000 lb., it snapped again. It was removed and taken to the Observatory. The block showed one tension crack above the hole and two below. When returned to the press this block burst at 590,000 lb.

The small syenite specimen, S_1, showed the greates number of yield points. The energy with which it burst was markedly greater than that of either of the others. The specimen burst at 340,000 lb., after sustaining pressure up to 364,000 lb.

F-6 Tabulation of Experimental Data

Specimen	Net Area	Bursting Pressure	Pressure per sq. in.
	sq. in	lb.	lb.
P	14.2	294,000	20,700
S_1	13.8	364,000 (?)	26,400
S_2	19.1	590,000	30,900

The cylinders cut from the slabs sawn from S_2 were, presumably, freer from incipient joints than the large regular block made from the same rough rock. The average of their crushing strengths was found to be 36,266 lb./sq. in. which is a value in fair agreement, all things considered, with the last value in the final column above.

Without doubt, the crushing strength of the rock in the mine, subjected to semi-confining pressures, is greater than this value and the compression/pressure ratio is less.

F-7 Conclusions

The following conclusions seemed warranted, even though the conditions of the experiment differed so greatly from conditions in the mine. The fact that the results of the experiments were qualitative rather than quantitative seemed unimportant in the circumstances. Some of the conlcusions outlined below would have been evident from a priori considerations, but they were emphasized by the experiments.

It was concluded that:

(a) The gauge as at present designed was more sensitive than required. A reduction in sensitivity would result in a marked gain in stability.

(b) The range of the clamping device seemed to be sufficient.

(c) The graph of Figure 39, showing the typical behaviour of a prepared block under unilateral pressure, could not be considered any indication of the behaviour of rock in place under confining pressure.

(d) It was unlikely that the gauge would be damaged by any strain short of actual crushing.

(e) The fact that the behaviour of blocks under unilateral pressure was essentially the same suggests that the law of consistent behaviour may be determined for rocks under pressure at the mine.

(f) The lines of spalling in a drill hole are 90° from the axis of compressive stress.

(g) Tension cracks in a drill hole indicate the axis of compressive stress.

(h) It is not likely that a pillar will crush under pressure before ample warnings have been given by sudden yieldings in its component blocks. Some of these take place long before crushing conditions are reached.

(i) The syenite specimen had a specific gravity of 2.81. Presumably, the average mine value would be about 3. Thus, on an isolated pillar under homogeneous rock, the pressure would be 1300 lb./sq. in for each 1000 ft. in depth. The small test specimens were crushed at from 32,000 to 39,000 lb./sq. in., corresponding, roughly, to depths of from 25,000 to 30,000 ft. Confining pressures would probably render rock stable at even greater depths. Faulting and other departures from uniform conditions, so prevalent in the mine, explain failures at lesser depths. These considerations are in accord with previous conclusions from seismic recording of bursts that pressure of overburden alone is sufficient to account for these failures.

(j) As rock under unilateral pressure after yielding becomes as strong as before, this is even more likely to be the case for rocks under mine conditions.

(k) A pillar bursts because of partial relief of confining pressure. That is to say, it bursts from a combination of confining pressure and resultant unilateral pressure. The former tends to increase the strength of the rock prior to bursting, but contributes to the force of the burst when it comes. Because of the resultant directional pressure, the drill hole in the mine will go out of round under conditions tending to favour bursting.

(l) To detect the conditions developing at a given point in the mine two gauges, measuring compression in two directions at right angles, should be used. Preferably at least two such pairs should be set at different depths in the same hole. Similar quadruple set-ups should be employed near the middle of the arch of a dome and also near the abutment on the smaller pillar end. The gauges in the centre of the dome should be set in at a considerable depth — well within the zone of compression. Those near the pillar should be just within the zone of spalling. Eight gauges, as suggested above, could be arranged to record through a single amplifier etc., and possibly on a single recording meter.

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Report G

Kirkland Lake Seismograph Records

1941

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G-1 Summary Discussion

The seismograph and auxiliary equipment were modified considerably during 1940, resulting in a recording time loss of 6.14 per cent (see D-6). Few changes were made in 1941 and these did not seriously interrupt the recording. The time loss in 1941 was only 3.08 per cent. At no time was the time correction unknown, and for most of the year the adjusted corrections were classed as 'A', i.e. dependable to within ± .5 sec. As a result, except for the time losses set forth in Table A, the check on rockbursts at Lake Shore was continuous. It is known that no burst of any importance occurred during any of the interruptions to service.

Only two bursts (those of July 30, listed as No. 255C in Table D) were of sufficient magnitude to register on the Benioff seismograph at Ottawa. The data obtained permitted a fairly precise determination of seismic propagation time to Ottawa and a less accurate value to Shawinigan Falls. The burst was not registered at Seven Falls or at any of the New England stations.

The correlation of mine data and instrument records for 1941 was most satisfactory. The detailed reports on all bursts at Lake Shore were made available regularly to the writer in Ottawa as well as to those working at Kirkland Lake. The correlation was most carefully done by O.E. Andrew of the Lake Shore staff, and the seismograms were subjected to close scrutiny throughout the year. In some cases, bursts were reported at Lake Shore that were not registered on the seismograph; others, not listed, appear on the records.

The first group, bursts listed but not registered by the surface seismograph, includes more or less important rock falls with or without slight shocks to start them. It is readily understandable that during the off-shift periods (in general from 3 a.m. to 7 a.m.and from 3 p.m. to 7 p.m.) the blasting immediately preceding many have loosened some rock masses and that very slight bursts may suffice to cause rock falls of several tons. Such slight strain bursts may not have released sufficient energy to register on the surface seismograph, approximately a quarter of a mile distant.

Bursts in the second group, those registered but not listed, are usually more severe. They may occur in abandoned workings of Lake Shore Mines, or in adjacent mines. A few of them were identified as having occurred in other mines, but no regular reports from those mines are available. If such a burst were of sufficient magnitude to register at Ottawa it could, no doubt, be definitely located and the data could be used for velocity determinations. In the meantime, the surface seismograms indicated all these relatively severe releases of energy and provided a complete record of the burst activity in the vicinity of the installation. The records were of sufficient value to warrant a recommendation that they be continued at their present standard throughout 1942.

G-2 Lost Time

The importance of maintaining the surface seismograph in continuous, efficient operation was emphasized in Report D. An analysis of the time lost during 1941 showed a marked improvement over the results for 1940, the lost time being reduced from 6.14 to 3.08 per cent.

A further reduction would result if automatic signals were installed to warn of the failure of the light source; the time lost from such failures in 1941 was 5866 min. out of a total time loss of 16,168 min. Had all light-source losses been avoided, the lost time for 1941 would have been reduced to 1.96 per cent.

G-3 Distribution of Bursts

The continuity and uniformity of recording in 1941 was much better than in 1940. Installation of the testing device on Aug. 4 provided a check on the uniformity for the remaining part of the year. Previously, the recording of the daily blasting was the only proof of continued sensitivity. It seems certain, however, that all bursts of sufficient intensity to be of any interest in this investigation were registered.

The mine seismograph was not operating continuously during the year. When its records were available they were scanned in conjunction with those of the surface instrument and the mine reports. Some, but not all of the bursts reported but not registered at the surface were found to have been registered on the mine seismograph.

The mine reports are listed in G-4. Of the 77 bursts reported, 50 were recorded by the surface seismograph and 19 were not; five may have been recorded, but the record is not certain; one could not have been recorded as the seismograph was not operating when it occurred, and two others may have failed to record for the same reason.

Of the 19 that did not record, only three were in the more distant (eastern) end of the mine: the recording of one other burst that occurred in that end is also open to question. It does not appear, then, that the greater distance is a serious factor in the explanation for non-recording of some reported bursts. Of the 77 bursts reported, 20 occurred in the eastern end of the mine.

In the tabulation below, the seismograph records have been divided into four categories on the basis of the range in half-millimetres of the half-amplitudes on the records as made by the bursts — A, half-amplitudes up to 10; B, 11-20; C, 21-30, D over 30. The fifty bursts certainly recorded fall into the categories as follows: A-12; B-15; C-5; D-18. The tabulation gives the analysis of all records obtained by the surface seismograph.

	A	B	C	D	Total
Jan.	15	3	2	1	21
Feb.	9	6	3	2	20
Mar.	7	7	2	2	18
Apr.	6	14	4	3	27
May	7	6	5	0	18
June	12	11	3	0	26
July	29	10	9	0	48
Aug.	9	9	2	5	25
Sep.	16	10	0	6	32
Oct.	17	15	1	9	42
Nov.	6	6	1	8	21
Dec.	1	4	0	3	8
Total:	134	101	32	39	306

There is a noticeable increase in the number of the largest bursts (D category) after August 1. After November 17, when a strike began and production was curtailed, the number in this category was only two and for December three. All categories fall off noticeably after November 17.

The total numer of bursts reported by the mine or recorded on the surface seismograph in 1941 was about 325. If we deduct most of those in category A, many of which are of the order of the largest blasts, we may say that at least 200 bursts of considerable intensity occurred during 1941, although it does not follow that all of these occurred in the Lake Shore mine.

G-4 Larger Rockburst Located and Listed by Lake Shore Mines

This list of rockbursts was given in the original report as Table D. The disturbances are classified as strain and crush bursts and the latter are further subdivided into heavy, medium, and light. The distinctions are not sharply defined. It is believed that a strain burst simply releases strain in the rock; it may, however, cause rock slides, or sections of the surface of the workings may spall off. A crush burst, on the other hand, is one in which the rock of a pillar is completely broken down. The terms heavy, medium, and light are based on the estimates of the miners and are derived from the integrated impressions given by the noise and shock experienced and the damage done. There are no precise criteria. The terms were not used in the reports received at Ottawa until after the end of March.

In the tabulation, the strain or crush bursts are combined into one chronological series. The numbers followed by S indicate strain bursts; those followed by C are crush bursts. The table shows the serial numbers of the S and C series, as given by the mine records, the date, the Eastern Standard Time as reported by the miners, a rough indication of the location, and an estimate of the number of tons of rock displaced. The mine reports give many other details that cannot be included here, and are accompanied by plans and elevations of the sections of the mine effected.

The capital letters, H, M, or L, appended to a C-serial number in the first column indicate respectively a heavy, medium, or light burst, as 243C-H. The capital letters elsewhere in the columns refer to a key given at the end of the tabulation.

Larger Rockbursts Located and Listed
by Lake Shore Mines

No.	Date	Time	Location	Tons	Remarks
292S	Jan. 4	1:15 p.m.	3901W	2	Recorded
293S	" 16	8:15 p.m.	4301W	-	No trace
294S	" 18	10:50 p.m.	3202W) 3314W)	2	Recorded
295S	" 18	1:30 a.m.	3018W) 3202W)	9.5	A
236C	" 19	12:25 p.m.	2901W	-	B
296S	" 21	10:00 p.m.	4001W	-	Recorded
296S+	" 26	C	817E	70	Recorded
297S	Feb. 6	8:05 p.m.	3701W	5	Recorded
237C	" 12	D	3301W	50	Recorded
238C	" 13	10:24 a.m.	3501W	?	Recorded
239C	" 17	?	4202E	?	Recorded
298S	" 17	9:15 a.m.	3214W	1	No trace
240C	" 18	4:00 p.m.	3401W	83	Recorded
241C	Mar. 10	10:45 a.m.	3301W	85	Recorded
299S	" 10	5:10 p.m.	No. 4 S	-	No trace
300S	" 12	1:45 p.m.	4201W	.5	No trace
242C	" 27	E	3701W	?	F

No.	Date		Time	Location	Tons	Remarks
301S	Apr.	6	12:55 a.m.	3214E) 3307W)	8	No trace
243C-H	"	9	11:50 p.m.	3001W) 3002W) 3010W) 3025W) 3201W) 3202W) 3214W)	235	Recorded
244C-H	"	12	5:45 a.m.	4002E	G	Recorded
302S	"	16	7:10 p.m.	3002W	12	Recorded
245C-L	"	18	2:45 p.m.	4202E	50	H
246C-L	"	27	10:30 a.m.	5001W	60	No trace
247C-L	"	29	1:50 a.m.	3401W	20	I
303S	May	3	J	4202E	5	No trace
304S	"	15	2:50 p.m.	3307W	50	Recorded
305S	"	16	K	4001W	15	No trace
248C-M	"	20	2:55 a.m.	3401W) 3406X) 3409W) 3414W)	220	Recorded
249C-L	"	20	8:45 p.m.	4001W	150	Recorded
306S	"	23	8:00 p.m.	4301W	5	Recorded
307S	"	23	9:55 p.m.	4202E	20	Recorded
308S	June	5	1:45 a.m.	3307W	8	No trace
309S	"	5	10:25 a.m.	4001W	2	No trace
250C-L	"	12	9:20 a.m.	4301W	10	No trace
251C-M	"	13	2:45 a.m.	3802E) 3902E)	170	Recorded
310S	"	15	L	4001W	20	M
252C-M	"	20	1:25 a.m.	3301W) 3401W) 3501W)	40	Recorded
311S	"	28	2:41 a.m.	4201W	5	Recorded
253C-M	June	29	2:40 a.m.	4001W) 4201W)	75	Recorded
312S	July	10	N	4001W	50	O
313S	"	17	2:30 a.m.	No. 6S	23	No trace
314S	"	21	3:00 p.m.	4202E	10	P
315S	"	22	9:00 p.m.	Q	.5	No trace
254C-L	"	23	3:00 p.m.	4502E	R	No trace
316S	"	24	2:40 p.m. 8:30 a.m.	No. 6S	10	Recorded
317S	"	25	3:00 p.m.	4202E	R	Recorded
318S	"	29	3:48 a.m.	?	10	No trace

No.	Date		Time	Location	Tons	Remarks
255C-H	"	30	9:39 p.m. 9:46 p.m.	3901W) 3908W) 4001W) 4201W) 4301W)	T	Recorded Recorded
319S	Aug.	1	8:15 p.m.	U	20	No trace
256C-L	"	12	3:05 p.m.	3802E) 3902E)	20	Recorded
257C-L	"	16	D	4301W	40	Recorded
320S	"	26	2:45 p.m.	No. 6 S	-	No trace
258C-L	"	29	6:15 p.m.	4402E) 4502E)	60	Recorded
321S	Sep.	3	D	3307W	10	Recorded
322S	"	10	2:35 a.m	No. 6 S	10	Recorded
259C-L	"	11	1:20 p.m	V	72	Recorded
323S	"	18	3:20 a.m.	3906E	R	Recorded
260C-H	"	20	2:30 a.m.	4302E) 4401E) 4402E) 4501E) 4502E)	sev- eral tons each loc.	Recorded
261C-M	"	21	1:45 p.m.	4402E) 4502E)	100	Recorded
262C-L	"	23	9:40 p.m.	2401W) 2501W) 2504W) 2575X)	60	Recorded
263C-L	"	27	3:00 p.m.	4201W) 4301W)	?	Recorded
324S	Oct.	8	9:25 a.m.	3325X	8	Recorded
325S	"	9	3:05 a.m.	5401W	.5	No trace
264C-L	"	11	3:10 a.m.	4002E) 4202E)	170	Recorded
326S	"	21	10:30 p.m.	4301W	15	W
265C-M	"	24	3:01 a.m.	4202E	X	Recorded
266C-L	"	24	4:27 a.m.	4200X	40	Recorded
327S	"	24	7:00 a.m.	3307W	20	Y
328S	"	25	7:15 p.m.	No. 6S	2	No trace
328S+	"	28	10:26 p.m.	3202W	2	Recorded
328Sx	"	28	11:15 p.m.	3202W	35	Recorded
329S	Nov.	14	D	4001W	20	Recorded
330S	"	17	10:30 a.m.	4502E	1	Z
267C-M	"	19	10:30 a.m.	4409X) 4501E)	50+	Recorded
268C-M	Dec.	7	8:40 a.m.	4501E) 4502E	125	Recorded

A If dates are correct, the serial numbers 294S and 295S are inverted. At 1:30 a.m. on the 19th, which might possibly be intended for 295S, there was no trace.

B The seismograph not recording at this time, owing to lamp failure.

C Time reported simply as 'between shifts'. The report was not included in the regular S series and has been assigned the number 296S+ by the writer.

D Time reported as 'between shifts, p.m.'.

E Reported simply as 'between shifts'.

F Adjustment of apparatus interfered with the record during the p.m. off-shift period. There was no trace on the a.m. off-shift period.

G 'Several hundred tons'.

H Recorded very feebly.

I It is not certain that this was recorded. There was no trace at the time and date given; but, if either were in error, it might have been the record at 2:28 a.m. on the 29th, or at 1:46 on the 30th.

J Time given as 'between day and night shifts'.

K Time given as 'between 3 a.m. and 7 a.m.'

L Time given as 'between Saturday night and Monday day shift'.

M Either No. 116 and 117 of the serially numbered bursts recorded on the surface seismograph might be 310S.

N Time given as '3 to 7 p.m.'.

O Two bursts at 3:00 and 3:01 p.m., which are probably to be identified jointly as 312S.

P Small offset at 2:24 p.m. on 21st may be 314S, but the record is very feeble and the time does not agree well with the reported '3 p.m.'.

Q Level 5200 in pilot raise of No. 6 shaft.

R 'Several tons'.

S 'Five bursts of which three were heavy'.

T The damage due to these bursts (there were three) was great. The several displacements were reported as '210 tons', 'several hundred tons', '30 tons', and 'a small amount'.

U 'No. 4 shaft at 5325-ft. level'.

V Pillar between 2722 and 2725 cross-cuts. Note the very small half amplitude on the surface seismograph (5 half mm.) for a displacement of 72 tons.

W Discrepancy of 20 min. in time. The recorded amplitude is large, but there is no other offset that may be identified as 326S, for which the displacement was 15 tons.

X 'Several tons' and '30 tons'.

Y Not recorded, but may have occurred while sheets were being changed at 7:06:30 to 7:07:30 a.m.

Z Burst 330S is reported as having occurred at 10:30 a.m. on the 17th. There is no trace of an offset at that time. It is possible that No. 290 (Surface Seis.) at 10:35 a.m. on the 16th might be so identified.

Report H

Velocity of Elastic Waves and Structure of the Crust in the Vicinity of Ottawa, Canada

The data upon which this study is based were obtained from ten rockbursts that occurred during a period of about 3 years in the Lake Shore mine, Kirkland Lake, Ont. and were registered on the short-period, vertical Benioff seismograph at Ottawa. Such bursts are strictly comparable to earthquakes as regards the mechanics of energy release. At least two of them were so severe that they were recorded at Weston, Mass. at an arcual distance of 581 miles.

The ten bursts originated at depths ranging from about 2000 ft. to 4000 ft. and, in plan, lie within a rectangle 1600 ft. by 500 ft. As the arcual distance from Ottawa to Lake Shore Mines is 450 km. (279 mi.), the foci were essentially at the same distance from the recording station, the variation being less than one part in 7000. Regarding the bursts as earthquakes, they may be said to have originated at zero depth.

The records were all made on the same seismograph, set at the same constants, and having a paper speed (synchronous motor drive) of 60 mm./min. The time service throughout was that of the Dominion Observatory. The correction to be applied is much less than the error of reading even the most sharply marked phase on the seismograms. For such well-marked phases, the error of reading the arrival times at Ottawa is about ± .25 sec.

Only two of the bursts were accurately timed at Kirkland Lake, eight of them having occurred before the installation of the seismograph there. The paper speed of this instrument was 30 mm./min. The time marks were put on the seismogram by a Dent chronometer, mounted in a supplementary wooden box supported by a bracket on a brick wall of an inside basement room. The chronometer had been reinstalled, after cleaning and adjusting, twelve days before the bursts (within about 7 min. of each other on July 30, 1941), and had been rated by automatically recorded time signals, in general oftener than once a day, and always at least once. For the entire 12 days the rate was zero, the correction at each check being + 15.0 sec. The time of occurrence could be read from the sharply defined record to within ± .5 sec.

In the above circumstances, and with two records available for averaging, it is safe to say that the travel time for the well-marked phases is known to within about half a second.

H-1 Tabulation of Data

Record	Date	Time	Depth	Intensity	Coordinates (x-y-z)
A	XII-27-38	23:49:50	2700	6	9-5-13
B	III-11-39	20:49:07	3500	2	12-2- 5
C	III-28-39	13:09:28	3000	1	16-0-10
D	VIII-31-39	2:51:55	3600	9	9-2- 4
E	VIII-31-39	3:01:55	3600	8	9-2- 4
F	IX- 2-39	13:44:50	3800	5	8-2- 2
G	IX-19-39	22:54:44	(2000)	10	8-5-20
H	IX-19-39	23:06:59	(2000)	7	8-5-20
I	VII-30-41	21:39:02	4000	3	0-0- 0
J	VII-30-41	21:46:17	4000	4	0-0- 0

Record designations are assigned in chronological order.

Times are given in E.S.T. on the 24-hr. system beginning at midnight. The occurrence times for bursts A to H inclusive were computed from the Ottawa records, using the same elapsed times as obtained for the bursts I and J, which were the only ones directly timed by the Kirkland Lake seismograph. The second of the three bursts shown in Figure 41., occurring between I and J, was not of sufficient intensity to register at Ottawa.

Brackets on depth numbers indicate approximate values. Bursts G and H together extended, in depth, from 800 ft. to 3000 ft. in a shaft pillar, the greatest damage being from 1400 ft. to 2600 ft.

Intensity numbers (1-10) simply relative intensities, increasing with the number order.

The coordinates x-y-z are expressed in hundreds of feet, x being measured positively E 30°N, y being measured positively N 30° W, and z being measured positively upward from 4,000 feet.

Zero of coordinates is taken at the position of the bursts of July 30, 1941.

Greatest ranges are: x = 1600 ft.
y = 500 ft.
z = 2000 ft. (± 600 ft.)

Geographical coordinates of No. 5 Shaft, Lake Shore Mines:
80° 02'43" W.
48° 08'57" N.

Geographical coordinates of the Ottawa station are:
75° 42'57" W.
45° 23'38" N.
Computed azimuth, Kirkland Lake to Ottawa, S 49° E.
Computed azimuth, Ottawa to Kirkland Lake, N 45° W.
Computed arcual distance Ottawa to Kirkland Lake, 279 mi. (450 km., 4°).

H-2 Layout of Seismograms in Figure 42

When the ten records are copied so as to be as exactly as possible on the same scale, and are mounted so as to place a certain well-marked phase on each in the same vertical line, it is found that at least five phases are clearly defined on each, several others appearing on some of the records only.

If the crust in the region concerned be considered to have two discontinuities defining three layers and if the layers, in order from the surface down, be designated as 1,2, and 3, then P_1, P_2, and P_3 indicate respectively the longitudinal waves arriving at Ottawa through the three layers in order; and similarly, S_1, S_2, and S_3 indicate respectively the transverse waves arriving at Ottawa through the same three layers.

The five phases definitely recorded on all the records are identified, in order of arrival at Ottawa, as P_3, P_2, S_3, S_2, and S_1. On every seismogram P_2 is very sharply defined. There is an indication of P_1 on records A,B,D, E, and G, but it is not sharply recorded on any of these. The other phases are well defined on some and not as well on others. However, knowing that the shocks had a common origin, that the intensity (with its governing factors) is practically the only cause of variation in trace, and that the travel times for all must be the same, it is permissible to combine the ten records to obtain:

(a) the time sequence of arrival of the phases.
(b) the focal time for each of the ten bursts.

These data are set forth in the next section.

H-3 Readings for the Ten Seismograms

Arrival Times for an Arcual Distance of 450 km. (279 mi.)

Rec.	H	P_3	P_2	P_1	S_3	S_2	S_1
-	0	1:01.5	1:11.5	(1:22.5)	1:48	2:01	2:13.5
A	23:49:49.5	50:51.5	51:01	(51:12.5)	51:38	51:51	52:03
B	20:14:06.5	15:08.5	15:18	(15:30)	15:55	16:08	16:21
C	13:09:28	-	10:40	(10:51)	11:16	11:30	(11:43)
D	2:51:55	52:56	53:06	(53:18)	53:43	53:56	(54:08)
E	3:01:55	2:57	3:07	(3:18)	3:43	3:56	4:08
F	13:44:50	45:52	46:02	(46:13)	46:38	46:51	47:03
G	22:54:44	55:45.5	55:55.5	(56:06.5)	56:32.5	56:45	56:57
H	23:06:58.5	(8:00)	8:10	(8:22)	8:46	9:00	9:12
I	21:39:01.5	-	(40:13)	(40:25)	(40:50)	(41:03)	41:15
J	21:46:17	47:19	47:28.5	(47:40)	48:05	48:18	48:30

The entries in the first line are minutes and seconds of elapsed time, obtained by taking zero focal time and the best estimate of phase time obtained from the records. All the other entries are the hours, minutes, and seconds (in the first column) or minutes and seconds (in the remaining columns) of recorded time for each rockburst.

Brackets indicate that an increase of energy seems to be recorded at the expected phase time, but that the phase cannot be accurately timed.

The P_1 values for records A and G are the two readings used to get that range value in the first line.

L-waves appear definitely on record H only.

H-4 Explanation of Figures 41 and 42

Figure 41 presents the Kirkland Lake surface seismograph records of three bursts that occurred at Lake Shore on July 30, 1941. These are designated I, Ia, and J. The second burst did not register on the Ottawa seismograph: the others produced respectively the seismograms designated I and J in section H-1. The times of occurrence (H) are:

H_I = 21:39:01.5 H_{Ia} = 21:39:09.5 H_J = 21:46:17

Figure 42 presents the ten seismograms listed in section H-1. They were compiled into the composite lay-out, care being taken to have the scale exactly the same throughout. They were then laid out in order chronologically from top to bottom, with the well-marked phase on each (P_2) in line. The following points should be noted:

(a) The principal phases are marked, e.g. a straightedge from P_3 at the top to P_3 at the bottom will pick out that phase on each of the seismograms.
(b) Interval P_3 to P_2 was obtained from the records A and G.
(c) Interval P_2 to P_1 was obtained from the records A and G.
(d) Interval P_2 to S_3 was obtained from the records A, H, and G.
(e) Interval S_3 to S_2 was obtained from the records A, B, H, and J.
(f) Interval S_2 to S_1 was obtained from the records A and F.
(g) Interval H (focal time) to P_2 was obtained from record J.
(h) Extra phases may be noted as follows:
   (1) about 1.5 sec. after every phase on record D.
   (2) about 1.5 sec. after P_3 on the records A and G.
   (3) about 3 sec. after S_3 on records A and H.
   (4) about 3 sec. after S_2 on records A, F, and J.
   (5) about 2 sec. after S_1 on records A and J.
   (6) about 3 sec. after S_1 on records A, B and J.

H-5 Earth Structure Deductions

In 1934, Saint Louis University published a set of "Tentative Tables of Travel Times for Near Earthquakes", prepared under the direction of Father Joseph S. Joliat, S.J., and based on velocity values determined by Jeffreys for northern Europe, namely:

	V_p	V_s
1	5.4 km./sec.	3.3 km./sec.
2	6.3 km./sec.	3.7 km./sec.
3	7.8 km./sec.	4.35 km./sec.

Joliat assumed that the focus lay at the bottom of the uppermost layer, not at the surface as is the case with rockbursts. A comparison of the travel times obtained for the rockburst records at Ottawa (H) with the Joliat values (J) for the same distance (450 km.) follows:

Travel Times for an Arcual Distance of 450 km.

	P_3	P_2	P_1	S_3	S_2	S_1
J	62.5	72.	83.	111	122	134
H	61.5	71.5	(82.5)	108	121	133.5
J-B	58.	-	-	104	-	-

The travel times shown in the latest tables by Jeffreys and Bullen (J-B) are also given for P_3 and S_3 the only values tabulated by them for such a short distance. They assume a depth of focus of 14.5 km. in a layer 15 km. thick.

Differences of the magnitude found in the above were to be expected because of the difference in focal depth, but they may also be due, in part, to the differences in structure (and associated velocities) in the vicinity of Ottawa as compared with those of northern Europe, where the instrumental data that were the basis for the Jeffreys-Bullen tables were collected; these tables were used, in turn, by Joliat, in connection with an arbitrarily selected, hypothetical, crustal structure, in computing his tables for near earthquakes.

The sequence of arrival times in the H line above gives one set of points defining travel-time curves for rockburst records in the vicinity of Ottawa. Up to an arcual distance of 10° (1110 km., 690 mi.) such curves may be considered to be straight lines. One more set of points would define these lines and permit the computation of rockburst travel time tables; these, with some small modifications, could be adapted to apply to local earthquake tables. From the same data, the thickness of each of the layers and the six velocities concerned could be deduced.

Burst G was well recorded at Weston, Mass., and at Shawinigan Falls, Que., thus furnishing two such sets of points. The focal time for the burst can be obtained with considerable precision, on the basis of the ten burst seismograms recorded at Ottawa. There is, however, only one record defining two other points on each of the travel time graphs at each of the other stations. A least squares solution is necessary to permit the deduction of the most probable values to fit the observational data of varying weights. A set of tables based on the deduced structure and velocities, and assuming a focus at the surface, can then be computed. These tables can be used in the vicinity of Ottawa for both rockbursts and earthquakes. The corrections necessary to convert the tables for use where the focus is not at the surface must also be computed and supplied.

It is evident from the preliminary work on the material that the P-velocities are higher than those obtained by Jeffreys for northern Europe and used by Joliat in his tables. The values, subject to corrections, obtained by the preliminary investigation are:

$$P_1 = 5.5 \text{ km./sec.}$$
$$P_2 = 6.5 \text{ km./sec.}$$
$$P_3 = 8.1 \text{ km./sec.}$$

as compared with those of Jeffreys given in section H-5 above. The S-velocities appear also to be slightly higher than the corresponding Jeffreys figures there tabulated.

In terminating this analysis of the ten rockburst records, it is to be noted that other phases appear on some of the seismograms. These are, perhaps, more easily noted on record A. Some of these are more pronounced on the Shawinigan Falls record of burst G. This is to be expected since the Ottawa record was made on a vertical Benioff seismograph and the Shawinigan Falls record on a horizontal Wood-Anderson instrument. The Weston records are Benioffs, both horizontal and vertical. When they are received, these extra phases will be studied in an attempt to deduce other peculiarities of structure in the area.

H-6 Evidence of Rockburst Mechanism

A further point of interest should be noted. The fact that these records were due to a burst might lead to the supposition, a priori, that the first impulse would be anaseismic, away from the origin. In every case however, this first impulse was kataseismic, i.e. toward the origin. The rock yielded, bursting out into the stope and development drifts, and the impulse was transmitted as a rarefaction. As at date of writing, the rockburst records obtained at Ottawa are all definitely kataseismic.

H-7 Summary

The centre of each of the ten bursts was located within a few feet, but for the purpose of preparing travel time tables, they may all be considered to have occurred at a single point at the surface. Two of the bursts were accurately timed on the surface seismograph at the mine.

Six phases were registered on each seismogram, being more sharply marked on some records than on others. Five of these are well defined on nearly all the records. It was thus possible to deduce a set of arrival times at a distance of 450 km. for a burst (or earthquake) occurring at the surface, and this set of times was known with considerable precision, since all the readings could be combined. The distance was determined within one part in 7000, the depth within 2000 ft., and the travel times with an error of $\pm$ .5 sec.

These travel times were compared with those obtained by Joliat in computing his Tables for Near Earthquakes, based on the velocities deduced by Jeffreys for northern Europe and arbitrarily assuming an earth structure with two layers above the Mohorovicic discontinuity. The differences were minor and may be explained as largely due to the fact that Joliat assumed the focus to lie at the bottom instead of the top of the upper layer.

On the strength of the comparisons afforded by the ten seismograms, the focal time of each burst may be considered as known to within a half second. One burst was so severe that it registered at Shawinigan Falls Que. (576 km., 358 mi.) and Weston, Mass. (935 km., 581.) also. These records afforded a means of deducing the earth structure and velocities in the vicinity of Ottawa, and made possible the construction of tables for rockbursts and earthquakes in that area up to 10° (1110 km., 690 mi.)

Further work on this problem was interrupted because of the pressure of research duties at the mine. It was later resumed by John H. Hodgson, who obtained points on the time-distance curves by setting up temporary stations at ever-increasing distances from Kirkland Lake and utilizing the records from rockbursts timed by the Kirkland Lake seismograph and located in the mine by the staff of Lake Shore Mines. A brief introduction to this work will be found at the end of this publication and a list of papers on the subject will be found in the Bibliography in the Appendix.

A paper by the writer, based on the material of Report H, appeared in the Bulletin of the Seismological Society of America, Vol. 32, No. 4, 249-255, 1942.

Report J

Initial Obert Experiments
April 15, 1941 to June 30, 1942

During the period under review, the experiments with the microgauge were continued. On July 30 the gauge was slightly injured by the triple bursts in 4200W, the first and last of which are the only two so far recorded at Ottawa since December 1938.

Improvements to the mine and surface seismographs greatly improved their recording. The strain gauge caught in a burst on 3001W on July 8, 1941 was recovered, repaired, and again placed in service.

Experiments leading to the development of ultrasonic equipment had progressed to a point where the instruments were about ready for service when contact was made with Dr. Leonard A. Obert, of the United States Bureau of Mines. His experience indicated that the ultrasonic vibrations could not be picked up more than a few feet from their source. He was obtaining good results with instruments sensitive to vibrations of 1000 c.p.s., but subaudible.

Dr. Obert was most cooperative; he accepted an invitation to demonstrate his equipment, both at Frood and at Lake Shore. As a result, towards the end of June 1942 three sets of Obert instruments were in operation at Lake Shore. On June 30, the writer assumed direct conduct of the underground program.

After Obert's visit in late October, a listening program was begun at a selected number of drill holes in the west pillar. This was continued without interruption to the end of the project on November 30, 1945. Report J deals with these developments in the order in which they occurred.

J-1 Mine Seismograph Program

This instrument was reconditioned and was moved on August 11 to a point about 120 ft. west of the junction of 3053W drift, which connects with 3052 cross-cut at a point about 1500 ft. north of the north vein (Figure 27). Electricity was carried to this point, so the seismograph no longer depended on battery operation. The seismometer employed was Heiland geophone No. 357, and the recorder a commercial 5-milliampere Esterline-Angus meter. The amplifier, built by Gibbs, was equipped with a wave filter. Twice each day for a period of about 5 minutes a telechron clock repeatedly placed and lifted a test weight on and off the mass of the geophone, by means of the device illustrated in Figure 43. The records were changed once a week and analysed.

J-2 Control Panel for the Surface Seismograph

As considerable lost time was experienced with the surface seismograph because of lamp failure, a warning device was designed and put in operation by Gibbs. The 115-volt supply provided a power source for the synchronous motor and the light; a transformer between the lamp and the supply cut the voltage. Into this circuit Gibbs introduced a resistance. Bridging this resistance and using the voltage drop across it, a copper oxide rectifier provided current to operate a relay. As long as the light was in service the relay remained open. If it failed, the relay closed a circuit that actuated buzzers in the laboratory and in Gibbs' house.

This device, together with the circuit to drop a test weight on the geophone, made it desirable to have a control panel set up. This proved most useful in reducing lost time in the recording of the surface seismograph, and made it very convenient to adjust the light intensity, etc. A telegraph key in the adjoining radio room permitted the operator to close the relay that placed the test weight on the geophone. This was done each day before removing the completed seismogram and also just after putting a fresh sheet on the drum.

J-3 Severe Rockbursts of July 30, 1941

On July 30, at about 9:40 p.m., three severe rockbursts occurred from the 3900-ft. level to the 4300-ft. level, causing considerable damage. The first and last of the shocks were of sufficient intensity to record at Ottawa — the first such recording since the rockburst of December 28, 1938, also the first of the recording rockbursts to be timed at Kirkland Lake. Report H deals with the data from these bursts.

J-4 Experiments with the Microgauge

While the experiments with the microgauge, described in Report F, were being carried out during May and June 1941, Gibbs and Hallick experimented at the mine with a specimen gauge left at the mine by Hollinsworth, in an attempt to stabilize the zero and to obtain data underground.

On July 28, the gauge was installed in a bore hole at the back of the safety station at the extreme south end of the main cross-cut on the 4200-ft. level. It showed some variation during the first three days, which seemed to indicate that pressure was lessening in the azimuth of the bore hole crossed by the gauge contacts.

The heavy triple burst of July 30 occurred while the gauge itself was temporarily replaced by the reference standard. This device had just been installed when the burst occurred. The next morning the gauge was again placed in operation in the same drill hole. The drift of the previous three days had disappeared. It is possible that the gauge movement prior to the burst may have been due to temperature effects that later became equalized. The equipment was in good working order, but the only azimuth that could be checked with the single gauge did not present a complete picture of conditions.

J-5 Meeting with Obert

In September 1941, the writer met Dr. Leonard A. Obert of the United States Bureau of Mines in Washington. Dr. Obert had been studying rockbursts for some years, and had developed an instrument that recorded subaudible (but not supersonic) snaps. These are said to indicate, by an increase in the number per minute, the imminence of a rockburst. Dr. Obert was invited to try his equipment in the Frood mine at Sudbury and at Lake Shore Mines. The visit was made to Sudbury on October 17-21 and to Kirkland Lake, October 22-26. The report of the meeting of Hodgson and Obert in Washington is given in section J-6 below and of the visits to Frood and Lake Shore in section J-7.

J-6 Notes on Obert Equipment

(a) Recording Paper

The Obert seismic equipment uses a paper specially developed by the Western Union Telegraph Company for use in its facsimile transmission work. The paper is three-layered, that next the drum being aluminum-coloured (this is probably a special conducting material), the middle layer black, and the face of a thin, hard, smooth-surfaced paper. Recording is accomplished by a stylus carrying a current of about 7 milliamperes to 180 to 200 volts.

The stylus can record clean-cut lines at frequencies as great as 10 c.p.s.. At a paper speed of 2 inches a minute, close tracings are not confused, as would occur as a result of halation in photographic recording, and blotting if ink were used. Other advantages are: low friction on stylus; low price; no development delays; no lighting problems; ability to see the results of tests and adjustments as made.

The only disadvantage is that if the stylus remains too long on one spot (as in the case of the paper feed failing) the paper may become ignited. However, the paper smoulders, rather than burns, and so no fire hazard is involved, although damage to the drum and stylus may result. The paper is marketed under the name 'Teledeltos'.

(b) Pick-up Device

The pick-up device utilizes the piezo-electric effect. Two crystals of Rochelle salt are separated by a conducting leaf at one potential with connected conducting leaves at the other potential on the outer faces. The built-up crystal is 2.5" long, 0.75" wide, and 0.25" thick; the natural frequency of the crystals is 800-900 c.p.s.

The crystal is 'spring-board' mounted in a heavy metal cylinder with rounded ends, one of which has a water-tight gasket for the electric cable. The whole pick-up is 7" long and a little more than one inch in diameter. It is simply laid in a drill-hole that has been blown clean and dry by compressed air.

Total cost of the pick-up, which is made in the Bureau of Mines (U.S.) workshops, is $6-8, exclusive of labour, as against $150-200 for the commercial seismic pick-ups hitherto used.

(c) Recording System

The recording system uses an amplifier, filters, and recorder made at the Bureau. The recording device consists of a writer coil, designed to obtain high impedance, operating a steel stylus. The output current from the amplifier is rectified. The amplifier has practically flat gain for the range 50-10,000 c.p.s., but the system is peaked slightly by the natural frequency of the crystal pick-up.

Two recording devices are used to register the impulses from one geophone. One operates through an integrating device with an integrating time of one-tenth of a second (referred to as the 'A' recorder), and the other through a device with a time of one second ('B' recorder).

The devices record side by side on Teledeltos paper, the A recorder indicating the amplitude of the maximum throw or voltage variation of a wave train, and the B the integrated energy. By careful comparison of the dual record it is therefore possible to determine whether an impulse was from a nearby small pulse with a wide amplitude but small train, or originated as a more severe shock at a greater distance. By comparing the dual record from various points in the mine, as well as the reports made by miners, it is possible to determine approximately where all the larger pulses originate.

(d) U.S. Field Work with Obert Equipment

Most of the recent work with the Obert equipment was done in the Ahmeek Mine, Ahmeek, Mich. At this mine, blasting is almost entirely restricted to 15 minutes twice daily, at which times the recording devices are shut off. Speed of operation is relied on to keep ahead of bursting conditions, and no large bursts are experienced: small bursts occur in cycles.

In the work here, it was noted that when the detected snaps in the vicinity of any given pick-up become numerous (sometimes 200-300 per ten-minute interval) a burst occurs in that part of the mine within 24 hours. The snaps are always more active for a short time after blasting: they are quite inaudible, and can be detected by the seismic equipment only.

The above is directly opposite to what had been expected. It had been thought that the frequent releases of pressure shown by the recorded snaps would preclude a build-up of pressure, and that a burst would be expected only after a period of quiescence. Obert suggested that the frequent noises indicate a general increase of pressure with slight release along some of the fault faces, leading up to a build-up of pressure to bursting value in one or more of the blocks. The suggestion seems reasonable in view of the different occasions when a burst has followed a period of marked unrest, and is supported to some extent by the initial plotting at Lake Shore of integrated burst activity.

(e) Characteristics of Recording

The Obert equipment is much more sensitive than that used at Lake Shore: the blow of a one-pound hammer on the wall of a drift 1,000 ft. distant gives offsets of about one-eighth of an inch on the record. This method is, in fact, used a rough test of sensitivity. The chief disturbance comes from rock drilling--something scarcely affecting the Lake Shore equipment. The reason is that drill disturbance is of high frequency, about 1,000 c.p.s., while the Lake Shore equipment is sensitive to frequencies of about 100 c.p.s. Filters can greatly reduce drilling noise, but cannot eliminate it.

(f) Observations on Frequency

Obert considers that impact on an elastic body causes the generation of a wide spectrum of frequencies. If these are plotted for various types of disturbance, the peak of the spectrum curve occurs at characteristic positions along the frequency abscissa. He considers also that blast and burst spectra have peaks at different frequencies, but that each generates some amplitude at all frequencies: moreover, the waves damp out in the rock at distances that vary with the frequencies. He believes that the snaps with which he has been working carry for 20 ft. or less, and that his studies are therefore limited to areas within 20 ft. of the equipment.

Evidently, the amplitude of the record made by any type of equipment depends on such factors as:

(i) The energy released in the various frequencies, i.e. the initial spectrum curve.
(ii) The filter system, which cuts down the intensities of record for certain frequencies.
(iii) The gain factor of the amplifiers for various frequencies.
(iv) The resonance characteristics of the pick-up, and the recording mechanism for various frequencies.
(v) The distance from source to recorder, which causes higher frequencies to damp out more than the lower one, i.e. the spectrum at the recorder.
(vi) The path between the source and the recorder, which tends to be better in some parts of a mine than in others.

Obert considers that it is quite possible to build equipment that would record the snaps that he believes occur under increasing pressure at frequencies as high as 15,000 c.p.s. He believes, however, that such snaps could not carry for more than 2 or 3 inches (or as many feet at most), and that data from so small a volume of rock would be of little value. If we decided to carry on work along the lines he had developed, he recommended the use of Y-cut quartz crystals, as they are not affected by moisture.

(g) Direct Approach to the Problem

To design the optimum equipment for detecting and recording mine noises and sub-audible snaps that might serve to give warning of approaching bursts, the factors listed in the preceding section would have to be studied in detail, particularly those concerned with frequencies. The studies would involve the securing of records at various frequencies with optimum response characteristics in order to determine for which choice of frequency the most definite warning of an impending burst is conveyed. Obert considered that this frequency would be about the 1,000 c.p.s. level.

(h) Alternative Methods

In the course of studying the elastic constants of rocks under pressure, Obert found, as had Birch and others, that the velocity curve flattens markedly after pressures definitely below bursting values have been reached. It cannot therefore be used to predict bursts, but is of value in determing pressures in residual pillars from which it is desired to extract the ore.

Obert has constructed a high-speed camera that makes it possible to measure directly velocities over paths of 1,000 ft. or less with a timing accuracy approaching $\frac{1}{1,000}$ of a second. In carrying out direct measures of seismic velocity, he found that a short length of wire laid in the drift at the recording point would pick up the electric surge caused by blasting 1,000 ft. and more away. He suggested that this is the cause of the high-frequency disturbances preceding the blast frequencies as shown in Figures 29c, d & e, the surge of the blasting current being carried by the rock and picked up by the seismometers. Later experiments at Lake Shore tended to confirm this theory.

J-7 Experiments at Frood and at Lake Shore

(a) Frood:

It was decided to visit Frood mine on the night of Oct. 19, as this was one of the alternate Sundays when the mine was not operating. The company arranged to have a number of holes drilled on the 2800-ft. level, near the top of No. 6 shaft, where the ground had been working for sometime. Cracks developing in the hoist room are being measured and studied regularly.

Frood mine has two large mineralized areas with a narrow, horizontal section connecting them. The initial development was done at the 2800-ft. level and mining continued upward. At the same time, open-pit mining was started on the surface and development drifts were opened below the 2800-ft. level.

Obert, Elves, Hollinsworth and the writer listened in at the prepared holes until about midnight. There were snaps from time to time, perhaps an average of four or five a minute. A few of these could be heard without the equipment, but most of them were quite inaudible without it: Obert said that the low pitch indicated that they were coming from a distance of about 1,000 ft. This would indicate the possibility of working ground at a distant point where the more frequent, higher-pitched noises, indicative of bursting conditions, might be heard; such noises do not carry more than about 50 ft. It was therefore decided to try a listening post on the 3100-ft. level. The holes were to be prepared on the following day so that listening could be done that night during the off-shift period.

No air or water being immediately available at the location selected, it was necessary to have lines laid. This work was just finished, and the drillers had not started, when a rockburst heaved the track for a dsitance of 60 ft. along the drift, broke timber, and threw out several tons of loose rock. The ground continued to 'talk', so the drillers did not put any holes in the burst section, but began drilling 10 ft. or so to the south, and continued at intervals for several hundred feet; similar holes were drilled north of the burst section. All were blown clean, ready for the experiments. The party consisted of Elves, Obert, A.E. Prince (Assistant Electrical Superintendent), and the writer. The first stop was made at one of the holes on the 2800-ft. level. The snaps were about the same as those heard the night before. They were about as frequent as they had been and were of the same low pitch, indicating a relatively distant origin.

The outfit was then moved to the 3100-ft. level and the first set-up was made at the hole nearest the south end of the burst section. The snapping was practically continuous. It sounded something like static, but many snaps had the hissing, spitting sort of sound heard when a neon sign has a poor connection. Heavier ones could occasionally be heard without the equipment.

The pick-up was left in this hole and another was placed in a hole some 75 ft. to the south. Two amplifiers and two sets of head phones permitted the observers to listen to both places at the same time. It was at once apparent that the high-pitched snaps were much more frequent in the hole nearer the burst section and that there was a marked lack of simultaneity in this sort of sound in the two locations. The heavier snaps were simultaneous. Occasionally a crack could be heard progressing through the rock as a crack crosses an ice-covered lake with a ripping sound on a very cold night.

Listening in at successively farther points going south, it was found that the high-pitched noises fell off until, at about 300 ft., there was not much more snapping than had been heard on the 2800-ft. level. (The direct distance from the burst on the 3100-ft. level, to the listening post on the 2800-ft. level was about 500 ft.)

While reeling in the line from the farthest south hole and while about 100 ft. from the burst section, another burst occurred at 3:45 a.m. This heaved the track still more in the section previously affected and also heaved the track in the next parallel drift 44 ft. to the east. It broke timber in both drifts and threw out several tons of loose rock in each.

The party returned to the hole first used, and installed the geophone. The activity was found to be about the same as before, as nearly as one could judge. The line was then carried through the burst section to place the geophone in various holes north of the section, the amplifiers remaining at the south end. It was found that the rock became noisier with 'local' cracking to the north, and that easily audible snaps and bumps were more numerous. At about 5 a.m., it was decided to move out. No further observations were made at Frood.

(b) Lake Shore:

On October 23, Obert, the writer, and mine personnel examined sections in 3202W, 3811E, 3802E, and 4301W. There were some diamond drill holes in each vicinity that had not been partly closed by the slabbing of exposed faces, and it was arranged that these should be cleaned out and the experiments begun in the afternoon shortly after blasting.

Two holes were tried in 3811E at approximately 500 ft. east of the main cross-cut on the north vein. The nearest (farthest east) hole was about 20 ft. west of the stoping on this vein. A few 'local' noises were heard and also a few distant ones, but there was very little activity. None of the sounds could be heard except with the equipment.

The party then moved to 4301W, to a point about 700 ft. west of the main cross-cut on the north vein. This is almost immediately below the large burst of July 30 last that affected the 3900-, 4000- and 4200-ft. levels. The ground here was a good deal more noisy. Practically all of the snapping was local. None could be heard except with the equipment. Attempts to plot the snaps on a time scale show an average of about three per minute.

This occurrence pattern in the mine with which Obert is best acquainted (Ahmeek, Mich.) would not indicate bursting conditions. Until the high-pitched snaps were recording from 20-30 per minute, that ground is considered safe. However, as stressed by Obert, the significance of the occurrence pattern at Lake Shore could only be learned by continuing observations over a period sufficiently long to include a burst in the vicinity of the listening post.

Although the observations were being made in the Lake Shore off-shift period, drills could be heard working in Teck-Hughes mine at a distance of not less than a quarter mile. These were sufficiently disturbing to prevent an accurate counting, but Obert was of the opinion that most of the local unrest would have registered if the recorder had been equipped with the proper filters.

It was decided to listen in at the same position on 4301W on the afternoon of Oct. 24 before, during, and after blasting. The amplifiers were kept at No. 5 shaft on the 4300-ft. level and cables were run to the pick-up placed just below the stoping. About 1200 ft. of cable was run out, but the listening was done through 1500 ft. There was no impairment of the sensitivity. Matching transformers were used at each end of the cable.

It was learned that the mining in the stopes immediately above the 4300-ft. level had not progressed far enough for blasting at the end of the shift. However, there were other stopes higher in the mine and in the same general area to be blasted.

It was found, even before blasting, that the rock was noisier in this section than it had been the day before. All the snaps were local in character. After blasting was completed, they increased in number and a few were audible. One was fully of burst proportions, but it is not known whether it caused damage anywhere. Careful counting by different members of the party gave snapping noises of 10-15 per minute at a time about an hour after blasting. Whether this indicates dangerous conditions can only be learned by experience.

On Oct. 25, two diamond drill holes on the 4200-ft. level were used. The more westerly of these was in the south wall of the small triangular pillar at the intersection of the north and diagonal veins with the main cross-cut. The other was in 4201E, about 200 ft. east of the cross-cut on the north vein. Two or three days before, a small burst had heaved the track and knocked down several tons of rock on the main cross-cut on this level. The relaying of the track had just been completed. Two pick-ups and two amplifiers were used, with two sets of head phones, so the activity in the two holes could be compared. It was found that the noise was nearly all local in character and much of it not simultaneous. Sometimes the west pick-up was the noisier, sometimes the east. Careful counting showed 8-22 snaps per minute about half an hour after blasting had been completed. This ended the experimenting at Lake Shore.

J-8 Specifications for Obert's Equipment

Obert's equipment for studying the subaudible snaps consists of three units, for which the following specifications are given:

Unit No. 1:

(a) A three-stage amplifier operated from the power supply, having a voltage gain of over 100,000 (from the grid of the first tube to the plate of the last tube).

Linear to frequency to within 2 db. from 150 to 10,000 c.p.s. An attenuator (0 to 45 db. in steps of 2.5 db.) is inserted between the first and second stages.

(b) A filter system consisting of a 2500-cycle and a 7500-cycle high-pass section with switching arrangement so that either section can be cut in. The filters have an attenuation of 40 db. in the first half octave below cut-off and an insertion loss of less than 3 db.

(c) A calibration circuit operated by a switch on the amplifier panel, showing the over-all response (with the exception of the first two stages) of the recorder.

(d) This unit is enclosed in a gumwood, copper-lined, carrying case with cover. Two 1620 and one 6P5 tubes are included.

Unit No. 2:

(a) A non-linear peak-limiting amplifier for compressing the recording scale.

(b) A one-stage, low-gain amplifier for independent regulation of the fast and slow recorder.

(c) Two signal rectifiers and time-constant circuits, one having a time constant of approximately 0.1 sec., the other of approximately 1.0 sec.

(d) Two class B amplifiers with approximately 8 watts output.

(e) A 90-120-volt, 25-60-cycle power supply (140 v.a.) having a voltage regulation such that the sensitivity of the recorder does not change appreciably on a power line fluctuating by as much as 15 per cent. All of the equipment is operated from this power supply.

(f) This unit is contained in a gumwood case with cover. The following tubes are included: 1-6J7-G, 2-5v4-G, 2-6p5-G, 2-6ZY5-G, 1-VR75, and 1-VR150.

Unit No. 3:

(a) This unit contains two magnetic recorders using Teledeltos paper at a speed of approximately 3 in. per minute: they will operate over eight hours on a 125-ft. roll of recording paper. The recorders are driven by telechron synchronous motors and a time mark is made on the paper every other minute.

(b) Five hundred feet of shielded two-conductor microphone cable with connectors.

The necessary connectors for all units are furnished. Amphenol plugs are used throughout.

J-9 Purchase of Obert Recorders

At the time Obert left Lake Shore (October 26, 1941), it was agreed that steps would be taken to arrange for the purchase of three complete sets. These were delivered to Lake Shore on May 20, and were at once placed in service.

Figures 44 and 45 present, respectively, a side and an end view of the Obert recorder with the box removed. Figure 86 shows a complete set in service and Figures 82, 83, 84, and 85 give the wiring diagrams for the sets, with some changes made in the light of experience. For example, the improved sets had two of the 0.1 sec. time-constant circuits, the 1.0 sec. integrating circuit being abandoned in favour of having twice the coverage with a given recorder.

The pictures of the uncovered recorder show the two alnico magnets, each with a writer coil and stylus. The roll of paper can be seen below the magnets in Figure 44. In Figure 45 the paper is in place for recording under the stylus points. The time-marking device can be seen in Figure 45, just above and to the right of the handle on the upper feed roller. A stylus in permanent contact with the paper near the edge receives a writing voltage for about ten seconds each two minutes, tracing a short dash on the record.

J-10 Listening Experiments:

Using a geophone loaned by Obert and the amplifier (LSM-10) designed and built by Gibbs for the supersonic studies previously planned, a listening program was begun November 5, and continued each day (except Sundays and holidays) until June 20, 1942. At first the LSM-10 amplifier * was used and later the LSM-11; then, beginning May 21, the Obert recorders went into service. From time to time during the period May 21-June 20, it was necessary to use the LSM-11, owing to trouble with the Obert writer coils.

Beginning November 5, listening was done on the 3825-ft. level, the geophone being below 3811E drift in 3906E stope and the amplifiers in the charging station on the main cross-cut. Listening continued until May 1, when the equipment was moved to a 'doghouse' on the main cross-cut on the 4200-ft. level, remaining there till June 20. During the entire period November 5 — June 20, most of the listening was done during the afternoon blasting period (2:45 - 4:55 p.m.). Geophones were installed in several of six holes in 4201W-7; these holes were all in the south (hanging) wall, and were about 6 ft. deep and 30 ft. apart. Attempts were made to record for 10 minutes from each hole by means of a switch in 4201W-7, operated from the cross-cut.

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* Note: See sec. L-9 for description of LSM-10 and LSM-11.

Beginning May 21, Obert recorders were used whenever possible, but the writer coils burned out one after another, so the LSM-11 was used for listening when the recorders were not available. The program continued until June 20. The writer arrived at Kirkland Lake on June 17, at which time the writer coils of the Obert recorders were all out of commission, as well as some of the six replacement coils Obert had furnished.

It was decided to discontinue the listening program on June 20 and to concentrate on getting new coils made and the Obert equipment operating as soon as possible. This was accomplished by June 30, when a regular program with the Obert recorders was begun on the 4200-ft. level in 4201W-7. The equipment was supplied with the A.C. mine electric service, which was specially wired out to this point, some 700 ft. west of the main cross-cut.

J-11 Analysis of Data Obtained in Listening Program

(a) There was a marked difference between 3906E stope and 4201W-7 drift, the latter being much the more active location, in a ratio of about 10:1.

(b) Blasting in the vicinity of the geophones markedly increased the count, many cracks following the blast.

(c) The average of cracks per minute (C/M) is given in the following tables, but the number occurring in each successive minute varied greatly. For example, on June 20 the average for 60 min. was 5.7, but the number in any one minute varied as follows:

C	O	C	O
1	2	6	12
2	1	7	9
3	6	8	5
4	7	9	2
5	13	10	3

C = the number of snaps in a given minute.

O = the number of different minutes when the count was the number given in C.

(d) Greater cracking activity preceded and immediately followed the one small burst experienced while actually listening in on the 4201W-7 post.

(e) It was concluded that recording should be attempted in the vininity of 4201W-7.

J-12 **Summary of Listening Observations in Stope 3906E**

November 5, 1941 to April 30, 1942

Date	C/M	Date	C/M	Date	C/M	Date	C/M	Date	C/M	Date	C/M
N5	3.2	D 4	.3	J 2	.5	F 4	1.1	M 5	.9	A 2	1.8
6	1.2	5	.4	3	.4	5	B	6	1.4	3	1.4
(7)	.5	6	.7	5	2.0	6	.2	7	1.1	4	1.6
(11)	.4	8	.6	6	2.0	7	1.9	9	.5	6	.6
11	1.1	9	.5	7	.7	9	C	10	.4	7	.5
(12)	2.0	10	.5	8	1.7	10	1.4	11	4.4H	8	2.0
12	2.1	11	.7	9	.2	12	D	12	1.0	9	J
(13)	.8	12	2.5	12	.1	13	.1	13	.7	10	.4
13	1.4	13	.5	13	A	14	.6	14	.9	11	J
14	1.3	15	1.0	17	.4	16	E	15	G	13	.8
15	.9	16	.4	19	1.1	17	.9	17	.8	14	1.0
17	1.2	17	1.0	20	.2	18	.8	18	2.6I	15	1.4
18	1.5	18	.2	21	.5	19	F	19	.7	16	.9
19	.9	19	1.2	22	1.6	20	1.0	20	1.2	17	1.4
20	1.1	20	.7	23	.5	21	.6	21	1.2	18	.5
21	.9	21	.5	24	.3	23	G	23	1.0	20	1.1
22	.7	22	1.2	26	.6	24	.6	24	1.1	21	1.2
24	.4	23	.8	27	.5	25	.4	25	.5	22	1.2
25	.3	24	.5	28	.3	26	.6	26	1.0	24	.7
27	1.2	27	1.9	29	1.9	27	.2	27	.7	25	.8
28	1.4	28	.9	30	.6	28	.9	28	1.0	27	.4
29	1.0	29	1.4	31	2.6	M 2	.7	30	.3	28	.1
D2	.4	30	.9	F 2	.2	3	.7	31	.8	29	.6
3	.3	31	1.6	3	1.9	4	.8	A 1	1.4		

Dates in brackets indicate observations made from 2:45 to 3:55 a.m.

A Insensitivity traced to geophone (Obert's). Replaced by one made by Hallick, beginning January 17.
B No blasting in stope, Only 6 snaps in 110 min.
C New dual amplifier installed February 9.
D Drill operating prevented good listening.
E Replaced battery.
F Geophone trouble spoiled record.
G Crusher and conveyor running.
H Several bursts heard in listening.

I New section started in 3906E stope.

J Listening by Gibbs. Testing Equipment.

J-13 Summary of Listening Observations in 4201W-7

May 1 to June 20, 1942

Date	C/M	Date	C/M
M 1	8.1	M 27	3.7
2	6.4	28	9.2
4	5.6	29	3.2
5	4.1	30	7.5
6	2.9	J 1	8.3
7	2.5	2	4.8
8	6.3	3	#
9	5.2	4	7.8
11	5.5	5	5.1
12	4.4	6	8.8
13	6.2*	8	2.6
14	2.2	9	1.5
15	7.5	10	2.4
16	10.3	11	1.2
18	7.2	12	.9
19	5.0	13	2.0
20	5.2	15	5.4
21	10.1	16	11.6+
22	7.0	17	3.8
23	9.0	18	5.7
25	7.3	19	5.3
26	8.3	20	5.7

* Heaviest snaps and greatest activity seemed to be in H4.

\# Testing and adjustment of equipment by Gibbs.

\+ Small burst occurred during listening period, with great increase in activity.

J-14 Recommendations for Research Program

The development of the various geophysical programs undertaken at Lake Shore Mines had now reached a point where it was definitely established that a geophysical characteristic (subaudible snapping) existed, and that it was probably indicative of strain conditions approaching burst proportions; also that the equipment available was adequate for a thorough study of this phenomenon in a selected section of the mine. The various phases of this problem had now to be studied intensively and persistently. The following recommendations were therefore submitted:

(a) Personnel:

That the responsibility for maintaining and adapting the equipment rest with Gibbs; that the problem of developing and carrying through an underground program be given to someone thoroughly interested and qualified to carry it through; and that Hallick be assigned to assist jointly in these closely related duties.

(b) Locale:

That the study be confined to the west pillar. Initially the investigations should cover both sides of that pillar throughout its entire elevation. As experience dictated, the study might later be directed more particularly to key points whose existence and position had become evident as the work progressed.

(c) Recording Equipment:

That shelters be provided on three levels to be selected, and that these be located in that part of the drift that is central to the pillar (within the stoped region). These shelters should be made as safe as is reasonably practical and supplied with 110-volt alternating current. From these shelters, lines could be run out to reach any selected point in the pillar, in drift or stopes.

(d) Listening Equipment:

That a light truck be designed and built to accommodate the battery-operated listening equipment, making it easily possible to reach, on any level, the holes to be drilled for geophone installation.

(e) Geophone Holes:

That a considerable number of drill holes be located by survey and run out into the solid. These should be located wherever strain conditions seem to be building up in any part of the pillar.

(f) Mapping of Mine Work:

That an isometric chart of the pillar be constructed for use as a base on which to plot the progress of the mine work in the pillar. A chart, brought up to date on, say, Friday of each week should be made available to the geophysical services on Saturday.

(g) Recording Program:

That records be obtained regularly at each of the three recording stations for such times of the day and such points on the pillar as may be found desirable from day to day.

(h) Listening Program:

That some part of each working day be spent with the listening equipment in an endeavour to track down the active section or sections of the pillar and to determine whether they are stationary or migrate as mining progresses.

(i) Observing Program:

That the man appointed to take charge of the underground program devote sufficient time to become thoroughly familiar with every part of the pillar, the stopes as well as the drifts. He should have access to the reports of the shift bosses, who should be instructed to bring to his attention anything that, in their opinion, has any bearing on the problem of determining the strains on the pillar. As experience may indicate, the study of subaudible snapping should be supplemented by records of strain gauges, scratch plates, photographic repeats, etc.

(j) Reports:

That once a week a confidential report is to be submitted to the company, showing graphically the work done and the conclusions drawn to date, and adding such brief comments as seem necessary.

The above recommendations were presented on June 26, 1942, and were approved. Later, Mr. Blomfield asked the writer to develop and carry through the underground program, leaving Gibbs free to deal with the heavy and complex instrumental problems. Hallick was assigned to assist both, and the new program began as of July 1, 1942.

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Report K

July 1 to December 31, 1942

In spite of the interruptions to service, the first six months of the reorganized program yielded most valuable data, which are presented in detail in this report.

K-1 Instrument Trouble

(a) Writer Coils Burning Out:

When the program began on July 1, the chief trouble with the equipment was due to the burning out of the writer coils at a rate of nearly one a day for some weeks. It was found that the cause was the damp air charged with explosion fumes; this was remedied by installing a 50-watt lamp in each recorder box, since when no coil has burned out.

During the period when the coils were burning out, it was necessary to take at least one recorder to the surface nearly every day, with the result that for the first month there is little continuity of instrumental hook-up, as will be noted from the tabulated data given later in this report. The sets were designated 111, 222, and 333, keeping the three sets of three units each assembled as they were when received.

A complete statement of operating conditions requires one to give hole number, geophone number, and attenuation in decibels. This is usually abbreviated as: 222 H4 G2 D10, or in practice as: 222H4G2D10.

(b) Recording Paper Fires:

Soon after the program began, a series of fires occurred in the recording units, owing to the recording paper catching fire from the stylus. Sometimes the only result was the loss of a record. On other occasions, the plastic spools were burned and had to be replaced by wooden ones.

At first, fires were due to the recording running side ways on the recorder and so becoming warped up off the contact platen just enough to permit fires to start. Later, they were due to the traction of the drive roller being too slight to move the paper. When this was remedied by reducing back tension, the paper moved from the supply roller in jumps which lifted it from the platen and again caused fires.

Finally, on September 22, recorder 2C caught fire early in the morning and burned the unit badly. This fire threatened to spread in the recording room. The wooden recorder boxes were then replaced by ones made of steel, the drive rollers were made of knurled brass (which tend to snuff out a smouldering record), and the C units were checked for alignment (and found to be quite badly out). When these points had been corrected the fires ceased.

(c) Other Instrument Troubles Encountered:

The following difficulties were not persistent, but cropped up erratically from time to time:

(1) Shorting of the stylus to chassis by filaments of steel wool that were so small as to be almost invisible.

(2) Failure of soldered joint holding stylus point on the arm. Some points also burned off.

(3) Disintegration of geophone crystals owing to moisture penetrating the case.

(4) Poor contacts at amphenol connectors.

(5) Broken strands of shielded cable caused slight holes in casing, leading to infiltration of water and the development of electrolytic action, with resulting electrical disturbance (static) on the recording lines.

(6) Burning out of radio tubes and a transformer, the latter of a type that could not be exactly duplicated (nearly all replacements at this time had to be more or less unsatisfactory substitutions).

(7) Some record paper rolls were a shade too wide, resulting in a failure of the drive. Such rolls when found (usually only one in a package of ten) had to be discarded.

(8) Voltage fluctuations in AC power line.

K-2 Listening Program

In order that the pillar might be surveyed as thoroughly as possible to locate strategic operating positions, a listening program was begun at once. From the beginning it was found necessary to do all the listening during the off-shift periods, but a sufficient length of time after blasting.

At first, listening was done with LSM-11 and LSM-12; these are amplifiers used with head sets, but not giving any record. Later, when the Obert recorders were connected by cable lines from the central recording rooms to widely distributed geophones that could be connected at will, it was found desirable to listen in over the Obert units, which furnished a record at the same time.

To permit the use of an extra listening set (LSM-11 or LSM-12) and get a record from one hole while recording on the Obert set from another, Gibbs devised an extra stylus, manually operated, for the Obert recorder. Using it, the operator listened over the extra set and recorded what he heard by means of the extra stylus on the Teledeltos paper of the Obert instrument, the extra stylus tracing an extra line on the record. The listening from one hole was thus recorded and correlated with the Obert record from another.

This procedure resulted in the operator attaining a most useful familiarity with the nature of the records. The timbre of the sound heard is often sufficient to permit the identification of the source, whereas the record gives much the same sort of response to many types of disturbance. It thus became possible to note the slight differences in the records and to know more about the nature of the activity from day to day.

K-3 Underground Recording Rooms and Layout of Drill Holes

Cable was run from the doghouse on 4206W-6 (Station B) to holes H4, H25, H19, and H20, all on the 4200-ft. level (for layout of holes see section K-6). Another line was run from station B down through the manway just to the west of the station to the flatback above 4301W-7. This served to connect H23, and later H24, to Station B. Another line was run west from B for about 185 ft. to the flatback above 4201W-7, thence up the manway at section line 8W to 4001W, and thence east to H27. Similar lines were run in 3801W, west from the station in 3801W-9 (Station C) to H22. The line was continued east for about 250 ft. to the manway about 30 ft. west of section line 6W, and to the flatback above 3901W-6. Here it was led west in the more southerly of the divided drifts (3908W-7) to H13 and H18.

After the conference with Obert, it was decided to drill a 30-ft. hole (H28) beside H25, another 30-ft. hole (H29) in 3801W-9, and a third 30-ft. hole (H30) in 3908W-6. These holes were to be connected to their respective stations and the program was to consist of regular daily runs from 4 to 5 and 6 to 7 a.m. and p.m. (see section K-8). There were to be two recorders at Station B, recording from two selected holes of the available list, H24-25-26-27-28. Listening was to be carried out in the other adjacent holes. There was to be one recorder at Station C, recording from H29, with listening from H30.

It was planned that a testing oscillator should be built by Gibbs to Obert's design, and that the recording sets should be calibrated and maintained at a selected, intercomparable standard of sensitivity, which was to be tested at regular intervals.

It was proposed also to build a capacity bridge to test, from the observing stations, the lines from the geophones, these being in place on the lines, the set-up in the hole not being disturbed.

It was further decided to wedge 7-ft. steel bars, 1 3/8" diameter, into 6-ft. holes drilled near each geophone position. On the end of each bar was to be mounted a tapping mechanism, to be designed and built by Gibbs, operated electrically from the station concerned. The tappers were designed to give a slight kick to the buried geophone, which should record as on offset on the record. Though these offsets would differ for the different geophone holes, they should always be the same for any given hole, regardless of what geophone or recorder was being used. Gibbs also planned to build a shaking table to test and calibrate the geophones.

As the supply of shielded cable was strictly limited, arrangements were made to replace all lines by BXL cable and to run parallel to each line of BXL a line of style B wire, which could be used to operate the tappers.

In order that the coverage of the pillar might be greater with the limited equipment available, Gibbs was to design and build time switches, so that two geophones, in widely separated boreholes, could operate automatically for alternate half-hours on the same recorder.

K-4 Handling of Records

The records as taken from the Obert recorders consisted of rolled strips of Teledeltos paper 2 inches wide and 30 ft. long. To permit the study of these records and to provide a means of ready reference to any point, equipment and procedure were designed to simplify the accordion-pleating of the strips so that they cuuld be mounted in book form. Each book carried the serial number of the record, and was paginated with a numbering machine. Thus a reference to 30337B indicates an 8-inch section of Record No. 303, appearing on the right-hand side (B) of the book when opened at page 37.

K-5 Conclusions and Recommendations

The following conclusions and recommendations are based on the work done in this period:

(a) It was clearly demonstrated that anything less than a 6-ft. hole is useless. The 30-ft. holes were quite satisfactory and seemed deep enough. It was proposed to adopt 30-ft. holes as standard for this work, and to have them cased for 6 to 8 ft., with the casing projecting at least one foot from the wall to provide an attachment for the tapper. It was found that the 100-ft. hole (H25) did not extend beyond the zone of compression. The bottom of this hole was sometimes more and sometimes less active than the bottom of the 30-ft. hole drilled beside it.

(b) A sensitivity slightly less than that used during the period covered by this report should be adopted as standard.

(c) Tapping on the north (foot) wall was not picked up by geophones on the south (hanging) wall at distances at all comparable with those over which tapping on the south wall was picked up by the same south-wall geophones. Geophones set in holes in the north wall on several different levels have shown little or no ground activity either by listening or recording. When bursts occurred, it was the hangingwall that came in.

(d) The 'slow' tracks of the three Obert recorders proved of little value and, with coverage of the pillar with a sufficient number of geophones, they became even less important. The new recorders had two 'fast' tracks instead of one fast and one slow.

(e) A voltage regulator should be obtained for each observing station (doghouse).

(f) The making of records into books after they have been scanned, compared, and analysed has proved most valuable, rendering the data readily accessible for checking and comparisons as further ideas developed from later observations.

(g) Effective listening was impossible at Lake Shore except during off-shift hours. Continuous recording was possible at such times only. When activity in any region becomes acute, it is recommended that the recorders and geophones concerned be run on 24-hr. schedule in an effort to record up to and through a burst. When ground is not dangerously active, it seems sufficient to record for alternate half-hours from each geophone for the hours 3-7 a.m. and p.m. When records are run 24 hours a day, only the schedule hours may be used in the statistical study.

(h) Many small and some medium snaps (as recorded at the sensitivity level in use during the period under review) recorded on one geophone and not on another, and vice versa, when distances of 50 to 75 ft. separated the geophones. This was not a matter of relative sensitivity of equipment or of the efficiency of emplacement of the geophones. It sometimes occurred when the holes were only 25 ft. apart. However, some medium snaps were clearly shown to be simultaneous over several levels. The significance of these anomalies must await analysis of the records.

(i) All records taken on schedule hours should be retained, annotated, analysed, and made up into book form, and sections of 24-hr. runs not on schedule should be carefully labelled and dated, but kept in roll form, unless some part of them becomes important.

(j) In general, the ground about to burst (within a week or so) showed great subaudible activity, even when the walls did not 'talk'. Data to show whether this activity increases or falls off immediately prior to a burst were lacking. It was safe to say that the subaudible method clearly indicated the sections actively dangerous, but prediction of the time of a burst was not clearly demonstrated. It was hoped that an analysis of the records into large, medium, and small offsets might show prediction trends in one special group.

(k) Small pre-bursts occur in badly strained ground for some days prior to destructive pillar bursts. These are too small to register on the surface seismograph and, in fact, show a (probable) falling off in intensity at a distance of 70 ft. between adjacent geophones.

There seems to be no prediction of these bursts either by increase or decrease of activity at the geophone showing the best record. After-snaps are very numerous and continue for from half a minute to 5 minutes or more. Many of these are now recorded and several have been heard during the listening periods.

(l) An examination of the back records in conjunction with the records of the surface seismograph should be made as soon as possible to determine the shift of pressure after a burst. The small bursts occurring in strained ground and presumably indicating serious conditions have not been known to record on the surface seismograph; nor, except in one case, is there known to be any relation between a burst in one part of a pillar and a change in ground activity in another part.

(m) It seems probable that a section of a pillar not under strain at the moment might be suddenly subjected to critical strain within a few minutes by a heavy burst in the pillar either above or below it. Such a danger might be detected promptly if equipment designed for such emergencies were available.

(n) As soon as an Obert set is available for use on a mobile listening post, the listening program at the recording stations should be abandoned in favour of using the short time available each day in exploration over a greater section of the pillar.

(o) Steps should be taken to put in pipe conduits (1.5" diam. at least) from each level to adjacent levels throughout the pillar. Each time a rill is completed, a pipe conduit should be put in place before the fill is poured, unless a connection has already been made between the levels concerned.

(p) Some more direct and regular connection should be made between the progress of mining in the region under study and the activity of the ground as shown on the records. It is clear that much of the fluctuation in activity is due to the amount of powder used, the number of holes blasted, and the approach of the rill to the top and towards the pickup geophone. It is strongly recommended that steps be taken to make this mining information readily available in some simple routine manner for the regular use of the rockburst survey.

(q) A good deal of valuable equipment is maintained in the underground observing stations. The fact that it is vital to the work and almost irreplaceable makes it more valuable than its cost would indicate. Much of the time of trained observers is spent in these stations. In view of the experience so far gained, it is strongly urged that the stations should always be built:

- (i) Well in the fill region, with no part of the pillar between the doghouse and the cross-cut.
- (ii) Against the north (foot) wall.
- (iii) With timbers competent to take pressure, and sided with two-inch plank.

The station at 4201W-6 may be cited as an example of a satisfactory structure, except that it is built against the south wall.

(r) Until the calibration and standardization of the recorders and geophones is accomplished, and checking is done regularly as a routine procedure, the program will operate under a considerable handicap, since undisputed conclusions can never be drawn from the observations.

K-6 Test Holes Assigned to Rockburst Research

Test holes 1-30, drilled for use in the rockburst program during the period covered by this report, are plotted in plan and elevation in Figure 47. Plan and elevation have each a vertical scale indicated by the 125-ft. difference in the levels. The section lines on each chart indicate an east-west distance in intervals of 100 ft. In each diagram, west and east are respectively to the left and right as one faces the charts. In the projection of the plans, the oblique lines run down and to the left (south) and up and to the right (north), the scale division in each direction indicating 50 ft. The following table gives the drilling data for each hole and indicates its position in the mine.

No.	PD or DD No.	Date	Location and Wall	Depth	Remarks	
1	PD	May	4201W- 6-S	6' 1"	Good hole, fairly solid rock.	
2	PD	"	4201W- 6-S	3' 7"	Good hole in solid rock.	A
3	PD	"	4201W- 7-S	4' 6"	Ground shattered.	A
4	PD	"	4201W- 7-S	5' 2"	Good hole; solid rock.	
5	PD	"	4201W- 8-S	?		B
6	PD	"	4201W- 9-S	?		B
7	DD	July 2	4201W- 9-S	1' 0"		A, C, D
8	DD	" 2	4201W- 7-N	3' 6"	Good hole, solid rock.	A, D
9	PD	" 3	4001W- 7-S	5' 0"	Tandem holes in fair condition	
				5' 0"	when drilled.	

No.	PD or DD No.	Date	Location and Wall	Depth	Remarks	
10	PD	" 3	4001W- 8-N	5' 0"		E
11	PD	" 11	3801W- 8-S	6' 1"	Tandem holes, in fair	
				6' 4"	condition when drilled	
12	PD	July 11	3801W- 9-N	6' 0"	Rough at inner end; solid.	
13	PD	" 11	3908W- 8-S	5' 11"	Rough for 2', then good.	
14	PD	" 13	4301W- 7-S	4' 10"	Rough.	
15	PD	" 13	4301W- 7-S	5' 1"	Very rough for 2', then good	
16	PD	" 13	4301W - 8-S	4' 9"	Broken ground 18" in the hole.	
17	PD	" 13	4001W- 8-S	5' 0"	Broken ground; rough.	
18	PD	" 13	3908W- 7-S	6' 0"	Irregular; wavy.	
19	PD	Aug. 7	4201W- 9-S	6' 0"	Ground loose; beside H7.	
20	PD	" 7	4201W-10-N	6' 1"	Good ground; smooth.	
21	DD-3679	" 15	4201W- 7-S	30' 0"	Beside H4	F
22	PD	" 28	3801W- 9-S	5' 4"	Very loose. Tandem holes,	
				5' 4"	good at inner ends.	
23	DD	" 30	4301W- 7-S	4' 6"	Good ground,	A, D, G
24	DD-3704	Sep. 16	4301W- 7-S	30' 3"	Near H15	H
25	DD-3679	" 22	4201W- 7-S	103' 0"	Beside H4	I, J
26	DD-3707	" 23	4201W- 9-S	30' 0"	Beside H7 and H19.	K
27	DD-3708	" 23	4001W- 7-S	29'10"	Beside H9.	L
28	DD-3735	Oct. 28	4201W- 7-S	29' 9"	Beside H4, H21,and H25.	M

No.	PD or DD No.	Date	Location and Wall	Depth	Remarks	
29	DD-3742	Nov. 5	3801W- 9-S	30' 3"	Beside H22.	N
30	DD-3744	" 6	3908W- 7-S	29' 6"	Beside H18.	O

A. Some PD (percussion drill) holes (and a few DD, or diamond drill holes mostly shallow) are 'bootlegs' left from earlier operations and were taken over for this program.

B. Original depth of this hole not known. The ground was very badly shattered when later breaking a rill from stope 4301W-7 and on November 6, when examined, the hole was quite blocked.

C. Clean, smooth DD bootleg in what was later found to be a slab of loose.

D. DD hole; number not known.

E. Hole blocked at depth of about 2 ft. when steel was pulled.

F. This hole was the first deep DD test hole. It was drilled right beside H4. The work was finished August 15 but the hole was not used until September 1. It was later deepened to 103 ft. and numbered H25. The ground is fairly good. Hole gave good results as H21.

G. Hole found in south wall of 4301W-7 stope, on flat-back.

H. DD-3704 (H24), begun September 16; finished September 16.
   0' - 30'3" all porphyry.
   0' - 8'3" core badly broken up. 14 pulls with 3" or 4" of ground core at each pull.
   8'3" - 30'3" core not so badly broken up; rock jointed with planes about 3" or 4" apart. 12 pulls; no ground core.
   No sludge.

I. See F. above. This hole was originally H21 (30 ft. deep). It was deepened to 103 ft. and given the number H25. The ground in the extension is very good.

J. DD-3679 (H25), begun September 17; finished September 22. Hole deepened from 30 ft. to 103 ft. Old hole (H21) required reaming 18 ins. at 2 ft. and 18 ins. at 10 ft.
   30' - 31' shattered porphyry.
   31' - 31'7" ground core.
   31'7" - 37' porphyry badly broken up. Pieces average 2" long. 4 pulls.
   37' -61' porphyry not badly broken up. 9 pulls.
   61' - 63'9" porphyry not shattered.
   63'9" - 88'4" porphyry not shattered. 4 pulls.
   88'4" - 103' porphyry not shattered; 3 pulls.
   No sludge returned to collar of hole.

K. DD-3707 (H26), begun September 23; finished September 23.
   0' - 19'9" porphyry core badly shattered. 18 pulls.
   19'9" - 30' blocky porphyry. 7 pulls.
   No sludge.

L. DD-3708(H27), begun September 23; finished September 23.
0' - 6' shattered porphyry.
6' - 11' shattered porphyry; few quartz stringers.
11' - 29' 10" shattered porphyry.
No sludge. 19 pulls in 30'

M. DD-3735(H28), begun October 28, finished October 28.
0' -11' badly shattered porphyry. 17 pulls, with 2" to 6" of ground core at each pull.
11' - 29'9" porphyry not badly broken up.

N. DD-3742(H29), begun November 5; finished November 5.
0' - 2'8" crushed porphyry. 4 pulls; core badly broken up.
2'8" - 6'6" crushed lamprophyre and quartz (75 per cent quartz). Core not badly crushed. 3 pulls.
6'6" - 22' lamprophyre. Core in short pieces 1" to 2", but not badly crushed.
22' - 30'3" lamprophyre. 3 pulls. Core not badly crushed.

O. DD-3744(H30), begun November 6; finished November 6.
0' -10' badly shattered porphyry. 12 pulls. 2" to 4" ground core at each pull.
10' - 29'6" not badly broken porphyry. 7 pulls.
This hole was not drilled in position intended. It is about 50 ft. too far east.

K-7 Dates of Recording from Test Holes

The only holes used in the recording program were: Nos. 3,4,7,8,9,11,19,20,21, 22,23,24,25,26,27,28. These were occupied on the dates indicated in the tabulation below: (separation lines indicate week-ends.)

July

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
4	4	4	4	4	4		4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	7	4	4	
									8							8	8	8	8	7	7	7	7	7	7	7		7	7	
																				8	8	8	8	8						

August

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
7	7	7	7	7	7	19	19	19	19	19	19	19	19	19	19	19	19	19	9	9	9	9	9	9	9	9	9	11	11	9
									20	20	20	20	20	20	20	20	20	20	19	19	19	19	19	19	23	23		23	23	11

September

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3	4	4	3	3	3	3	3	3
9	21	21	21	21	21	21	21	21	21	21	21	21	21	21	19	9	9	9	9	4	4	22	22	4	4	4	4	4	4
11	22	22	22	22	22	22	22				22	22	22	22	22	22	22	22	22	22	22								

October

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
3	3	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	25
4	4	4	4	4	25	25	25	25	25	25	25	25	25	22	22	22	22	22	22	22	22	22	22	22	22	22	26	28	26	28
														25	25	25	25						25	25	25			2 8		

November

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25
28	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28	28

December

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
25	25	25	25	25	25	24	25	25	25	24	24	24	24	25	24	24	24	24	24	24	24	24	24	24	24	24	25	25	25	24
28	28	28	28	28	28	25	25	25	25	25	25	25	25	27	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25
						28	28	28	28	28	28	28	28	28	28	28	26	26	26	26	26	26	26	26	26	26		25	25	26
																	28	28	28	28	28	28	27	27	27	27				28
																							28	28	28	28				

K-8 Record Analysis, Holes 1-30

In the following tabulation, the successive headings have the following signification:

Rec. = record serial number
Fr. = from
To. = to
ABC-G-Db. = recording set-up (see section K-la)
Mx.)
Av.) = maximum, average and minimum snaps-
Mn.) per minute (s.p.m.) estimated as explained toward the end of section K-4.
S. = schedule for recording, where:
a = 3-4 and 6-7, a.m. and p.m.
b = 4-5 and 6-7, a.m. and p.m.
c = 4-4:30 and 6-6:30, a.m. and p.m.
d = 4:30-5 and 6:30-7, a.m. and p.m.

H3

Rec	Fr	To	ABC-G-Db			S	Mx	Av	Mn	Remarks
	Sp	Sp								
167	21	22	111	4	5	a	4	2	0	
170	22	23	111	4	5	a	6	3+	0	
		26								
176	25	26	333	4	5	a	2	1-	0	A
178	26	28	333	4	5	a	3	1-	0	
180	28	29	333	1	5	a	3	1-	0	
182	29	30	333	1	5	a	5	1+	0	B
		Oc								
184	30	1	333	1	5	a	7	2	0	

Rec	Fr	To	ABC-G-Db	S		Mx	A	Mn	Remarks
		Oc							
186	1	2	333	1	5	a	5	2	0
188	2	3	333	1	5	a	6	4	0
190	3	5	333	1	5	b	4	2	0 New schedule b.
192	5	6	333	1	5	b	8	4	0

A. Stylus writes very lightly.

B. Record of a burst at 3:46 a.m., September 30. Compare note K' for H4. Activity greater for the remainder of the hour, then return to slight activity. No bursts are reported by the mine for this time, but burst 286C occurred in 1607W drift at 2:05 a.m., Sept. 30 and was well recorded on the surface seismograph. The burst at 3:46 a.m. does not appear on the surface seismogram, but it is undoubtedly a small burst not far from 4201W-7.

H4

Rec	Fr	To	ABC-G-Db	S			Mx	Av	Mn	Remarks
	Jn	J1								
1	30	2	111	2	5	a	-	-	-	A, B
	J1									
2	2	4	111	2	0	a	-	-	-	A, B, C
3	4	6	212	2	22	a	6	3	1	D
7	8	9	211	2	22	a	18	?	0	E, F
8	9	10	223	2	15	a	35	?	1	G, H
9	10	11	223	2	15	a	15	?	1	I
11	11	13	223	2	20	a	4	2	0	J
12	13	14	311	2	20	a	-	-	-	K
13	14	15	222	2	20	a	2	1+	0	
14	15	16	222	2	20	a	2	1+	0	

Rec	Fr	To	ABC-G-Db			S	Mx	Av	Mn	Remarks
15	16	17	222	2	15	a	2	1+	0	
16	17	18	222	2	15	a	2	1+	0	
19	18	20	313	2	2	a	-	-	-	K
20	20	21	222	2	15	a	1	1-	0	
23	21	22	313	2	2	a	0	0	0	L
26	22	23	222	2	10	a	2	1-	0	
30	23	24	313	2	2	a	2	1-	0	M
32	24	25	313	2	2	a	-	-	-	N
36	25	25	313	2	2	0	2	1-	0	O
38	25	27	313	2	2	a	-	-	-	K
42	29	30	111	2	10	a	34	9	1	P, Q
43	30	31	222	2	5	a	-	-	-	R
	Ag	Ag								
45	1	3	222	2	5	a	15	4	1	
47	3	4	222	2	5	a	6	3+	2+	S
49	4	5	222	2	5	a	-	-	-	K
52	5	6	222	2	5	a	T	T	T	T
53	6	7	222	2	5	a	10	4	2	U
55	7	8	222	2	5	a	10	5	3	
57	8	10	222	2	5	a	7	4	3	
59	10	11	222	2	5	a	6	4	1	
62	11	12	222	2	5	a	5	2+	0	

Rec	Fr	To	ABC-G-Db			S	Mx	Av	Mn	Remarks
65	12	13	222	2	5	a	14	5	2	
68	13	14	222	2	5	a	6	3	2	
71	14	15	222	2	5	a	6	3	0	
74	15	17	222	2	5	a	-	-	-	K
77	17	18	222	2	5	a	8	5	0	V
80	18	19	222	2	5	a	8	6	1	W
83	19	20	222	2	5	a	6	3	1	
86	20	21	222	2	5	a	30	15	0	W, X
89	21	22	222	2	5	a	14	8	0	
92	22	24	222	2	5	a	12	6	0	Y
95	24	25	222	2	5	a	5	3	0	
98	25	26	222	2	5	a	5	3	0	Z
101	26	27	222	2	5	a	20	10	5	A'
104	27	28	222	2	5	a	6	4	0	B'
107	28	29	222	2	5	a	6	4	2	C'
109	29	31	222	2	5	a	5	3	0	B'
		Sp								
111	31	1	222	2	5	a	3	2-	0	
	Sp									
115	1	2	222	2	5	a	12	5	1	
119	2	3	222	2	5	a	18	7	2	D'
122	3	4	222	2	5	a	12	5	2	

Rec	Fr	To	ABC-G-Db			S	Mx	Av	Mn	Remarks
125	4	5	222	2	5	a	15	6	3	A'
128	5	7	222	2	5	a	14	5	2	E'
131	7	8	222	2	5	a	10	5	2	A'
134	8	9	222	2	5	a	7	4	1	
136	9	10	222	2	5	F'	F'	F'	F'	F'
138	10	11	222	2	5	a	7	4	0	
140	11	12	222	2	5	a	7	4	2	
142	12	13	222	2	5	a	10	6	2	A'
	Sp	Sp								
143	13	14	222	2	5	a	8	5	1	
148	14	15	222	2	5	a	7	4	1	A'
151	15	16	222	2	5	a	11	6	1	A'
154	16	17	222	2	5	a	10	5	1	A'
157	17	18	222	2	5	a	-	-	-	G'
160	18	19	222	2	5	a	6	4	1	A'
163	19	21	222	2	5	a	6	4	1	A'
166	21	22	222	2	5	a	6	3	0	
169	22	23	222	2	5	H'	-	-	-	H'
172	23	24	111	2	5	a	4	2-	0	I'
174	24	25	111	2	5	a	4	1-	0	J'
175	25	26	111	2	5	a	5	2	0	
177	26	28	111	2	5	a	5	2	0	

Rec	Fr	To	ABC-G-Db			S	Mx	Av	Mn	Remarks
179	28	29	111	2	5	a	9	4	1	
181	29	30	111	2	5	a	12	5	2	K'
		Oc								
183	30	1	111	2	5	a	10	4	2	
	Oc									
185	1	2	111	2	5	a	9	4	2	
187	2	3	111	2	5	a	20+	10+	3	
189	3	5	111	2	5	a	25+	15+	5	L'
191	5	6	111	2	5	b	30+	15+	5	New schedule b.
193	6	7	111	2	5	b	15	10+	3	
195	7	8	111	2	5	b	40-	15+	5	M'
197	8	9	111	2	5	b	15+	8+	3	N'
199	9	10	111	2	5	b	20+	10+	4	O'
201	10	12	111	2	5	b	20-	10-	3	
203	12	13	111	2	5	b	15+	8+	3	
205	13	14	111	2	5	b	15+	8+	3	
207	14	15	111	2	5	P'	-	-	-	P'
210	15	16	111	2	5	P'	-	-	-	P'
214	16	17	222	2	0	b	15+	8+	3	Q'
217	17	19	222	2	0	b	15+	8+	3	Q', R'
219	19	20	111	2	5	b	15+	8+	1	S', T'
221	20	21	111	2	5	b	10+	5+	3	T'

Rec	Fr	To	ABC-G-Db			S	Mx	Av	Mn	Remarks
223	21	22	111	2	5	b	10+	5+	3	T'
225	22	23	111	2	5	b	10+	5+	3	U'
227	23	24	111	2	5	b	25+	10+	3	V'
230	24	26	222	2	0	b	5	1+	0	W'
233	26	27	222	2	5	b	5	2-	0	
235	27	28	111	2	5	b	10	5+	4	X'
237	28	29	111	2	5	b	5+	4+	3	Y'
239	29	30	111	2	5	b	5+	4+	3	
241	30	31	111	2	5	b	5+	4+	3	Z'

A. Only occasional small offsets.

B. Very insensitive. Only small offsets at long intervals.

C. Recorder coil burned out on 1C. Replaced 1A and 1C with 2A and 2C.

D. Slow stylus burned out early on July 5.

E. Sudden increased activity 3 a.m., July 9.

F. The record on July 8 was averaging about 1 s.p.m. but when the set came on automatically and unchanged as to constants at 3 a.m., July 9 the activity had increased to about 18 s.p.m. It got down to about 2 s.p.m. by 7 a.m., July 9. July 8-9 was a Wednesday-Thursday.

G. Sudden increased activity at 3 a.m., July 10.

H. Again a greatly increased activity after the night shift blasting. Minimum by 7 a.m., July 10 was about 3 s.p.m.

I. Increased activity less on second day.

J. July 12 was a Sunday. Activity small.

K. Record burned in service.

L. Record absolute blank - instrument trouble.

M. Just before 4 p.m. on July 23 the record ran crookedly and the remainder of the record is distorted but partly legible. It is clear that the normal activity was maintained.

N. E.A.H. forgot to turn record on.

O. Record ran 3-4 and 6-7 p.m., July 25 and was then changed Saturday evening, July 25, by E.A.H., after the burst at 11 a.m., July 25, in stope 4301W-9. Shortly after 6 p.m., July 25, the record ran crookedly but is legible. The activity in this 6' hole, some 300 ft. from the burst and closing off about 4 hr. previous, is markedly low. The attenuation was only 2Db.

P. Marked increase in activity.
Q. This is a marked increase in activity, but it is to be noted that the instrumental set-up was changed since the preceding records.
R. Record lost unaccountably.
S. Uniformly moderate activity.
T. The activity through most of the record was about: Max. 6 s.p.m.; Av. 4 s.p.m.; Min. 2 s.p.m., but a succession of bursts registered from 3-4 a.m., August 6. See Note J for H7.
U. First record in doghouse B (4201W-6).
V. Some small bursts (?) registered shortly before 4 a.m., August 18.
W. Activity diminishes through record.
X. First definite evidence of ore skipping 3-4 a.m., August 21, in No. 4 shaft.
Y. Activity on both styli.
Z. Well-defined activity.
A'. Definite evidence of ore skipping in No. 4 shaft, 3-4 a.m.
B'. Activity began 6 p.m., August 26.
C'. Definite evidence of ore skipping 3-4 p.m., August 28. Location not known.
D'. Small burst about 4 p.m., September 2.
E'. First tapping tests. When tapping done on south wall it registered very well, but not when done on north wall.
F'. Record not turned on (E.A.H.) till 6 a.m. Then there was a Max. 7 s.p.m.; Av. 3 s.p.m.; Min. 1 s.p.m. Record ran 6-7 a.m., September 11.
G'. AC supply plug left improperly inserted by Z.E.G. No record.
H'. No record. Paper caught fire. Recorder badly burned. Set 222 taken to surface for extensive repairs.
I'. Record that looks like a burst recorded for about 4 min. at about 6:55 p.m., September 23.
J. Again evidence of activity at 6:55 p.m., September 24 which, coming at same time as previous day, discredits the assumption that the records were due to bursts. They do not resemble blasts, however; cause not known.
K'. Record of what was almost certainly a burst at 3:46 a.m., September 30. Compare I' and J' note above. The activity during the 14 min. which remained of the record after the burst averaged about 55 s.p.m., but it was down to 10+ s.p.m. when the record came on again at 6 a.m. Compare note B for H3.
L'. Paper stuck for a short time. Motor kept running and paper released.
M'. Record ran simultaneously with No. 194, this one in the 6-ft. hole and No. 194 in the 100-ft. hole. The activity was great in both, slightly greater in H25 (the deeper hole) and the coincidences were surprisingly few.
N'. First 'pull out' test between H25 and H4. Compare record of No. 198 in H25.
O'. Character of record changed since previous day owing to adjustment of recorder. Lines now quite faint.
P'. Record stuck and nearly caught fire. No record till 6 a.m., when E.A.H. began listening program. Traction was weak on the feed and the back tension too strong. The record would run when tested and then fail to start when turned on by the time clock.

Q'. A most unusual sensitivity. Both stylus records alike in appearance. The s.p.m. count seems valid however. See note F for H25.

R'. Very wide zero which almost moved the fast stylus to the edge of the record.

S'. Activity low for the first hour, then back to the level reported in the s.p.m. columns.

T'. Too much voltage on recording styli.

U'. Fast stylus recording many of the offsets as double. Probably due to carbon on the writing point.

V'. Paper ran crookedly much of the record. Edge burned off for nearly 6 min. beginning page 22704. Fortunately record did not catch fire, but smouldered out.

W'. Recorder decidedly out of adjustment. More activity recorded on the slow stylus than on the fast one. Beginning 3 p.m., October 25, activity up to Max. 15+, Av. 4+, Min. O, but fell off again after an hour. Latter end of record seems good but activity very low -- about Av. 1.

X'. Paper did not feed until E.A.H. began listening at 6 a.m. Many small holes burned in record, but no fire.

Y'. First 40 min. of record show instrument insensitive, but a sudden return to normal recording at a time when no one was near the instruments. Normal recording continued throughout the remainder of the record.

Z'. For further recording from 4201W-7, see tabulations for H25 and H28.

(Note: the above noted instances of the improper feeding of record paper, with burning of parts of the record, culminated in a serious fire in station B (4201W-6) on September 22. Improvements were introduced as soon as they could be completed, but the set 111 in H4 was not changed over until about the end of October.)

H7

Rec	Fr	To	ABC-G-Db			S	Mx	Av	Mn	Remarks
	J1	J1								
24	21	22	131	1	10	a	0	0	0	Absolutely blank. Instnuments.
27	22	23	313	1	2	a	3	1-	0	
29	23	24	222	1	10	a	5	1	0	A
31	24	25	222	1	10	a	5	2+	1	
35	25	25	222	1	10	B	27	6	3	B
37	25	27	222	1	7	C	20	15	6	C
39	27	28	222	1	5	a	30	15	10	Marked activity, entire record.

Rec	Fr	To	ABC-G-Db	S	Mx	Av	Mn	Remarks	
40	28	29	222 1 5 a		30	10	3	D	
41	29	30	222 1 5 a		23	8	4	E	
44	30	31	111 1 10 a		135+	50	25	F	
	Ag	Ag							
46	1	3	111 1 10 a		150+	50	25	G	
48	3	4	111 1 10 a		85+	H	H	H	
50	4	5	111 1 10 a		70	I	I	I	
51	5	6	111 1 10 a		50+	J	J	J	
54	6	7	111 1 10 a		-	-	-	K	Recording changed to H19, at 6-ft. hole drilled in south wall right beside H7.

A. A series of small continuous bursts from 6:32 p.m., July 23 to the shutting off of the record at 7 p.m. When the record came on again at 3 a.m., July 24, it was again normal with a maximum of about 5 s.p.m. and an average of less than 1 s.p.m.

B. The stope nearest H7 (4301W-9) burst at a little after 11 a.m., July 25. The record was changed by E.A.H. at 8 p.m., July 25, so ran only 3-4 and 6-7 p.m. on July 25. The activity was marked. It is to be noted that H7 is only a foot deep and was later found to be in a large slab of loose.

C. Activity markedly greatest beginning 3 p.m., July 26. By 6 a.m., July 27, after a Sunday of no mining, the record was down to an average of less than 1 s.p.m.

D. Activity began to be great at 3 a.m., July 29. During the p.m. runs on July 28, it was an average of about 5 s.p.m.

E. Activity began to be great at 3 a.m., July 30. During the p.m. runs on July 29, it was an average of about 5 s.p.m. A small burst registered 3:28 a.m., July 30, and a larger one, recording for more than a minute, registered at 3:43 a.m., July 30.

F. Marked activity throughout record. Burst about 6:31 p.m., July 31, recorded for nearly two minutes.

G. Very marked activity began 3 a.m., August 2, and gradually diminished over the week-end, August 2 being Sunday. Most of the activity was small and on the fast stylus but there were about 2 s.p.m. on the average of strong throws on both. In spite of the very marked activity there were no bursts.

H. Record began very actively with average of more than 75 s.p.m. The activity fell off gradually during the recording.

I. Beginning with an activity of about 25 s.p.m. on the average, all small, the activity increased during the period 6-7 p.m., August 4. From 6:50 to 6:53, three small bursts recorded. Two others of short duration but strong offsets occurred at 3:10 and 3:18 a.m., August 5, and a succession of these followed almost continuously till 4 a.m., when normal strong activity was resumed to the end of the record.

J. Abnormal activity began 3 a.m., August 6, and continued till the closing off at 4 a.m. A succession of severe bursts occurred. Normal strong activity was resumed at 6 p.m., August 6. See note T for H4.

K. Entire record open circuit oscillations.

H8

Rec	Fr J1	To J1	ABC-G-Db			S	Mx	Av	Mn	Remarks
10	10	11	312	5	0	a	2+	1-	0	A
17	17	18	313	5	2	a	1+	1-	0	
18	18	20	222	5	15	a	1-	1-	0	B
21	20	21	313	5	2	a	1-	0	0	C
22	21	22	222	5	15	a	1+	1-	0	
25	22	23	131	5	2	a	1	0	0	D
28	23	24	131	5	0	a	0	0	0	E
33	24	25	131	5	0	a	1	1-	0	F
34	25	25	131	5	0	H	0	0	0	G, H

A. Slow stylus coil burned out July 11.
B. Very little on entire record.
C. Record almost complete blank.
D. One snap only on entire record.
E. Record absolutely blank. Instrument trouble?
F. Very little activity. Instrument OK.
G. No activity recorded.

H. The instrument was in good order so far as is known, but no activity was recorded. It ran 3-4 and 6-7 p.m., July 25. After the burst in 4301W-9 stope the record was removed by E.A.H., Saturday evening, July 25.

H9

Rec	Fr	To	ABC–G–DB			S	Mx	Av	Mn	Remarks
	Ag	Ag								
87	20	21	111	5	5	a	20	15	2	A
90	21	22	111	5	5	a	100+	60	30	B
93	22	24	111	5	10	a	100+	C	C	C
96	24	25	111	5	5	a	25+	15	5	Mostly small amplitude.
99	25	26	111	5	5	a	30+	20	10	Well defined activity.
102	26	27	111	5	5	a	25+	15	10	
105	27	28	111	5	5	a	50+	25	10	D
108	28	29	111	5	5	a	50+	25	10	E
		Sp								
113	31	1	111	5	5	a	20	15	10	
	Sp									
116	1	2	111	5	5	a	8	5	1	F
158	17	18	111	5	5	a	50+	30+	20+	G
161	18	19	111	5	5	a	100+	75+	50+	H
164	19	21	111	5	5	a	40+	25+	15+	I

A. Activity diminished through record.
B. Activity diminished very little.

C. Strong activity as indicated from 3-4 p.m., August 22, then markedly less over the week-end. Only 1 to 2 s.p.m. towards end of record. Compare note H for H19.
D. Strong activity began 3 a.m., August 28. Previously quite moderate.
E. Activity increased slightly 3 a.m., August 29.
F. No evidence of anything like static.
G. Slow stylus coil shorted to chassis by bit of steel wool. Not recording after first half hour. Strong activity on fast stylus seems real.
H. Strong activity seems real.
I. Definite falling off of activity (Saturday-Sunday).

H11

Rec	Fr	To	ABC-G-Db			S	Mx	Av	Mn	Remarks
	Ag	Ag								
111	29	31	333	1	10	a	8	4	0	A
		Sp								
114	31	1	333	1	5	a	20	10	5	
	Sp									
117	1	2	333	1	10	a	12	6	0	Very wide zeros.

A. The geophone was placed in H11 by F.J.H. in mistake for H22, which accounts for the short run on this hole. This is the first recording done on 3801W.

H19

Rec	Fr	To	ABC-G-Db			S	Mx	Av	Mn	Remarks
	Ag	Ag								
56	7	8	111	1	10	a	200+	A	A	A
58	8	10	111	1	10	a	65+	B	B	B
60	10	11	111	4	10	a	100+	C	C	C
64	11	12	333	4	5	a	20	10	2	D
67	12	13	333	4	5	a	15	10	3	D

Rec	Fr	To	ABC-G-Db		S		Mx	Av	Mn	Remarks
70	13	14	333	4	0	a	25	10	3	D
73	14	15	333	1	0	a	36	15	5	E; much small amplitude.
76	15	17	333	1	0	a	100+	F	F	F
79	17	18	333	1	0	a	50+	25	15	Mostly small amplitude.
82	18	19	333	1	0	a	70+	25	15	Mostly small amplitude.
85	19	20	333	1	0	a	100+	50+	25	G; strong activity.
88	20	21	333	1	5	a	150+	60+	40	Strong activity throughout.
91	21	22	333	1	5	a	75+	40+	25	Strong activity throughout.
94	22	24	333	1	5	a	150+	H	H	H
97	24	25	333	1	5	a	75	25	10	D; mostly small.
100	25	26	333	1	5	a	85	30	15	Mostly small.
	Sp	Sp								
155	16	17	111	3	5	a	60	30	20	I; slow coil burned out.

A. For earlier recording from this same position see the report for H7, which is right beside H19. The former is only about a foot deep, while the latter is 6 ft. deep. This is the first recording from H19. Activity is very great throughout. During the latter part of the period 3-4 a.m., August 8, a succession of bursts is recorded.

B. Activity was moderately strong on August 8. Beginning 3 p.m., August 9 (Sunday), strong activity was begun which continued, diminishing only slightly, to the end of the record.

C. Moderately active to 3 a.m., August 11, when the activity became very marked, diminishing only slightly to the end of the record.

D. The small frequent activity of these records may be instrumental, owing to non-grounding of centre tap of the geophone transformer.

E. Installed internal transformer on G1. (Note that the recorded activity did not fall off, on the contrary it increased, which seems to nullify the suspicion of note D above.)

F. Marked activity from beginning of record, diminishing towards the end of record which covers a week-end.
G. Small burst 3:12 a.m., August 20.
H. Very great activity 3-4 p.m., August 22. It then diminishes gradually over the week-end to about 10 s.p.m., all small, on August 24. Compare note A for H9.
I. Decided change in character of record beginning 3 a.m., the amplitude being greater. Slow coil burned out 3:42 a.m.

H20

Rec	Fr Ag	To Ag	ABC-G-Db			S	Mx	Av	Mn	Remarks
61	10	11	333	6	5	a	1	0+	0	Very quiet; hole in N wall.
63	11	12	111	6	10	a	15	3	0	A
66	12	13	111	6	5	a	150+	50	40	B
69	13	14	111	6	10	a	38	25	10	C
72	14	15	111	6	10	a	15	10	0	Small amplitude; diminishing.
75	15	17	111	6	10	a	15	5	0	Nearly all on fast stylus.
78	17	18	111	6	10	a	10	4	0	All small amplitude.
81	18	19	111	6	5	a	20	D	D	D
84	19	20	111	6	5	a	20	15	10	Activity small, continuous.

A. Some activity of small amplitude on fast stylus, beginning 3 a.m., August 12, but died down soon.
B. Mostly small-amplitude activity on fast stylus only. This and the activity on the previous record may be static due to non-grounding of centre tap on geophone transformer; also, cable not shielded. (Note: trouble began to show up about this time from poor cable and from weathered joints, which had to be found and repaired when the evidence of their presence was found on the records.)
C. Small-amplitude activity. Markedly greater, beginning at 3 a.m., August 14.
D. Activity, all small, confined to 3-4 p.m., August 18.

H21

Rec	Fr Sp	To Sp	ABC-G-Db			S	Mx	Av	Mn	Remarks
120	2	3	111	4	5	a	15	8	1	First record in a 30' hole.
123	3	4	111	4	5	a	12	8	2	
126	4	5	111	4	5	a	40+	20+	10+	A
129	5	7	111	4	5	a	30+	15+	6+	Tapping test.
132	7	8	111	4	5	a	30-	15-	6-	
135	8	9	111	4	5	a	30-	15-	6-	A
137	9	10	111	4	5	a	30+	15+	6+	B
139	10	11	111	4	5	a	15	8	3	Good clean record.
140	11	12	111	4	5	a	15	8	3	A, C
144	12	13	111	4	5	a	9	7	1	D
145	13	14	111	4	5	a	9	7	1	
149	14	15	111	4	5	a	15	9	2	D
152	15	16	111	4	5	a	18	9	2	D, E

A. Very pronounced evidence of skipping on Shaft No. 4. The first noticed in the 30-ft. hole at 3-4 a.m.

B. Skipping very pronounced 3-4 a.m. Also what seems to have been a burst, lasting about 2 min. at 3:48 a.m.

C. Much quieter 3-4 p.m., September 11. Also 6-7 p.m. the same date. Activity was resumed at 3-4 a.m., September 12.

D. Skipping very pronounced 3-4 a.m.

E. This hole was deepened from 30 ft. to 103 ft. on September 22. Operating began on October 6 from the deepened hole, renumbered H25.

H22

Rec	Fr	To	ABC-G-Db		S	Mx	Av	Mn	Remarks
	Sp	Sp							
118	2	3	333	1	10	a	5	1-	0 Wide zero.
122	3	4	333	1	10	a	5	1-	0
124	4	5	333	1	5	a	10	4	2 A
127	5	7	333	1	5	a	7	3	2 B
130	7	8	333	1	5	a	10	5	3 B
133	8	9	333	1	5	a	-	-	- C
146	12	14	333	1	5	a	-	-	- D, E
147	14	15	333	1	5	a	3	1	0 F
150	15	16	333	1	5	a	2	1-	0
153	16	17	333	1	5	a	2	1-	0 G
156	17	18	333	1	5	a	2	1-	0
159	18	19	333	1	5	a	2	1-	0
162	19	21	333	1	5	a	2	1-	0 H
165	21	22	333	1	5	a	2	1-	0
168	22	23	333	1	5	a	I	1-	0 I
171	23	24	333	1	5	a	2	1-	0 Wide zero.
173	24	25	333	1	5	a	J	1-	0 J
	Oc	Oc							
209	15	16	333	3	0	b	3	1-	0 K; new schedule b.

Rec	Fr	To	ABC-G-Db			S	Mx	Av	Mn	Remarks
212	16	17	333	3	0	b	4	1	0	Wide zero.
215	17	19	333	3	0	b	4	1	0	L
218	19	20	333	3	0	b	4	1+	0	
220	20	21	333	3	0	b	4	1+	0	M
222	21	22	333	3	0	N	-	-	-	N
224	22	23	333	3	0	b	3	1-	0	
226	23	24	333	3	0	b	4	1+	0	
228	24	26	333	3	0	b	2	1-	0	O
231	26	27	333	3	0	b	2	1-	0	
234	27	28	333	3	0	b	2	1-	0	

A. Mostly small; wide zero.

B. Many small offsets on fast stylus increase during progress of record. Zero very wide. The numerous small offsets possibly due to instrumental trouble. First tapping tests on walls made on this record. They were well marked when done on south wall, but little or nothing showed when done on the north wall.

C. Record not turned on (E.A.H.)

D. Record valueless.

E. First hour of record, continuous oscillations as if a circuit were open. Then wide zero for remainder of record. Some line trouble apparently.

F. Zero still too wide.

G. Second half of record shows an increased activity at the rate of 11-12 s.p.m., but it seems probable that the record is the result of instrument trouble. This is especially true since the next record (R156) shows a return to slight activity.

H. Instrument seems OK.

I. Only first two periods recorded; recorder out of order.

J. Only first period recorded. Recorder 3C taken to surface for adjustment.

K. Record shows very poor pickup. May be instrumental but possibly due to poor rock condition.

L. Wide zero continued to 3 p.m., October 18, when an open circuit recorded with a few small interruptions for two hour-records, after which the wide zero was resumed.

M. Too much voltage on slow stylus. Towards the last half of the record considerable very small activity recorded on the fast stylus only. May be instrumental.
N. The record paper did not run, owing to slippage in drive. No record.
O. The record showed very small activity, as reported in the s.p.m. columns, except for the period 3-4 p.m., October 25, when it ran: Mx 8; Av.4, and Mn 1, after which the low activity was resumed. Zero was too wide throughout, but especially during the active hour.

H23

Rec	Fr Ag	To Ag	ABC-G-Db			S	Mx	Av	Mn	Remarks
103	26	27	333	1	10	a	25	10	10	A, B
106	27	28	333	1	10	a	40	30	10	B
110	29	31	111	6	5	a	25	15	10	

A. Mostly small, possibly instrumental in part.
B. Definite evidence of ore skipping 3-4 a.m.

H24

Rec	Fr Dc	To Dc	ABC-G-Db			S	Mx	Av	Mn	Remarks
306	7	8	111	3	10	b	5+	2+	0	A
318	11	12	111	3	10	b	15-	10 -	2	
321	12	14	111	3	10	b	5+	3+	0	
324	14	15	111	3	10	c	5+	3+	0	B; new schedule c.
330	16	17	111	3	10	c	15+	10-	3	C
333	17	18	111	3	10	b	20+	10-	0	
336	18	19	111	3	10	d	30+	10+	0	D; new schedule d.
338	19	21	333	3	10	c	-	-	-	E
340	21	22	333	3	10	b	20-	10-	5-	F

Rec	Fr	To	ABC-G-Db	S	M	Av	Mn	Remarks
342	22	23	333 3 10	d	20-	10-	5-	
344	23	24	333 3 10	d	40-	20+	20-	
346	24	28	333 3 10	d	10+	10-	5+	G
		Ja						Starting January, 1943.
358	31	2	333 3 7	d	15+	10-	5-	

A. Friction of writing stylus with record much too great.
B. Time switch installed to run H24 and H26 each alternate half-hour from 4-7 a.m. and p.m., with H24 coming on at the hour and H26 at the half hour. But the time switch did not close properly, so that it was always open circuit for H26 with much oscillation and no record.
C. Last half of record was entirely lost, owing to open circuit oscillations.
D. Last half of record shows noticeable falling off in activity.
E. Entire record lost, owing to ineffective contacts on the time switch.
F. Considerable time lost, owing to ineffective contacts on the time switch.
G. Activity increased; at end of record about Av. 30+.

H25

Rec	Fr	To	ABC-G-Db	S	Mx	Av	Mn	Remarks
	Oc	Oc						
194	6	7	333 4 0	b	40+	20+	10+	A; first record in 100' hole.
196	7	8	333 4 0	b	50+	25+	15+	
198	8	9	333 4 0	b	40+	20+	10+	B
200	9	10	333 4 0	b	40-	20-	10-	
202	10	12	333 4 0	b	40+	20+	10+	C
204	12	13	333 4 0	b	20+	15+	10+	D
206	13	14	333 4 0	b	20-	15-	10-	E
208	14	15	333 4 0	b	40+	20+	10+	

Rec	Fr	To	ABC-G-Db			S	Mx	Av	Mn	Remarks
211	15	16	222	4	10	b	15+	10+	5+	F
213	16	17	111	4	5	b	50+	30+	15+	
216	17	19	111	4	5	b	40+	20+	10+	G
229	24	26	111	4	5	b	2	1-	0	H
232	26	27	111	4	5	b	3	1-	0	I
		Nv								
242	31	2	333	6	5	b	10-	5+	1	J
	Nv									
245	2	3	111	4	5	b	20+	15+	5+	
247	3	4	111	4	5	b	20+	15+	5+	K
248	4	5	333	4	0	b	10-	5+	1	L, M, N
251	5	6	111	4	5	b	20+	15+	5+	
253	6	7	111	4	5	b	15+	10-	3	
255	7	9	111	4	5	b	15+	10-	3	
257	9	10	111	4	5	b	10-	5+	3	O
259	10	11	111	4	5	b	10+	5+	3	O
261	11	12	111	4	5	b	5	1+	0	
263	12	13	111	4	5	b	10-	5+	2	O
265	13	14	111	4	5	b	20-	10+	4	O
267	14	16	111	4	5	b	20-	10+	3	O
269	16	17	111	4	5	b	15+	10-	5	P
271	17	18	111	4	5	b	10+	5+	3	O

Rec	Fr	To	ABC–G–Db			S	Mx	Av	Mn	Remarks
273	18	19	111	4	5	b	40–	15+	5	O
275	19	20	111	4	5	b	30+	10+	5	O
277	20	21	111	4	5	b	20+	10+	3	O
279	21	23	111	4	5	b	20+	10+	3	O
281	23	24	111	4	5	b	20–	10–	3	O
283	24	25	111	4	5	b	20–	10+	3	O
285	25	26	111	4	5	b	20–	10+	3	O
287	26	27	111	4	5	b	10+	10–	3	O
289	27	28	111	4	5	b	10+	10–	3	Q
291	28	30	111	4	5	b	15+	10–	2	R
		Dc								
293	30	1	111	4	5	b	20+	10–	0	S
	Dc									
295	1	2	333	4	5	b	20+	10+	5+	Zero too wide.
297	2	3	333	4	10	b	15+	10–	5–	Good record.
299	3	4	333	4	10	b	20–	10–	5	T
301	4	5	333	4	10	b	20–	10–	5	
303	5	7	333	4	10	b	20+	10+	4	U
305	7	8	333	4	10	b	20–	10–	3	
308	8	9	333	4	10	b	20–	10–	3	V
309	8	9	111	4	10	b	20–	10–	3	V
311	9	10	333	4	10	b	15+	10–	3	V

Rec	Fr	To	ABC–G–Db			S	Mx	Av	Mn	Remarks
312	9	10	111	4	10	b	15+	10–	3	V
314	10	11	333	4	10	b	20+	10–	3	V
315	10	11	111	4	10	b	20+	10–	3	V
317	11	12	333	4	10	b	25+	10+	4	
320	12	14	333	4	10	b	25+	10+	4	W
323	14	15	333	4	10	b	40+	10–	6	X
326	15	16	333	4	10	b	25+	10–	4	
329	16	17	333	4	10	b	25+	10+	2	Y
332	17	18	333	4	10	b	40–	20–	10–	
335	18	19	333	4	10	b	40+	20+	5+	
337	19	21	222	4	10	d	20+	10+	5+	New schedule d.
339	21	22	222	4	10	d	20+	10+	5+	
341	22	23	222	4	0	d	40–	20–	5+	
	Dc	Dc								
343	23	24	222	4	0	d	40+	25+	20–	Z
345	24	28	222	4	0	d	20+	10+	5+	A'
348	28	29	222	4	0	b	20–	5+	0	B', C'
349	28	29	333	4	2	b	25+	10–	2	B', C'
350	28	29	111	4	5	b	20+	10+	3	B', C'
351	29	30	222	4	0	b	20–	10–	5	D'
352	29	30	333	4	7	b	20+	10+	5+	D'
353	29	30	111	4	7	b	20+	10+	5+	D'

Rec	Fr	To	ABC-G-Db			S	Mx	Av	Mn	Remarks
354	30	31	222	4	0	b	30+	10+	5+	D'
355	30	31	333	4	7	b	30+	10+	5+	D'
356	30	31	111	4	7	b	30+	10+	5+	D'
		Ja								
357	31	2	222	4	0	c	20+	10+	5+	

A. Ran simultaneously with No. 195 in H4. See note M' for H4.

B. First 'pull-out' test between H4 and H25; compare record No. 197 in H4. Deeper hole the more active.

C. Activity fell off somewhat towards the end of the record, which ran over Sunday.

D. Fairly continuous activity.

E. Record caught fire but went out, leaving small burned hole.

F. Feed seems irregular. Frequent small stoppages marked by burned holes, beginning on page 21115. Very bad on page 21119. Both styli give records that look much the same — a most unusual result. This is the first record from 222 since it was repaired after the fire of September 22. See Note H' for H4. It was fortunate that it did not catch fire again at this time.

G. Paper caught fire and burned quite a section off one edge for nearly 2 min. on page 21603. The paper was feeding crookedly at the time. It came back to normal after about 40 min. Burned off at about 3:50 p.m. October 18, and the record stopped. During the last hour the paper slipped badly, remaining stationary, hence the burn-off. Did not catch fire, however.

H. Most remarkable change in H25 since October 19.

I. Paper ran crookedly during much of record. No fire. Voltage high on styli.

J. Styli have too much friction with paper. Does not prevent most of the recording, but makes record very irregular, as stylus does not return to zero after each throw.

K. May be small burst registered at 6:57 p.m., November 3. Slight trace on 24613A and well recorded on 24713A.

L. Record began to run crookedly on page 24809. The edge was burned off the record for nearly 7 min. on page 24810. The record came back to position and no fire resulted.

M. The stylus friction is much too great.

N. Looks like a small burst at 6:57 p.m., November 4. In view of note K above, the record may be instrumental. It appears also on 24912, which seems to show that the disturbance is mechanical, but it may be seismic. If not, cause is not known. See also 25813A.

O. Many electrical disturbances, lasting some minutes at a time, causing slight 25-cycle oscillation and a widening of the zero; cause is instrumental.

P. Well-recorded burst lasting about 4 min. on page 26903 . Less well registered on 26803 for H28.

Q. Severe oscillations resembling bursts on page 28919 for H25. They do not appear on corresponding pages of record 288 for H28, the latter being the newly adjusted 222 set.

R. Burst felt by E.A.H. at 6:22 a.m., November 30. See page 29144A for H25 and compare 29043B for H28.

S. Burst at 4:12 p.m., November 30 (see page 29306B); compare 29206B for H28.

T. Some good records of ore-pass noise during the listening period.

U. A series of bursts registered, beginning at 6 p.m., December 6; becoming quite violent at 6:12 p.m. (page 30337B); compare page 30230B on H28.

V. Recorders 333 and 111 ran on an input divider, giving two records from the same hole.

W. Activity falls off considerably towards the end of the record, to Av. 5– s.p.m.

X. Maximum activity falls off very rapidly.

Y. Activity becomes greater in second half of record, reaching Max. 30+, Av. 20+ Min. 10–.

Z. Activity reported was on first period of record. The activity fell off to about Max. 20+, Av. 10+, Min. 5+.

A'. Activity fell off to about Av. 5+ by the end of the record.

B'. H25G4 was run through a voltage divider onto 111, 222, and 333. The results were far from satisfactory as regards equivalent recording.

C'. Heavy burst at 6:06 p.m., December 28, recorded on all three sets.

D'. Simultaneous recordings on 111, 222, and 333, from H25G4. Adjustment of sensitivity much better.

H26

Rec	Fr	To	ABC–G–Db			S	Mx	Av	Mn	Remarks
	Oc	Oc								
236	28	28	333	1	0	a	3	1–	0	A
240	30	31	333	1	0	B	3	1–	0	B
	Dc	Dc								
336	18	19	111	1	10	c	5	3	1	
338	19	21	333	1	10	c	–	–	–	C
342	22	23	333	1	10	c	20–	10–	5–	D
344	23	24	333	1	10	c	10–	5–	0	

Rec	Fr	To	ABC-G-Db			S	Mx	Av	Mn	Remarks
346	24	28	333	1	10	c	10-	5-	0	E
		Ja								
358	31	2	333	1	7	c	-	-	-	F

A. Recorder all in good order, as blasting is well recorded. But in this 30' hole in 4201W-9 the activity has fallen almost to zero. For previous recording in this region see tabulation for H19.

B. Last hour (6-7 a.m., October 31) of this record was run: 111G6H28.

C. Entire record lost owing to ineffective contacts on the time switch.

D. Considerable time lost owing to ineffective contacts on the time switch.

E. Greatly increased activity towards the end of the record, up to Av. 50+. May be instrumental but does not appear to be so.

F. Time-switch contacts very poor. Continual oscillations during the H26 part of the record.

H27

Rec	Fr	To	ABC-G-Db			S	Mx	Av	Mn	Remarks
	Dc	Dc								
327	15	16	111	6	10	b	A	A	A	A
347	24	28	111	6	10	b	10-	2-	0	B

A. Record very active: Av. 25+, but this may be instrumental, as the connecting cable is very long. If not, H27 must be very active. The activity increased slowly to 4 a.m., December 16, when it became quite pronounced as noted above, and so continued.

B. Voltage too high on styli.

H28

Rec	Fr	To	ABC-G-Db			S	Mx	Av	Mn	Remarks
	Oc	Oc								
238	29	30	333	6	0	b	1	0+	0	A
240	30	31	333	6	0	b	6	3	1	B

Rec	Fr	To	ABC-G-Db			S	Mx	Av	Mn	Remarks
		Nv								
243	31	2	111	2	5	b	20–	10+	2	
	Nv									
244	2	3	333	2	0	b	10+	5+	2	C
246	3	4	333	2	0	b	5+	2+	0	D
249	4	5	111	2	5	b	5+	2+	0	
251	5	6	333	2	0	b	20–	10–	2	D
252	6	7	333	2	0	b	5+	1+	0	
254	7	9	333	2	0	b	15+	5+	0	
256	9	10	333	2	0	b	10–	5+	1	
258	10	11	333	2	0	b	10–	5+	1	
260	11	12	333	2	0	b	10–	2	0	E
262	12	13	333	2	0	b	10+	10–	3	
264	13	14	333	2	0	b	20–	10+	4	
266	14	16	333	2	0	b	20–	10–	3	
268	16	17	333	2	0	b	15+	5+	3	F
270	17	18	333	2	0	b	15–	10–	3	E
272	18	19	333	2	0	b	20–	10+	3	E
274	19	20	333	2	0	b	10+	10–	3	G
276	20	21	333	2	0	b	20–	10+	3	H
278	21	23	333	2	0	b	20–	10+	3	

Rec	Fr	To	ABC-G-Db			S	Mx	Av	Mn	Remarks
280	23	24	333	2	0	b	20+	10+	4	I
282	24	25	222	2	5	b	5	2+	0	J
284	25	26	222	2	5	b	5+	2+	0	
286	26	27	222	2	5	b	5+	2+	0	
288	27	28	222	2	5	b	4+	2+	0	
290	28	30	222	2	5	b	5+	2-	0	K
		Dc								
292	30	1	222	2	5	b	10-	3+	0	L
	Dc									
294	1	2	222	2	5	b	5+	2+	0	
296	2	3	222	2	0	b	5+	2+	0	
298	3	4	222	2	0	b	10-	5	1	
300	4	5	222	2	0	b	10+	5+	0	M
302	5	7	222	2	0	b	5+	5-	1	N
304	7	8	222	2	0	b	10+	5-	1	
307	8	9	222	2	0	b	15+	5+	2	
310	9	10	222	2	0	b	5+	3+	0	
	Dc	Dc								
313	10	11	222	2	0	b	15+	10-	1	
316	11	12	222	2	0	b	15+	10-	1	
319	12	14	222	2	0	b	15+	10-	1	O
322	14	15	222	2	0	b	15+	10-	1	

Rec	Fr	To	ABC–G–Db	S	Mx	Av	Mn	Remarks
325	15	16	222 2 0	b	10–	5+	0	
328	16	17	222 2 0	b	10+	5+	2	
331	17	18	222 2 0	b	20+	10–	2	O
334	18	19	222 2 0	b	20+	10–	2	
337	19	21	222 2 0	c	20+	10–	2	P; new schedule c.
339	21	22	222 2 0	c	40–	20+	15+	
341	22	23	222 2 0	c	40–	20+	15+	
343	23	24	222 2 0	c	50+	40+	20+	Q
345	24	28	222 2 0	c	30+	20+	10+	R
		Ja						
357	31	2	222 2 0	d	5+	2+	0	New schedule d.

A. This activity is plainly instrument trouble. 111H4G2 for the same period gives a normally active record (see No. 239 for H4). G6 was taken to surface and the crystal was found to have been destroyed by moisture.

B. New crystal in G6. Works very well.

C. A number of disturbances, lasting a minute, more or less, which are probably due to electrical disturbance, since some are so identified during the listening period, 6–7 a.m.

D. Friction of styli on paper much too great.

E. Too much voltage on the styli.

F. Some bursts, lasting about 4 min., on page 26803. Very pronounced on page 26903 for H25.

G. Record ran crookedly, pages 27407 to 27409. Caught fire on edge (page 27407) and burned off edge for nearly 5 min. but did not set fire to record. Record resumed position and no recording lost.

H. Towards the end of the record many small offsets registered on the fast stylus. May have been instrumental.

I. Activity falls off towards end of record.

J. Note that this falling off of activity is not real. The set 222 has been substituted for 333.

K. Burst felt by E.A.H. at 6:22 a.m., November 30. See page 29043B (H28) and compare 29144A (H25).

L. Burst at 4:12 p.m., November 30, hardly registers on 29206B, but is very well marked on 29306B (H25). Is this due to lack of calibration or to the fact that H25 is the deeper hole?

M. Activity falls off towards the end of the record.

N. Fairly well-marked burst occurred at 6:12 p.m., December 6 (page 30230B); this was much better marked on 333 H25 G4 Db 10, on page 30337B.

O. Record falls off considerably towards the last, giving Av. 5-.

P. Some lost time owing to poor contacts on time switch.

Q. Activity reported was for first period only. It fell off until at the end of the record it was down to Max. 20+, Av. 10+, Min. 5+.

R. Activity fell off gradually to about Av. 5+ by the end of the 4-day record.

K-9 Sample Records of Particular Interest

(1) Figure 48:

On the left-hand side of this illustration are shown a series of records leading up to a rockburst at 11 a.m., July 25, and to a second burst at 6:31 p.m., July 31. The bracketed numbers refer to corresponding serial numbers on the sections of records shown. Sections 1 to 7 show the activity at H7 (4201W-9-S) at a series of intervals from July 22 to July 31.

The rockburst of July 25 occurred in 4301W-9, about 125 ft. below H7. It is to be noted that H7 was later found to be in a slab of loose and probably not in very good contact with the solid rock of the pillar; it was only a foot deep (see section K-6). Of the samples shown, the nearest preceding record is No. 4, taken at 3:30 a.m., some 7.5 hours before the burst. It cannot be said to show any warning. Moreover, the record from H8 (4201W-7-N) as given in section K-8 showed no activity whatever about the time of the severe burst of July 25. As noted in K-6, this is a good hole in solid rock, 3'6" deep; it is 125 ft. above the burst and 200 ft. east. H8 is in the north (foot) wall. Evidently some 230 ft., even through solid rock, is too far to expect the subaudible, relatively high-frequency snaps to be picked up by the recorders.

On the other hand, consider sections 5, 6, and 7; the last one, about 15 hr. before the burst of July 31 at 6:41 p.m., shows warning activity of about 75 s.p.m. The activity continued after the burst, as can be seen from the activity for H7, records 44 and 46, as reported in K-8.

The series of sample records shows, then, one case where warning was a failure, in spite of the reasons mentioned. The other case indicates a good measure of warning activity, well before the time of the burst.

No. 3 shows a small burst that occurred near the geophone and lasted about two minutes. It is a good example of the way such small bursts record. Bursts such as this do not record on the surface seismograph as a rule. If one is listening to them underground, they are quite striking while the earphones are in place but, these removed, there is not a sound in the empty mine.

On the opposite side of Figure 48 are shown some typical recordings. No. 8 shows a marked increase of activity after the lapse of seven hours. The left-hand side was made at 7 p.m., July 9, and the right at 3 a.m., July 10, when the recorder again went into service. Such increases are said to indicate critical conditions, but no burst occurred in this case.

In No. 9, the 15 offsets beginning to the right of centre are due to blasts that did not occur in the Lake Shore mine. They could barely be heard with the unaided ear. They are of longer duration than the snaps to the left, and have a full record on the upper (slow) stylus — an indication that they originiated at a considerable distance.

No. 10 shows the type of record obtained if the line from the geophone to the recorders is open or partly open. At first this type of record (obtained from lines that were sometimes open and sometimes closed, giving short runs of wild recording) was thought to have been caused by rock slides in stopes near the pick-up geophones.

No. 11 is a record of 'static' caused by slight electrical impulses picked up by the geophone-to-recorder cable or due to electrolytic action at a poor joint or a broken strand in the cable. Note that all the static is on the lower (fast) stylus and that three small snaps are to be identified by small irregularities on the upper line. This 'static' can be eliminated by making sure that good cables are used, with proper joints and no broken strands, and with a good shield.

No. 13 shows the record obtained in 4201W-8, owing to the sliding of ore in the pass at the cross-cut 800 ft. or more away, when skipping ore in No. 4 shaft. The skip intervals are approximately 70 sec. Two small sections, some 20 min. apart, are here given to show the effect as the amount of ore in the pass diminishes. After about an hour it fades down to a slight irregularity on the lower (fast) stylus.

(2) Figure 49:

This shows the history of activity in 4201W-8, leading up to the holing through of a 16-ft. rill from 4301W-8 on September 5. Records 1 to 9 and 10a to 13a were all made on the same recording equipment at H4. The series 10b to 13b was made from a geophone in a 30-ft. DD hole (H21) close to H4.

Note that:

(1) The series in H4 shows a definite growth up to the time of greatest stress, September 5.

(2) The series in H21 shows a much more marked increase on September 4. It is unfortunate that H21 was not occupied prior to September 2.

It is concluded that a 30-ft. hole is much more informative than one six feet deep. In this case the hole (H4) is the best of all the twenty odd 6-ft. holes drilled for this study.

If then, a 30-ft. hole is more informative than a 6-ft., what could one expect from a 100-ft. hole? To answer this question, H21 was deepened on September 22 to 103 ft., and several 'pull-out' tests were made; these are shown in Figure 49.

(3) Figures 50 and 51:

These show a series of records made to compare the recording in a 100-ft. hole with that in a good 6-ft. hole. The respective holes, H25 (formerly H21) and H4, are drilled side by side in 4201W-7, as shown in Figure 46.

A geophone (G2) in the 6-ft. hole (H4) was run without any resetting on Obert unit 222. Another (G4) was run throughout the test on Obert unit 111 in H25. The geophone in H25 was run for four minutes at a depth of 100 ft., then another four minutes at a depth of 94 ft., and so on, at depths successively 6 ft. less. The comparative records from the second of these pull-out tests are shown in this illustration. On each record a sensitivity test (T) is recorded as a result of tapping (generally five times) on a steel anchor bolt let into the south wall of recording station B in 4201W-6. The bolt is at a distance of 125 ft. to 150 ft. from the collars of the two holes (see Figure 47).

The tests (T) show up well on each pair of records, indicating that contact with the rock was good at each setting and that the bottom of the 100-ft. hole is more active than the bottom of the 6-ft. The questions therefore arise:

(1) How deep would one need to go to get beyond the zone of compression?
(2) How would the simultaneous recordings from a 30-ft. hole, say, compare with those from the 100-ft. hole?

To answer the second question, a 30-ft. DD hole (H28) was drilled close to H4 and H25. The comparison tests were made through a long series of records from H25 and H28. (see section K-8).

*

Report L

January-March, 1943

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The main events of the first three months of 1943 were the heavy crush bursts of January 29 and March 31. The first completely wrecked the section of the west pillar where the instruments were in operation, destroying all the available geophones and burying one of the three Obert sets. The second burst was also in the west pillar, but higher up. It completed the devastation of the pillar but did not materially increase damage to the research program.

The compilation of data of section K-8 was given in full because it leads up to the burst of January 29. This rockburst is the outstanding case where the records seem to give a decided warning. For the same reason, full data from holes H29 and H31 are given, these being the two holes from which records were obtained right up to the time of the burst. The most interesting results of the entire program were obtained at this time.

L-1 Recording Program in January

Determination of the best locale for the investigation, elimination of instrument trouble, and initiation of a regular program were completed by the end of 1942, and the program as developed was carried through regularly in January.

Three sets of Obert recorders and seven geophones were available. The recorders were set as follows: one was placed in station C on 3801W-9, and recorded alternately, by means of a time switch, from geophones in H29 in 3801W-9 and H31 in 3908W-7, the cable for the latter reaching the upper level via the manway rising from the 3950-ft. level at section 6.3W: two others were placed in station B on 4201W-6; one of these alternately served H27 in 4001W-7 and H24 in 4301W-7, the cable for the former coming down through the manway rising from the 4200-ft. level at section 8W, and that for the latter going down the manway from the 4200-ft. level at section 5.8W. These positions are shown in Figure 62. The third Obert set alternately served H25 and H28 in 4201W-7. All holes were in the south, or hangingwall, and each was 30 ft. deep except H25, which was 103 ft.

The seventh geophone was placed in H26 in 4201W-9 and was arranged for listening only. Except for occasional time-switch trouble, the program ran without interruption through January to the time of a large burst that occurred on January 29.

L-2 <u>The Bursts of January 29 and March 31</u>

On January 29, at 2:12 a.m. Eastern War Time (E. S. T. plus 2 hrs.), a heavy crush burst occurred in the exact section under investigation. The levels from 3825 to 4325 inclusive were affected. The drifts were more or less completely closed westward from approximately the line of section 6.

The levels 3825 and 3950 (see Figures 54 and 55) were completely blocked: 3901W (see Figures 55 and 56) was badly shattered. Within a few days, however, it was possible to get through on the south drift 3908W. The timber was badly shattered in 4001W drift (Figure 57) and the drift was blocked for a short distance at the line of section 6, but was opened with little delay. The flatback over 4301W-7 collapsed completely, and some damage was done in the drift. In Figures 47, 58, and 62, a large number of rectangles appear on the elevations along the tops of the various drifts. These are the cement plugs to which reference was made in section B-3. The rockburst of January 29 dropped these plugs down into the drifts (Figure 54). They were much harder to deal with than rock, so much so that the west end of the 4201W drift was opened up by means of a by-pass drifted through the footwall around the closed section of 4201W.

The effects of the burst on the instrumental equipment were disastrous. As was reported in section K-3, the part of the west pillar under investigation had been specially wired with heavy BXL cable for geophone lines and style B wire for the testing tappers. Practically all this wiring was destroyed. Every geophone was lost. The Obert set on 3801 W-9 was buried and was not recovered. The station on 4201W-6 was badly shaken up, but the instruments were not damaged. The program was left with two Obert sets, no geophones, and no cable.

As quickly as possible the station on 4201W-6 was put into shape again and a hole 52 ft. deep (H32) was drilled in the south wall just west of it. This was not drilled at right angles to the wall, but with a strong westward tendency, to bring the far end of it well inside the pillar some distance west of the blocked point in the drift. Recording began here on February 13.

Another doghouse was built on 3801W, at about section 6, immediately east of the point at which the drift was blocked. A hole (H33) was drilled in the south wall close to the blocked point of the drift and bearing strongly to the west, so as to get as far into the pillar as possible. This hole was 53 ft. deep.

One of the recovered Obert sets served on 4201W-6; the other was installed in 3801W-6. When 3908W was cleared, it was found that H31 was not damaged, and geophone No. 1 was recovered from it. The BXL cable down the manway from the 3825-ft. level to the 3950-ft. level was tested and found intact. Its drift sections were replaced and H31 was connected to the set in the new station on 3801W-6. Recording from H31 and H33 began on March 2; some time-switch trouble occurred, but was finally cleared on March 6.

The program from H31, H32, and H33 ran without interruption during the rest of March, with no great activity showing at any time, either on the recorders or during listening tests. Then on March 31, at 3.41 a.m. E.W.T., there occurred another crush burst that affected the levels 3200 to 3950 in the west pillar. The sections of 3801W and 3901W that had been cleared after the burst of January 29 were again completely blocked. No damage was sustained by the equipment on 4201W-6, but the station on 3801W-6 was badly shaken up, the entire set being thrown from the bench to the floor, but without damage. Holes 31 and 33 were lost, together with the geophones and cables.

After a survey of the damage, the company decided, owing to the scarcity of manpower, to abandon for the duration of the war the mining operations in the west pillar from 3325 to 4200 inclusive, except between 3950 and 4075. The seismic investigations in that part of the mine were discontinued, and steps were taken to locate on the east side.

L-3 Records of the Bursts of January 29 and March 31

These bursts were multiple, as shown by the Kirkland Lake seismograph records (Figures 52 and 53). The first and second sections (89 sec. apart) of the January burst were recorded in overlapping fashion on the Ottawa seismogram. The Kirkland Lake record shows that the second section was much the larger. Only the large first burst of March 31 was recorded at Ottawa. The phases are very sharply marked on the Ottawa record. The seismograms can both be used in a further study of elastic wave propagation but that for the March burst will be especially valuable. A comparison of these records with those given in Report H shows how well the phases are defined and how exactly they follow the time pattern of the earlier bursts.

L-4 Analysis of the Records

It was realized early in January that additional staff and more equipment would be needed to cope with the volume of records coming in.

An additional clerical assistant was therefore engaged, and an emergency wooden comparator was constructed by Gibbs, pending the design of a more permanent instrument. The latter was built in the Observatory machine shop, and is shown in the two lower plates of Figure 60. It provides a means of rapidly and conveniently handling the records, of analysing and tabulating the counts, and of noting the times and nature of coincidences between the records. It automatically reduces the time scale from record to 'comparator sheet' by a factor of 1/2. Adjustments are provided to care for parallax between the recording styli of a set and for synchronizing the records. Only 3 to 5 inches of record can by synchronized at any one time with an accuracy suitable for noting coincidences, since the slightly different rates of travel of the recording paper cause the records to get out of step after a few minutes on the comparator. Five inches only of each of three records are, therefore, exposed simultaneously on the machine. It was found necessary to compare longer sections to permit of annotating the records for time and synchronization marks. Accordingly, an annotator was built at Ottawa (see top picture of Figure 60). This permits rapid and convenient handling of the records, and exposes 15 inches or more of each of the three records at once. These two machines have greatly assisted in the analysis of the records. Counting has been done with the aid of a Veeder tally and, when the record was very active, the use of a small hand magnifier.

The January-March counts were tabulated as shown in L-12. The number of comparator sheets used for the period was 1017. The data for January only are listed in the report, as those for February and March were too scanty to permit any deductions with regard to the burst of March 31, which probably originated on the 3325-ft. level, some 500 ft. away from the nearest geophone.

The section of the west pillar that burst on January 29 (3825 ft. to 4325 ft.) was covered as completely as possible by the equipment available. The records, made up into book form and paginated, together with the numbered comparator sheets, were indexed by the analysis. The whole forms the first basic reference obtained at Lake Shore. The magnitude of the burst was unique in a seismic survey of this kind, and it was considered desirable to have these data ready for further examination in the light of later experience. It was not planned to continue such an elaborate system indefinitely.

The data in section L-12 show that the counts varied from period to period (alternate half hours from 4-7 and 16-19 hrs.). These p.m. counts might be expected to be higher, as they occur soon after blasting, but this is not always the case, as appears in Figure 59 and as noted in section L-7. It seemed best to average the p.m. and a.m. counts separately and to plot the values obtained. (Figure 59). The elevation of the mine for the sections concerned is shown in Figure 58. The graph of Figure 59 is discussed in section L-7.

L-5 Shifting Pressures

It has long been known that pressures in the mine, shift from point to point in the pillar, sometimes owing to the progress of mining operations, sometimes because of bursts, and sometimes from unknown causes. A well-recorded example of this is seen in the series of records shown in Figure 61.

On the 3825-ft. level, H29 (3801W-9) recorded on Obert set 111 in the doghouse on 3801W-6 for the first half of each of the hours 4-7 and 16-19. The same set recorded from H31 on 3908W-7 for the last half of these hours. There are, therefore, no simultaneous recordings from these two geophones but, except for the absence of coincidences, this does not greatly matter. Sections of the twelve records from H29 are set side by side with sections of the twelve records from H31, taken only half an hour later in each case. Each section shows 2 min. 40 sec. of record. The period covered was January 16-18. January 17 was Sunday, when no work was done in the mine.

For the part of the pillar being studied, blasting was over about an hour before the first section, shown in the upper left corner, and mining was resumed shortly after the last record section, shown in the lower right corner. It is clear that, during the period of a week-end, when no work was done in the mine, the pressure gradually passed from the vicinity of H29 to the vicinity of H31. Moreover, although these holes were only slightly over 250 ft. apart, the activity at one did not record at the other. This (or these) centres of activity burst 10 days later.

L-6 Salvoes and Bursts

On July 25, 1942, a burst occured in 4201W-9. The only records prior to this burst (Figure 48) were obtained for a few days from H7 (sample 3 of that illustration was reported in section K-9 (1) as a small burst). These were noticed first during the period preceding the burst of July 25. After that burst no more were noticed until late in December, when both Hallick and the writer heard what, for want of a better name, were dubbed 'salvoes'. These increased in number during January: when they recorded they were exactly like sample 3 of Figure 48. In January they were very numerous in both the upper and lower levels of the section of pillar being investigated. They could never be heard except through the amplifiers. It seems certain that these disturbances are seismic.

At other times, a single sharp snap could be heard with the unaided ear, but the recorder, after registering the initial sharp offset, continued to record snaps for some time. These disturbances were spoken of as bursts, although, except for the initial snap, nothing could be heard with the unaided ear, no damage was done, and they did not register on the surface seismograph.

Both types of disturbance were extremely local. Sometimes there was a marked difference between the records of H25 and H28, which were side by side in 4201W-7, the former 103 ft. deep and the latter 30 ft. They often did not record full on a geophone in the level next to that on which they registered as a maximum. Sometimes, when occurring in the deep hole H25, they would register at H29 in 3801W-9, but not at H27 in 4001W-7, only one level away.

It was thought that the occurrence of these salvoes and small bursts in a section of pillar indicated over-all pressure conditions approaching a critical point. One explanation advanced for their recording on H29, but not on H27 or H24 at the same time as on H25, is as follows: as has been previously reported, slight disturbances do not readily traverse a discontinuity (fault, break, or vein); if the walls of the pillar are laminated, with the supports for the deep-lying arch resting on the heavy pillars above 3700 and below 4325, then a disturbance originating in this deep-lying arch, which is penetrated by the deep hole H25, would not readily break through to the inner laminations to record on H27 (4001W-7). There were other evidences of this segregation of disturbances into arches.

L-7 <u>The Graph of Record Counts for January 1943</u>

The points for this graph were obtained from the record analyses by taking separately the values for large, medium, small, and total snaps for all p.m. and all a.m. observation periods each day. As plotted, the upper line shows the totals, the next the small, the next the medium, and the bottom the large snaps. The first ordinate after the date line shows the a.m. average, the second the p.m. average. Any question arising as to irregularities or breaks in the graph, not explained in the text following, can be answered by reference to section L-12.

H29 was very close to a working stope, but no other hole in service was nearer than 50 ft. This is especially interesting when the relative counts for p.m. and a.m. times each day are considered. On the 3825-ft. level, the p.m. counts (right after blasting, which occurs from 2^h to 3^h p.m. for these levels) are higher as a rule than the a.m. counts for the same day. All the high peaks are p.m. But on the 3950-ft. level (H31) the reverse is the case. All a.m. peaks are higher than those for the corresponding p.m. times.

It is likely that the counts on H29 are unduly affected by mining operations, as this hole was less than 25 ft. from a working stope that was close to breaking through to the 3825-ft. level from below.

It is interesting to trace a curve through the a.m. points and another through the p.m. points for H31. Each rises towards the date of the burst (January 29). On the other hand, those for H29 consistently flatten out towards that date.

Neither the large counts (lowest of the graph lines) nor the medium ones are very informative. The small are the best of the three, but there seems no valid reason, in the light of these graphs, for counting anything but the totals. The large and medium snaps should be noted for coincidences, but to count them separately seems a waste of time. Note the importance of recording small snaps.

It is evident that a count of 100 snaps per minute indicates a dangerous condition; but, in this all-too-short set of data, there are three peaks of nearly or greater than 100 without a burst. It is also to be regretted that the record for H29 and H31 for January 28-29 was lost with the recorder and cannot now be recovered.

The sharpness of the peaks is remarkable. If pressures build up and fall at this rate, it is evidently necessary to record 24 hours a day, or at least for short periods at close intervals for a full day, so that the records do not stop 8-10 hours before a burst.

The fact that the peaks for H29 do not coincide with those for H31, though the holes are only about 250 ft. apart, shows clearly that critical pressure is quite local and that the record reflects conditions within only a short distance, probably 50-100 ft., from the geophone. All seven geophones were in service and were distributed as evenly as possible over the suspect section of the pillar. It was fortunate that the earlier attempts to obtain crystals and transformers had been made, for these arrived only just in time to permit the construction of new geophones after all those on hand had been lost in the burst.

The 100-ft. hole (H25) is not much more informative than the adjacent 30-ft. hole (H28). It is most unfortunate that, at the time when the comparison would have been most valuable, January 15-18, no records were obtained from H28, owing to the fact that the time-switch on 3801W-9 was giving trouble.

From a consideration of the Kirkland Lake record (Figure 52) and the graphs of Figure 59, it seems evident that the first (smaller) burst of January 29 occurred on the 3950 or the 3825-ft. level, or both, and that this initial burst allowed pressure to fall on 4200, raising it above the critical point and resulting in the general burst. During the fall of 1942, the conditions on 4200 had several times been considered critical, while the upper levels (3825 and 3950) were quiet. When, in January, the upper levels became critical, the counts on the lower levels fell, owing, no doubt, to the temporary relief afforded by the pressure taking up on the higher levels.

Evidently, in an extensive pillar such as this, it is necessary to have long-term observations over as much of the pillar as possible. If pressure gradually passes from point A to appear at B, some distance above or below, the load is still poised with respect to A, and a burst at B will probably result in another at A.

L-8 Deductions and Recommendations

It becomes increasingly evident that critical pressures are very limited in extent, that they build up and decrease quite rapidly, and that geophones indicate the conditions as critical only when within about 50 ft. Moreover, long-term, wide-area observations must be made to learn what points lying within 500 ft. or so of a region at the time critical have been under severe pressure some weeks or months previously with no relief from a burst. Recording should evidently be done continuously or at frequent intervals throughout the 24 hours, so that the entire diurnal variation in activity may be known. Many holes must be used, serviced first by an intensive listening program to locate critical regions and then covered by a close network of geophones and recorders. The recorders must, as far as possible, be kept well in the fill, and it must be possible to instal them in any of the drifts under observation. Geophones are almost certain to be lost in a burst.

It was therefore recommended that:

(a) At least 100 crystals and 50 transformers be ordered, and that the necessary casings should be made in preparation for a time when many geophones will be simultaneously required.

(b) Holes 30 ft. deep be drilled as soon as possible at regular intervals of about 100 ft. in the hangingwall in each drift to be studied. This, at the moment, indicated the west pillar on the 3200 level and in both drifts on the east side from the 4700 level up or down as far as critical conditons were suspected.

(c) One geophone be placed in the hole nearest the centre of the pillar on each drift to be studied, and left there for the use of the listening program, to give one control point in each drift at which irregularities due to a different placing of a portable geophone could receive some check. These geophones should be included in the regular underground testing program.

(d) A regular daily listening program be begun at once, using the light-weight portable outfit under construction. At least three levels should be completely covered every day. Three or four minutes listening at each hole would suffice for this reconnaissance survey. The readings should be tabulated and plotted each day.

(e) Two portable instrument boxes of wood be designed and built on surface. These should be designed to house the three units of an Obert set with all normal auxiliary equipment. They should be wired for lights and outlets and have an external socket into which the AC supply could be plugged. The boxes should have hinged covers, to give ready access to the recorders and provide a bench top for working.

(f) In each level to be studied, an observing site be selected well within the fill section and on the side of the pillar towards the cross-cut, preferably against the footwall. At each site, a pair of L-shaped supports made of pipe should be set, with one end of each in a hole in the wall and the other firmly placed on the floor of the drift. These would provide a support for the portable instrument box. Above each site, heavy new lagging or timbering should be placed to enable the operators to work without hats in front of the instruments. To each site an AC supply be wired, terminating in a plug for connecting to the instrument box.

(g) For the time being, the set-ups on 3200W, 4201W, and 4700E be the only ones to be operated regularly and that until better arrangements can be made the records be run every alternate 15 min. throughout the 24 hours if this can be done without injuring the recorders.

(h) As soon as the listening program discloses a critical region, the portable instrument box be taken at once to the drift concerned and at least two geophones be connected to record every alternate 15 min. for the 24 hours.

(i) Time switches be made to enable four geophones to record, two and two, for alternate 15 min. on each new Obert unit.

(j) Large-scale elevations of each drift on the east side, similar to the one made for the west pillar, be made for the use of the survey.

(k) For all recording, the counts should be restricted to totals only and the coincidences noted only in the large and small categories. All records should be carefully studied, counted, tabulated, plotted, and booked each day as received. Routine testing of all equipment, including the control geohpones, should be carried forward on a regular program.

(l) Some means be found for implementing recommendation of section K-5(p). It is obvious that the progress of mining has a distinct bearing on the building up and movements of critical pressures. Some simple arrangement should be made whereby the survey engineers can, as a matter of routine, note the mining that has gone on each day in the section under survey and plot the information on the record graphs.

L-9 Instrument Development

After a year's experience with subaudible vibration recording instruments at Lake Shore Mines, it seemed worth while to describe some of the work done in servicing and repairing these intsruments and in manufacturing associated parts and apparatus.

Geophones were first constructed after the Obert pattern, using brass pipe for cases and brass for crystal mounting tables. Originally, a transformer was placed at the collar of each drill-hole used, to properly couple the high-impedance rochelle salt crystal into the low-impedance transmission line to the recorder. Later, small coupling transformers were installed within the geophone cases themselves. The cases were made originally with a packing gland, to pass shielded cable into the case and maintain a water-tight joint, but this system was abandoned later. An amphenol connector was mounted on the geophone case.

In the first geophones constructed, the rochelle salt crystal was mounted by wedging it with mica into a slot cut in a brass post. It was then firmly cemented in place with Duco cement. Later, instead of the mica wedges, a larger slot was cut in the support post, and a brass plate clamped against the crystal with small machine screws.

In a new type of mounting devised by Obert,a small steel plate was clamped across the end of the crystal, making a much simpler and more rugged support than any that had been used before; this mount was used in the geophones received in March 1943.

Originally, geophones were loaded into holes with an unwieldy, plumber's 'snake'. This is still used for deep holes, but for holes up to 30 ft. in depth a special set of loading poles was developed, made of 6-ft. lengths of 3/8-inch iron pipe, one of which, to be used next the geophone, has welded on a short length of one-inch pipe with a slot for the geophone cable. The sections are provided with a special coupling device by means of which a sufficient number may be coupled together to set the geophone at the desired depth. By pushing with the poles and pulling with the cable, the geophone may be adjusted until it is certain that contact with the floor of the hole is good.

It was evident early in the program that some means must be devised for turning the recorders on and off. Consequently, Telechron 'Organizer' clocks, used in controlling home radios in accordance with a pre-arranged schedule, were first tried. As they automatically cleared themselves after a program was finished, changes had to be made in the internal construction in order that they would repeat, every twelve hours, whatever schedule had been set up. These clocks gave good service; their chief drawback was that the operation of the switch might vary by about a minute, more or less, at different settings, making it difficult to correlate records made at different locations in the mine. (It was later found that the larger snaps, recorded by all sets, made it possible to correlete even widely separated recording outfits.)

To enable recorders to cover more than a single hole, it was decided to make up switches that would, at regular intervals, connect to an amplifier either one of two geophones. Double-pole, double-throw switches of a toggle type, actuated by a synchronous clock mechanism, were constructed. Telechron clocks were again used, the face and hands being removed and a special spindle driven by the minute hand gear supporting a crank arm connected to the switch mechanism, which was thrown each half hour.

It was soon realized that some method of identifying which of the two geophones was connected at a given instant must be worked out. An extra pair of contacts was therefore placed on each switch so that, when one pair of contacts was closed, an auxiliary circuit caused an extra writing stylus to make a continuous line on the edge of the record, as long as that particular geophone was connected. These clock switches were not too satisfactory, owing to the fact that while the toggle action was fast, the clock motion was slow, resulting in an interval during which the contact pressure was lightened, allowing stray disturbing voltages to be impressed on the connecting cables. Plans were therefore made to change to microswitches, which had been in short supply.

Some means of easily changing from geophone to geophone while listening to the rock noises was needed. To do this, a switch-in device (LSM-13) was constructed. It consisted of two double-contact switches arranged to connect any one of six geophones to either of the two amplifier channels that comprised LSM-11. This made it possible to listen to a geophone with one ear while the other listened to one some distance away. In this manner, holes could be quickly compared for activity and simultaneity.

Simultaneous comparison of two recorders was achieved by a device that splits the signal from one geophone and supplies it to the input circuits of the two amplifiers to be compared; this amounts to connecting the input transformers in parallel. The loss of sensitivity occasioned by this parallel connection proved negligible. While originally intended for testing with a geophone under actual recording conditions, the input comparator proved invaluable in laboratory testing. A test impulse oscillator is connected through the input comparator to the recorder under test and at the same time to a recorder known to be properly adjusted. Examination of the two records obtained gives a check, not only of the amplifier and recorder, but also of the validity of the output of the test impulse oscillator while the test is being made.

High-grade vacuum-tube smplifiers for listening to subaudible vibrations in rock must have high amplification and stability, and must be readily portable: low battery drain is also desirable. It was decided, after a number of experiments, to construct an amplifier with four 6.3-volt tubes that would utilize the regular storage batteries used for miners' lamps. Such an instrument would weigh about 10 1/2 pounds, and could be readily carried in a haversack. All the operator would have to do would be to insert a geophone in each hole as he reached it.

A program such as that being carried on at Lake Shore depends largely on the comparison of results recorded by instruments of the same type located at various points. It was therefore essential to have some means whereby it could be ensured that the various instruments were identical in their responses, and would remain so over long periods. This was achieved by means of a test impulse oscillator built from a design furnished by Dr. Obert, which was designated LSM-14. It operates by applying a pulse of fixed length and amplitude to the input terminals of a recorder amplifier by depressing a switch. Once the instrument is adjusted to give the most suitable pulse length and amplitude, with a fixed frequency, all subsequent standardizing tests are made with the same settings of the controls. As the cycle is controlled by the circuit characteristics, once the switch is depressed there is no question of the personal equation affecting the test. The instrument is easily portable, and the various recording instruments can therefore be readily checked in situ.

The test impulse oscillator, while affording an excellent means of checking the amplifier-recorder combination, gives no check of the geophone itself. As the geophone is the source of the electrical impulses that are the basis of the recorded observations, it was of first importance that its responses should be uniform. A shaking table, vibrating in response to energy supplied by a master oscillator, was therefore built. A geophone placed on this table drives its own voltage amplifier, to which a vacuum tube voltmeter is attached; this provides a means of comparing the results of changes of frequency of amplitude.

The method described in the preceding paragraph is, of course, impracticable underground. It was therefore decided to investigate the possibility of devising an instrument for underground use that would make use of the fact that if a capacity is connected to one pair of terminals of an ideal transformer, the other pair exhibits a capacitive reactance that is a function of the original capacity and the impedance ratio of the transformer. Tests were therefore made of the capacitive reactance of the low-impedance side of the geophone transformers, the high-impedance sides being conencted to the rochelle salt crystals. By this means it was determnied that geophones in good condition gave capacitance values of 1.4 to 3.4 microfarads, whereas defective ones gave values in excess of 70 microfarads. The measurement of capacity of each geophone and connecting cable is measured immediately after installation, and entered along with data determined from the laboratory test. Capacity measurements are then made weekly at the same time as the routine tests of recorders, and will indicate gradual or complete failure of the crystal.

For an over-all test of each geophone and its amplifier-recorder, a set of tappers was installed in the vicintiy of each installation. These consist of a steel pendulum that may be swung against the end of a steel rod set in the rock by means of a motor-driven cam. While this test will not give comparable records, in view of the different ground conditions, the records for a given installation should be identical unless some change has occurred in the system.

Shortly after the recorders were installed, trouble was experienced with the writer coils, which burnt out in a very short time. It was found that the moist, acid mine air caused electrolytic corrosion, and installation of a 50-watt electric lamp in the recorder boxes remedied the situation. Later, coils were wound on bakelite forms and impregnated with moisture-proof wax, as an added precaution.

Trouble was also experienced with charring, and occasionally burning, of the paper rolls. This was finally traced to misalinement, apparently caused by rough handling during shipping, which resulted in faulty contact with the platen. As the recording in this type of machine is electrical, the poor contact caused arcing at the recorder stylus. All machines were adjusted to give perfect alinement, and no further difficulty from this cause was experienced.

As underground line voltage seldom exceeds 90 volts, which is not satisfactory for operating electronic instruments, transformers were installed at each recording station to raise the voltage to approximately 110 volts, at which point fluctuations could be remedied by the automatic regulation device incorporated in the amplifier.

At some high-gain adjustments, the writer styli were found to oscillate wildly without any impulse from the geophone. The cause was discovered to be small changes of current occurring at the writing point, causing large voltage changes at the point where the current was taken from the power supply. Filter sections between this point and the plate circuit of the first high-gain amplifier tube eliminated most of the trouble, which was finally cured by applying a by-pass condenser directly between the supply point and ground, across the current-limiting resistors and writer point; by this means, also, much higher amplifications were made possible.

L-10 Test Holes Used, January to March, 1943

The only test holes used for recording purposes in the rockburst research program during the period January-March 1943 were: Nos. 24, 25, 27, 28, 29, 31, 32, and 33. These are located on the plan and elevation diagrams of Figure 62. Plans and elevations have each a vertical scale indicated by the 125-ft. difference between the levels. The section lines are 100 ft. apart. In the projection of the plans, the oblique lines run down and to the left (south) and up and to the right (north), the scale division, both east-west and north-south, being 50 ft.

L-11 Dates of Recording from Test Holes

Records from the holes noted in the preceding section were made on the dates indicated in the tabulation below. The solid vertical rulings show week-ends.

January

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24			
25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25			
27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27			
28	28	28	28	28	28	28	29	28	28	28	28	28	28	29	29	28	28	28	28	28	28	28	28	28	28	28	28			
29	29	29	29	29				29	29	29	29	29	29	31	31	31	29	29	29	29	29	29	29	29	29	29	29			
										31		31	31				31	31	31	31	31	31	31	31	31	31	31			

February

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
												32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32

March

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
32	31	32	31	32	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	31	32
	32		32	33	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	32	
			33		33	33	33	33	33	33	33	33	33	33	33	33	33	33	33	33	33	33	33	33	33	33	33	33	33	

Drillers' reports for holes from H1 to H30 inclusive were given in section K-6. The reports for H31, H32, and H33, used in the above program, will appear in section M-2. The limited recording of February and March was due to the loss of geophones in the burst of January 29.

L-12 Record Analysis for H29 and H31, January-March 1943

It seems sufficient in this publication to give the analysis for H29 and H31 only, as these were the only holes from which informative data were obtained. They operated until January 28 only, the recorder, together with its records for January 29, being lost in the rockburst.

In the following tabulation, the successive headings have the following signification:

Rec	=	record number.
Fr	=	from (date of).
To	=	to (date of.)
Epoch	=	the instant, in Eastern War Time, beginning at midnight on the 24-hr. system, about which the averaging interval was taken. In the case of a two-day record, an underline indicates the interval as being in the second part of the record. As the records are changed about 7:30 a.m., the first instant given on any day is in p.m. time.
AP	=	the averaging period, i.e. the number of minutes over which the counts were made and averaged.
L,M,S,T,	=	the average s.p.m. of, respectively, the large, medium and small snaps; and the total value of all three categories added, only the counts for the fast stylus having been considered.
N	=	the serial number of the comparator sheet (inserted in the original report for the use of the operators and clerical staff).
Con-Rec	=	concurrent records read for coincidences with the record being tabulated.
Co'ce	=	coincidences between records. The first entry shows the number of coincidences between the record being tabulated and the first concurrent record for the entire averaging period; the second shows the number of coincidences between the record being tabulated and the second concurrent record for the same period (unless the notes indicate otherwise at any point).
Notes	=	index letters for the series of notes immediately following the tabulation.

Throughout the entire period covered by the analysis, the recorder used for both holes was 111, which was run at 7 Db. The geophone used in H29 was G5; that used in H31 being G1. The holes are, respectively, on the 3825 level and the 3950 level, as shown in Figure 61. The drillers' reports for the holes were given in section K-6.

Rec	Fr Ja	To Ja	Epoch	AP	L	M	S	T	N	Con-Rec		Co'ce		Notes
362	2	4	16:20	–	–	–	–	–	1	H26	H25	–	–	A
362	2	4	16:48	–	–	–	–	–	2	H24	H28	–	–	A
362	2	4	18:22	–	–	–	–	–	3	H26	H25	–	–	A
362	2	4	18:48	–	–	–	–	–	4	H24	H28	–	–	A
362	2	4	4:20	–	–	–	–	–	–	H26	H25	–	–	A
362	2	4	4:52	–	–	–	–	–	5	H24	H28	–	–	A
362	2	4	6:22	–	–	–	–	–	6	H26	H25	–	–	A
362	2	4	6:48	–	–	–	–	–	7	H24	H28	–	–	A
362	2	4	16:20	–	–	–	–	–	8	H26	H25	–	–	A
362	2	4	16:46	–	–	–	–	–	9	H24	H29	–	–	A
362	2	4	18:18	–	–	–	–	–	10	H26	H25	–	–	A
362	2	4	18:48	–	–	–	–	–	11	H24	H28	–	–	A
362	2	4	4:17	–	–	–	–	–	12	H26	H25	–	–	A
362	2	4	4:47	–	–	–	–	–	13	H24	H28	–	–	A
362	2	4	6:20	–	–	–	–	–	14	H26	H25	–	–	A
362	2	4	6:48	–	–	–	–	–	15	H24	H28	–	–	A
365	4	5	16:18	–	–	–	–	–	16	H27	H25	–	–	B
365	4	5	16:48	–	–	–	–	–	17	H24	H28	–	–	B
365	4	5	18:18	–	–	–	–	–	18	H27	H25	–	–	B
365	4	5	18:46	–	–	–	–	–	19	H24	H28	–	–	B

Rec	Fr	To	Epoch	AP	L	M	S	T	N	Con-Rec		Co'ce		Notes
365	4	5	4:10	-	-	-	-	-	20	H27	H25	-	-	B
365	4	5	4:44	-	-	-	-	-	21	H24	H28	-	-	B
365	4	5	6:10	-	-	-	-	-	22	H27	H25	-	-	B
365	4	5	6:42	-	-	-	-	-	23	H24	H28	-	-	B
368	5	6	16:14	16	1.2	13.8	48.5	63.4	24	H27	H25	1	1	C
368	5	6	16:46	16	.6	4.5	19.4	24.5	25	H24	H28	3	3	C
368	5	6	18:16	16	.8	3.6	12.5	16.9	26	H27	H25	5	5	
368	5	6	18:46	16	.6	3.1	12.9	16.6	27	H24	H28	2	2	
368	5	6	4:20	16	.9	5.9	29.8	36.6	28	H27	H25	5	5	
368	5	6	4:44	16	.3	1.4	10.4	12.2	29	H24	H28	8	8	
368	5	6	6:10	16	1.9	7.4	21.4	30.7	30	H27	H25	10	10	
368	5	6	6:48	16	.3	1.5	7.6	9.3	31	H24	H28	4	4	
371	6	7	16:18	16	0.0	.1	3.6	3.6	32	H27	H25	-	-	D,E,
371	6	7	16:46	-	-	-	-	-	33	H24	H28	-	-	D,E,F,
371	6	7	17:14	16	0.0	0.0	2.0	2.0	34	H27	H25	-	-	D,E
371	6	7	17:46	16	0.0	0.0	1.2	1.2	35	H24	H28	-	-	D,E
371	6	7	18:14	16	0.0	0.0	1.8	1.8	36	H27	H25	-	-	D,E
371	6	7	18:46	16	0.0	.2	3.7	3.9	37	H24	H28	-	-	D,E
371	6	7	4:14	16	.2	2.3	65.7	68.1	38	H27	H25	-	-	D,E,G
371	6	7	4:48	15	.6	3.7	17.1	21.4	39	H24	H28	-	-	D,E,H
371	6	7	5:14	16	0.0	0.0	.7	.7	40	H27	H25	-	-	D,E
371	6	7	5:46	16	0.0	0.0	.5	.5	41	H24	H28	-	-	D,E

Rec	Fr	To	Epoch	AP	L	M	S	T	N	Con-Rec		Co'ce		Notes
371	6	7	6:14	16	0.0	0.0	.8	.8	42	H27	H29	-	-	D,E
371	6	7	6:40	16	0.0	0.0	.9	.9	43	H24	H28	-	-	D,E
376	8	9	16:16	16	.9	4.8	18.8	24.5	56	H25	H28	7	7	I
376	8	9	16:44	16	.6	3.2	12.8	16.6	57	H24	H28	9	9	
376	8	9	17:12	16	.5	2.8	9.9	13.2	58	H25	H28	6	6	
376	8	9	17:40	16	.6	1.9	10.9	13.4	59	H24	H28	4	5	
376	8	9	18:10	16	.4	2.7	10.2	13.3	60	H25	H28	9	9	
376	8	9	18:40	16	.7	2.3	9.9	12.8	61	H24	H28	6	7	
376	8	9	4:16	16	.8	1.9	10.0	12.7	62	H25	H28	3	3	
376	8	9	4:46	16	.9	1.5	10.9	13.4	63	H24	H28	4	4	
376	8	9	5:12	16	.8	2.7	9.6	13.1	64	H25	H28	5	5	
376	8	9	5:44	16	.7	1.7	10.1	12.4	65	H24	H28	3	4	
376	8	9	6:18	16	1.4	1.4	10.0	12.8	66	H25	H28	10	10	
376	8	9	6:48	16	.5	1.7	8.5	10.7	67	H24	H28	7	9	J
379	9	11	16:13	16	5.8	22.4	49.1	77.2	68	H27	H25	16	-	K
379	9	11	16:39	16	4.3	20.7	35.4	60.3	69	H24	H28	3	-	K
379	9	11	17:09	16	4.6	15.9	40.1	60.6	70	H27	H25	8	-	K
379	9	11	17:41	16	3.3	13.8	38.1	55.1	71	H24	H28	10	-	K
379	9	11	18:09	16	3.8	10.5	36.1	50.3	72	H27	H25	9	-	K
379	9	11	18:49	16	2.6	10.4	38.7	51.6	73	H24	H28	6	-	K
379	9	11	4:08	16	2.4	6.1	19.8	28.3	74	H27	H25	4	-	K

Rec	Fr	To	Epoch	AP	L	M	S	T	N	Con-Rec		Co'ce		Notes
	Ja	Ja												
379	9	11	4:42	16	2.1	6.6	18.6	27.3	75	H24	H28	6	-	K
379	9	11	5:08	16	2.1	6.6	17.8	26.5	76	H27	H25	12	-	K
379	9	11	5:46	16	2.8	5.6	19.9	28.3	77	H24	H28	5	-	K
379	9	11	6:16	16	2.4	6.4	18.7	27.5	78	H27	H25	6	-	K
379	9	11	6:42	16	3.7	5.0	16.6	25.3	79	H24	H28	9	-	K
379	9	11	16:09	16	2.1	5.5	12.0	19.6	80	H27	H25	1	-	K
379	9	11	16:41	16	1.6	4.3	8.6	14.4	81	H24	H28	1	-	K
379	9	11	17:16	16	2.6	4.3	13.7	20.6	82	H27	H25	6	-	K
379	9	11	17:40	16	2.1	3.8	12.6	18.4	83	H24	H28	3	-	K
379	9	11	18:10	16	1.4	4.1	15.4	20.9	84	H27	H25	11	-	K
379	9	11	18:40	16	2.2	3.7	9.8	15.7	85	H24	H28	6	-	K
379	9	11	4:10	16	1.4	5.1	14.1	20.6	86	H27	H25	2	-	K
379	9	11	4:48	16	1.6	4.8	9.8	16.2	87	H24	H28	7	-	K
379	9	11	5:10	16	.6	3.1	13.1	16.7	88	H27	H25	5	-	K
379	9	11	5:46	16	1.6	3.9	11.8	17.3	89	H24	H28	2	-	K,L
379	9	11	6:14	16	1.1	3.4	11.9	16.4	90	H27	H25	3	-	K
379	9	11	6:46	16	2.0	2.9	11.4	16.2	91	H24	H28	1	-	K
382	11	12	16:41	16	4.6	9.0	34.1	47.7	93	H24	H28	5	5	
382	11	12	17:41	16	2.8	8.5	24.8	36.1	95	H24	H28	3	3	
382	11	12	18:41	16	2.6	6.7	21.2	30.4	97	H24	H28	5	5	

Rec	Fr	To	Epoch	AP	L	M	S	T	N	Con-Rec		Co'ce		Notes
382	11	12	4:42	16	3.7	5.7	13.9	23.3	99	H24	H28	6	8	
382	11	12	5:44	16	3.1	3.6	12.1	18.7	101	H24	H28	10	11	
382	11	12	6:42	-	-	-	-	-	103	H24	H28	-	-	M
383	12	13	16:15	28	9.2	12.6	10.9	32.7	104- 5	H24	H28	11	13	N,O
383	12	13	16:45	29	6.1	7.2	14.4	27.6	106- 7	H27	H25	18	18	P
383	12	13	17:15	29	4.4	4.7	12.0	21.1	108- 9	H24	H28	7	8	P
383	12	13	17:45	29	4.1	5.9	10.8	20.8	110-11	H27	H25	9	10	P
383	12	13	18:15	29	4.7	7.0	14.5	26.1	112-13	H24	H28	4	4	P,Q
383	12	13	18:45	-	-	-	-	-	114-15	H27	H25	2	4	P,R
383	12	13	4:15	28	3.2	4.6	11.6	19.4	116-17	H24	H28	2	3	S
383	12	13	4:44	28	2.4	4.5	11.3	18.2	118-19	H27	H25	1	1	T
383	12	13	5:16	-	-	-	-	-	120-21	H24	H28	1	1	U
383	12	13	5:44	-	-	-	-	-	122-23	H27	H25	-	-	U
383	12	13	6:15	-	-	-	-	-	124-25	H24	H28	-	-	U
386	13	14	16:15	24	5.9	7.9	11.9	25.7	128-29	H24	H28	3	4	V
386	13	14	17:17	24	5.1	8.6	11.3	25.1	132-33	H24	H28	4	6	V
386	13	14	18:18	26	4.1	7.9	10.9	22.9	136-37	H24	H28	9	10	W
386	13	14	4:12	10	2.0	23.0	33.7	58.7	140	H24	H28	5	0	V,X
386	13	14	5:08	10	2.2	18.3	33.1	53.6	142	H24	H28	0	0	V
386	13	14	6:16	10	2.6	16.9	26.3	45.8	144	H24	H28	0	0	V
389	14	15	16:09	16	3.5	12.9	23.6	40.0	146	H24	H28	3	5	
389	14	15	17:17	16	4.1	13.0	22.1	39.2	148	H24	H28	4	4	

Rec	Fr.	To	Epoch	AP	L	M	S	T	N	Con-Rec		Co'ce		Notes
389	14	15	18:11	16	4.9	15.9	23.9	44.8	150	H24	H28	5	5	
389	14	15	4:10	16	4.6	23.6	34.9	63.2	152	H24	H28	4	4	
389	14	15	5:24	14	1.9	20.9	33.8	56.6	154	H24	H28	4	4	
389	14	15	6:12	16	2.8	13.0	27.4	43.3	156	H24	H28	5	5	
392	15	16	16:12	16	6.8	16.9	18.0	41.6	158	H24	H25	6	7	V
392	15	16	17:12	16	4.3	10.3	17.0	31.6	160	H24	H25	3	3	
392	15	16	18:18	16	6.1	12.6	19.4	38.1	162	H24	H25	7	7	Z
392	15	16	4:12	16	3.1	10.1	26.4	39.6	164	H24	H25	8	10	A'
392	15	16	5:18	16	2.5	9.6	16.4	28.4	166	H24	H25	3	4	
392	15	16	6:12	16	2.1	7.6	14.5	24.2	168	H24	H25	14	14	
395	16	18	16:12	2	8.0	65.0	100.0	173.0	170	H24	H25	6	6	B'
395	16	18	17:11	16	4.8	26.9	38.7	70.4	172	H24	H25	8	8	
395	16	18	18:17	16	3.9	15.1	31.8	50.7	174	H24	H25	7	9	
395	16	18	4:18	16	3.4	7.8	21.3	32.4	176	H24	H25	11	11	
395	16	18	5:12	16	2.8	8.3	22.4	33.5	178	H24	H25	7	7	
395	16	18	6:20	16	2.4	6.6	21.3	30.2	180	H24	H25	6	6	
395	16	18	16:25	16	1.9	4.8	13.9	20.6	182	H24	H25	2	2	
395	16	18	17:16	16	1.8	6.3	15.8	23.8	184	H24	H25	1	1	
395	16	18	18:18	16	2.1	6.9	18.4	27.4	186	H24	H25	2	3	
395	16	18	4:14	16	1.4	4.8	17.1	23.3	188	H24	H25	3	3	
395	16	18	5:12	16	.9	6.4	15.3	22.7	190	H24	H25	0	0	

Rec	Fr Ja	To Ja	Epoch	AP	L	M	S	T	N	Con-Rec		Co'ce		Notes
395	16	18	6:14	16	.8	4.3	20.0	25.1	192	H24	H25	4	4	
398	18	19	16:13	16	6.4	22.3	40.3	68.9	194	H24	H28	3	3	C'
398	18	19	17:19	16	4.0	10.6	28.8	43.3	196	H24	H28	6	6	
398	18	19	18:16	16	3.3	9.8	28.8	41.9	198	H24	H28	1	1	
398	18	19	4:14	16	1.6	7.6	17.6	26.8	200	H24	H28	0	1	
398	18	19	5:14	16	1.9	6.0	12.9	20.7	202	H24	H28	0	0	
398	18	19	6:24	12	2.1	6.5	15.8	24.4	204	H24	H28	2	2	
401	19	20	16:13	16	2.3	8.0	14.6	24.9	206	H24	H28	11	14	
401	19	20	17:11	16	3.3	5.9	14.3	23.5	208	H24	H28	8	10	
401	19	20	18:13	16	2.5	6.0	17.8	26.1	210	H24	H28	5	5	
401	19	20	4:16	16	2.1	6.2	13.1	21.3	212	H24	H28	4	4	D'
401	19	20	5:14	16	1.7	6.4	14.9	23.1	214	H24	H28	1	0	
401	19	20	6:12	16	1.4	6.7	12.2	20.3	216	H24	H28	4	5	
404	20	21	16:17	16	1.0	1.6	3.2	5.8	218	H24	H28	13	13	E'
404	20	21	17:15	16	1.8	6.1	13.9	27.7	220	H24	H28	11	13	
404	20	21	18:15	16	1.5	5.9	17.7	25.1	222	H24	H28	8	11	
404	20	21	4:18	16	1.8	5.7	18.4	25.9	224	H24	H28	5	7	
404	20	21	5:12	16	2.1	5.3	15.0	22.3	226	H24	H28	2	3	
404	20	21	6:14	16	2.3	4.9	14.3	21.4	228	H24	H28	2	2	
407	21	22	16:15	16	2.8	45.1	65.8	113.7	230	H24	H28	4	4	
407	21	22	17:21	16	1.3	10.5	36.2	48.0	232	H24	H28	5	6	

Rec	Fr	To	Epoch	AP	L	M	S	T	N	Con-Rec		Co'ce		Notes
407	21	22	18:15	16	1.9	6.6	32.6	41.1	234	H24	H28	4	5	
407	21	22	4:16	16	3.8	8.3	21.2	33.2	236	H24	H28	7	9	F'
407	21	22	5:14	16	3.6	6.6	19.9	30.2	238	H24	H28	9	13	G'
407	21	22	6:14	16	2.4	5.0	15.5	22.9	240	H24	H28	4	4	
410	22	23	16:21	16	1.1	7.2	38.8	47.1	242	H24	H28	2	2	
410	22	23	17:17	16	1.1	5.2	29.2	35.5	244	H24	H28	1	4	
410	22	23	18:17	16	1.1	3.3	23.8	28.2	246	H24	H28	3	4	
410	22	23	4:15	16	2.2	4.8	24.1	31.1	248	H24	H28	1	1	
410	22	23	5:15	16	2.1	4.1	19.4	25.5	250	H24	H28	3	3	
410	22	23	6:15	16	2.8	4.8	18.0	25.6	252	H24	H28	6	6	
413	23	25	16:15	16	1.6	5.1	23.1	29.7	254	H24	H28	1	1	
413	23	25	17:15	16	1.1	4.4	16.5	21.9	256	H24	H28	3	4	
413	23	25	18:15	16	1.4	4.3	16.9	21.6	258	H24	H28	1	2	H'
413	23	25	4:17	16	3.8	5.2	13.4	22.4	260	H24	H28	2	5	
413	23	25	5:19	16	2.7	4.9	13.5	21.1	262	H24	H28	5	5	
413	23	25	6:17	16	2.9	4.6	11.6	19.0	264	H24	H28	8	8	
413	23	25	16:17	16	1.4	3.4	9.5	14.4	266	H24	H28	2	3	
413	23	25	17:17	16	1.1	4.3	11.3	16.7	268	H24	H28	3	4	
413	23	25	18:19	16	1.8	3.8	11.3	16.9	270	H24	H28	8	11	
413	23	25	4:19	16	1.0	3.6	9.8	14.4	272	H24	H28	1	1	
413	23	25	5:21	16	1.1	3.7	10.0	14.8	274	H24	H28	3	3	

Rec	Fr	To	Epoch	AP	L	M	S	T	N	Con-Rec		Co'ce		Notes
413	23	25	6:21	16	1.0	3.9	9.9	14.8	276	H24	H28	3	3	
416	25	26	16:19	16	1.6	3.4	10.4	15.4	278	H24	H28	4	4	
416	25	26	17:23	16	2.0	4.8	11.4	18.2	280	H24	H28	2	2	I'
416	25	26	18:17	16	1.1	2.9	9.0	13.1	282	H24	H28	3	4	
416	25	26	4:17	16	.6	2.8	8.8	12.1	284	H24	H28	2	3	
416	25	26	5:17	16	.8	2.5	8.9	12.1	286	H24	H28	2	3	
416	25	26	6:17	16	1.1	3.6	19.4	24.2	288	H24	H28	4	5	
419	26	27	16:21	16	.6	2.9	15.3	18.8	290	H24	H28	4	4	J'
419	26	27	17:17	16	.9	2.8	10.1	13.8	292	H24	H28	3	3	
419	26	27	18:17	16	.8	2.3	10.1	13.1	294	H24	H28	4	5	
419	26	27	4:21	16	.4	2.7	19.9	22.9	296	H24	H28	1	1	
419	26	27	5:17	16	.8	2.3	10.6	13.7	298	H24	H28	3	5	
419	26	27	6:23	16	.8	2.0	10.0	12.8	300	H24	H28	0	0	
422	27	28	16:17	16	3.4	5.5	12.1	21.0	302	H24	H28	26	45	
422	27	28	17:17	16	1.7	4.1	8.6	14.4	304	H24	H28	0	0	
422	27	28	18:17	16	1.6	3.6	11.1	16.4	306	H24	H28	5	6	
422	27	28	4:17	16	1.0	2.8	12.5	16.3	308	H24	H28	0	3	
422	27	28	5:17	16	.7	3.1	9.0	12.8	310	H24	H28	6	7	
422	27	28	6:21	16	1.9	4.7	12.1	18.7	312	H24	H28	9	9	

The burst of January 29 occurred at 2:12 a.m., $19^h\ 12^m$ after the record No. 422 was completed at 7 a.m., January 28.

A. Entire record was useless, owing to open circuit.
B. Entire record was useless, owing to open circuit.
C. Coincidences between record 368 (H29) and the other concurrent holes 367(H27) and 366(H29) are difficult to determine, owing to extremely active conditions on 3801W-9.
D. A most peculiar record (Jan. 6); almost quiescent except for salvoes of short duration —about a minute. On January 8 we found bad contacts in an amphenol coupling. No listening was done on 3801W-9 on Jan. 6. Geophone was reset Jan. 5, being inserted only about 12 ft. Stylus voltage too high throughout the record.
E. New schedule begun, 4^h–7^h a.m., and p.m., alternating holes every half hour.
F. Omitting salvoes, the count was only about .6 s.p.m., which is of so little value that it is not tabulated.
G. Beginning at 4 a.m. January 7, the character of the record changed to almost continuous small offsets. They are not 'static' and seem real. They follow blasting.
H. A heavy salvo omitted from the count. Snaps very numerous of this record 371(H29).
I. The geophone was reset to a full depth of 30 ft. Record 371(H29) for January 6-7 was poor, largely because of poor contacts at the amphenol coupling. The hole was reamed on January 7, to permit the geophone to be reset to its full depth.
J. Voltage too high on stylus. Centre broken towards the end of the record.
K. Record 377(H28, H25), for January 9-11 is useless, owing to mistake in setting attenuator after modifications to the recorder.
L. Stylus voltage too high towards the end of the record.
M. Record 382(H29) having time-switch trouble this part of the run.
N. The first section of this record completely analysed into 9 classes.
O. Salvoes of small intensity merged in the records appear on page 38302. One of these was disregarded in the count.
P. Coincidences checked out by E.A.H. from record books, as there had been an error in comparing records.
Q. Short salvo at 6:03 p.m. January 12. See page 38313A*.
R. Record 383(H29) turned off at 6:45 p.m. January 12 by accidental change in setting of the program clock.
S. Record fails to show traces of the salvoes shown on record 385(H24) and 384(H28)
T. See note U for H25. (omitted in this publication).
U. Record ran only 14 min. when it was turned off by accidental change in setting the program clock. The coincidences with 385(H24) and 384(H28) are thus for 15 min. only. From 5:15 a.m. January 13 to the end of the run the coincidences are all out and the counts for the two geophones are mixed. They are therefore omitted. They could be deduced for 14 min. intervals if care were taken, as some coincidences do exist to identify the times on this record.
V. Time switch gave trouble, leading to a somewhat shortened record for some runs during the 24 hrs. and quite spoiling some others. Note: E.G. began checking totals and coincidences at the beginning of this record, continuing to the end of this report.
W. A burst registered on record 386(H29), beginning just before 7 p.m. January 13 (see page 38618A.) This burst registered as a single offset on H27 and H25 (see

* Figures of this type of course refer to the machine records as put up in book form.

pp. 38818A and 38718A — marked N on the records).

X. See Note S for H24 (not included in this publication).

Z. Record shows bunching of offsets quite markedly.

A' A rather long and open salvo began about 4:13 a.m. January 16 and continued for about 5 min. It was marked by a wide zero with much small activity on H24, by discrete offsets of all types on H25 and by a slightly wider zero with activity both large, medium, and small on H29. Compare pages 39419, 39319, and 39219. Another short salvo appears on H24 at about 4:27 and continues for 2 min. It shows heavy snaps on H25, likewise (but fewer) on H29. Compare pages 39421A, 39321A, and 39221A.

B' This activity so great only 2 min. counted. The coincidences with H29 were, however, checked over for 16 min.

C' Small salvo beginning about 4:06 p.m. January 18 on H29. No trace on H24 or H28. Compare pages 40002A, 39902A, and 39802A, at point marked X.

D' See note S for H28, regarding a short salvo at 4:17 a.m. January 20 which was well marked on H28 and H24. There was practically no trace on H29 at that time, but there were many very small salvoes on H29 during the run 4–4:30. One of these appears about 4:19 with two others on page 40120B immediately following. These are represented on H28 and H24 by sharp single snaps.

E' Between 4:05 and 4:07 p.m. January 20, a series of what look like blasts recorded on H28, but not on H24, or H29, which ran concurrently. A short burst recorded on H29 at 4:06 but no trace of it, except as a single snap, appears on H24 or H28. Compare pages 40602A, 40502A, and 40402A.

F' See note X for H28 (omitted from this publication).

G' Snaps come in little groups which almost become small bursts. See page 40725B at point marked M.

H' Stylus voltage too high.

I' Rather ill-defined salvo lasting about a minute, began at 5:24 p.m. January 25 on H29. No trace on H24 or H28. See pages 41809A, 41709A, and 41609A.

J' See note D' for H28 (omitted from this publication).

H31

Rec	Fr	To	Epoch	AP	L	M	S	T	N	Con-Rec	Co'ce	Notes
	Ja	Ja										
382	11	12	16:19	-	-	-	-	-	92	H27 H25	- -	A
382	11	12	17:15	-	-	-	-	-	94	H27 H25	- -	A
382	11	12	18:11	-	-	-	-	-	96	H27 H25	- -	A
382	11	12	4:12	-	-	-	-	-	98	H27 H25	- -	A,B

Rec	Fr	To	Epoch	AP	L	M	S	T	N	Con-Rec		Co'ce		Notes
382	11	12	5:16	-	-	-	-	-	100	H27	H25	-	-	A,C
382	11	12	6:18	12	1.6	6.8	32.8	41.1	102	H27	H25	4	4	D
386	13	14	16:46	24	1.0	4.2	9.1	14.3	130-31	H27	H25	11	10	E
386	13	14	17:47	-	-	-	-	-	134-35	H27	H25	-	-	E
386	13	14	18:47	-	-	-	-	-	138-39	H27	H25	-	-	E
386	13	14	4:48	-	-	-	-	-	141	H27	H25	-	-	E,F
386	13	14	5:57	-	-	-	-	-	143	H27	H25	-	-	E
386	13	14	6:40	-	-	-	-	-	145	H27	H25	-	-	E
	Ja	Ja												
389	14	15	16:41	-	-	-	-	-	147	H27	H25	-	-	G,H
389	14	15	17:51	-	-	-	-	-	149	H27	H25	-	-	G
389	14	15	18:47	-	-	-	-	-	151	H27	H25	-	-	G
389	14	15	4:42	-	-	-	-	-	153	H27	H25	-	-	G, I
389	14	15	5:42	-	-	-	-	-	155	H27	H25	-	-	G
389	14	15	6:50	16	.6	4.1	10.4	15.1	157	H27	H25	1	3	
392	15	16	16:52	16	1.0	3.9	6.4	11.3	159	H27	H25	14	14	
392	15	16	17:42	16	.6	3.6	6.7	10.8	161	H27	H25	8	8	
392	15	16	18:42	16	.3	3.8	11.3	15.3	163	H27	H25	3	4	
392	15	16	4:40	16	.6	8.7	15.2	24.2	165	H27	H25	12	13	
392	15	16	5:46	16	.1	6.6	9.3	15.9	167	H27	H25	9	9	
392	15	16	6:42	16	.4	5.3	10.4	16.1	169	H27	H25	11	11	
395	16	18	16:40	16	.8	5.3	12.9	18.9	171	H27	H25	9	9	

Rec	Fr	To	Epoch	AP	L	M	S	T	N	Con-Rec		Co'ce		Notes
395	16	18	17:41	16	.4	.8	4.7	5.9	173	H27	H25	8	8	
395	16	18	18:41	16	.4	5.2	29.0	34.6	175	H27	H25	6	7	
395	16	18	4:40	16	.3	10.3	15.4	26.0	177	H27	H25	3	3	
395	16	18	5:42	16	.6	8.8	12.9	22.4	179	H27	H25	11	12	
395	16	18	6:46	16	.5	7.3	12.9	20.6	181	H27	H25	8	8	
395	16	18	16:50	16	.7	6.1	40.8	47.6	183	H27	H25	3	3	
395	16	18	17:46	16	.2	4.8	34.7	39.6	185	H27	H25	0	1	
395	16	18	18:48	16	.1	6.8	43.6	50.5	187	H27	H25	6	6	
395	16	18	4:44	16	.3	17.5	60.9	78.7	189	H27	H25	2	2	J
395	16	18	5:31	2	9.0	43.0	93.0	145.0	191	H27	H25	0	0	K
395	16	18	6:41	2	4.0	35.0	88.0	127.0	193	H27	H25	0	0	
398	18	19	16:45	16	1.3	4.7	15.2	21.1	195	H27	H25	13	12	
398	18	19	17:43	16	1.2	4.1	12.2	17.4	197	H27	H25	9	9	
398	18	19	18:42	16	.4	5.9	16.5	22.7	199	H27	H25	5	3	
398	18	19	4:42	16	.8	11.6	27.6	39.9	201	H27	H25	2	2	
398	18	19	5:42	16	.6	10.6	22.1	33.3	203	H27	H25	1	1	
398	18	19	6:42	16	.3	15.2	38.6	54.6	205	H27	H25	1	1	
401	19	20	16:41	16	2.1	3.8	8.6	14.5	207	H27	H25	14	14	L
401	19	20	17:43	16	1.8	3.3	6.9	12.0	209	H27	H25	13	13	
401	19	20	18:41	16	.8	2.9	6.3	10.0	211	H27	H25	10	10	
401	19	20	4:42	16	.8	3.4	17.9	22.1	213	H27	H25	8	8	
401	19	20	5:44	16	.4	3.1	9.9	13.4	215	H27	H25	6	6	

Rec	Fr	To	Epoch	AP	L	M	S	T	N	Con-Rec		Co'ce		Notes
401	19	20	6:44	16	.4	2.7	8.8	11.8	217	H27	H25	7	7	
404	20	21	16:43	16	.6	2.4	8.5	11.6	219	H27	H25	10	11	
404	20	21	17:43	16	.7	2.1	6.4	9.3	221	H27	H25	8	10	
404	20	21	18:47	16	.6	2.5	6.3	9.4	223	H27	H25	9	13	
404	20	21	4:46	16	1.1	3.6	11.9	16.6	225	H27	H25	11	11	
404	20	21	5:44	16	1.2	3.2	8.9	13.3	227	H27	H25	14	16	
404	20	21	6:44	16	1.3	4.2	8.8	14.2	229	H27	H25	9	11	
407	21	22	16:43	16	1.8	3.3	8.1	13.2	231	H27	H25	17	19	
407	21	22	17:43	16	.9	1.9	8.8	11.6	233	H27	H25	10	12	
407	21	22	18:43	16	.6	2.6	8.9	12.1	235	H27	H25	9	10	
407	21	22	4:42	16	2.3	4.3	20.2	26.7	237	H27	H25	11	11	
407	21	22	5:44	16	1.5	2.1	12.4	16.0	239	H27	H25	9	13	
407	21	22	6:44	16	.9	3.4	11.3	15.6	241	H27	H25	5	5	
410	22	23	16:47	16	1.3	3.3	10.6	15.6	243	H27	H25	19	24	
410	22	23	17:47	16	1.4	3.5	9.3	14.2	245	H27	H25	6	6	
410	22	23	18:47	16	1.1	2.4	9.7	13.2	247	H27	H25	12	12	
410	22	23	4:47	16	1.9	3.9	24.3	30.1	249	H27	H25	8	8	
410	22	23	5:47	16	1.4	2.6	17.1	21.2	251	H27	H25	11	13	
410	22	23	6:47	16	1.4	3.9	18.4	23.8	253	H27	H25	11	13	
413	23	25	16:43	16	1.7	3.7	11.4	16.8	255	H27	H25	10	10	
413	23	25	17:43	16	1.3	3.0	11.1	15.3	257	H27	H25	7	10	
413	23	25	18:43	16	1.0	3.6	13.1	21.7	259	H27	H25	11	13	
413	23	25	4:45	16	1.6	6.8	25.1	33.5	261	H27	H25	8	8	M

Rec	Fr	To	Epoch	AP	L	M	S	T	N	Con-Rec		Co'ce		Notes
413	23	25	5:45	16	1.4	3.4	18.9	23.7	263	H27	H25	8	9	
413	23	25	6:45	16	1.8	3.8	9.4	14.9	265	H27	H25	10	11	
413	23	25	16:49	16	1.1	3.3	8.8	13.1	267	H27	H25	9	9	
413	23	25	17:49	-	-	-	-	-	269	H27	H25	-	-	M
413	23	25	18:45	16	1.3	3.8	29.0	34.1	271	H27	H25	4	4	O
413	23	25	4:45	16	1.1	4.1	37.4	42.7	273	H27	H25	-	-	P
413	23	25	5:45	-	-	-	-	-	275	H27	H25	-	-	P
	Ja	Ja												
413	23	25	6:51	16	1.3	3.1	67.4	71.8	277	H27	H25	6	7	Q
416	25	26	16:49	16	1.5	6.6	35.5	43.6	279	H27	H25	3	3	
416	25	26	17:47	16	1.0	4.9	34.8	40.7	281	H27	H25	11	14	
416	25	26	18:45	16	.9	4.4	30.4	35.8	283	H27	H25	10	17	
416	25	26	4:51	16	.7	5.9	49.6	56.2	285	H27	H25	0	1	R
416	25	26	5:53	16	1.2	4.6	43.8	49.6	287	H27	H25	0	1	
416	25	26	6:49	16	.6	5.6	70.4	76.6	289	H27	H25	1	1	
419	26	27	16:47	16	.8	5.2	47.3	53.3	291	H27	H25	12	13	S
419	26	27	17:45	16	1.3	3.2	41.8	46.3	293	H27	H25	14	14	
419	26	27	18:45	16	1.2	4.2	47.4	52.8	295	H27	H25	9	11	T
419	26	27	4:47	16	1.7	11.7	84.1	97.4	297	H27	H25	1	2	
419	26	27	5:53	16	.9	12.1	76.1	89.1	299	H27	H25	0	0	
419	26	27	6:51	16	1.0	13.3	73.5	87.8	301	H27	H25	0	0	
422	27	28	16:45	2	4.5	40.5	92.0	137.0	303	H27	H25	5	5	U
422	27	28	17:49	16	2.3	33.7	60.5	96.4	305	H27	H25	4	4	

Rec	Fr	To	Epoch	AP	L	M	S	T	N	Con-Rec		Cc'ce		Notes
422	27	28	18:47	16	1.6	26.0	56.9	84.5	307	H27	H25	1	1	
422	27	28	4:47	16	1.5	16.3	51.3	69.1	309	H27	H25	5	5	
422	27	28	5:44	14	.5	18.5	44.8	63.8	311	H27	H25	4	4	V
422	27	28	6:45	16	2.4	16.5	38.9	57.9	313	H27	H25	10	10	W

A. First record on 3801W-9 with two geophones (H29, H31). Time switch spoiled much of the record. Voltage was too high on styli.

B. Long salvo beginning 4:10 and lasting 4 min. followed by another beginning 4:16 and lasting 4+ min. running into time-switch change. Some traces of these on record 381(H27) and record 380(H25), but not nearly as much as on this record 380(H31).

C. Reference to Note P (H25) omitted from this publication.

D. Time switch worked all right till 4 min. before the end of the comparison run. Thus coincidences with record 381(H27) and record 380(H25) are for 12 min. only.

E. Time switch gave some trouble, leading to a somewhat shorter record for some runs for the 24 hrs. and totally spoiling some others (Note: Began reading for shorter periods, owing to pressure of work).

F. Reference to H25, omitted from this publication

G. Time switch gave trouble on H31.

H. What may have been a burst shows only on 389(H31)? just about the time the switch changed. No trace on other records. See page 38904.

I. What may have been a burst shows only on 389(H31). Does not appear on other records. Began about 4:42 a.m. January 15 and lasted 3 min. See page 38922B.

J. A light trace of a salvo at 4:38 a.m. January 18; appears on H31 only. No trace on H27 or H25. See page 39556A.

K. So active that only 2 min. were read (by E.A.H. on April 14). Sudden sharp increase on a Monday morning when no work was done since early Sunday morning. Compare pages 39556A (4:32 a.m. January 18); 39561B (5:32 a.m. January 18); 39567A (6:32 a.m. January 18).

L. A short salvo of strong offsets lasting less than a minute occurred at 4:40 p.m. January 19. It was well marked on H27, H25, and H31. Compare pages 40305A, 40205A, and 40105A.

M. A series of faintly developed salvoes, lasting each about one minute, began at 4:47 a.m. January 24 on H31 . They did not appear on H27 or H25 until about 4:57, when they were faintly developed also on H25. Compare pages 41522, 41422, 41322 to 41524, 41424, and 41324.

N. Poor contact on time switch. Zero very wide.

O. Stylus voltage too high.

P. Poor contact on time switch. Record hardly legible.

Q. This count must be taken with reserve. The time switch contacts were very poor.

R. Some evidence of ore skipping on this record. See page 41624A and compare with 41824.

S. Reference to H25, omitted in this publication.

T. Reference to H25, omitted in this publication.

U. A small section of H31 came on record 422 on the first page. It lasted only 2 min. before being stopped by the time switch, but the activity recorded was of extraordinary energy. Coincidences with H27 and H25 checked only for 2 min.

V. A small sharp burst occurred at 5:49 a.m. January 28. It registered for about 2 min. on each record (H27, H25, H31). It was more sharply marked on H25, but there were many more small ones registered on H31. The larger snaps in the burst were as well marked on H27 as on H25. Compare pages 42428, 42328, and 42228.

W. The set 111 and the records 425(H29, H31) were lost in the burst of January 29, which closed the drift 3801W for more than 300 ft.

L-13 Salvoes and Bursts Registered in January 1943

In the following tabulation, the successive headings indicate:

No	=	Serial number assigned to the disturbance.
Ja	=	The January date.
T	=	Type: burst or salvo.
Began	=	Nearest minute when the disturbance started, given in Eastern War Time on the 24-hr. system beginning at midnight.
Dur	=	The duration, to the nearest half-minute.
Con-Rec	=	The concurrent records running at the time of the disturbance.
Con-Rec Page	=	Page of the record where the disturbance registered, inserted for use in refererring to the registration.
Inten	=	The estimated intensity on an ascending scale of 5.
Rem	=	A series of indexed remarks following the table.

Note: These so-called 'salvoes' are extremely local in their registration. They seem to occur when pressures are building up, and to become few or absent after large bursts. The choice of the name is perhaps unfortunate, but it was the one adopted at the time they were first noticed. See figure 47.

No.	Ja	T	Began	Dur	Con-Rec			Con-Rec Pages			Inten			Rem
1	5	S	4:39	2.0	H29	H28	H24	36516	36316	36416	-	3	3	
2	6	S	16:11	0.5	H29	H28	H24	37102	36902	37002	1	-	-	A

No	Ja	T	Began	Dur	Con-Rec			Con-Rec Pages			Inten			Rem
3	6	S	16:13	1.0	H29	H28	H24	37102	36902	37002	1	–	–	A
4	6	S	16:15	1.0	H29	H28	H24	37102	36902	37002	2	–	–	A
5	6	S	16:22	2.0	H29	H28	H24	37103	36903	37003	2	–	–	A
6	6	S	16:40	4.0	H29	H28	H24	37105	36905	37005	2	–	–	A
7	8	S	4:16	4.0	H27	H25	–	37319	37219	–	–	3	–	B,C
8	8	S	4:22	2.0	H27	H25	–	37320	37220	–	–	3	–	B,C
9	8	S	4:28	2.0	H27	H25	–	37321	37221	–	–	2	–	B,C
10	9	S	4:16	4.0	H29	H25	H28	37619	37520	37419	0	2	3	C
11	9	S	4:22	2.5	H29	H25	H28	37620	37520	37420	0	2	3	C
12	9	S	4:30	7.0	H29	H25	H28	37621	37521	37421	0	?	4	D
13	12	S	5:02	5.0	H31	H28	H24	38224	38024	38124	–	3	–	E
14	12	S	5:12	6.0	H31	H28	H24	38225	28025	28125	–	4	–	E
15	12	B	16:08	1.0	H29	H28	H24	38302	38402	38502	2	1	1	F
16	12	B	16:10	1.0	H29	H28	H24	38302	38402	38502	3	1	1	F
17	12	S	18:37	0.5	H29	H27	H25	38316	38516	38416	0	0	2	
18	13	S	4:04	2.0	H29	H28	H24	38317	38418	38519	0	3	2	
19	13	S	4:13	2.0	H29	H28	H24	38318	38419	38519	0	3	2	
20	13	S	4:23	5.0	H29	H28	H24	38319	38420	38520	0	3	2	
21	13	S	4:50	0.5	H29	H27	H25	38322	38523	38423	1	2	0	
22	13	S	5:41	1.0	H29	H27	H25	38325	38528	38427	0	0	2	
23	13	B	18;59	1.5	H29	H27	H25	38618	38818	38718	3	1	1	G
24	14	B	4:20	0.5	H29	H28	H24	38620	38720	38820	1	2	2	H
25	14	S	4:25	1.0	H29	H28	H24	38620	38720	38821	1	3	2	

No	Ja	T	Began	Dur	Con-Rec			Con-Rec Pages			Inten			Rem
26	14	B	4:33	10.0	H31	H27	H25	38621	38821	38721	0	2	5	I
27	14	S	4:55	1.0	H31	H27	H25	38623	38823	38723	0	0	2	
28	14	S	4:57	1.0	H31	H27	H25	39623	38823	38723	0	0	1	
29	14	S	16:30	4.5	H31	H27	H25	38904	39104	39004	4	–	0	J
30	15	S	4:42	3.5	H31	H27	H25	38922	39122	39022	3	0	0	
31	15	B	16:13	0.5	H29	H25	H24	39202	39302	39002	3	5	5	K
32	16	S	4:13	4.5	H29	H25	H24	39219	39319	39419	4	3	2	
33	16	S	4:27	1.5	H29	H25	H24	39221	39321	39421	3	4	4	
34	18	S	4:38	1.0	H31	H27	H25	39556	39756	39656	2	0	0	
35	18	S	16:06	1.0	H29	H28	H24	39802	39902	40002	2	0	0	
36	19	S	16:40	1.5	H31	H27	H25	40105	40305	40205	3	5	5	K
37	20	S	4:18	0.5	H29	H28	H24	40120	40220	40320	2	2	2	L
38	20	S	5:25	1.0	H29	H28	H24	40126	40226	40226	1	1	1	
39	20	S	16:06	0.5	H29	H28	H24	40402	40502	40602	3	2	2	M
40	21	S	4:07	0.5	H29	H28	H24	40419	40519	40619	0	2	2	
41	21	S	4:46	0.5	H31	H27	H25	40422	40623	40522	1	1	2	
42	21	B	16:03	0.5	H29	H28	H24	40701	40801	40901	2	3	3	N
43	21	S	16:28	2.0	H29	H28	H24	40704	40804	40904	1	4	3	O
44	22	S	4:26	2.0	H29	H28	H24	40721	40821	40921	1	5	3	
45	22	S	5:16	0.5	H29	H28	H24	40725	40825	40925	2	1	0	
46	22	S	16:13	0.5	H29	H28	H24	41002	41102	41202	0	4	3	
47	22	S	16:47	0.5	H31	H27	H25	41005	41205	41105	0	0	2	
48	23	S	5:32	0.5	H29	H28	H24	41027	41126	41227	1	3	2	

No	Ja	T	Began	Dur	Con-Rec			Con-Rec Pages			Inten			Rem
49	24	S	4:23	0.5	H29	H28	H24	41320	41420	41520	1	3	2	P
50	24	S	4:47	2.0	H31	H27	H25	41322	41522	41422	2	0	0	Q
51	25	S	17:24	1.0	H29	H28	H24	41609	41709	41809	2	0	0	
52	26	S	4:12	4.0	H29	H28	H24	41619	41719	41819	2	4	2	R
53	26	S	4:19	0.5	H29	H28	H24	41620	41720	41820	1	3	0	
54	26	S	4:25	7.0	H29	H28	H24	41620	41720	41821	2	4	2	S
55	26	S	16:37	0.5	H31	H27	H25	41904	42104	42004	5	5	5	
56	27	S	4:00	4.0	H31	H27	H25	41918	42118	42017	3	3	4	T
57	27	S	4:13	4.0	H29	H28	H24	41919	42018	42119	2	4	1	U
58	28	S	4:14	2.0	H29	H28	H24	42219	42319	42419	2	4	1	V
59	28	B	5:49	4.0	H31	H27	H25	42228	42428	42328	5	3	4	
60	28	S	16:06	0.5	-	H25	H24	-	42601	42701	-	5	5	W
61	28	S	16:19	0.5	-	H25	H24	-	42603	42703	-	4	4	W

A. May not be seismic. No trace on concurrent records. H29 was not recording snaps at this time, but these salvoes (?) were recorded.

B. Only H27 and H25 recording at the time of these salvoes and H27 was spoiled by bad contacts on the time switch.

C. May not be seismic but no other cause known. Set was working well on H25. But compare Nos. 7, 8, and 9 with Nos. 10,11, and 12. Sets working well on H25 and H28 for the latter three salvoes. It seems strange that there should be such a close agreement in time for the two successive days.

D. Time switch changed H25 to H24 and interfered considerably with the record. The salvo began to record on H25 and continued to do so on H24, being less in each case than H28.

E. Switch trouble interfered with both H31 and H24.

F. These bursts registered with many closely recorded offsets on H29, but only the initial strong burst and a few strong succeeding snaps registered on H28 and H24.

G. Strong burst with closely registered snaps on H29. Initial snap on H27 and H24 only.

H. Small initial snap on H29 and some closely recorded smaller snaps. Larger initial snaps and one large succeeding snap on H28 and H24.

I. There seems to be nothing the matter with H31 record, but there is no trace of this burst of such outstanding magnitude on H25.

J. A series of salvoes on H31 just as switch changed. No trace on H25. H27 was having time-switch trouble. May not be seismic.

K. A short series of all strong snaps, beginning and ending abruptly.

Shortly after 4:18 a short salvo registered on H29 with no registration on H28 or H24, except two snaps. During this entire record H29 registration tended to run in groups.

M. A short salvo registered on H29 with nothing but the larger snaps showing on H28 or H24. But on H28 there was a series of what looks like blasts (at a time when blasting does not occur) which register hardly at all on H29 and only slightly more on H24. It is not known what this disturbance was, but it seems surely to have been seismic. See Note N.

N. Two sharp bursts registered on H28, slightly less heavily on H24 and still less on H29. But on H28 a series that looks like blasts registered just before this burst; these show very slightly on H29, and only a little more on H24. See Note M.

O. A series resembling blasts on H28; these are fairly well marked on H24 and hardly to be found on H29. Nearly all record 407(H29, H31) for January 21-22 shows the snaps as having a tendency to occur in groups.

P. On H29 only the major snaps of the short salvo are registered.

Q. A series of such small salvoes occurred on H31 and not on H27 or H25. One began at 4:56 a.m. January 24 and lasted about a minute, and another began at 4:59 and lasted about half a minute.

R. A long-drawn-out salvo on H28 with a recrudescence at 4:15 a.m. January 26. Only the larger snaps registered on H29 and H24.

S. A long-drawn-out salvo on H28 with a recrudescence at 4:29 and another at 4:31. Registered only faintly on H29 and H24, except for the larger snaps. But on H29 there is a series of groups of snaps at intervals during the period 4:30 to 5:00 a.m. January 26.

T. A salvo that was best registered on H25 occurred just before the time switch changed. When it did change to H29, H28, H24, the record continued on H28, but did not register on H29 or H24.

U. A long-drawn-out salvo on H28 that was only partly recorded on H29 or H24. It was preceded on H28 by a few abrupt short salvoes that resemble ore skipping records but were not due to this cause.

V. Well-marked salvo on H28. Only the larger snaps registered on H29 and the salvo was merely a widening of the zero on H24. It was plainly seismic.

W. The record 425(H29, H31), for January 28-29 was lost in the crush burst of January 29.

*

Report M

April 1943 - January 1944

At the end of the period covered by the last report, a heavy rockburst had just taken place (March 31, 1943), completing the destruction of the seismic set-up on the west pillar that had been heavily damaged by the rockburst of January 29.

The west pillar seemed to have been relieved from strain by the two bursts. A short listening program over the various levels showed very low activity. The equipment was therefore to the east side of the mine to levels 4450-4825.

A series of new holes was drilled on these levels in the east drifts at about section 3. As the holes became available, they were placed on the listening program and, as the recorders were made ready for service, came into the recording program.

The present report deals with the studies set up and carried on in the new locale. It seems desirable to preface the account with a statement of the theories and deductions formulated as a result of the program in the west pillar.

M-1 Theories and Deductions Based on West Pillar Survey

The theories and deductions arrived at by the seismic survey operators, as of the summer of 1943, were the result of the experience gained in the west pillar survey. They may be stated as follows:

A. At Lake Shore, rockbursts are apparently caused entirely by the weight of superincumbent rock, which is unequally distributed owing to the block-faulted structure and the progress of mining. It is believed that there was no inherent strain surviving from the geologic history.

B. The term 'rockburst' should be extended to include any sudden release of rock strain energy, whether or not it is accompanied by evidence in the mine. The burst may be classified as follows:

(a) Crush Bursts, due to failure of rock under compression.
(b) Strain Bursts, due to failure of rock in shear or tension.
(c) Slip Bursts, due to slipping of rock on fault planes, either exposed or far in the walls. The results of the blow delivered by the elastic rebound from such a slip may involve the fall of loose or the overthrow of timber and equipment, sometimes possibly quite far from the point of the slip which, on the other hand, may be evidenced only by the concussion.

C. The snapping picked up by the Obert equipment during the off-shift periods consists of at least three classes of snaps:

(a) General Snapping generally sounding low-pitched, whether heavy or light, and sometimes heard without the equipment; registered through more than one geophone and believed to be due to slipping of breaks or faults and the fracturing of rock, whether loose or in the wall.
(b) Local Snapping generally sounding high-pitched, whether heavy or light, and alomst never heard without equipment; seldom recording simultaneously on more than one recorder.
(c) Distant-local Snapping sounding much like the local type but so faint that the snaps can be picked up, in general, only when listening with earphones, the heaviest ones alone being recorded. Local and distant-local snapping are believed to be indicative of rock yielding under strain, either compression or shear. Some minute fracturing is also probably included.

D. For some time before a rockburst is imminent, the general snaps tend to become stronger and more frequent and then to diminish in number as the pressure is built up. Moreover, the local type tends to increase, if the locus of pressure is near enough to the geophones (75 ft. for recording, or 200 ft. for listening) to be registered or heard.

E. If the incidence of local-type snapping increases on several geophones and does not exceed on any one, say, 20 s.p.m. (for the early morning off-shift count), there is no localized danger in that part of the mine adequately serviced by geophones.

F. If the count for local type exceeds 20 s.p.m. (morning count), close observation should be kept on the stope or stopes affected, especially as the listening is done in the early morning, which time the recorders indicate as being the least active of the day.

G. If the morning count rises to over 80 s.p.m., the stope concerned should be allowed to to rest or, if worked, the next blasting should be made abnormally heavy. High counts do not necessarily indicate an impending burst, but they are an evidence of strain and should be treated with respect, especially until further experience has been gained.

M-2 Test Holes on the East Side

The test holes on the east side (also three on the west side drilled since the list previously given in section K-6) are tabulated below and are shown postioned in plan in Figure 65. It will be noted that:

A. The holes drilled first were all located in section 2E or 3E. Later, some were drilled in section 4E and still later in section 6E. The explanation of this procedure will appear later in this report.

B. All except one were diamond drill holes run especially for the survey. All the DD holes after H36 were cored for the first 5 ft. from the collar, and had 6-ft. lengths of inch and a half iron pipe set in, with a foot of the pipe projecting.

C. Except for two holes drilled for a special purpose in January 1943, no holes were available on the east side, even for the listening program until late in May. The holes in section 6E were not ready for service until late in November.

Test Holes Assigned to Rockburst Research

No.	DD	Date	Location and Wall	Depth	Remarks
31	3744	Nov. 6'42	3908W-7-S	29'6"	Replaced H30
32	3808	Feb. 7'43	4201W-5-S	51'0"	Diagonal
33	3829	Feb. 28'43	3801W-6-S	51'0"	Diagonal
34	3780	Jan. 15'43	4701E-2-S	140'1"	30° up
35	3779	Jan. 13'43	4701E-3-S	164'7"	30° up
36	3876	May 25'43	4402E-3-S	29'0"	Fairly solid
37	3877	May 25'43	4402E-3-N	28'9"	Fairly solid
38	3878	May 27'43	4401E-3-S	39'5"	Broken ground
39	3881	May 29'43	4702E-3-S	32'0"	Some seams
40	3882	May 29'43	4701E-3-S	29'3"	Fair ground
41	3879	May 28'43	4802E-3-S	30'0"	Some seams
42	3880	May 28'43	4801E-3-S	32'0"	Fair ground
43	3883	May 31'43	4502E-3-S	30'0"	Good ground
44	3884	June 1'43	4501E-3-S	30'7"	Broken ground
45	3899	June 23'43	4501E-4-S	30'9"	Good ground
46	3901	June 24'43	4701E-4-S	30'0"	Broken ground

No.	DD	Date	Location and Wall	Depth	Remarks
47	**		4702E-2-S	1'6"	Bootleg
48	3974	Nov. 20'43	4502E-6-S	30'2"	Badly broken
49	3975	Nov. 20'43	4401E-6-S	30'0"	Broken ground
50	3976	Nov. 23'43	4501E-6-S	30'1"	Badly broken
51	3977	Nov. 25'43	4701E-6-S	30'4"	Broken ground
52	3978	Nov. 23'43	4802E-6-S	30'2"	Badly broken
53	3979	Nov. 24'43	4801E-6-S	30'0"	Badly broken
54	3980	Nov. 26'43	4702E-6-S	30'0"	Fair ground

The dates given in the above tabulation show the time when the hole was finished.

**This hole was a percussion drill hole, hence has no DD number. The time when it was drilled is not known, but it was about the same time as the adjoining holes.

H34 and H35 were drilled upward at an angle so that any water draining into them would find outlet. They were very deep, with the object of trying to find the depth of the so-called 'zone of compression'. It was difficult to keep the geophones from sliding out. These holes were soon partly closed, owing to slipping on fault planes.

M-3 Use Made of Test Holes, April '43 to January '44

As soon as the holes were drilled they were added to the listening program, and continued on that program even when they began recording. The recording program was delayed while the recorders, damaged by the bursts in the west pillar, were being repaired. The following table shows the number of days in each month when the respective holes were recording, the totals at the foot of the tabulation showing the number of such days per month.

Number of Recording Days in East Side Holes
April 1943 — January 1944

H	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan
31	—	—	—	—	—	—	—	—	—	—
32	30	15	—	—	—	—	—	—	—	—
33	—	—	—	—	—	—	—	—	—	—
34	4	31	18	—	—	—	—	—	—	—
35	3	31	18	—	—	—	—	—	—	—
36	—	—	—	—	—	—	20	30	31	31
37	—	—	—	—	—	—	—	—	—	—
38	—	—	—	—	—	—	20	30	31	31
39	—	—	12	30	2	30	—	—	—	—
40	—	—	—	30	31	30	31	30	31	31
41	—	—	—	19	31	30	31	30	31	31
42	—	—	—	19	31	30	31	30	31	31
43	—	—	—	29	31	30	31	30	31	31
44	—	—	—	20	27	30	31	30	31	31
45	—	—	—	13	31	30	31	24	—	—
46	—	—	—	8	31	30	31	29	—	2
47	—	—	—	—	27	30	31	30	30	31
48	—	—	—	—	—	—	—	2	31	31
49	—	—	—	—	—	—	—	—	23	31
50	—	—	—	—	—	—	—	6	31	31

H	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan
51	—	—	—	—	—	—	—	—	29	31
52	—	—	—	—	—	—	—	—	23	26
53	—	—	—	—	—	—	—	—	24	31
54	—	—	—	—	—	—	—	—	31	30
T	37	77	48	168	242	270	288	301	439	461

M-4 The Listening Program

After the writer was placed in direct charge of the underground program on July 1, 1942, the listening program was expanded, and for the period reviewed — April 1943 to January 1944 — the following was the regular routine.

From 3 a.m. to 7 a.m., when the mine was deserted, listening was carried out at the 4450, 4575, 4700, and 4825 levels. The records were then removed, and the instruments set for automatic recording. The removed records were then taken to the surface for reduction, and entered on a form in duplicate. The original was left at the mine office, where copies were made for distribution to mine officials, and the duplicate was filed in the survey office.

M-5 Proposed Stope Survey

The studies in the west pillar indicated that the subaudible snaps were indeed generated as a result of rock strain, that the s.p.m. increase as the pressure goes up, and that such high counts presumably indicate critical conditions. Furthermore, it was demonstrated that the high counts did not carry more than about 75 ft. in the rock, also that the points of critical pressure build up very rapidly and may as rapidly move to another location.

It was also shown that automatic recording leaves much to be desired. It can cover a limited section only; it is expensive to set up and to operate; it is difficult to maintain the recording apparatus in efficient operation; and it can operate for a limited time only each day — during off-shift periods.

For these reasons, it would appear that the survey can best be accomplished in practice with portable listening equipment, to be used as conditions indicate that it is desirable. Such conditions can best be interpreted by those in charge of the mining operations.

This listening can be done even in shift time; there are always brief interludes in the noise of mining operations of sufficient duration to permit an operator to detect critical snapping.

The listening should be done at frequent intervals, preferably by one operator assigned for this purpose. In this way, one man can build up experience, making him expert in the interpretation of the activity he hears.

One of the mine employees was assigned to undertake this work, and it was hoped that within a short time the proposed program would prove its value as a safety measure. However, the program fell through almost before it was begun, which the writer considers most unfortunate. He is still* firmly of the opinion that the subaudible method has great possibilities as a protection and that the proposed program is the only way in which such protection can be achieved as a routine service.

M-6 Discussion of Some Research Problems

At various conferences between the officials of the mine and the engineers of the seismic survey, questions were raised which were debated quite generally by all present. It seemed desirable to prepare replies to these questions in the form of a memorandum, which appeared as Appendix I of Report M. It is given here practically in full:

A. Basic Assumptions:

The entire program was based on the suggestion, made independently by the writer and others, that faint, subaudible snapping may be generated in rock subjected to serious strain and that, if such snapping is found to occur, it probably indicates a focus of pressure if, as is to be expected, it proves to be localized. Further, it may offer a means of prediction, if it develops a sufficiently long time before the pressure becomes critical.

B. Subaudible Snapping Proved to Exist, to Attenuate at Short Distances, and Tentatively Assumed to Indicate Strain:

The experiments by Obert in U.S. mines, the experience at Frood in 1942, and all subsequent work at Lake Shore Mines prove that subaudible snapping exists and that it attenuates at short distances, and suggest that it is probably due to rock strain. It is certain that faint, subaudible snaps are sometimes generated in rock that is about to burst or is presumably in a state of serious strain, but there is still a question as to whether it always develops. The noises are real, not static or instrumental, and can be heard over one line when they are recording on another, when the geophones are adjacent in the lay-out. A very good example (among thousands) occurred between 5 and 5:30 a.m., February 12. Snaps counted as distant-local type on other lines could, in many cases, be seen to record on the line from H40.

* In 1957

C. Significance of Rate of Snapping:

It is tentatively assumed that the rate of incidence of the localized high-pitched snapping varies directly with increasing strain. Linearity is not assumed; indeed the change of rate is suspected of accelerating as the strain approaches a critical value. There has been no proof to the contrary as yet, but such noises did develop prior to the burst in 4201W-10 on July 25, 1942; in 3825 and 3950 level geophones in the west pillar in January 1943; and in three cases where geophones were near a point where a sill was taken out and where presumably the strain was great.

D. Extraneous Noises not a Serious Handicap:

The recorders are very sensitive, and noises of many kinds may be heard, and even registered, at considerable distances. This, however, is not a serious handicap, as man-made and machine noises are easily differentiated, either on the records or when heard: this is true also of rock runs and cave-ins.

The occasional snapping that occurs from time to time within a radius of, say, 1,000 ft. of a geophone will sometimes register and can generally be heard on geophones. But experience shows that snapping of this type never gives high counts and is far from being localized. It is tentatively assumed that until the count is both high and localized it may be disregarded from the standpoint of the existence of strain foci, at least within the range of the geophones. There is much evidence favouring this assumption, and none to the contrary.

E. Routine Counts May Have Value

It is assumed that much of the general snapping is due to the movement of blocks of ground of various sizes, and that the continuance of such snapping is, if anything, a sign that localized pressure is not developing. There is some indication that simultaneous snapping decreases as localized snapping develops.

It is felt that, however laborious it may be, tabulations of all counts and study of their simultaneity from day to day should be carried on until a completely satisfactory record of a burst or bursts has been secured.

F. Geologic Structure Affects Counts

It is proposed to examine the geologic structure by means of a portable tapper, as it has been shown by the records that it does affect the counts. Experience indicates that structure has a marked effect in some cases and not in others.

As an example of the former, it may be noted that H46 is in 4701E-4 and H40 in 4701E-3. Each hole is 30 ft. deep and in the south wall of the drift. The distance between is 135 ft. In November 1943, H46 had high counts and H40 low. Now H40 has high counts and

H46 low, in spite of the fact that H46 is much nearer to a working stope than is H40. It would be most instructive to have a series of 30-ft. holes, drilled about 30 ft. apart, from a point about 30 ft. west of H40 to a point about 30 ft. east of H46. Then a study could be made, using the portable listening equipment, at this series of holes, when the regular records showed a marked difference in the counts from the two holes.

As a further example of a hole which seems isolated, one might cite H34 (4702E-6), which sometimes develops both local and general snapping that does not register well on other geophones.

To sum up: If and when geologic structure seems to be interfering with the counts, experiments should be conducted with the tapper and by drilling to determine where the geophone (s) should be installed to protect any given stope.

G. Evidence for Prediction Lacking.

In the west pillar, localized snapping registered in increasingly higher counts for some days prior to the burst of January 29, 1943. But on the east side, to date, there has not been a single case of a burst occurring where a geophone was within 75 to 100 ft. and where listening or recording was going on prior to the burst.

Furthermore, the most that can be determined by this method, even if it proves as successful as can reasonably be expected, is that it will indicate points of critical pressure. The factors which combine to cause a burst are so many and so unknown that all one could reasonably say is that a danger point exists if the count becomes localized and active. Long experience with properly placed equipment might help to segregate the acutely critical from the critical cases. Certainly, the contribution of experienced miners must carry much weight in deciding how a focus of critical strain should be treated. The method can only state that such a focus exists and indicate when it ceases to be critical.

H. Qualifications for Listening:

It is the considered and firm opinion of the writer that the problems raised with regard to the possible need for peculiar listening powers in observers need not be a source of great concern. The questions have suggested a special type of filter which, if successful, will be extremely useful in deciding whether the localized snapping goes up at a higher rate than the general type and will permit an analysis of the spectrum of frequencies to find out what range is the most informative for listening as well as recording. But, even if fully successful, the counts can only tell where the critical points are, not whether a burst will occur.

Experience shows that, when the counts are high, there is always a large percentage of localized snaps, i.e. very high counts are never wholly general. All counts may rise in a certain section of the mine, but only the point of critical strain will show very high counts.

Two men, equipped respectively with the present type instrument and with the hypothetical filter design, under the same circumstances, would bring back the same reports of critical conditions which might or might not result in a burst. But, if such points are systematically detected and are studied as to their history under various circumstances by both miners and geophysicists, experience should, in time, permit some graduation in estimating the degree of menace to be assigned to any newly detected focal point. The only qualifications a listener must have, so far as the frequency question is concerned, are good hearing and persistent patience.

M-7 Rockbursts Located, April 1943 to January 1944

	Date	No.	Time	Class	Location	Rock Displac't
A	Apr. 7	345S	3:55 p.m.	-	4402E-5 to 4502E-5	small
B	" 9	297C	7:05 p.m.	heavy	4450E to 4825E	several hundred tons
C	June 2	346S	2:45 p.m.	-	4802E-3	25 tons
D	July 13	298C	2:30 p.m.	light	4902E-2	30 tons
E	Aug. 18	299C	2:30 p.m.	light	4801E-5	several tons
F	Sep. 29	300C	1:19 a.m.	med'm	1801W-11	50 tons
G	Oct. 5	301C	2:32 p.m.	med'm	4701E-4 to 4801E-4	160 tons
H	" 15	302C	5:45 p.m.	light	3 shft. plr.	10 tons
I	" 26	303C	12:20 p.m.	heavy	3 shft. plr.	over 1,000 tons
J	" 29	304C	3:00 p.m.	light	4701E-6	several tons
K	Dec. 13	305C	3:20 p.m.	med'm	4801E-7	100 tons
L	" 18	306C	3:30 p.m.	light	4502E-5	25 tons
M	Jan. 5	347S	3:30 p.m.	-	4502E-5	25 tons
N	" 10	307C	3:30 p.m.	light	4501E-5	several tons

Date	No.	Time	Class	Location	Rock Displac't
O " 13	348S	3:30 p.m.	-	4502E-5	10 tons
P " 20	308C	4:35 p.m.	med'm	3501E-5 to 3811E-5	sev.hun. tons
Q " 28	349S	3:30 p.m.	-	4801E-7	15 tons

The above list shows only the burst that occurred during the period indicated and that were located and investigated in Lake Shore Mines. More than 120 bursts were of sufficient magnitude to register on the seismographs. Some serious interruptions to the recorder on the 3075-ft. level in January 1944 leave in doubt the exact number of bursts that might have registered. Seventeen bursts (5 strain, 12 crush) were surveyed and reported as above shown. All but four (B, F, H, I,) occurred during or close to the afternoon blasting in the off-shift period. All but four (E, H, I, P,) occurred in the section of the mine directly under investigation (east side, 4325-ft. level to the 4950-ft. level). The second burst (Oct. 26) in No. 3 shaft pillar (I) registered on the seismograph at Ottawa.

Of the unlocated bursts (more than 120 in that time), it is known from record indications that most of them occurred in the block of ground under investigation. Listening experience shows that this section of the mine is the most consistently active. It appears from the experience so far gained that the 4700-ft. level is the best rockburst laboratory available in the mine at this time. There seems to be no reason to regret the choice of locale or to wish for a more promising place to study. It has become necessary to recognise the fact of slip bursts and to direct every effort to solve the special problems connected with this type of disturbance.

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Report N

This report was a bibliography which, in the present publication is somewhat amplified and relegated to an Appendix.

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Report O

February 1944 -- June 1945

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There was a large measure of continuity during the period in the underground program, along the lines described in Report M. The writer continued in charge of this work, ably assisted by Hallick, to whom is due much credit for keeping the investigation going efficiently. Mrs. Grace resigned in November 1944, and was replaced by Miss Mary Hallick, who proved a most capable and devoted assistant.

O-1 Recording Program

As of January 31, 1944, the recording program on the east side of the mine, from the 4450-ft. level to the 4825-ft. level, was well established. From time to time since, geophones have deteriorated and had to be changed. In some cases, where a hole had been partly closed by slips along fault planes, the defective geophone has had to be abandoned. When this occurred, the hole was re-drilled and incorporated into the program as soon as possible. A tabulation of the holes and their locations is given in section O-6.

Interruptions occurred occasionally when lines were damaged by mining operations. In general, such breaks were of short duration. Somewhat longer lapses resulted from extensive timbering or mining operations involving drifts in which cable lines were strung. The most important of these was in 4802E, where a considerable amount of re-timbering was done in December 1944 and the first two or three months of 1945. Another important interruption held up the holes in 4701E (except H40 and H55)during the latter part of April and early part of June 1945. Some reduction in coverage also resulted when recorders were brought to surface for repairs. One fairly long break occurred during October and November, when recorder 4 was on surface for about six weeks for use in developing a high-speed chronograph.

All available recorder channels were used every day. When the usual holes were not in operation, others were put on the recording program for the time being. When there was a shortage of recorders, the holes in good order were serviced each day on the listening program.

An outline of the recording maintained appears in section O-7. It is to be noted that all possible coverage was maintained during the entire period. From July 1, 1942 to the end of June 1945, about 2700 records were made. Most of these were about 40 ft. long; many were considerably longer. All were carefully studied and their data were entered daily into the tabulations and graphs.

O-2 Listening Program

Experience gained prior to the period covered by this report showed that listening is best carried on during the early morning, off-shift hours. Every hole available, whether in the recording program or not, was included in the listening program every day except Sundays, up to the end of February 1945, when some omissions were unavoidable.

The writer spent more than half his time at Kirkland Lake, going underground each day at 3 a.m. and remaining until the day shift began (8 a.m. during the winter months and 7 a.m. in the summer).

In November 1944, some difficulty was experienced in making clear just what degree of seismicity the operator felt should be assigned to each hole each day. The count alone was not a sufficient index, since the 'normal' count on some holes was much higher than on others. Several tentative drafts of a scheme for describing the seismicity were tested for some weeks by both operators, each independently assigning a 'seismicity factor' to his listening at each hole. After several amended drafts had been tried out, a scale called a 'Seismicity Factor on a Scale of Ten' was drawn up. This was found to work out satisfactorily and was adopted as standard practice.

The factor gives considerable satisfaction to each of the operators as a reasonable statement of his estimate of the seismicity of each hole each day. It is seldom that Hodgson and Hallick differ by even one point, in listening to a group of 30 to 38 holes each morning.

O-3 Seismicity Factor on a Scale of Ten

The seismicity factor or index of critical conditions is an attempt to permit a daily plotting of underground data as they appear to the operator. Subject to change as the idea is worked out, the following significance is to be given the factor by operator and management:

0. Trace only.
1. Definitely subnormal for the hole concerned
2. Low normal activity
3. Count about normal, but no definite D or L indication (see below)
4. Normal activity for the hole concerned; some D or L; no trace of 'viciousness' in the sound of the snaps
5. High normal for the hole; trace of viciousness or moderately high D-count; not markedly sporadic; no salvoes
6. Higher than normal; high D with definite viciousness, sporadic occurrence, or salvoes
7. Vicious local snaps; counts at least twice normal; possible sporadic with salvoes or with D-type snaps too high to count accurately
8. Counts definitely high; at least four times normal for hole concerned; vicious local snaps or salvoes

9. High vicious local snaps that can be counted; association with any particular stope uncertain or leaving some doubt with the operator as to immediate critical conditions
10. Very high vicious local snaps, near or above possibility of counting, definitely identified with a given stope or stopes; no doubt in operator's mind that work should be suspended.

The letter D or the letter L will follow the factor number, meaning distant or local. The former indicates that the conditions reported was not exactly at the hole but that it was determined from the distant-local snapping heard there. The letter L indicates that the condition reported was based on local-type snapping and that the pressure locus is close to the hole indicated.

For the special attention of shift bosses the following simplification indicates the nature of the report and is indicative of the attention required:

0 to 5 No special attention, unless it shows change since the previous day's report
5 to 6 Activity just becoming worthy of notice by those in charge underground
6 to 7 Shift boss or captain should examine ground reported
8 Condition definitely acute, but not critical; examination should not be neglected
9 Conditions critical, but there may be explanatory circumstances (heavy blast, still removed, etc); operator could possibly concur in decision to continue work
10. Conditions definitely critical in operator's opinion

O-4 Rockbursts Experienced

In the following section a list is given of the 34 rockbursts that occurred at Lake Shore during the period covered by this report, and that were located and reported on by the engineering staff. An analysis shows that only three of these occurred in time and place that might have resulted in their being predicted: in each case, the burst occurred some hours after the listening and recording had ceased.

Two of the bursts were quite small, as evidenced by the reports; the third displaced about 100 tons and was classed by the engineers as a 'light crush burst'. There was some measure of prediction for this burst, definitely from one hole and generally from the holes in section 6, which were reported as showing signs of strong seismic activity. It occurred more than four hours after the listening and recording had ended.

It must be concluded, that the rockburst activity was low on account of the reduced mining schedule -- too low to afford the necessary experience in the ground under survey.

However, the bursts that were located and surveyed were not the only ones that occurred at Lake Shore. There were several hundred during the seventeen months covered by this report. These were small bursts, bursts occurring in unused workings, or bursts too far in the wall to throw down loose. Such bursts occurred frequently with the blasting, and sometimes also in off-shift periods.

O-5 <u>Rockbursts Located, February 1944 to June 1945</u>

	Date		No.	Time	Class	Location	Rock Displac't
A	Feb.	9	350S	3:15 p.m.	-	4901E-6	42 tons
B	"	15	309C	3:32 a.m.	light	4704XC 4801E-5 4801E-Dr	5 tons 25 tons 40 tons
C	Mar.	11	351S	3:30 p.m.	-	4801E-7	15 tons
D	"	14	352S	3:03 p.m.	-	4902E-Dr at XC	total of 28 tons
E	Apr.	6	353S	3:33 p.m.	-	4502E-5.3	4 tons
F	"	18	354S	10: a.m.	-	4501E-5.3	small amount
G	"	20	355S	7:15 p.m.	-	5001E-Dr	15 tons
H	"	22	356S	3:30 p.m.	-	4801E-7	5 tons
I	"	29	357S	3:35 p.m.	-	4401E-6	10 tons
J	May	8	310C	3:45 p.m.	med'm	3209E-Dr 3202E-Dr	90 tons 30 tons
K	"	19	358S	10:05 a.m.	-	4501W-8.1	1 ton
L	June	1	359S	bet. shfts.	-	4701E-6	10 tons
M	"	2	360S	2:35 p.m.	-	4502E-5.3	2 tons
N	"	19	311C	11:01 a.m.	light	4701E-Dr 4801E-7	total of 100 tons
O	"	24	361S	2:35 p.m.	-	4501E-Dr	25 tons

	Date		No.	Time	Class	Location	Rock Displac't
P	Aug.	12	312C	11:08 a.m.	med'm	4001W-Dr 4201W-Dr 4201W-11	50 tons 25 tons 75 tons
Q	"	15	362S	2:35 p.m.	-	4501E-5.3	2 tons
R	"	29	363S	2:30 p.m.	-	4401E-6	10 tons
S	Sep.	6	313C	2:55 p.m.	med'm	4401E-Dr 4501E-Dr 4701E-Dr	5 tons 50 tons 5 tons
T	Oct.	5	364S	2:35 p.m.	-	4401E-6 4401E-Dr 4301E-Dr	all three small
U	"	25	314C	5:30 p.m.	med'm	4801E-Dr 4901E-Dr	100 tons 120 tons
V	Jan.	15	365S	bet. shfts.	-	4802E-Dr	10 tons
W	"	22	366S	9:30 a.m.	-	4701E-Dr	2 tons
X	Jan.	27	315C	2:50 p.m.	light	4301W-Dr 4408W-Dr	25 tons 5 tons
Y	Feb.	15	367S	3:33 p.m.	-	4901E-6.2	55 tons
Z	"	21	368S	bet. shfts.	-	5001W-Dr	30 tons
a	Apr.	9	369S	8:10 a.m.	-	4901W-9	2 tons
b	"	17	316C	2:05 p.m.	light	4001W-15	80 tons
c	"	20	370S	1:50 a.m.	-	No.4 shft 4825' +	25 pounds of concrete
d	May	22	317C	2:35 p.m.	med'm	4002E-Dr 4202E-Dr	50 tons 100 tons

	Date		No.	Time	Class	Location	Rock Displac't
e	"	26	318C	2:40 p.m.	light	3001W-Dr 3201W-1 3051XC 3075XC No. 1 shft	total given as much loose shaken down
f	"	28	319C	9:45 p.m.	med'm	4901E-Dr 4901E-6.3	250 tons cannot estimate
g	June	4	371S	9:10 a.m.	-	4301XC No. 1 shft	about 3 tons
h	"	26	320C	1:15 p.m.	light	5001W-8	70 tons

The above list shows only the burst that occurred during the period indicated and that were located and investigated at Lake Shore. The seismograms indicated many more small strain bursts, nearly all of which occurred with the blasting. Twelve of the bursts were identified as crush type and 22 as strain. The crush bursts were either light or medium; none were heavy.

The time of occurrence was associated with blasting on 18 occasions, 3 were 'between shifts' and 6 others were reported at times which were on the night off-shift. The remaining 7 occurred between 8 a.m. and 10 a.m. These are the ones that might have been detected by the microseismic service. They are listed as: F,K,N,P,W, a,g.

Of these, K,P, a, and g were located so far out of the territory under study that microseismims could not have been picked up from them. We may refer to the listening data for the other three: F,N, and W.

Burst F: April 18, 1944, No. 354S, 10 a.m., 4501E-5:3, 'small rock displacement'. Listening report No. 414 shows full-time listening on April 18 from 6:08 a.m. to 7:08 a.m. There was a moderately high count (20+) on H49 in 4401E6, showing D-type snaps. This hole is just above the burst. H50, just below it, had a count of 10+, a rather high value for this hole, which has shown a consistently low count; the activity here, moreover, included L-type snaps. On the whole, there was very little indication that a burst was imminent: it would certainly not have been predicted. It must be noted, however, that H50 is definitely in a non-sensitive location. The rockburst report shows that only a small amount of muck was blown off the north wall of stope 4501E5:3 at a point about half-way between 4450-ft. and 4575-ft. levels. This was definitely a minor disturbance.

Burst N: June 19, 1944, No. 311C, 11:01 a.m., 4701E-Dr and 4801E-7, total of 100 tons. Listening report No. 467 shows full-time listening on June 19, from 6:08 a.m. to 6:57 a.m.. The rockburst report shows that stope 4801E-7 had its south wall shattered from the 4700-ft. to the 4825-ft. levels, at section 7. Much loose was shaken down on 4701E-Dr also, above this stope. The holes nearest to this burst were: H55 in 4704XC, H51 in 4701E, and H53 in 4801E. There was a high count (20+) from H55, with L-type snaps included, and the operator notes: 'A large amount of distortion was recorded on all the records, but it registers more from the holes in section 6. Interference seems to be seismic'. H51 showed a count of 0+, the snaps being of the general type only. H53 is given exactly the same rating as H51. Except for the general interference mentioned by the operator and the high count on H55, there was no indication of this burst on the nearby geophones, some five hours before the burst. This is, of course, quite a long time, but there was no blasting in the meantime, or at the time of the burst. Fortunately, it occurred at lunch time, so no one was injured.

Burst W: Jan. 22, 1945, No. 366S, 9:30 a.m., 4701E-Dr., 2 tons. Listening report No. 649 shows full-time listening on Jan. 22, from 3:47 a.m. to 5:11 a.m. The comment is 'None very active'. The rockburst report shows that about two tons of rock was shaken off the drift wall at about section 4. The hole nearest to this burst is H40, or H56. H40 showed a count of 0+, the snaps being all G-type. The seismicity factor (adopted prior to the time of this burst) was given as 1D, about the lowest that can be assigned. The operator notes that: 'H40 does not pick up the tapper', indicating that the geophone there had deteriorated to a very low efficiency. H56, however, had a count of 20- and a factor of 4D.

Thus, after almost a year and a half of study by means of the subaudible method, during which every effort was made to have as complete coverage as possible of the territory assigned, only three bursts occurred in circumstances that afforded any chance of prediction. Of these, one (F) was very small. Another (W) was also small (2 tons displacement). The third (N) was of considerable magnitude — 100 tons — and even this was classed as 'light' in the rockburst report made by the mine engineers. Furthermore, it occurred some four hours after listening. For this there was some fair measure of prediction from H55, and the operator's comment of considerable interference in section 6, which he stated 'seems to be seismic'.

The conclusion seems to be that the rockburst activity was too low, on acount of the reduced mining schedule under wartime conditions, to afford the necessary experience in the block of ground under survey.

O-6 Test Holes, Nos. 55-107

H	DD	Date	Location and Wall	Depth	Remarks	
55	4038	Mar. 23'44	4704XC-E	53'	Drilled diagonally E40°S	A
56	2959	Mar. 23'44	4701E-4-S	72'+	Old DD hole	B
57		May 26'44	4702E-2-N	4'+	Bottleg to check 4702E-2-N	
58	4083	Aug. 7'44	4702E-2-N	56'	Special diagonal hole	C
59	4084	Aug. 9'44	4702E-4-S	30'3"	Replacing H39	D
60	4055	Aug. 16'44	4401E-6-S	30'	Replacing H49	E
61		Sep. 9'44	4502E-2-S	4'+	Bootleg replacing H43	
62	4112	Oct. 27'44	4502E-3-S	30'4"	Replacing H43 and H61	F
63	4111	Oct. 27'44	4502E-6-S	31'9"	Replacing H48	G
64	4124	Nov. 29'44	4802E-3-S	29'10"	Replacing H41	H
64A		Dec. 21'44	4802E-0-N	4'-	Replacing H64	I
65	?	Feb. 9'45	4701E-6-S	30'	Replacing H51	J
66		Dec. 15'44	4701W-1-N	4'+	Bootleg	K
67	?	"	4701W-1-N	30'+	Old DD hole	K
68		"	4701W-2-N	4'+	Bootleg	K
69		"	4701W-2-N	4'+	Bootleg	K
70		"	4702E-2-S	4'6"	NP - 4700	M
71		"	4702E-2-N	"	"	M
72		"	4702E-2-S	"	"	M

H	DD	Date	Location and Wall	Depth	Remarks	
73		"	4702E-2-N	"	"	M
74		"	4702E-2-S	"	"	M
75		"	4702E-3-N	"	"	M
76		"	4702E-3-S	"	"	M
77		"	4702E-3-N	"	"	M
78		"	4702E-3-S	"	"	M
79		"	4702E-3-N	"	"	M
80		"	4702E-3-S	"	"	M
81		"	4702E-4-N	"	"	M
82		"	4702E-4-S	"	"	M
83		"	4702E-4-N	"	"	M
84		"	4702E-4-S	"	"	M
85		"	4702E-4-N	"	"	M
86		"	4702E-4-S	"	"	M
87		"	4701W-1-S	"	Bootleg.	L
88		"	4701W-1-S	"	"	L
89		"	4702W-1-S	"	"	L
90		Feb. 1'45	4802E-2-S	"	NP - 4800	M
91		"	4802E-2-N	"	"	M
92		"	4802E-2-S	"	"	M
93		"	4802E-2-N	"	"	M

H	DD	Date	Location and Wall	Depth	Remarks	
94		Feb. 1'45	4802E-2-S	4'6"	NP - 4800	M
95		"	4802E-3-N	"	"	M
96		"	4802E-3-S	"	"	M
97		"	4802E-3-N	"	"	M
98		"	4802E-3-S	"	"	M
99		"	4802E-3-N	"	"	M
100		"	4802E-3-S	"	"	M
101		"	4802E-4-N	"	"	M
102		"	4802E-4-S	"	"	M
103		"	4802E-4-N	"	"	M
104		"	4802E-4-S	"	"	M
105		"	4802E-4-N	"	"	M
106		"	4802E-4-S	"	"	M
107		Feb. 9'45	4704XC-E	50'		N

A Log H55 0'-28' Badly broken and shattered porphyry; much lost core; 24 pulls; several weak seams, some stronger ones at 19', 38', and 27'

28'-53' Porphyry, less broken and shattered; 10 pulls; possible seams at 31', 38', and 45', no casing.

B H56 is an old DD hole in very good condition; canted slightly upward from the collar; cleaned out to a depth of 72' on or about March 23'44; extends to a much greater depth.

C H58 is a specially drilled DD hole running diagonally NW from a collar on the north wall of 4702E2; cuts diagonally behind the anvil of the tapper; emerges in 4700 main crosscut; hole cased at both ends to a depth of about 6'; core shows porphyry; small slips at 12' and 45'10".

D	Log H59	0'-30'3"	Badly broken up 50 per cent lost core; weak fractures at 19.5', 23', and 26.5'; no sludge return.
E	H60 is a DD hole run for sampling but taken over to replace H49, which was lost by closure; cants downward from the collar at about 19°.		
F	Log H62	0'-19'	Core slightly broken; good recovery; 7 pulls.
		19'-30'4"	Good solid rock.
G	Log H63	0'-7'4"	Very badly crushed porphyry; much lost core; 8 pulls; calcite seam 7'4".
		7'4"-23'	Not so badly broken; 11 pulls; strong break 16'-18'.
		23'-31'9"	Good ground; good ore recovery.
H	Log H64	0'-29'10"	Very badly broken all the way; 23 pulls; core losses up to 10" in places.

I H64A is a bootleg in 4802E near the main cross-cut and in the north wall.

J H65 was drilled in 4701E-6-S to replace H51, which had been lost owing to closure.

K H66, H67, H68, and H69 are holes, in order going west, in the north wall in 4701W1 to 4701W2. H67 is an old DD hole in good condition. It is over 30' deep, for a geophone was located in it at that depth. The others are old PD holes, shallow, but clean and in good condition.

L H87, H88, and H89 are old PD test holes, in order going west, in the south wall in 4701W1 to 4701W2. They are shallow, but clean and in good condition.

M Holes 70-86 were drilled in 4702E, the even-numbered holes in the south (hanging) wall, the odd-numbered holes in the north (foot) wall. H70 is 50' east of the main cross-cut and the successive even-numbered holes are at 30' intervals to H86. H71 is 65' east of the main cross-cut and the successive odd-numbered holes are at 30' intervals to H85. Holes 90-106 were drilled in 4802E, the even-numbered holes in the south wall, the odd-numbered holes in the north wall. H90 is 50' east of the main cross-cut and successive even-numbered holes are at 30' intervals to H106. H91 is 65' east of the main cross-cut and the successive odd-numbered holes are at 30' intervals to H105. All the holes 70-106 are PD type, as deep as they could be drilled in what was often very poor wall. The effective depths vary from 4' or less to about 6'. All were drilled for use in the Intensive Seismic Program (NP).

N H107 was drilled paralled to H55, which was lost owing to slippage along a diagonally crossing fault plane.

O-7 Recording from Holes 36-107, February '44 to June '45

The following table shows the number of days of recording from holes 36 to 107 for the period. In the original report, these data were recorded to show the particular days when each hole was employed during that time. In addition, a series of notes (43 in all) explained the lapses in operation for the various holes concerned.

It does not seem worth while to report the data so fully in the present publication. The information given serves to show the extent and continuity of the operation for the seventeen months concerned.

Where any of the new program (NP) holes are used, outside the regular NP schedule, they are reported by their proper numbers (e.g. H96 for February 1945); but where the group of holes is carried on the combined program, using the time switches and reducing the records to a composite photograph, the entry in the last line, after hole designation NP, covers them all.

Number of Recording Days for Holes 36 to 107

February 1'44 to June 18'45

H	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	T
36	29	23	19	21	29	31	31	30	31	30	31	18	...	...	...	...	...	323
38	29	23	19	12	29	31	31	30	31	30	31	18	...	...	...	...	...	314
40	29	31	30	31	30	31	31	30	31	30	31	31	28	23	30	31	18	496
41	29	31	30	16	11	31	31	30	11	...	...	...	...	...	...	...	...	220
42	29	31	30	31	22	31	31	30	11	27	31	31	28	31	21	31	18	464
43	29	29	24	31	30	31	29	...	...	...	...	...	...	...	...	...	...	203
44	29	29	24	31	30	31	31	30	31	30	31	31	28	27	28	31	18	490
46	14	11	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	25
47	29	31	30	31	30	31	16	...	...	...	...	...	...	...	10	31	11	250
48	29	29	24	31	30	31	29	24	6	...	...	...	...	...	...	...	...	233
49	29	23	19	21	29	23	...	...	...	...	...	...	...	...	...	...	...	144
50	29	28	24	31	30	31	31	30	31	30	31	31	28	27	28	31	18	489
51	29	31	14	31	30	31	31	30	31	30	31	31	9	...	...	...	...	359
52	29	31	30	16	22	31	31	30	11	1	12	...	...	...	19	31	18	312
53	29	31	30	31	30	31	31	30	11	22	31	31	28	31	21	31	18	467
54	29	31	30	31	30	31	31	30	21	30	31	31	28	28	30	31	18	491
55	...	4	30	25	24	...	28	7	...	21	...	...	...	...	...	...	...	139

H	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	T
56	...	...	10	25	26	31	31	30	31	30	31	31	28	31	19	...	16	370
57	...	...	...	...	27	31	...	...	...	...	...	...	...	...	...	...	...	58
58	...	...	...	...	...	...	27	3	10	...	...	...	...	...	...	...	...	40
59	...	...	...	...	...	...	15	30	21	30	31	31	28	28	30	28	18	290
60	...	...	...	...	...	...	14	30	31	30	31	18	...	...	...	...	...	154
61	...	...	...	...	...	...	...	24	31	2	...	...	...	...	...	...	...	57
62	...	...	...	...	...	...	...	...	...	23	31	31	28	31	28	31	18	221
63	...	...	...	...	...	...	...	...	...	23	31	31	28	31	28	31	18	221
64	...	...	...	...	...	...	...	...	...	...	19	15	28	31	21	...	...	114
64A	...	...	...	...	...	...	...	...	...	...	12	16	...	...	...	31	18	77
65	...	...	...	...	...	...	...	...	...	...	...	...	17	23	19	...	8	67
96	...	...	...	...	...	...	...	...	...	...	...	...	10	24	...	...	...	34
107	...	...	...	...	...	...	...	...	...	...	...	...	2		11	31	10	54
NP	...	...	...	...	...	...	...	...	...	...	...	..8	28	31	30	31	25	153

Note: At the time Report O was written, the April recording was in hand to April 18, only except for some NP values included in that line for the last entry.

O-8 Intensive Seismic Program

Experience at Lake Shore with the subaudible method showed that the geophones pick up the microseismims, and that the Obert recorders register them, at a rate varying with time and, for identical times, with place. Experiments by Obert at the Bureau of Mines, College Park, Md., have shown that pressure alone, without resulting cracking or change in strength, is the cause of microseismims.

Small samples of solid rock were cut into symmetrical blocks about 4"x2"x2", having plane-parallel faces, top and bottom. Holes were drilled in the blocks to accommodate regular Obert geophones. The blocks, carrying geophones connected to Obert recorders, were placed in a special hydraulic press, designed to hold high pressures with negligible loss, without keeping the pump running. The pressure was raised level by level, in steps usually of 2,000 lb./sq. in.to the point of failure of the specimen, a count being made, for five minutes at each level, of the number of microseismims heard through the headphones and recorded on the Teledeltos paper. It was definitely shown that:

> Microseismims are generated by pressure even where there is no apparent failure of the rock.

> The number of microseismims per minute (C/M) rises markedly at about 80 per cent of the bursting strength and continues to increase up to the point of failure.

The data from these experiments were made available to the writer at a conference arranged by Obert at Ishpeming, Mich., Oct. 27-29, 1944. The experiments were reported to the Department and to Lake Shore, and it was decided as a result to undertake a long-term experiment, with closely spaced holes, using as many geophones as possible, in a section of the mine known to be unstable. This was designated the Intensive Seismic Program.

The idea was to select a small two-level region of the mine, known to be unstable, to drill a large number of holes at 30-ft. intervals and to arrange to record daily throughout both off-shift periods from <u>any</u> nine holes on each level, using the stepping switches to yield a defined schedule of eleven recordings of equal length per hour for three hours in each period. This would yield, from the two levels, a 45-ft. strip of dual recording, showing records from eighteen different holes, with one hole on each level recording three times per hour as a check. Finally it was planned to mount each day's record on a specially designed board and to photograph it on an 8"x10" negative, making one print for the Mine and one for the Observatory. These prints were to be analysed in a brief monthly report, indicating the outstanding features.

It was hoped in this way to be able to select the eight holes on each level that could be shown by test to be in solid ground, yielding microseismim records, and to be sure, in the event of a burst in the region selected, of getting at least some record sections within the distance required to get a recording of the microseismim increase preceding the burst.

It seemed increasingly certain that the method, if it was to provide effective protection for the miners, would have to be carried on as a listening program conducted by competent operators serving the working stopes during shift hours. It was hoped that, by means of the new program, a very decisive proof would be forthcoming that the method would be effective.

A sample record appears as Figure 77. A printed explanation of the set-up, applicable to every day, appears on the left-hand side, as it does on every photograph. The explanation is thus immediately available whenever any record is being examined. The long-hand entries on the right hand side of the photograph are peculiar to that set of recording alone.

RESEARCH DATA FILES

The initial arrangements made between the Observatory and Lake Shore Mines provided that the surface seismograph records should become the property of the Observatory, and that all other data should be turned over to the Mine. In accordance with this agreement, and through a further arrangement at the time the research was terminated, all the Mine data were taken to Ottawa to be put in order for filing and reference. All the research data, except the records of the surface seismograph, were completed and finally delivered to Lake Shore Mines.

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STUDIES OF SEISMIC WAVE PROPAGATION FROM ROCKBURSTS

The perfecting of time-distance curves for short epicentral distance has always been a difficult problem where earthquakes are used as the energy source. It is never possible to determine with accuracy the exact time of an earthquake or its epicentre and depth of focus. In the case of short-distance tables, this uncertainty is serious. Furthermore, any such tables prepared for a given part of the earth are not likely to be universally applicable.

Experiments utilizing explosions as the source had been carried out by a number of investigators in various regions. This procedure has the advantage that the operator knows for each explosion not only its exact position, but also the exact time of the blast, thus permitting the use of sensitive seismographs with an open time scale. The results obtained differed from the generally accepted tables for nearby earthquakes by amounts greater than the errors of observation for the blast studies. It was thought that these differences were perhaps due, in part at least, to the difference in the nature of blasts and earthquakes.

Rockbursts, which are in effect miniature earthquakes, could, at least for those occurring in the Kirkland Lake area, be located precisely in depth as well as laterally. With an accurately controlled seismograph at that place, they could be timed very closely to the nearest second or better. If time-distance tables could be obtained for the traverse from Kirkland Lake to Ottawa, they would be of particular interest and value, since they would apply to the structure in and below the Canadian Shield. The studies outlined in Report H had shown that for the larger bursts good records could be obtained on the Benioff vertical at Ottawa and even on the Wood-Anderson at Seven Falls, Que.

It was decided to undertake a major research program, extending over several years, to determine travel times from the Kirkland Lake rockbursts. A modern seismograph vault was constructed on Hallick's property, in the town but away from the heavy traffic. Three-component Benioff seismographs, together with the requisite time-keeping and radio equipment, were installed. Hallick was placed in charge of the station, operating it in his spare time. A vault on solid rock was possible, as the soil was only from three to four feet deep; it is shown in Figure 81. Experience over the years (the station is still in operation in 1957, as part of the Canadian seismological service) has shown that highly sensitive seismographs can operate in this semi-underground vault without appreciable disturbance. The traverse from Kirkland Lake to Ottawa, with available roads indicated, is shown in Figure 78. Figure 79 shows an excellent record of a rockburst by a Benioff vertical seismograph at the Dominion Observatory: this burst occurred in a mine near Lyon Mountain, N.Y., 102 miles away.

According to the plan, temporary seismograph stations were to be established as nearly as possible along the line of the traverse and at ever-increasing distances from Kirkland Lake. Bases were to be cast in cement on bald rock outcrops in locations as far as possible from local disturbance. The project was begun in the spring of 1946, the first station being established at Dane, Ont., about 5 miles from Kirkland Lake.

A pre-fabricated movable hut was used to protect the instruments. Timing was maintained by chronometers, checked at least once a day by radio signals. Where possible, Hydro power was used for driving the drums, etc. Where it was not available, storage batteries operating through 60-cycle alternators were used. A typical station lay-out is illustrated in Figure 80.

In practice, a station was operated until a well-timed and well-located rockburst in the Kirkland Lake area had given sufficient data for the distance involved. Excellent cooperation was received from the various mining companies in the Kirkland Lake camp. The distance values were determined with the help of the Geodetic Survey of Canada.

While waiting for a rockburst to record at the operating station, the next site was prepared. Moving to a new station usually took about twelve hours.

The project was placed under the immediate direction of John H. Hodgson. His studies appeared in a series of published papers, as listed in the bibliography at the end of this publication.

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Report W

Laboratory Tests of Microseismic Method
for Detecting Critical Rock Pressures

by

Hodgson, Langford, and Bailey

The following report was prepared on the completion of a series of tests at College Park, Md., in February, 1947, with the collaboration of Dr. Obert and his associates at the U.S. Bureau of Mines. These experiments were similar to those previously reported in section O-8. The report was issued in mimeographed form for limited distribution only. It is included in the present publication to round out the evidence for and against the sub-audible method of detecting critical rock pressures.

W-1 Introduction

The microseismic (or subaudible) method of detecting critical rock pressures in mines subjected to rockbursts and rock falls was developed and applied in the United States by Leonard A. Obert, Senior Physicist, U.S. Bureau of Mines, Central Experimental Station, College Park, Md. He and his associates designed and built equipment for studying and recording the subaudible snapping, or 'microseismims', assumed to be associated with rocks under pressures approaching their crushing strength. Publications reporting the progress of this work are listed, with Obert as senior author, in the bibliography (Appendix).

In Canada, a long series of research studies on rockbursts was conducted during 1939 to 1945 inclusive at the Lake Shore mine, Kirkland Lake, Ontario, under the direction of Ernest A. Hodgson, Chief, Division of Seismology, Dominion Observatory, Ottawa. These experiments were requested by Lake Shore Mines Limited and were carried out at the company's expense. For the last half of the period, the microseismic method was used exclusively, the equipment being furnished through the collaboration of the U.S. Bureau of Mines, together with some designed and assembled by the Canadian investigators, chiefly by Zack E. Gibbs.

During the seven years of the program, and especially during the last half of the time, much was learned regarding rockbursts —the rate of development of critical pressures, their migration in the mine, the distances over which microseismims can be heard or recorded, the mechanism of bursts, etc. Full details of this work were reported in a series of mimeographed papers, which are presented here in condensed form.

It was concluded by the Canadian investigators that critical pressures can be detected in the mine by the microseismic method. In spite of the fact that the equipment is very sensitive, and that mine noises, even in vacated workings during off-shift hours, are quite numerous, microseismims, indicating increasingly critical pressures, can be distinguished by several criteria, of which the two most important are:

(a) They have a characteristic, high-pitched timbre, quite different from noises caused by falling rocks, distant drills, rock runs in ore passes, etc.

(b) When the pressures are becoming critical, microseismims are very numerous (sometimes more than 100 per min. at Lake Shore) and these high rates of incidence persist for longer periods, sometimes hours or even days.

Thus, integrated mine noises caused by the casual fall of bits of rock in the workings never become sufficiently numerous to be confused with a warning run of microseismims. Furthermore, when noises do become numerous, as in a run of rock in an ore pass, the disturbance is easily distinguished from microseismims by the brevity of the run and by the difference in timbre of the sound as heard over the headphones.

It was not concluded that prediction of rockbursts can be made by this method, at any rate in the Lake Shore mine, since critical pressures migrate quite rapidly, sometimes within a few hours, in a block-faulted mine of this kind. It was believed, however, that even for such a mine a method could be worked out that would indicate whether or not a given stope was under critical pressure at any given time. It is still Hodgson's belief that this could be done. In large measure, this persisting belief arises from the experience gained during the hundreds of hours of study spent underground at Lake Shore Mines.

On the other hand, it must be admitted that, with one or two exceptions, no crudescence of microseismims observed at Lake Shore was followed by a rockburst. Nevertheless, positive failure of the method to detect critical pressures was never definitely shown. That is to say, no burst of any consequence occurred, except in conjunction with blasts, under conditions where prediction should have been made and was not.

Hence, the net result of the Canadian research seems to be that those operating the equipment underground believe that it can be perfected to a point where critical pressures can be detected at a given time and in a given place, but that prediction of bursts cannot be made, since critical pressures so often shift without a burst taking place. Others believe that microseismims, if they exist as such, cannot be distinguished from casual mine noise, and that a high rate of incidence of snaps, however caused, cannot be interpreted as an indication of dangerously critical pressure, much less as a prediction of rockbursts.

As part of the research carried out by Obert and his associates, prepared rock specimens were subjected to compression in a hydraulic press at sustained stages from low values up to crushing magnitudes, as reported in section O-8 The results obtained may be regarded as supporting the belief that the basic theory of the microseismic method is sound. If this basic principle be admitted, further research would seem to be warranted.

In view of the differences of opinion indicated in the second paragraph above, a request was made through the Associate Committee on Geophysics of the National Research Council of Canada that the latter sponsor further laboratory experiments along the lines of the preceding paragraph, the work to be done at the U.S. Bureau of Mines, Eastern Experimental Station, College Park, Md., under the direction of Dr. Obert and his associates, using typical specimens of rocks from Canadian mines. It was proposed that observers be sent from Canada, in the persons of a seismologist, an electronics engineer, and a mining engineer. These suggestions were approved and arrangements were made through the President of the National Research Council of Canada with the Director of the U.S. Bureau of Mines. The three men appointed were: Ernest A. Hodgson, Seismologist, Dominion Observatory, Ottawa; George B. Langford, Professor of Mining Geology, University of Toronto; and Ralph Bailey, Physicist, of the National Research Council.

Samples of rock were secured from Little Long Lac mine, Geraldton, Lake Shore mine, Kirkland Lake, International Nickel Company, Copper Cliff, all in Ontario; Central Cadillac mine, Cadillac, and Sigma mine, Bourlamaque, in Quebec. Unfortunately, the samples from Little Long Lac were lost in transit, and were not found in time to be used in the experiments. Section W-8 gives the information supplied by each mine regarding its samples, together with the identification number assigned in each case by the Bureau of Mines, as BM-488, where 488.1, 488.2, 488.3 indicate the three experimental cylinders cut from the same sample. These cylinders are 1 5/8 inches in diameter and 3 1/4 inches in length. They are designated "Type 2D" since the length is twice the diameter. The area of the end of the cylinder is approximately 2 square inches. The samples supplied by the mines met the indicated specification that they were to be of a size and shape 'which will permit cutting a 6-in. cube, free from flaws, from each sample'.

The experimental cylinders were prepared at College Park early in January 1947, and thin sections were prepared and sent to a Bureau of Mines petrographer for study and report. The experiments were scheduled to be run Saturday and Sunday, February 1-2, and Saturday and Sunday, February 8-9, as only at these periods could the building be completely vacated. The work was carried through as planned.

W-2 Apparatus

The description of the apparatus has been prepared by Mr. Bailey, who has also arranged for the wiring diagrams included in the description of the electronic equipment.

A. The Electronic Equipment:

(a) The Geophone: The piezo-electric effect is utilized as the basis of this pickup device. It consists of Rochelle salt crystals in the usual two-layer buildup. A conducting leaf between the layers provides one electrical connection, and a grounded foil metal sheath the second. This crystal unit measures approximately 2.5 in. x 0.75 in. x 0.25 in. and is mounted in a metal housing. One end of the crystal unit is clamped and glued securely to a 1/4 in. platform, while the remainder swings free. This 'springboard' mounting produces a resonant frequency response of approximately 1,000 c.p.s. The geophones are of two forms, one enclosed in a metal pipe, the other designed to be clamped to a cylindrical specimen of Type 2D. Both types are shown in Figure 86.

(b) High-gain Amplifier: Signals from the geophone are applied to a conventional three-stage amplifier (6J7, 6J7, 6P5), having an over-all gain of 100,000. Each stage is well shielded and has decoupling in the plate supply lines. Attachment for high-impedance earphones is provided for listening purposes. See Figure 82 for wiring diagram (Bailey after Obert).

(c) Record Amplifier: This unit consists of a compressor, driver, rectifier, and power stages. The compressor stage consists of a duo-diode-pentode (6B8G) with part of its output rectified and applied back to its grid as a variable bias. The output of this stage is approximately a logarithmic function of the input. This is desirable so that large signals will not go off scale. The following stage (6P5) provides an impedance match with the rectifier (6ZY5). The rectified signal from this stage is applied as a bias to the output power stage (6F6). Variable response times can be achieved by selecting proper RC combinations in the grid circuit of the 6F6. See Figure 83 for wiring diagram (Bailey after Obert).

(d) Writer Circuit: The recorder consists of a magnetically-operated stylus and a moving tape. The stylus is an aluminum arm about 6 in. long, carrying a tension spring, pivots, and a small coil. This coil (which operates like a voice coil in a loudspeaker) provides the external plate impedance for the 6F6. Plate current variations in this power stage are therefore translated into mechanical movements of the stylus, which, in turn, records on Teledeltos paper. A telechron motor moves this tape at the rate of 1.5 in. per min.

For purposes of correlation of data and economy in design, each complete apparatus consists of two circuits or channels of similar construction. The two 6F6 plates of the recorder amplifiers are attached to terminals 1 and 2 of the writer circuit (see Figure 84 as drawn by Bailey after Obert). They thus obtain their plate supply voltage through L_1 and L_2 from source three. In the writer circuit (schematic), two of the arrows represent the styli of channels 1 and 2 respectively, while the third represents an additional stylus whose current supply is dependent upon a motor-driven switch arrangement to provide recorded time intervals on the margin of the tape. All three styli record on the same tape and are provided with current from source three.

(e) Power Pack: Operation is from a 110-volt A.C. source. A transformer (UTC-70518) provides for two 5-volt rectfier windings, two 6.3-volt windings, and a high-voltage winding. The filter consists of choke input, high LC combinations, and two regulator tubes (VR/150 and VR/75). Negative bias for the power stage (6F6) is obtained by a second 5V4, operating off a portion of the high-voltage transformer winding. For wiring diagram of the Power Pack see Figure 85 (Bailey after Obert).

B. Hydraulic Press:

The hydraulic press shown in Figure 86 is known as a Southwark Tate Emery Universal Testing Machine, product of the Baldwin Southwark Division, Baldwin Locomotive Works, Philadelphia. It is a rugged hydraulic press and sensitive pressure indicator. It can be obtained in a number of sizes; the one in use at College Park has a maximum scale of 120,000 pounds.

Briefly, the operation is as follows: oil is pumped into a hydraulic cylinder, thus pushing a ram upwards. Attached to the ram is a work table, carrying two compression columns and a top crosshead. Between the top crosshead and the table is an adjustable crosshead supported from the fixed base of the press by means of the threaded columns shown in Figure 86. The motor shown in the illustration permits positioning the adjustable crosshead when clamping a specimen in the press, above or below this crosshead. (The wires shown in the illustration have nothing to do with the experiments here reported; they were installed for other work).

When pressure is applied to the hydraulic cylinder, a specimen attached between the adjustable crosshead and the top crosshead will be put in tension by the upward travel of the top crosshead. One placed below the adjustable crosshead will be compressed by the upward movement of the table.

The pressure generated in the hydraulic cylinder is transmitted to the indicator dial. By closing a valve, the pressure can be maintained on the specimen for some minutes with very low percentage loss.

Three decade ranges are provided on the same press. The dial numbers exposed on the complete scale are automatically changed by the mechanism selecting the range. The three maximum pressures available on the College Park press are: 1,200, 12,000, and 120,000 pounds.

W-3 Preliminary Tests

The first of the preliminary tests was made late on Friday afternoon, January 31; the others were run during the following two days, Saturday and Sunday, February 1-2. They were conducted by Dr. Obert, with Maurice Shelton operating the press. Notes were made by the Canadian observers.

The first test resulted in a broken geophone crystal. Only two clamping geophones were available. Shortly after, the second was damaged. Other trouble also developed, necessitating further repairs. These interruptions resulted in a somewhat haphazard program of observing. The chief net result of the tests was that the observers became experienced in the technique involved and that a series of values of the bursting pressure was obtained for the specimens (in general two each) cut from the samples submitted from the Canadian mines. The description and the identification numbers of these samples are given in section W-8. The code used to describe the type of failure experienced in the bursting of a specimen is explained in section W-9. The crushing loads and the bursting code for each specimen broken in the preliminary tests are tabulated in section W-10.

W-4 Preparations for the Final Tests

The final tests were run Saturday and Sunday, February 8-9. As Dr. Obert had to be out of town on a business trip, his place was taken by Dr. Wilbur Duvall of his staff. As before, Shelton operated the press, and Langford, Bailey, and Hodgson were present throughout.

In the interval between the two series of tests, data forms had been prepared and a planned program laid out, designed to obtain as many qualitative data as possible with a minimum of risk to geophone crystals.

The planned program is outlined in section W-11. The form used for recording data is that appearing throughout section W-12. Prior to each test, the equipment was checked throughout by determining its response to the ticking of a watch laid in a prescribed relationship to the geophone. Although this is by no means a quantitative test, and fails to indicate the seat of any trouble that may occur, it is, nevertheless, a definite indication that everything is in good order if certain minimum criteria are met, e.g. if the observer can hear the watch so placed, when listening with the earphones, having the attenuator set at 47.5 Db.

Routine checking of the equipment between successive tests served to ensure that all recording and listening was done under optimum conditions.

W-5 Final Tests

It was felt that all data obtained in the final tests should be presented in this report, both the notes and the record tape. The forms appearing in section W-12 give the detailed notes on every specimen broken during the second week-end. The reproduction of the record tape sections in Figure 88 is complete except for four one-minute sections made during the earlier tests on specimen 17. These were spoiled in mounting and had to be discarded.

The following comments should be read with reference to the data sheets in section W-12 and to Figure 88. In the data sheets, pressures are given either in full or in decimals of thousands of pounds, e.g. 62.7 or 62,700 pounds. These values always refer to the dial readings. As the specimen cylinders are two square inches in cross-section, the given values must be divided by two to give pounds per square inch.

The following points should be noted:

A. Twenty-two specimens are included in these final experiments, of which eighteen were type 2D, the others type X. All the 2D specimens were from samples sent from Canadian mines, Nos. 11 and 18 being from the same sample (N-3). Only one X-shaped specimen, No. 17, was from Canadian samples.

B. The three most active specimens were all X-shaped. All were granite, No. 19 from North Carolina, No. 20 from Mineville, N.Y., and No. 21 from Lyon Mountain, N.Y.

C. Most of the specimens began to show marked activity at about 50 per cent of their bursting strength, with high activity after 80 per cent was reached. This is shown most markedly in the case of specimens 7,8,12, and 16. These either burst with the geophone recording, or gave such swarms of warning microseismims that the pressure was released in time to avoid such an eventuality. Tests 34 and 40 (Figure 88) show evidence at the right-hand end of each that the specimen was close to bursting. The zero line is lifted. See similar evidence in Tests 87, 109, and 110.

D. The microseismims were generally more numerous just at the beginning of a minute test run. The valve being shut after a fairly rapid rise of pressure, the activity was generally greater in the initial part of the run. See Tests: 59, 93, 94, 95, 96, 99, 103, 105, Figure 88. See Tests 40, 52, 91 for reverse case.

E. Where the pressure was left at a given level for some time, the activity tended to be sporadic. See Tests: 68, 70, 106.

F. A release of pressure, after a sustained level had been maintained for a minute or more, caused a temporary swarm of microseismims. These soon died out if the valve was again closed, holding the pressure at the decreased value.

G. It seems necessary to correct a mistaken impression as to the conduction of microseismims across a rock-steel interface. In the case of specimen No. 12, the geophone was not successful in picking up the subaudible snaps (known, however, to be actively occurring in the specimen) when the geophone was laid on the table of the press. Later, when in contact with the side of the specimen under pressure, or when in contact with a specimen not under pressure; but itself in contact with one that was, the microseismims travelled across the interfaces; rock-to-rock, rock-to-rock, and rock-to-geophone. At the time, Hodgson insisted that there was something wrong with the first case, for it was quite out of line with his experiences in the mine.

On examining the notes for specimen No. 20, it will be seen (Note D) that there was good communication through the rock-steel interface. And this will be evident on referring to Test No. 96, where the record was made with the geophone lying free on the table of the press. It is not known, and it is now impossible to say, why there was no pick-up in the first part of the experiment on specimen No. 12.

H. In general, the specimen did not break on the cemented joints. Specimen No. 9 was an exception; it did break on a joint.

I. In the case of specimen No. 22, Langford pointed out that there was evidence of a chlorite fault with a displacement of a quarter-inch in the exposed face of the coned fragment.

J. Sample N-3, from the International Nickel Company, showed no warning microseismims on the record (see No. 11 in section W-12). Warning microseismims were heard, but the gain (held constant or approximately so throughout the entire series) was not great enough to permit recording. The microseismims were sufficiently pronounced in this case (as heard in the headphones) to cause those listening to call for a release of pressure — too late to save the specimen, as shown in the notes.

K. Microseismims were always generated in swarms when a specimen was spalling, but they also appeared in swarms in the case of specimens that were, apparently, not changed in any way by the pressure, for example, No. 5. When such specimens were removed from the press and examined, no cracks were visible, the specimen rang true and it did not break when dropped on the floor.

L. Evidently the 2D shape is much more satisfactory than the X type, in addition to being much more easily prepared. In the X type, the wings tend to crack off and the specimen spalls on the inside of the geophone channels. It would be most interesting to test carefully made cylindrical specimens of much larger diameter in a heavier press, and to carry through an extended research on a much wider scale, making a determined effort to discover what mechanism, other than spalling or cracking, can cause these characteristic subaudible snaps.

M. Thin specimens of each of the samples from the Canadian mines were studied by a petrographer of the U.S. Bureau of Mines. His report is given in full in section W-13.

W-16 Report by Professor Langford

The details of the experiments carried out at College Park, and descriptions of the apparatus, have been capably given by Dr. E.A. Hodgson and Mr. Ralph Bailey. My participation in this work was as an observer, and my comments must be in the nature of observations based on other people's work.

There is no doubt that microseismims are created in rock specimens under compressive stress, and that the number and intensity of the microseismims increases as the rock approaches the point of failure. This was not the case in every specimen, but in almost all. The microseismims, when heard in the headphones, have characteristic sounds that are similar for all types of rocks tested. It is said that they can be distinguished from mine noises when using the apparatus underground. I have made no underground observations, so cannot speak from experience. However, I believe it should be possible for a trained operator to distinguish microseismims from mine noises.

Petrographic studies are being made of all the specimens tested by the officer who makes such studies on all the rocks tested for microseismims at the Experimental Station. Although he was not as familiar with the Precambrian rock types as with younger rocks, it was felt that his observations would be especially valuable from a comparative viewpoint. From the work he has done for the Bureau of Mines, the petrographer has drawn the following general conclusions:

(a) Coarse-grained rocks are weaker than fine-grained rocks of the same type.
(b) Foliated rocks are weaker than massive rocks.
(c) Hydrothermally altered rocks are weaker than fresh rocks.

He pointed out that these observations were very general, as they were many other features that had important influences on rock strength. However, these were the only rules that have much semblance of general application. Examination of the slides was not completed as this part of the report was written, but in a preliminary discussion with the petrographer it seemed likely that the general conclusions would apply to the Precambrian rocks.

The conclusions I would draw from my observations of the experiments may be stated as follows:

A. Existing data on microseismims are very meagre, and of a qualitative nature only. We have no definite knowledge of their place and mode of origin, neither do we know what they actually mean in terms of stress or strain. To attempt to apply such a relatively unknown theory to the solution of a practical problem is not wise. It may lead to many false alarms and a discrediting of the whole. It would be wiser to know more about microseismims before trying to interpret those heard in mines.

B. Microseismims are only one aspect of stressed rocks. Our knowledge of the behaviour of rocks under pressure is very fragmentary. We know something about isolated phases of the problem, but there are many gaps in our knowledge. The subject is of vital interest to the geologist and geophysicist, as well as to the mining engineer. All the Precambrian rocks have been, and many still are, under considerable stress. We can never have a complete understanding of these rocks until we know a great deal more about their behaviour under stress.

C. A proper understanding of the tectonics of our Precambrian area, which in turn is closely allied to the subject of ore deposits, cannot be gained without a great deal of experimentation on rocks under stress.

D. We have no proper theories of rock failure. The so-called Strain Ellipsoid theory was formulated to explain the conditions that existed up to the point of rupture. In dealing with faults, shears, fractures, etc., we are dealing with material after failure. Present theories are very inadequate.

There is a great scope for research on rocks under pressure. This should not be undertaken for the sole purpose of predicting rockbursts. In the first place, one might be chasing a will-o-the-wisp, and the failure to get positive results might bring discredit on the whole program. Secondly, a broad and basic scientific investigation of rocks under pressure is needed, and the importance of the problem to the geologist and geophysicist may be lost sight of if it is undertaken merely from the rockburst angle.

Economic and structural geology badly need the stimulation that can come only from scientific contributions to our basic knowledge. There are virtually no organizations today doing fundamental research on the problems of the Canadian Shield. This Shield is the largest and richest Precambrian area in the world. Canada should be the fountainhead for scientific research on all problems related to Precambrian geology. The mining industry, if it is to continue, must find new mines. The best place to find them is under the areas of overburden. Our present geological and geophysical knowledge is not equal to the task. In all this vast need, the problem of the behaviour of rocks under pressure is an important item.

I have discussed these conclusions with R.G.K. Morrison, of Mysore, India, a recognized authoirty on the practical side of rockbursts. He is in entire agreement with them.

W-7 Comments by Bailey and Hodgson

Professor Langford's two colleagues fully concur with his views and conclusions, as set forth above. They are such as could only properly be formulated by a geologist.

At the same time, there are two points that should be brought out, in view of the reasons for conducting the experiments at College Park at this time. It may reasonably be objected that our knowledge of microseismims is by no means meagre; but, on the other hand, there is no doubt that 'we have no definite knowledge of their place and mode of origin, neither do we know what they actually mean in terms of stress and strain.'

It has been suggested in some quarters that microseismims may simply be some form of interference arising in the electronics equipment. Here, in his own special field, Mr. Bailey is in a position to state that this is quite out of the question. Microseismims, whatever be the mechanism of their origin, arise in the specimen under pressure.

As regards Professor Langford's remarks on the field of research on rocks under pressure (that they should not be undertaken specifically for the purpose of finding a predictor for rockbursts), his fellow delegates are in complete agreement. It is to be hoped that the type of research he has outlined may be undertaken and prosecuted with vigor.

W-8 Identification of Samples Received

Sample Sources and Dates Received

Designation	
L1-L7	Lake Shore Mines, Kirkland Lake, Ontario, October 7, 1946.
C1-C3	Central Cadillac Mines, Cadillac, Quebec, December 30, 1946.
N1-N6	International Nickel Company, Copper Cliff, Ontario, January 6, 1947.
S1-S2	Sigma Mines, Bourlamaque, Quebec, January 14, 1947.

SD-No.	BM-No.	Identification
L1	BM-487	Basic Syenite - prepared specimen
L2	-488	Basic Syenite - rough
L3	-489	Syenite Porphyry - rough
L4	-490	Syenite Porphyry -rough
L5	-491	Red Syenite - rough
L6	-492	Red Syenite - rough
L7	-493	Altered Syenite Porphyry - rough
C1	BM-484	Altered Aplite
C2	-485	Volcanic Sediments
C3	-486	Banded Iron
N1	BM-499	Quartzite - Horizon 2400 ft. below surface
N2	-500	Rhyolite - 2400 ft. below surface
N3	-501	Peridotite - 1200 ft. below surface
N4	-502	Granite - 1500 ft. below surface
N5	-503	Norite - 4000 ft. below surface
N6	-504	Gabbro - 5000 ft. below surface
S1	BM-508	Intrusive diorite-porphyry (known as Type C), from 350 ft. below surface in central part of the mine. Composed essentially of plagioclase crystals with minor hornblende; considered secondary alteration to carbonate, chlorate, and minor quartz.
S2	-509	Intrusive diorite-porphyry (known as Type C), from 1850 ft. below surface in central part of the mine. Composition as in S1, showing plagioclase, more hornblende, but less carbonate and chlorite alteration.

In addition to the above tabulated material and data, the International Nickel Company included a hand specimen of sulphide ore, too small to be used in the experiments; and Central Cadillac Mines furnished a map of its workings.

Three 2D-type cylinders were cut from each sample, of which two were run in the preliminary tests and one in the final, with the following exceptions:

(a) None were cut from sample L-1, as it was not possible to obtain a full-sized cylinder from the prepared specimen sent.

(b) Two cylinders only were obtained from samples C1 and N6, the other cores breaking short. One of each was run in the preliminary series and one in the final tests.

(c) One cylinder only was unbroken as cut from sample C3. It was run in the final tests.

(d) Five cylinders in all were cut from sample N3. Three of these were run in the preliminary tests and two in the final series.

(e) An X-type specimen was cut from sample L4. It was run in the final tests.

In addition to the samples from Canadian mines, several samples from other sources were tested, as follows:

(a) BM-475, Mt. Airy Granite from North Carolina, from which three 2D-type cylinders and one X-type specimen were cut. Of these, the three cylinders were run in the preliminary series and the X-type was tested in the final run.

(b) BM-390, Granite from a depth of 1813 ft. in the hangingwall of the mine of the Republic Steel Corporation, at Lyon Mountain, N.Y., from which one X-type specimen was cut, which was tested in the final series.

(c) BM-391, Granite from the hangingwall in the Upper Harmony Vein of the mine of the Republic Steel Corporation at Mineville, N.Y., from which one X-type specimen was cut, which was run in the final series of tests.

W-9 Code Designating Type of Rock Collapse

As a brief indication of the type of rock collapse under pressure, a three-digit designation was assigned according to the following schedule. It was used in connection with the 2D-type specimens only.

Type of Failure	Type of Cone	Fragmentation
1 Slow crush	1 Two cones	1 Grain size
2 Crush	2 One cone	2 Small fragments
3 Shatter	3 Asymmetric cones	3 Large fragments
4 Violent shatter	4 No cones	4 Pieces

For example: 424 indicates that the specimen shattered violently, producing only one cone and several good-sized pieces.

W-10 Table of Comparative Data Obtained in Preliminary Tests

The following table summarizes the burst data obtained from the experiments performed during the first week-end. The columns, in order below, give the BM-numbers, the Sample Designation numbers, the values of the crush pressures (CP-1, CP-2, CP-3) for each of the test cylinders of each sample that were broken in the preliminary tests, and the Burst Code Designation (BCD-1, BCD-2, BCD-3) for each cylinder of the sample broken in those tests.

BM-No.	SD-No.	CP-1	CP-2	CP-3	BCD-1	BCD-2	BCD-3
484	C1	55.9	---	---	(423)	---	---
485	C2	36.6	48.8	---	(244)	(344)	---
488	L2	50.0	60.8	---	(344)	(323)	---
489	L3	116.2	119.0	---	(421)	(444)	---
490	L4	80.6	113.0	---	(421)	(422)	---
491	L5	110.0	* 98.0	---	(443)	(412)	---
492	L6	47.9	---	70.0	(323)	---	(422)
493	L7	40.0	91.0	---	(324)	(442)	---
499	N1	57.1	° 35.0	---	(344)	#	---
500	N2	77.8	80.0	---	(412)	(423)	---
501	N3	84.9	24.0	78.4	(443)	(144)	(423)
502	N4	96.0	91.0	---	(422)	(412)	---
503	N5	67.8	70.0	---	(412)	(412)	---
504	N6	116.4	---	---	(422)	---	---

* Pronounced slip plane showing gouge.

° Cylinder developed a crack.

\# Pressure not carried up to bursting, but a fracture was visible.

BM-No.	SD-No.	CP - 1	CP - 2	CP - 3	BCD-1	BCD-2	BCD-3
508	S1	65.0	64.0	—	(412)	(424)	—
509	S2	23.2	54.2	—	(344)	(424)	—

W-11 Test Procedure

The procedure in the preliminary tests was directed mainly towards determining the crushing strength of two of the three test cylinders prepared from each of the Canadian samples. These tests yielded two values of the load required to crush a cylinder of each sample, together with data from a somewhat haphazard program of listening and recording with the instrumental equipment at various pressure levels below that of bursting. Listening was carried out in many cases close to the breakdown. When swarms of microseismims gave sufficient warning, the geophone was removed from the specimen cylinder and the pressure again applied at slowly increasing values until the cylinder broke. In two such cases, the break occurred with the geophone in place. In each case, the crystal was damaged and had to be replaced.

Thus, in the preliminary tests, two values of the crushing load were obtained, in general, for each sample, leaving one prepared cylinder of each for the final tests. (In the case of BM-501, all three cylinders were broken. Two further specimens of this sample were prepared for the final tests). A general idea was also gained of the behaviour under load of each specimen type. From the data obtained, it became possible to estimate with reasonable accuracy the maximum safe load that could be applied to the remaining cylinder. Forms were prepared for recording data and the following procedure was adopted as standard for the final tests. These were arranged with a view to obtaining all possible data from each sample, without danger of breaking the geophone crystal.

Referring to the forms used in reporting the results of the final tests (see section W-12), the procedure adopted was as follows:

(a) Calibrate the geophone by placing it at one end of a piece of board about 3"x6", lying on the bed of the press, having the concavity of the geophone arch downward. Place a watch at the other end of the board, about 4 inches away from the geophone. In the line marked Calibration, enter the number of the geophone and the channel used, at G and C respectively. If the equipment is all in order, the watch should be heard at an attenuation of 47.5 Db. After AMn enter the minimum value of the attenuator setting at which the watch ticks just begin to register on the recording apparatus. After AMx enter the value of the attenuator setting that will just allow the watch to record full scale.

(b) Assign a serial specimen number for reference and enter it, together with the data as to sample source, specimen shape, and rock type, in the appropriate spaces on the top line of the form.

(c) In the first column, enter the BM-number for the sample concerned, followed in the three lines below by the terminal decimals of that number. In the second column, list the value of the crush load (CL) obtained for each of the test cylinders already broken, entering the value for each cylinder opposite the terminal decimal of the BM-number concerned. Enter a T in the second column to designate the specimen represented in the current tests for the form concerned.

(d) By examining the notes of the preliminary tests and noting the crush loads required to break the two previous cylinders of that sample, determine an Estimated Maximum Safe Load (EMSL) to be entered in the space provided in column 2.

(e) In the column headed TL (Test Loads) compute and enter, in order descending, the following fractions of the EMSL, namely:

.5	.8	1.0	1.2
.6	1.0	1.2	1.4
.7			
.8			

(f) The set having been calibrated prior to each specimen run, raise the pressure to the first TL-value, i.e. half the EMSL. Run a carefully guarded test, listening and recording for at least one full minute, and noting the attenuator setting used under AR (Attenuator Reading) and the channel used under C. Enter the total number of microseismims heard in the minute interval under the heading AN (Audible Number). If the run is longer than a minute, the number entered is to be the average per minute. Enter under RN the recorded number, selecting and indicating the minute used where the run is greater than a minute. If any room noises should cause offsets on the tape, they are to be marked in pencil on the record. Make every effort to keep the tape clear of all such disturbances. If it is necessary to repeat any test, retain the acceptable data only on the forms and mark the tape xxxxx for the section abandoned. Repeat the procedure of this section for the next three lines, dealing with .6, .7, and .8, respectively of the EMSL.

(g) Lower the pressure to a safe value, remove the geophone, raise the pressure to the full value of the EMSL, then lower the pressure again to a safe value, replace the geophone, and repeat the procedure of section (F) above for a repeat measure at .8 (EMSL) and for a measure at 1.0 (EMSL). These measures complete the entries for Reset No. 1. Follow the procedure of this section for the values under Reset No. 2 and Reset No. 3. using the test pressures already computed and entered in column 3.

(h) In the event that the specimen has not yet been broken, remove the geophone and carry the pressure up to the bursting point. Enter that value after the heading Crush Load. Determine the code designation for the burst and enter it after the heading Code. Compute for each test load used the percentage value of TL/CL and enter these in the column headed BV (percentage of bursting value).

(i) Keep a close record of all observed data in each test under the heading Notes. If space is too limited, assign to such notes an index letter designating full entries in the lines at the bottom of the tabulation.

(j) In the column headed T enter the serial number of the test, to be used later to identify the record section concerned.

W-12 Data Forms

No. 1 Source=C1 Shape=2D Type=Altered Aplite

BM-484	CL	TL	AN	RN	AR	C	Notes	BV	T
.1	55.9	25.0	34	4	15	B	Very faint snaps	56	1
.2	T	30.0	23	3	15	B	Very faint snaps	67	2
.3		35.0	46	4	15	B	Very faint snaps	78	3
EMSL	50.0	40.0	62	30	15	B	A, B, C	89	4

Reset No. 1 ....

Reset No. 2 ....

Crush Load=45.0 Code=244 Calibration: G=1, G=B, AMn=45, AMX=32

Note: A. Only two specimens were obtained from sample C1, and only one of these was broken in the preliminary tests.

B. Some medium-sized snaps registered at 40,000.

C. In Reset No. 1, the pressure was raised to 50,000 without breaking the specimen. It was lowered to 35,000 and then rapidly raised. The specimen burst at 45,000. The geophone crystal was broken by the burst. Pending repair, Geophone 2 (of the clamp-on style, as was No. 1) was used for the further experiments.

Note: The complete form is shown for specimen No. 1, although in this case there are no entries in the reset sections. From this point on, only that part of each form will be given in which some data are entered. This will conserve space without the omission of any experimental data.

No. 2 Source=C2 Shape=2D Type-Volcanic Sediments

BM-485	CL	TL	AN	RN	AR	C	Notes	BV	T
.1	36.6	20.0	25	5	15	B	Poor record	51	5
.2	48.8	24.0	16	4	15	B	Good record	61	6
.3	T	28.0	74	N	15	B	A,B	71	7
EMSL	40.0	32.0	80	N	15	B	C	81	8

Crush Load=39.3 Code=344 Calibration: G=2, G=B, AMn=45 AMx-22

Notes: A. The letter N in the column headed RN indicates that the recorded snaps were numerous.
B. Very active during this test, especially at the beginning.
C. Good record; some snaps 3/4 scale.

No. 3 Source=L2 Shape=2D Type=Basic Syenite

BM-488	CL	TL	AN	RN	AR	C	Notes	BV	T
.1	50.0	25.0			15	B	A	42	9
.2	60.8	30.0	3	1	15	B	B	50	10
.3	T	35.0	20	9	15	B	C	58	11
EMSL	50.0	40.0	30	21	15	B	D	66	12

No. 3 Source=12 Shape=2D Type=Basic Syenite

Reset No. 1	40.0	10	15	15	B	E	66	13
	50.0	C	N	15	B	F	83	14

Crush Load=60.0 Code-423 Calibration: G=2, C=B, AMn=45, AMx=22

Notes: A. Poor recording; a few weak snaps.
B. Recording interrupted by wind.
C. Recording only fair; one 3/4-scale snap near the end of the record.
D. One nearly full-scale snap recorded.
E. One 3/4-scale snap recorded; much trash on record; wind was howling.
F. Record good. All above a trashy zero line is real.
G. Before testing this specimen, it was observed to have a joint plane bevelling off from about central position on the end of the specimen to come out on the curved side about 3/4 of the way down. The joint was solidly cemented (natural). The specimen did not break at the joint.

No. 4 Source=L3 Shape=2D Type=Syenite Porphyry

BM-489	CL	TL	AN	RN	AR	C	Notes	BV	T
.1	116.2	50.0	C		15	B	A. Faint snaps	50	15
.2	119.0	60.0	C	7	15	B	B	60	16
.3	T	70.0	C	9	15	B	Some snaps half scale	70	17
EMSL	100.0	80.0	70	N	15	B	Record good	80	18

Crush Load=100.0 Code=422 Calibration: G=2, C=B, AMn=40, AM_x=25

Notes: A. The letter C in columns AN or RN indicates that the audible snaps or the recorded ones, as the case may be, are continuous.
B. Two or three 3/4 scale snaps on record.

No. 5 Source=L4 Shape=2D Type-Syenite Porphyry

BM-490	CL	TL	AN	RN	AR	C	Notes	BV	T
.1	80.6	40.0			15	B	A		19
.2	113.0	48.0	20		15	B	B		20
.3	T	56.0	50	3	20	B	C		21
EMSL	80.0	64.0	70	2	20	B	D		23
Reset No. 1		64.0	15	7	20	B	E		23
		80.0	40	12	20	B	F		24
Reset No. 2		80.0	60	27	20	B	G		25
		96.0	80	22	20	B	H		26

Crush Load= Code= Calibration: G= , C= , AMn= , AMx=

Notes: A. A few faint snaps heard. Record poor; much trash.
B. Some 1/4-scale snaps, but record is trashy.
C. Record now OK, except for parts marked x.
D. Two snaps about half-scale.
E. Most of the snapping was recorded; not very lively.
F. One snap recorded full scale.
G. Record is good during this test.
H. Record good, about 3/4-scale.

This specimen was the cylinder which was fluted owing to a flaw in the diamond drill. It started to crack audibly at 95,000. It was then run up to 100,000 in the expectation that it would break. It did not. It was brought down to 80,000 and the geophone put in place. The geophone was removed after the last test at 96,000. The pressure was run up to 112,000 with some audible snapping. The specimen did not break. Specimen preserved.

No. 6 Source=L5 Shape=2D Type=Red Syenite

BM-491	CL	TL	AN	RN	AR	C	Notes	BV	T
.1	110.0	50.0		1	20	B	A	52	27
.2	98.0	60.0	C	4	20	B	B	63	28
.3	T	70.0		14	20	B	C	73	29
EMSL	100.0	80.0	30	14	20	B	D	83	30

Crush Load=96.0 Code=443 Calibration: G=2, C=B, AMn=45, AMx=25

Notes: A. Continuous faint snaps. Record OK.
B. Some snaps recorded full scale.
C. Quiet, record poor, interference from drive belt.
D. Number of snaps full scale at beginning, then falling off in rate of incidence.

A slip plane was observed on the face of the crushed cone of this specimen. Gouge in plane. The specimen broke very violently, breaking the glass shield.

No. 7 Source=L6 Shape=2D Type=Red Syenite

BM-492	CL	TL	AN	RN	AR	C	Notes	BV	T
.1	47.9	25.0	C	10	20	B	A	63	31
.2	T	30.0	10	4	20	B	B	75	32
.3	70.0	35.0	C	17	20	B	C	87	33
EMSL	50.0	40.0	C	C	20	B	Good record	100	34

Crush Load=40.0 Code=213 Calibration: G=2, C=B, AMn=42, AMx=17

Notes: A. Faint snaps. Ten sharp ones recorded.
B. No snaps of any size recorded. Four small ones.
C. Record good. Snaps recorded about 1/4-scale at the beginning of the record, and about 1/2-scale at the end.

The specimen was run for about three minutes at 40,000. A good record was obtained. It grew progressively more active and then burst. Prior to the test, the specimen was observed to have cracks (cemented naturally) across the end and traversing the speci-

No. 8 Source=L7 Shape=2D Type=Altered Syenite Porphyry

BM-493	CL	TL	AN	RN	AR	C	Notes	BV	T
.1	40.0	25.0	2	5	20	B	A	57	35
.2	91.0	30.0	20	6	20	B	Record OK	68	36
.3	T	35.0	N	32	20	B	B	79	37
EMSL	50.0	40.0	N	30	20	B	C	91	38
Reset No. 1		40.0		26	20	B	D	91	39
		45.0	N	N	20	B	E		

Crush Load=44.0 Code-324 Calibration: G=2, C=B, AMn=42, AMx=17

Notes: A. Record OK where not x'd out.
B. Some snaps recorded full scale.
C. Record is good; rapid falling off of rate of incidence.
D. Very quiet. Record poor, owing to drive belt interference.
E. This specimen was very noisy at 45,000. There was a sudden build-up, indicating failure, so pressure was released and specimen removed. Cracks were observed from end to end. Replaced in press. Broke at 44,000. In the Reset No. 1, the specimen was run up to 50,000. A chip broke off and then the specimen broke later at the lower value indicated.

No. 9 Source=N1 Shape=2D Type=Quartzite from 2400' depth

BM-499	CL	TL	AN	RN	AR	C	Notes	BV	T
.1	57.1	20.0	15	0	20	B		39	41
.2	35 +	24.0	10	2	20	B	A	47	42
.3	T	28.0			20	B	B	55	43
EMSL	40.0	32.0	20	7	20	B	Signs of recording	63	44
Reset No. 1		32.0			20	B	C	63	45
		40.0	6	9	20	B	Recorded only a few	78	46
Reset No. 2							D		
		48.0	C	14	20	B	Record good; all real	94	47

Crush Load=51.0 Code=344 Calibration: G=2, C=B, AMn=45, AMx=30

Notes: A. Two snaps recorded, about 1/4-scale.
B. Trouble with carbon on stylus; interfered with the recording.
C. Very few audible snaps; none recorded.
D. Omitted this test. Did not reset. The specimen broke on a joint. Gouge on face of the cone. One such joint was noticed before the specimen was tested.

No. 10 Source=N2 Shape=2D Type=Rhyolite from 2400' depth

BM-500	CL	TL	AN	RN	AR	C	Notes	BV	T
.1	77.8	35.0	50	0	20	B	No record	45	48
.2	80.0	42.0	32	3	20	B	A	54	49
.3	T	49.0	30	3	20	P	B	63	50

No. 10 Source=N2 Shape=2D Type=Rhyolite from 2400' depth

EMSL	70.0	56.0	50	2	20	B	Very faint	72	51
Reset No. 1		70.0	C	N	20	B	Very active	89	52

Crush Load=78.0 Code=412 Calibration: G=2, C=B, AMn=45, AMx=32

Notes: A. Twenty-five snaps in first half minute, five in next quarter minute, two in last quarter.
B. Faint snaps. Recording OK.

Snapping was very pronounced at 70,000. Pressure lowered to 65,000, then brought back to 70,000 and held for a time, but the snapping had ceased. Pronounced joint noted on untested specimen.

No. 11 Source=N3 Shape-2D Type=Peridotite from 1200' depth

BM-501	CL	TL	AN	RN	AR	C	Notes	BV	T
.1	84.2	35.0	C	0	20	B	None recorded	47	53
.2	24.0	42.0	C	0	20	B	Very weak snaps	56	54
.3	78.4	49.0	C	0	20	B	Even more quiet	65	55
EMSL	70.0	56.0	C	0	20	B	Very quiet	75	56
Reset No. 1		65.0	C	1	20	B	A	87	57
		70.0	C	1	20	B	Very quiet	93	58

Crush Load=75.0 Code=444 Calibration: G=2, C=B, AMn=45, AMx=25

Notes: A. Did not reset. Very quiet.

Pressure continued without resetting to 75,000. Burst was very pronounced; surges appeared just before it. The pressure was lifted but not quickly enough.

Five specimens in all from this sample were broken. The test here outlined was on specimen BM-501.4. In every case, there was ample warning so far as the audible snapping was concerned, but the gain was not high enough to register the relatively faint snaps generated by this type of rock.

No. 12 Source=N4 Shape=2D Type=Granite from 1500' depth

BM-502	CL	TL	AN	RN	AR	C	Notes	BV	T
.1	96.0	45.0	C	7	20	B	A	67	59
.2	91.0	54.0	C	C	20	B	B	81	60
.3	T								
EMSL	90.0								

Crush Load=67.0 Code=444 Calibration: G=2, C=B, AMn=42, AMx=17

Notes: A. Rapid decay; recording OK.
B. Very active; pressure released.

Noted crack across specimen before test. Decided to use cylindrical geophone No. 59 after test started. Checked this geophone and found it OK. Laid it on bed of press beside the supporting steel bearing plate. Picked up very little across the interface, steel to steel. Then laid geophone on top of a pile of steel pieces, in contact with the specimen under pressure. The pick-up was practically as good as with the special clamp-on geophones. Then tried several pieces of rock between the specimen under pressure and the geophone and the pick-up was apparently as good as before. Ran the pressure up to 54,000. Chip came out. Very active while the chip was splitting out, then remarkably quiet. Geophone removed and specimen burst at 67,000.

Geophone trouble developed just as test was beginning. The first tube noise was becoming very strong also. Replaced the 6J7 tube in the B-channel, with satisfactory results.

No. 13 Source=N5 Shape=2D Type=Norite from 4000' depth

BM-503	CL	TL	AN	RN	AR	C	Notes	BV	T
.1	67.6	35.0	9	0	20	B	Recorder OK	57	61
.2	70.0	42.0	10	2	20	B	Very small, Record OK	69	62
.3	T	49.0	C	0	20	B	More lively	80	63
EMSL	70.0	56.0	C	3	20	B	A little more lively	92	64
Reset No. 1							Ommitted reset		
		70.0	C	7	20	B	Very active A	115	65
Reset No. 2									
		73.0					A, B	120	

Crush Load=61.0 Code=323 Calibration: G=2, C=B, AMn=42, AMx=17

Notes: A. The meaning of readings at 115 and 120 per cent of the bursting value will be explained in note below.

B. Started to spall; removed from the press.

When the specimen spalled at 73,000, the pressure was dropped and the specimen did not burst. When, on raising the pressure, the specimen burst, the value was only 61,000 pounds.

No. 14 Source=N5 Shape=2D Type=Gabbro from 5000' depth

BM-504	CL	TL	AN	RN	AR	C	Notes	BV	T
.1	116.4	50.0	10	1	20	B	A	44	66
.2	T	60.0	N	5	20	B	B	52	67
.3		70.0	C	N	20	B	C	61	68
EMSL	100.0	80.0	C	3	20	B	D	70	69

No. Source=N5 Shape=2D Type=Gabbro from 5000' depth

Reset No. 1							Omitted reset		
		85.0	C	N	20	B	E	74	70

Crush Load=115.0 Code=422 Calibration: G=2, C=B, AMn=37, AMx=15

Notes: A. Snaps small and weak. Recording OK.
B. One full-scale snap. No decay.
C. Ran tape for two minutes. Specimen spalled and was then quiet.
D. Decay, but recording was OK.
E. Ran tape five minutes. Markedly sporadic.

Small pieces broke off top and bottom edges when specimen was first clamped in the press. A preliminary test load of 40,000 pounds was found safe and the test was then run as indicated above, without any resetting.

No. 15 Source=S1 Shape-2D Type=Intrusive Diorite Porphyry

BM-508	CL	TL	AN	RN	AR	C	Notes	BV	T
.1	65.0	30.0	5	1	20	B	A	45	71
.2	64.0	36.0			20	B	Occasional Snaps	54	72
.3	T	42.0	12	3	20	B	Faint snaps	63	73
EMSL	60.0	48.0	C		20	B	B	72	74
							Omitted reset		
Reset No. 1									
		60.0	C	C	20	B	Very noisy	90	75

Crush Load=67.0 Code=424 Calibration: G=1, C=B, AMn=45, AMx=15

Notes: A. Very faint snaps. Recording OK.
B. Decaying from continuous to occasional snaps.

This specimen was obtained from a depth of 350'. Compare with Test Specimen 16, below. It was run up to 60,000 pounds. Very noisy. Cut down to 55,000 as quickly as possible. Small chips had spalled. Did not dare replace the geophone. Ran the pressure up to 67,000, where the specimen burst violently.

No. 16 Source=S2 Shape=2D Type=Intrusive Diorite Porphyry

BM-509	CL	TL	AN	RN	AR	C	Notes	BV	T
.1	23.2	12.5	6	5	20	A	A	23	76
.2	54.2	15.0	8	3	20	A		27	77
.3	T	17.5					Omitted		
EMSL	25.0	20.0	7	6	20	A	Very small snaps	36	78
		25.0		3	20	A	B	46	79
Reset No. 1									
		30.0		3	20	A	Three small real snaps	55	80
		35.0	10	1	20	A	C	64	81
Reset No. 2									
		40.0	23		20	A	Recorder OK.	73	82
		45.0	C	4	20	A	D	82	83
Reset No. 3									
		55.0	C	C	20	A		99	84

Crush Load=55.0 Code=344 Calibration: G=1, C=A, AMn= , AMX=

Notes: A. Recorded four snaps at start, then rapid decay.
B. Omitted reset.
C. Omitted reset.
D. Faint. Four recorded. Variable zero due to snaps.

This specimen was from a depth of 1850'. A calibration was made, but the notes were mislaid. The set was however, in good order throughout the test. Compare this specimen (16) with the previous one (15), which came from a much shallower depth.

No. 17 Source=L4 Shape=X Type=Syenite Porphyry

BM-490	CL	TL	AN	RN	AR	C	Notes	BV	T
.1		60.0	30		20	B	Record good. A		
.2		72.0	N	10	20	B	B		
.3		84.0	16		20	B	C		
EMSL	120.0	96.0	30		20	B	D		
							Omitted reset.		
Reset No. 1									
		118.0	C	12	20	B	E		85

Crush Load= Code= Calibration: G=59, C=B, AMn=37, AMx=22

Notes: A. Record good; small surge. Unfortunately, all but the last section of this record was spoiled in mounting.
B. Record mostly good.
C. Record good.
D. Record good; half-scale snap is real.
E. Record good, amplitude tapering off.

The procedure outlined in section W-11 was varied with the X-type specimens. There was no resetting. The geophone was left in place except when the specimen was dangerously close to bursting, when it was removed from the run-up of pressure and then replaced. (This is easily done for these specimens for the geophone is the cylinder type and is not clamped on but is simply laid in the cradle at the side of the specimen).

In this test the pressure was stopped at 116,000 and then raised to 118,000. Pressure was released very gradually from 118,000 to 110,000. Brought up again to 118,000. The record was good throughout. The specimen was not broken. The press was too small to break a specimen of so great cross-section.

No. 18 Source=N3 Shape=2D Type=Peridotite from 1200' depth

BM-501	CL	TL	AN	RN	AR	C	Notes	BV	T

Crush Load=45.0 Code=444 Calibration: G=2, C=B, AMn=45, AMx=25

Notes: Tested the No. 1 geophone repaired by Duvall. It gave the above calibration values on test.

This specimen is the fifth made from the same sample. No warning was recorded by any of the specimens of this rock. Audible warning only was detected.

It was decided to run this specimen up to 70,000 without the geophone and then go back and make tests. The specimen broke unexpectedly at 45,000 pounds.

No. 19 Source=N.C. Shape=X Type=Mt. Airy Granite, N. Carolina

BM-475 CL	TL	AN	RN	AR	C	Notes	BV	T
.1	30.0	10	6	20	B	A	73	86
.2	40.0	C	C	20	B	B	98	87

Crush Load=41.0 Code= Calibration: G=59, C=B, AMn=45, AMx=35

Notes: A. One 3/4 scale snap, real. Record OK.
B. See notes for specimen No. 17 as to X-type procedure.

The initial pressure was raised to 45,000. Then one wing began to break. Pressure was then released to 29,000 and brought up to 30,000 with the results shown above. At 40,000 there was a great deal of snapping. The wing, broken off in the initial run, was removed from the specimen while recording. Fracture was noted on the main portion when taken from the press. The top of this specimen was not bevelled. Bevelled steel plates were used and it is thought that the pressure was not delivered uniformly, resulting in the early failure.

No. 20 Source=N.Y. Shape=X Type=Granite, Mineville, N.Y.

BM-391 CL	TL	AN	RN	AR	C	Notes	BV	T
.1	20.0	C	N	20	B	Record good	31	88
.2	25.0	C	N	20	B	Record good	38	89
.3	30.0	C	N	20	B	Good record, full scale	46	90
EMSL	35.0	C	C	20	B	Good record, full scale	54	91

No. 20 Source=N.Y. Shape=X Type=Granite, Mineville, N.Y.

	40.0	C	C	20	B	A		62	92
Reset No. 1									
	45.0	C	N	20	B	B		69	93
	50.0	C	N	20	B	C		77	94
Reset No. 2									
	55.0	C	C	20	B	Very active		85	95
	60.0	C	C	20	B	D		92	96
Reset No. 3									
	65.0	C	C	20	B	E		100	97

Crush Load=65.0 Code= Calibration: G=59, C=B, AMn=45, AMx=27

Notes: A. After 35,000, the specimen was removed and observation made. There was no sign of fracture. One edge was powdery, owing to rough edge ground off by the press. The specimen was then returned to the press and pressure brought up again to 40,000 and continued as indicated above.

B. Record good; half scale.

C. Became very violent at 50,000. Pressure released. Dropped to 48,000, brought back to 50,000. Very active.

D. Very active, then decreasing. The geophone was moved to the bed of the press and held in position with a piece of wood. As can be seen by the record (Figure 88), this time the energy was transferred across the steel-to-steel interface without noticeable loss.

E. Geophone was on bed of press. As pressure reached bursting value, the specimen yielded and the snapping was communicated to the geophone on the bed of the press. It was possible to witness the gradual breakdown of the specimen. However, it finally broke violently.

No. 21 Source=N.Y. Shape=X Type=Granite, Lyon Mt., N.Y.

BM-390	CL	TL	AN	RN	AR	C	Notes	BV	T
.1		20.0	3	15	20	B	Large to small snaps		98
.2		25.0	C	N	20	B	As above		99
.3		30.0	22	15	20	B	Quiet uniform record		100

No. 21 Source=N.Y. Shape=X Type=Granite, Lyon Mt., N.Y.

EMSL	35.0	C	N	20	B	OK throughout	101
Reset No. 1	40.0	C	C	20	B	Half-scale snaps	102
	45.0	C	N	20	B	Lively; falling off	103
Reset No. 2	50.0	C	N	20	B	A	104
	55.0	C	N	20	B	Falling off a little	105
Reset No. 3	60.0	C	N	20	B	B	106
	65.0	C	N	20	B	C	107
Reset No. 4	70.0	C	C	20	B	D	108
	75.0	C	C	20	B	E	109

Crush Load= Code= Calibration: G=59, C=B, AMn=37, AMx=15

Notes: A. A curious buzzing sound, which had been vaguely troublesome as background noise when listening, suddenly stopped at this point. Set worked well, both before and after, but was much more comfortable to work with after the buzzing stopped.

B. Two-minute run, active, no decay.

C. Two-minute run, very active.

D. Five-minute run, very active.

E. Five-minute run, very active; wing broke off the X-shaped specimen.

At 80,000 the microseismic activity was very great and continued so for a long run of over five minutes (T=100). The pressure dropped slowly from 80,000 to 40,000. Held there and released. Specimen removed and preserved. One wing fractured. Poorly defined foliation (Langford).

The procedure was varied in the case of this specimen. It was put in the press and a cylindrical geophone put in one of the side slots. Then the pressure was run up in stages of 5,000 pounds, from 20,000 to 80,000 as indicated above. The specimen did not crush. T=100 is included in Figure 88, showing the record at 80,000 pounds.

No. 22 Source=C3 Shape=2D Type=Banded Iron

BM-485	CL	TL	AN	RN	AR	C	Notes	BV	T
.1	T	10.0			20	B	Very quiet. Record OK	16	111
.2		20.0	C	3	20	B	A	32	112
.3		30.0	C		20	B	Quieter, recorder OK	48	113
EMSL		40.0	C		20	B	B	65	114
		50.0	C	2	20	B	C	81	115
Reset No. 1		60.0	C	2	20	B	Quiet	97	116

Crush Load=62.0 Code-324 Calibration: G=2, C=B, AMn=37, AMx=15

Notes: A. Snaps weak, but one recorded half scale.
B. Very faint and decaying.
C. Small snaps, and decaying.

Only one specimen of this sample was prepared, as it was very friable. Hence there was no previous test value to use as a guide. Procedure was carried through with considerable caution. Specimen broke without warning. Broke clamping geophone No. 2. Chlorite fault in specimen; 1/4 inch movement disclosed by the fragments (Langford).

W-13 Report on Petrography of Rocks from Canadian Mines

The following report dealing with the petrography of rocks submitted by Canadian mines for the program reported in the preceding sections was prepared by H.W. Jaffe, Petrographer, U.S. Bureau of Mines Experimental Station, College Park, Md.

Group I - Cadillac Mines, Ltd., Cadillac, Quebec

1. Rhyolite porphyry (altered aplite), BM-484

This is a light gray porphyritic rock composed of euhedral to anhedral phenocrysts of albite lying in an aphanitic groundmass of quartz, muscovite, albite, and a minor amount of calcite. The average grain diameter of the phenocrysts is 1 mm., the groundmass, 0.01-0.05 mm. A maximum of 2.6 mm. was recorded for an albite phenocryst.

The rock has been deformed, either during the end stages of crystallization or at a distinctly later period. Quartz has yielded more readily than feldspar and has been granulated. The latter mineral has been bent and fractured. Where displacement occurs, fine-grained quartz and muscovite have flowed into the fractures in the feldspar.

The euhedral character of many of the phenocrysts and their grain size indicate that the rock was originally a porphyry, rather than an aplite*.

2. <u>Greenstone (volcanic sediments), BM-485</u>

This is a dark green to black rock, composed almost wholly of quartz and chlorite. It is thoroughly crenulated on a very fine scale. The average grain diameter lies in the range of 0.07-0.15 mm.

Glass and textures usually characteristic of volcanic rocks are absent and the term 'volcanic sediments' is not applicable from a purely petrographic standpoint. The field data indicate that this rock occurs interbedded with Precambrian lava flows and may be intimately associated with them. It may have been derived from the flows or otherwise altered from them, but this cannot be determined solely by microscopic studies. Accordingly, the more general name, greenstone, is preferred.

3. <u>Skarn (banded iron), BM-486</u>

This is a banded, predominantly black rock, composed principally of quartz, magnetite, hematite, and carbonate. Accessory amounts of chlorite, apatite, and sulphide complete the mineralogy. The carbonate generally occurs in veinlets. The average grain diameter lies in the range of 0.08-0.3 mm.

Group II - Lake Shore Mine, Ltd., Kirkland Lake, Ontario

1. Not studied (labelled 'basic syenite'), BM-487.
2. <u>Altered syenite (basic syenite), BM-488</u>

This is a greenish-gray rock composed principally of altered feldspar and altered pyroxene. The rock contains major amounts of both soda and potash; presumably two feldspars represent the unaltered material. Feldspar is deformed and to a considerable extent fractured and sericitized. Pyroxene occurs in euhedral cross sections and prismatic grains, all showing heavy pseudomorphous alterations. The pyroxene has been changed to hornblende; which, in turn, has been replaced by talc, chlorite, and calcite. Minor amounts of apatite, sulphide, and chloritized biotite complete the mineralogy.

The rock is relatively coarse-grained, having an average grain diameter of 1-5 mm.

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*Note: The rock names in brackets are those given by the mines sending the rocks. In connection with the names given by Mr. Jaffe, see his explanation in the final paragraph for No. 7 of Group II.

3. Rhyolite porphyry (syenite porphyry), BM-489

This rock has a mottled appearance and shows pale green albite phenocrysts lying in a dark reddish-gray matrix. The albite phenocrysts show a rude parallelism.

The essential minerals are albite and quartz; the latter is finely distributed throughout the matrix. Minor amounts of apatite, chlorite, sulphide, calcite, and sericite complete the mineralogy. All the phenocrysts are albite or slightly zoned albite-oligoclase and show slight to moderate alteration to sericite. The groundmass is composed essentially of fine-grained feldspar and considerable quartz. The resolution of the fine-grained groundmass requires careful examination as the quartz may be easily mistaken for feldspar. Accordingly, the name rhyolite porphyry is offered in preference to 'syenite porphyry'.

The phenocrysts have an average grain diameter of 0.5-1.5 mm.; the groundmass 0.02-0.05 mm.

4. Rhyolite porphyry (syenite porphyry), BM-490

This rock is very similar to BM-489.

5. Red rhyolite porphyry (red syenite), BM-491

This rock has a mottled appearance and shows light grey to green albite phenocrysts lying in a pink to red matrix. The red color is probably due to hematitic stain. Microscopically, the rock is similar to BM-489. The following significant differences are noted:

a. The rock contains some corroded quartz phenocrysts.
b. It shows marked deformation, with granulated and fractured albite phenocrysts traversed by veinlets of sericite and quartz.
c. It contains considerably more carbonate than BM-489.
d. In general, it is more altered than BM-489.

6. Red rhyolite porphyry (red syenite), BM-492

This rock is very similar to BM-491.

7. Altered red rhyolite porphyry (altered syenite porphyry), BM-493

This rock is similar to BM-491 and may be considered a badly deformed and altered variant of the latter. It shows more sericite and carbonate, more granulation, and the introduction of quartz and sulphide in veinlets.

General.

In describing the rocks BM-489-493, the names rhyolite and ryholite porphyry have been selected in preference to syenite and syenite porphyry, largely on descriptive criteria; in these instances, the presence of appreciable quartz. It is quite possible that field evidence would show that these rocks are syenites and have undergone some silicification along with other modifying factors. In BM-493, for example, there is the suggestion of introduced quartz that is different in character from the quartz observed in the groundmass of the other rocks. In the classification of complicated rocks, where field data are not available, and where the sequence of events is not obvious, the petrographer must use the mineral composition as the prime consideration.

Group III - International Nickel Company, Sudbury, Ontario

1. Rhyolite or fine-grained granite (quartzite), BM-499

This is a dark grey rock composed principally of quartz, albite, biotite, and muscovite. A smaller amount of orthoclase is present. Some of the biotite is altered to chlorite, but the rock is otherwise fresh.

The grains are anhedral and the texture is sutured. The average grain diameter is 0.2 mm. According to its mineralogy and texture, the rock appears to be a rhyolite or fine-grained granite, rather than a quartzite.

2. Rhyolite (rhyolite), BM-500

This is a dark grey rock composed essentially of quartz and biotite with lesser amounts of feldspar. The biotite is well oriented and the quartz somewhat elongated, giving the rock a microscopic foliation. Small lenses of fine-grained feldspar are oriented parallel to the foliation.

The average grain diameter lies in the range of 0.1-0.5 mm.

3. Perknite or pyroxenite (periodotite), BM-501

This a dark grey-green rock composed principally of diopside and actinolite. Minor amounts of biotite, chlorite, and sulphide are present.

The average grain diameter is 0.25 mm. and the maximum 3 mm. for a grain of actinolite.

Olivine was not observed, hence the name periodotite is not applicable. Either perknite or pyroxenite may be used.

4. Granite (granite), BM-502

This is a normal granite of pink and grey color with sporadic black splotches. The essential components are quartz, microcline, and myrmekite, with lesser amounts of biotite. Minor amounts of sericite and chlorite are present as alteration products of feldspar and mica respectively. A moderate amount of strain and granulation was noted.

The average grain diameter lies in the range of 0.5-1.5 mm.; the maximum is 5 mm. for a grain of microcline.

5. Gabbro (norite) - BM-503

This is a mottled dark grey-green rock composed essentially of labradorite, hornblende, and biotite. Apatite and sulphide are present in minor amounts.

The rock has an ophitic texture and an average grain diameter of 1.5 mm. Hornblende and biotite occur in place of pyroxene and may have replaced this mineral. Hypersthene was not observed and the name 'norite' is therefore not applicable.

6. Metagabbro (gabbro), BM-504

This is a dark green rock composed essentially of labradorite and actinolite-hornblende. Accessory minerals include apatite, biotite, sulphide and quartz. The rock has been subjected to deformation and granulation. Elongated pockets of crushed plagioclase and ferromagnesian minerals have produced a texture approaching that of a gneiss.

The average grain diameter lies in the range of 0.08-0.3 mm.

7. Not studied (sulphide ore -- hand specimen -- no core cut) BM-505

Group IV - Sigma Mines, Bourlamaque, Quebec.

1. Diorite porphyry (diorite porphyry), BM-508

This rock is composed essentially of oligoclase, biotite, and a lesser amount of quartz. Minor amounts of andesine, albite, apatite, sulphide, magnetite-ilmenite, and sphene are present as the accessories. The plagioclase is clouded by intrusions of fine-grained epidote. Alteration to chlorite, calcite, sericite, and epidote is heavy.

The average grain diameter lies in the range of 0.05-0.15 mm., for the groundmass and 1-2 mm. for the phenocrysts.

2. Diorite porphyry (diorite porphyry), BM-509

This rock is very similar to BM-508, but contains more biotite and is less altered.

*

Summary

Throughout this entire publication, one outstanding fact must be borne in mind: Practically all the experience reported was obtained in one mine — that of Lake Shore Mines, Kirkland Lake, Ontario. All descriptive references are applicable at the epoch of the report in which they occur; conditions have since changed many of them. The conclusions outlined in the final section of this publication apply to that particular mine. They might, or might not, be applicable to others.

Lake Shore Mines has been described in some detail in Report B. It is a hard-rock gold mine, in which the country rock is very brittle. The orebodies lie in veins that are very much jointed. The mine may be described as dry, but the air is moist and, because of the explosives used underground, is quite acid. There is very little dust, and ventilation is excellent.

A further point to be kept in mind is that the opinions expressed are those of the writer. The experience on which they are based is outlined in the various reports presented, but he alone is responsible for their formulation.

* * *

The work falls naturally into three main sections:

(1) The establishing and maintaining of a surface seismograph at Lake Shore, chiefly for the purpose of timing rockbursts that might record at Ottawa and elsewhere, furnishing data for the determination of travel time curves for seismic waves over the Canadian Shield.

(2) The interim investigations underground, with what was at first very meagre equipment, for the purpose of finding some means of predicting rockbursts.

These include:

(a) Strain Gauges
(b) Makeshift mine seismograph recording
(c) Microgauge measurements of bore-hole closure
(d) Attempts to determine frequency values for bursts and blasts
(e) Use of seismic survey equipment (for the purpose outlined in (d)) and also to obtain velocities of seismic waves over short underground paths and to detect any variations therein due to changes of pressure.

(3) Experience with the microseismim method, i.e. the study of subaudible vibrations of about 1,000 c.p.s., as a means of predicting rockbursts.

The strain gauge experiments were confined to a single instrument and, while the results were encouraging the method was too cumbersome to be of much value.

The makeshift mine seismograph was gradually developed into a most useful instrument and then gave valuable service throughout the program.

The microgauge gave promise of useful application, but was abandoned in favour of the microseismic method. There was not sufficient staff to carry out both investigations and the mine officials decided to concentrate on the latter.

The frequency studies indicated that the bursts and blasts each generate a wide spectrum of seismic frequencies, the former up to 200 to 400 c.p.s. and the latter 40 to 60 c.p.s. Other mine noises, except drills, were found to generate frequencies of about 100 c.p.s. The frequency for drills was about 200 c.p.s. But all efforts to build a positively selecting filter failed. Several filters were built that helped a great deal but none was completely successful in suppressing waves from the larger blasts.

The subaudible or microseismic method was in use from about June 1942 to October 31, 1945 — the close of the program. It is the results of this method which are of major interest in the reports. Report W is based on laboratory tests of this method, carried out after the Lake Shore program was closed.

* * *

Initially, the main objective of the Observatory was to obtain data for travel-time tables. This objective was never lost sight of. Every effort was made to obtain accurate data and <u>to have no lapse in the recording.</u> At first, this necessitated the rigid routine and careful supervision shown in Reports A, D, and G. This was especially true in the early stages, when the servicing of the seismograph was being carried out by inexperienced operators. As the work went on, and Gibbs and Hallick took over, this supervision was not required. All concerned were keenly interested in maintaining unfailing operation of the surface seismograph. Mr. O.E. (Ted) Andrew was equally concerned with the mine seismograph records (G-1); and, being in the geological office, did much to correlate the mine seismograph records with mining operations. A paper based on the then available travel-time data is given as Report H.

The writer was very much interested in the subaudible method, which he had suggested in 1923 (Bib. No. 47) as a means of predicting earthquakes. In January 1940, he proposed this as one of the possible means of predicting rockbursts. No effort or expense was spared by the survey engineers or the mine officials to give this method a thorough trial under the conditions obtaining at Lake Shore.

The entire program was carried out under wartime conditions of scarcities and restrictions. All recommendations made to Lake Shore Mines were approved at once and every effort was made to secure the required supplies. The influence of Mr. Blomfield was such that priorities otherwise unobtainable were given promptly. The cooperation of the U.S. Bureau of Mines and Dr. Obert was obtained at a time when conditions were most difficult.

There were, however, unavoidable delays in shipment. Many commercially built instruments, which would have saved much time and work, were simply not obtainable. However, owing to the efforts of the mine officials and the skill and ingenuity of Gibbs, the program did not suffer materially from wartime conditions, in so far as the equipment was concerned.

There was one such influence which did affect the program. Because of the war there was a lessened mining activity at Lake Shore. On the one hand, this made it easier to have periods in the mine free from disturbances due to mining; but, on the other hand, there were fewer rockbursts. The ones that did occur were (except for two in seven years) too small to record at Ottawa, and so did not help the travel-time project. Of the many smaller bursts, most occurred at or just after blasting, and did not provide any opportunity for prediction, except in a very few cases.

The first heavy burst during the program did not take place until January 29, 1943. It was in the West Pillar (Report L) and was the one outstanding case, apart from the experience in the Frood mine (J-7a), where the best deductions can be made from microseismim data. These are discussed in section L-7 and illustrated in Figure 59. The latter is based on records from high-class equipment that are quoted in full in the report indicated. The coverage was rather meagre, as only seven geophones were available at that time. Long-outstanding orders for crystals and transformers had not yet been delivered.

Of the seven geophones recording the preliminary conditions preceding the above burst only two survived. They were still the only available pick-ups when the second heavy burst took place on March 31, 1943. Moreover, they were much too far away from the source to record any microseismims. By June 1943, the outstanding orders were filled and there were soon close to a hundred geophones completed or in the last stages of construction. From that time on, there was no lack of coverage. Unfortunately, in the succeeding and final 2 years of operation, only three small bursts that could possibly have been predicted occurred (O-4; O-5).

Throughout this very trying period, members of the survey group found strongly reinforced the conclusion that in any final, regular program of mine protection the daily check-up must be carried out by means of listening, not by recorders.

While this was recognized and stressed, they were insistent that any program adopted must be rigorously maintained, and that every possible care must be taken to record, index, and file all data that might possibly be relevant up to and through a burst or bursts within the recording range of the geophone installation, so that every factor contributing to the possible solution of the problem of prediction might be available for study and evaluation.

After the seven final months of painstaking work with the intensive seismic program (O-8), maintaining all the meticulous care to standardize equipment (L-9), ensure complete and unbroken coverage, and digest and report to all concerned all data observed, two or three very small bursts only were registered.

By this time, the entire equipment needed drastic overhaul. The mine officials decided to terminate the program on October 31, 1945. That the expected burst did occur some 6 weeks later in the very section covered by the intensive program is one of the most disappointing aspects of the matter.

*

Conclusions

The following are the writer's conclusions from the data of the entire research:

(1) Strain gauges and bore-hole gauges give some promise of indicating increasing pressure, but their application in a mine such as Lake Shore would be cumbersome. Electric strain gauges would perhaps be of value, but the walls of all openings in this mine are so slabbed that the use of gauges would be inconclusive.

(2) Velocity measurements are useless as pressure indicators. Pressure moves so rapidly from point to point (L-5) that it is impossible to say what path the seismic waves follow from burst or blast to the recorder. This fact, coupled with the strong probability that the paths between identical termini would vary from one test to another, and the difficulty of maintaining lines free from attack by acid-charged water (E-3) make the method of little or no value as a pressure indicator. It did prove useful in determining the peak frequencies of blasts and bursts.

(3) It would seem to be firmly established by the experience in the mine and by the laboratory tests (Report W) that microseismims are generated by strain or compression in the rock, that they increase in number per minute with increasing pressure and that this increase becomes accelerated as the limit of strength is approached. This would seem to make then an ideal means of predicting rockbursts. Obert has found such methods very satisfactory in some U.S. mines. Their application in Lake Shore Mines is another matter, as the following paragraphs show.

(4) Pressure at Lake Shore moves very rapidly from point to point (L-5). As a result, a dangerous condition at a given point may pass to another part of the working before a burst occurs. A blast or burst in another section of the mine may suddenly transform a 'safe' point to a dangerous one, which again may or may not burst.

(5) The conditions next above make the application of this method to safety procedure most hazardous. A stope is found 'dangerous' one morning, and the men are removed to work elsewhere; a day or two later it is reported 'safe', and the men are sent back. A blast or burst elsewhere suddenly shifts the pressure on the stope once more and it bursts. The mine officials are left to explain why they sent men back into a danger zone.

(6) Microseismims with frequencies of 1,000 c.p.s. seem to be the most informative (L-7). The standard geophones were equally sensitive in pick-up when constructed to be sensitive to vibrations of 2,000 c.p.s. The

microseismims at 1,000 c.p.s cannot be recorded at distances of more than about 75 ft. in Lake Shore rock, but can be heard over the headphones up to 200 ft. or so.

(7) It is extremely difficult to maintain sensitive equipment of the required type underground. If adequate coverage is required, the cost of installation is high and also that of maintenance for more than a few months. It required constant expert attention to keep equipment in an efficient operating condition.

(8) In view of the conclusions above, it would seem that the only possibility of applying microseismim equipment to a safety program in a mine such as Lake Shore is that mentioned in sections M-6(H) and O-8.

(9) The 'doming theory' seems to apply in the Lake Shore mine (B-4 & L-6). Briefly, the theory is that the pressures underground are supported by pillars* of many forms and locations. The material between pillars is supported by arches that extend back into the country rock. As pillars are removed, new arches form and strain bursts of various magnitudes occur. If and when the pressure on any pillar exceeds the strength of the rock, a burst takes place, the magnitude of which is a function of the volume of rock involved and its bursting strength. The writer's experience supports this theory so far as the Lake Shore mine is concerned. Note especially the recording from adjacent deep and shallow holes as reported in section K-9(3).

(10) There seems to be no residual strain in the rock at Lake Shore in the sense of strain resulting from its geologic history. The almost complete absence of strain indications at many points in the mine and the distribution of the centres indicating pressure favour the conclusions of this paragraph and the preceding.

(11) Bursts at Lake Shore generate longitudinal seismic vibrations (P-waves) that are kataseismic (having the initial movement away from the recording station and in line with the traverse from burst to recorder). In this connection see section H6; further conclusions drawn from the travel-time investigation are found throughout Report H, and are summarized in section H-7.

(12) The writer concurs fully with Dr. Langford with respect to the desirability of establishing some organization in Canada charged with the responsibility of carrying out research on all features of rock behaviour under pressure. This should include both rocks in place and those studied under laboratory conditions.

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* See footnote, p.27, for definition of 'pillar'.

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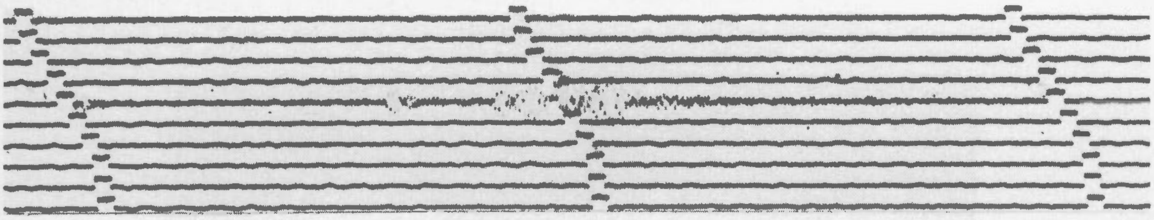
ILLUSTRATIONS



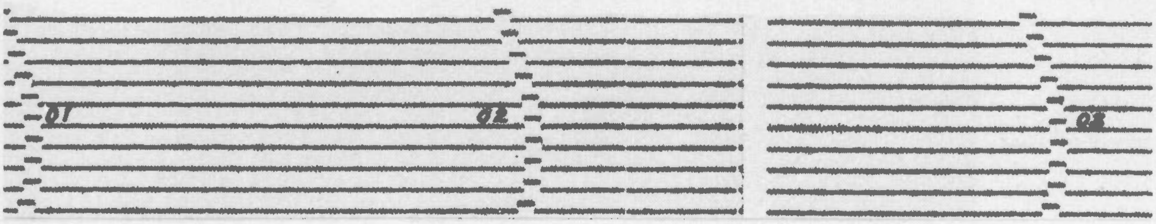


Fig. 1 Ottawa Short-period Benioff Record of Lake Shore Burst of December 27, 1938.

Fig. 2 Ottawa Short-period Benioff Record of Blast near New Haven, Conn. (40,000 lbs. of dynamite)

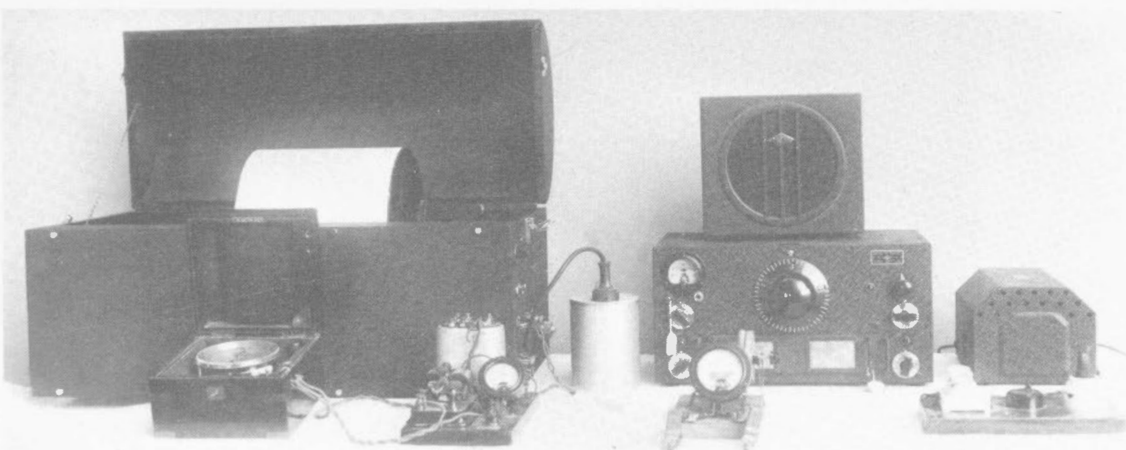


Fig. 3 Kirkland Lake Seismograph Equipment, 1939.

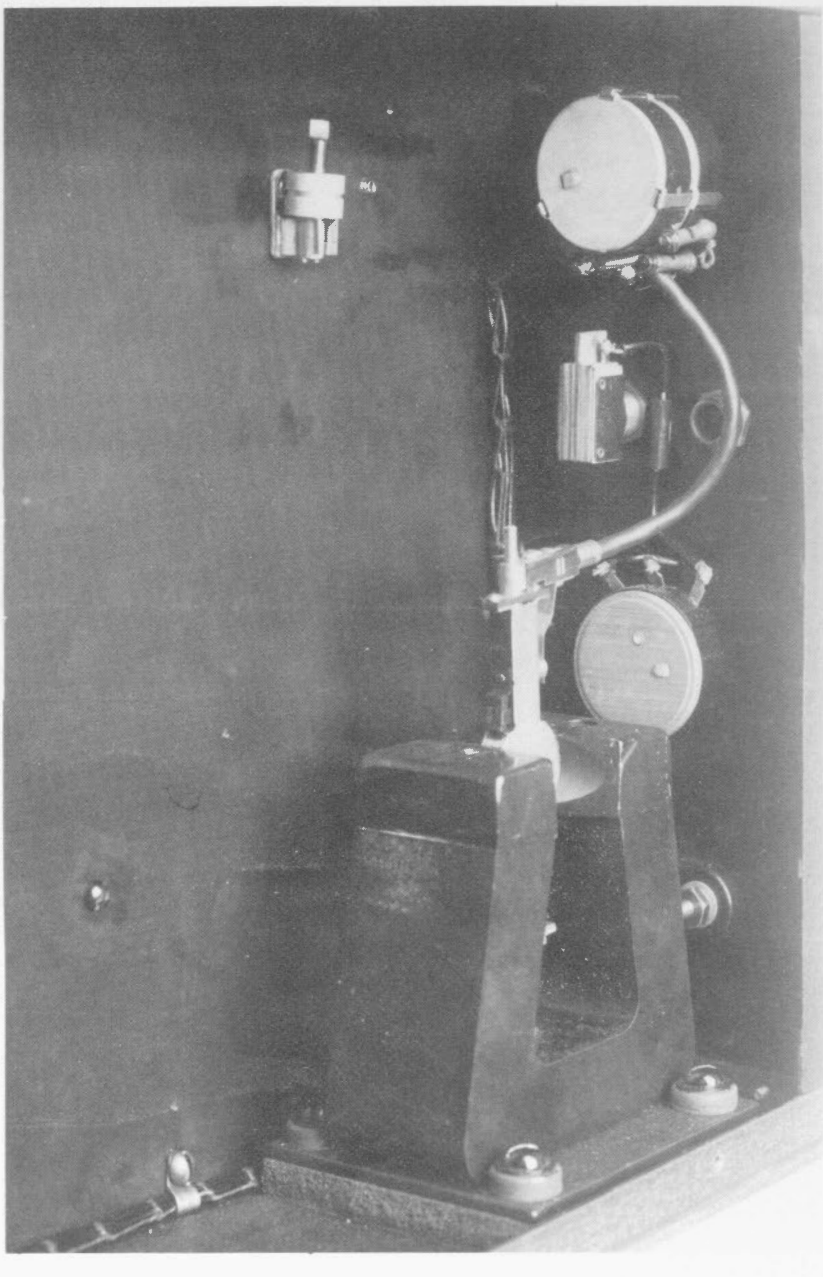


Fig. 4 Galvanometer Assembly, Surface Seismograph.

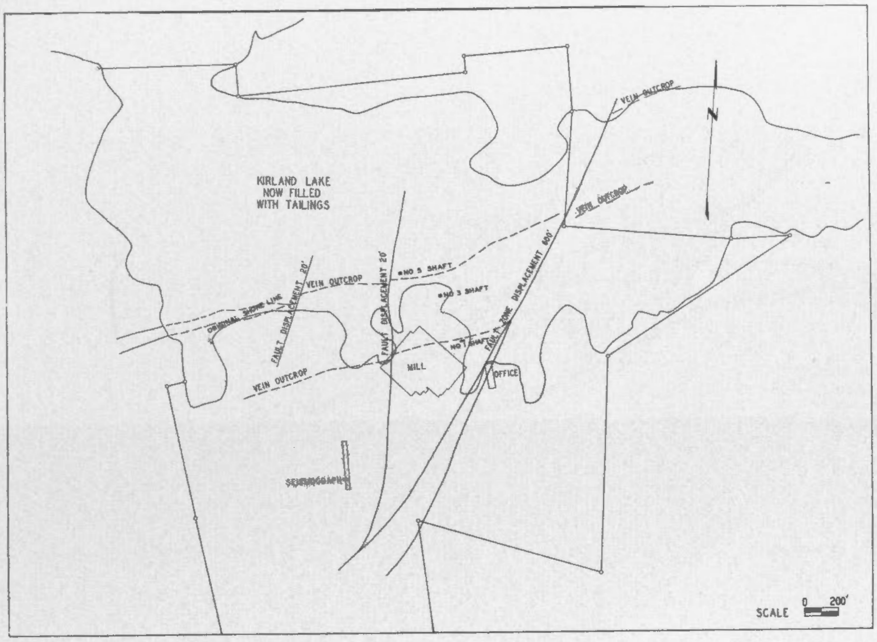


Fig. 5 Plan of Lake Shore Mines, Kirkland Lake.

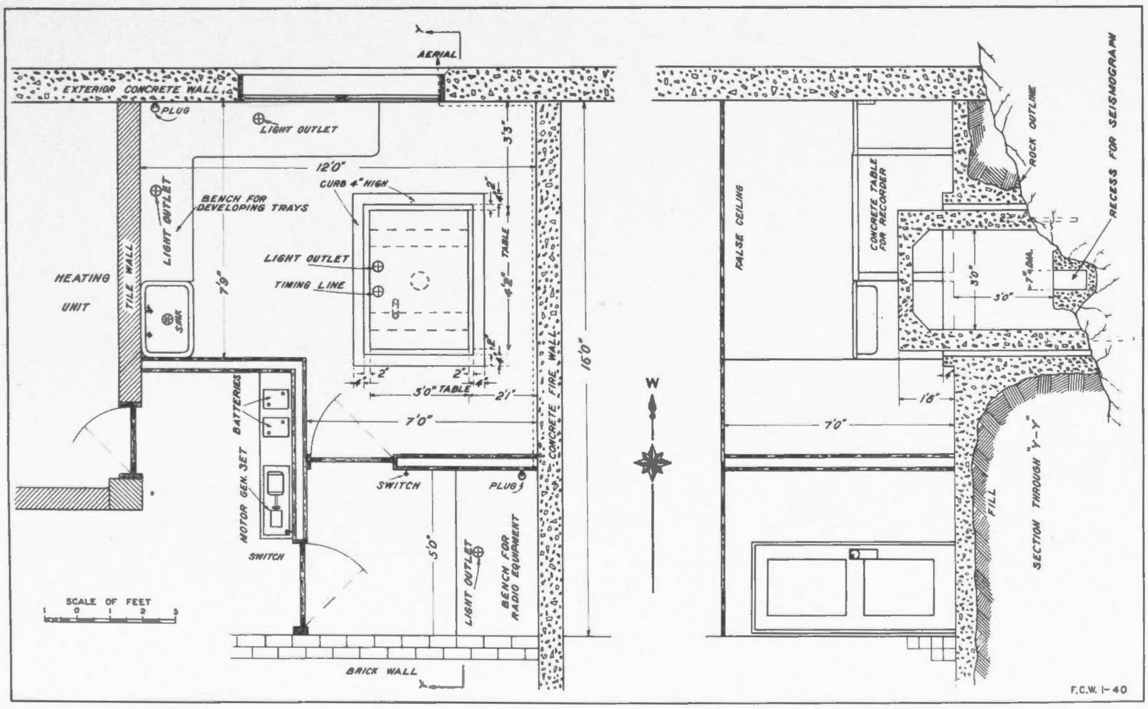


Fig. 6 Surface Seismograph Recording and Developing Room.

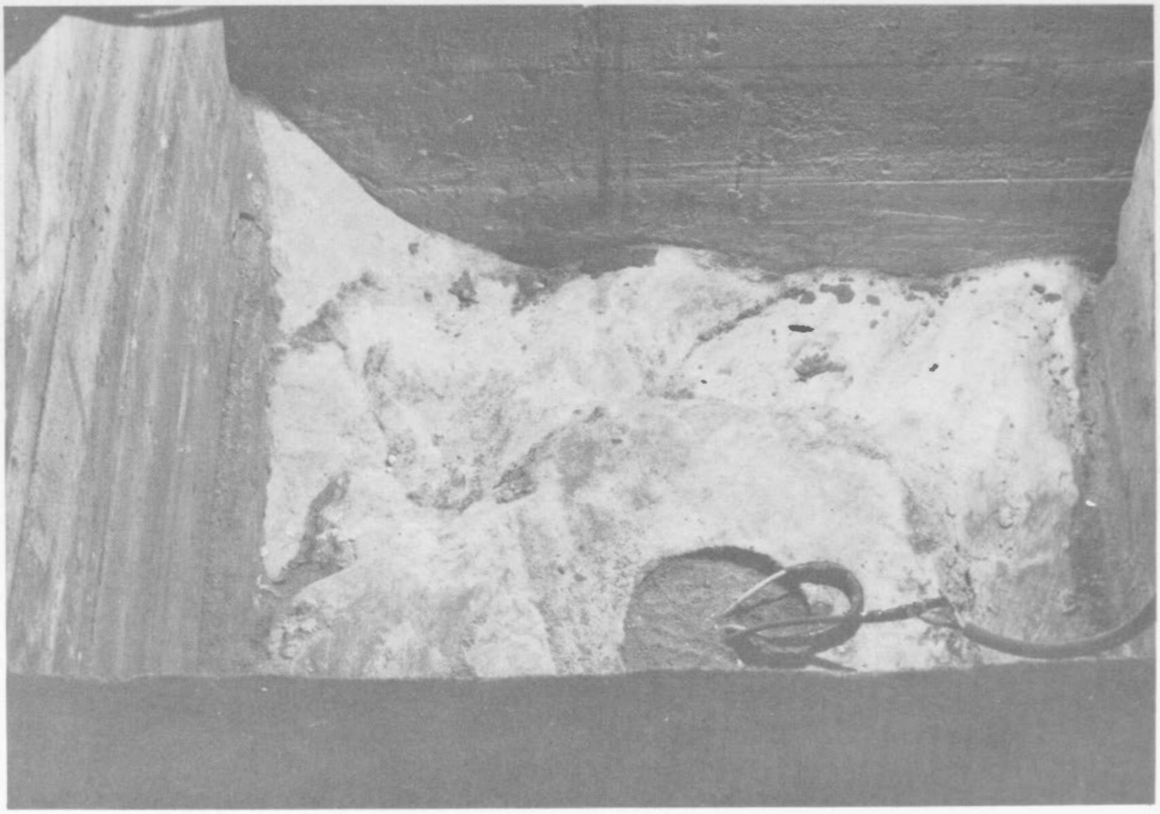


Fig. 7 Seismograph Emplacement

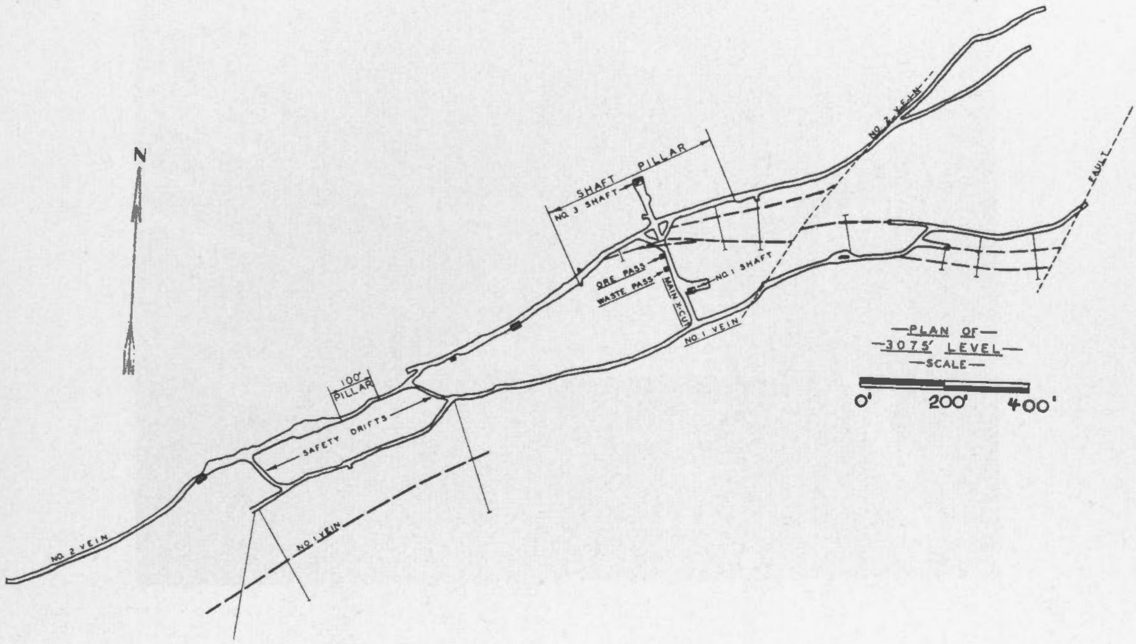


Fig. 8 Plan of 3075-ft. Level, Lake Shore Mines.

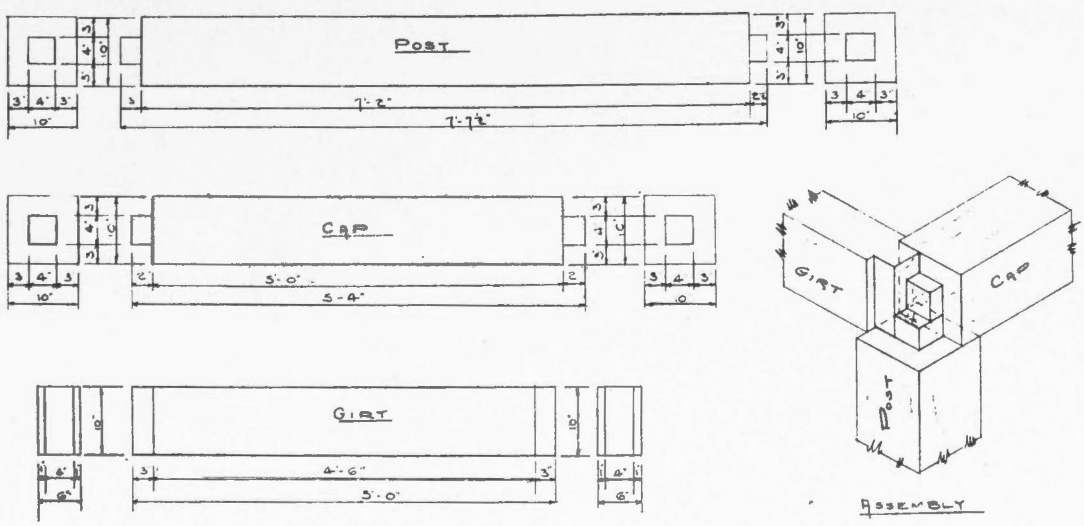


Fig. 9 Detail: Square-set Timbering.

Fig. 10 Beam Broken by End Thrust.

Fig. 11 Safety Crosscut.

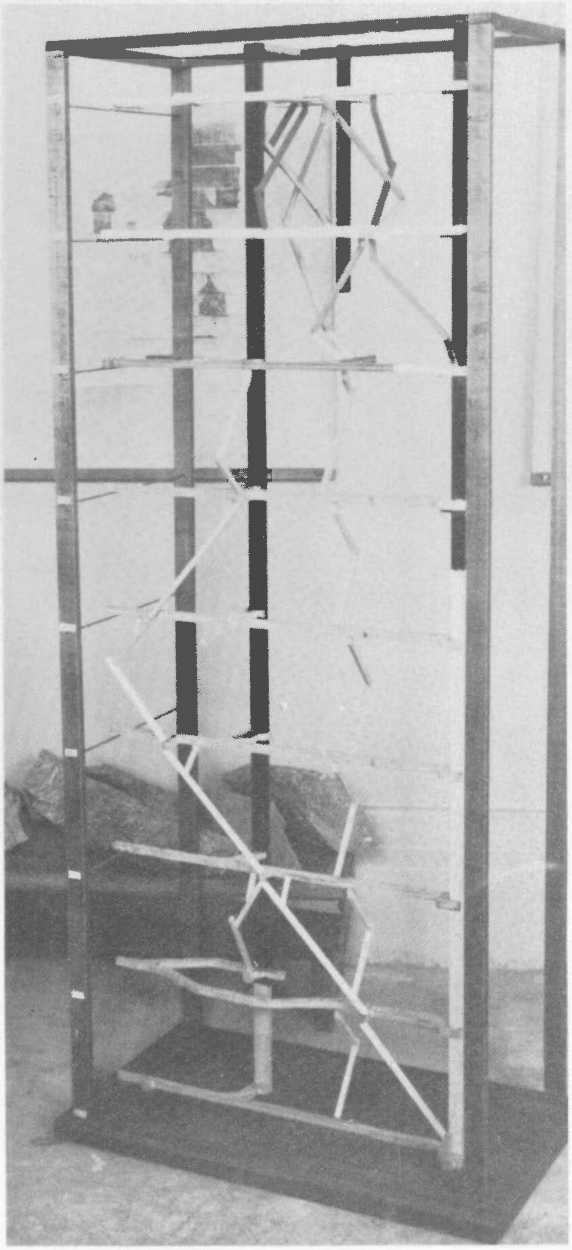


Fig. 12 Model of Ore Passes: 4325 to 5450-ft. Levels

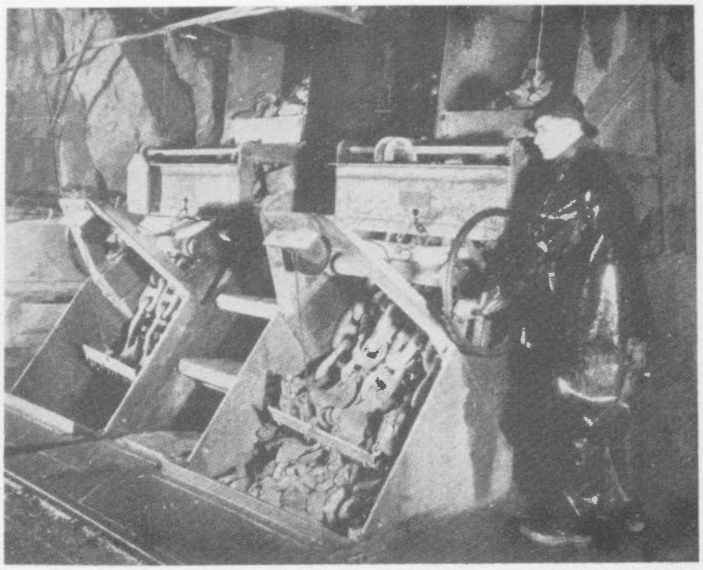


Fig. 13 Loading Pocket on 2950-ft Level, Showing Cramp Gates.

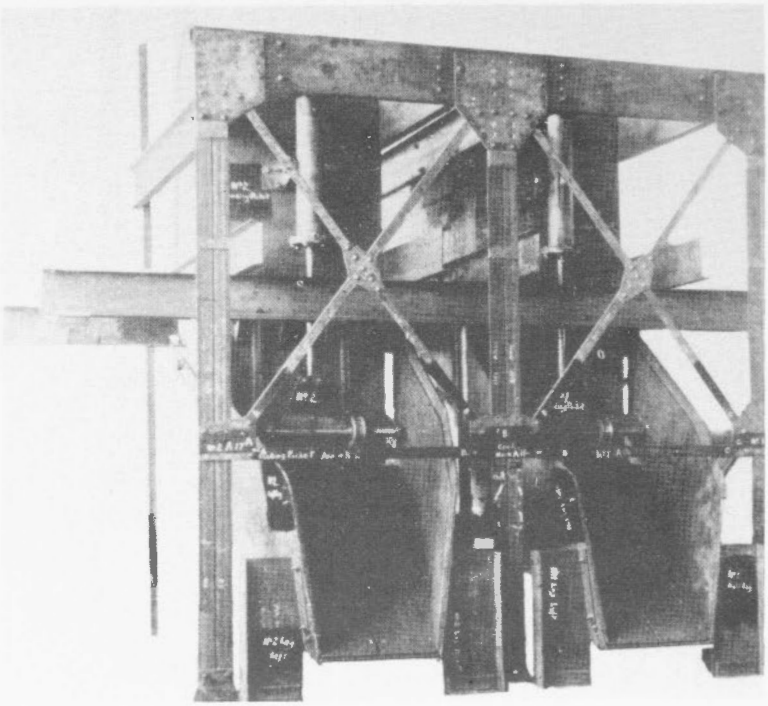


Fig. 14 Loading Pocket at Discharge Bins.

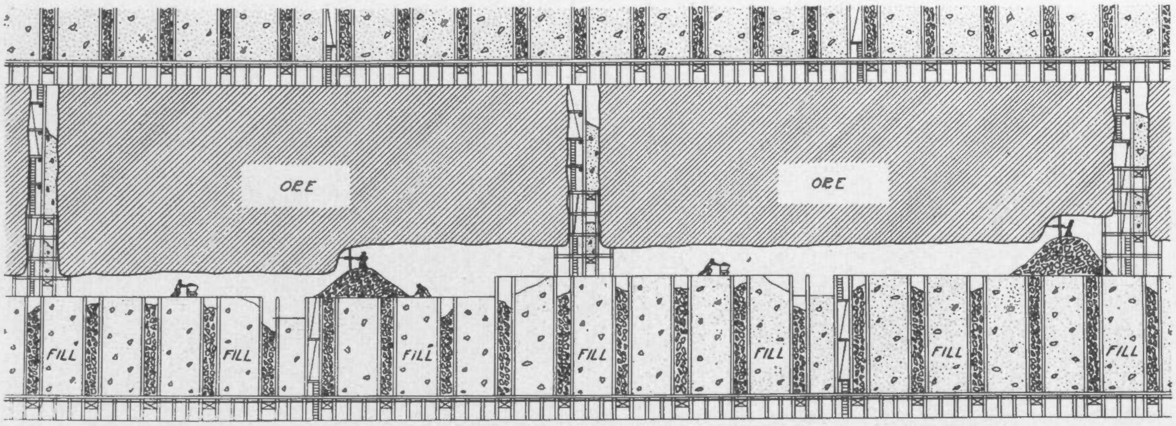


Fig. 15 Horizontal Cut-and-fill, Open Stope

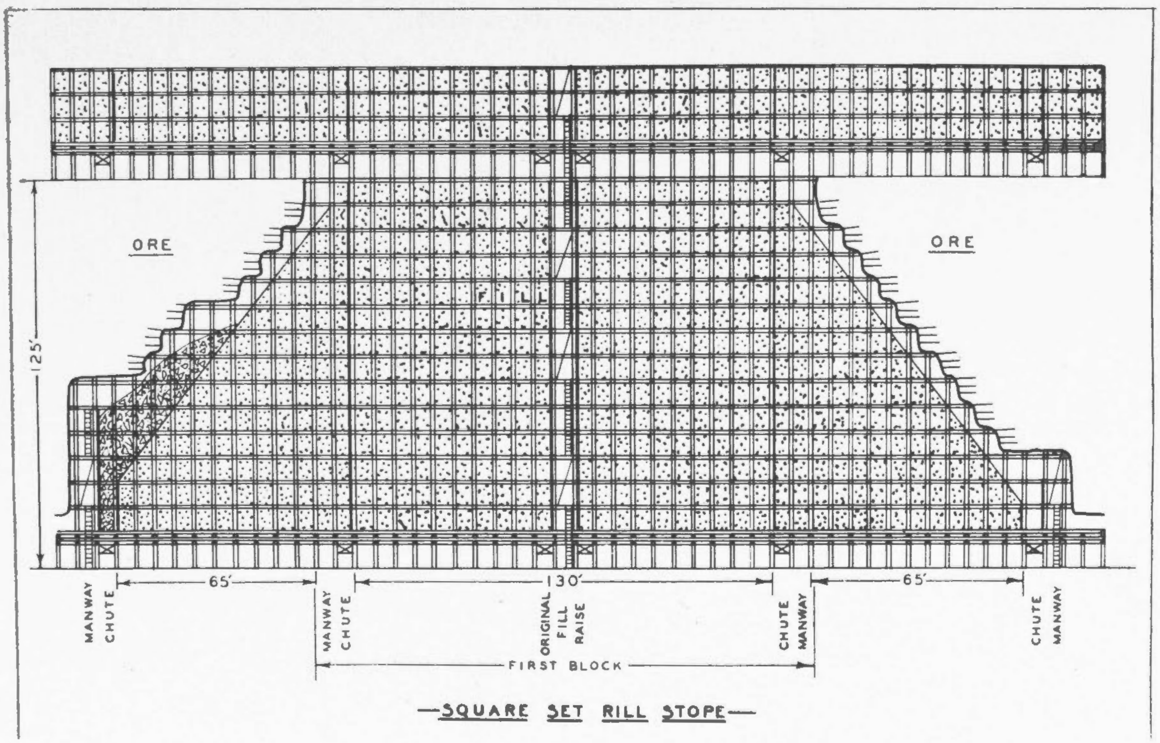


Fig. 16 Square-set Rill Stope.

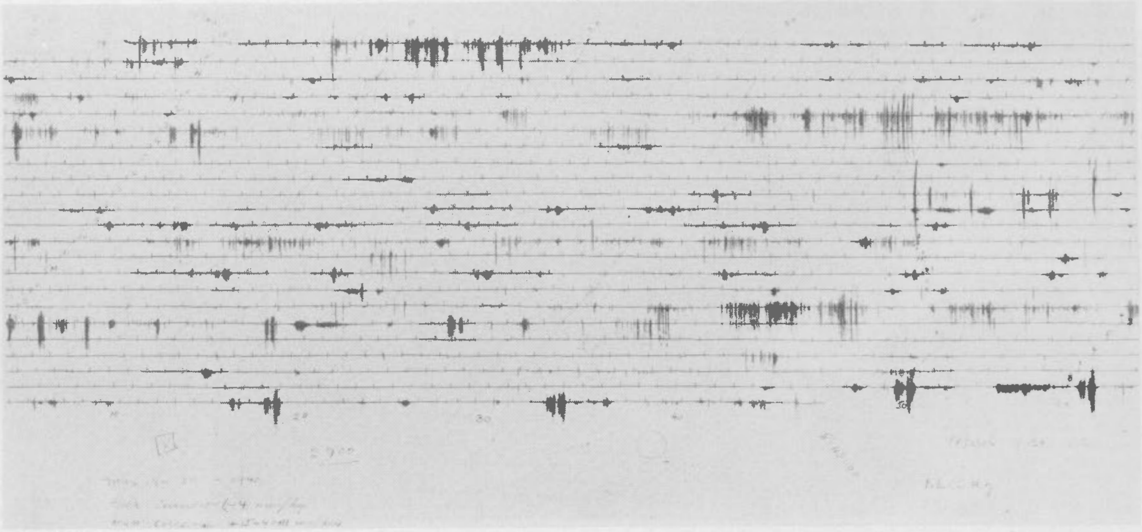


Fig. 17 Record on Hollinsworth Recorder with Brush Crystal Detector (2950-ft. level)

Fig. 18 Interior Heiland Geophone, Mine Seismograph.

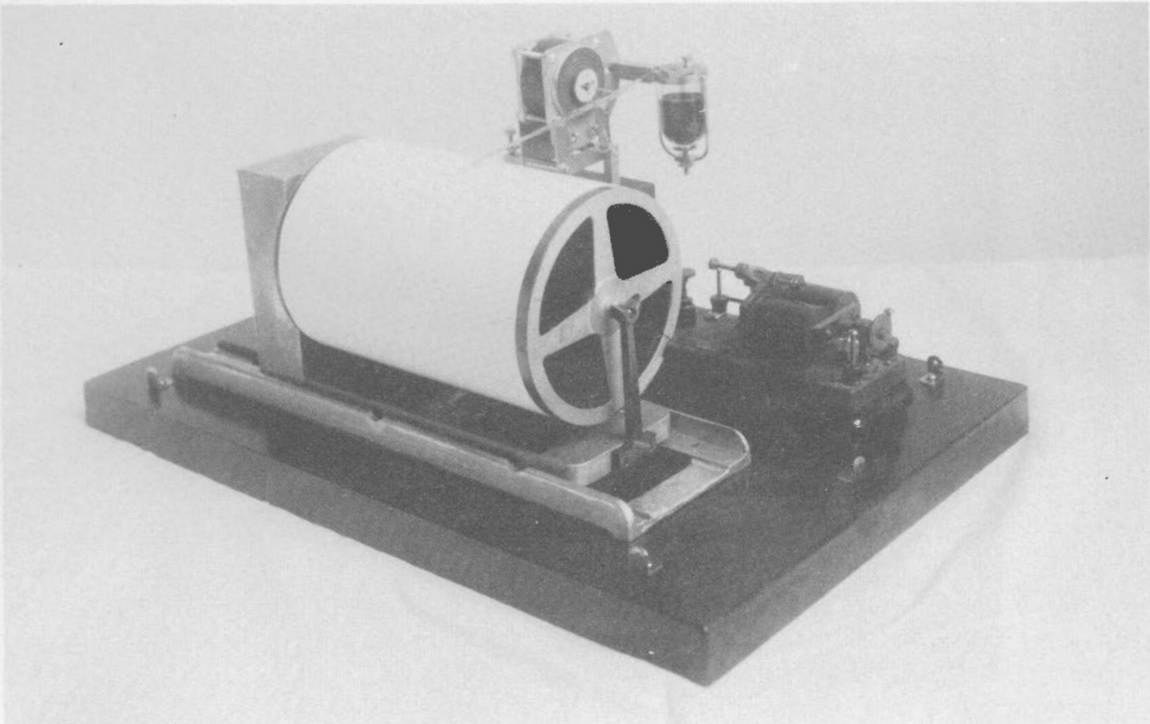


Fig. 19 Hollinsworth Recorder.

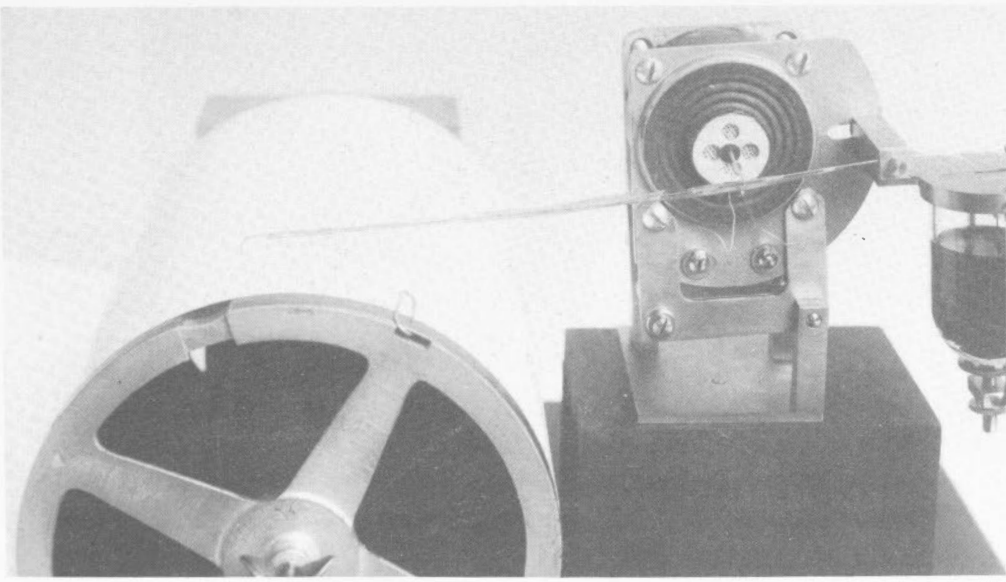


Fig. 20 Hollinsworth Recorder (pen detail).

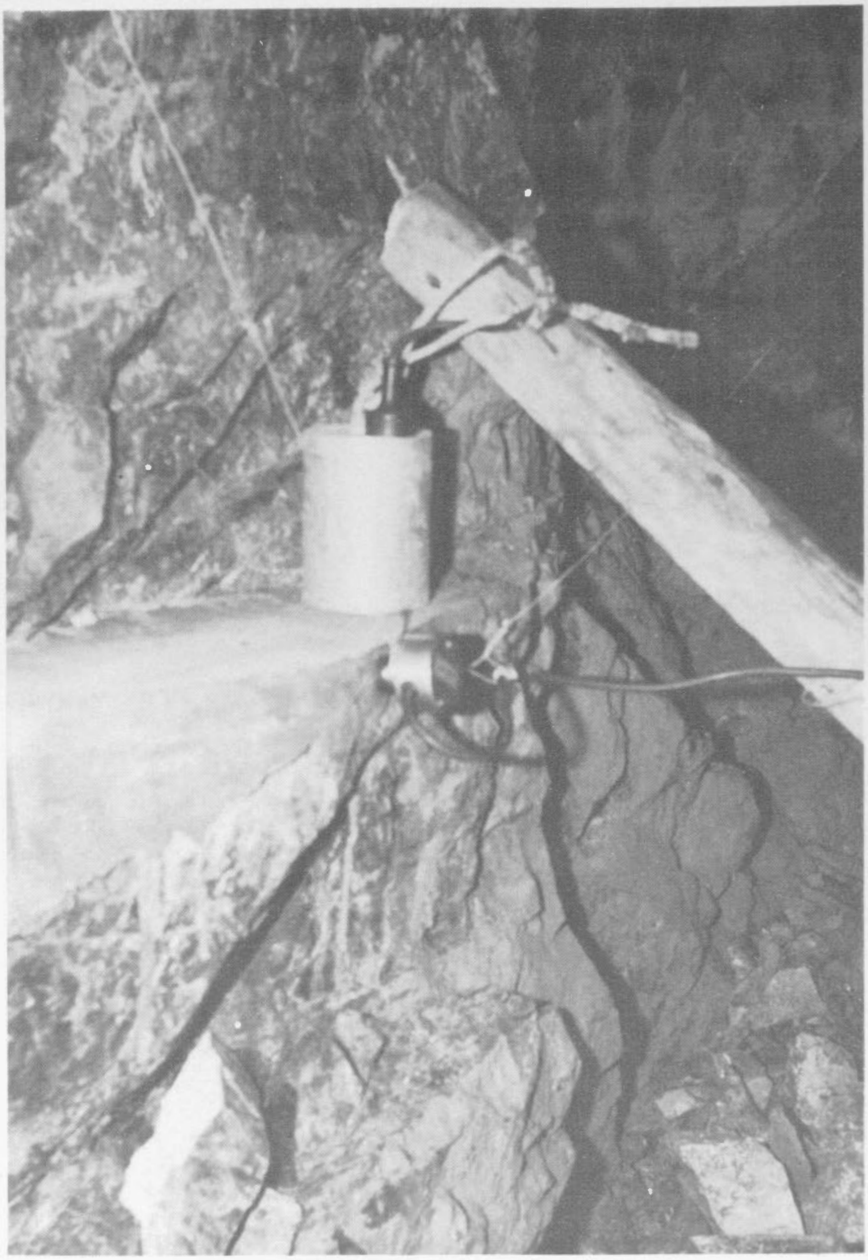


Fig. 21 Heiland Geophone and Crystal Detector (3950-ft. Level).

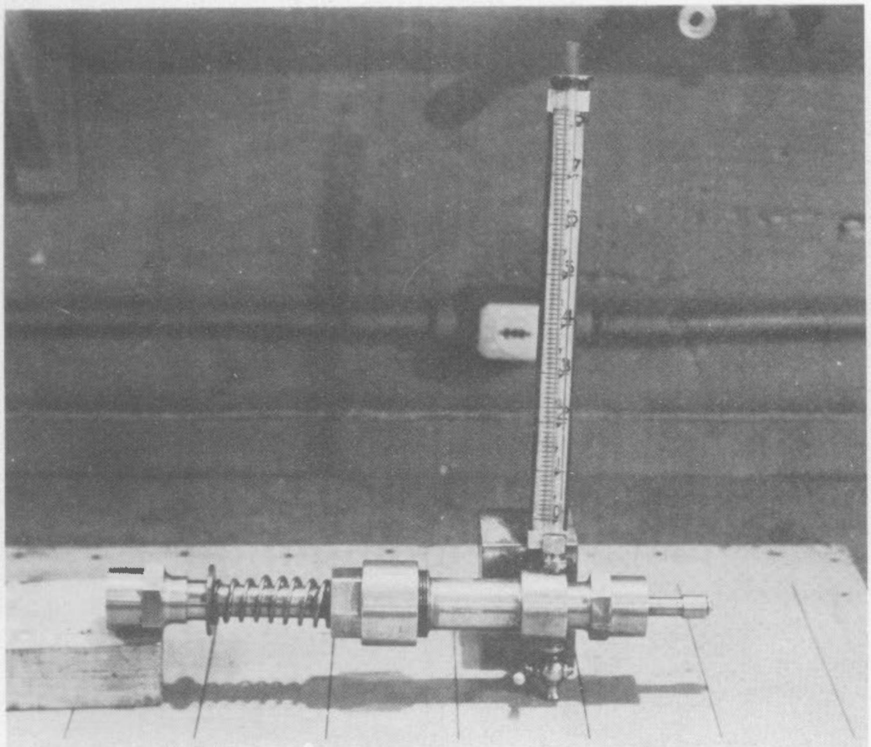


Fig. 22 Hydraulic Strain Gauge

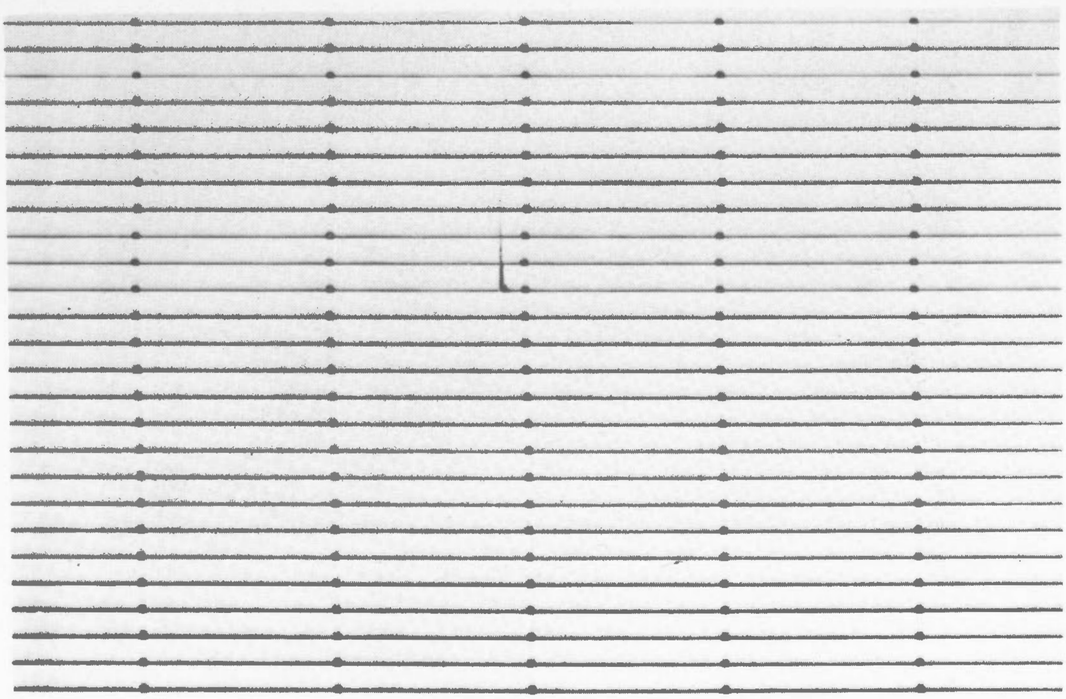


Fig. 23 Rockburst Record on Improved Surface Recorder.

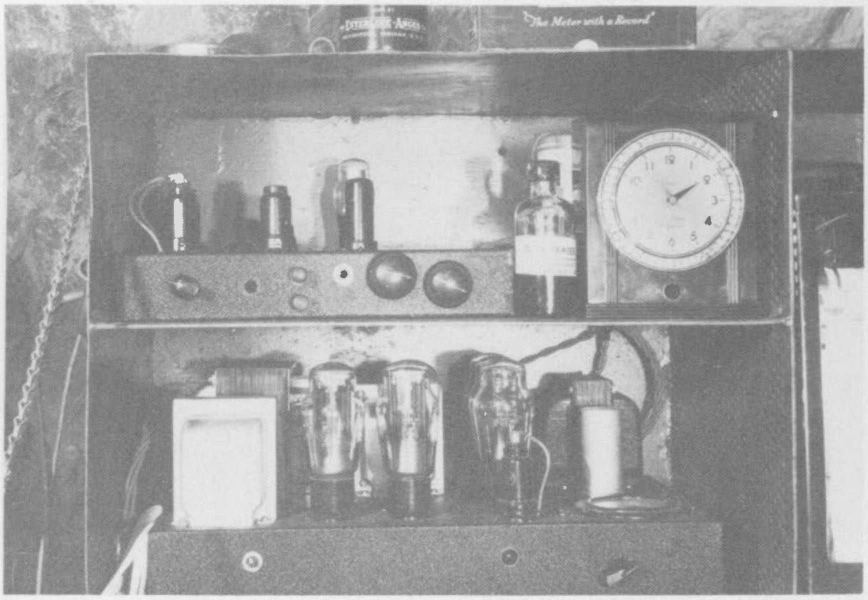


Fig. 24 Amplifier-Timer-Recorder: Mine Seismograph.

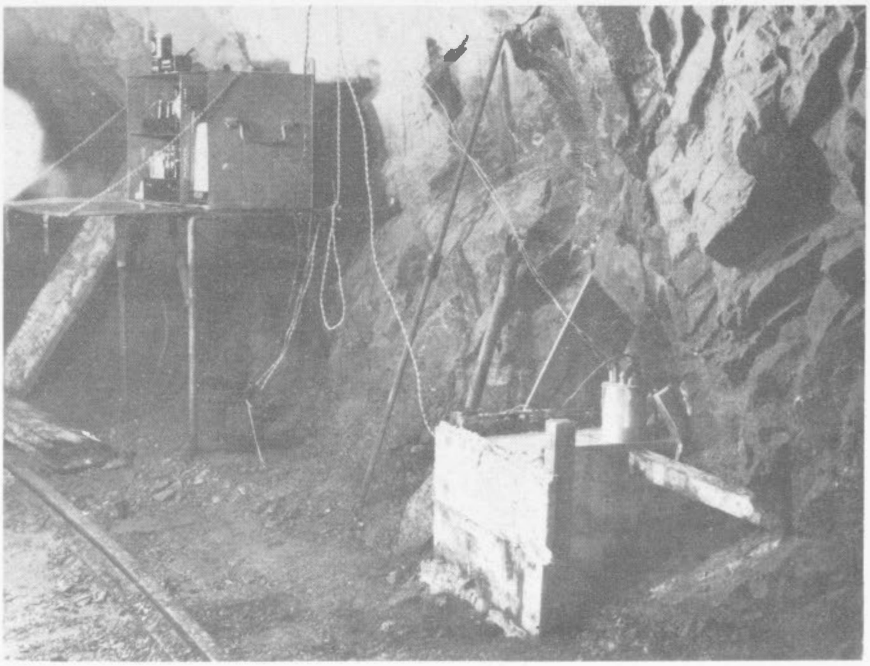


Fig. 25 Mine Seismograph Set-up (3052 Crosscut).

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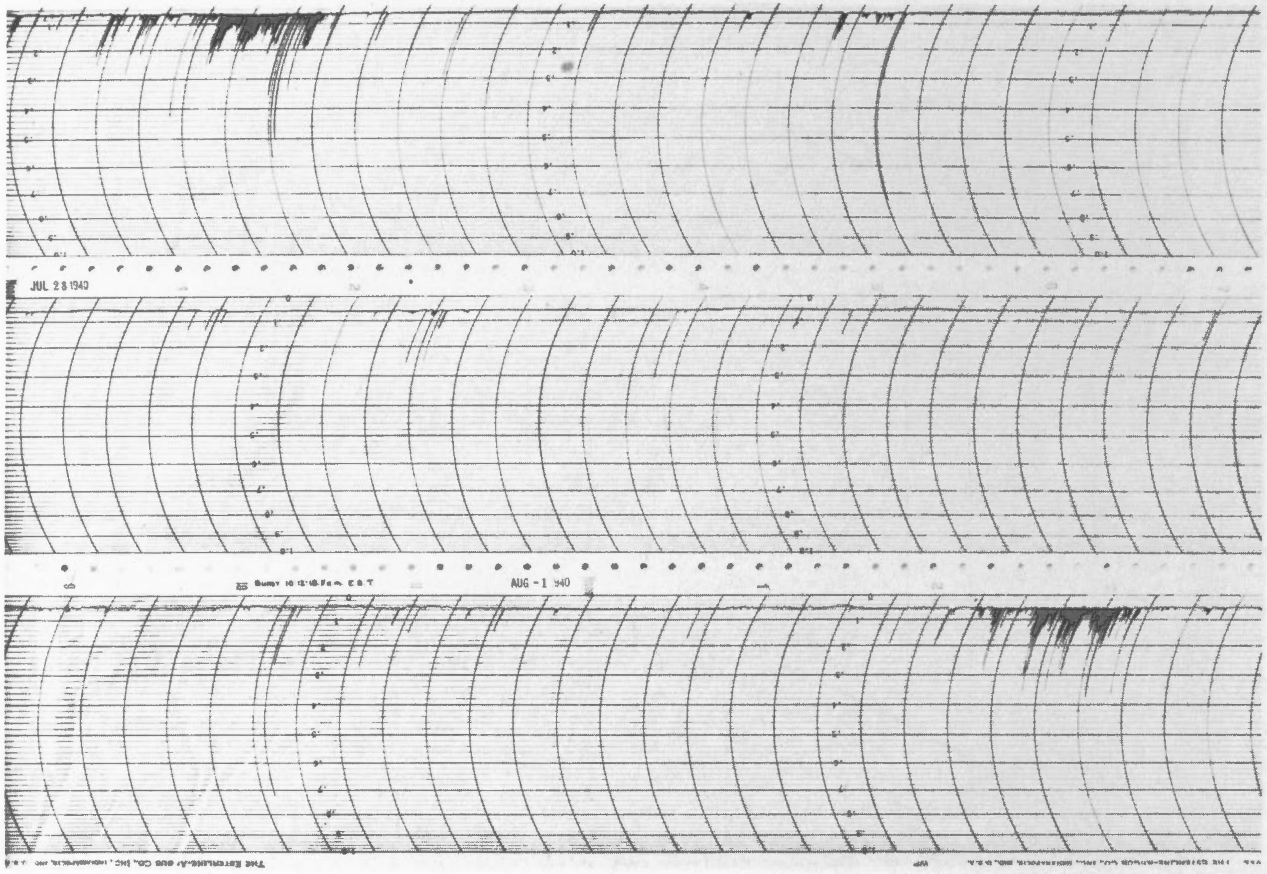


Fig. 26 Record on Esterline-Angus Recorder: Mine Seismograph.

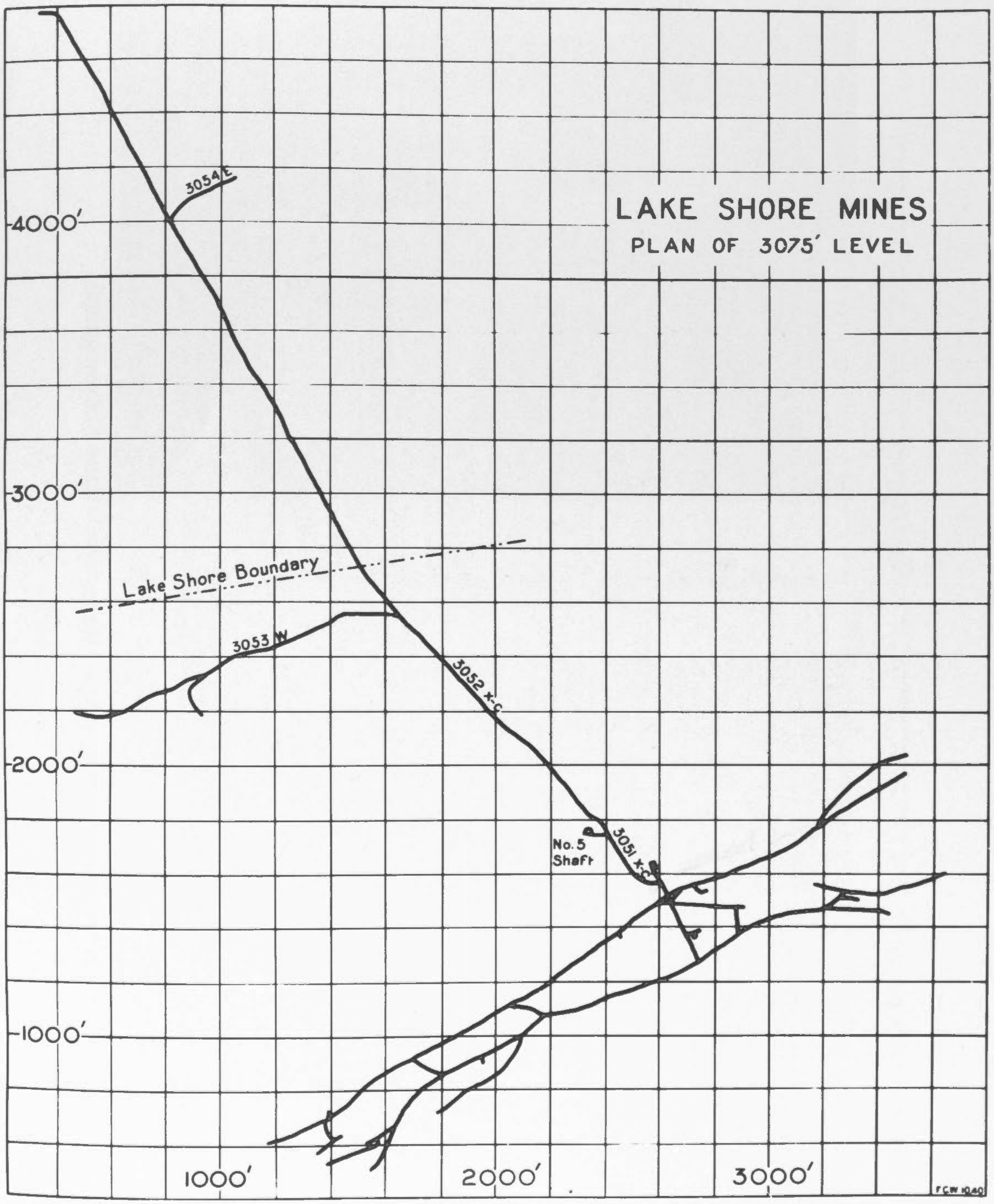


Fig. 27 Plan of 3075-ft. Level, Lake Shore Mines.

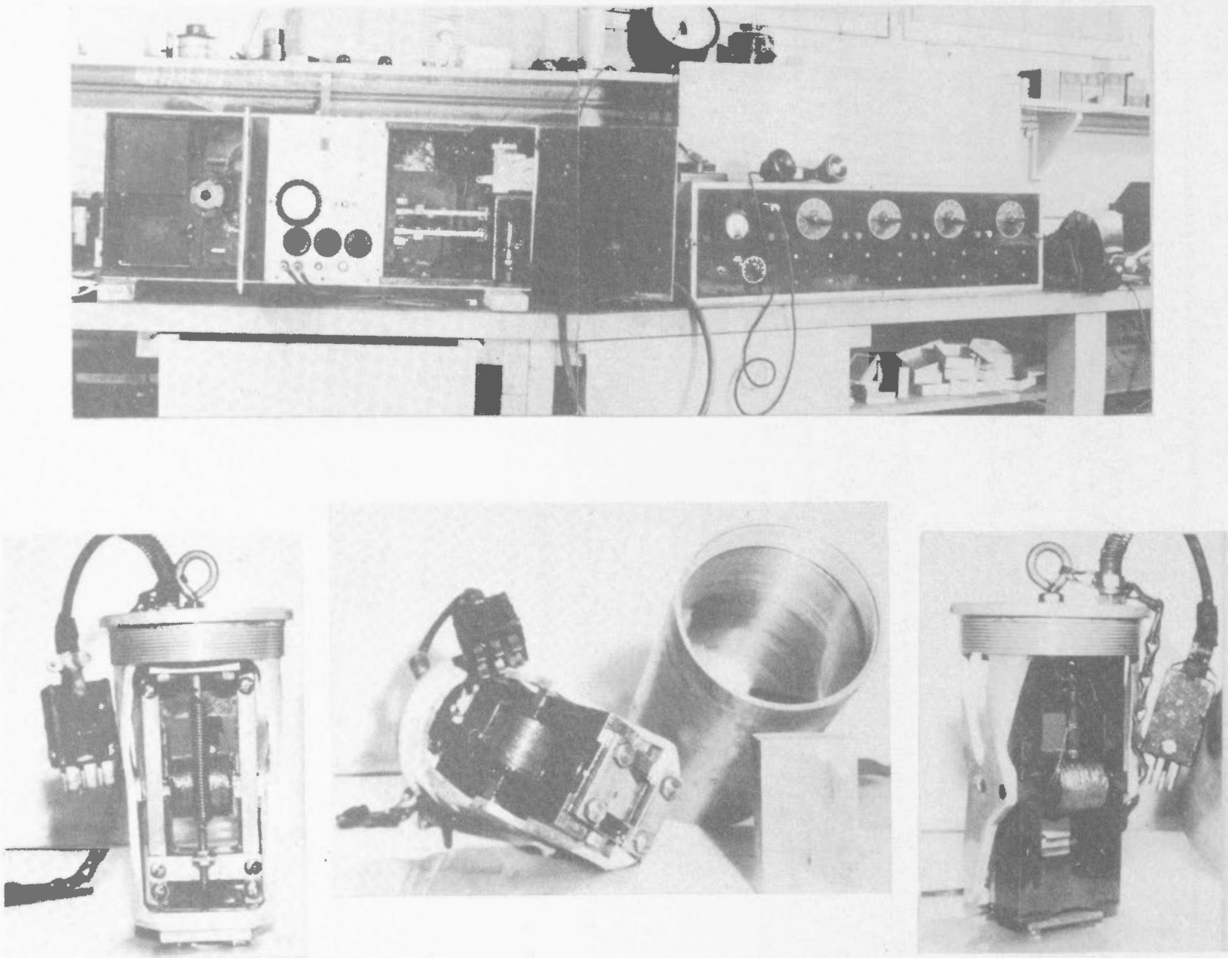


Fig. 28 High-speed Seismograph Equipment Leased from Leet.

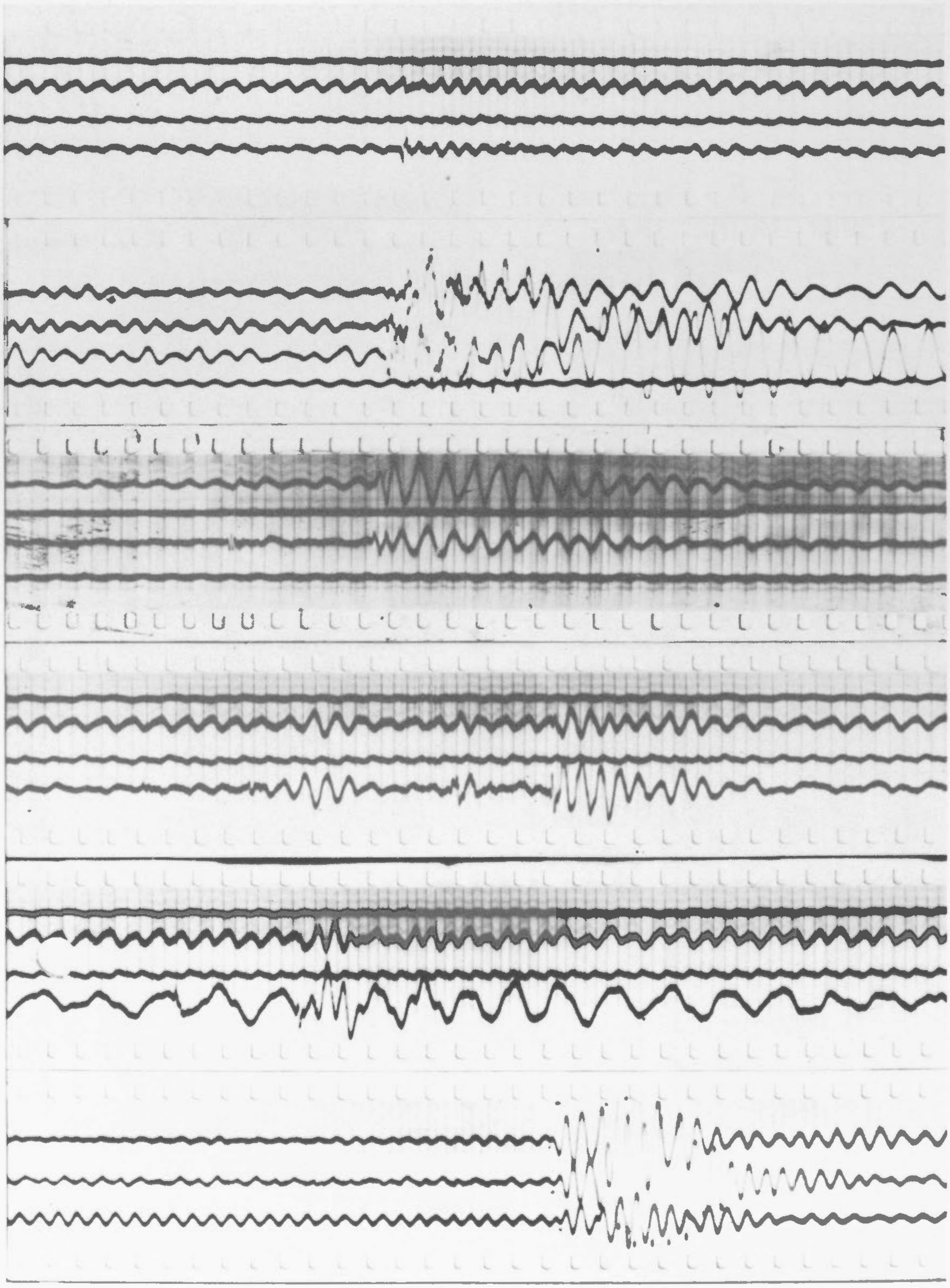


Fig. 29 Records (a) to (f): Leet Equipment (underground)

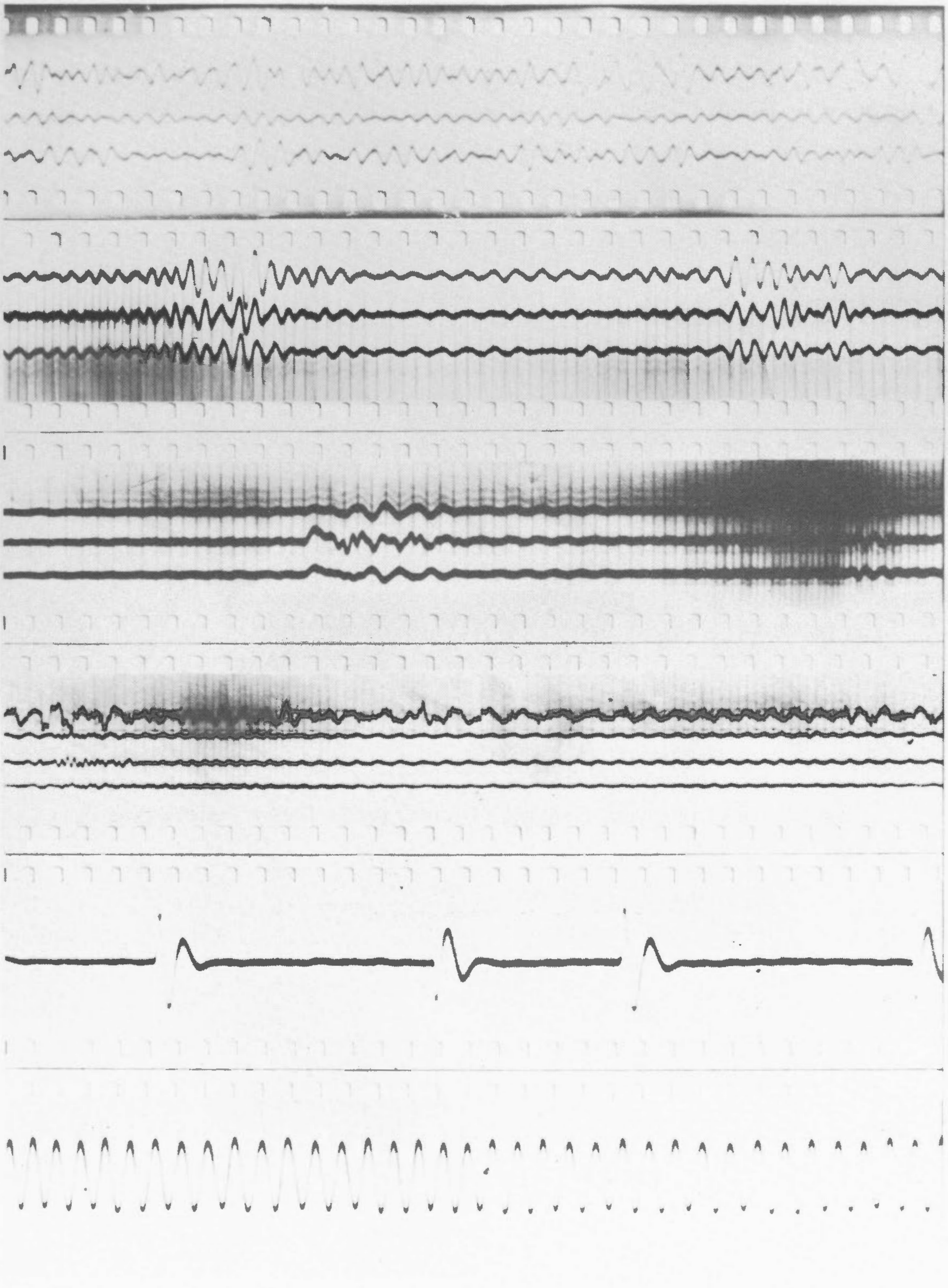


Fig. 30 Records (a) to (f): Leet Equipment (check records).

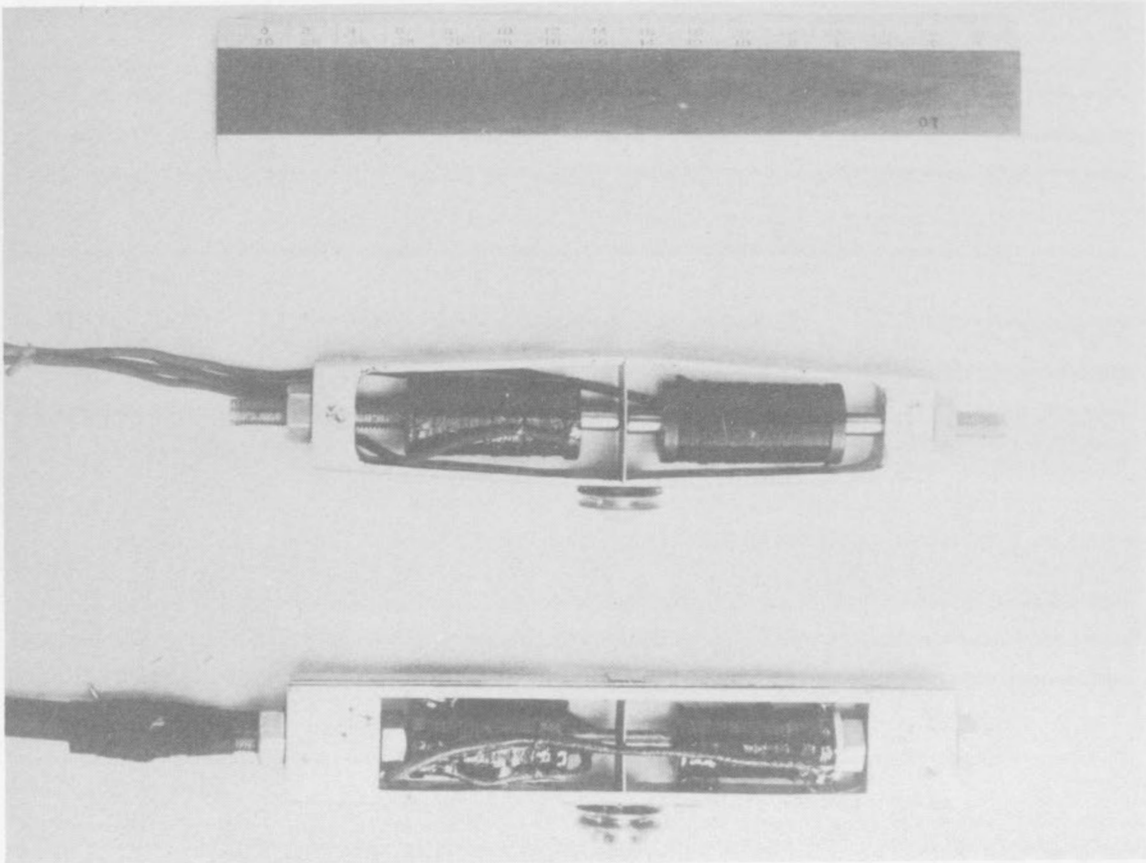


Fig. 31 Hollinsworth Borehole Convergence Gauge (microgauge).

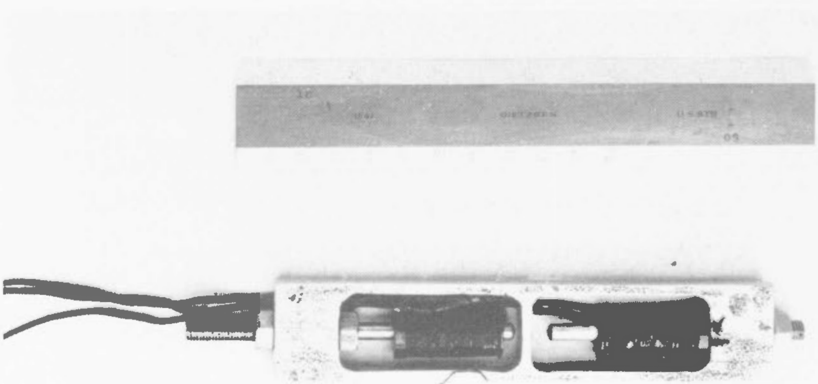
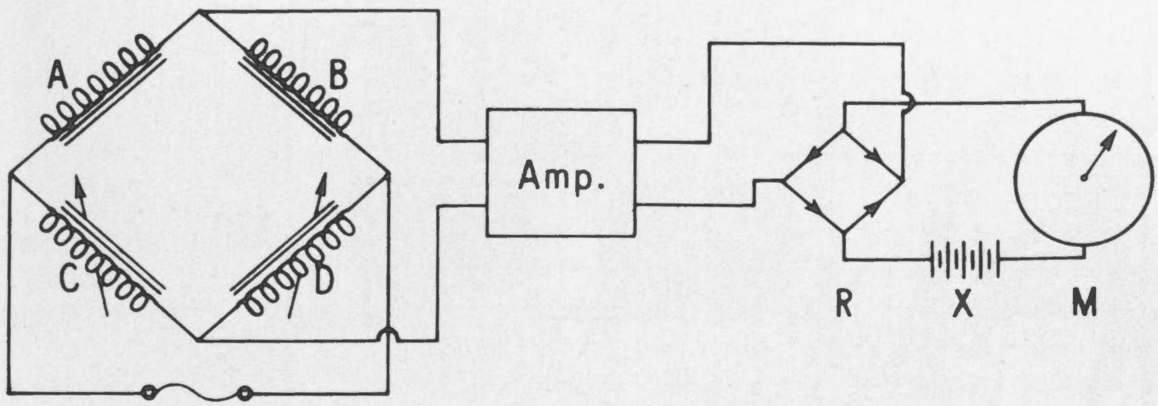


Fig. 32 Hollinsworth Calibrating Gauge.



Wiring Diagram of Microgauge

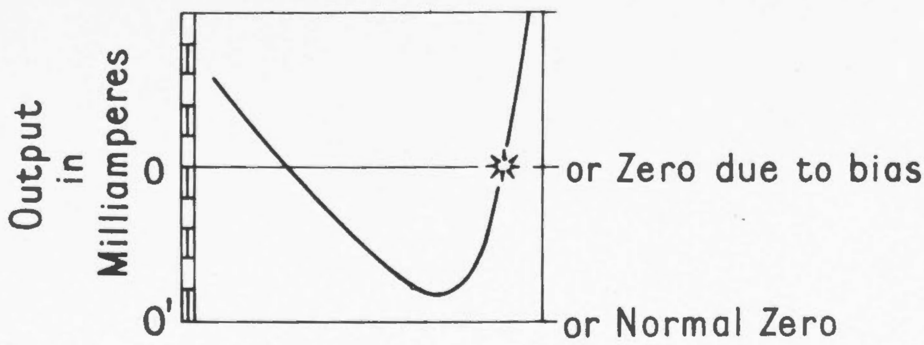


Fig. 33 Hollinsworth Microgauge Wiring Diagram.

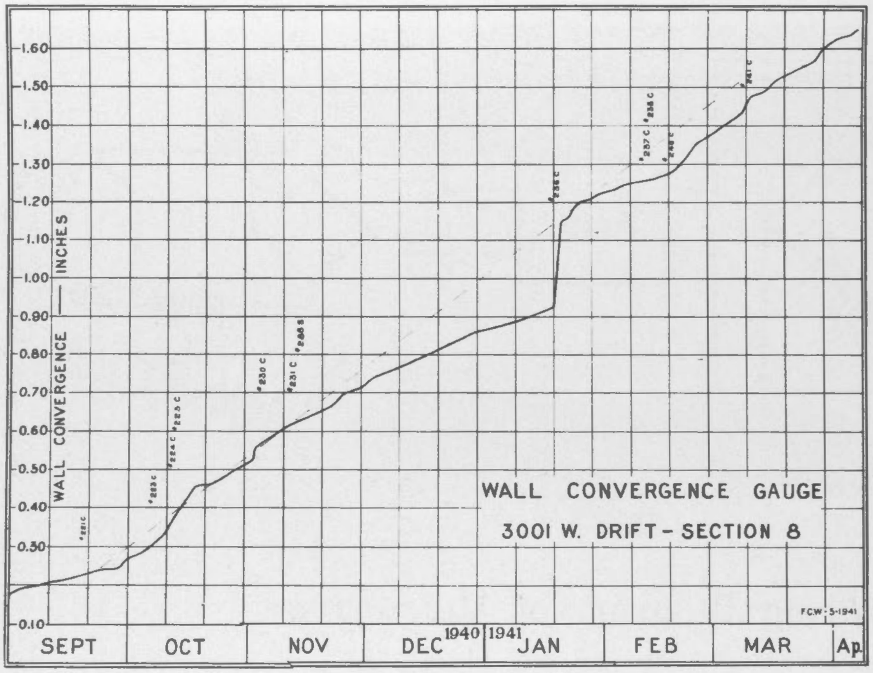


Fig. 34 Record Hydraulic Converg- ence Gauge.

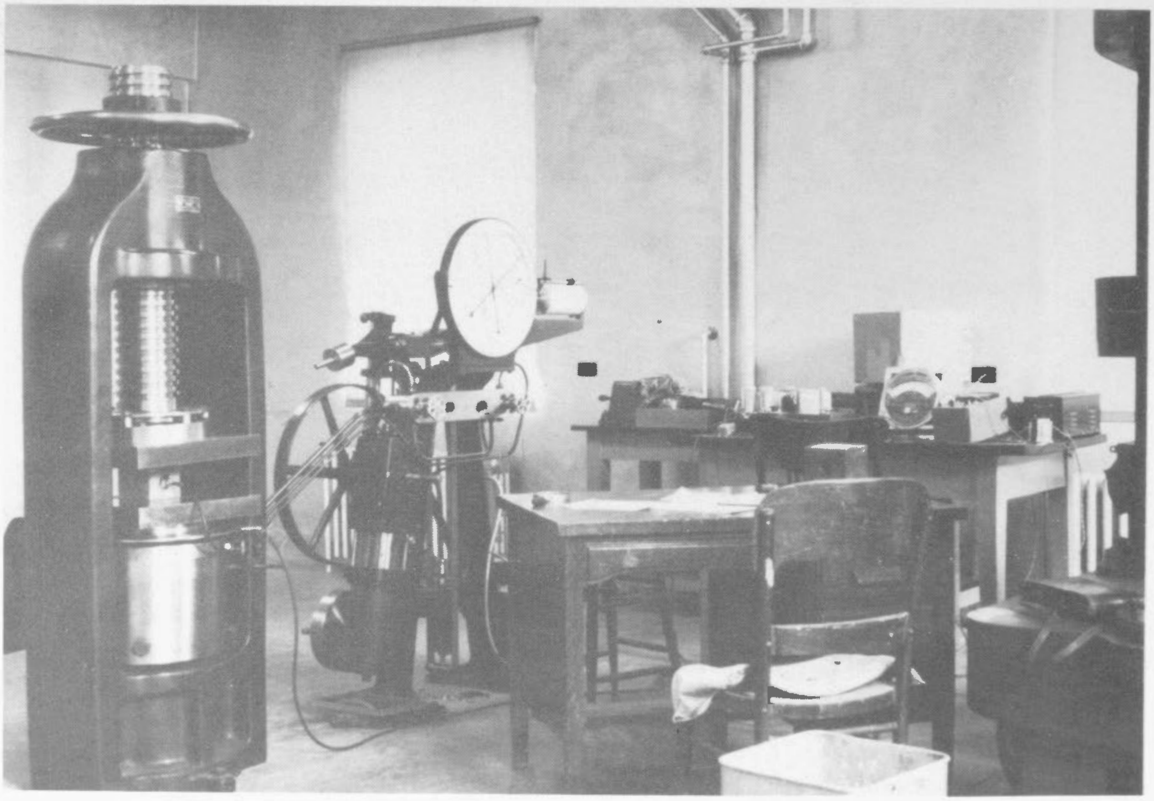


Fig. 35 Hydraulic Press Tests of Hollinsworth Gauge.

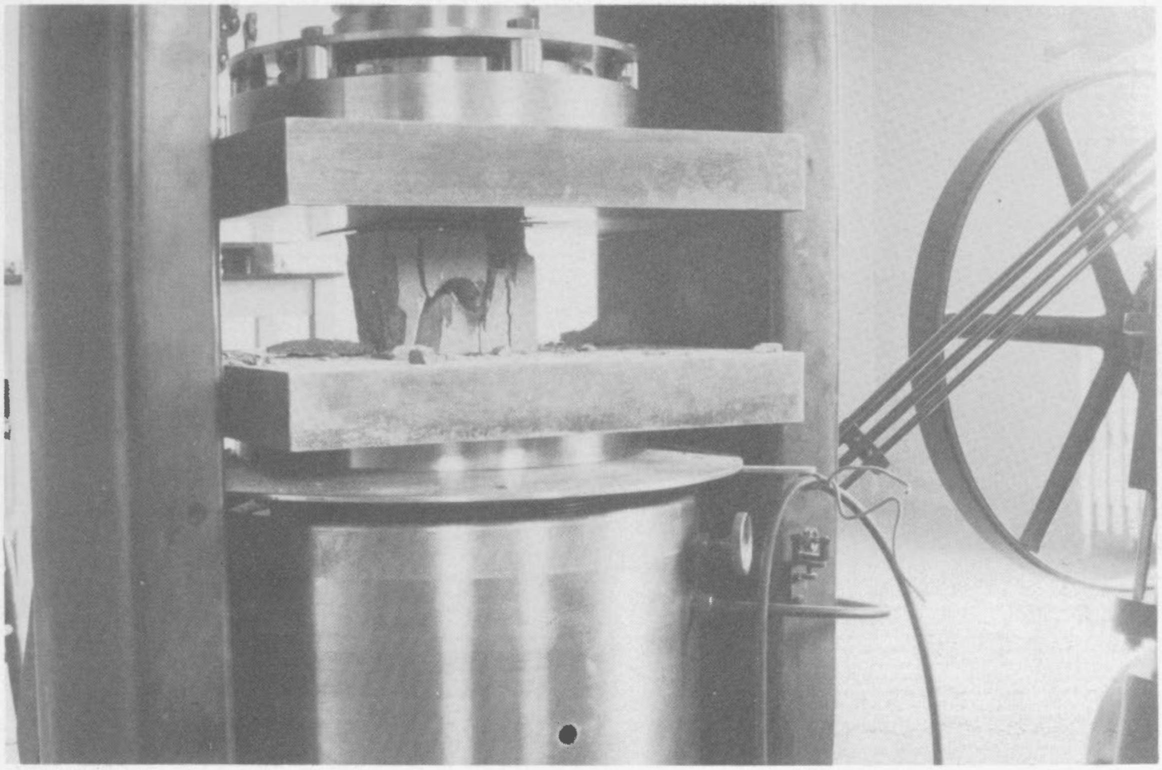


Fig. 36 Rock Crushing Experiments with Hollinsworth Gauge.

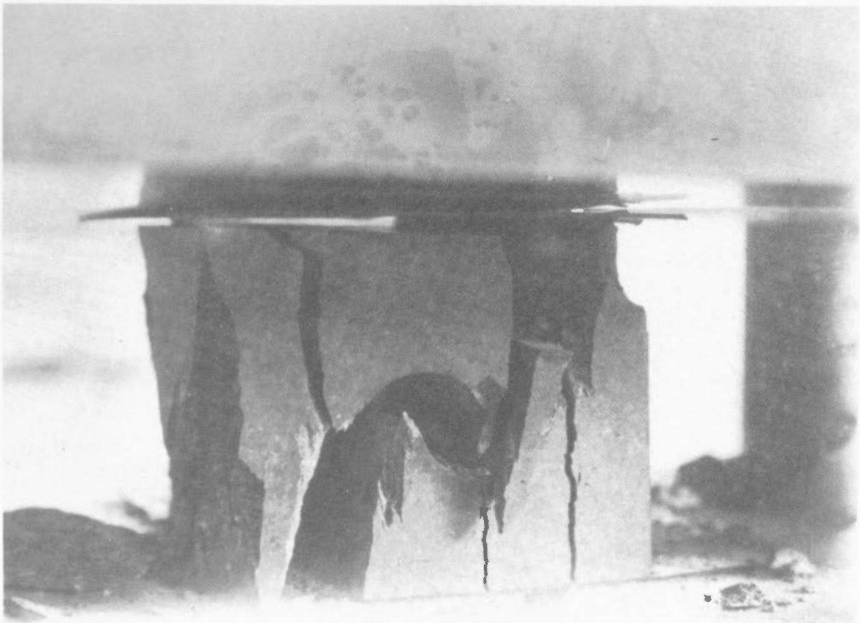


Fig. 37 Small Syenite Block after Crushing.

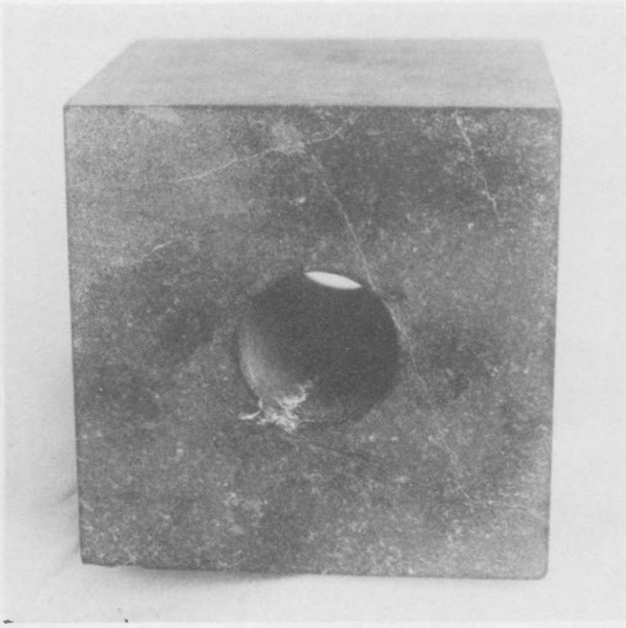


Fig. 38 Porphyry Specimen $\underline{P}$ after Pressure to 9,150 lbs/sq. in.

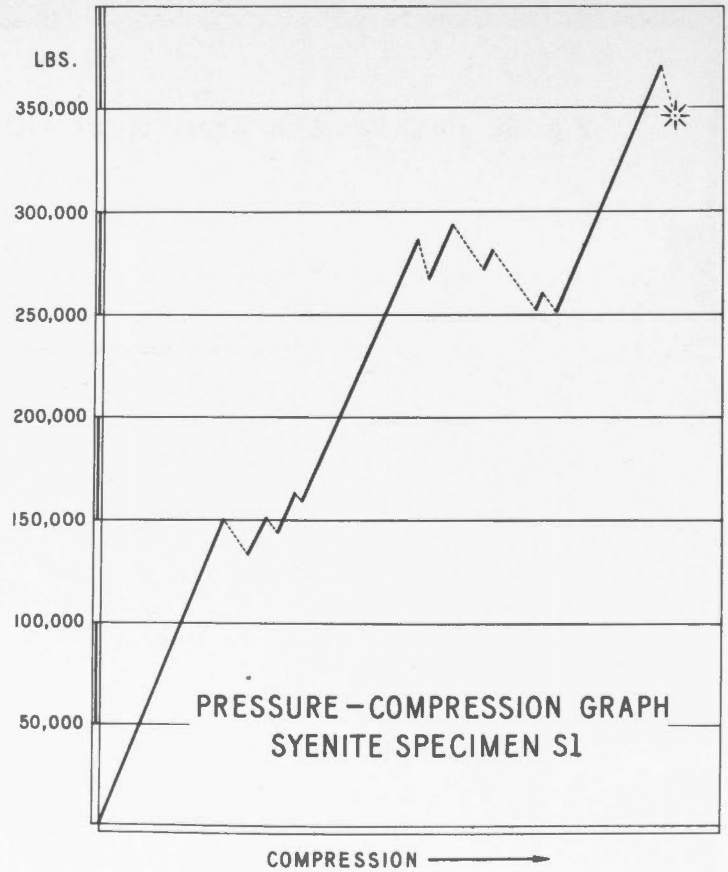


Fig. 39 Pressure Compression Graph - Syenite Specimen S_1.

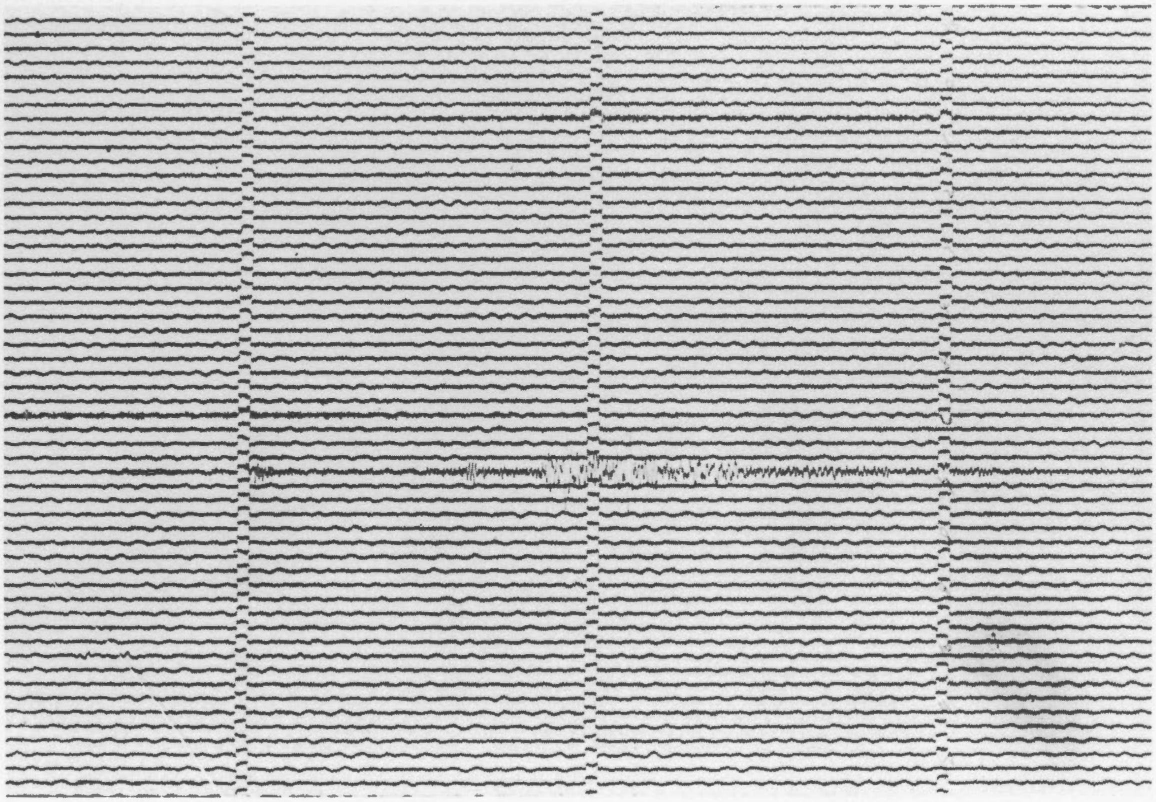


Fig. 40 Typical Ottawa Record of Kirkland Lake Rockburst.

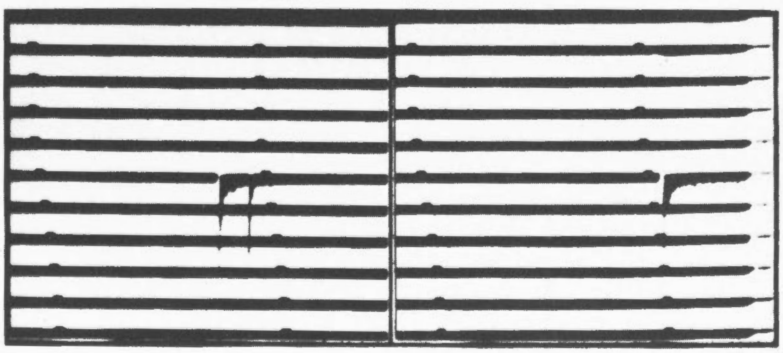


Fig. 41 Bursts I, I_a and J as Recorded on the Lake Shore Surface Seismograph, July 30, 1941.

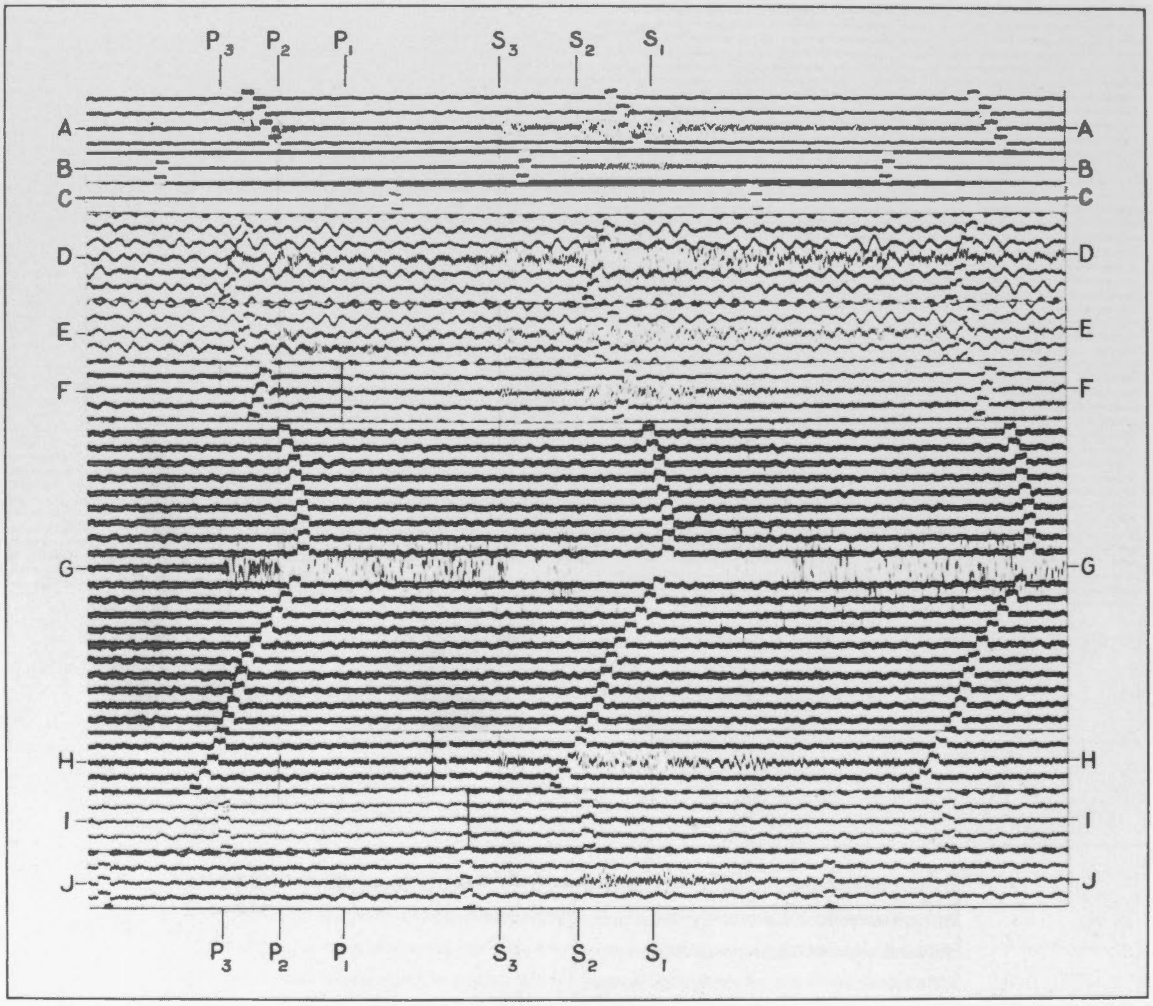


Fig. 42 Comparison of Records from the Benioff Seismograph at Ottawa

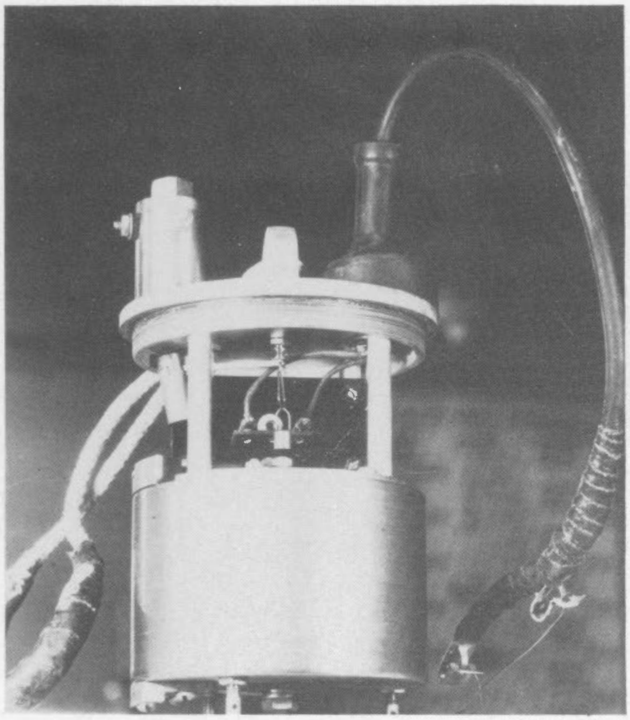
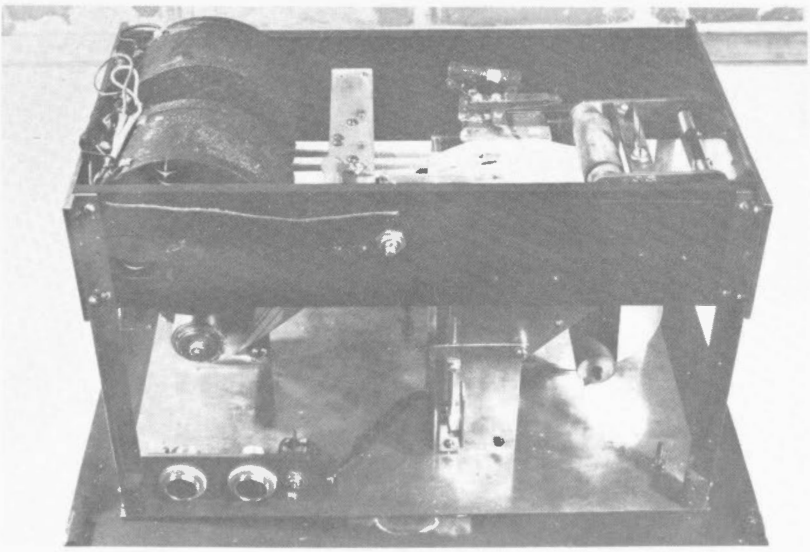


Fig. 43. Heiland Geophone with Sensitivity Tester.

Fig. 44 Side View Obert Recorder



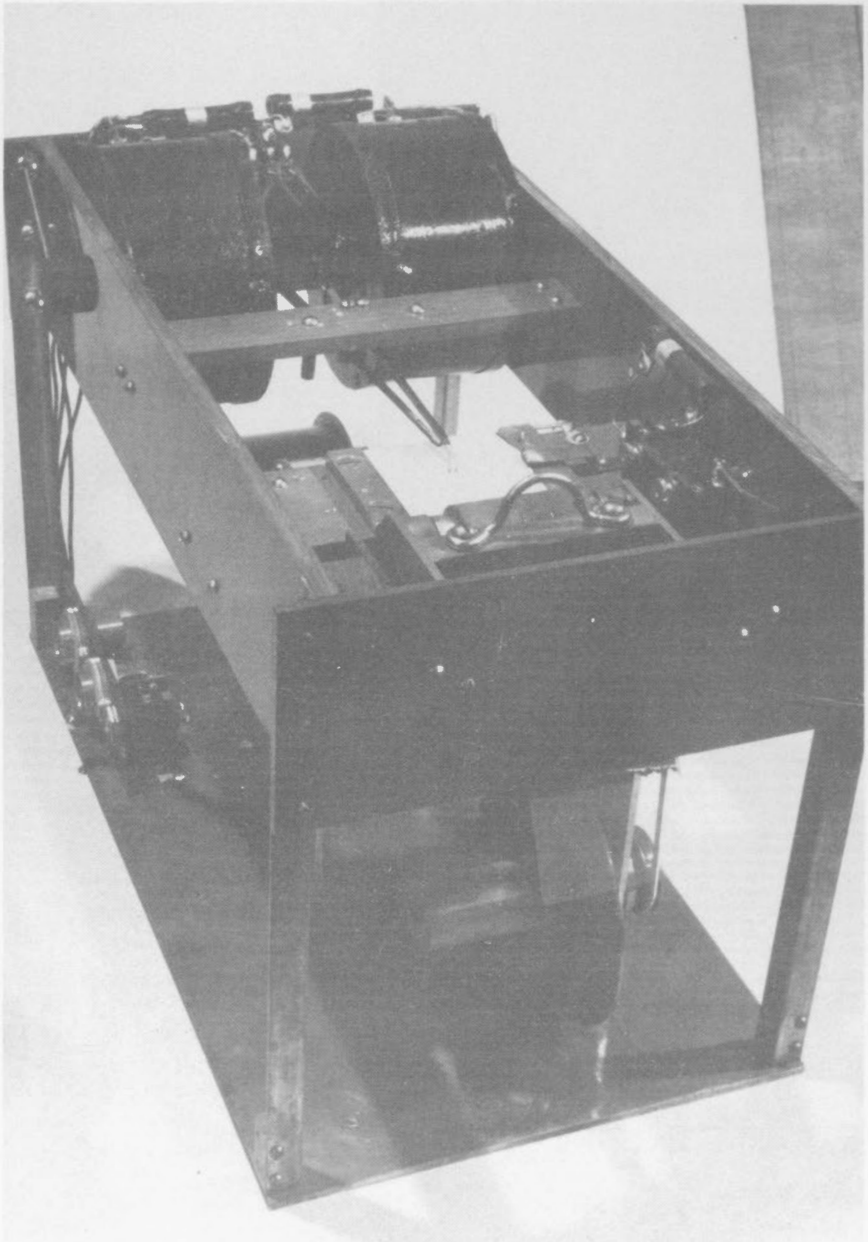


Fig. 45 End View: Obert Recorder.

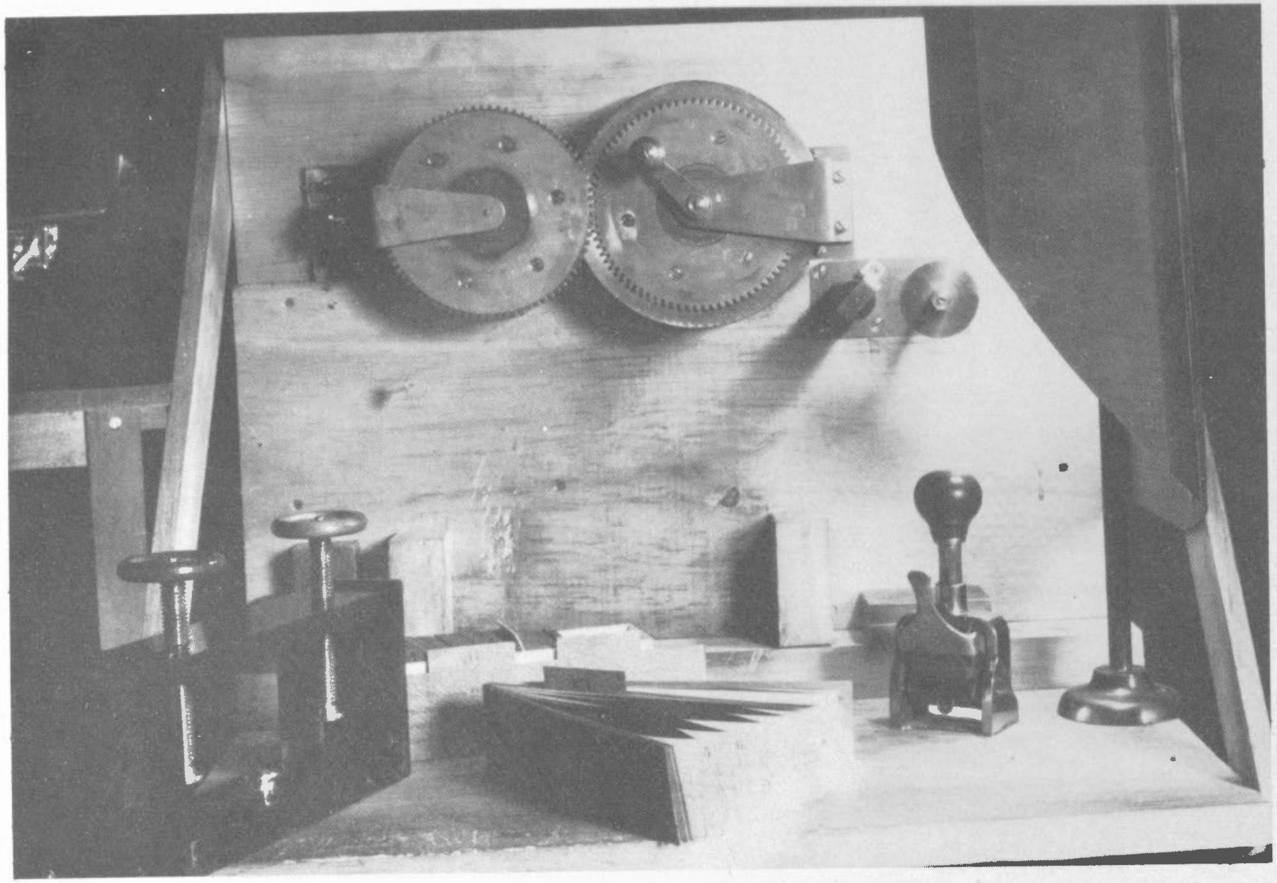


Fig. 46 Record Pleater and Accessories.

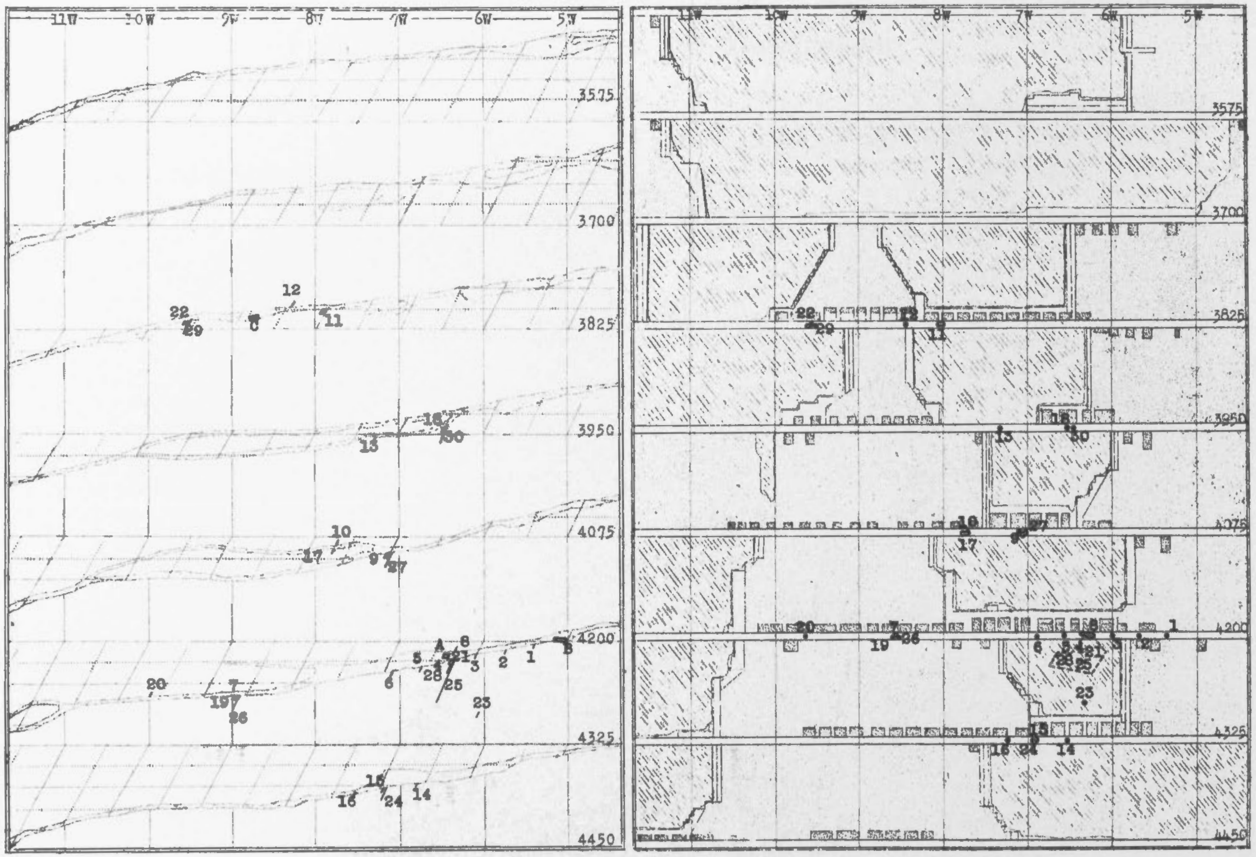


Fig. 47 Location of Test Holes Nos. 1-30.

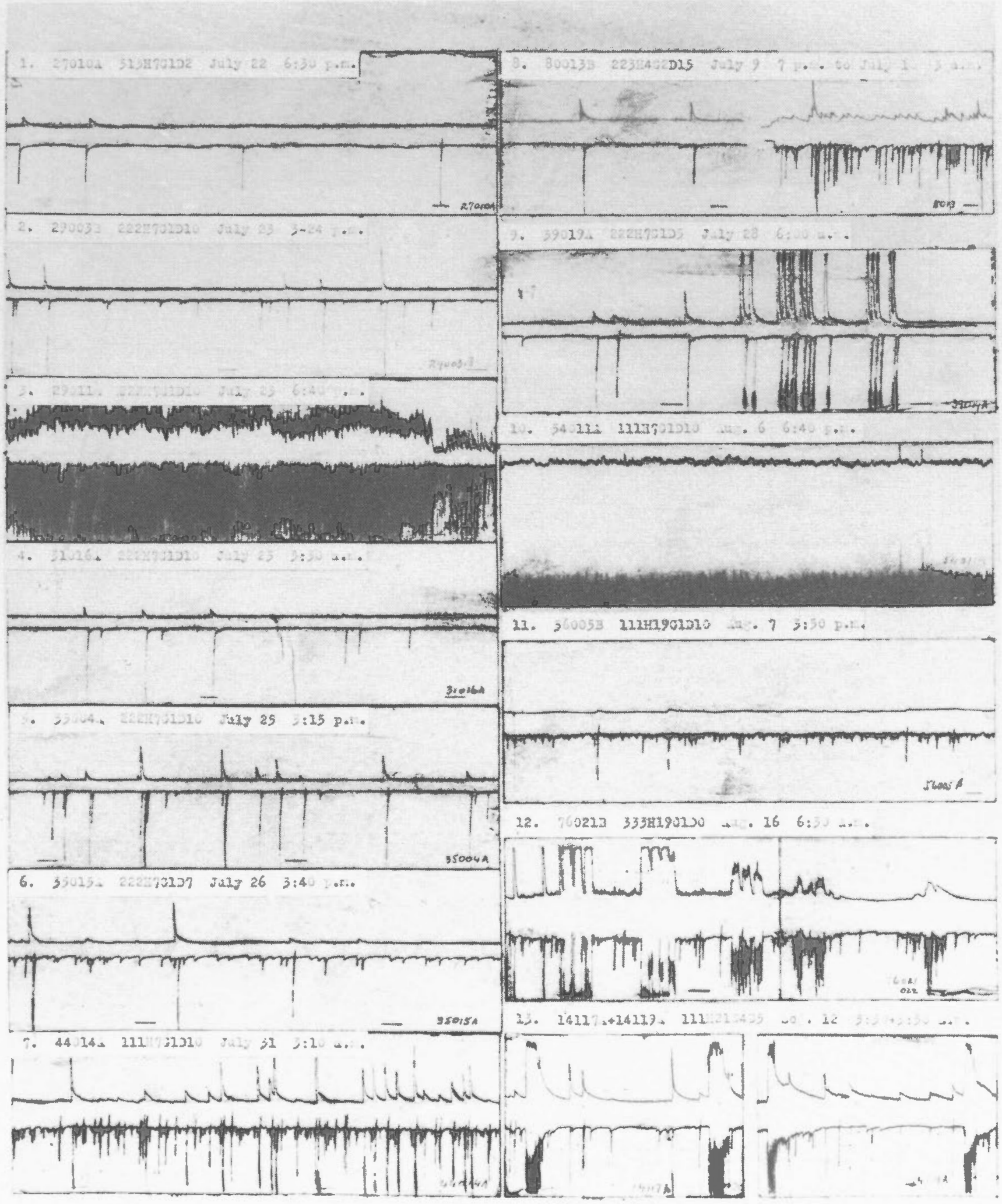


Fig. 48 Record of Activity in 4201W10 in Relation to the Rockburst of July 25 (together with some typical interference records).

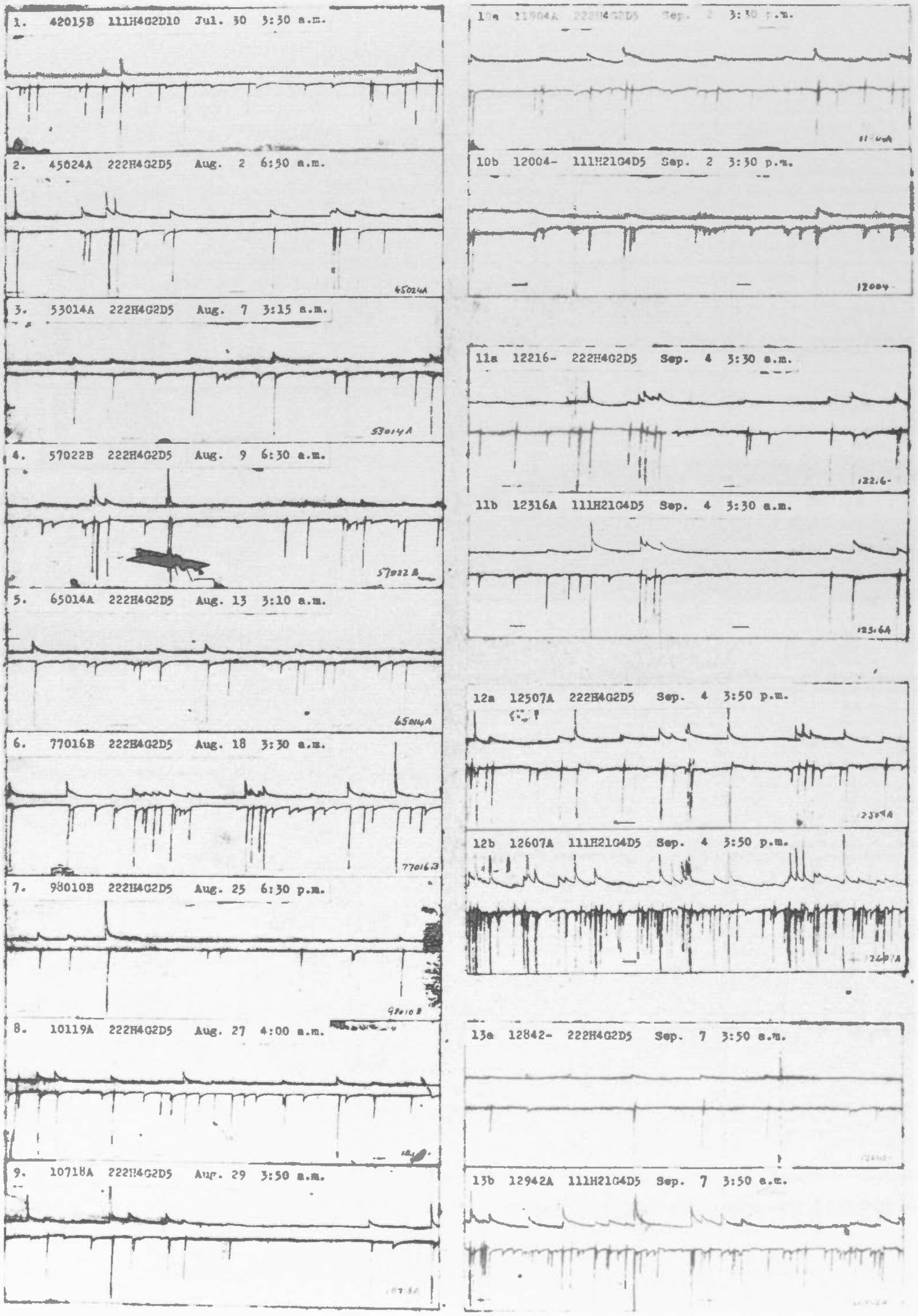


Fig. 49 Record of Activity in 4201W8 (up to and after bringing through a raise from 4300-ft. level on Sept. 5).

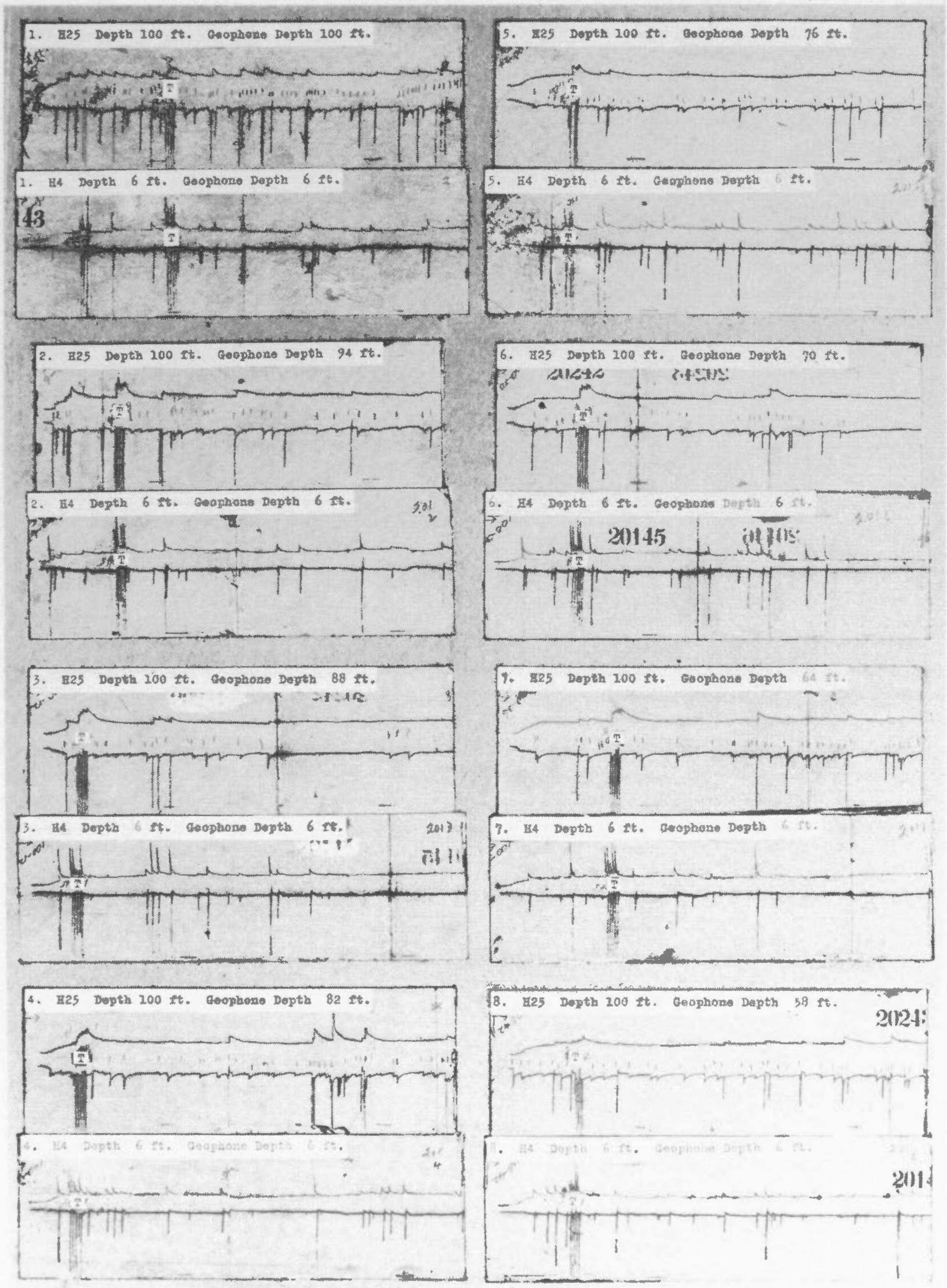


Fig. 50 Comparison of Recording in Adjacent Deep and Shallow Holes (deeper records).

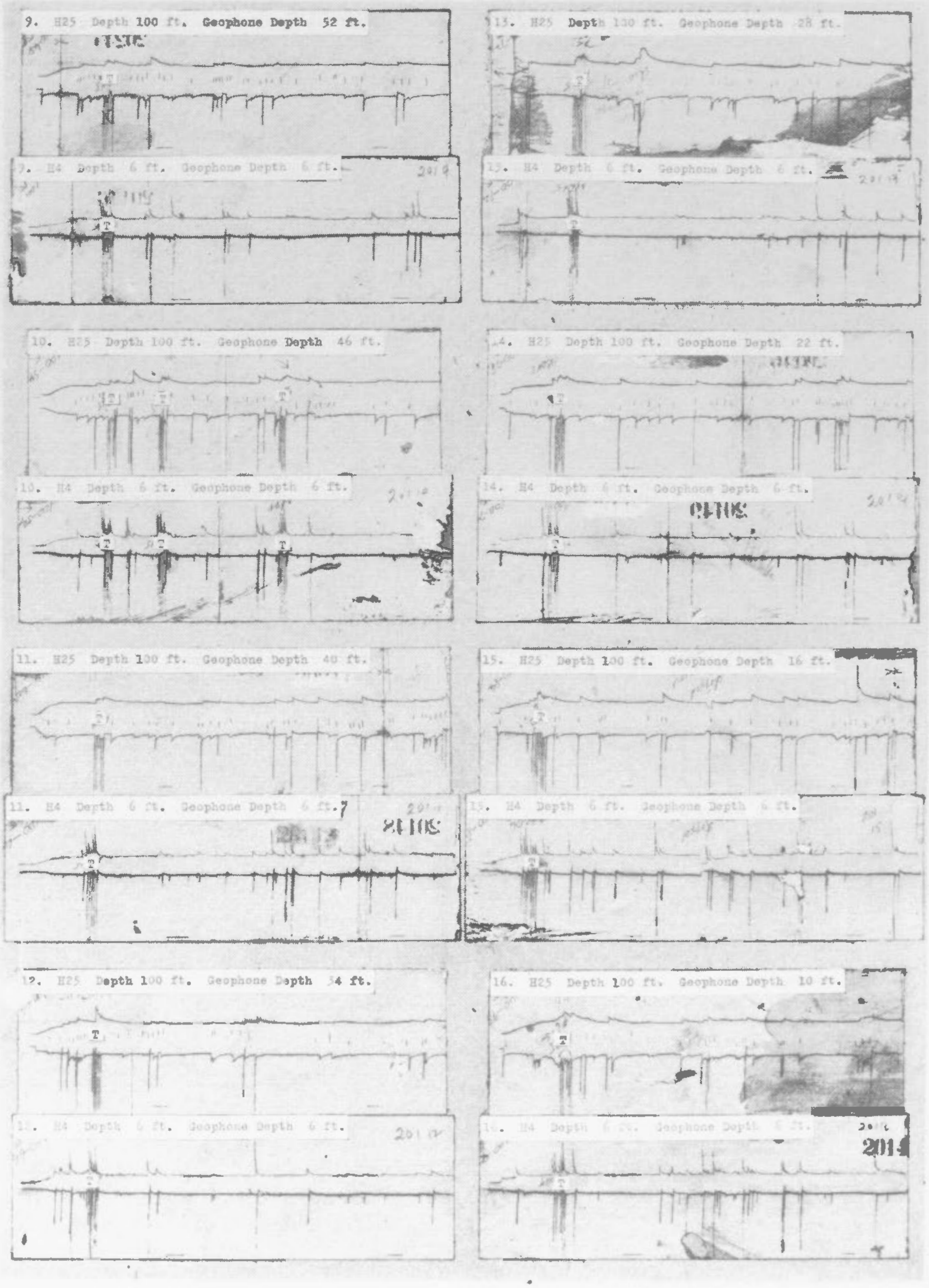
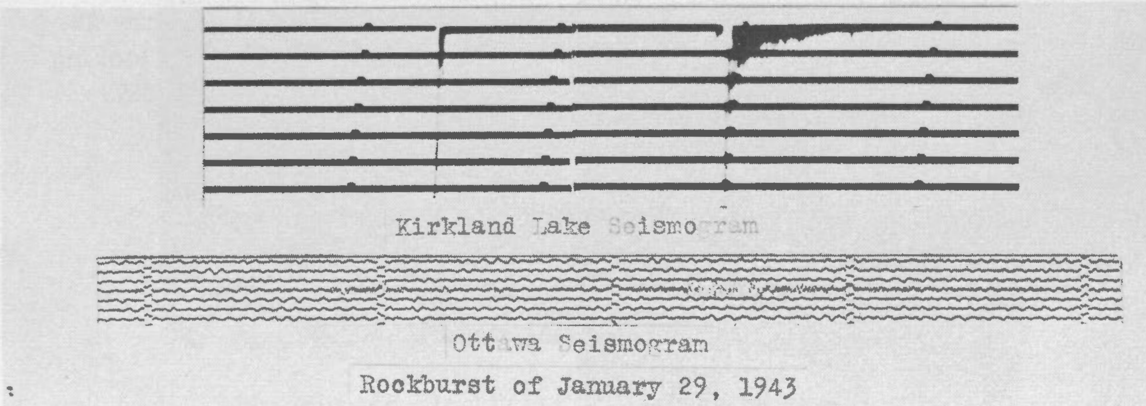


Fig. 51 Comparison of Recording in Adjacent Deep and Shallow Holes (shallower records).



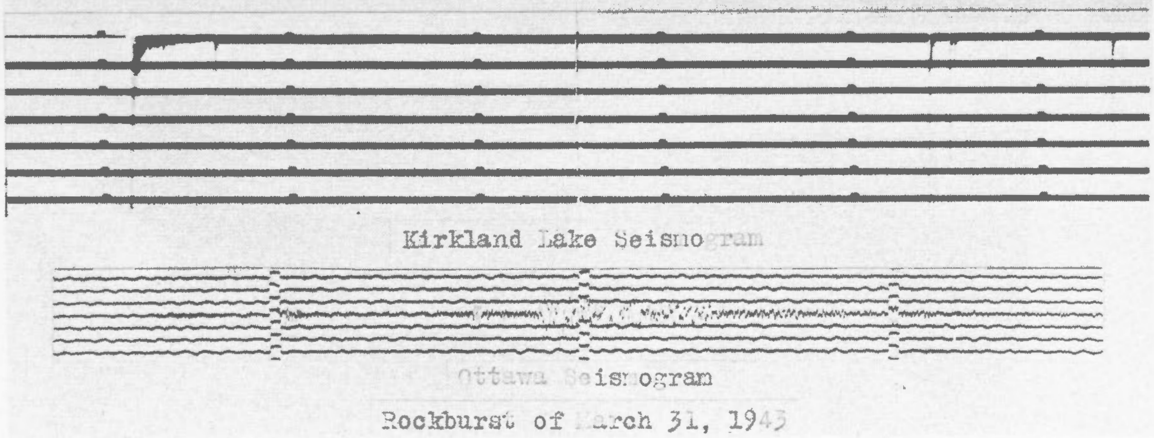


Fig. 52 Kirkland Lake and Ottawa Seismograms of the Rockburst of January 29, 1943.

Fig. 53 Kirkland Lake and Ottawa Seismograms of the Rockburst of March 31, 1943.

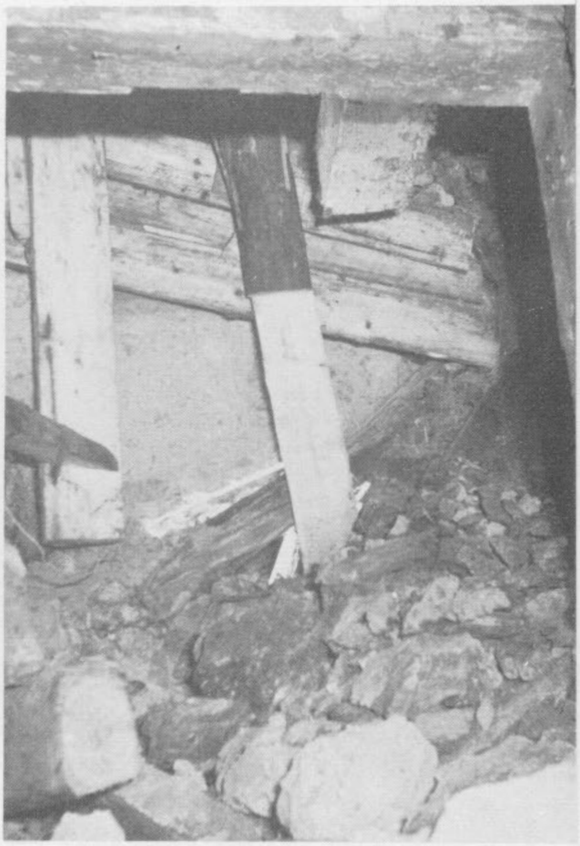


Fig. 54 Rockburst of January 29, 1943; 3801W Drift looking west from Sec. 6.5W.

Fig. 55 Rockburst of January 29, 1943; 3901W Drift, looking west from Sec. 6.5W.

Fig. 56 Rockburst of January 29, 1943; 3908W Drift, looking west from Sec. 7W.

Fig. 57 Rockburst of January 29, 1943; 4001W Drift, looking west from Sec. 6.7W.

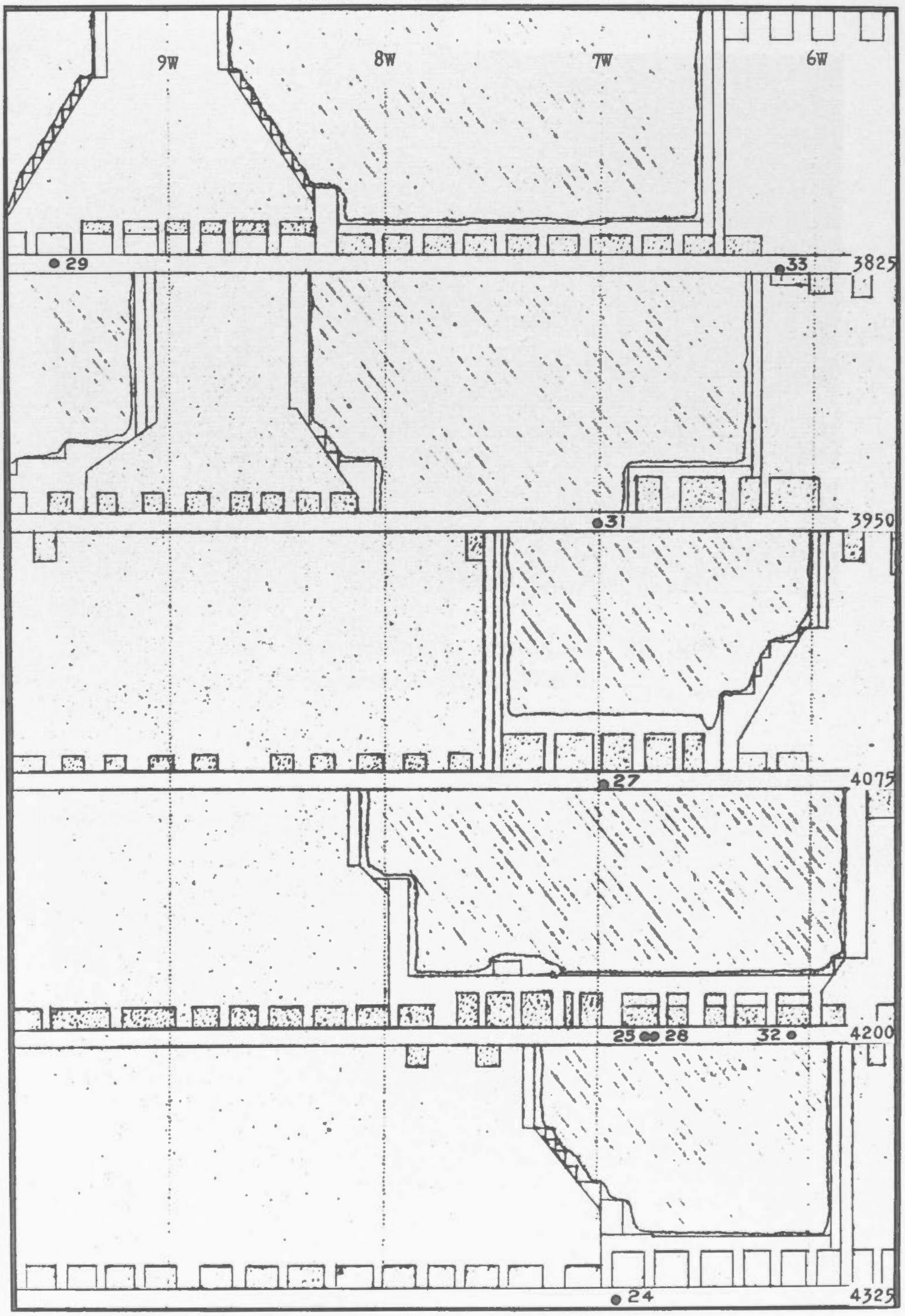


Fig. 58 Sections of West Pillar Affected by Rockburst of January 29, 1943.

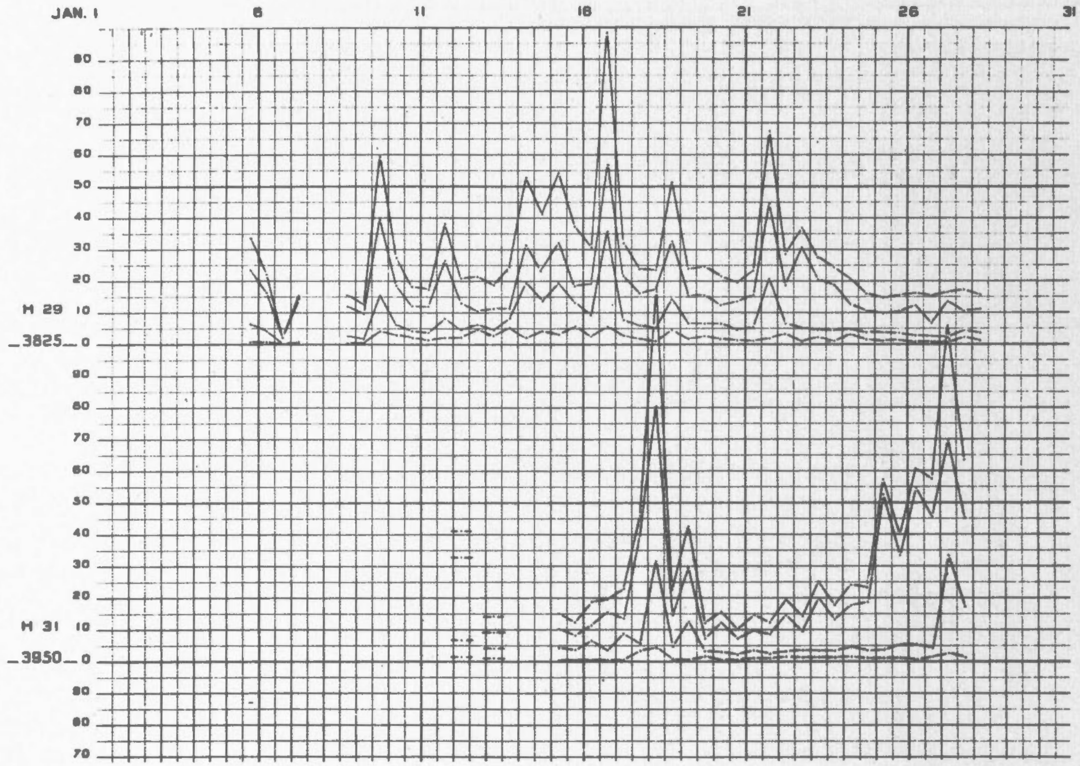


Fig. 59 Record Counts: Holes 29 and 31; January 6-28, 1943.

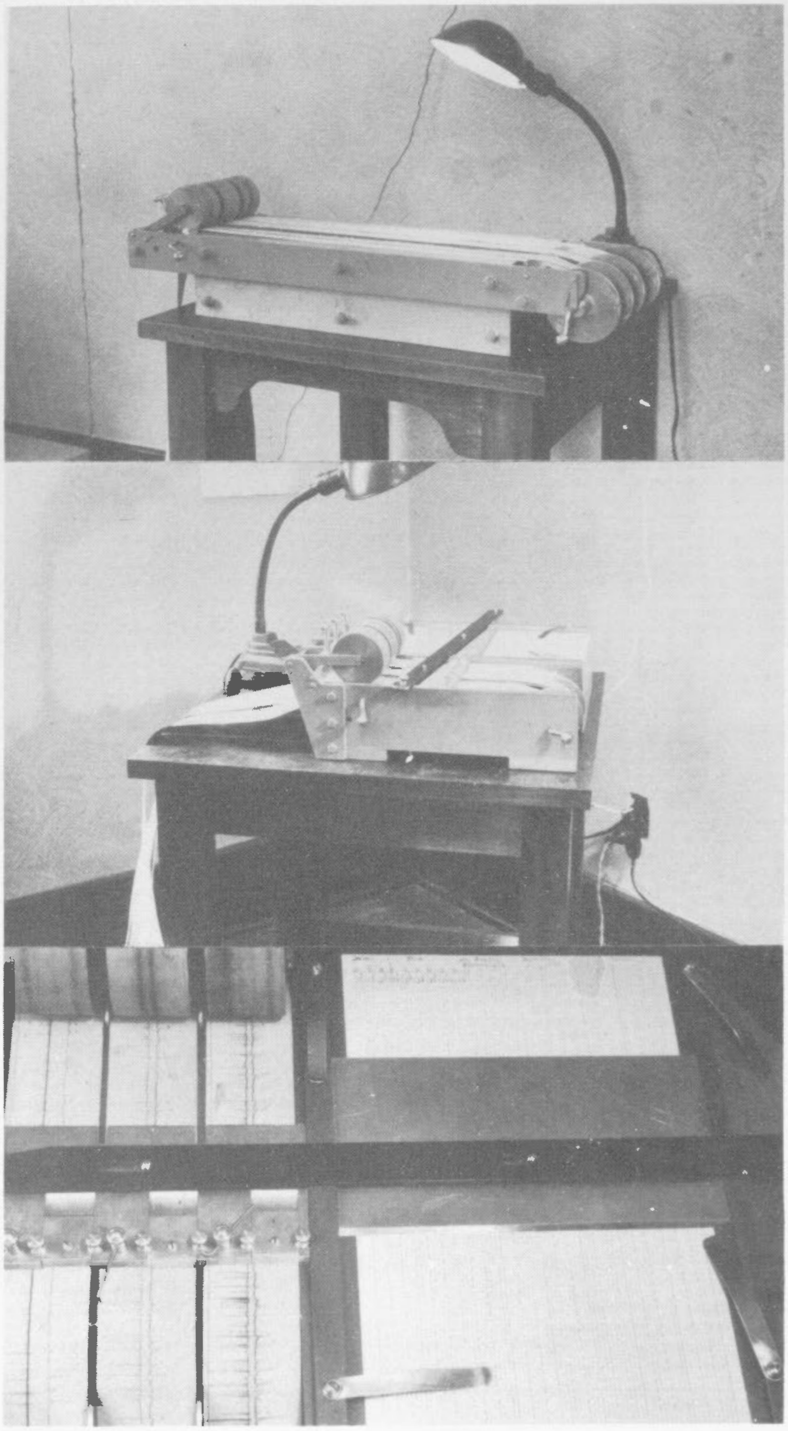


Fig. 60 Annotator and Comparator.

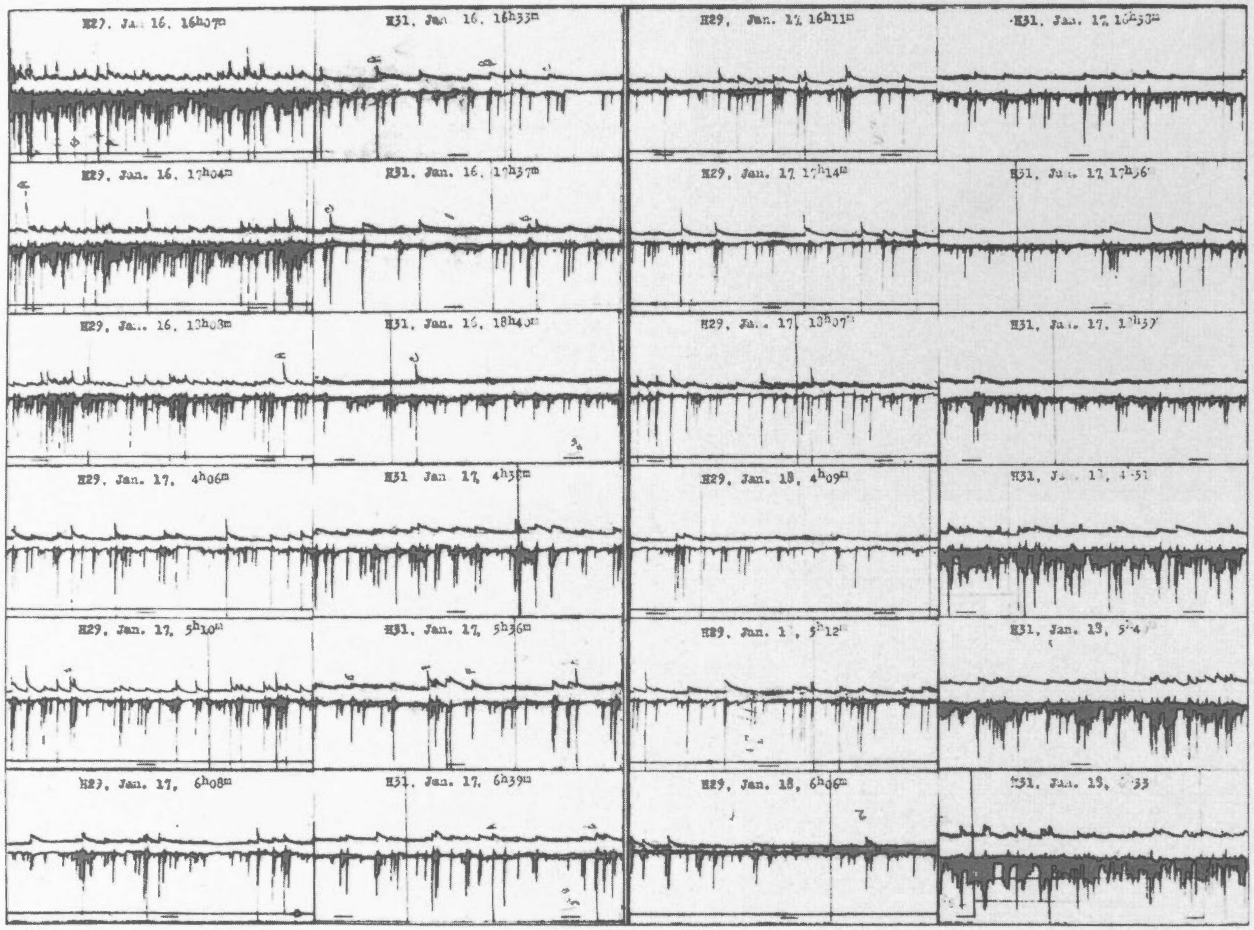


Fig. 61 Pressure Shift, January 16-18, 1943.

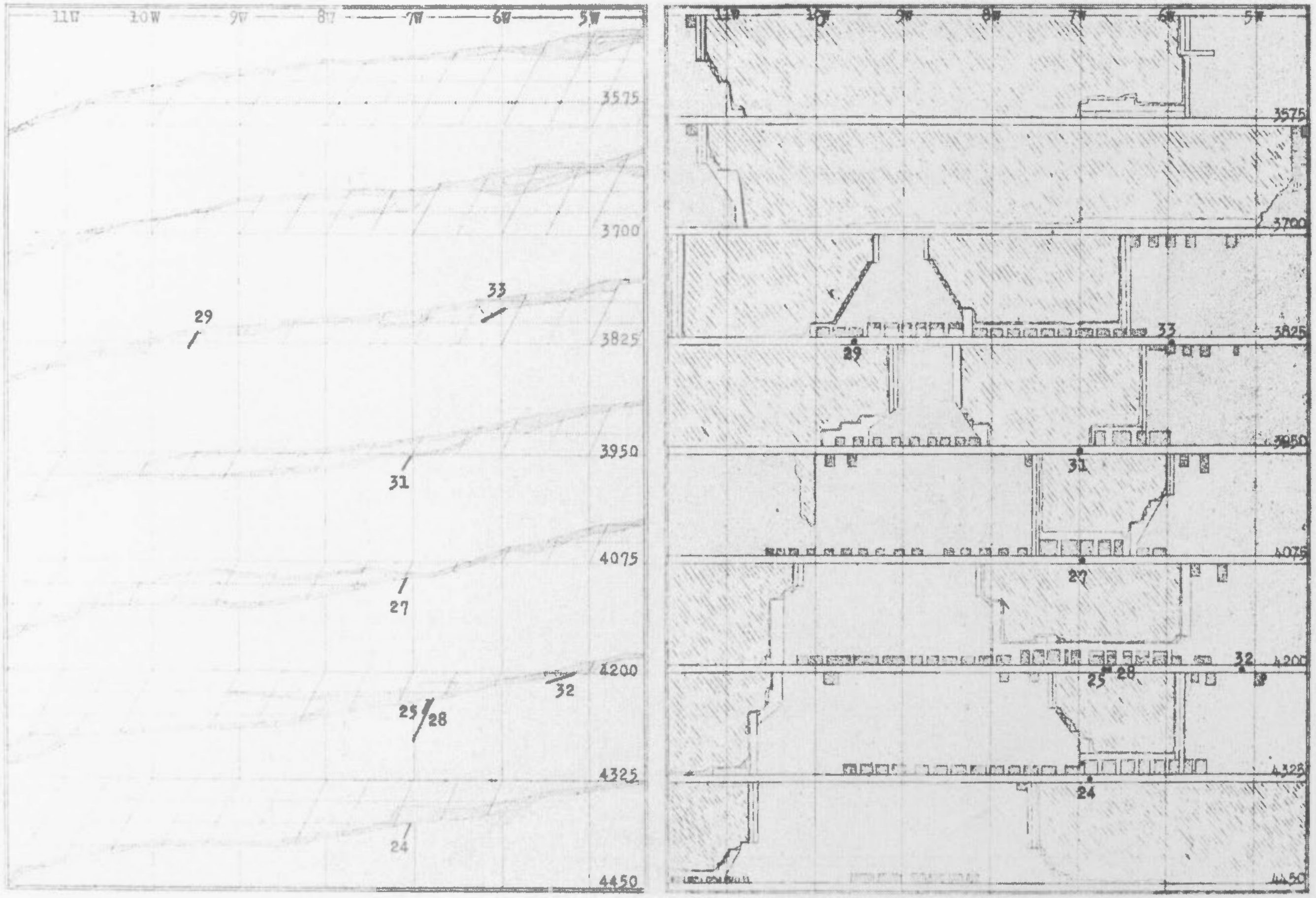


Fig. 62 West Pillar Showing Geophone Placements.

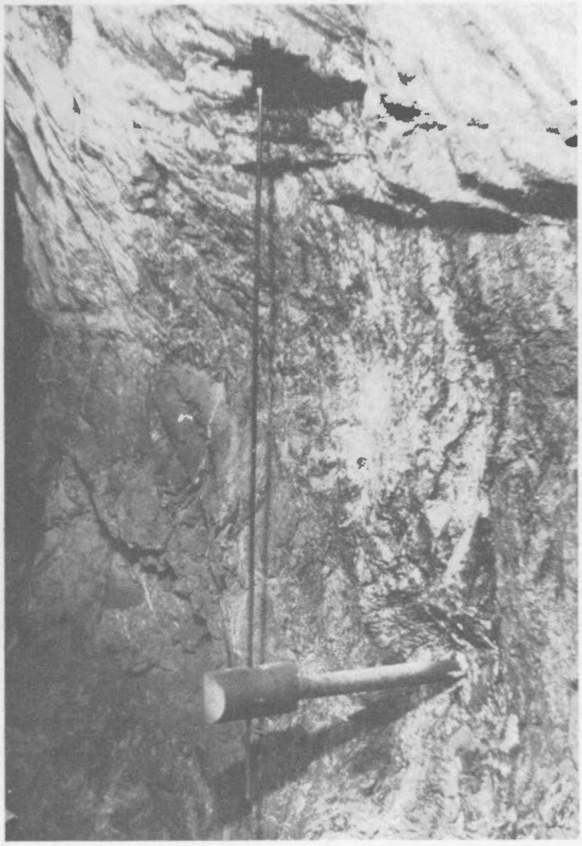


Fig. 63 Test Hammer;
4700-ft. Level.

Fig. 64 Loading Geophone
into Borehole.

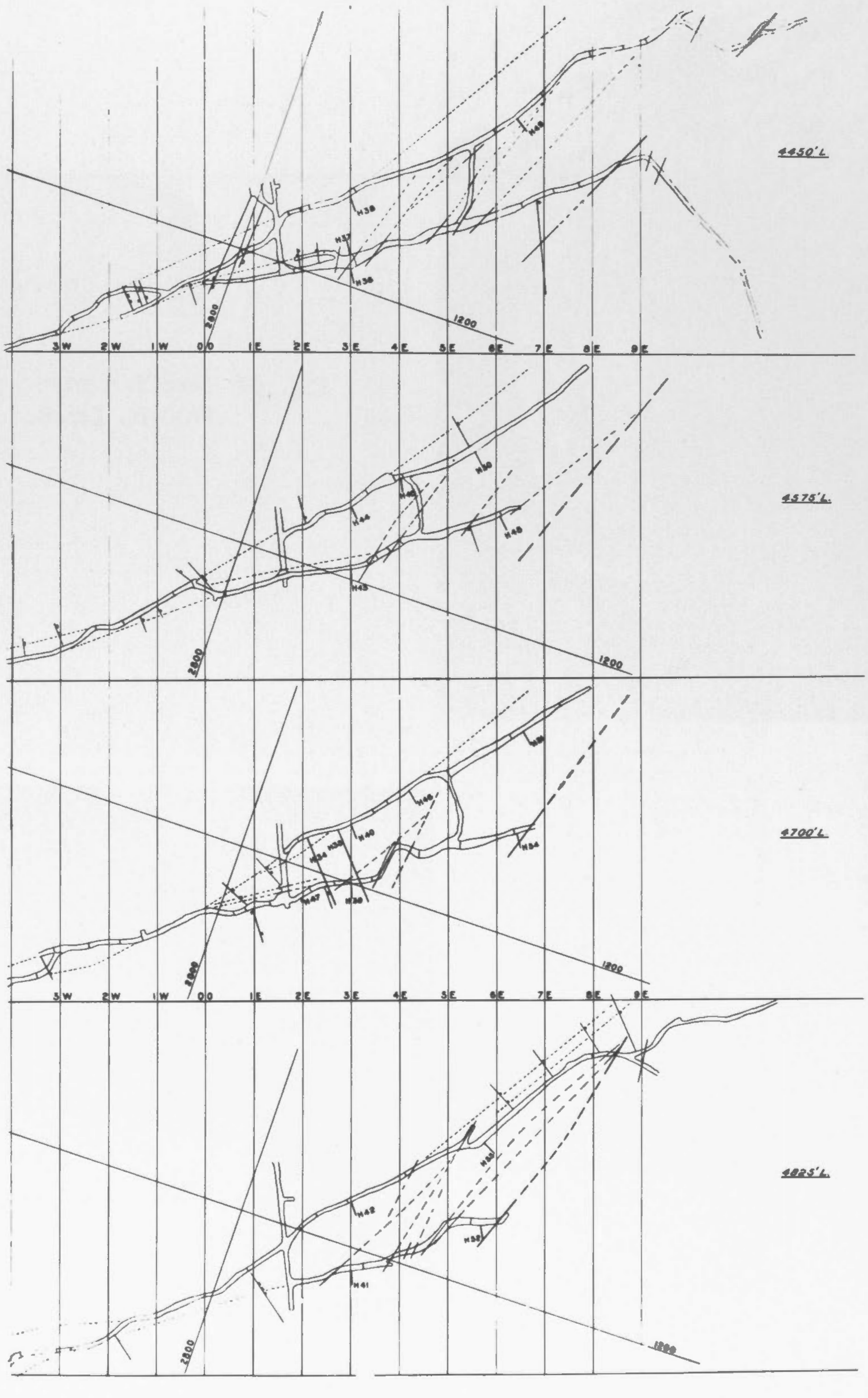
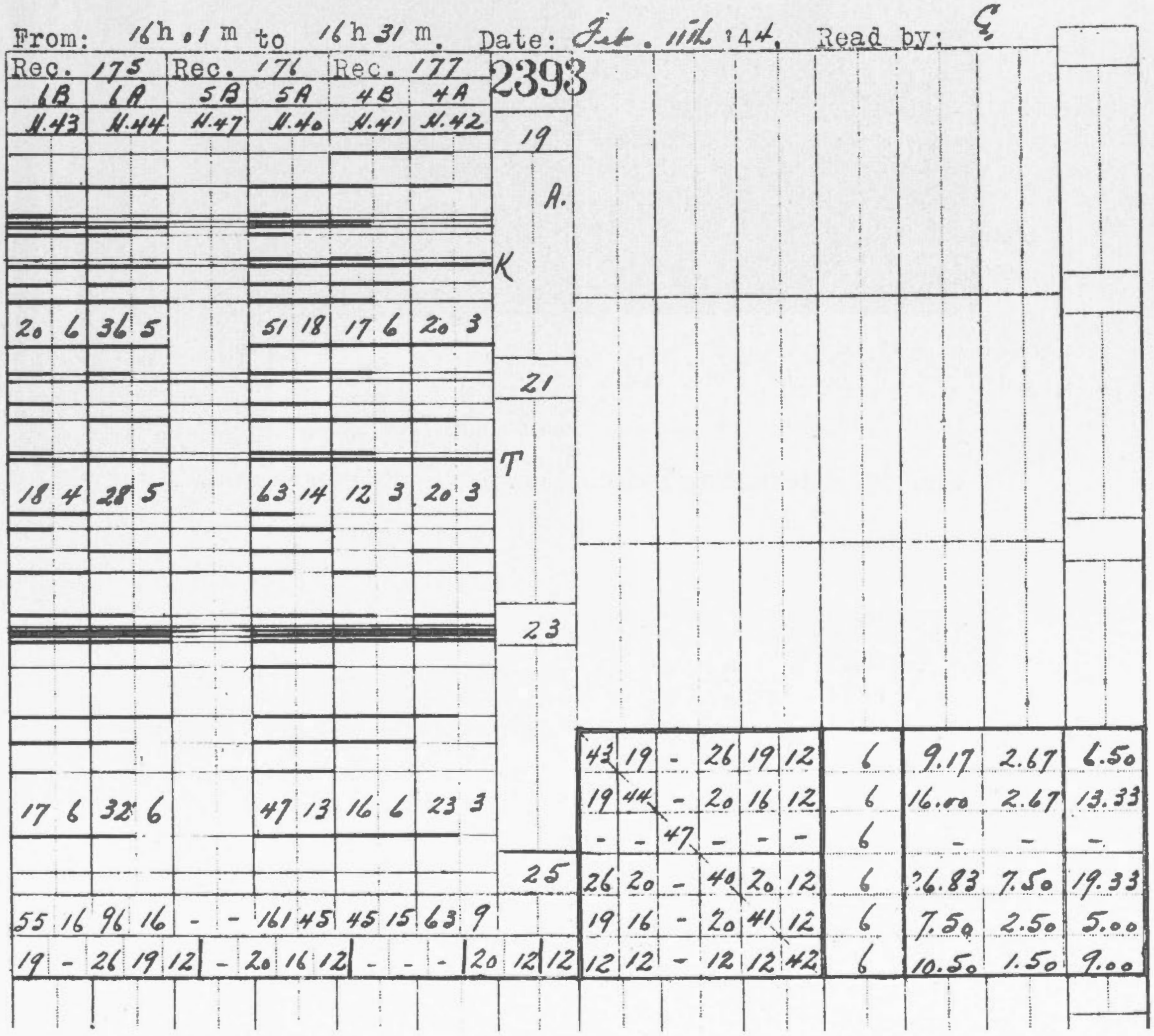


Fig. 65 Location of Test Holes Nos. 31-54.



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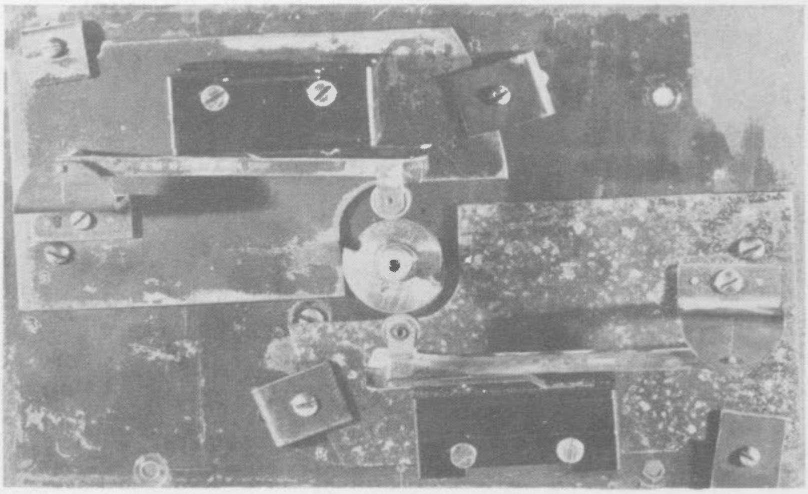

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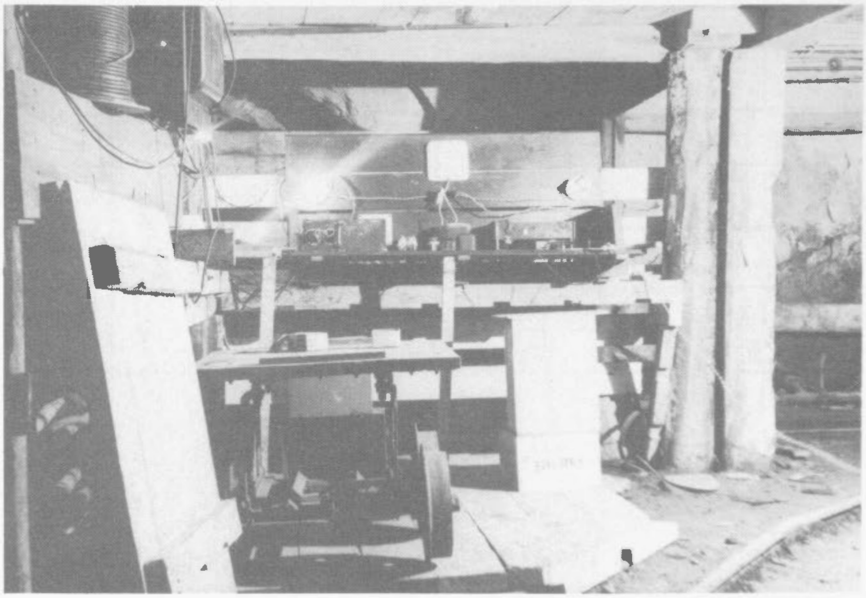

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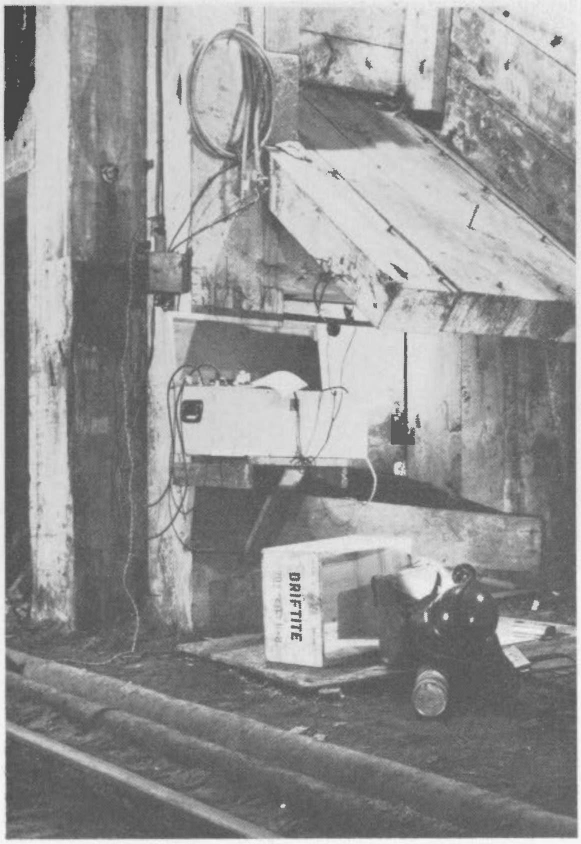

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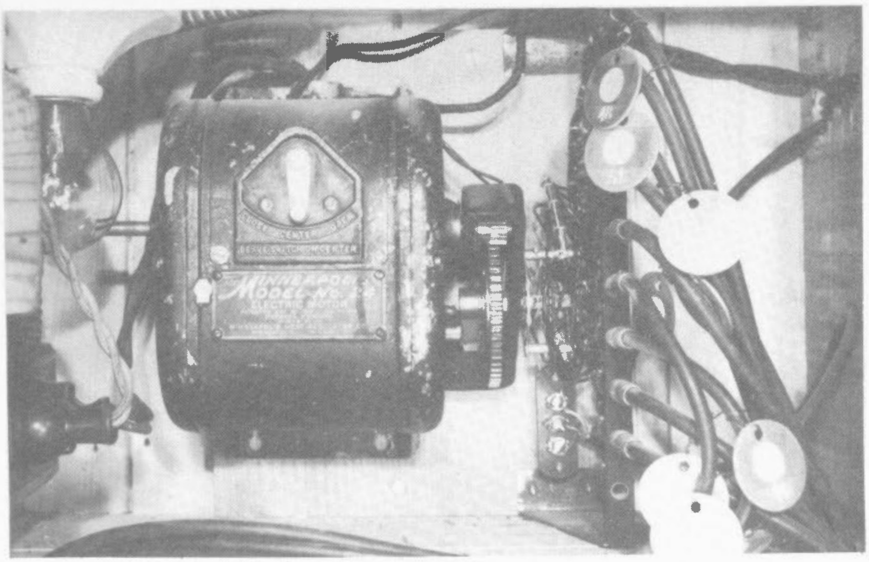

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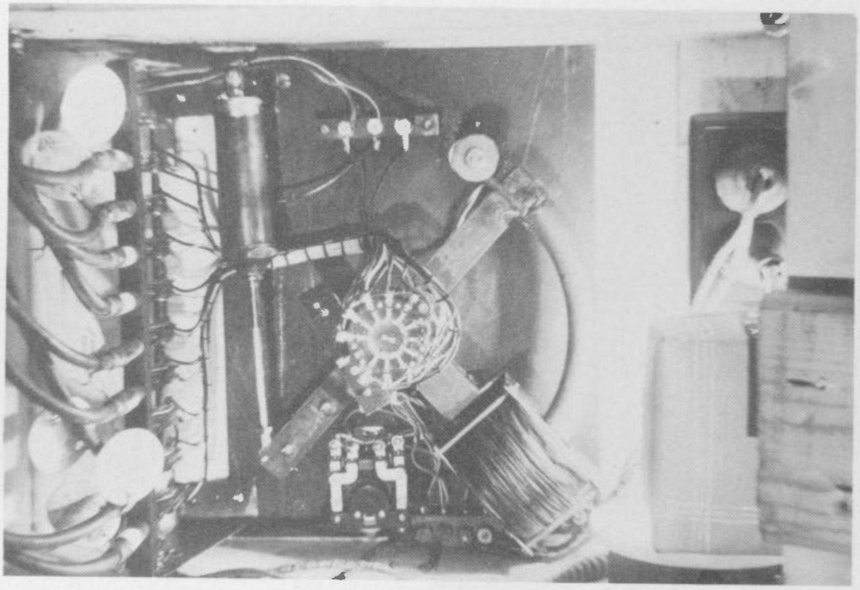

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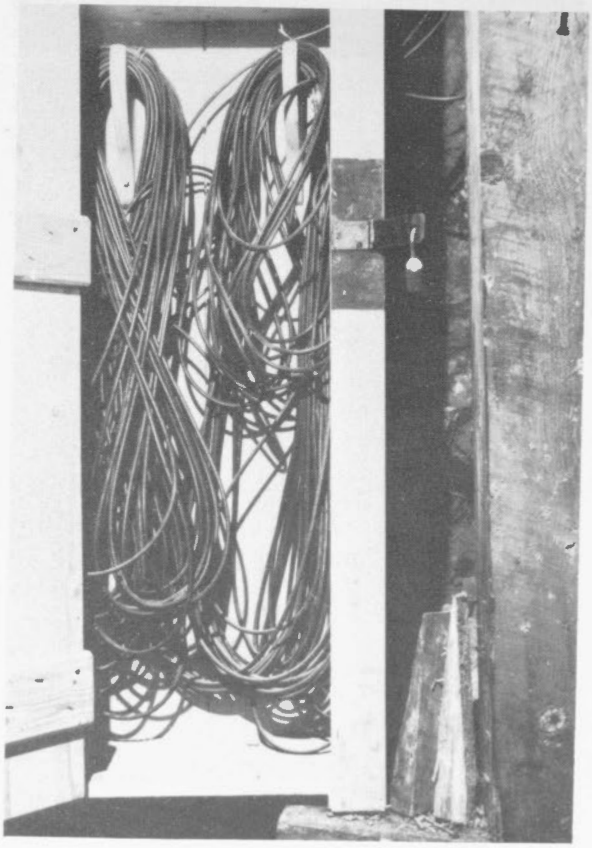

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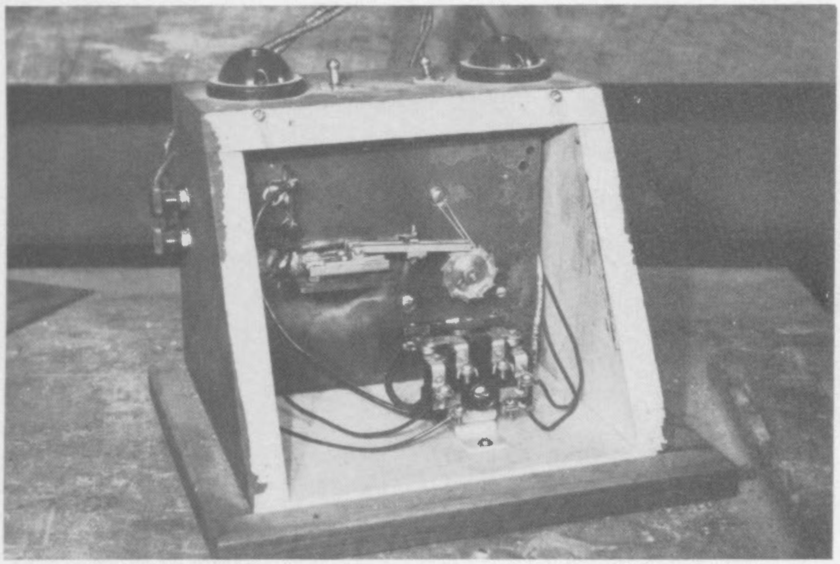

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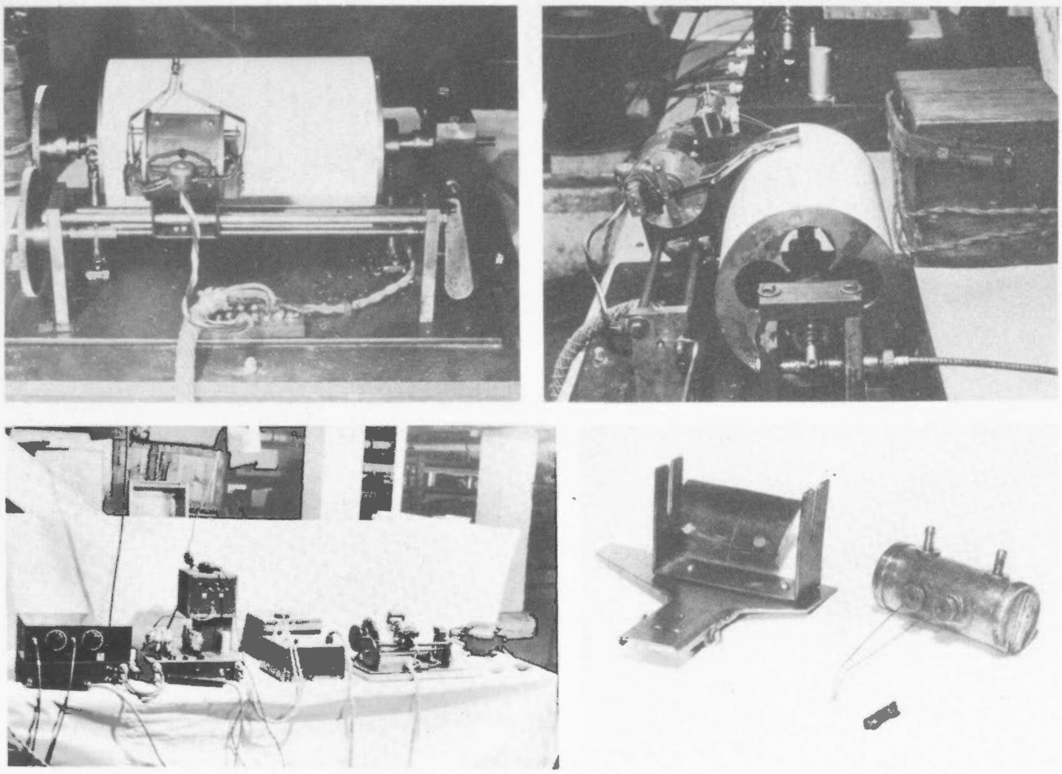

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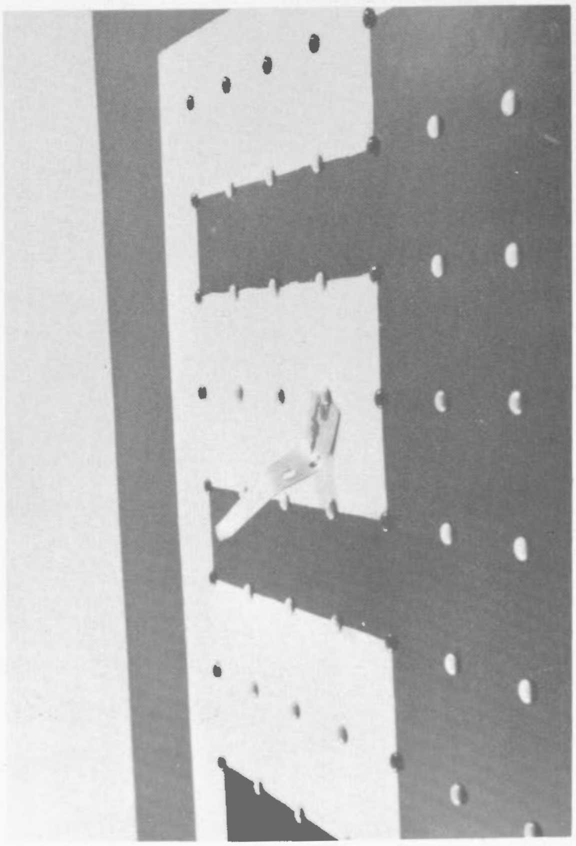

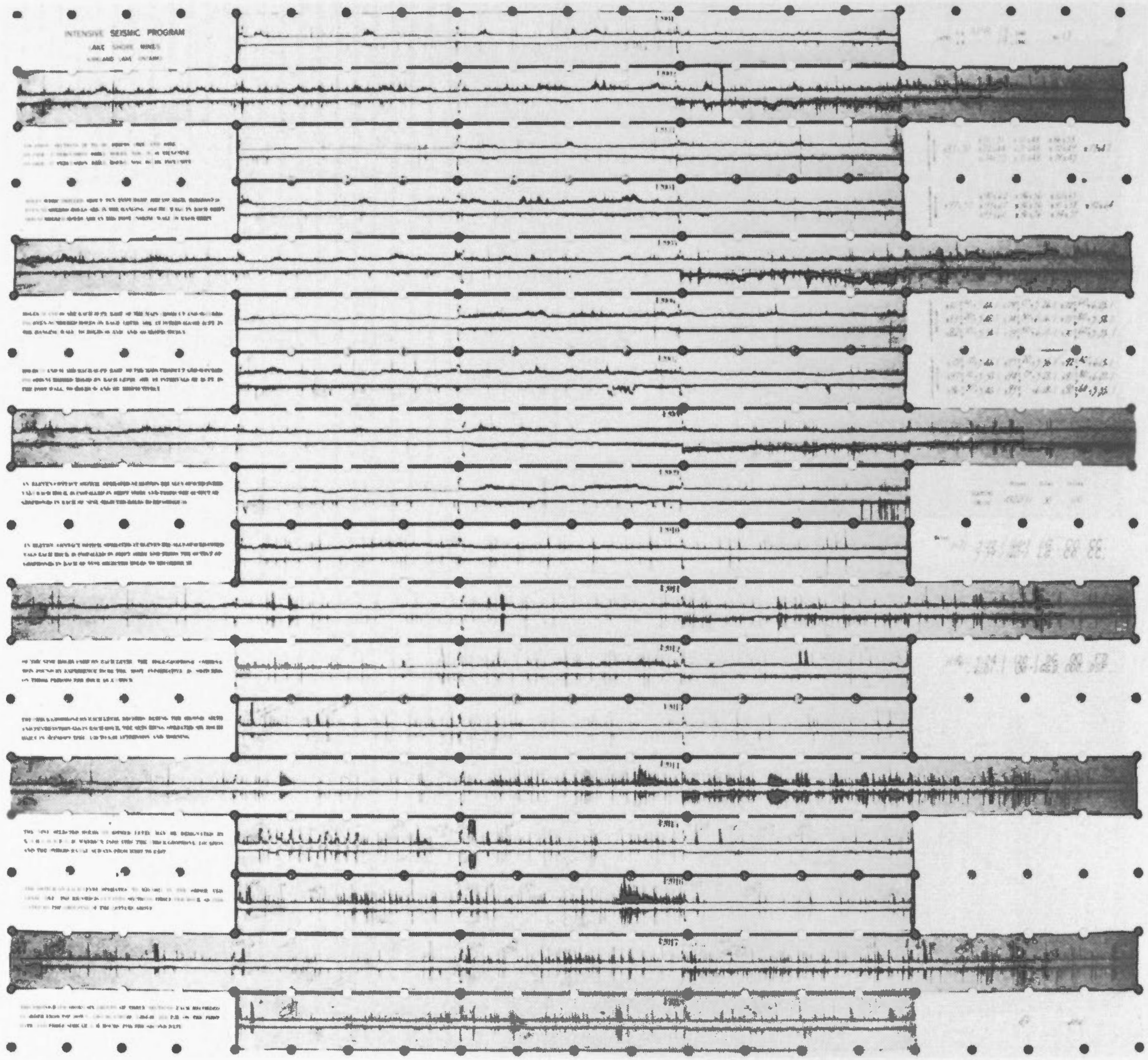

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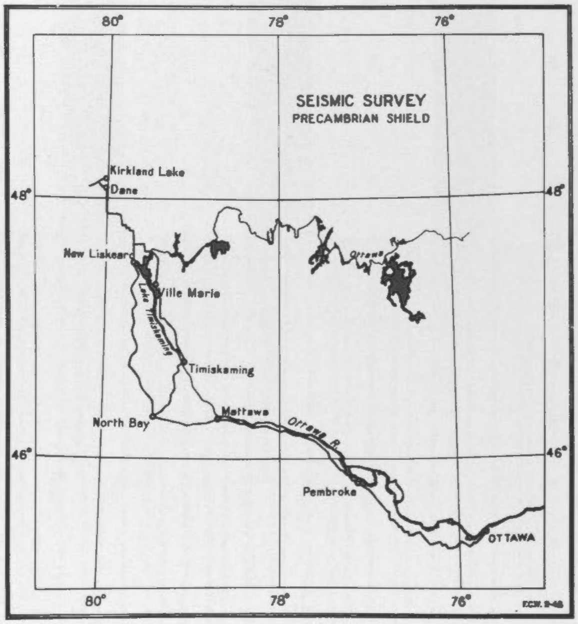

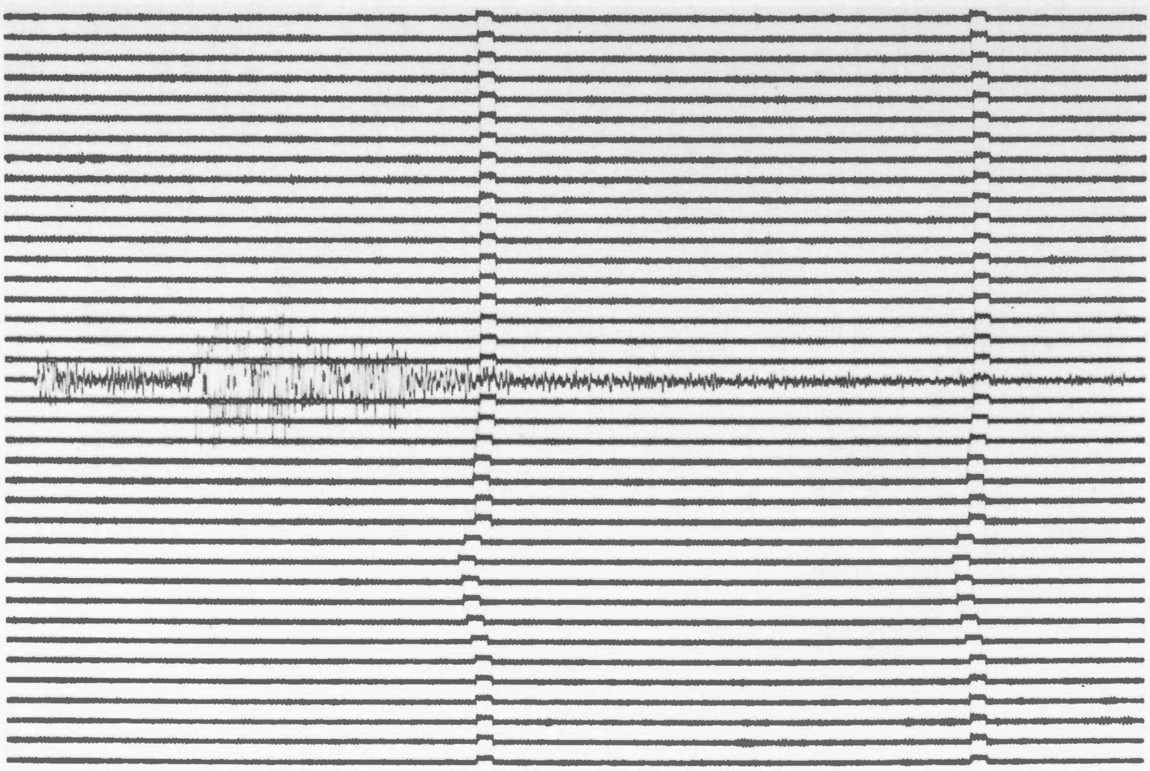

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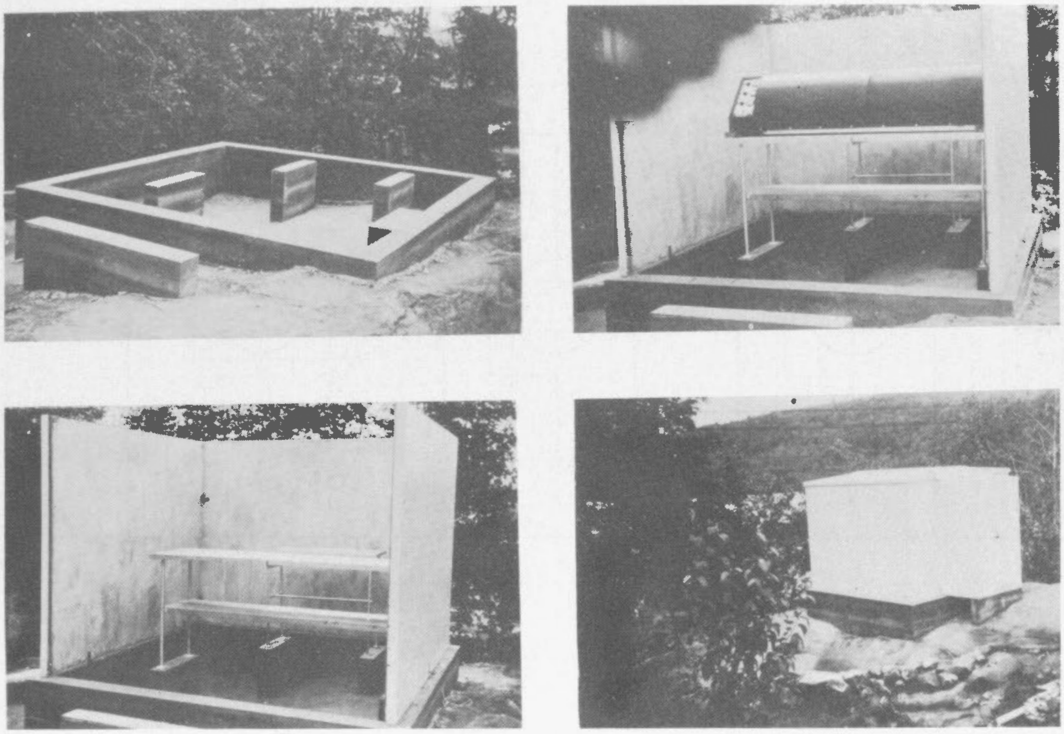

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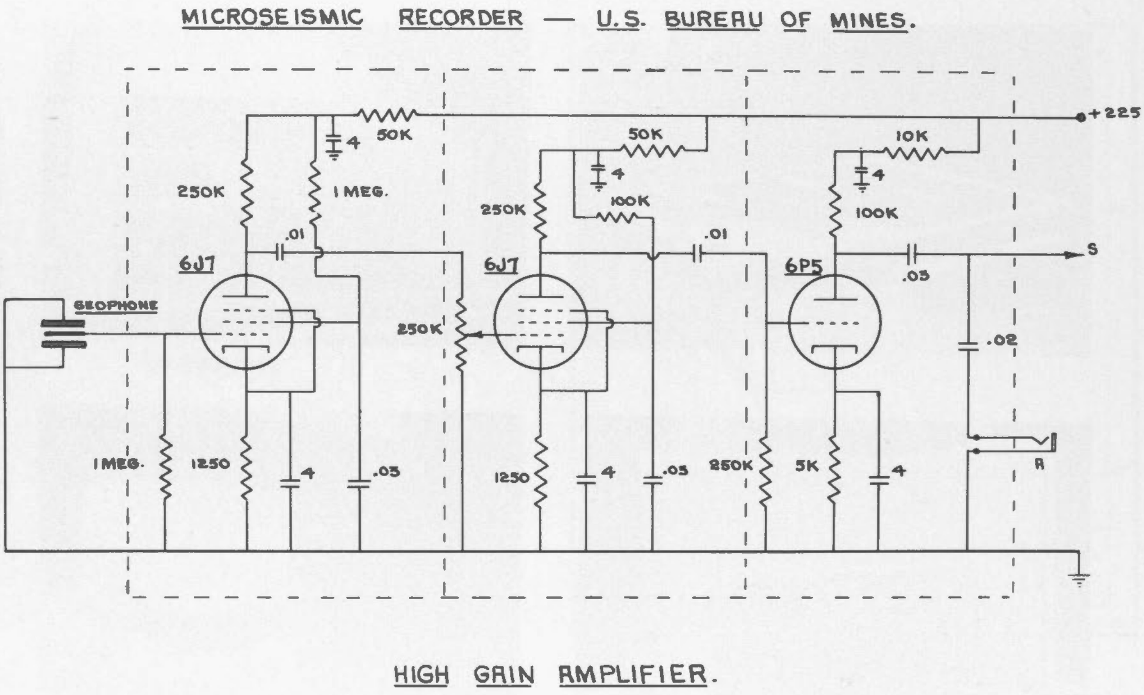

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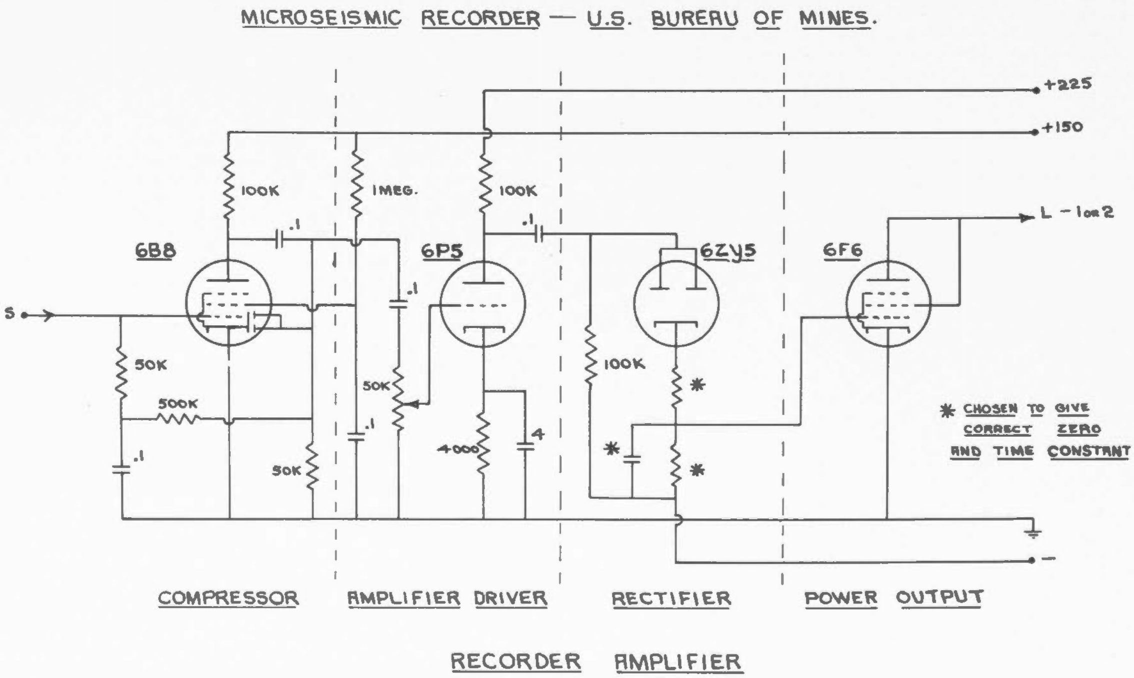

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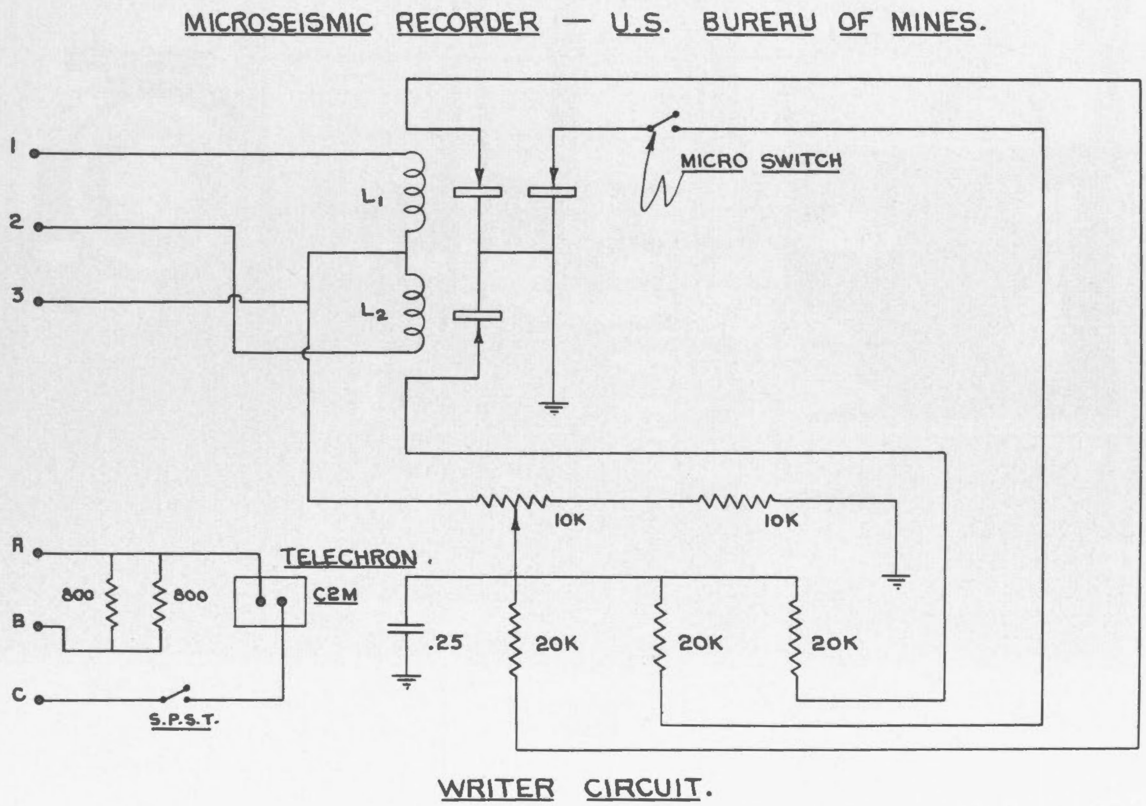

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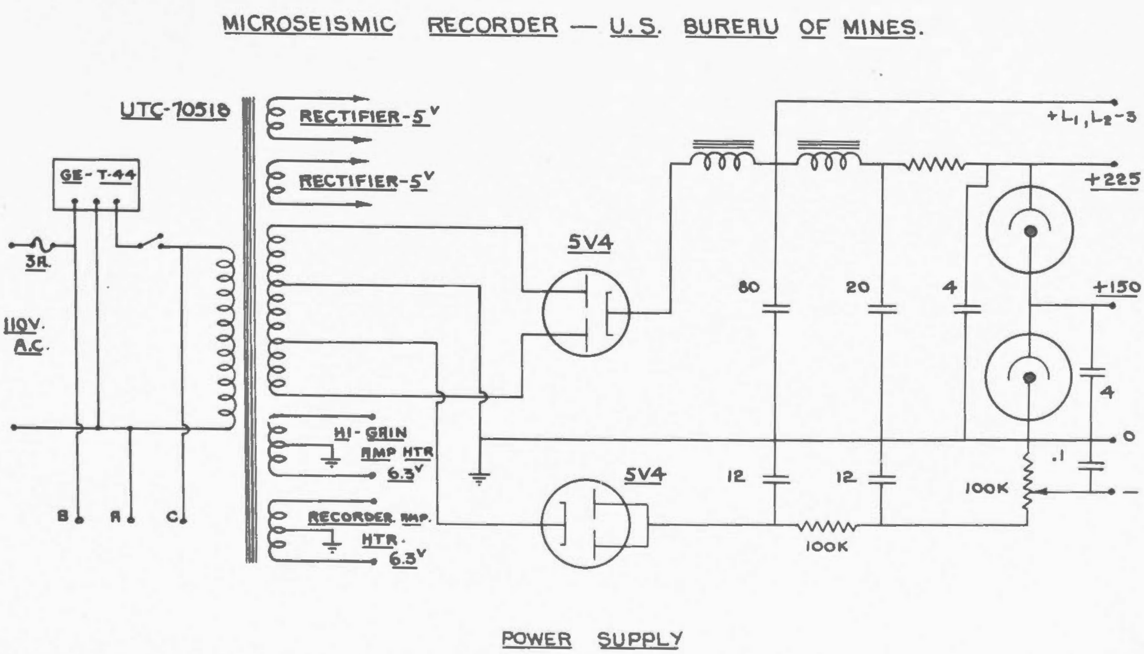

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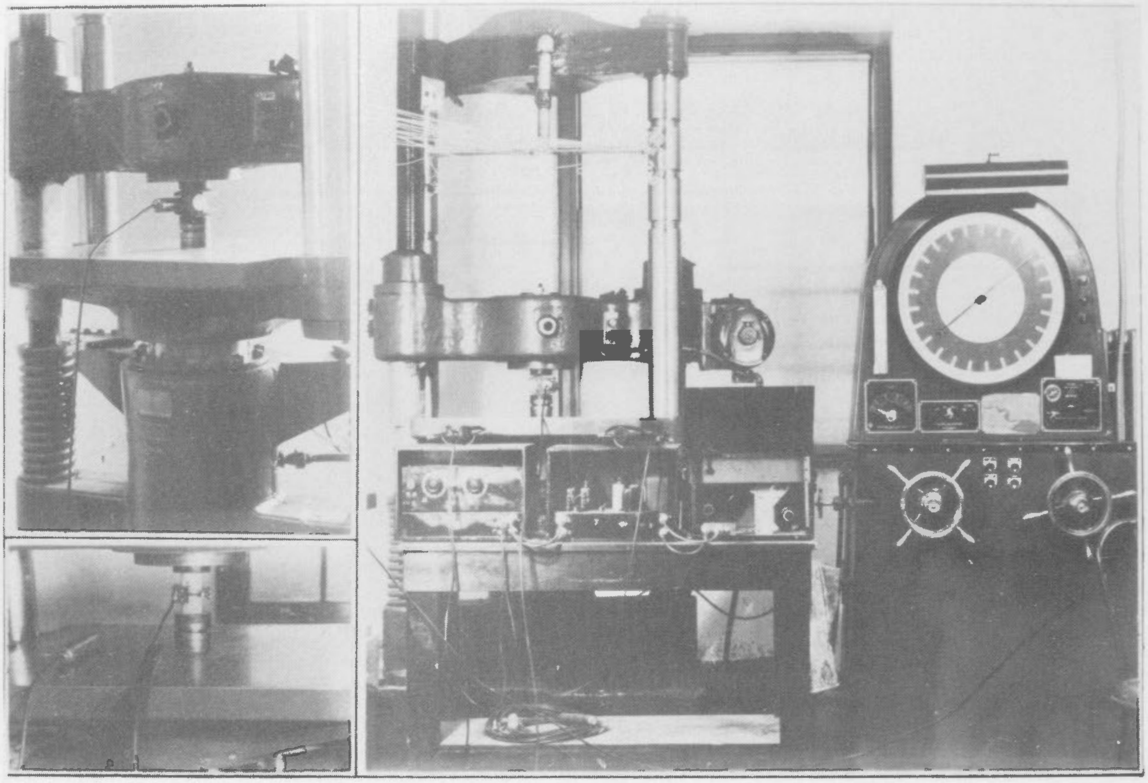

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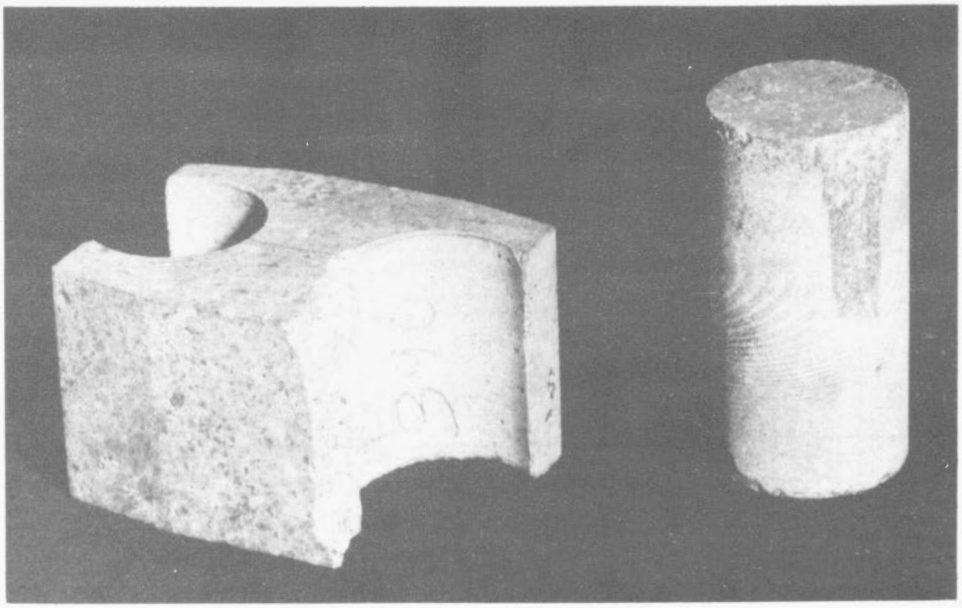

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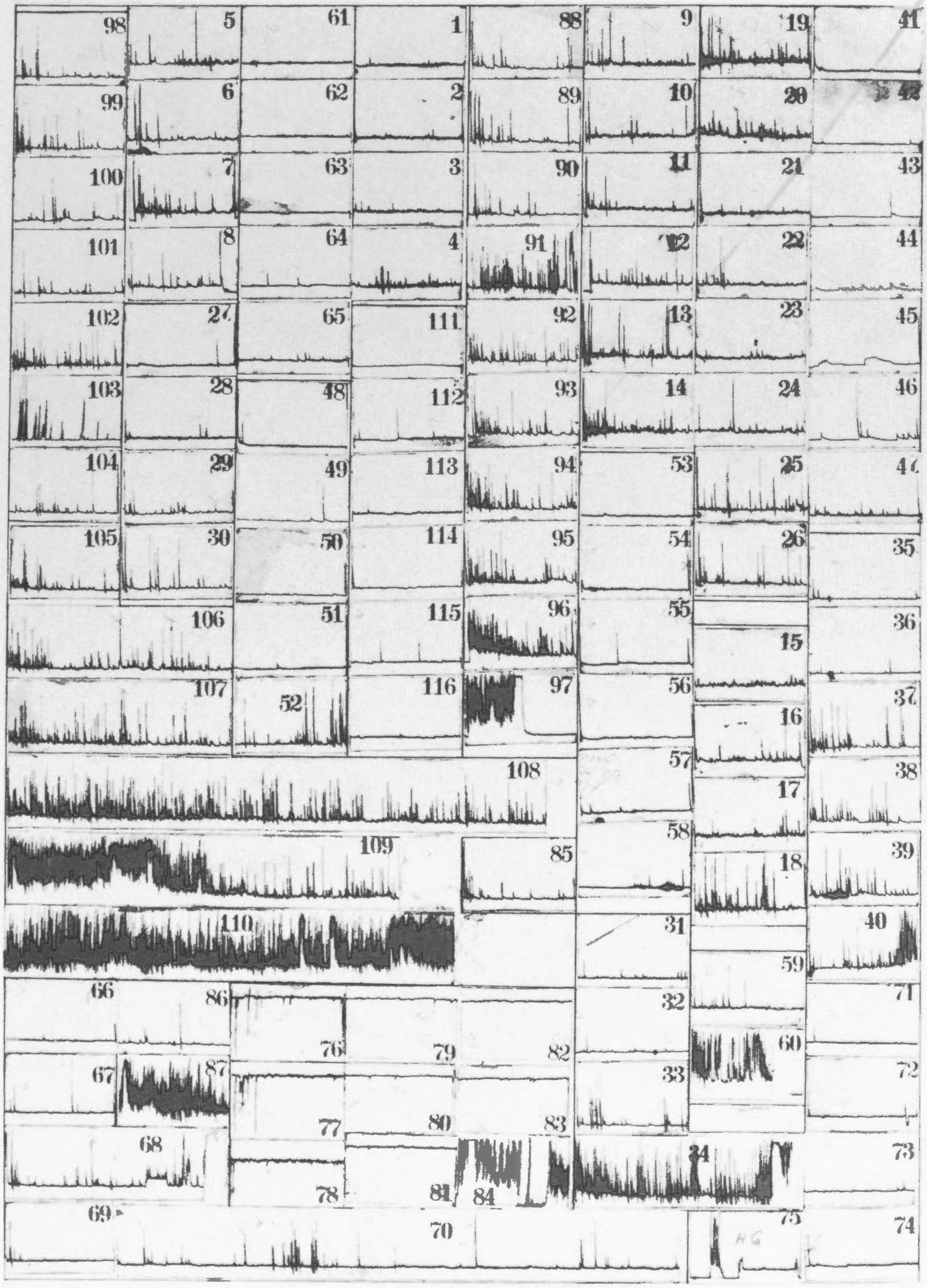

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THE MECHANICS OF FAULTING, WITH SPECIAL REFERENCE TO THE FAULT-PLANE WORK

(A Symposium)

JOHN H. HODGSON, *Editor*

INTERNATIONAL UNION OF GEODESY AND GEOPHYSICS
ASSOCIATION OF SEISMOLOGY AND PHYSICS OF THE EARTH'S INTERIOR
ELEVENTH GENERAL ASSEMBLY, TORONTO, CANADA

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The Mechanics of Faulting, with Special Reference to the Fault-Plane Work

(A Symposium)

Foreword

The idea for this Symposium originated shortly after the Tenth General Assembly of the International Union of Geodesy and Geophysics. Several seismologists interested in the fault-plane work were present at those meetings but, under the pressure of the heavy program and in the absence of a session formally devoted to their subject, there was little opportunity for dis cussion. It was suggested to Prof. K. E. Bullen, President of the Association of Seismology and Physics of the Earth's Interior, that a fault-plane Symposium should be arranged at the Eleventh Assembly; with the concurrence of the Bureau of the Association Prof. Bullen agreed, and asked the writer to arrange the Symposium.

Because of the large number of papers presented at the Toronto meetings it was possible to assign only a morning session to the fault-plane Symposium. This gave each speaker about twenty minutes, too short a time for adequate presentation. It seemed desirable that the papers should be printed in a single volume so that the complete presentation of all the authors would be available for comparison. Because the meetings were to be held in Canada, and because the Symposium dealt with a subject in which it is very much interested, the Dominion Observatory offered to print the Symposium in its Publications. We are indebted to Dr. Marc Boyer, Deputy Minister, who agreed to this arrangement on behalf of the Department of Mines and Technical Surveys, to President K. E. Bullen and Secretary J. P. Rothé who gave the permission of the Association, and to the several authors who have allowed their papers to be published in this way.

The meetings in Toronto suffered from the absence of two important contributors to the fault-plane work, Prof. H. Honda and Dr. A. R. Ritsema. Dr. Ritsema submitted his manuscript for printing in this volume which, to some extent, filled the lack caused by his absence, but Prof. Honda had already had his paper printed in Japan for distribution at the meeting, so that no paper was available from him. In editing the Symposium I was repeatedly struck with the fact that no adequate treatment of fault-plane studies could be given without bringing in the work of the Japanese, and I therefore sought permission of Prof. Honda to reproduce his already-published paper. This permission was granted and the paper will be found reprinted in the present volume. I am very much indebted to Prof. Honda and to the editors of *The Science Reports of Tôhoku University* for permission to do this.

In arranging the Symposium it would have been desirable to have had the papers presented in a logical order: those dealing with theory or the fundamentals of method first, then those giving the summary of the results obtained by various working groups, and finally papers dealing with the interpretation of results. It was not possible to follow this order completely at Toronto because several titles were submitted after the program had been arranged; this has been rectified in these printed proceedings, which follow the order outlined above.

It is inherent in the nature of symposia that they do not provide final answers; the present volume can only present a survey of current fault-plane work and its interpretation. It seemed desirable however that a summary should be provided, to define areas of agreement and disagreement among the various authors and to point the direction of future research. As Editor, I have taken the liberty of providing this summary in a final paper. The manuscript of this paper was circulated to all the authors, and their comments have been incorporated as much as possible; nevertheless I must bear the responsibility for any inadequacies it may have as a survey of the present volume.

JOHN H. HODGSON,
Editor

Motion at the Source of an Earthquake

BY PERRY BYERLY AND WILLIAM V. STAUDER, S.J.
University of California, Berkeley, California, U.S.A.

ABSTRACT

NAKANO's theoretical development emphasizes the effect of seismic disturbances at large distances from the source and develops equations of first motion in P and S for several types of source mechanisms. These equations are compared to the methods of approach of various investigators, and two mechanisms in particular are singled out: a single couple, which represents motion along a fault, and a double couple, which represents a compressive and tensile stress at right angles. Methods of transformation and projection permit the application of the theory for an infinite homogeneous earth to the heterogeneous earth. Possible uses of S phases are noted. Single observations of the first motion of S offer the possibility of resolving the ambiguity in fault-plane solutions from P alone in which the single couple is the mechanism assumed. Identification of the second nodal surfaces of SV and SH offers a criterion for deciding which mechanism, the single couple or the double couple, is operative in particular earthquakes. Further, simple relations involving the ratios SH/SV, P/SH, P/SV suggest other approaches to the problem of motion at the source of an earthquake. S phases, however, are to be used with great care.

THEORY

The theory in back of the interpretation of the motion at the source of an earthquake from the first motions in the waves recorded on seismograms was first published by HIROSHI NAKANO in 1923. Departing from formulae developed by STOKES and assuming an infinite homogeneous elastic solid, he took a source of form $f(t)$ at the origin in a Cartesian reference system and computed the equations of wave accelerations for P waves and S waves at large distances.

These were of the form

$$\left.\begin{aligned} \delta_{ax} &= (lx + my + nz)\, \frac{x}{4\pi\rho a^2 r^3}\, f''\left(t - \frac{r}{a}\right) \\ \delta_{bx} &= -\,[(lx + my + nz)x - lr^2]\, \frac{f''\left(t - \frac{r}{b}\right)}{4\pi\rho b^2 r^3}\ . \end{aligned}\right\} \tag{1}$$

Here l, m, n are direction cosines of the force at the origin and r is the distance of the observing point from the source. The speeds of P and S are a and b and the density is ρ. There are three equations of each type, the three components of P and S. There is no assumption involved for a homogeneous medium. There is an assumption, perhaps, in extending the theory to a heterogeneous medium, but experience proves it justified as far as direction of first motion of P goes.

NAKANO then proceeded to extend the theory to several systems of forces. First he took a couple of lever arm Δs, the direction cosines of which were λ, μ, ν. The member $\vec{F}$ of the couple which has a downward component will be taken as acting at the positive end of Δs.

The equations for acceleration at a large distance were of form

$$\left.\begin{aligned} \delta_{ax} &= (\lambda x + \mu y + \nu z)\,(lx + my + nz)x\, \frac{\Delta s\, f'''\left(t - \frac{r}{a}\right)}{a^3 r^4} \\ \delta_{bx} &= -\,(\lambda x + \mu y + \nu z)\,[(lx + my + nz)x - lr^2]\, \frac{\Delta s\, f'''\left(t - \frac{r}{b}\right)}{b^3 r^4}\ . \end{aligned}\right\} \tag{2}$$

Note that the power of a (or b) in the denominator has increased by one, the function $f''(t-r/a)$ having been differentiated once. The Soviet seismologists speak of the order of the source, n. This quantity depends on the number of differentiations and therefore on the power of

a (or b). These speeds appear as a^{n+1} in their formulae. Two couples having moments about a common point are additive and do not increase the order. However, two couples whose moments are not about a common point increase the order again by one, another differentiation being involved.

NAKANO treated a number of cases. HONDA has also developed such equations, (HONDA *et al.*, 1956) preferring wave amplitude to acceleration. They have been developed in the Soviet Union also, as reviewed by KEYLIS-BOROK (1956).

A study of equations (2) reveals a number of means by which, given seismograms from stations well distributed over the earth, one can deduce the nature of the force system at the source. In theory one could do it with very few stations.

The pertinent relations are as follows:

1. The signs of the first motion in P and in S as they emerge form a pattern on the face of the earth which is dependent on the nature of the forces at the source.
2. The ratios of the earth amplitudes of the incident waves P, SH and SV bear a simple relationship to the source.

For example, a single impulsive force would send a P compression into one-half space and a rarefaction into the other. The nodal plane of P would bisect the force, which would be perpendicular to it. There would be a nodal line for S waves which would pass through the force.

However most seismologists have found more complex forces to be more reasonable and useful, in particular sources of a single couple or a pair of couples at right angles in a single plane.

The latter is equivalent to two forces in line directed toward the origin plus two others in line at right angles to the first, and oppositely directed. This latter type of source is favored by HONDA (*see* Figure 1).

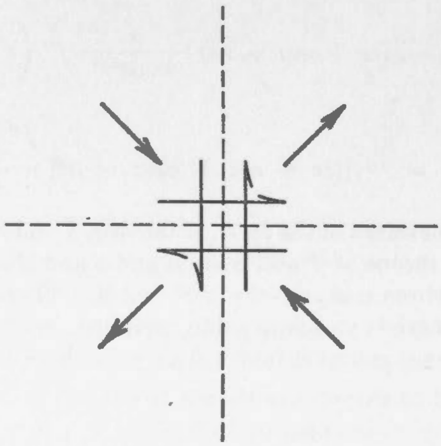

Figure 1. Pair of couples at right angles equivalent to tensions and compressions at right angles to each other and oblique to the pair of couples.

The single couple is used in North America, in Holland, and seems the most successful in the Soviet Union. The two types each give an identical quadrant distribution of P. The distribution of first motion of S, on the other hand, differs for the two cases (*see* Figure 2). A study of the distribution of S might discriminate between the two types of sources. The difficulties in finding the first motion in S, however, are grave.

The American view has been much influenced by the 1906 California earthquake and also the 1940 Imperial Valley earthquake. Both had long surface faults with horizontal slippage. To us it is the fling, the displacement along the fault, which is the source of the waves. To us who hold the elastic rebound theory, if HONDA's source is established, it will mean that the source of the waves is the release of strain in the large body of rock about the source, strain which had accumulated there due to external forces. Then the pairs of arrows representing strain need not be of the same length. Neither would the two possible fault planes necessarily coincide with the nodal planes of P. They would rather be inclined up to 15° to 20° toward the direction of the maximum compressive strain. Many Japanese seismologists consider faulting as a result of the earthquake—not its cause. They seem to have no difficulty in postulating a sudden application of force systems in the earth, rather than a sudden release after a slow accumulation of strain.

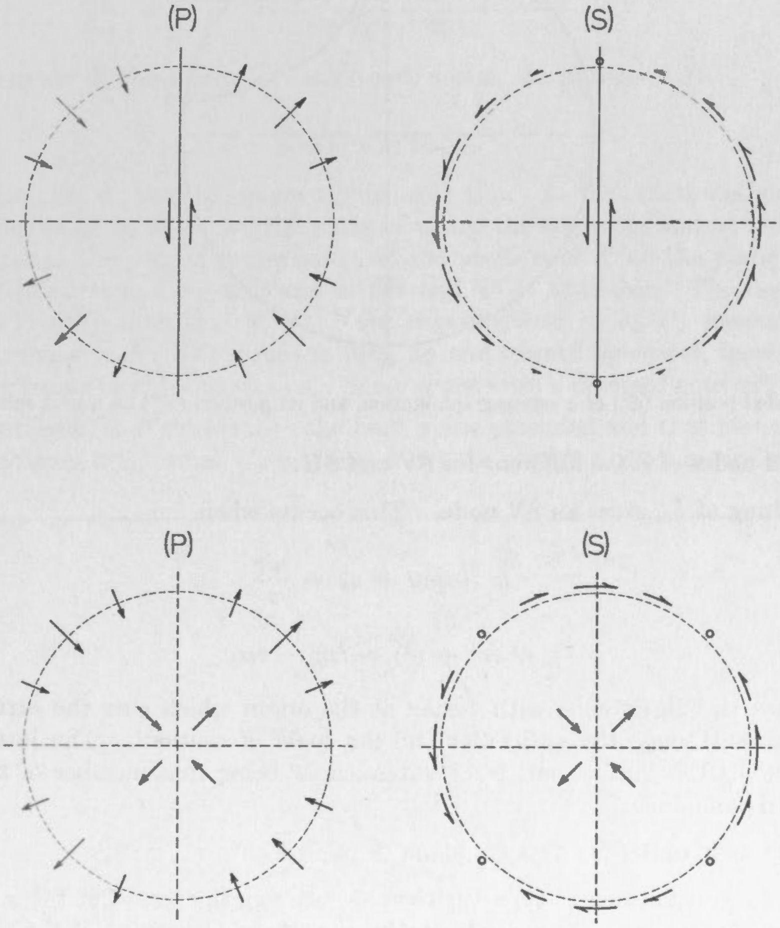

Figure 2. Distribution of first motion of P and S for a simple couple (top) as opposed to that for a pair of couples at right angles (bottom).

NON-HOMOGENEOUS EARTH

The first problem faced in applying Nakano's equations is the application of theory for an infinite homogeneous medium to the heterogeneous earth.

This is accomplished by considering the seismograph station position not at S, its location, but at S' (extended position on the earth's surface) or at S'' on a unit sphere about the focus, as in Figure 3. The first is the American method, the second that of the Soviets. Thus the equivalent seismic rays become straight lines. Also when one considers the amplitudes he must always reduce to amplitude of incident wave from observed surface motion.

We note from equation (2) that both P and S have nodes (zeros) in the fault plane

$$\lambda x + \mu y + \nu z = 0,$$

and that P has an additional node in the plane

$$lx + my + nz = 0$$

which is perpendicular to the forces of the couple. This plane has been called the auxiliary plane. The fault plane and the auxiliary plane separate regions of first compressions and first rarefactions.

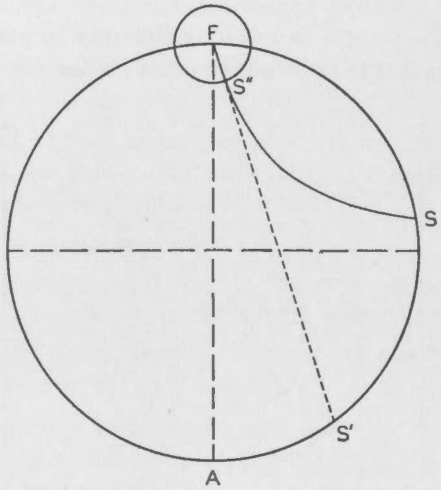

Figure 3. Extended position (S') of a seismograph station, and its position (S'') on a unit sphere about the focus.

The second nodes of S are different for SV and SH.

The vanishing of $\delta_{b\theta}$ gives an SV node. This occurs when

$$lx + my + nz = \frac{n^2 r}{z}$$

or

$$n^2 (x^2 + y^2) = lzx - mzy$$

This defines an elliptic cone with vertex at the origin which cuts the earth's surface in a circle which passes through the anticenter and the 'pole of motion'. The latter is defined as the point on the earth's surface cut by $\vec{F}$ extended, $\vec{F}$ being that member of the couple which has a downward component.

The second node of SH is a vertical plane through $\vec{F}$.

Now transform equations of type (2) to spherical coordinates. Let the x axis be directed north, the y east, the z down. The coordinates of the extended position of the station are r, φ, θ where r is distance, θ is angle of incidence and φ is azimuth of station (measured from north through east).

Equations of type (2) transform to

$$\left.\begin{aligned}
\delta_{ar} &= \frac{\Delta s}{4\pi\rho} \frac{f'''\left(t - \frac{r}{a}\right)}{a^2 r^2} (\lambda x + \mu y + \nu z)\,(l \sin\theta \cos\varphi + m \sin\theta \sin\varphi + n \cos\theta) \\
\delta_{b\varphi} &= -\frac{\Delta s}{4\pi\rho} \frac{f'''\left(t - \frac{r}{b}\right)}{b^2 r^2} (\lambda x + \mu y + \nu z)\,(l \sin\theta - m \cos\varphi) \\
\delta_{b\theta} &= \frac{\Delta s}{4\mu\rho} \frac{f'''\left(t - \frac{r}{b}\right)}{b^2 r^2} (\lambda x + \mu y + \nu z)\,[(l \cos\varphi + n \sin\varphi) \cos\theta - n \sin\theta].
\end{aligned}\right\} \quad (3)$$

We note that δ_{ar} corresponds to P motion, $\delta_{b\varphi}$ to SH motion, and $\delta_{b\theta}$ to SV motion.

We may now rotate the x (and y) axis through Φ about the vertical z axis until $\vec{F}$, that member of the couple which has a downward component, lies in the xz plane. Then in equation (3) $m = 0$ and $l = \cos\psi$, $n = \sin\psi$ where ψ is the plunge of the motion.

Then

$$\left.\begin{aligned} \frac{\delta_{ar}}{\delta_{b\varphi}} &= -\frac{b^3}{a^3}\,\frac{\sin\theta\cos(\varphi-\Phi)+\cos\theta\tan\psi}{\sin(\varphi-\Phi)} \\ \frac{\delta_{b\theta}}{\delta_{b\varphi}} &= \frac{\sin\theta\tan\psi-\cos\theta\cos(\varphi-\Phi)}{\sin(\varphi-\Phi)}\;. \end{aligned}\right\} \qquad (4)$$

The unknowns are Φ, the azimuth of the trend, and ψ, the plunge of $\vec{F}$.

PROJECTIONS

In order to proceed we turn to stereographic projection. In the oldest method the extended station S' is projected on to an equatorial plane of which the epicenter and anticenter are poles, with the anticenter as the pole of projection. At the position of S' on the plane is entered the algebraic sign of the first motion of P and of SH and SV if available. The beginning of S is more difficult to identify than that of P. Note that increase in $\delta_{ar}(P)$ means motion away from epicenter, increase in $\delta_{b\theta}$(SV) means motion up and toward epicenter, increase in $\delta_{b\varphi}$(SH) is to right looking from epicenter to station. Some writers use a reversed convention for SV.

The nodal surfaces for P are planes—the fault plane extended and that plane perpendicular to it to which the forces are normal. These planes cut the earth's surface in circles and therefore

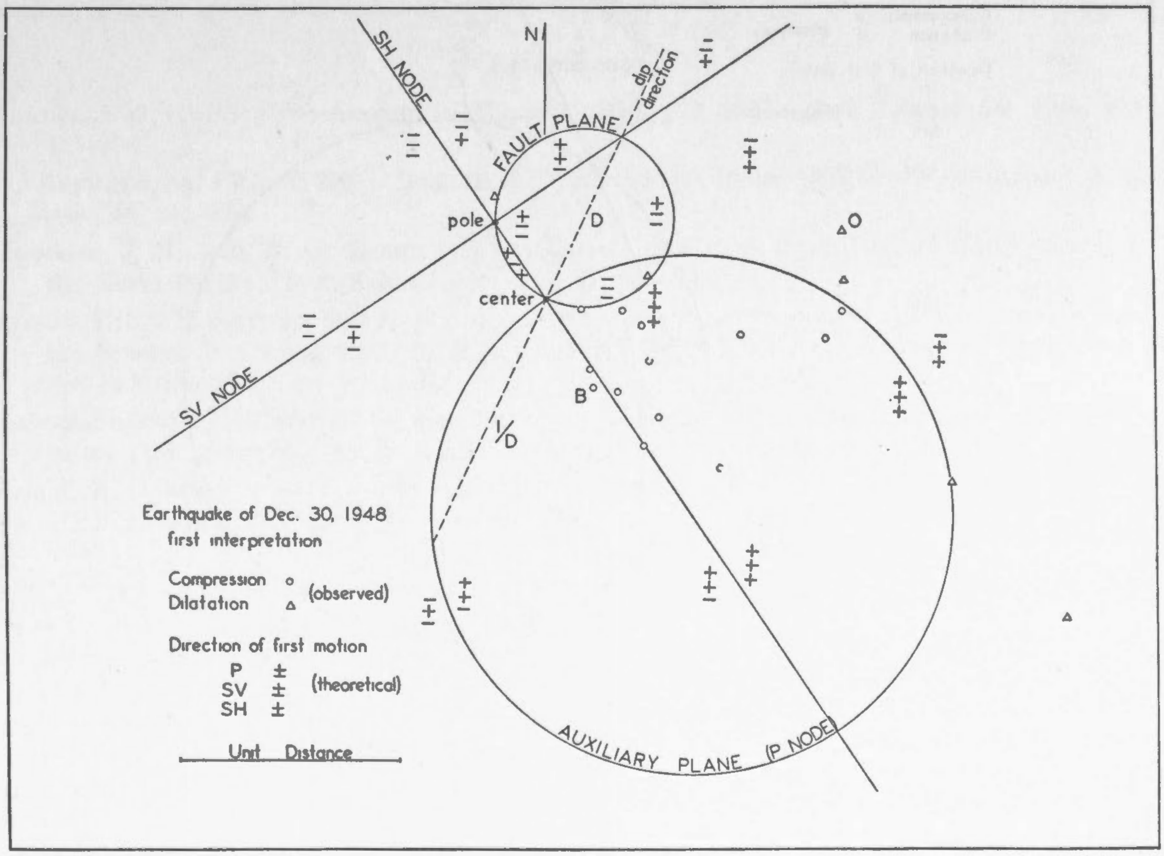

Figure 4. The fault-plane solution, after SCHEIDEGGER (1957), of the earthquake of December 30, 1948. The smaller circle is chosen as representing the fault plane. Signs of P, SV, and SH in the various domains are indicated. O corresponds to the position of Ottawa, B to Berkeley.

project as circles on the equatorial plane. Therefore on the projection two circles are to be drawn through the origin (projection of focus) such that, on crossing either, the sign of P changes. The diameters drawn through the origin have the azimuths of the dip of the fault and the dip of the auxiliary plane, respectively. The dip of the auxiliary plane is the complement of the plunge of the force $\vec{F}$. The lengths of these diameters give the magnitude of the dips.

In the drawing of the two circles there is the constraint that

$$\cos\alpha = \frac{\tan\psi}{\tan\delta}$$

where ψ is the plunge of the motion, δ the dip of the fault, and α is the angle between the traces of the fault and auxiliary plane. If one circle is well determined the above relationship determines a straight line which is the locus of the center of the second circle.

Figure 4 gives an example after SCHEIDEGGER (1957) in which he gives data for P waves of a given earthquake and then, selecting arbitrarily the smaller circle as representing the fault plane, draws the nodes of SV and SH. He gives the direction of first S motion at Ottawa only, which is that $\delta_{b\varphi}$(SH) is +. We have added to his figure the signs of $\delta_{b\varphi}$(SH) and $\delta_{b\theta}$(SV) in the various domains.

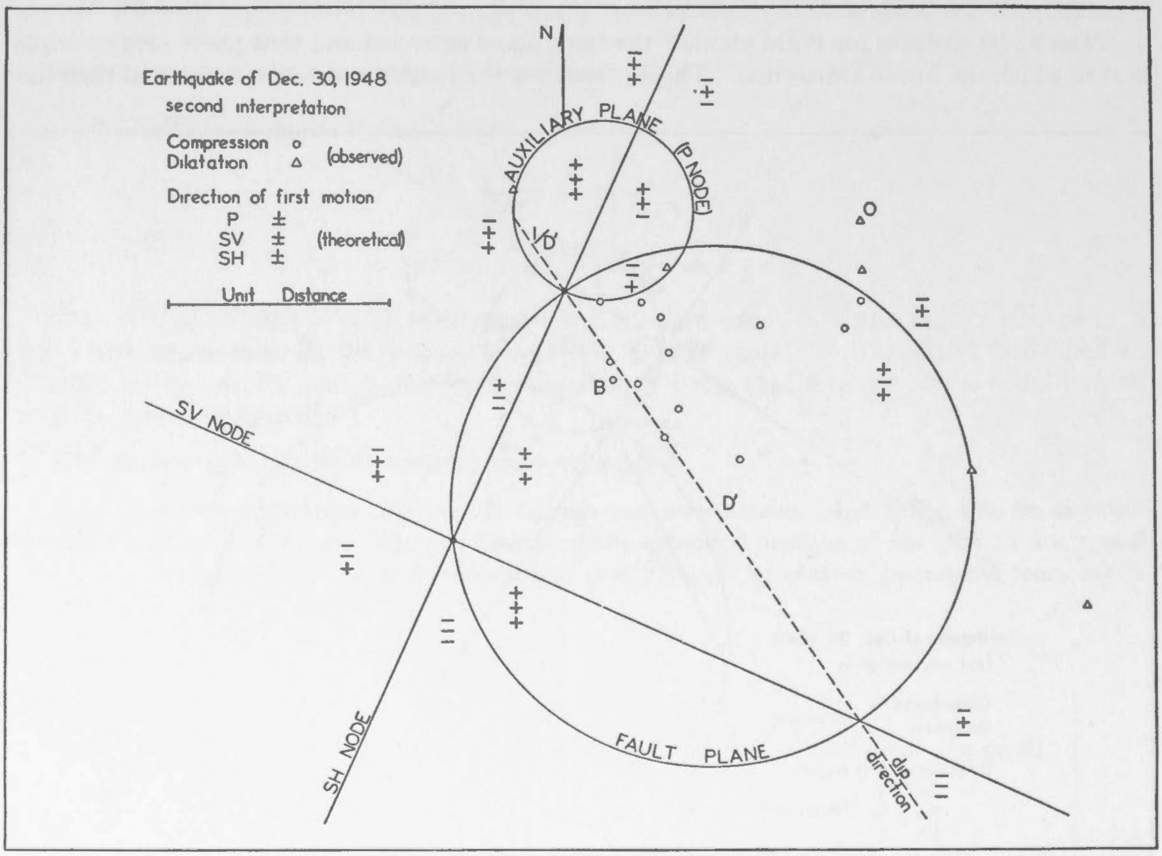

Figure 5. Fault-plane solution of the same earthquake as in Figure 5, with the larger circle assumed the fault plane.

In Figure 5 is drawn the similar figure with the larger circle assumed the fault plane. We see that the single observation at Ottawa determines that the first assumption was correct. A similar check by investigating the first motion of S at Berkeley was attempted. The test proved inconclusive, for it was impossible to determine for certain the beginning of SV and SH.

Soviet scientists plot the station at S'' in Figure 3. They have variously used the top, center, and bottom of the focal sphere as the pole of projection, according to SCHEIDEGGER. The most common practice seems to use the top of the focal sphere with the Wulff net as the basis of their stereographic projection.

Until recently the Soviet scientists have worked with data limited to observations recorded within the U.S.S.R. This limitation placed a severe restriction on their work and forced the development of other methods. In addition, then, to the ordinary methods from the observation of the first motion of the first motion of P, they have developed techniques, both analytic and graphical, for the determining of the direction of the motion vector by use of ratios such as those indicated in equation(4). KOGAN and MALINOVSKAYA (1953), for instance, have described a graphical procedure. The method is similar to that whereby in an area of metamorphic rocks one may determine the axis of folding from single observations of the dip and strike of the original bedding and of the orientation of the plane of foliation. The ratio SH/SV fixes a plane containing the motion vector, the seismic ray, and the total vector of displacement in a transverse wave. A second plane, having a similar geometric significance, is fixed by other ratios, say P/SH. The intersection of the two planes as plotted on a Wulff net determines the motion vector. Theoretically it would be possible to determine the motion from the data of a single station; a statistical average of determinations from several stations is more desirable and serves as a measure of reliability.

Methods using ratios of SH to SV imply that this ratio is constant. In the experience of the authors, this ratio varies greatly during the passage of the S group. This would render the use of ratios troublesome. Unless one can identify the first arrival of S, usually an uncertain process, it would appear that S should be used with great care.

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Statistics and the Fault Plane, a Conjecture

BY R. E. INGRAM, S.J.

Rathfarnham Castle, Dublin, Eire

ABSTRACT

The paper is a note pointing to the possibility that statistics may be used to give the best position of the boundaries separating compressions from dilatations in fault-plane solutions. Tentative solutions are given for two simple cases, where separation is in terms of a single straight line, and where it is in terms of two straight lines. In each case a discriminating function is used to determine the best equation for the lines.

The success of the analysis of mechanisms of earthquakes by the fault-plane technique, using a graphical method, suggests that the same problem might be investigated with purely mathematical tools. The problem may be stated in the following way. On the surface of the earth-sphere, or in the plane of projection, the extended positions of stations form two classes of points. The first class records a compression, it is supposed that there are N^+ of such, the second class records a dilatation and it is supposed that there are N^- of these. For the sphere it will be required to find two perpendicular planes, passing through the origin—which is the epicentre—dividing the compressions from the dilatations. On the plane of projection, corresponding pair of curves must divide the plane in a similar way. If the plotting is done on the tangent plane at the epicentre, the curves are circles: if on the tangent at the antipodes they are straight lines.

Let us first consider the simplest case, which is that of a single force at the epicentre. If we use the tangent plane at the antipodes as the plane of projection, the projection of the auxiliary plane is a straight line dividing the plane into two regions. One region contains all, or as many as possible, of the N^+ points and the other contains all, or as many as possible, of the N^- points. Our data is that we are given the N^+ and N^- points in the plane and we are required to find the equation of the line. This we do by using a discriminating function (FISHER, 1950), provided the points satisfy certain conditions. It is intended to give a more detailed account of the restrictions on the distribution of the points at a later date.

Referred to suitably chosen axes in the plane (e.g. y is North and x East) the N^+ points have coordinates (x, y) and the mean value of the N^+ points is found. Let (x^+, y^+) denote this point. Likewise let (x^-, y^-) denote the mean value of the N^- points. We now relabel x and y, calling them for ease in summation x_1 and x_2.

Let $S = S(x_1, x_2) = l_1x_1 + l_2x_2 + l_3 = 0$ be the line dividing N^+ from N^-; so that, in so far as it can possibly be done, the N^+ points make $S > 0$ and the N^- points make $S < 0$ (or vice versa). It is required to find l_1, l_2, l_3.

Let (α_{ij}) be the matrix of coefficients

$$\alpha_{ij} = \Sigma x_i x_j - \Sigma x_i \, \Sigma x_j / \mathrm{N} ,$$

where the summation is taken over all the points (N) (values of x_i, x_j) and $\mathrm{N} = \mathrm{N}^+ + \mathrm{N}^-$.

Let $S^+ = S(x_i^+, y_i^+)$ and $S^- = S(x_i^-, y_i^-)$, usually called the expectation values.

Finally, let
$$W = \frac{(S^+ - S^-)^2}{l_i \, \alpha_{ij} \, l_j}$$

in which a repeated index indicates summation (Einstein convention). The lower term is thus a quadratic form but restricted to values 1, 2 of i and j.

The theory (FISHER, 1950) states that l_1 and l_2 are given by maximizing W,

i.e.
$$\frac{\partial W}{\partial l_i} = 0,$$

$$2(x_i\,\alpha_{ij}\,x_j)\,(S^+ - S^-)\,(x_i^+ - x_i^-) - (S^+ - S^-)^2\,2\alpha_{ij}\,l_j = 0,$$

$$\alpha_{ij}\,l_j = \frac{(x_i\,\alpha_{ij}\,x_j)\,(x_i^+ - x_i^-)}{S^+ - S^-}\ ;$$

thus l_j is proportional to $(\alpha_{ij})^{-1}\,(x_i^+ - x_i^-)$, where $(\alpha_{ij})^{-1}$ is the "information" matrix, the inverse of (α_{ij}). The third cœfficient, l_3, may be chosen to make $S^+ + S^-$ equal to zero.

Having found the equation, a standard test, e.g. SNEDECOR's F Test, may be applied to discuss the value of this discriminating function. Such tests have their value, moreover, for graphical solutions as well.

A pair of lines in the same plane of projection may be discussed in a similar way. The function S is now
$$S = (a_1x + a_2y + a_3)\,(b_1x + b_2y + b_3),$$
with the orthogonal condition*
$$a_1b_1 + a_2b_2 + a_3b_3 = 0$$
or
$$S = l_1x_1 + l_2x_2 + l_3x_3 + l_4x_4 + l_5x_5\ ,$$
with
$$l_1 = a_1b_1,\quad l_2 = a_2b_2,\quad l_3 = a_1b_2 + a_2b_1,\quad l_4 = a_1b_3 + a_3b_1,\quad l_5 = a_2b_3 + a_3b_2,$$
and variables
$$x_1 = x^2 - 1,\quad x_2 = y^2 - 1,\quad x_3 = xy,\quad x_4 = x,\quad x_5 = y.$$
We calculate l_i in the same way
$$l_i \propto (\alpha_{ij})^{-1}\,(x_j^+ - x_j^-)$$
where
$$\alpha_{ij} = \Sigma x_ix_j - \Sigma x_i\,\Sigma x_j/N$$

Alternatively, we may first find one line and use it to give values to the points to obtain a second line.

At this stage it will be more profitable to work directly with points on the sphere having coordinates
$$x = D \sin i \cos i \cos \alpha\ ,$$
$$y = D \sin i \cos i \sin \alpha\ ,$$
$$z = D \cos^2 i\ ,$$
where i is the angle of incidence of the ray leaving the focus, α is the azimuth of the station relative to the epicentre and D is the diameter of the sphere. The HODGSON tables give cot i.

The required discriminating function is then a plane
$$S = l_1x + l_2y + l_3z = 0$$
or a pair of perpendicular planes
$$S = (a_1x + a_2y + a_3z)\,(b_1x + b_2y + b_3z) = 0,$$
with
$$a_1b_1 + a_2b_2 + a_3b_3 = 0,$$
or
$$S = l_1x_1 + l_2x_2 + l_3x_3 + l_4x_4 + l_5x_5$$
$$l_1 = a_1b_1 \text{ etc.} \qquad \text{and } x_1 = x^2 - z^2 \text{ etc.}$$
when a_3b_3 is eliminated.

The coefficients may then be calculated as previously.

*This condition expresses the fact that the perpendicular from the origin on one line, multiplied by its intercept on the other, is the square of the diameter of the sphere (unity).

Finally, we must note that this type of investigation takes account of the general situation rather than the accurate drawing of a curve to pass between points. If one remembers that, to a first order of approximation, the amplitude is zero on the line and approaches zero near the line, the value of so accurate a drawing may be questioned. On the other hand, the method of discriminating functions depends on the mean values of the coordinates, x_i. Thus, to give a fair picture, we would in all probability have to take typical stations from a well marked region to avoid biasing the result. The use of amplitudes would help remedy this fault.

This note is intended to call the attention of geophysicists to the aid they may possibly obtain from the mathematical departments of the institutes in which they work. It is a tentative solution.

Example: The N^+ points are given in the (xy) plane as the points $(3,-3)$, $(4,\ 1)$, $(-2,-3)$, $(0,-6)$, $(0,\ 4)$ and the N^- points as $(2,\ 4)$, $(0,\ 6)$, $(-2,\ 0)$, $(-4,-2)$ and we require a line dividing the $+$ from the $-$ points. Proceeding with the calculations, we obtain

$$53l_1 + 17l_2 = 2 \qquad (x^+, y^+) = (1, -1.4)$$
$$17l_1 + 111l_2 = -3.4 \qquad (x^-, y^-) = (-1,\ 2)$$

which give

$$2.14l_1 + 2.80l_2 = 0,$$

and we take the approximate line

$$S = y - 1.3x - 0.3 = 0\ ,$$

the constant term being chosen to make $S^+ + S^- = 0$.

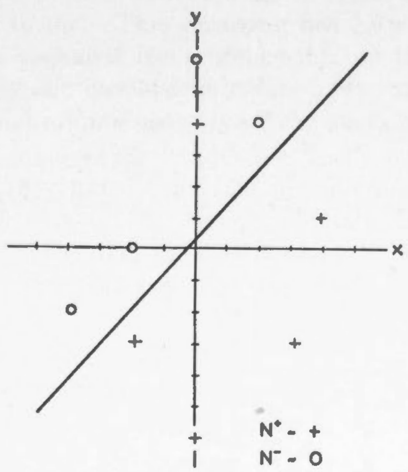

Figure 1.

From the diagram (Figure 1) we see that (0,4) is on the wrong side of this line. But no line satisfies the conditions and hence this line is acceptable. Is it the best solution?

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Mechanisms of Faulting*

BY C. HEWITT DIX

California Institute of Technology, Pasadena, California, U.S.A.

ABSTRACT

The faulting picture shown by E. M. ANDERSON in his book using C. E. INGLIS' stress calculations is examined, and it appears difficult to extract energy for radiation in seismic waves from such a picture. Before and after the formation of such a crack the stress energy appears to be approximately the same.

However if there are two pre-existing 'lubricated' approximately co-planar sheet regions or sheet regions weaker than their surrounding rocks with a strong solid region between them, then this solid between may be ruptured and energy radiated. This may be modified to include the growth of a simple single lubricated crack but this later process does not seem adequate for large earthquakes.

INTRODUCTION

In a very valuable study E. M. ANDERSON (1951) has discussed faulting and dyke formation. His discussion is rich with field evidence. He seeks an understanding of the evidence in terms of basic physical principles and relationships.

The subject is one of fantastic difficulty. Geological observations mostly at the earth's surface must be interpreted. Success in this is probably in a strict sense impossible. So one must fall back on the multiple alternative process. To help push the assessment of probabilities of the alternates one tests every picture of any mechanism as severely as possible.

It is my purpose to apply a simple test to the general picture left by a reading of ANDERSON'S book. The result was a surprise to me. It forced me to recast my view of the process in a way which seems quite important to me. This recasting has helped me to "understand" several field observations which have appeared incomprehensible on the basis of the view I have of ANDERSON'S processes. Clearly the conclusions reached here will have to be modified. They may be of temporary service and are presented for that reason.

I acknowledge the help of many earlier students of this problem, especially the publications of BENIOFF (1949), HAFNER (1951), HUBBERT (1951), HILL and DIBBLEE (1953), MOODY and HILL (1956), ALLEN (1957), INGLIS (1913), GRIFFITH (1921, 1928), and many others. I am particularly indebted to D. F. HEWETT, C. F. RICHTER, C. R. ALLEN, ALLAN R. SANFORD, THANE MCCULLOH, PHIL BLACET, WILLIAM CHAPPLE and M. KING HUBBERT for many discussions on this subject.

Although the study can be related to the fault plane studies of this symposium it is forcing things a bit to do so. This report therefore contains only the part of the study most directly bearing on fault plane studies in the sense of this symposium. The other aspects will be presented elsewhere. This must be qualified a bit. I first learned of the viewpoint of Professor BELOUSOV at the Toronto meeting, and believe his view and mine to be in agreement. It may be that he and his associates have anticipated my studies but I have not been able to find publications to this effect. I do know, however, that Professor BENIOFF (1949), gave arguments in favor of zones of weakness some years ago.

THE CALCULATION OF STRESS ENERGY OF A FAULT

In Figures 1a and 1b are shown a situation without a fault and with a fault respectively. The stress fields at great distances away are, in the limit, the same. Both Figures represent idealized two-dimensional problems in elasticity. The lines drawn represent directions of principal stress. An orthogonal set of curves to these (not drawn) may be imagined which also represents principal stress directions.

*Publications of the Division of Geological Sciences, California Institute of Technology, Pasadena, California. Contribution No. 891.

Though I recalculated ANDERSON's curves (which were earlier calculated by C. E. INGLIS, 1913; see also MUSKHELISHVILI, 1953) (my Figure 1b, his Figure 35), I got the same results shown by ANDERSON on his page 164 but with a little more detail at greater distances. My curves are to be taken to be curves across which the principal tensile stress is a maximum.

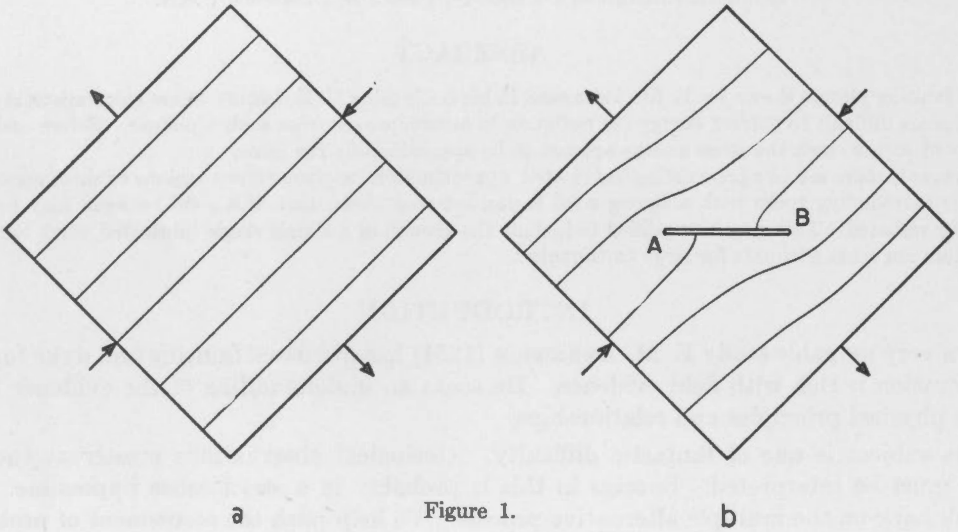

Figure 1.

In making the calculation a hydrostatic state of stress has been removed in both cases so that the hydrostatic pressure in the crack is taken as zero. The principal stresses at infinity are equal and opposite for both cases.

Let us now calculate the stress energy for the two cases. I did this by a numerical integration for a particular example. My idea was that I could in this way get a measure of what might be the energy available for radiation in the form of an earthquake. The two figures came out approximately the same!

Thus if we imagine the energy radiated in the form of an earthquake for a process which consists of a transition from the state represented by Figure 1a to the state represented by Figure 1b, this energy has to come from a source not yet mentioned. When thermal effects are taken into account the situation is even worse. My conclusion, stated at the meeting was that the picture presents no mechanism for making earthquakes.

A POSSIBLE MECHANISM

In what follows I shall indicate a *possible* mechanism which deviates from the picture just presented as little as possible.

Refer to Figure 2. The curves again are sketched (not yet computed in this case) to represent principal stress directions across which the orthogonal stress is a tension. The crack of Figure 1b is now sealed and its complementary extension on both sides is now open.

The situation is singular at A' and B' but let us avoid that problem by taking AA' and BB' large compared with AB. The stress applied should approach zero as one approaches A' and B'. If ones makes the stress also approach zero as D and C are approached in the proper symmetrical way, then the external applied stress will not rotate the piece considered.

Given zero stress in BB' and AA' on the crack surface, i.e., zero pressure and lubricated, for a given external applied stress, the shear stress between A and B becomes arbitrarily large as AB becomes artibrarily small. If rupture occurs motion will continue until the elastic spring has lost its energy in radiation of waves out through the elastic solid.

The above picture appears to contain some useful aspects. But it is grossly oversimplified. It shares with Figure 1 a failure to take proper account of the $r^{-\frac{1}{2}}$ singularity (GRIFFITH, 1921) at *A* and *B*. First let us hold to the mathematical hypotheses which introduce the singularity. Then we notice two cases: (a) the pressure inside the crack is zero but shear stress has an $r^{-\frac{1}{2}}$ singularity; and (b) shear stress is not applied but pressure inside the crack is not zero. In each case no real material would hold together even when the applied stress or internal pressure is arbitrarily small. So neither Figure 1b nor 2 can represent any final state nor even a static state at all.

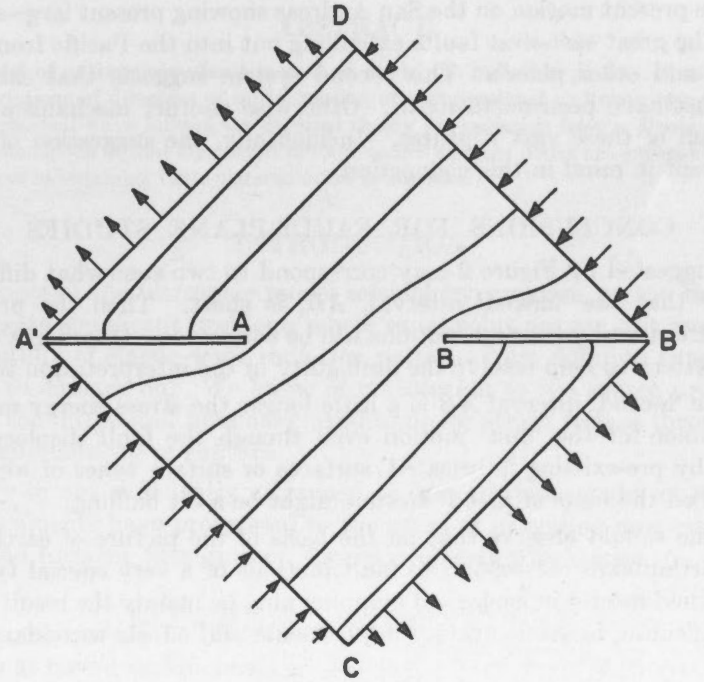

Figure 2.

As is so often the case, the villain in this scene is our forgetfulness regarding the limitations of the mathematical formulation of the physical situation—we assumed arbitrarily small strains. The neighborhoods of our singular places require a different treatment. Also the ideal sheet crack is calculated as the limit of a sequence of open rounded cavities (elliptical cylinders in Figure 1b usually). The limiting situation is selected not because it seems closer to the true case, but because of its simpler formulae. Probably one should replace the term 'crack' by 'crack with rounded ends' *and* also leave a region at each rounded end where the hypothesis of 'arbitrarily small strains' fails more or less seriously.

The above considerations do not weaken the argument about energy available for radiation. It therefore appears probable that a transition from Figure 1a to Figure 1b is ruled out. Figure 2 as an initial state and Figure 2 with *AB* ruptured as a final state appears to represent roughly a possible mechanism for the generation of earthquakes.

Our arguments have thus led us to the conclusion that *before* rupture can take place, cracks, sheet-like zones of weakness, sheets of melted material or the like must exist. This raises quite serious questions. I see no objection to the injection of a melt along a sheet. However the orientation of this sheet is likely to be such that its normal is the direction of maximum principal tensile stress. The reason for this orientation is that assuming isotropic cohesion (or negligible cohesion) of the rock, such an orientation corresponds to the direction of opening requiring least work for the injection process. For such an orientation however there is no shear stress in the sheet direction. It therefore appears necessary to change the stress pattern after the formation of the sheets or else guide their formation by some lack of isotropy of the materials. This latter process appears to have happened in California in the case of the San Andreas fault zone. The maximum principal stress appears to be east-west. This is the right orientation to form the clockwise lateral displacement observed on the San Andreas. However the San Andreas is slipping clockwise about 5 cm. per year indicating its 'lubrication' or weakness in some sense. Its direction seems to be influenced by the continental boundary. Local reorientation of stress to account for small dykes and faults is easy to imagine. But a great reorientation would be more difficult. There are however indications that great reorientations should not be ruled out. These are, first, the present motion on the San Andreas showing present large-scale stress orientation and, second, the great east-west faults extending out into the Pacific from Cape Mendicino, Point Conception and other places. This second system suggests that earlier the maximum principal stress must have been north-south. Otherwise another mechanism must be appealed to for the formation of these vast ruptures. Incidentally, the suggestion of Vening-Meinesz (1947) should be kept in mind in this connection.

CONCLUSIONS FOR FAULT-PLANE STUDIES

The picture suggested by Figure 2 may correspond to two somewhat different situations.

First consider that the 'locked' interval, AB, is short. Then the principal fault-plane motion and the pattern set by the first motions will be consistent. One might even use the elongated after-shock pattern to help resolve the ambiguity in the interpretation from first P motion.

However if the 'locked' interval AB is a little longer the stress energy may not be released in this simple manner for the 'first' motion even though the fault displacement is probably ultimately guided by pre-existing 'lubricated' surfaces or surface zones of weakness. In such a case interpretation on the basis of first P motion might be a bit baffling.

Incidentally one should observe that on the basis of the picture of earthquake origin here presented, large earthquakes correspond to fault motions of a very special type. On the other hand the faults studied mostly in geological mapping may be mainly the result of slow dissipative motions, mainly reflecting isostatic gravity adjustments and effects secondary to these.

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Elastic Wave Radiation from Faults in Ultrasonic Models*

BY FRANK PRESS

California Institute of Technology, Pasadena, California, U.S.A.

ABSTRACT

An ultrasonic model of an impulsive fault is used to study the radiation pattern of compressional and shear waves. Azimuthal variations of direction of initial motion of compressional and shear waves are described. The behavior of the compressional wave follows the classical theory for radiation from a dipole source. The behavior of the shear waves is anomalous in that significant motion occurs whereas nodes are expected. The relation of this work to current practices in obtaining fault-plane solution is discussed.

INTRODUCTION

The main purpose of the ultrasonic model seismology program at the Seismological Laboratory is to investigate significant problems where exact solutions are not available. From this point of view, the study of elastic wave radiation patterns from different types of sources was a natural one for us to embark on. We know of no solution to the source problem which takes into account all of the initial and boundary conditions for strain release through a fault having finite length and finite velocity of rupture.

Our technology is not sufficiently advanced to make a true model of a fault. However, we believe our experiments have progressed to the point of providing new insight into the fault solution problem and focusing attention on special problems which arise.

EXPERIMENTAL PROCEDURE

Two dimensional model techniques were employed (OLIVER *et al.*, 1954). In such models, motion is uniform over the thickness of the sheet so that sources and detectors on the face of the model occupy positions corresponding to the interior of a three-dimensional medium.

The representation of unipole and multipole sources is particularly convenient with barium titanate bimorph transducers (Figure 1). When used as detectors, these transducers offer the advantage of ready conversion from compressional to shear sensitivity by rotation of 90°.

The experimental procedure consists of observing compressional and shear wave radiation patterns at the circumference of the thin disk of plexiglas at the center of which the source is located. This corresponds to observations along the trace on the focal sphere of a plane perpendicular to the fault and auxiliary planes. Amplitudes, pulse shapes and directions of initial motion are observed.

In this paper, we report on results for impulsive singlet and dipole sources. To simulate a fault, we have introduced a slit between two elements of a dipole. Our model differs from an actual fault in that the finite velocity of rupture and locking is not taken into account.

RESULTS

SINGLET

Results for this source are depicted in Figures 2 and 3 where actual seismograms are shown for each recording position. It is important to establish (Figure 4) that the amplitude variation with azimuth follows the theoretical cosine and sine law since multipole sources will be formed by superposition of singlets.

*This research was sponsored by the Office of Ordnance Research, U.S. Army; California Institute of Technology, Division of the Geological Sciences, Contribution No. 848.

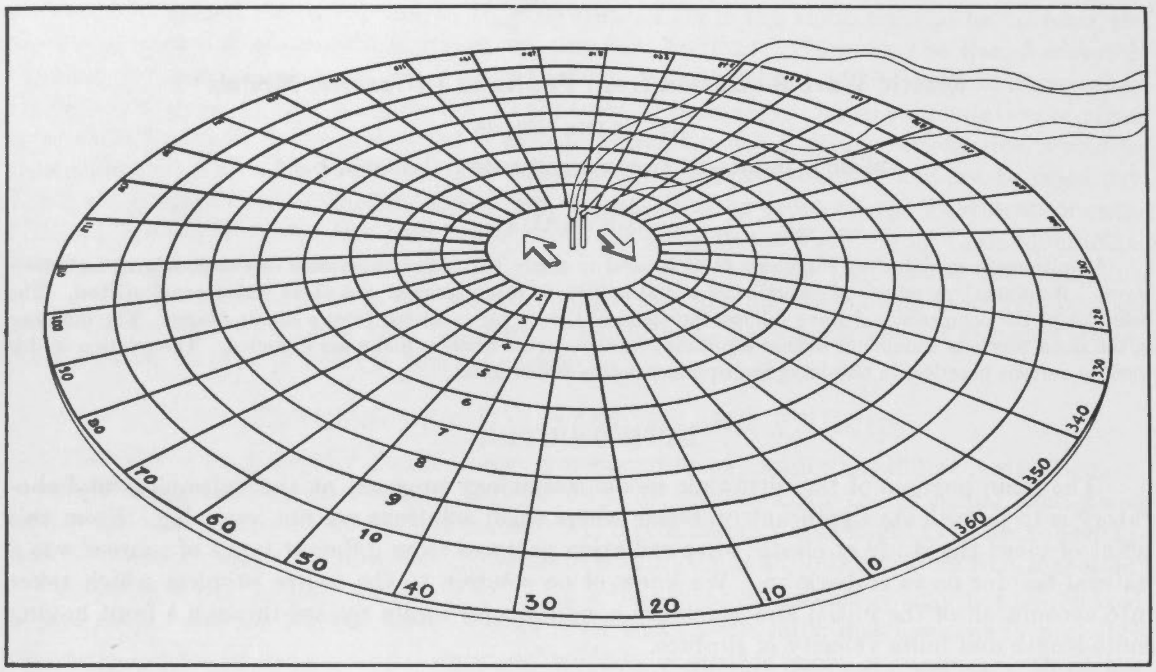

Figure 1. Two-dimensional model of dipole source.

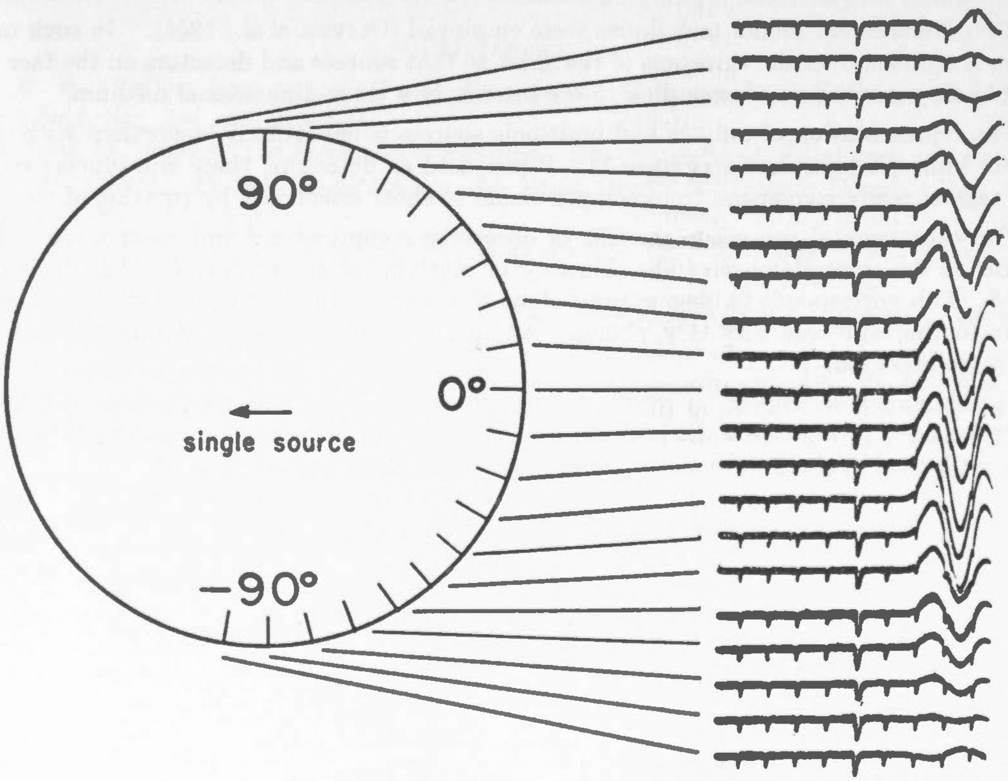

Figure 2. Compressional waves from a singlet source. Upward trace motion corresponds to inward motion on the model.

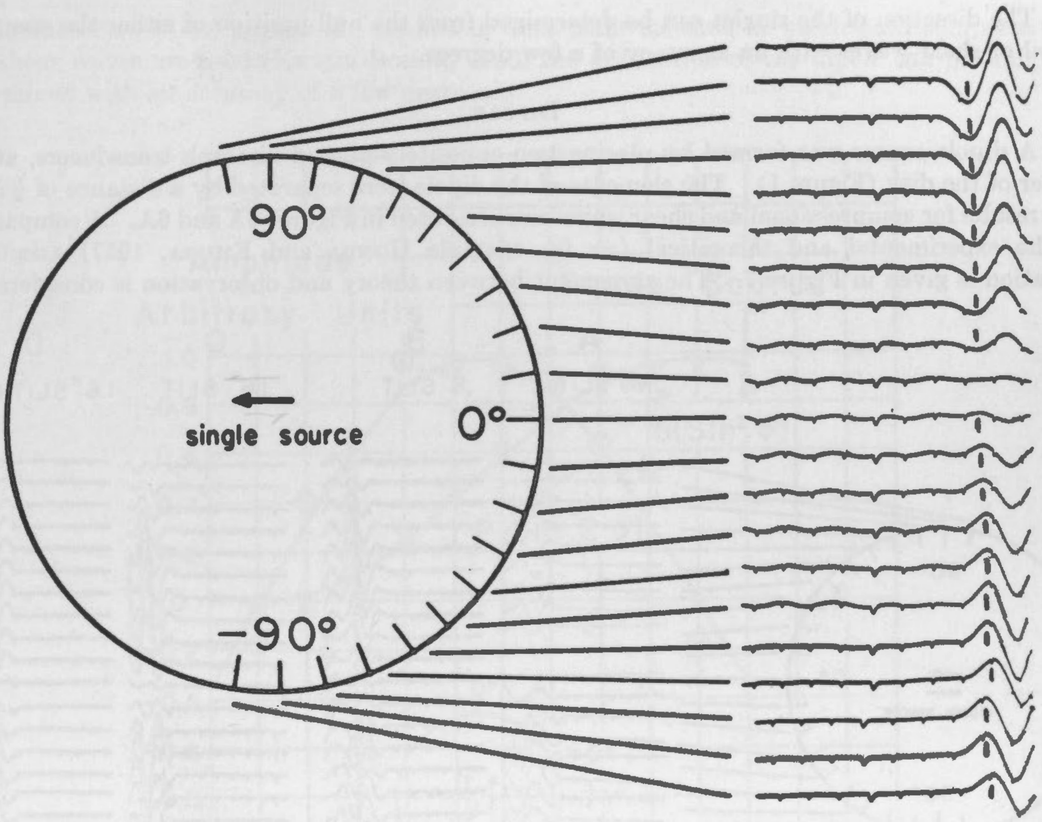

Figure 3. Shear waves from a singlet source. Downward trace motion corresponds to counterclockwise rotational motion on the model.

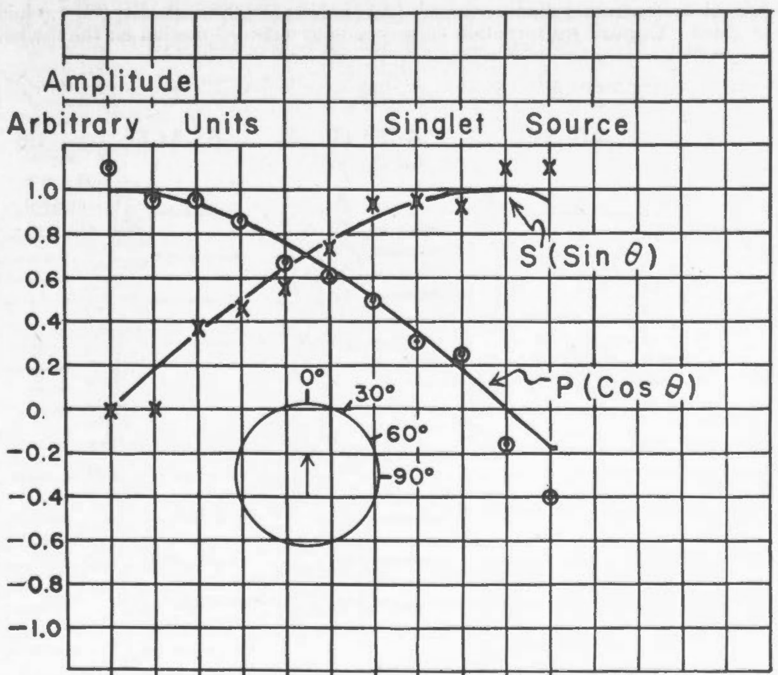

Figure 4. Observed and theoretical amplitude variation with azimuth for singlet source.

The direction of the singlet can be determined from the null position of either the compressional or shear waves with an accuracy of a few degrees.

Dipole

A dipole source was formed by placing two oppositely phased bimorph transducers, at the center of the disk (Figure 1). The elements of the dipole were separated by a distance of $\frac{1}{4}$ inch. The results for compressional and shear waves are presented in Figures 5A and 6A. A comparison of the experimental and theoretical (*see* for example Honda and Emura, 1957) azimuthal variation is given in Figure 7. The agreement between theory and observation is considered to

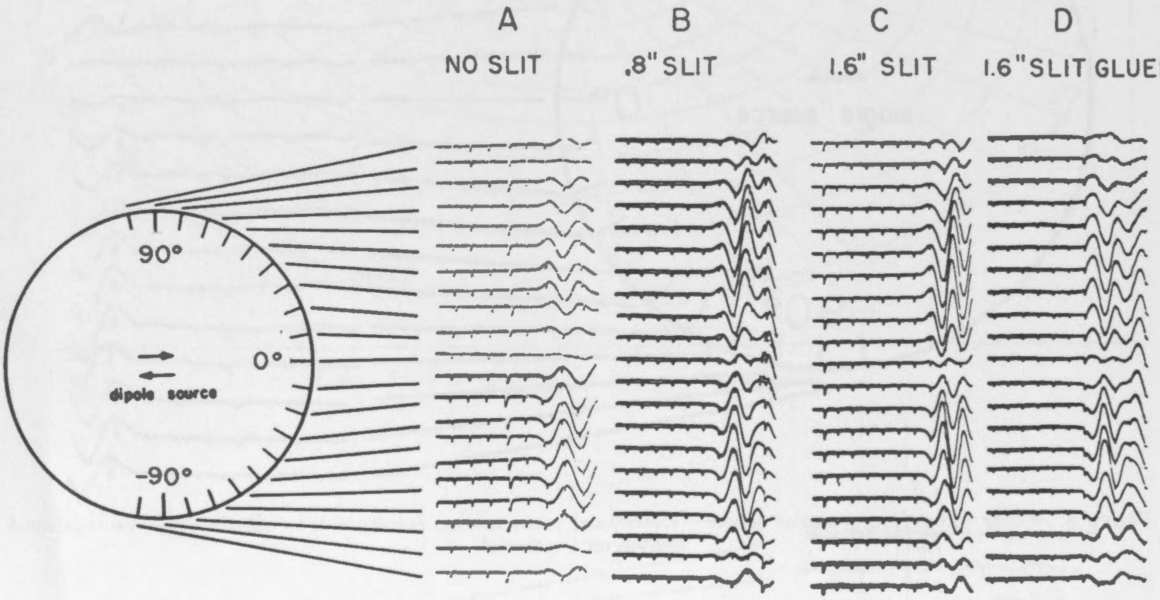

Figure 5. Compressional waves from a dipole source. (A) No slit; (B) 0.8 inch slit; (C) 1.6 inch slit; (D) 1.6 inch slit glued. Upward trace motion corresponds to outward motion on the model.

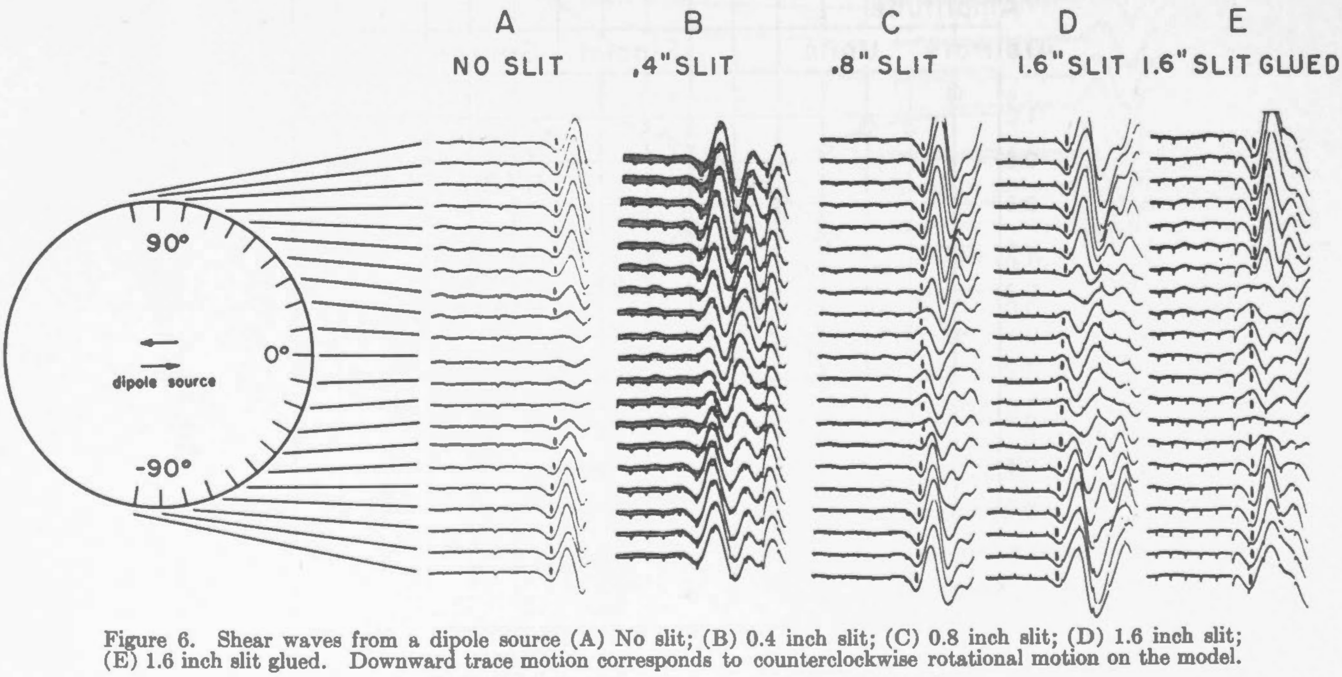

Figure 6. Shear waves from a dipole source (A) No slit; (B) 0.4 inch slit; (C) 0.8 inch slit; (D) 1.6 inch slit; (E) 1.6 inch slit glued. Downward trace motion corresponds to counterclockwise rotational motion on the model.

be satisfactory. If one applies the method of fault-plane solution in which both compressional and shear waves are used (KEYLIS-BOROK, 1956) the orientation of the dipole can be uniquely determined with an accuracy of a few degrees.

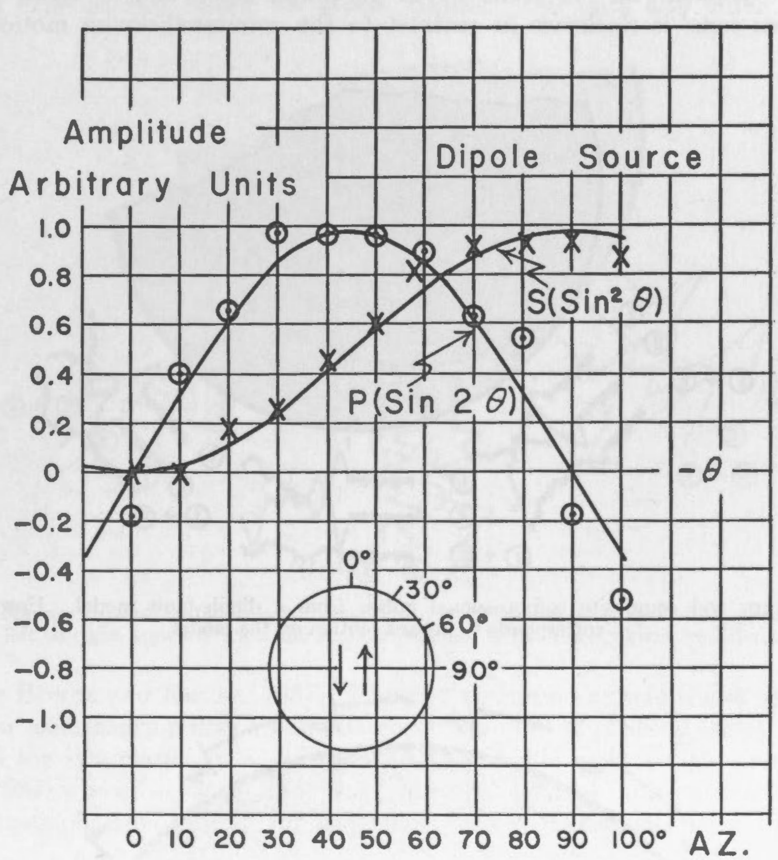

Figure 7. Observed and theoretical amplitude variation with azimuth for a dipole source.

DIPOLE-FAULT

In order to represent faulting, a narrow slit was cut between the two elements of the dipole, the void being filled with silicone. Free slipping and continuity of normal stress and displacement across the slit were provided for in this manner. The slit length was varied to study the effect of fault length on radiation pattern. In one experiment, the slit was glued to simulate a zone of reduced rigidity between the elements of the dipole.

Compressional waves observed for this model are shown in Figures 5B, C, D. The main features obtained for the dipole without slit are repeated in these seismograms. It is of some interest to see the manner in which the separate contributions from each side of a fault (elementary pulses) are superposed. In Figure 8, seismograms are presented which show elementary pulses separately and superposed as observed at three positions. The main feature in determining polarity of the composite pulse is the delay and greater attenuation of the elementary pulse which crosses the fault enroute to the point of observation. We interpret these results as a verification of the basic assumptions made for the radiation pattern of compressional waves in fault-plane solutions.

Shear waves from the dipole-fault model are presented in Figures 6B, C, D, for slits of varying lengths. These lengths correspond respectively to ½, 1, and 2 wave lengths for shear waves. Figure 6E depicts seismograms for a glued slit, i.e., a model of a fault as a zone of reduced rigidity.

A striking feature becomes apparent when the dipole-fault seismograms are compared with those of the simple dipole. Whereas shear wave amplitudes near 0° decrease to negligible values for the latter model (Figure 6A) the fault models show significant amplitudes in this zone. The null positions are displaced 25°–35° from that of the simple dipole and the sense of shear motion in the 'anomalous zone' is clockwise in contrast to the counterclockwise motion in the zones ± (30°–90°).

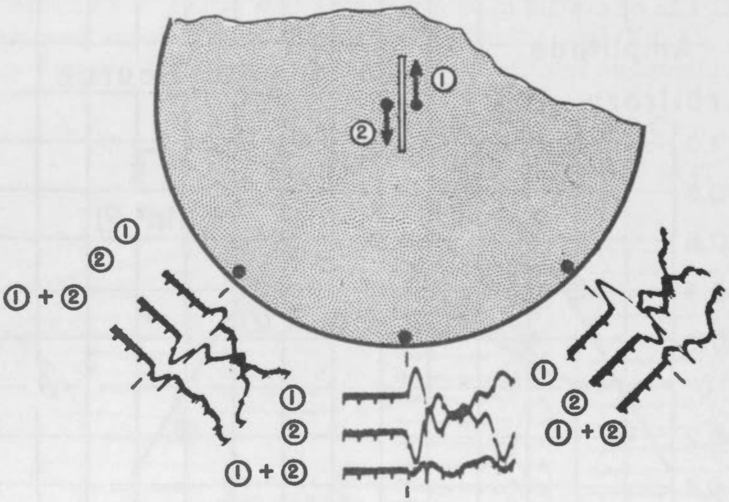

Figure 8. Elementary and composite compressional pulses from a dipole-fault model. Upward trace motion corresponds to inward motion on the model.

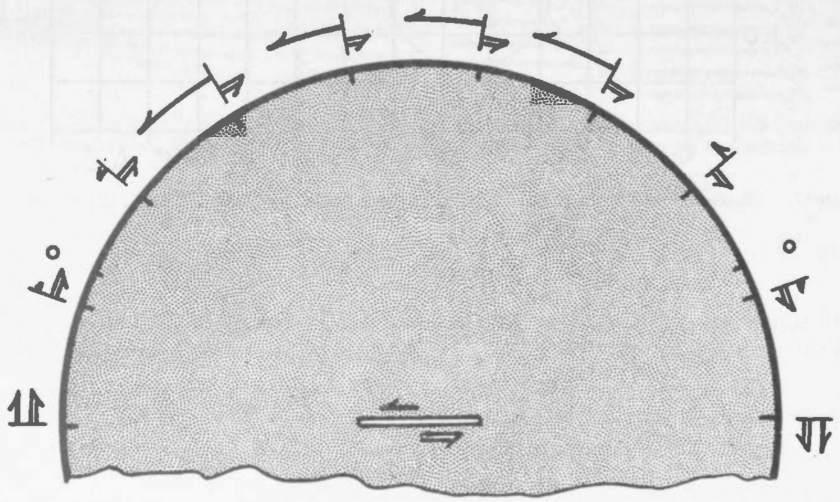

Figure 9. Sense and amplitude of elementary shear pulses in a lubricated dipole-fault model.

The anomalous shear waves may be studied further in Figure 9 where the sense and amplitude of the elementary pulses from each side of the fault are indicated separately by arrows. The near side of the fault produces waves with maximum amplitude at 90° diminishing to zero at about 25° and 155°. The sense of motion is contrary to that of the source in the range 0–25° and 155°–180°. The far side of the fault contributes waves having the same sense as the initiating impulse and showing little variation in amplitude over the range 0–180°. Figure 10 shows the corresponding seismograms for three positions together with composite pulses formed by superposition of the elementary pulses. It is seen how the two in-phase elementary pulses at 0° combine to give a resultant shear motion having the same order of magnitude as that recorded at 90°. These results were first reported in 1956 (PRESS, 1957). KATO and TAKAGI (1957) seem to have independently obtained somewhat similar results.

The shear wave radiation pattern for our dipole-fault models differs significantly from the theoretical and experimental results for dipole sources. Our data also differ with results for

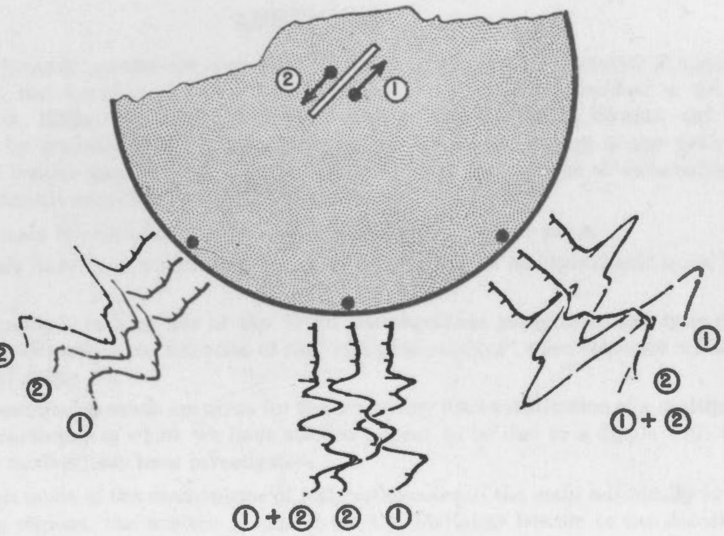

Figure 10. Seismograms showing elementary and composite shear pulses in a dipole-fault model. When reading seismograms from left to right, upward trace motion corresponds to counterclockwise rotational motion on model.

quadrupole (*see* HONDA and EMURA, 1957). The null position occurs in the range 25°–35° rather than 45° and the elementary pulses are in phase at 0° and out of phase at 90°. Thus, we cannot verify either of the two classes of assumptions usually made by investigators (KEYLIS-BOROK, 1956; HONDA, 1934) who incorporate shear wave data to determine fault-plane solutions uniquely. It is necessary to emphasize however that the validity of our fault model has not been established beyond doubt.

It is a pleasure to acknowledge the assistance of John H. Healy in the experimental program.

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The Study of Earthquake Mechanism

BY V. I. KEYLIS-BOROK

Geophysical Institute, U.S.S.R. Academy of Sciences, Moscow

ABSTRACT

The determination of dynamic parameters of earthquake foci (the mechanical character of rupture at the focus, the fault-plane orientation, the direction of movement) is made by the method described in the 1954 Assembly publications (KEYLIS-BOROK, 1956a). It is, in principle, similar to the method of BYERLY and of the Japanese seismologists, as described by BYERLY in the present symposium. The main feature of the method is the use of S waves, which makes the results single-valued and drastically reduces the number of observations necessary, as well as the ratios of displacement amplitudes in different waves.

The following are the main improvements in method achieved within recent years.

a. Simple methods have been worked out to exclude the influence of discontinuities on the shape of the observed waves.

b. A graphical method, making use of the Wulff stereographic projection, has been developed, which makes it possible to determine the direction of the "straightened rays" when there are refracting boundaries of any number and shape.

c. Additional theoretical grounds are given for the commonly used substitution of a multipole for the focus. While almost all earthquakes which we have studied appear to be due to a dipole with moment, several more complicated models have been investigated.

Determination has been made of the mechanisms of 300 earthquakes in the main seismically active zones of the U.S.S.R. and the adjoining regions: the western Pacific (from the Marianas Islands to the Aleutian Islands), the Hindu-Kush, the Pamirs and Tien-Shan, Kopet-Dag and Western Turkmenia, and the Caucasus. Of special interest is the Garm region (on the border of the Pamirs and Tien-Shan) where about 150 weak earthquakes, occurring within a small area, were studied.

The basic properties of dislocations in the foci of each zone have been found and compared with the general tectonics.

a. In some regions one strike direction predominates; in some instances this is parallel, in other instances transverse, to the strike of the main structures. In most regions however both systems are developed at the same time.

b. Faults with strong horizontal components of movement, and with strikes transverse to the structures are much more common in the seismic solutions than they are from geological data. However this is in line with some neotectonic data.

c. Vertical movements in the foci of some regions are characterized by the fact that during earthquakes a fault wall facing a tectonic depression is lifted up in the earthquake. This is in agreement with geological and geophysical evidence on the movements of surface foci in Japan: vertical movements during earthquakes are in the opposite sense to the secular ones.

The data obtained are of interest in deep tectonics, its relation with seismicity, etc. A great number of foci should be investigated in different tectonic regions. In this connection, international exchange of information and data is of paramount importance; this interchange is now very well established.

This report is an account of the Soviet work on earthquake mechanism (type of rupture, dip and strike of fault plane, motion direction at the source). This work is the continuation of the investigations reported by the author at the previous Assembly (KEYLIS-BOROK, 1956a).

In the first section some questions of method are considered. The second section summarizes some results of the study of nearly 300 earthquakes in the U.S.S.R. and adjacent districts.

QUESTIONS OF METHOD

As is well known, the study of earthquake mechanism is based on the displacement of various seismic waves.

We shall define as an *original wave* that wave which would be observed from a given source if the medium were a homogeneous ideally elastic one. We shall also consider the *straightened* *ray* which is the semitangent to the ray at the hypocentre. The determination of various characteristics of displacements in an original wave along the straightened ray is the first problem of an interpretation. Instead of rays we consider their stereographic projections ('virtual points of observation').*

The distribution of these characteristics is compared with the theoretical one which is calculated for the model source in a homogeneous medium. Mostly it comes to drawing nodal lines according to arrival signs of original waves. The direction of the axis of the model is then determined to obtain the earthquake mechanism as above defined.

The idea of such an interpretation procedure belongs to BYERLY.

Japanese seismologists employed an inverse procedure, calculating the theoretical field of displacements in a non-homogeneous medium and comparing it directly with observations.

The principles of BYERLY's methods and of those used in the work to be reported here seem to be alike. The main difference is that we employ the signs of transverse waves SV and SH in phases S, SS, sS, PS and so on, and ratios of displacement amplitudes P/SH, SV/SH. It makes the interpretation unambiguous and greatly lessens the quantity of observations required. We use a Wulff stereographic projection which seems to be more convenient; perhaps it is not only the matter of habit.†

A detailed account of the method we employ has already been given (BESSONOVA, *et al.*, 1957), together with related theoretical questions. A general description and a detailed discussion of interpretation procedure have also been published in English (KEYLIS-BOROK, 1957,). To avoid repetition we shall give a summary only of some questions of method investigated during recent years.

One of the main questions concerned is the excluding of the influence of intermediate boundaries on the form and direction of displacements. This is of particular importance in the study of near earthquakes and in employing reflected and head waves of different types.

THE DISTORTION OF DISPLACEMENT FORMS

To determine a displacement in an original wave we have to exclude the influence of reflections at all boundaries, including the Earth's surface, met by a real wave.

If the angle of incidence at any of these surfaces is more than critical, in which case the reflection or refraction coefficients are complex, the observed wave differs from the original wave not only in intensity but in the form of displacement as well (the number, amplitudes and periods of extrema)‡.

Similar phenomena arise when the rays focus, or when they reflect at a boundary of a non-ideal elastic medium.

However all the possible variations in the forms of reflected and refracted waves for a given primary wave form can be represented theoretically by a set of 'standard curves' (MALINOVSKAYA, 1957). Curves for two possible original waves are shown in Figure 1. The parameter φ is the argument of a complex number. This number is determined as a product of all plane wave reflection and refraction coefficients; these coefficients allow for all intersection of real rays with the boundaries. The upper curve in each column ($\varphi = 0$) coincides with the corresponding original wave forms. An observed displacement is the product of a curve in Figure 1 and some factor ρ determining the wave intensity.

The method of calculating φ and ρ is treated elsewhere (MALINOVSKAYA, 1957; PETRASHAIN, 1957a, b). As Figure 1 shows, the correlation between the original and observed waves, and the

*In previous papers I have used the less apt expression 'conventional point'.

†During recent years various interpretation procedures have been growing more and more close. For example, RITSEMA (1955) independently suggested the use of Wulff's projection and transverse wave signs. SCHEIDEGGER (1957) has examined the replacing of the Wulff projection by the projection introduced by BYERLEY. GUTENBERG (1955) used the ratio of SV/SH amplitudes to remove ambiguity.

‡*See* the author's report: "Dynamical Methods of Studying the Earth's Interior."

ratio of their amplitudes, depends greatly upon the magnitude of φ. These waves differ even in the number of extrema. For $\varphi \neq 0°$ or $180°$ usual methods do not enable us to determine either the sign or the amplitude of the original wave. The change of wave form as described above occurs more often in near earthquakes. For example it can happen for the S wave when a thin low-velocity layer exists close to the surface. In this case the angle of incidence at the base of the surface layer is, as a rule, more than critical.

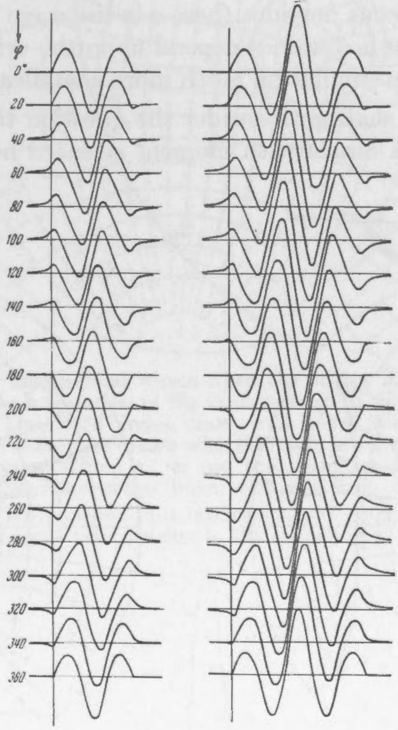

Figure 1. Variations, due to total reflection phenomena, in the displacement form for the two examples of original waves represented by the curves $\varphi = 0$.

For distant earthquakes a change in the wave form can take place when the wave is associated with a non-ideal elastic medium. This condition might obtain at the mantle-core boundary, so that some distortion of the wave form of PcP, PcS, PKP etc. is possible.

The sudden change of φ also occurs for ordinary P or S waves in cases when the front makes a caustic.

Using standard curves we can allow for the displacements form change when determining the sign or amplitude of a primary wave. In particular the influence of a surface layer upon transverse waves can be excluded by means of the diagrams given (Bessonova, *et al.*, 1957, *suppl.* III). In the case when total reflection has occurred at a free surface it is possible to exclude this influence, without using the standard curves, by means of the formula

$$u_b^P = \frac{1}{2 \cos i_o} [S_V \cos 2\, i_o - S_Z \sin 2\, i_o] ,$$

where u_b^P is the total displacement vector in the incident wave SV, S_Z, and S_V are the vertical and horizontal components of the surface displacement and i_o is the angle of incidence at the surface. It is interesting to note that in this case the vertical and horizontal displacement components differ in form and in phase.

Drawing of Nodal Lines when the Source is near a Boundary

The theoretical distribution of signs and nodal lines in a homogeneous medium is used to determine earthquake mechanism. The change of signs of separate waves at the boundaries, for example the sign of PP after reflection at a surface, may be allowed for in a comparatively simple way using the plane wave theory (Ingram and Hodgson, 1956).

The source itself can often be situated at a boundary or near it. If the distance between the boundary and the source is short compared with the quantity $vT/4$, the nodal lines can greatly differ from those in a homogeneous medium (here v is the wave velocity near the source and T is the first arrival period). The nodal lines depend upon the orientation of axes relative to the boundary and it makes their determination much more complicated.

Because of lack of space I shall not consider the question theoretically, but shall only give an example of nodal lines for a dipole with moment situated near a free boundary (Figure 2)

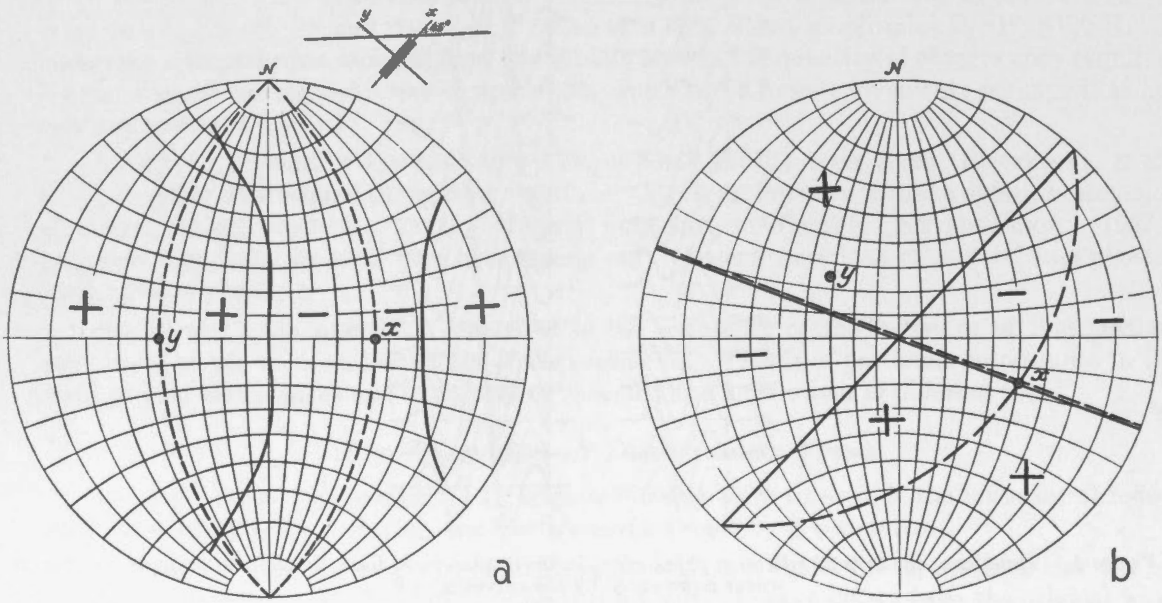

Figure 2. Examples of the nodal lines for (a) longitudinal waves and (b) SH waves, for a source near the free surface. In each case the dashed lines represent the usual nodal lines for the same source in a homogeneous medium. The nodal lines depend on the orientation of the axes x, y of the source relative to the free surface.

or an intermediate one (Figure 3). Similar calculations are carried out in cases which we considered to be typical. As is seen from Figures 2 and 3, usual methods of interpretation for such an earthquake can lead to great difficulties or to errors. One can avoid these difficulties using diagrams as shown in Figures 2 and 3 instead of the usual nodal lines. The circumstances are especially complicated for total reflection because of the above-mentioned change of displacement form. It can be seen from Figure 4 that the notion of nodal line itself looses its usual meaning.

Determination of 'Straightened Rays' in the Case of Curved or Inclined Intermediate Boundaries

The direction of straightened rays is characterized by azimuth α_h and inclination i_h. In Byerly's method instead of i_h the 'extended distance' $d = \cot i_h$ is considered; the fundamental calculations of d have been carried out by Hodgson and his colleagues and those of i_h by Ritsema.

It is usually supposed that α_h is equal to the azimuth from the epicentre to the station and that $\sin i_h = \dfrac{R_o}{R_h}\dfrac{v_h}{v_o} \sin i_o,$ where v is the velocity, R the distance from the centre of the earth and where subscripts h and 0 denote the source and observation point accordingly.

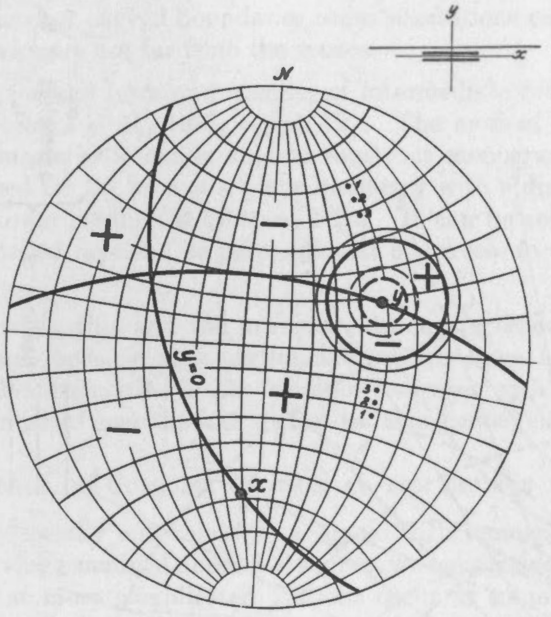

Figure 3. Additional nodal lines for longitudinal waves when the source is near an inner boundary. The fault ($y = 0$) is parallel to the boundary, the orientation of the fault relative to the free surface is arbitrary. The heavy lines represent the usual nodal lines. The closed circles, drawn with heavy lines, show the additional nodal lines in a medium with a lower velocity. The closed circles drawn with thin lines are the projection of a cone, outside of which the total reflection phenomenon occurs. Where a_i, b_i are the velocities of longitudinal and transverse waves respectively and ρ represents density, the closed circles drawn with solid lines correspond to $a_2/a_1 = 2.5$, $\rho_2/\rho_1 = 1.24$ and $a_i/b_i = \sqrt{3}$, while those drawn with dashed lines correspond to $a_2/a_1 = 4.8$, $\rho_2/\rho_1 = 1.3$ and $a_i/b_i = \sqrt{3}$. The additional nodal lines are due to the refraction at the boundary.

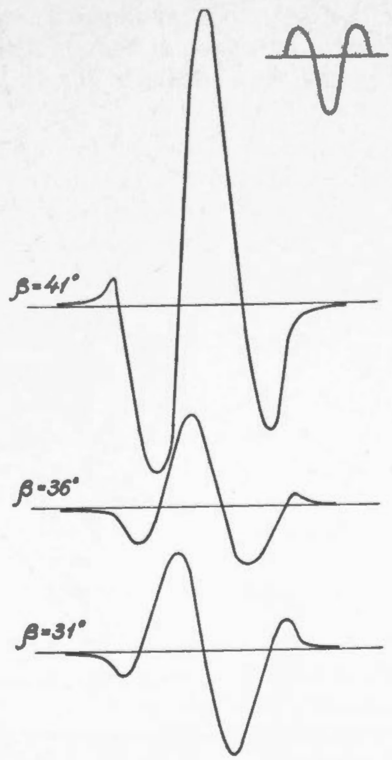

Figure 4. The Figure illustrates a change in first motion not related to the earthquake mechanism. It shows displacements in longitudinal waves along rays lying in a medium with a lower velocity (corresponding to points 1, 2, and 3 in Figure 3) and making the angle β with the y axis. The constants are the same as those corresponding to the solid circles in Figure 3. The form of the primary wave is shown in the upper right corner.

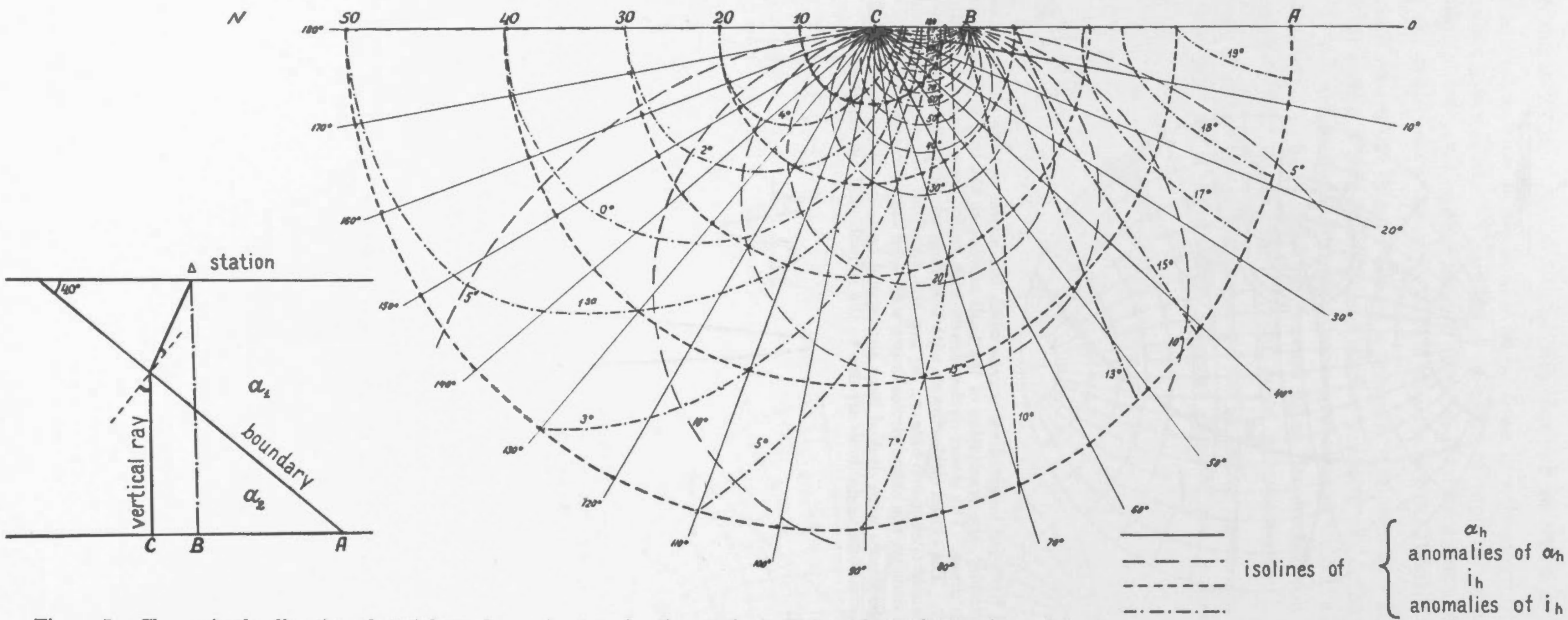

Figure 5. Change in the direction of straightened rays due to refraction at the inner boundary where $a_2/a_1 = 2.5$. A cross-section of the medium is shown in the lower left corner. All the isolines are given on a horizontal plane AC. The anomalies of i_h, α_h are, respectively, the differences $(i_h - i)$ and $(\alpha_h - \alpha)$, where i, α are the angles determined without allowance for the inner boundary. (After E. I. Galperin.)

α_h - the azimuth of the straightened ray;
i_h - its angle with the vertical.

If the wave meets inclined or curved boundaries these suggestions can lead to great errors, especially when the boundaries are not far from the source.

To determine α and i_h for any form and number of intermediate boundaries the graphical method is developed (BESSONOVA *et al.*, 1957, *suppl.* VI). The method is based upon the use of Wulff's projection. By means of it one is able to construct monograms of the type shown in Figure 5 which is composed for the case of a plane boundary with a dip of 40°. The ratio of velocities in the upper and lower medium is taken as 1:2.5. It can be seen from Figure 5 that the real direction of straightened rays can be perpendicular or reverse to that defined by means of the usual method.

The problems considered in this and the previous section are especially important when near earthquakes are studied, because near earthquake records have higher frequencies and because the influence of inhomogeneities in the medium increases with frequency. However for distant earthquakes boundaries near the foci are not to be neglected either.

MODELS OF COMPLEX MOTION AT THE SOURCE

Earthquake sources are usually equivalent to a dipole with moment (that is, to a model of a symmetrical fault). Having examined about 300 sources we have found almost no exceptions. However, the possibility that more complicated motions occur at some foci cannot be at all neglected. These motions can correspond to an asymetrical fault, a combination of a fault with a fractural opening, a fault with rotation, etc.

Point models of such motions and related nodal lines for P, SV, SH are shown in Figure 6. These models are defined (BESSONOVA, *et al.*, 1957; KEYLIS-BOROK, 1956b) by means of classical wave theory given by LOVE (1934) and STOKES.

The theoretical study of the above models and some ideas concerning the method of interpretation have been given elsewhere (BESSONOVA, *et al.*, 1957). The waves arising from various systems of multipoles have also been studied in Japan for a long time(HIRONA, 1948; HONDA *et al.*, 1952, 1957). The models are worthy of examination if there are great quantities of reliable data.

The models shown in Figures 6b and 6c seem to have the most interest; their nodal lines for P waves do not satisfy the 'orthogonality condition'. Some earthquakes discovered by HODGSON cannot be interpreted in the usual way; perhaps it would be interesting to study them using such models or to consider them in the light of the two previous sections.

THE MECHANISM OF EARTHQUAKES IN PRINCIPAL SEISMIC BELTS OF THE U.S.S.R. AND ADJACENT REGIONS

This chapter is a summary of the study of about 300 earthquakes. They are distributed in the regions in the following way (figures in brackets are the focal depths in kilometers): northwest edge of the Pacific Ocean from the Marianas Islands to the Aleutian Islands—29 (down to 580); the Hindu Kush—10 (150-240); Garm district—135 (down to 35); the Tien Shan—33 (10-20); Turkmenia—33 (down to 50); the Caucasus—57 (down to 50).

OBSERVATIONS USED

Distant earthquakes were studied mainly by use of the waves P, S, PP, SS, pP, sS, sP; for near earthquakes the waves $\overline{P}$, $\overline{S}$ and more rarely P_n and S_n (head waves) were taken. For some earthquakes we used recordings of both near and distant stations, the validity of this having been proved by correlating the forms of oscillation shown at near and distant stations. The interpretation was based mainly on arrival signs. The sign combination for P, SV, SH at each virtual point of observation has proved to be especially effective. It greatly reduces the number of observations required and enables us to study many comparatively weak earthquakes in local zones for comparison with tectonics. For example, 135 of the sources studied in the Garm district are concentrated inside a section of 70 by 140 km. This section is continually being studied by a special group of near stations. Experience shows that transverse waves are as reliable as secondary longitudinal waves (PP, pP, etc.) *if one uses seismograms rather than questionnaires.*

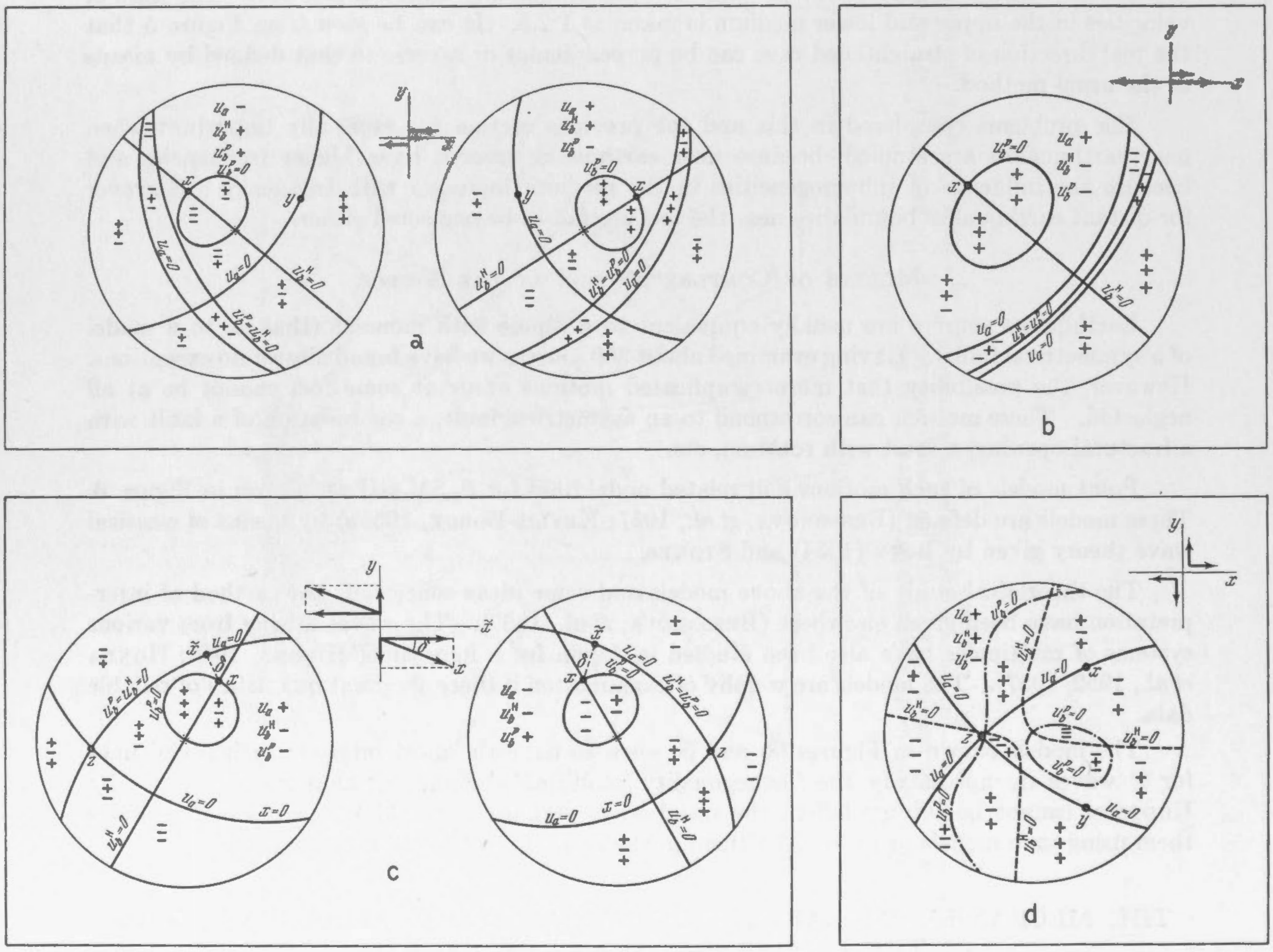

Figure 6. Nodal lines for various complex sources:
a—asymmetrical fault;
b—asymmetrical fracture openings;
c—combination of fault and fracture openings;
d—combination of the fault and rotation (or two perpendicular faults).

It can be estimated that the errors involved in determining the direction of fault-plane solutions are from 7° to 15° with the mechanism described here. To avoid errors of inaccurate drawing of the straightened rays is the most difficult problem.

Results of Interpretation

The mechanism of the earthquakes studied is shown in Figures 8 to 12; the notation used in these figures is described in Figure 7.

To make the generalization of results easier, summaries of the fault-plane stereographic projection and motion directions can conveniently be given by the method shown in Figure 13.

Such summaries for all the regions studied have been given elsewhere (BESSONOVA, *et al.*, 1957); a typical example is given in Figure 14.

A detailed description of the results of our work to date, and of its comparison with the tectonics of each region has been given in other publications (BESSONOVA *et al.*, 1957, KEYLIS-BOROK, 1956a).

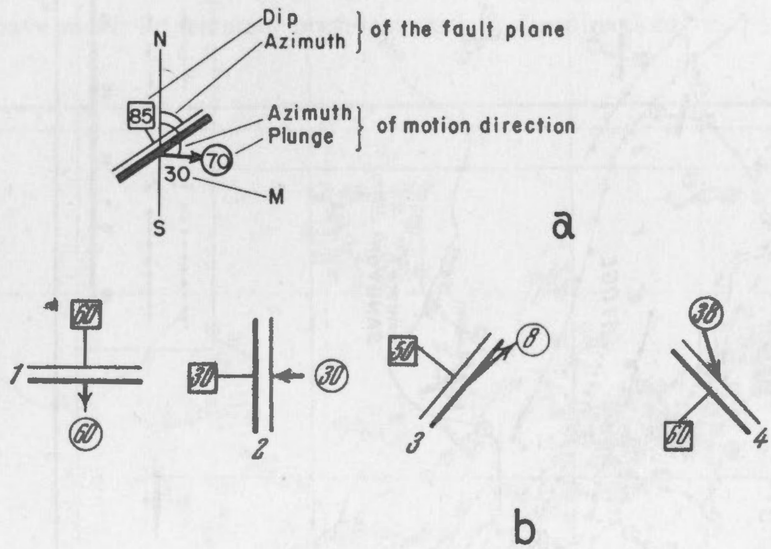

Figure 7a. The notation used in representing fault-plane solutions on maps. The heavy line represents that side of the fault that moved up. The number M is the identification number of the earthquake in the catalogue (BESSONOVA, *et al.*, 1957).

b. Some examples of the representation of fault-plane solutions.

1. Normal fault striking parallel to the latitude and dipping 60°N.
2. Thrust fault striking parallel to the meridian and dipping 30°W.
3. Strike-slip fault, dipping 50°NW. The direction of movements is NE with an inconsiderable (8°) uplift of the lower side.
4. Reverse-oblique slip fault.

In generalizing the results and comparing them with tectonic patterns one must bear certain limitations in mind.

(a) With a limited pattern of seismic stations it may not be possible to determine all possible fault systems. HODGSON, in his summary of this volume, has suggested that this may explain the difference between Soviet results and his own in the northwest Pacific. Another example is provided by the Garm district, shown in Figure 9. The special stations set out in this area were all south of the Hissar ridge, and their observations ($\overline{P}$, $\overline{S}$ waves) make it possible to determine with certainty only those faults in the Hissar ridge which strike nearly north-south and dip not more than 25° to 30°. To study all possible faults it is necessary to use additional observations from stations north of the ridge, or to use the head waves P_n, S_n at the southern stations.

Generally speaking, the system of observations will be free of this unpleasant 'selectivity' if a hypocentre is surrounded by conventional points (not necessarily by the stations themselves).

(b) The number of faults studied must be sufficiently large for the application of statistical criteria. For example, the first 30—40 faults studied in the Garm district indicated two prevailing strikes, the strikes transverse to the main structures appearing the more numerous. However, the later statistical analyses of about 150 faults showed clearly that the longitudinal faults were the more prevalent; transverse ones exist but they are not the dominant ones.

(c) Most of the earthquakes studied have been relatively weak; the general properties of their faults must be compared with tectonic features of a corresponding scale, which may be different than those corresponding to large earthquakes.

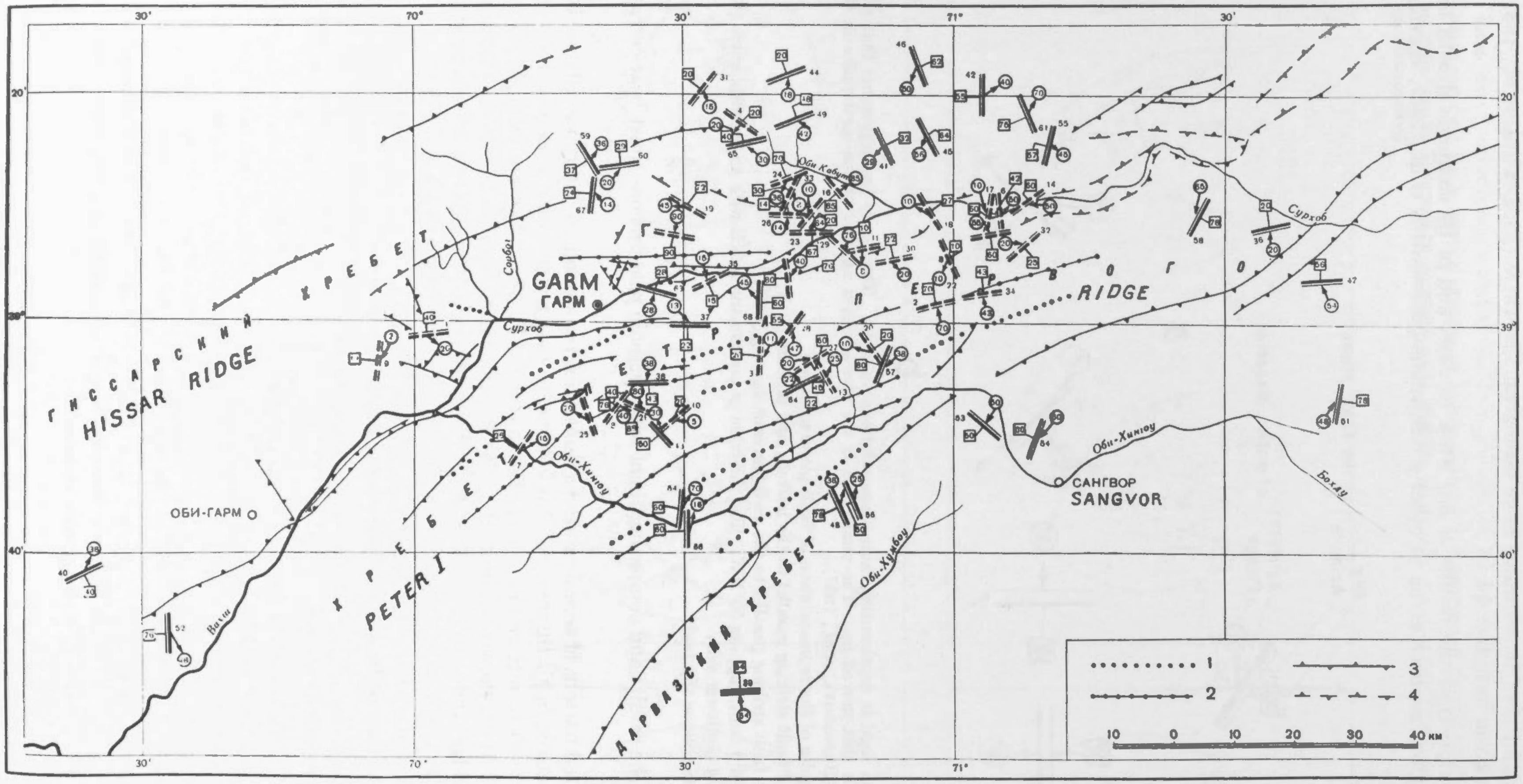

Figure 8. Fault-plane solutions for the Garm region. Legend:

1. Synclinal axes.
2. Anticlinal axes.
3. Tectonic ruptures.
4. Supposed tectonic ruptures. Solid lines represent comparatively strong earthquakes (1952-1954), recorded by local stations, dashed lines represent weaker earthquakes (1950) recorded by temporary stations.

(Interpretations made by T. I. Kukhtikova, S. D. Kogan, and L. N. Malynovskaya; tectonic data from I. E. Gubin; epicentres determined by T. I. Kukhtikova, I. L. Nersesov, and N. V. Fokina).

We shall describe here only some general patterns which seem to be sufficiently reliable.

(a) Faults of individual weak earthquakes do not usually show any correlation with local structure near the epicentre, this local structure often being so complicated that any correlation would be arbitrary. However, considering large areas, zones may usually be distinguished in which the faults have much in common, prevalent strikes, dip directions or the character of

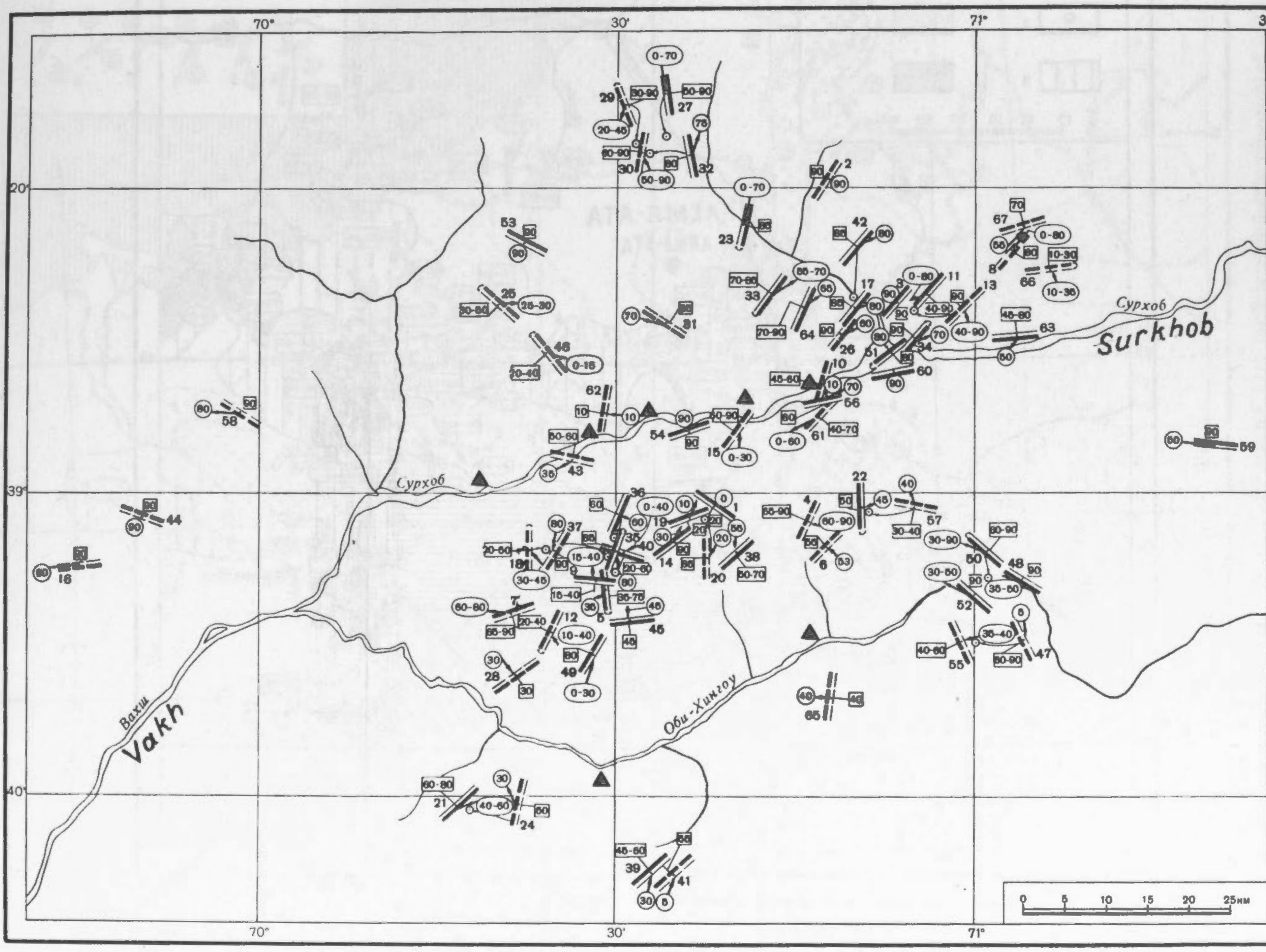

Figure 9. Fault-plane solutions for the Garm region derived from the observations of special expeditions made in 1955 and January and February of 1956. (Interpretation by L. N. Malinovskaya, G. I. Pavlova, and E. N. Bessonova; epicentres by I. L. Nersesov and T. I. Rautian).

motion being the same. Such zones coincide with large tectonic complexes, the prevailing properties of the faults being very different for different complexes. There is thus a clear correlation between earthquake faulting and tectonics, although the depth of the tectonic structures seems to be less than the focal depths of the earthquakes. This suggests that the formation of large tectonic complexes is not merely a surface phenomenon but proceeds to depth, and that earthquakes and these structures are parallel manifestations of a general process of the earth's crustal development.

(b) Eliminating, at first only qualitatively, the influence of the 'selectivity' of the stations, we can establish the fact that in the Askabad uplands and in the Garm district the prevalent fault strikes are nearly longitudinal to the main tectonic features. In many other regions two strikes can be noted, one longitudinal and the other transverse to the tectonic features. However, until the necessary statistical analysis has been applied it is not possible to say which is the more important.

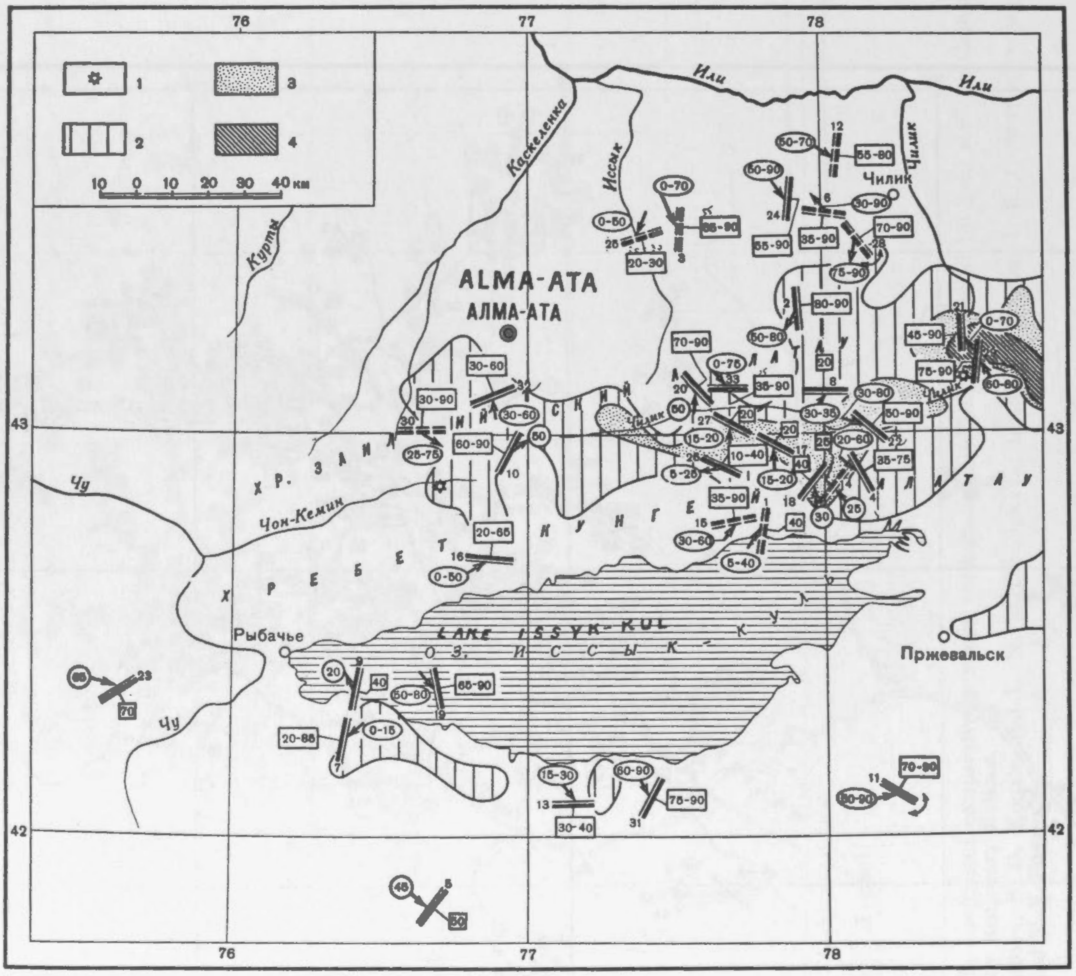

Figure 10. Fault-plane solutions for northern Tien-Shan. Legend:
1. Epicentres of strong earthquakes;
2, 3, 4. Contours giving the density of epicentres per 100 sq. km., 2 to 3, 4 to 6 and 7 to 13 respectively. (Interpretation by L. N. Malinovskaya; densities of epicentres according to N. V. Vvedenskaya; epicentres by T. M. Gorbunova, A. A. Fogel).

(c) It seems that intense horizontal motion direction components and, less definitely, transverse fault strikes are observed more often in fault-plane work than in the field. This has already been noted by Hodgson, Scheidegger, Ritsema and Byerly. This agrees with some data from geotectonics (Wegmann, 1955) concerning modern geological movements.

(d) In the foci of some districts the fault-plane strikes are parallel to the boundaries of tectonic depressions and upheavals, but that side of the fault which is nearer to the depression moves upward during the earthquake. This agrees with geological and geodetic data concerning motion direction at sources in Japan. There the vertical motion directions in the sources of earthquakes are directed opposite to the secular ones (Kobayashi, 1955), as if the earthquake were attempting to compensate for the secular change.

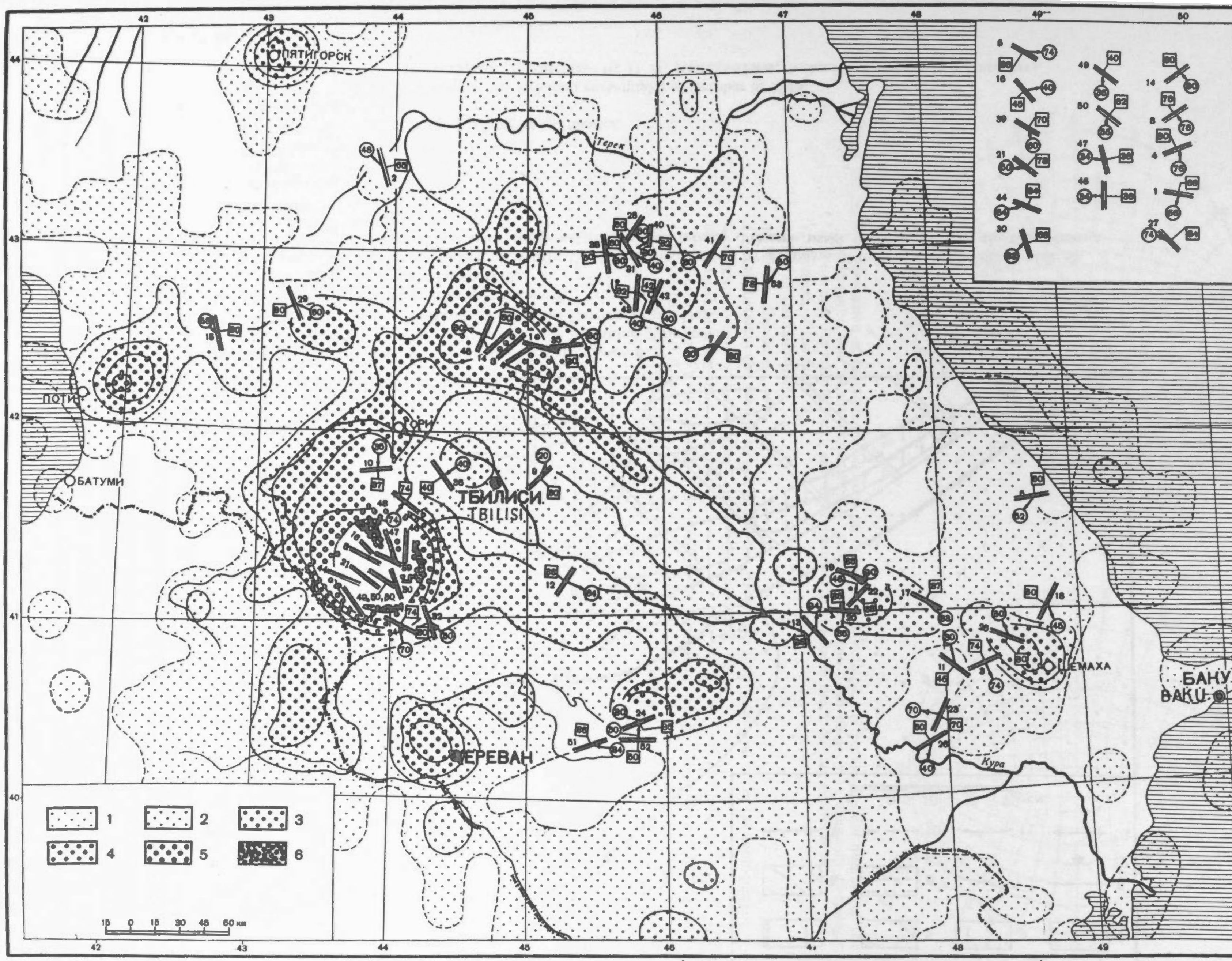

Figure 11. Fault-plane solutions for the Caucasus. For the sources of the Akhalkalaky upland, each fault is completely represented in the insert at top right. (Interpretation by O. D. GOTSADZE and L. N. MALINOVSKAYA; density of epicentres (after I. V. KIRILLOVA), per 900 km^2: 1—1 to 5; 2—6 to 10; 3—11 to 20; 4—21 to 30; 5—31 to 40; 6—40).

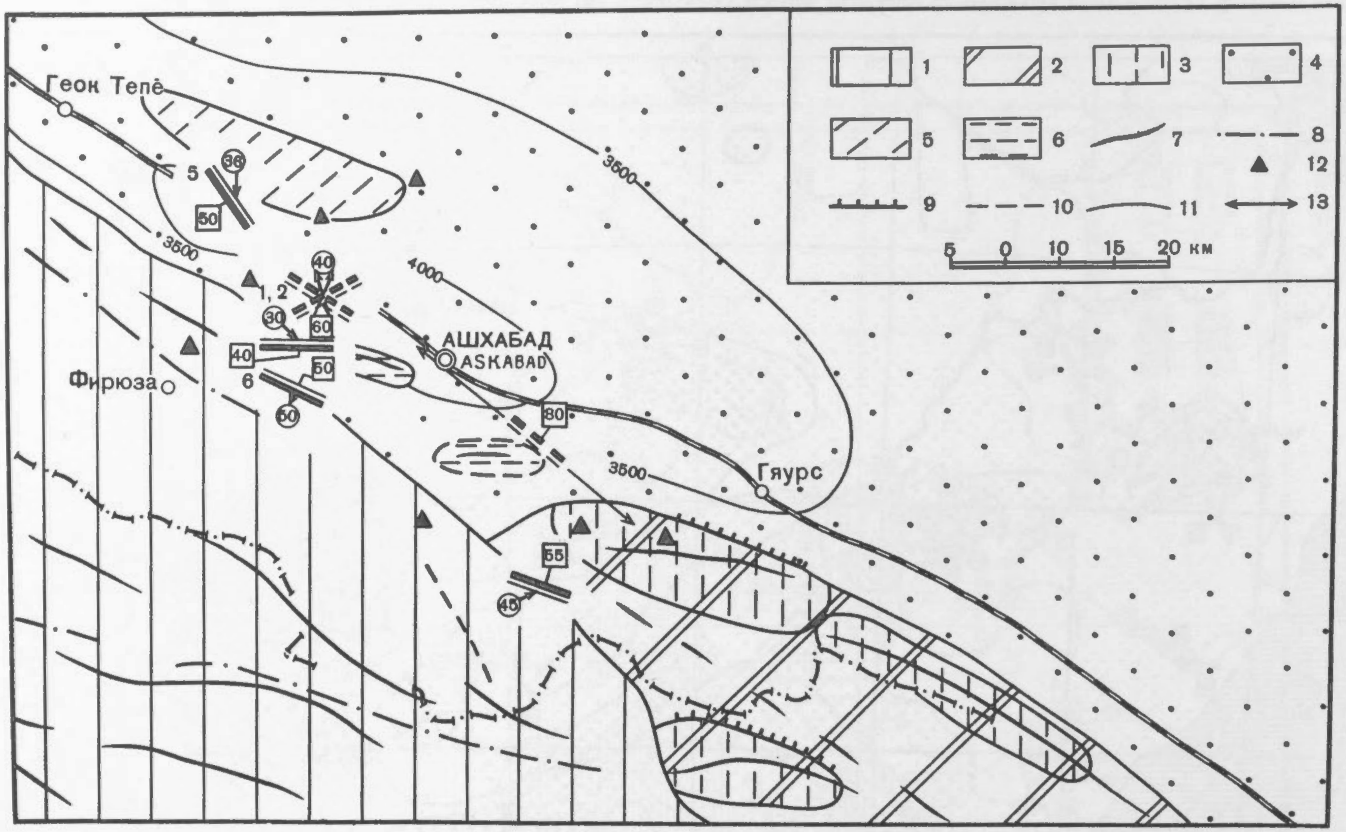

Figure 12. Fault-plane solutions for Askabad region. Legend:

1. Kopet-Dag anticlinorium (formed at the beginning of neogen).
2. Younger (the end of neogen) zone of the Eastern Kopet-Dag.
3. Large anticlinal structures within zone 2.
4. Trough in the Kopet-Dag foothills.
5. Gently sloping brachy-anticlinal within the trough determined by geophysical methods at the depth of 2—3.
6. Exposed brachy-anticlinal folds composed of the Quarternary Pliocene rocks. Formed during the Quarternary period.
7. Anticlinal axes.
8. Synclinal axes.
9. Thrusting lines.
10. Faults.
11. Isolines of the top of the Cretaceous sediments.
12. Seismic stations.
13. Axis of the epicentral zone of the Askabad earthquake of October 3, 1948.

(Interpretation by O. D. Gotzadze; hypocentres by D. N. Rustanovich; tectonic scheme by I. A.Rezanov).

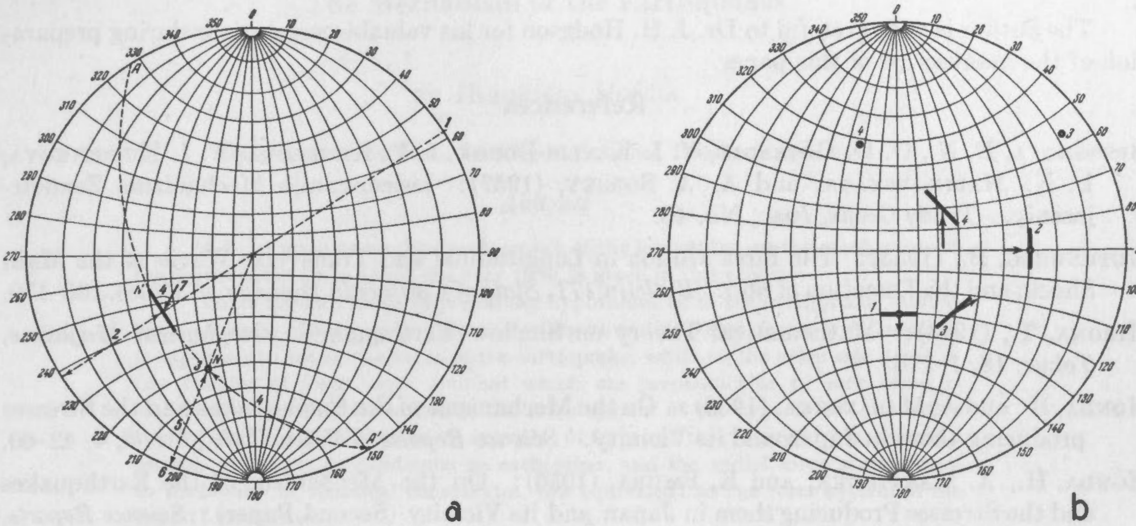

Figure 13. a. Representation of fault-plane solutions on summary projections. N represents the number of the earthquake, AA′ is the stereographic projection of the fault-plane (the summary projection shows only its middle part), and the numbered points have the following significance:

1. Azimuth of the fault dip.
2. Dip of the fault plane.
3. Motion direction.
4. Angle between the motion direction and the strike direction (measured off in the fault-plane).
5. Angle between the motion direction and the horizontal plane.
6. Azimuth of the motion direction.
7. The arrow is put near the wall of the fault moving upwards. Its projection to AA′ is directed to the motion direction.

b. Examples of fault-planes on summary projections. The numbers refer to the same fault-planes shown in Figure 7b.

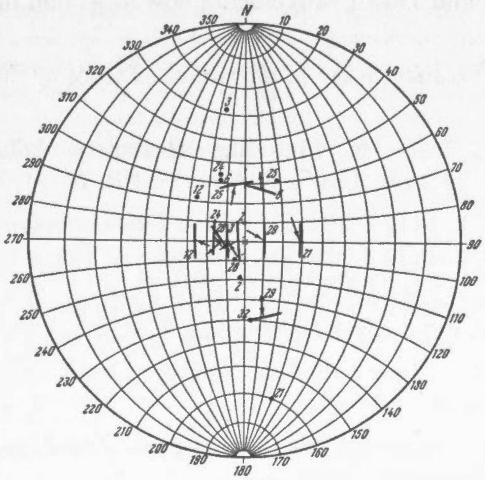

Figure 14. Summary of fault-plane solutions for northern Tien-Shan, the area to the north of the Zailiysky Ala-Tau ridge shown in Figure 10.

CONCLUSION

The main purpose of the study of earthquake mechanism is to look into the laws of the geotectonic development of the earth. One of the principal problems of further work is studying dislocation systems at foci in regions with various tectonic developments. While the different authors have their own particular methods and interests it is very encouraging for the coordination of further work that they are keeping in close touch, and that their methods are growing nearer.

The author is very grateful to Dr. J. H. Hodgson for his valuable suggestions during preparation of the manuscript of this paper.

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The Mechanism of the Earthquakes

BY HIROKICHI HONDA

Geophysical Institute, Faculty of Science, Tôhoku University

Abstract

A brief account on the development of the knowledge on the mechanism of the earthquakes since about the year 1930, is given in this report.

There are two kinds of prevailing hypotheses as to the earthquake mechanism. In one of them, a couple of two equal and opposite forces with moment is supposed to act at the focus of the earthquake, while in the other one a set of two couples of forces with moment which are perpendicular to each other is assumed. We will call the former the force system of the type I, and the latter that of the type II. A set of two couples of forces of the nature of pressure and tension which are perpendicular to each other, and the radial force proportional to $\sin 2\theta \cos\varphi$ in spherical coordinates, are equivalent to the force system of the type II respectively.

The distribution of the direction and magnitude of the initial motion of the P, S and ScS waves of the near deep and intermediate earthquakes, observed in Japan can be explained by the theories based on the assumption that the force system of the type II acts at the origin in an infinite elastic solid. The directions of the pressure of the stresses causing the earthquakes seem to be directed perpendicularly to the trends of the deep and intermediate earthquake zones in and near Japan. For the investigation of the P, S and surface waves and the deformation of the earth's surface observed in the cases of very shallow earthquakes occurred in Japan, the theories for the force system of the nature of the type II or the radial force proportional to $\sin 2\varphi$ in cylindrical coordinates, acting at the origin on the surface of a semi-infinite elastic solid, have been applied.

The stereographic projection methods which are appropriate for the investigation of the earthquake mechanism based on the observations at the stations distributed over the world, have been proposed and developed by P. BYERLY and J. H. HODGSON, and applied to the studies of numerous earthquakes by many seismologists, the force system of the type I being assumed as the basis of the investigation. The plane bisecting the couple of forces is considered to be the fault plane. The relations between the strikes and dips of the fault planes, the motion directions along the fault planes and the geological features, are investigated.

According to the theories on the elastic waves, the patterns of the initial motions of the P waves for the force systems of the types I and II, are the same to each other. As the differences of the effects of the force systems are to be noticed in the patterns of the S waves, it is desired that the S waves observed at the distant stations may be investigated further in detail.

1 Introduction

One of the most important problems in seismology may be the investigation of the mechanism of the earthquakes or the nature of the stresses producing the earthquakes, being based on the observations of the seismic waves. After F. OMORI and

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T. Shida, the studies in this line have been carried out by many seismologists, and the progresses of the researches up to about 1935 were summarized for example by H. Kawasumi (1937) in his historical sketch on the problem.

In the present paper, the author intends to state the development of knowledge concerning the problem since about 1930, the greater part of the earlier studies described in Kawasumi's summary being not mentioned here. The mathematical theories on the mechanism of the earthquakes are recapitulated in Chap. 2. The results of the investigations of the mechanism of the earthquakes occurred in Japan, based mainly on the seismological data obtained at near stations, are summarized in Chap. 3 An account on the development of the studies of the problem, made by P. Byerly, J.H. Hodgson and others, based on the data obtained at the stations distributed over the world, is described in Chap. 4. And some discussions on the problem are stated in the concluding remarks, Chap. 5.

2 Mathematical Theories

Some mathematical theories which concern with the generation of the elastic waves from the source in an infinite elastic solid or on a semi-infinite elastic solid, and are related directly with the study of the mechanism of the earthquakes, are recapitulated in the present chapter.

2-1. Infinite Elastic Solid. H. Nakano (1923) and T. Matsuzawa (1926) investigated theoretically the propagation of the elastic waves generated by the force systems of various types applied at a point in an infinite elastic solid; some of their results of calculation were recapitulated by Honda *et al.*, (1956).

Let us suppose at first that two equal and opposite forces of the magnitude $K\exp(i\omega t)/\varepsilon$ act in the direction of the x-axis, at the points $y=\varepsilon/2$ and $-\varepsilon/2$ on the y-axis, as are illustrated in Fig. 1, and name the force system that of the type I. And next suppose that two couples of these force systems act simultaneously at the origin in the directions of the x- and y-axes, as are shown in Fig. 2 (a), and name the force system that of the type II. The force system of the type II is equivalent to the set of two couples of forces of the nature of pressure and tension, as are shown in Fig. 2 (b), where the x'-axis bisects the angle xoy. We take the y-axis as the polar axis of the spherical coordinates r, θ, φ (Fig. 3), and denote the r, θ, φ-components of displacement by δ_r, δ_θ, δ_φ, the motion propagated with

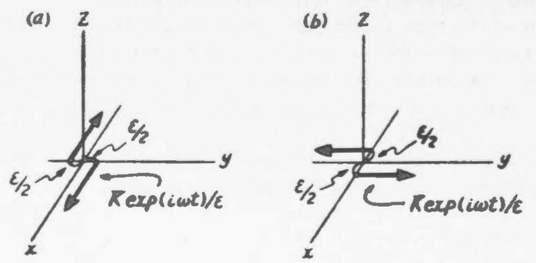


Fig. 1. The force system of the type I.

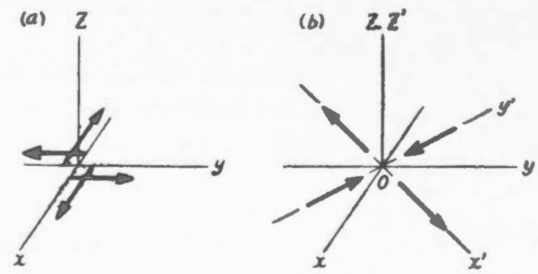


Fig. 2. The force system of the type II.

the velocity (v_p) of the P waves and that (v_s) of the S waves by p and s, the Lamé's constants by λ and μ, and the density by ρ. The displacement components of motion at large distances from the origin, produced by the force system of the type I or II are expressed as follows, in the limiting case when $\varepsilon \to 0$:

For the force system of the type I, we have,

$$\left.\begin{aligned}
\delta_{p,r} &= \frac{K}{4\pi}\frac{1}{v_p}\frac{1}{\lambda+2\mu}\frac{1}{2}\sin 2\theta\cos\varphi\frac{1}{r} \\
&\qquad \times\omega\exp\left\{i\omega\left(t-\frac{r}{v_p}\right)+i\frac{\pi}{2}\right\}, \\
\delta_{s,\theta} &= \frac{K}{4\pi}\frac{1}{v_s}\frac{1}{\mu}\cos^2\theta\cos\varphi\frac{1}{r} \\
&\qquad \times\omega\exp\left\{i\omega\left(t-\frac{r}{v_s}\right)+i\frac{\pi}{2}\right\}, \\
\delta_{s,\varphi} &= -\frac{K}{4\pi}\frac{1}{v_s}\frac{1}{\mu}\cos\theta\sin\varphi\frac{1}{r} \\
&\qquad \times\omega\exp\left\{i\omega\left(t-\frac{r}{v_s}\right)+i\frac{\pi}{2}\right\},
\end{aligned}\right\} \qquad \text{(1)}^{(65)} \text{ (Type I)}$$

$$\delta_{p,\theta} = \delta_{p,\varphi} = \delta_{s,r} = 0\ ,$$

$$\frac{1}{v_s}\frac{1}{\mu}\Big/\frac{1}{2}\frac{1}{v_p}\frac{1}{\lambda+2\mu} \doteqdot 10.40\ , \quad (\text{for } \lambda=\mu)$$

For the force system of the type II, we have

$$\left.\begin{aligned}
\delta_{p,r} &= \frac{K}{4\pi}\frac{1}{v_p}\frac{1}{\lambda+2\mu}\sin 2\theta\cos\varphi\frac{1}{r} \\
&\qquad \times\omega\exp\left\{i\omega\left(t-\frac{r}{v_p}\right)+i\frac{\pi}{2}\right\}, \\
\delta_{s,\theta} &= \frac{K}{4\pi}\frac{1}{v_s}\frac{1}{\mu}\cos 2\theta\cos\varphi\frac{1}{r} \\
&\qquad \times\omega\exp\left\{i\omega\left(t-\frac{r}{v_s}\right)+i\frac{\pi}{2}\right\}, \\
\delta_{s,\varphi} &= -\frac{K}{4\pi}\frac{1}{v_s}\frac{1}{\mu}\cos\theta\sin\varphi\frac{1}{r} \\
&\qquad \times\omega\exp\left\{i\omega\left(t-\frac{r}{v_s}\right)+i\frac{\pi}{2}\right\},
\end{aligned}\right\} \qquad \text{(2)}^{(65)} \text{ (Type II)}$$

$$\delta_{p,\theta} = \delta_{p,\varphi} = \delta_{s,r} = 0\ ,$$

$$\frac{1}{v_s}\frac{1}{\mu}\Big/\frac{1}{v_p}\frac{1}{\lambda+2\mu} \doteqdot 5.20\ , \quad (\text{for } \lambda=\mu)\ .$$

When we suppose that the radial force $F_r = F\sin 2\theta\cos\varphi\exp(i\omega t)$, Fig. 4, acts on the surface of the small spherical cavity of the radius a or the *model sphere* constructed around the origin, the displacement components at large distances from the origin in the limiting case when $a \to 0$, are given by

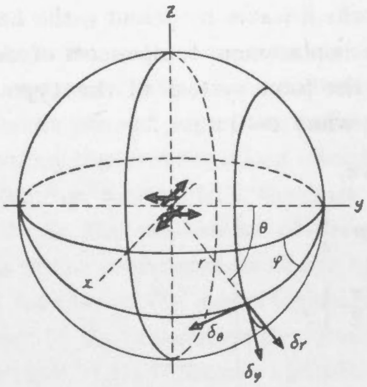


Fig. 3. The spherical coordinates.

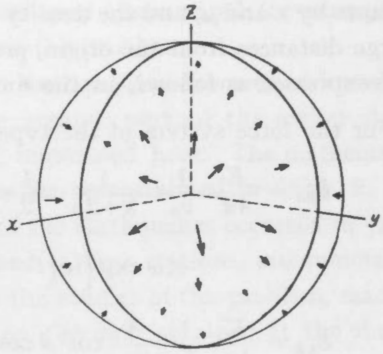


Fig. 4. $F_r/\exp(i\omega t) = F\sin 2\theta\cos\varphi$.[65]

$$
\left.
\begin{aligned}
\delta_{p,r} &= D\sin 2\theta\cos\varphi\,\frac{1}{r} \\
&\qquad \times\exp\left\{i\,\omega\left(t-\frac{r}{v_p}\right)+i\,\frac{\pi}{2}\right\}, \\
\delta_{s,\theta} &= \left(\frac{k}{h}\right)^3 D\cos 2\theta\cos\varphi\,\frac{1}{r} \\
&\qquad \times\exp\left\{i\,\omega\left(t-\frac{r}{v_s}\right)+i\,\frac{\pi}{2}\right\}, \\
\delta_{s,\varphi} &= -\left(\frac{k}{h}\right)^3 D\cos\theta\sin\varphi\,\frac{1}{r} \\
&\qquad \times\exp\left\{i\,\omega\left(t-\frac{r}{v_s}\right)+i\,\frac{\pi}{2}\right\},
\end{aligned}
\right\} \qquad (3)^{(65)}
$$

$$
D = a^3F\,\frac{h^3}{6\mu k^2+3\lambda h^2-2\mu h^2}\,, \quad h=\frac{\omega}{v_p}\,, \quad k=\frac{\omega}{v_s}\,.
$$

For $\lambda=\mu$, (3) can be expressed as follows;

$$
\left.
\begin{aligned}
\delta_{p,r} &= A_1\sin 2\theta\cos\varphi\,\frac{1}{r} \\
&\qquad \times\omega\exp\left\{i\,\omega\left(t-\frac{r}{v_p}\right)+i\,\frac{\pi}{2}\right\}, \\
\delta_{s,\theta} &= 5.20\,A_1\cos 2\theta\cos\varphi\,\frac{1}{r} \\
&\qquad \times\omega\exp\left\{i\,\omega\left(t-\frac{r}{v_s}\right)+i\,\frac{\pi}{2}\right\} \\
\delta_{s,\varphi} &= -\,5.20\,A_1\cos\theta\sin\varphi\,\frac{1}{r} \\
&\qquad \times\omega\exp\left\{i\,\omega\left(t-\frac{r}{v_s}\right)+i\,\frac{\pi}{2}\right\},
\end{aligned}
\right\} \qquad (3')^{(65)}
$$

$$
A_1 = \frac{1}{19\sqrt{3}}\,\frac{1}{\mu^{3/2}}\,\rho^{1/2}a^3F\,, \quad \left(\frac{k}{h}\right)^3 \doteq 5.20\,.
$$

The expressions (3′) are quite similar to (2). The force system illustrated in Fig. 4 is essentially equivalent to that of the type II shown in Fig. 2 (a) or (b), in the effects of producing the P as well as S waves. The direction of the maximum tension ($\theta=\pi/4$, $\varphi=0$ — $\theta=3\pi/4$, $\varphi=\pi$) and that of the maximum pressure ($\theta=3\pi/4$, $\varphi=0$ — $\theta=\pi/4$, $\varphi=\pi$) in the force system shown in Fig. 4, correspond to the directions of the forces of the nature of tension and pressure illustrated in Fig. 2 (b).

The rates of the energies e_p and e_s of the P and S waves expressed by (3′), which are propagated outward across a large spherical surface constructed around the origin, are expressed as follows (HONDA, 1951);

$$e_p=\frac{32\pi^3}{15}\frac{\rho v_p}{T^2}A_1^2\,,\qquad e_s=\frac{48\pi^3}{15}\frac{\rho v_s}{T^2}(5.20\,A_1)^2\,,\qquad T=\frac{2\pi}{\omega}\,. \tag{4}$$ (59)

When the force is not periodic but of shock type and is assumed to vary with time according to the expression $f(t)=1/(t^2+c^2)$, c being a positive constant, Fig. 5 (a), the corresponding displacement components are obtained by performing the operation

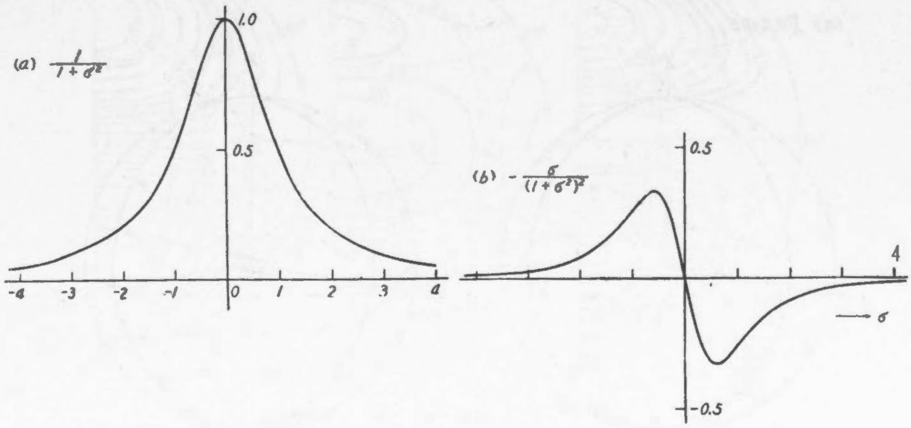


Fig. 5. $1/(1+\sigma^2)$ and $-\sigma/(1+\sigma^2)^2$.(65)

$$\frac{1}{\pi}\,Re\int_0^\infty d\omega\int_{-\infty}^{\infty}f(\alpha)\exp(-i\,\omega\,\alpha)\,d\alpha$$

to the expressions of δ obtained for the periodic forces. All the expressions (1), (2) and (3′) contain the same factor $\omega\exp\{i\omega(t-r/v)+i\pi/2\}$ as to ω, v being v_p or v_s according to the terms concerned, and we have

$$\frac{1}{\pi}\,Re\int_0^\infty \omega\,d\,\omega\int_{-\infty}^{\infty}\frac{1}{\alpha^2+c^2}\exp\left[-i\omega\left\{\alpha-\left(t-\frac{r}{v}\right)+i\frac{\pi}{2}\right\}\right]d\alpha$$

$$=-\frac{2}{c^3}\frac{\sigma}{(1+\sigma^2)^2}\,,\qquad \sigma=\frac{1}{c}\left(t-\frac{r}{v}\right). \tag{5}$$ (65)

The variation of $-\sigma/(1+\sigma^2)^2$ with σ, Fig. 5 (b), shows that the motions propagated with the velocities v_p and v_s for the aperiodic case, consist of a single to and fro movement respectively. The patterns of the distribution with respect to θ and φ of the direction and magnitude of the initial motion of the P and S waves for the impulsive force systems of the types I and II, are expressed by following formulae,

$$\left.\begin{array}{ll} (\delta_{p,r})_{\mathrm{I}} \cdots\cdots\cdots & \frac{1}{2}\sin 2\theta\cos\varphi\,, \\ (\delta_{s,\theta})_{\mathrm{I}} \cdots\cdots\cdots & \cos^2\theta\cos\varphi\,, \\ (\delta_{s,\varphi})_{\mathrm{I}} \cdots\cdots\cdots & -\cos\theta\sin\varphi\,, \end{array}\right\} \begin{array}{c}(6)\\ \text{(Type I)}\end{array}$$

for the force system of the type I, and

$$\left.\begin{array}{ll} (\delta_{p,r})_{\mathrm{II}} \cdots\cdots\cdots & \sin 2\theta\cos\varphi\,, \\ (\delta_{s,\theta})_{\mathrm{II}} \cdots\cdots\cdots & \cos 2\theta\cos\varphi\,, \\ (\delta_{s,\varphi})_{\mathrm{II}} \cdots\cdots\cdots & -\cos\theta\sin\varphi\,, \end{array}\right\} \begin{array}{c}(7)\\ \text{(Type II)}\end{array}$$

for the force system of the type II, and are illustrated in Fig. 6 (a) and (b). The initial motion of the P waves is condensational and rarefactional in alternate zones bounded by two planes which are perpendicular to each other, in both cases I and II. The

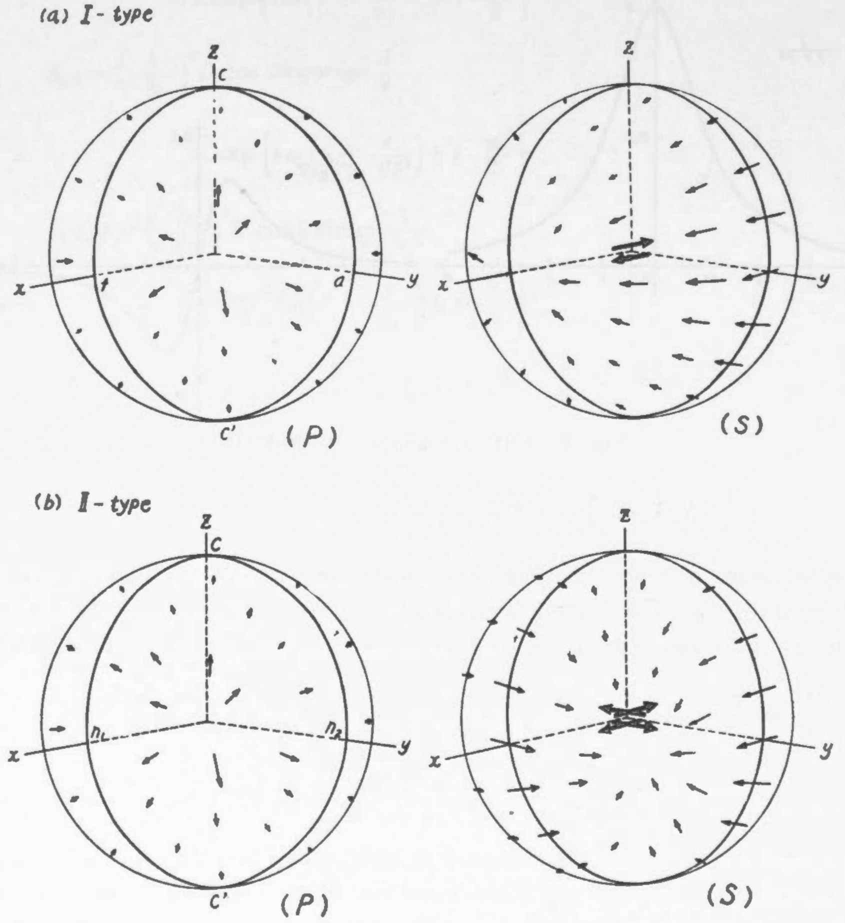


Fig. 6. The initial motion of the P and S waves; (a) for the force system of the type I, and (b) for that of II [65]

plane cfc' in Fig. 6 (a) is called 'the fault plane' and the plane cac' 'the auxiliary plane', and the direction of the forces 'the motion direction'. No distinction between the planes cfc' and cac' can be found, as far as only the initial motion of the P waves are concerned. The planes cn_1c' and cn_2c' in Fig. 6 (b) are the nodal planes for the P waves. The magnitude of the S waves is maximum in the auxiliary plane and minimum in the fault plane in the case I, whereas it is maximum in both nodal planes in the case II. The difference between the cases I and II, can be noticed in the distribution of the direction and magnitude of the initial motion of the S waves.

In order to illustrate the distribution with respect to θ and φ of the magnitude of the P and S waves emitted from the source for the case II, the values of $[P]=\sin 2\theta \cos\varphi$, $[S]=5.20\sqrt{(\cos 2\theta\cos\varphi)^2+(\cos\theta\sin\varphi)^2}$ and $[S]/[P]$ are shown in Fig. 7. The amplitude of the S waves is in general larger than that of the P waves except

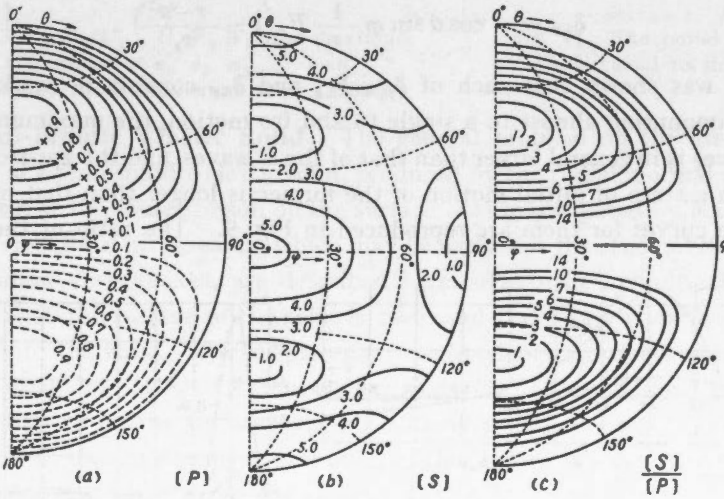


Fig. 7. $[P]$, $[S]$ and $[S]/[P]$.[51]

near the azimuths ($\theta=\pi/4$, $\varphi=0$; $\theta=3\pi/4$, $\varphi=0$; ......), where $[P]$ is maximum and $[S]$ is minimum (HONDA, 1934).

When the radius of the model sphere, whose surface is assumed to be subjected to the radial force $F_r=F\sin 2\theta\cos\varphi\exp(i\omega t)$, is not very small compared with the wave length l_p of the P waves, the ratio of the coefficients of the amplitude of the S waves to that of the P waves in (3') is not 5.20, but $5.20R$ for $\lambda=\mu$. The values of R for various values of a/l_p are shown in Fig. 8. (HONDA and T. MIURA, 1938). The amplitude of the S waves becomes even smaller than that of the P waves, when a/l_p is larger than a certain value. The general cases in which the radius of the model sphere is not very small and the force is impulsive instead of

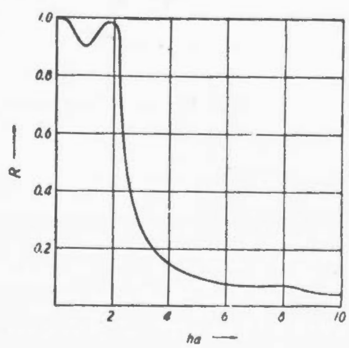


Fig. 8. R and $hc=2\pi a/l_p$.[56]

periodic, were treated by G. NISHIMURA and T. TAKAYAMA (1938) When the conditions at the surface of a spherical cavity of the radius a are given as follows,

$$\widehat{(rr)}_{r=a} = -Pf(t)\sin 2\theta\cos\varphi\,,\quad \widehat{(r\theta)}_{r=a} = \widehat{(r\varphi)}_{r=a} = 0\,,$$

$$\begin{aligned} f(t) &= t/t_m \cdot \exp(1 - t/t_m)\,, &&\text{for } t \geqq 0\,,\ t_m: \text{a positive constant,} \\ &= 0 &&,\ \text{for } t < 0\,, \end{aligned}$$

the displacement components are expressed as following;

$$\left.\begin{aligned} \delta_{p,r} &= \sin 2\theta\cos\varphi\frac{1}{r}F_1\left(t - \frac{r-a}{v_p}\right)\,, \\ \delta_{s,\theta} &= \cos 2\theta\cos\varphi\frac{1}{r}F_2\left(t - \frac{r-a}{v_s}\right)\,, \\ \delta_{s,\varphi} &= -\cos\theta\sin\varphi\frac{1}{r}F_2\left(t - \frac{r-a}{v_s}\right)\,. \end{aligned}\right\} \qquad (8)$$

And it was shown that each of $\delta_{p,r}$, $\delta_{s,\theta}$ and $\delta_{s,\varphi}$ consists of marked damped oscillation amounting almost to a single to and fro motion, the maximum amplitude of the S waves is in general larger than that of the P waves, and the apparent period of vibration in a state of initial motion of the former is longer than that of the latter. Some of the curves for them are reproduced in Fig. 9. The ratio of the maximum

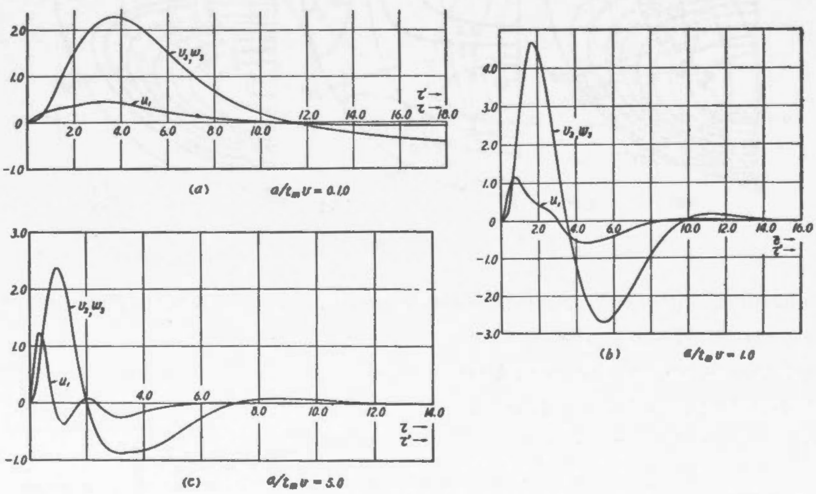


Fig. 9. $u_1 = F_1(\tau)$ and v_3, $w_3 = F_2(\tau')$. $\tau = t - (r-a)/v_p$, $\tau' = t - (r-a)/v_s$, $v = v_p$.
(After NISHIMURA *et al.*, 1938.)

amplitude of $\delta_{s,\theta}$ or $\delta_{s,\varphi}$ to that of $\delta_{p,r}$ is shown in Fig. 10; the ratio is maximum amounting to about 5.4 when $a/t_m v_p$ is small being less than unity, and it becomes very small especially when $a/t_m v_p$ exceeds 15.

The problems on the generation of the elastic waves in an infinite elastic solid from the source subjected to various prescribed forces have been investigated also by M. HASEGAWA (1930), H. JEFFREYS (1931), K. SEZAWA and K. KANAI (1932, 36, 41,42), KAWASUMI and R. YOSIYAMA (1935), SEZAWA (1935), G. NISHIMURA (1937),

W. INOUYE (1936,37,38), J.A. SHARPE (1942), BYERLY, A.I. MEI and C. ROMNEY (1949), Y. SATÔ (1949.50), S. HOMMA (1952), J. VANĚK (1953), P.A. HEELAN (1953), T. USAMI and T. HIRONO (1956), Z. DROSTE (1956), and R. TEISSEYRE (1956).

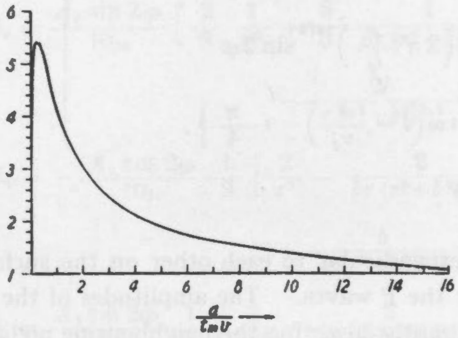


Fig. 10. $V_3, W_3/U_1$. U_1, V_3, W_3: the maximum amplitudes of u_1, v_3, w_3. $v=v_p$. (After NISHIMURA *et al.*, 1938.)

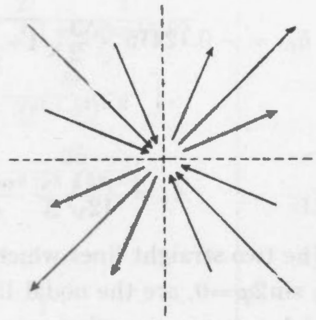


Fig. 11. The radial force proportional to $\sin 2\varphi$.

2-2. Semi-infinite Elastic Solid. The general problem on the disturbances at the surface of a semi-infinite elastic solid, produced by the radial, normal or transverse forces applied at the source region on the surface, was investigated by NAKANO (1930). Some of the results of his research, which may be useful for the study of the mechanism of very shallow earthquakes, are described here. Take the cylindrical coordinates (r, φ, z) so that the surface of the solid is $z=0$, and the z-axis is directed vertically downward into the solid. The displacement components are denoted by δ_r, δ_φ and δ_z. The periodic radial force $Ar^3 \sin 2\varphi \exp(i\omega t)$, Fig. 11, is assumed to be applied in the domain $r<\bar{r}$ on the surface, where $\bar{r}$ is smaller than the wave length l_p of the P waves. Then the displacement of motion of the surface is represented by the sum of three kinds of displacements which consist of δ_p, δ_s and δ_3 propagated with the velocities v_p, v_s and v_3 (v_3; the velocity of the Rayleigh waves) respectively. For the case $\lambda=\mu$, we have

$$\left.\begin{aligned}
\delta_{p,r} &= 6.9282\, A_1\left(2\pi\frac{r}{l_p}\right)^{-2}\sin 2\varphi \exp\left\{i\omega\left(t-\frac{r}{v_p}\right)\right\},\\
\delta_{p,\varphi} &= O\left(2\pi\frac{r}{l_p}\right)^{-3},\\
\delta_{p,z} &= -\,2.4494\, A_1\left(2\pi\frac{r}{l_p}\right)^{-2}\sin 2\varphi \exp\left\{i\omega\left(t-\frac{r}{v_p}\right)\right\},
\end{aligned}\right\} \qquad (9)$$

$$\left.\begin{aligned}
\delta_{s,r} &= O\left(2\pi\frac{r}{l_p}\right)^{-2},\\
\delta_{s,\varphi} &= -0.2887\times 3^{1/2}A_1\left(2\pi\frac{r}{l_p}\right)^{-1}\cos 2\varphi \exp\left\{i\omega\left(t-\frac{r}{v_s}\right)-i\frac{\pi}{2}\right\},\\
\delta_{s,z} &= O\left(2\pi\frac{r}{l_p}\right)^{-2},
\end{aligned}\right\} \qquad (10)$$

$$\delta_{3,r} = 0.08459\times\frac{3}{2}\sqrt{1+\frac{1}{\sqrt{3}}}\,A_1\left(2\pi\frac{r}{l_p}\right)^{-1/2}\sin 2\varphi\times$$

$$
\left.
\begin{aligned}
&\times \exp\left\{i\omega\left(t-\frac{r}{v_3}\right)+i\,\frac{\pi}{4}\right\},\\
\delta_{3,\varphi} &= O\left(2\pi\,\frac{r}{l_p}\right)^{-3/2},\\
\delta_{3,z} &= -\,0.12415\times\frac{3}{2}\sqrt{1+\frac{1}{\sqrt{3}}}\,A_1\left(2\pi\,\frac{r}{l_p}\right)^{-1/2}\sin 2\varphi\\
&\times \exp\left\{i\omega\left(t-\frac{r}{v_3}\right)-i\,\frac{\pi}{4}\right\},\\
A_1 &= \frac{1}{12\sqrt{3}}\,\frac{\omega^2\rho}{\mu^2}\,A\,\bar{r}^6 .
\end{aligned}
\right\}
\qquad (11)
$$

The two straight lines which are perpendicular to each other on the surface for which $\sin 2\varphi=0$, are the nodal lines for the P waves. The amplitudes of the P and Rayleigh waves are maximum in the azimuths bisecting the neighbouring nodal lines, whereas that of the S waves is maximum in the azimuths along the nodal lines.

HIRONO (1948, 49) investigated theoretically the propagation of the elastic waves in a semi-infinite elastic solid, which are produced from the source on the surface of the solid. When the radial force $\Pi_2(r)\cos 2\varphi\exp(i\omega t)$ is assumed to act in the region within a small circle of radius r_0 ($r_0 \ll l_p$) on the surface, the displacement component δ_R along the direction of R ($R=\sqrt{r^2+z^2}$), δ_θ along that of θ ($\tan\theta=r/z$), and δ_φ are given as following;

$$
\left.
\begin{aligned}
\delta_{p,R} &= -\,2A_2\,\frac{\cos\theta\sin^2\theta\sqrt{n^2-\sin^2\theta}}{D(\cos\theta)}\cos 2\varphi\\
&\times\frac{1}{kR}\exp\left\{i\omega\left(t-\frac{R}{v_p}\right)\right\},\\
\delta_{s,\theta} &= -\,n^2A_2\,\frac{\cos\theta\sin\theta\,(2\cos^2\theta-1)}{E(\cos\theta)}\cos 2\varphi\\
&\times\frac{1}{kR}\exp\left\{i\omega\left(t-\frac{R}{v_s}\right)\right\},\\
\delta_{s,\varphi} &= n^2A_2\sin\theta\sin 2\varphi\,\frac{1}{kR}\exp\left\{i\omega\left(t-\frac{R}{v_s}\right)\right\},
\end{aligned}
\right\}
\qquad (12)
$$

$$D(\cos\theta) = (n^2-2\sin^2\theta)^2+4\cos\theta\sin^2\theta\sqrt{n^2-\sin^2\theta}\ ,$$

$$E(\cos\theta) = (2\sin^2\theta-1)^2+4\cos\theta\sin^2\theta\sqrt{1/n^2-\sin^2\theta}\ ,$$

$$A_2 = -\,\frac{h^2}{\mu}\,\frac{i}{4}\int_0^{r_0}\Pi_2(r)\,r^2dr\ ,\qquad n=\sqrt{\frac{\lambda+2\mu}{\mu}}\ .$$

The dip angular distribution of $P=\delta_{p,r}$, $S_1=-\delta_{s,\theta}$ and $S_2=\delta_{s,\varphi}$, Fig. 12, are shown in Fig. 13 for the case $\lambda=\mu$. The cases in which the applied forces are not periodic but aperiodic of shock type, were studied also by HIRONO.

The deformation of a semi-infinite elastic solid by the statical force applied at the surface of it, was investigated by HONDA and MIURA (1935). The problem may be related to the study of the deformation of the earth's surface which is sometimes observed in severe very shallow earthquakes. When the radial statical force $F_r=$

$A_2\{r^3/(r^2+b^2)^{7/2}\}\sin 2\varphi$ is assumed to act on the surface, the displacement components δ_r, δ_φ and δ_z of the statical deformation at the surface, are expressed as following for the case $\lambda=\mu$;

$$\left.\begin{aligned}
\delta_r &= \frac{A_2\sin 2\varphi}{10\mu}\Big[\frac{2}{3}\frac{1}{r^2}+\frac{5}{3}\frac{1}{br\,(r^2+b^2)^{1/2}}-\frac{2}{3}\frac{1}{r^3\,(r^2+b^2)^{1/2}} \\
&\qquad -\frac{2b}{r\,(r^2+b^2)^{3/2}}-\frac{3}{2}\frac{br}{(r^2+b^2)^{5/2}}\Big], \\
\delta_\varphi &= -\frac{A_2\cos 2\varphi}{10\mu}\frac{1}{3}\Big[\frac{2}{r^3}-\frac{2}{br\,(r^2+b^2)^{1/2}}-\frac{2b}{r^3\,(r^2+b^2)^{1/2}} \\
&\qquad +\frac{b}{r\,(r^2+b^2)^{3/2}}\Big], \\
\delta_z &= \frac{A_2\sin 2\varphi}{10\mu}\frac{1}{3}\Big[\frac{2}{br^2}-\frac{2}{r^2\,(r^2+b^2)^{1/2}}-\frac{1}{(r^2+b^2)^{3/2}} \\
&\qquad -\frac{3}{2}\frac{r^2}{(r^2+b^2)^{5/2}}\Big].
\end{aligned}\right\} \tag{13}$$

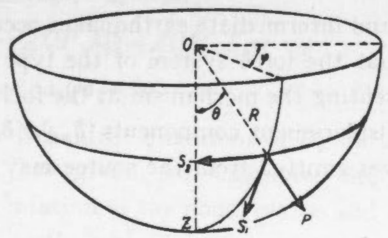


Fig. 12. The direction of motion of $P=\delta_{p,r}$, $S_1=-\delta_{s,\theta}$ and $S_2=\delta_{s,\varphi}$. (After HIRONO, 1948.)

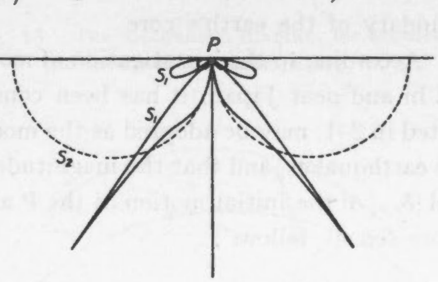


Fig. 13. The dip angular distribution of the body waves P, S_1 and S_2. (After HIRONO, 1948.)

The horizontal displacements at the surface are shown by the arrows in Fig. 14, b being assumed to be 10, where the shaded area means that the region is elevated slightly.

The problem on the deformation of the surface of a semi-infinite elastic solid, produced by a statical source lying beneath the surface of the solid, was investigated by F. J. W. WHIPPLE (1936), K. SOEDA (1944), and N. YAMAKAWA (1955).

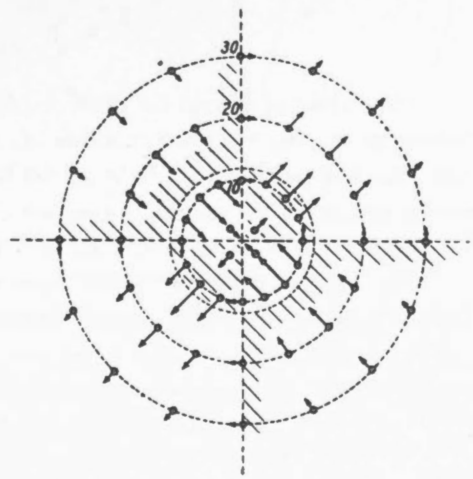


Fig. 14. Statical deformation of the surface.[55]

3 Investigation of Earthquake Mechanism based on the Observations at Near Stations

3-1. Mechanism of Deep and Intermediate Earthquakes.

3–1a. *Theories.* The investigation of the mechanism of the earthquakes in Japan, has been much facilitated by the use of the observations made at the seismological stations, which are equipped with the seismographs of the same type and distributed very closely. Some of the results of the studies on the mechanism of the deep and intermediate earthquakes, carried out in this country, are described in the present chapter.

In order to compute theoretically the motion at the earth's surface which are caused by the incident direct waves or the waves, reflected once at the earth's surface or the outer boundary of the earth's core, such as P, S, pP and ScS, we must take into account, (i) the mechanism of the generation of the seismic waves at the focus of the earthquake, (ii) the variation of the velocity of the waves with the depth from the earth's surface, and (iii) the reflection of the waves at the earth's surface or at the boundary of the earth's core

According to the investigation of many deep and intermediate earthquakes occurred in and near Japan, it has been considered that the force system of the type II stated in 2–1, may be adopted as the model representing the mechanism at the foci of the earthquakes, and that the magnitude of the displacement components $[\delta_{p,r}]$, $[\delta_{s,\theta}]$ and $[\delta_{s,\varphi}]$ of the initial motion of the P and S waves emitted from the source may be expressed as follows ;

$$\left.\begin{aligned}
[\delta_{p,r}] &= A_p \frac{1}{r} \sin 2\theta \cos \varphi \, , \\
[\delta_{s,\theta}] &= A_s \frac{1}{r} \cos 2\theta \cos \varphi \, , \\
[\delta_{s,\varphi}] &= -A_s \frac{1}{r} \cos \theta \sin \varphi \, . .
\end{aligned}\right\} \tag{14}$$

The values of A_p and the ratio A_s/A_p depend on the magnitude of the earthquake. When the values of the constants A_p and A_s and the orientation of the axes of the spherical coordinates of the model sphere are given, then the amplitudes of the initial motion of the seismic waves which are emitted in any direction θ, φ from the focus can be calculated by the use of the formulae (14).

Fig. 15 illustrates the model sphere of the earthquake mechanism, when it is viewed from the vertically upward direction u. We will call the projected figure the *mechanism diagram.* P_1 and T_1 on the sphere represent the directions of the maximum pressure and tension. Great circles n_1Qn_1' and n_2Qn_2' are the nodal planes for the P waves, and the hatched part and the blank part correspond to the directions in which the initial motions of the P waves are condensational and rarefactional respectively. The points of intersection of the great circle passing through P_1 and T_1, with n_1Qn_1' and n_2Qn_2' are denoted by M_1 and M_2. M_1 corresponds to the y-axis, M_2 to the x-axis, and Q to the z-axis in Fig. 4. If ua_1 and ua_2 are the arcs of the great circles which are perpendicular to n_1Qn_1' and n_2Qn_2' respectively, the directions of ua_1 and ua_2 are the dip directions, and ua_1 and ua_2 are the inclinations, and $90°-ua_1$ and $90°-ua_2$ are the dips of the nodal planes. The directions of n_1n_1' and n_2n_2' are the strikes of the planes. Obviously there hold following relations ;

$$P_1M_1=M_1T_1=T_1M_2=\cdots=45°,$$

$$QP_1=QM_1=QT_1=QM_2=\cdot=90°,$$

$$\angle a_1uM_2=\angle a_2uM_1=\cdots=180°,$$

$$a_2M_1=a_1M_2=\cdots\cdots\cdots=90°,$$

$$\angle ua_1M=\angle ua_2M_2=\cdots\cdots$$

$$=\angle QP_1M_1=\angle QM_1T_1=\cdots$$

$$=\angle a_1Qa_2=90°.$$

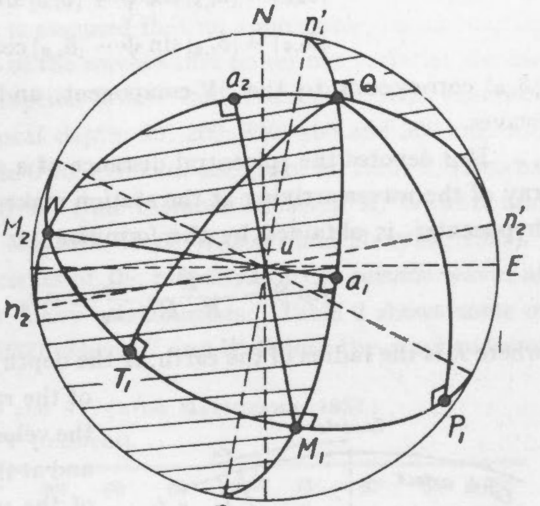


Fig. 15. The mechanism diagram for the deep and intermediate earthquakes.[65]

When the directions of P_1 and T_1 are given for example, the orientation of the nodal planes and so forth, are obtained by the use of the formulae of spherical trigonometry.

We denote by B a point on the mechanism diagram, corresponding to the direction of the seismic ray which makes the angle Θ with the vertical drawn upward at the hypocenter, and lies in the vertical plane directed in the azimuth Φ, being measured from the vertical plane passing through uM_1 (Fig. 16). Let $\alpha=uM_1$, $\beta=\angle uM_1a_1$, then from the formulae

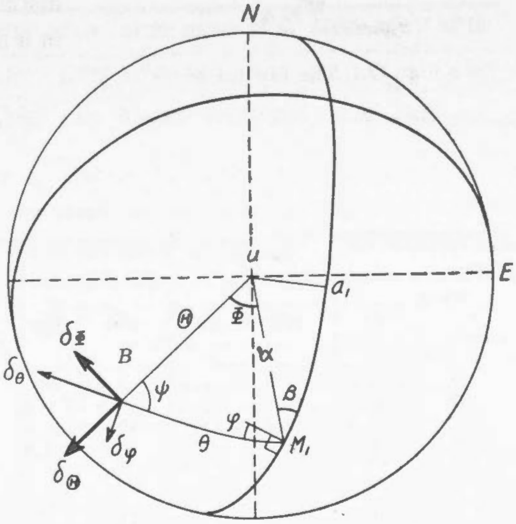


Fig. 16. Illustration of the direction of motion on the mechanism diagram.

$$\left.\begin{aligned}&\cos\theta=\cos\Theta\cos\alpha+\sin\Theta\sin\alpha\cos\Phi\ ,\\ &\frac{\sin\Phi}{\sin\theta}=\frac{\sin\left(\frac{\pi}{2}-\beta+\varphi\right)}{\sin\Theta}=\frac{\sin\psi}{\sin\alpha}\ ,\quad \psi=\angle uBM_1.\end{aligned}\right\}\qquad(15)$$

we can obtain the relations between (Θ,Φ) and (θ,φ,ψ). The Θ, Φ-components of displacement of the initial motion of the S waves, are

$$\left.\begin{aligned}[\delta_{s,\Theta}] &= [\delta_{s,\theta}]\cos\psi + [\delta_{s,\varphi}]\sin\psi\,, \\ [\delta_{s,\Phi}] &= [\delta_{s,\theta}]\sin\psi - [\delta_{s,\varphi}]\cos\psi\,.\end{aligned}\right\} \tag{16}$$

$[\delta_{s,\Theta}]$ corresponds to the SV-component, and $[\delta_{s,\Phi}]$ to the SH-component of the S waves.

If Δ denotes the epicentral distance of a station, the angle Θ which the seismic ray of the waves arriving at the station makes with the vertical drawn upward at the hypocenter, is obtained by the formulae ;

$$\sin\Theta = \frac{R}{R-H}\,\frac{v_h}{v_0}\cos e_0\,; \qquad \cos e_0 = v_0\frac{dT}{d\Delta}\,, \tag{17}$$

where R is the radius of the earth, H the depth of the focus, e_0 the angle of emergence of the ray at the earth's surface, and v_0 and v_h the velocities of the waves at the earth's surface and at the focus (Fig. 17). T is the travel time of the waves which arrive at the station.

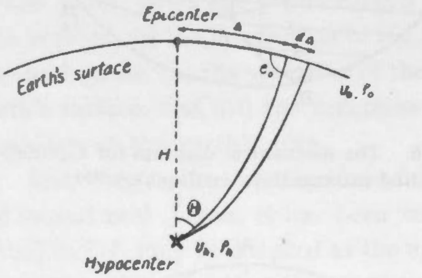


Fig. 17. The ray for P.

The distance factor f which represents the diminution of the amplitude of the seismic waves traveling along curved path with the distance from the hypocenter, instead of $1/r$ in a homogeneous medium, can be expressed as

$$f = \sqrt{\frac{\rho_h v_h}{\rho_0 v_0}}\sqrt{\frac{\sin\Theta}{R\sin\frac{\Delta}{R}\sin e_0}\,\frac{d\Theta}{d\Delta}}\,, \tag{18}$$

Table 1. Θ and f.

	$\Theta°$ [63]				
H km / Δ km	80	200	320	400	500
20	17.0	7.4	4.6	3.8	3.2
50	36.2	16.6	10.8	9.0	7.5
100	60.0	29.0	19.8	16.9	14.3
200	78.0	48.5	34.9	30.0	26.0
300	86.0	61.5	47.1	41.3	36.4
400	90.6	70.0	57.0	50.8	45.6
500	94.9	75.7	64.5	59.4	54.1
600	96.2	80.8	71.1	66.6	61.7
700	97.7	83.2	77.0	72.3	68.6
800	98.7	89.0	82.1	77.1	74.4
900	99.6	92.7	86.8	81.2	79.2
1000	100.7	96.1	90.0	84.8	82.9
1200	104.5	102.4	98.0	94.8	89.0
1400	109.7	108.6	106.3	103.9	98.5
1600	114.8	114.4	113.0	110.6	104.9
1800	119.9	119.5	118.7	115.4	109.7
2000	124.8	123.9	123.0	119.3	113.5
2400	132.8	130.6	128.8	125.0	118.7
2800	137.4	135.2	133.0	129.1	122.4
3200	140.6	139.0	136.1	132.2	125.5
3600	142.2	141.4	138.4	134.5	127.9
4000	144.0	142.8	139.8	136.1	129.8

	f $(10^{-8}\mathrm{km}^{-1})$ [60]				
H km / Δ km	80	200	320	400	500
20	1.98	0.934	0.836	0.541	0.458
50	1.62	842	702	497	432
100	1.23	678	580	455	405
200	0.426	448	425	390	361
300	293	343	347	338	325
400	219	276	287	294	293
500	162	225	243	259	263
600	121	193	211	224	237
700	92	170	187	175	212
800	75	152	160	141	189
900	68	137	155	134	165
1000	78	126	144	144	128
1200	93	109	128	152	143
1400	90	101	117	112	123
1600	82	85	93	89	95
1800	76	73	77	75	79
2000	69	62	62	62	64
2400	46	46	44	46	47
2800	34	36	34	37	38
3200	23	27	28	29	32
3600	16	20	23	24	26
4000	12	14	18	17	24

where ρ_0 and ρ_h are the densities of the earth's crust at the earth's surface and at the focus respectively. In deriving (18), it is assumed that no appreciable discontinuities exist in the earth, and that the periods of the waves suffer no serious variation during the propagation, and the effect of absorption is left out of account. The values of f calculated for the P waves, for the focal depth; 80, 200, 320, 400 and 500 km, and for the epicentral distance varying from 0 to 4,000 km are given in Table 1, (HONDA and H. ITÔ, 1951), which are based on the time distance tables of K. WADATI and others (WADATI, K. SAGISAKA, and K. MASUDA, 1933, WADATI and MASUDA, 1933).

The numerical values of the coefficients of the reflection of the seismic waves at the earth's surface have been given by many seismologists. Table 2 shows some of the results obtained by MATSUZAWA (1932), where U and W denote the amplitudes of

Table 2. Reflection of P and SV. (After MATSUZAWA, 1932,)

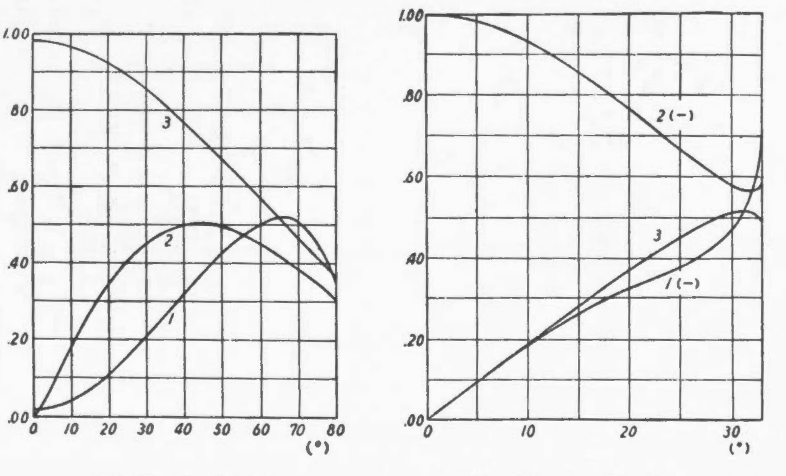
(a) P (incident).

i	0°	5°	10°	20°	30°	40°	50°	60°	65°	70°	75°	80°	85°	90°
U_p	0	.201	.400	.780	1.120	1.382	1.617	1.732	1.743	1.717	1.608	1.405	.971	0
W_p	2	1.990	1.963	1.858	1.692	1.479	1.241	1.00	.885	.771	.658	.530	.349	0

(b) SV (incident).

i	0°	2°35′	5°45′	11°23′	16°43′	21°47′	26°15′	30°00′	31°33′	32°52′	33°54′	34°40′	35°07′	35°16′
U_s	2	1.9965	1.981	1.937	1.869	1.789	1.730	1.732	1.787	1.901	2.12	2.511	3.28	4.899
W_s	0	.1160	.2302	.4503	.6443	.8124	.9325	1.00	1.0065	.9883	.9316	.8110	.5620	0

the horizontal and vertical components of displacement of the earth's surface, when the P or SV waves of unit amplitude of displacement are incident, the angle of incidence being i. The Poisson's ratio of the medium is assumed to be 1/4. The relative am-



(a) P (incident). (b) SV (incident).

Fig. 18. The relative amplitudes of the reflected P (1), reflected SV (2) and refracted P (3), when P (a) or SV (b) in the mantle is incident against the core.(60)

plitudes of the waves reflected or refracted at the surface of the earth's core, to those of P and S waves incident from the mantle, are illustrated in Fig. 18 (HONDA and ITÔ, 1951). The density of the mantle outside the core is taken as 6.0 g/c.c. and that of the core just within the boundary as 9.5 g/c.c. The velocities of the P and S waves in the mantle are taken as 13.0 and 7.25 km/sec respectively. The velocity of the P waves within the boundary of the core is taken as 8.5 km/sec, and that of the S waves as zero or the core is assumed to be liquid.

The initial motions of the P and S waves to be observed at the earth's surface can be calculated theoretically, being based on the theories and relations stated above. As an example of very simple cases, we will consider at first the case in which the polar axis of the model sphere representing the mechanism of the earthquake, is directed vertically upward. One of the nodal planes for the P waves is directed vertically and the other horizontally. Let us assume that the ray emitted in the direction (θ,φ) from the focus, arrives at the point of the earth's surface whose epicentral distance is Δ, and the azimuth to the epicenter is Φ. We can take $\Theta=\theta$ and $\Phi=\varphi$ in this case. The amplitude $[P]$ of the initial motion of the P waves at the earth's surface is expressed by

$$[P] = 2 f A_p \sin 2\theta \cos\varphi \,, \tag{19}$$

as it is practically twice that of the incident P waves.

The Δ and Φ-components, $[S]_\Delta$ and $[S]_\Phi$, of the horizontal motion of the earth's surface due to the incident S waves, are

$$\left.\begin{aligned} [S]_\Delta &= U_s f A_s \cos 2\theta \cos\varphi \,, \\ [S]_\Phi &= -2 f A_s \cos\theta \sin\varphi \,. \end{aligned}\right\} \tag{20}$$

The amplitude of the horizontal motion of the earth's surface due to the incident SH waves is just twice that of the incident ones. In Fig. 19 (a), are shown the

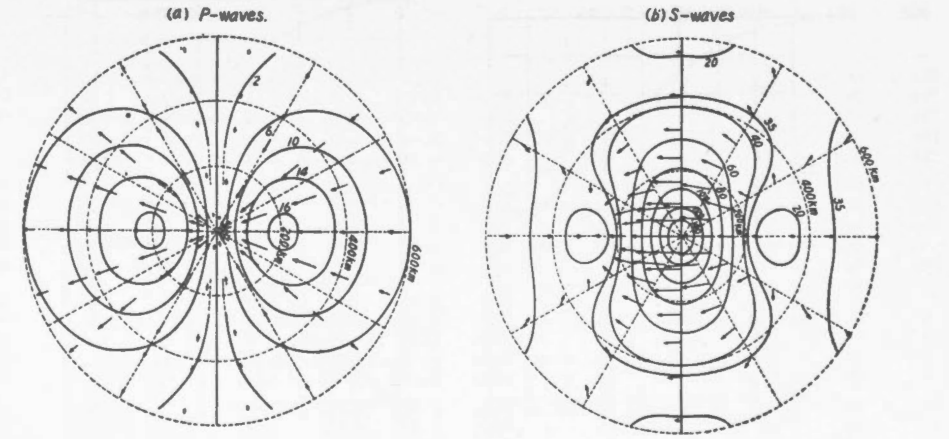


Fig. 19. The initial motions of P and S at the earth's surface for a special case. [51]

direction and magnitude of the initial motion of the P waves at the earth's surface, and in Fig. 19 (b) those of the horizontal components of the initial motion of the S waves, in the region within 600 km from the epicenter for the earthquake whose focal depth is 300 km. The ratio A_s/A_p is assumed to be 5.20 in the example.

Next, we will treat the general case in which the polar axis of the model sphere is directed in any direction. Let Φ be the azimuth of a point of the earth's surface to the epicenter measured from a certain direction, and Θ and Δ be the same as in foregoing example. The amplitude of the intial motion of the P waves at the earth's surface can be calculated by the use of apparently the same formula as (19). The horizontal components of the initial motion of the S waves are given by

$$\left.\begin{aligned} [S]_\Delta &= U_s f[\delta_{s,\Theta}]\ , \\ [S]_\Phi &= 2f\ [\delta_{s,\Phi}]\ . \end{aligned}\right\} \qquad (21)$$

The initial motion of the ScS waves at the earth's surface near the epicenter, can be also calculated theoretically. If the ray of the S waves emitted almost vertically downward from the hypocenter makes the angle e_c with the surface of the earth's core, and r_c is the radius of the core,

$$\cos e_c = \frac{R}{r_c}\frac{v_c}{v_0}\cos e_0\ , \qquad (22)$$

where v_0 and v_c are the velocities of the S waves at the earth's surface and just outside the core (Fig. 20). The angles $i_h=180° - \Theta'$ and $i_c=90°-e_c$ as are shown in the figure, and the distance factor f_{ScS} for the ScS waves are calculated (e.g. HONDA and ITÔ, 1951) by the use of the time-distance tables of WADATI and MASUDA (1934). When we assume that the earth's core is liquid, the δ_Φ component of the S waves is reflected totally at the core, and the ratio q of the amplitude of the reflected S waves to that of $\delta_{s,\Theta}'$ (SV waves) incident at the core can be obtained from Fig. 18(b). The radial and transverse components $[ScS]_\Delta$ and $[ScS]_\Phi$ of the horizontal components of the initial motion of the ScS waves to be observed at the earth's surface near the epicenter, are given by

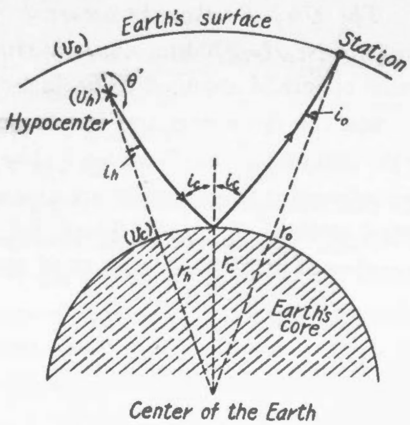


Fig. 20. The ray for ScS.

$$\left.\begin{aligned} [ScS]_\Delta &= -\ U_s\, q f_{ScS}[\delta_{s,\Theta'}]\ , \\ [ScS]_\Phi &= 2f_{ScS}[\delta_{s,\Phi}]\ . \end{aligned}\right\} \qquad (23)$$

3–1b. *Examples.* Some examples of the results of the investigation of the mechanism of the deep earthquakes occurred in Japan, are given below.

The Deep Earthquake occurred on June 2, 1929, *near Shima Peninsula.* The epicenter lies at $\lambda=137°.2$E, $\varphi=34°.3$N, and the focal depth $H=320$ km. The polar axis of the nodal sphere representing the mechanism of the earthquake, is considered to be inclined by 13° in the direction N98°E from the epicenter, and one of the nodal planes for the P waves strikes to N 8°E. The direction and magnitude of the initial motion of the P waves and those of the horizontal components of the S waves, are illustrated in Fig. 21, where the observed values are shown by the arrows of thick lines, and the

(a) ; P. (b) ; S.

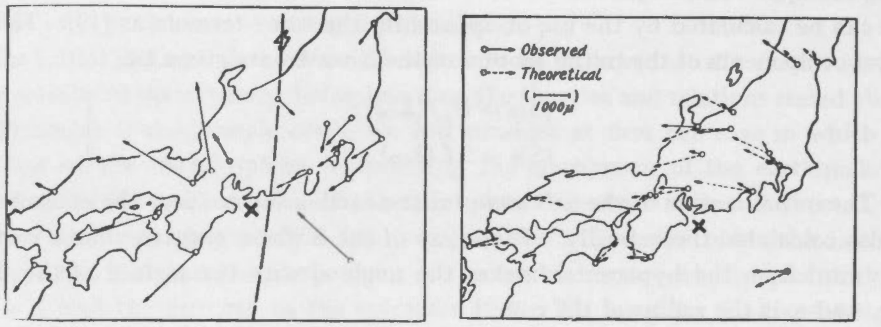


Fig. 21. The deep earthquake occurred on June 2, 1929, near Shima Peninsula.[51]
(a) The initial motion of P. (b) The horizontal component of the initial motion of S.

theoretically expected values by the arrows of dotted lines. A_p and A_s are assumed to be $A_p=4.94\times 10^5$ cm², $A_s=14.1\times 10^5$ cm². (HONDA, 1934. HONDA *et al.*, 1938.)

The Deep Earthquake occurred on Feb. 20, 1931, *near Vladivostok.* $\lambda=135.°7$ E, $\varphi=44°.5$ N, $H=320$ km, $A_p=18\times 10^5$ cm², $A_s=14\times 10^5$ cm². The polar axis of the model sphere is assumed to be inclined by 50° in the vertical plane N79° E passing through the epicenter, and the same vertical plane is considered to be one of the nodal planes for the P waves. The initial motions of the P and S waves observed and calculated theoretically are given in Fig. 22. The direction and magnitude of the initial motions of P, pP, S and ScS calculated theoretically for Stuttgart ($\Delta=76°$), being based on the assumption of the mechanism of the earthquake, are illustrated

(a) ; P. (b) ; S.

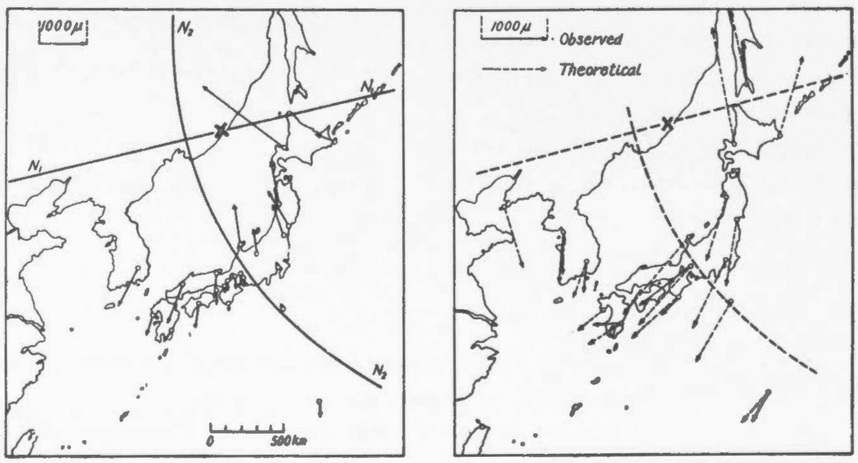


Fig. 22. The horizontal component of the initial motion of P (a) and S (b) for the deep earthquake occurred on Feb. 20, 1931, near Vladivostok.[60]

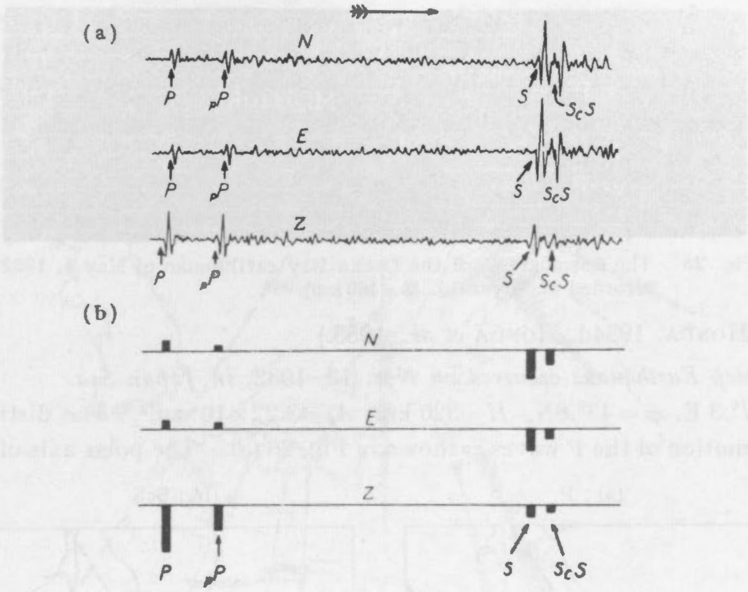


Fig. 23. The seismograms recorded at Stuttgart (a), and the initial motions of P, pP, S and ScS calculated theoretically (b), for the earthquake of Feb. 20, 1931.[60]

schematically together with the seismograms of these waves recorded at Stuttgart, in Fig. 23. (HONDA and ITÔ, 1951.)

The Deep Earthquake occurred on May 5, 1932, in Osaka Bay.

$\lambda=135^\circ.4$ E, $\varphi=34^\circ.6$ N, $H=360$ km, $A_p=5.92\times10^4$ cm,[2] ($A_s=5.20\times A_p$). The polar axis of the model sphere is considered to be directed vertically upward, and one of the nodal planes to be the vertical plane directed to N 35° W through the epicenter. The pattern of the condensation and rarefaction of the initial motion of the P waves, and the direction and magnitude of the horizontal component of the initial motion of the S waves observed and calculated theoretically, are illustrated in Fig. 24. The seismograms of the earthquake recorded at Miyazaki ($\Delta=480$ km) are shown in

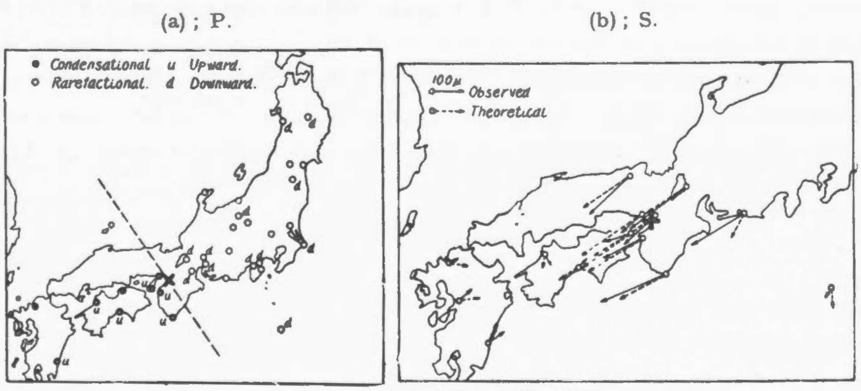


Fig. 24. The deep earthquake occurred on May 5, 1932, in Osaka Bay.[54],[64] (a); The initial motion of P. (b); The horizontal component of the initial motion of S.

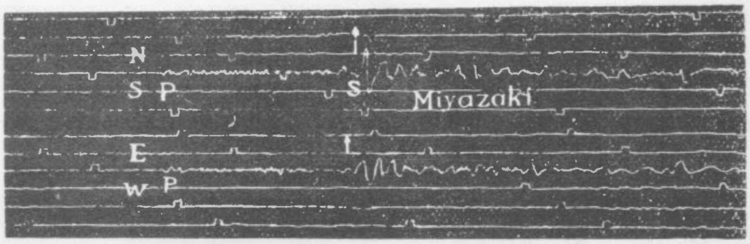


Fig. 25. The seismograms of the Osaka Bay earthquake of May 5, 1932, recorded at Miyazaki. (Δ=480 km).[54]

Fig. 25. (HONDA, 1934d. HONDA *et al.*, 1955.)

The Deep Earthquake occurred on Nov. 13, 1932, *in Japan Sea.*

$\lambda=137°.3$ E, $\varphi=43°.6$N, $H=320$ km, $A_p=3.22\times10^6$ cm². The distribution of the initial motion of the P waves is shown in Fig. 26 (a). The polar axis of the model

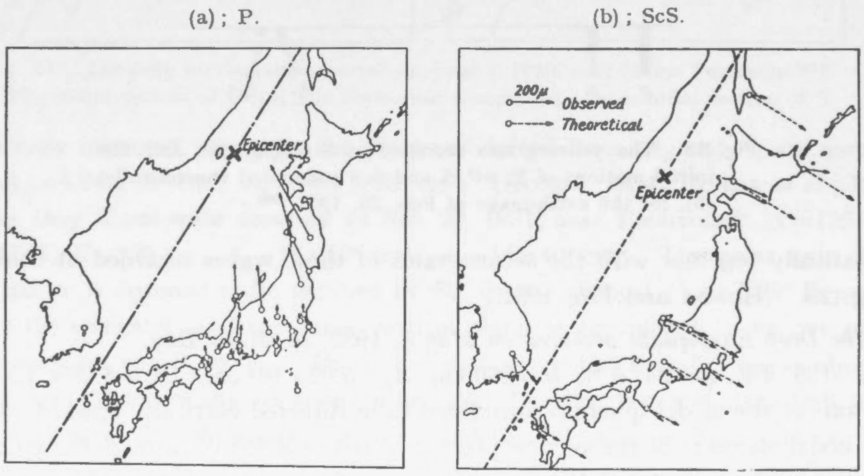


Fig. 26. The deep earthquake occurred on Nov. 13, 1932, in Japan Sea.[52],[64] (a); The initial motion of P. (b); The horizontal component of the initial motion of ScS.

sphere is considered to be directed vertically upward, and one of the nodal planes to be vertical plane directed to N 35°E passing through the epicenter. The observed horizontal components of the initial motion of the ScS waves, and those calculated theoretically from the assumption that the core is liquid and $A_s=5.20\times A_p$ provisionally, are illustrated in Fig 26 (b). As the observed amplitudes of the ScS waves are about half of those expected theoretically, A_s should be supposed to be about 2.6 A_p instead of 5.20 A_p. The seismograms recorded at some stations in this country are shown on a map in Fig. 27, to illustrate the regular distribution of the various types of the seismograms especially as to the relative amplitudes of the P and S waves, which is consistent with that expected theoretically. The seismograms including the ScS waves recorded at Siomisaki is shown in Fig. 28. (HONDA, 1933, 34b, HONDA *et al.*, 1955.)

The Deep Earthquake occurred on Dec. 1, 1936, *near the Island Yaku.*

$\lambda=129°.0$E, $\varphi=30°.7$ N, $H=270$ Km, $A_p=2.6\times10^5$ cm². The initial motions of the P waves are shown in Fig. 29 (a). The polar axis of the model sphere is con-

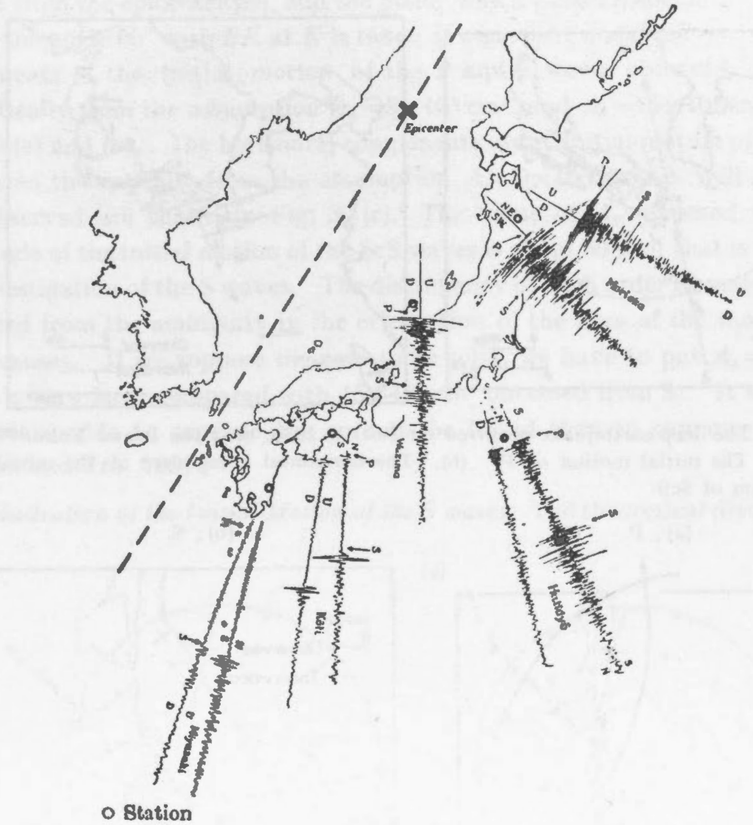


Fig. 27. The seismograms of the Japan Sea earthquake of Nov 13, 1932, recorded at some stations in Japan.[50]

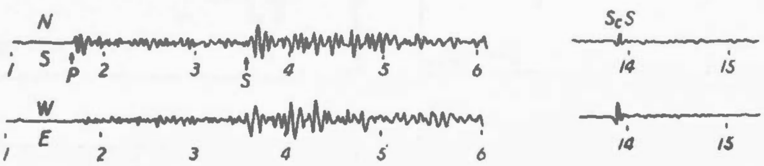


Fig. 28. The seismograms of the Japan Sea earthquake of Nov. 13, 1932, recorded at Siomisaki. ($\Delta = 1{,}124$ km).[52]

sidered to be inclined by 30° in the vertical plane striking N 10°E from the epicenter, which is taken to be one of the nodal planes. The horizontal components of the initial motion of the ScS waves observed, and those calculated theoretically based on the assumption that the core is liquid and $A_s = 3.5\times10^5$ cm², are illustrated in Fig. 29 (b). (HONDA and Y. HASAYA, 1940.)

The Deep Earthquake occurred on Apr. 21, 1939, *in Japan Sea.*

$\lambda = 140°.2$E, $\varphi = 47°.6$N, $H = 530$ km, $A_p = 5\times10^5$ cm², $A_s = 15\times10^5$ cm². The polar axis (K) of the model sphere is considered to be inclined by 60° in the direction

(a) ; P. (b) ; ScS.

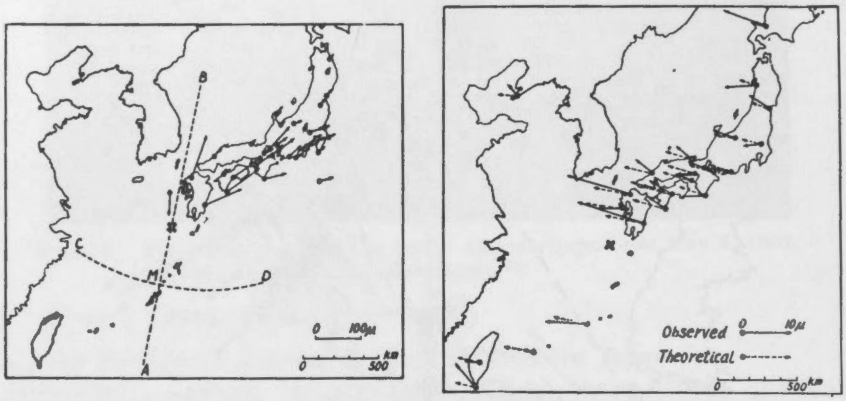
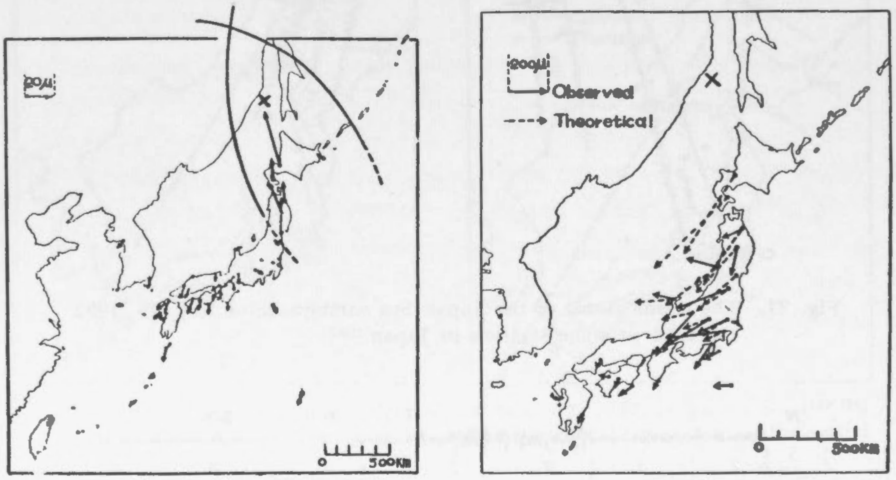


Fig. 29. The deep earthquake occurred on Dec. 1, 1936, near the Island Yaku.[58] (a). The initial motion of P. (b). The horizontal component of the initial motion of ScS.

(a) ; P. (b) ; S.



(c) ; ScS.

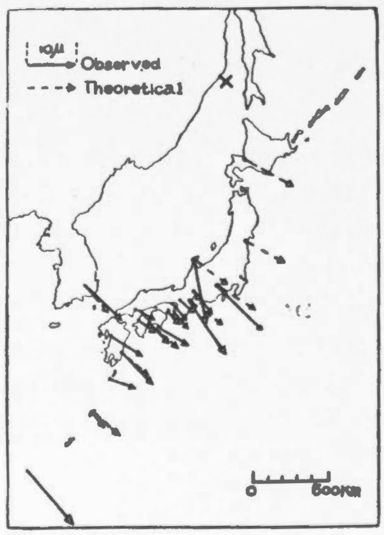


Fig. 30. The horizontal components of the initial motion of P (a), S (b) and ScS (c), of the deep earthquake occurred on Apr. 21, 1939, in Japan Sea.[60]

N 88°E from the epicenter (E), and the plane which passes through the polar axis and makes the angle 60° with EK at K is taken as one of the nodal planes. The horizontal components of the initial motion of the P and S waves observed, and calculated theoretically from the assumption $A_p=5\times10^5$ cm^2, and $A_s=15\times10^5$ cm^2 are shown in Fig. 30 (a) and (b). The horizontal components of the initial motion of the ScS waves calculated theoretically from the assumption $A_s=9\times10^5$ cm^2, as well as those actually observed are shown in Fig. 30 (c). The value of A_s supposed to explain the amplitude of the initial motion of the ScS waves is about 60% of that is obtained from the investigation of the S waves. The discrepancy of such order of magnitude may be produced from the ambiguity in the orientation of the axes of the model sphere and other causes. If we suppose the core to be solid, we have to put $A_s=180\times10^5$ cm^2, which is very large compared with 15×10^5 cm^2 obtained from S. It seems to be far more reasonable to suppose the core to be liquid than to suppose it to be solid. (HONDA and ITÔ, 1951.)

Illustration of the Initial Motion of the S waves. The theoretical distribution of the

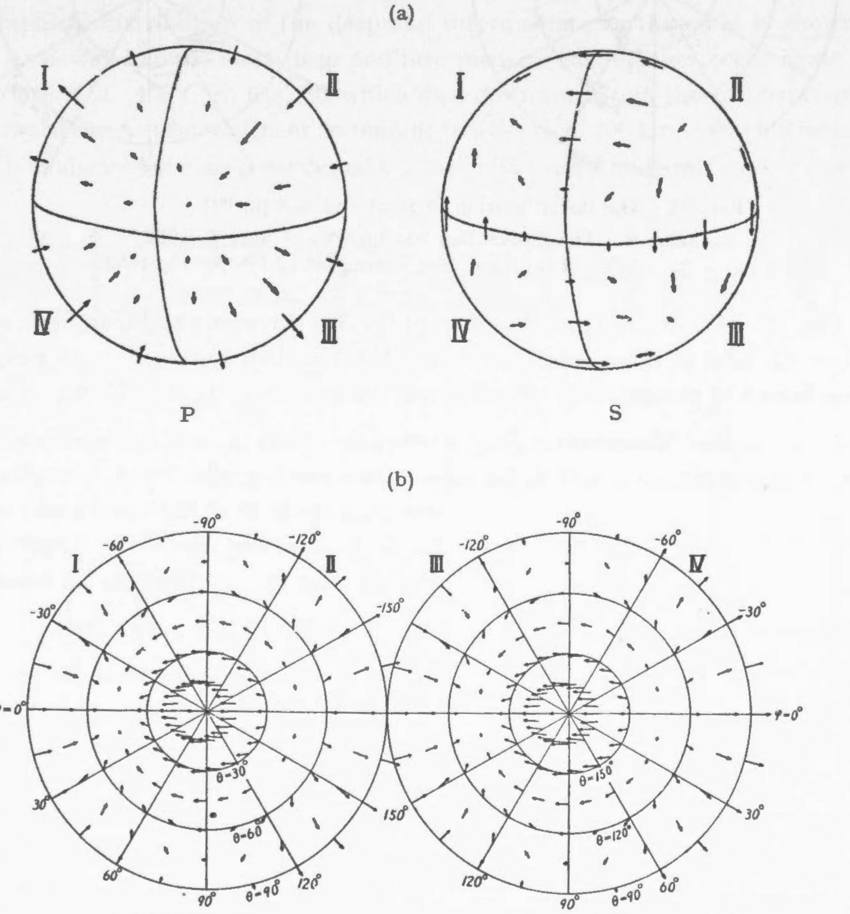


Fig. 31. (a). The initial motions of P and S on a sphere constructed around the focus.[64]
(b). The illustration of the initial motion of S.[64]

direction and magnitude of the initial motion of the P and S waves on a sphere which is constructed around the hypocenter and includes the model sphere in it, is illustrated schematically also in Fig. 31 (a). If the sphere is divided into two parts by one of the nodal planes for the P waves and are represented on one plane as is shown in Fig. 31 (b,) the distribution of the initial motion of the S waves can be represented by the arrows in the figure. I,II,III and IV show the corresponding quadrants in Fig. 31 (a) and (b) to each other. Fig. 32 (a) shows the direction of the initial motion of the S waves of the Osaka Bay earthquake of May 5, 1932 in the quadrants I and II,

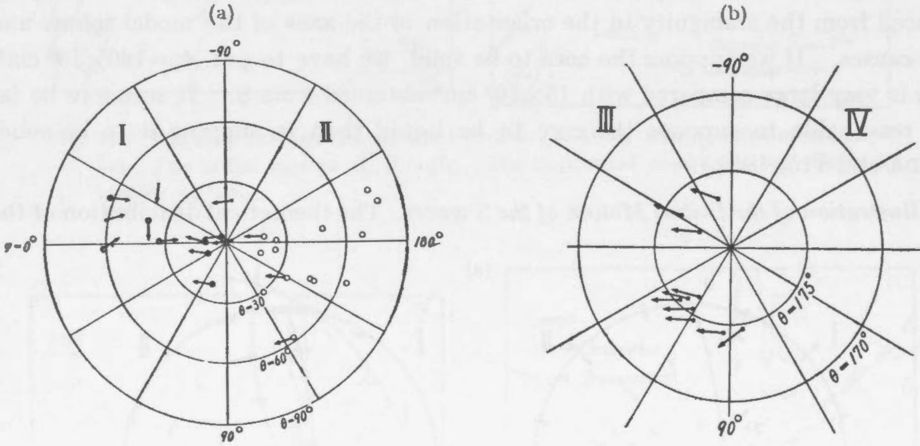


Fig. 32. The initial motion of S (a) and ScS (b).[64]
(a); S. The Osaka Bay earthquake of May 5, 1932.
(b); ScS. The Japan Sea earthquake of Nov. 13, 1932.

and Fig. 32 (b) shows the initial motion of the ScS waves of the Japan Sea earthquake of Nov. 13, 1932 in the quadrants III and IV. The distribution in both cases is consistent with the theoretically expected one shown in Fig. 31 (b). (Honda *et al.*, 1955.)

3–1c. *A_p, A_s and Magnitude of Deep Earthquake.* Both A_p and A_s have been evaluated for 11 deep earthquakes, and A_p for more 5 deep earthquakes. log A_p is proportional to the magnitude M of the earthquake estimated by B. Gutenberg and C. F. Richter (1949), Fig. 33, and the relation can be expressed by

$$M = 0.74 \log A_p + 2.61 \ .$$

log A_s is also proportional to M.

The relation between the ratio $[R] = A_s/5.20A_p$ and A_p is shown in Fig. 34. $[R]$ is nearly unity when A_p is very small, whereas it is very small for large A_p. That A_p is large means that the magnitude and hence the radius of the focal region may be large. The relation obtained here will probably be consistent with the theoretical relation illustrated in Fig. 8.

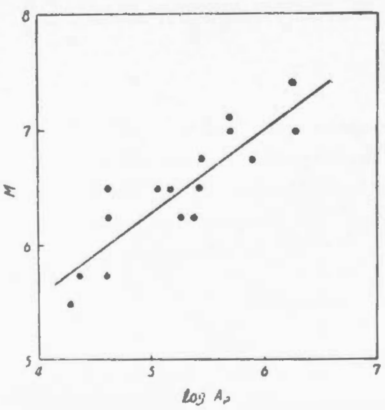


Fig. 33. log A_p and M.[59]

(HONDA, 1951, 54.)

The apparent periods of the initial motion of the deep earthquakes also become large with the magnitude of the earthquakes. (HONDA and ITÔ, 1940.)

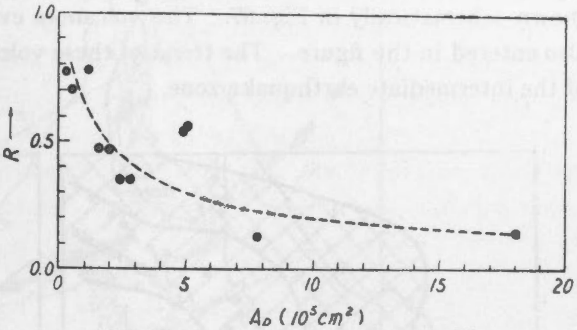


Fig. 34. A_p and $[R]=A_s/5.20\,A_p$.[63]

3–1d. *Statistical Investigation of the Mechanism of Deep and Intermediate Earthquakes.* The earthquakes are classed here as shallow when the focal depth does not exceed 100 km, intermediate when it is from 100 km to 250 km, and deep when it exceeds 250 km. There occurred 87 deep earthquakes, 58 intermediate earthquakes and 841 shallow earthquakes during the period 1927 to 1949 in and near Japan; all the earthquakes being classed as remarkable and moderate in this country. The geographical distribution of the deep and intermediate earthquakes is shown in Fig. 35. As is well known, most deep and intermediate earthquakes occur along the curved surface *ABC-A′B′C′* in Fig. 36, which dips downward from the eastern coast of Honsyû toward the Asiatic continent, extending to a depth of 400 km to 600 km beneath the outer boundary of the deep earthquake zone. The deep and intermediate earth-

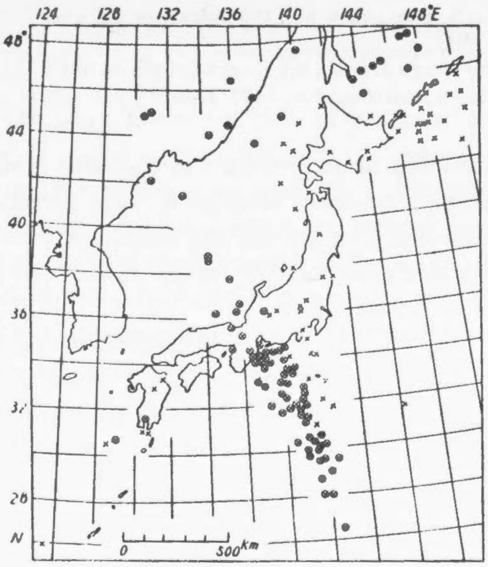


Fig. 35.

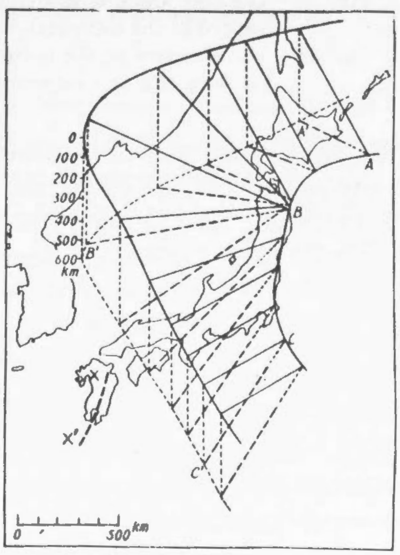


Fig. 36.

Fig. 35. The deep and intermediate earthquakes, 1927–1949.[61]
⊗ : deep earthquake, $H \geqq 250$ km.
× : intermediate earthquake, $250 > H \geqq 100$ km.

Fig. 36. The inclined surface (ABC-A′B′C′) along which the deep and intermediate earthquakes occur.[61]

quake zones and the region in which shallow earthquakes occur most frequently are shown schematically in Fig. 37. The volcanoes ever erupted in the historical time are also entered in the figure. The trend of these volcanoes is nearly coincident with that of the intermediate earthquake zone.

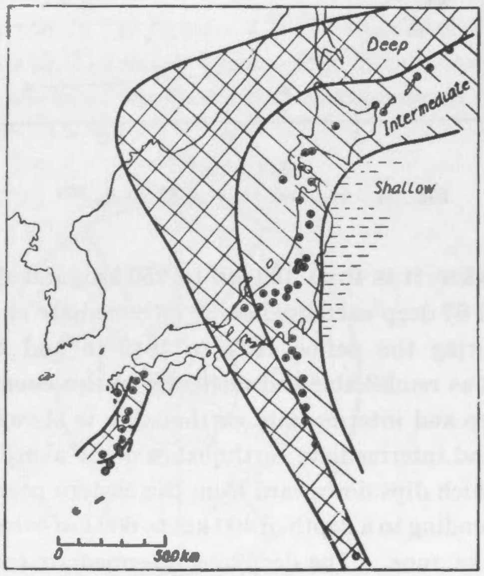


Fig. 37.

Fig. 38.

Fig. 37. The deep and intermediate earthquake zones, and the volcanoes (◉) ever erupted in the historical time.[61]

Fig. 38. The direction of the horizontal component of the maximum pressure for the deep (⊗) and intermediate (×) earthquakes, 1927-1949.[61]

The mechanisms of 34 deep earthquakes and 10 intermediate earthquakes, among the earthquakes occurred during the period, have been elucidated. The directions of the horizontal components of the maximum pressure for the earthquakes as are illustrated in Fig. 38, are directed nearly perpendicularly to the trends of the deep and intermediate earthquake zones and the active volcanic zone.

Let the deep and intermediate earthquake zones be divided provisionally into five regions (*ab*), (*c*), (*de*), (*fg*) and (*hi*) as are shown in Fig. 39, and consider a virtual earthquake corresponding to the mean state of the stresses causing the earthquakes in each region. Now it is assumed that one of the nodal planes of the P waves corresponds to the fault plane when faulting motion occurrs at the focus, whereas the earthquake is produced by the large scale stress of the nature of the force system of the type II acting in the vast region including the focal domain in it. And so, one of the nodal planes for each virtual earthquake being supposed to be a fault plane, the directions of the relative motion of the Pacific side to the Asiatic side are illustrated by arrows in Fig. 39. For the virtual earthquake in the region (*c*) for example, the dip direction of the fault plane is S34°E, the strike N56°E, the dip 73° and the slip angle 50°. The faulting motions are nearly reverse for the regions (*ab*), (*c*) and (*fg*), nearly transcurrent

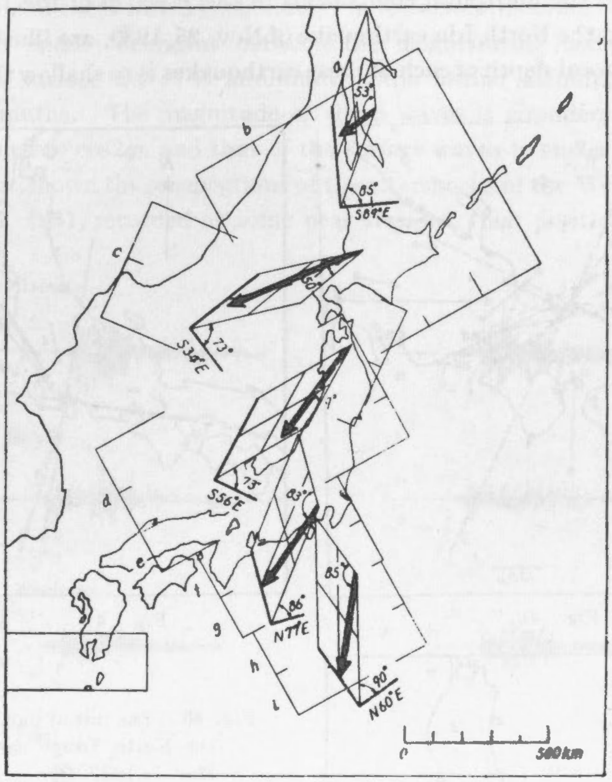


Fig. 39. The hypothetical direction of the relative motion of the Pacific side to the Asiatic side.[65]

for (*de*) and vertical for (*hi*). The directions of these relative motions do not lie in general in the surface *ABC-A'B'C'*. Anyhow, it seems to exists the general tendency for the Pacific side to be relatively forced downward and toward the Asiatic continental side, which is forced upward and toward the eastern offing of Honsyû. Of course, the choice of one of the two nodal planes as the fault plane is arbitrary, and the statement denoted here is only one of the various possible ways of explanation as to the causes of the deep and intermediate earthquakes in and near Japan. (HONDA *et al.*, 1952, 56).

3-1e. Various hypotheses concerning the tectonic activity of the circum-Pacific earthquake zones have been proposed by J. COULOMB (1945), H. BENIOFF (1949, 54, 55), H.H. HESS (1951), VENING MEINESZ (1954), J.T. WILSON (1954), H.STILLE (1955), and A.E. SCHEIDEGGER (1955, 56). Some of them seem to be consistent with a possible explanation of our statistical investigation, that the Pacific side is overthrusted by the Asiatic side. GUTENBERG and RICHTER (1951) stated that, 'possibly over a long period of geological time the uppermost layers surrounding the Pacific basin have been displaced toward its center relative to the lower layers'.

3-2. Mechanism of Very Shallow Earthquakes.

3-2 a. *Mechanism of Very Shallow Earthquakes.* The distribution of the direction and magnitude of the initial motion of the P waves of the North Tango earthquake of Mar. 7, 1927, and those of the horizontal components of the P waves of the Itô earthquake of Mar. 22, 1930, and the North Idu earthquake of Nov. 25, 1930, are illustrated in Fig. 40, 41 and 42. The focal depth of each of these earthquakes is so shallow that the focus can

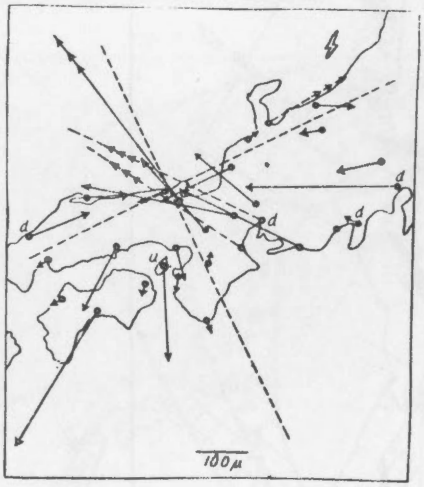


Fig. 40.

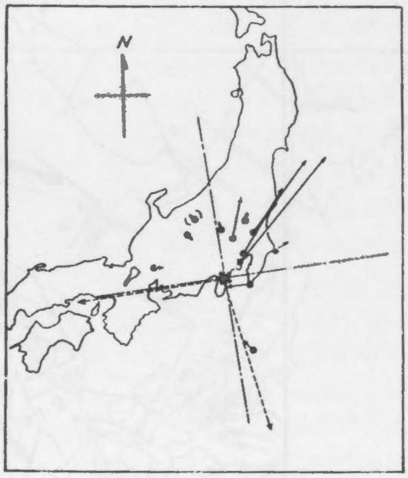


Fig. 41.

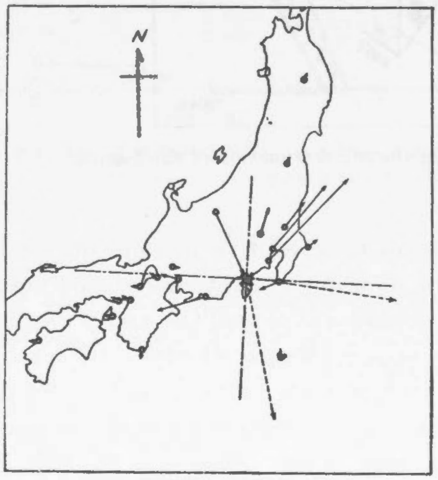


Fig. 42.

Fig. 40. The initial motion of P for the North Tango earthquake of Mar. 7, 1927.(48)

Fig. 41. The horizontal component of the initial motion of P for the Itô earthquake of Mar. 22, 1930.(47)

Fig. 42. The horizontal component of the initial motion of P for the North Idu earthquake of Nov. 25, 1930 (47)

be considered to lie in the earth's surface or within 10 or 15km from the earth's surface at most. The initial motions of the P waves are condensational in the two quadrants lying opposite to each other, and rarefactional in the other two quadrants, when the earth's surface is divided into four quadrants by two straight nodal lines crossing orthogonally at the epicenter. The magnitude of the initial motion of the P waves is minimum in the azimuths along the nodal lines and maximum in the middle azimuths between the neighbouring nodal lines, and its distribution can be approximately represented by the expression $(1/\Delta^2) \sin 2\varphi$; where Δ is the epicentral distance and φ is the azimuth of the station to the epicenter measured from one of the nodal lines.

Inspecting the seismograms of these and other very shallow earthquakes, it was found that the amplitude of the S waves is maximum in the azimuths along the nodal lines and minimum in the middle azimuths between the neighbouring nodal lines, and the amplitude of the surface waves is minimum in the former azimuths and maximum in the latter azimuths. The magnitude of the S waves is considered to be approximately proportional to $\cos 2\varphi$, and that of the surface waves to $\sin 2\varphi$.

In Fig. 43, are shown the seismograms of the aftershocks of the West Saitama earthquake of Sept. 21, 1931, recorded at some near stations, their positions relative to the

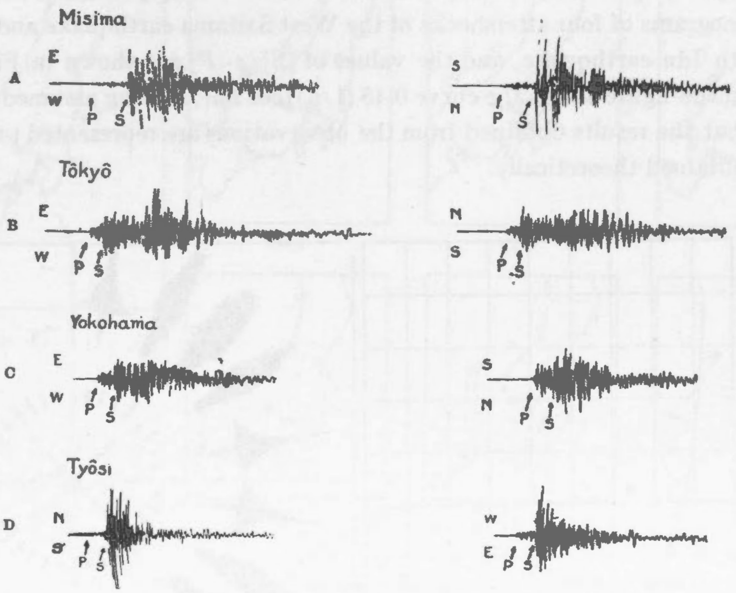


Fig. 43. The seismograms of the aftershocks of the West Saitama earthquake of Sept. 21, 1931.[48] (A),(B),(C) ; 1h22m Sept. 24, 1931. (D); 2h36m Oct. 3, 1931.

nodal lines being illustrated in Fig. 44. The focal depths of these earthquakes are also very shallow. The amplitudes of the P and surface waves are very small and those of the S waves are large at Misima and Tyôsi which are situated near the nodal line, whereas the amplitudes of P and surface waves are large and those of the S waves are small at Tôkyô and Yokohama situated in the middle azimuths between the neighbouring nodal lines.

When the radial force of the magnitude $Ar^3 \sin 2\varphi \times \exp(i\omega t)$, is assumed to be applied in the small circular area around the origin on the surface of a semi-infinite elastic solid, the amplitude of the P waves at a point on the surface is expected theoretically to be proportional to $(1/r^2) \sin 2\varphi$, (9), after NAKANO (1930), and the relation seems to be consistent with that obtained from the study of the observations of the initial motion of the P waves for very shallow earthquakes. The amplitudes of

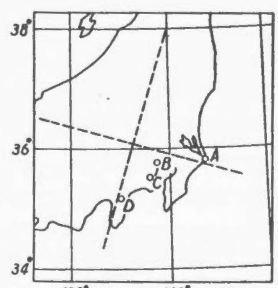


Fig. 44. The nodal lines for the aftershocks of the West Saitama earthquake.[48] A : Tyôsi, B : Tôkyô, C : Yokohama, D : Mishima.

the S and surface waves should be theoretically proportional to $\cos 2\varphi$, (10), and $\sin 2\varphi$, (11), respectively, and these relations also are consistent with those obtained from the observations. The ratio of the amplitude $[\delta_{s,\varphi}]$ of the S waves to the amplitude $[\delta_{p,r}]$ of the P waves at the station (r, φ) on the surface, can be expressed theoretically by the formula, by making use of (9) and (10),

$$\frac{1}{r}\frac{[\delta_{s,\varphi}]}{[\delta_{p,r}]} = 0.45 \cdot \frac{1}{l_p} |\cot 2\varphi|, \quad l_p\text{; the wave length of the P waves.}$$

The largest amplitudes $[P]$ and $[S]$ of the P and S waves respectively, were measured on the seismograms of four aftershocks of the West Saitama earthquake and a foreshock of the North Idu earthquake, and the values of $[S]/\Delta \cdot [P]$ are shown in Fig. 45. The thick line in the figure shows the curve $0.45\,(1/l_p)\,|\cot 2\phi|$, l_p being assumed to be 10km. It is seen that the results obtained from the observations are represented pretty well by the curve obtained theoretically.

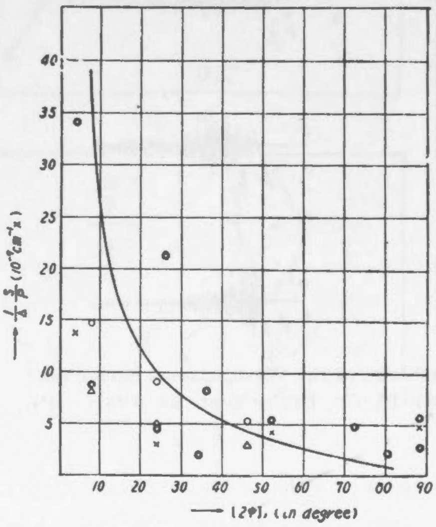


Fig. 45.

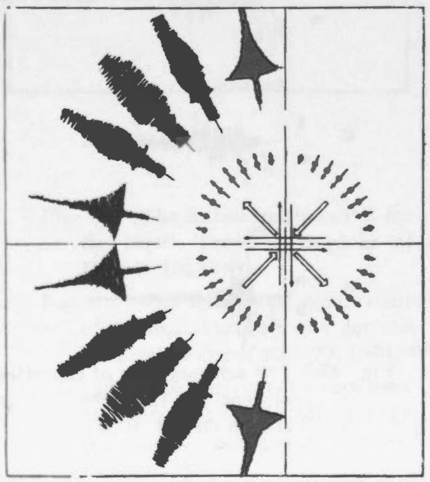


Fig. 46.

Fig 45. $[S]/\Delta \cdot [P]$ and $2|\varphi|$. Aftershocks of the West Saitama earthquake and a foreshock of the North Idu earthquake.[48]

Aftershocks of the West Saitama earthquake.

×; 21h46m Sept. 23, 1931. ◉; 1h22m Sept. 24, 1931.

△; 13h54m Sept. 28, 1931. ○; 2h36m Oct. 3, 1931.

Foreshock of the North Idu earthquake.

◎; 16h05m Nov. 25, 1930.

Fig 46. The mechanism and the types of the seismograms for very shallow earthquake.[48]

←: The initial motion of P.

The relations between the mechanism at the focus, the initial motion of the P waves and the types of the seismograms, are illustrated schematically in Fig. 46. (HONDA, 1931, 32a.)

KAWASUMI (1934a), and HONDA and H. WATANABE (1952) tried to take the effects of the increase of the velocity of the seismic waves from the earth's surface into account in the investigation of the magnitude of the P waves of the very shallow earthquakes, instead of treating the crust as homogeneous. The latter authors employed the results of HIRONO's theoretical studies (Sect. 2-2) on the P and S waves, emitted from the surface source into the interior of a semi infinite elastic solid.

3-2 b. *Mechanism of Aftershocks and Swarm Earthquakes.* The patterns of the condensation and rarefaction of the initial motion of the P waves of the West Saitama

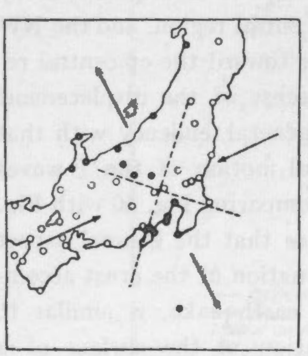


Fig. 47.

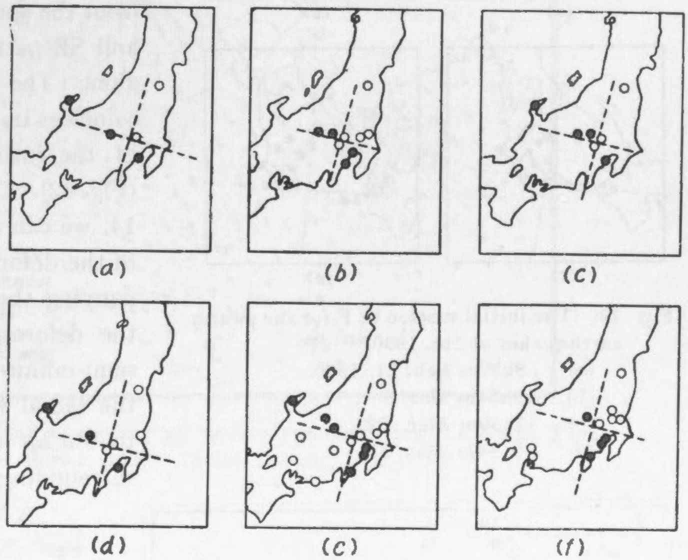


Fig. 48.

Fig. 47. The initial motion of P for the West Saitama earthquake of Sept. 21, 1931.[48]
●: Condensation. ○: Rarefaction.

Fig. 48. The initial motion of P for the aftershocks of the West Saitama earthquake.[48],[63]

●: Condensation. ○: Rarefaction.

(a)	15h49m Sept. 21, 1931	(d)	21h11m Sept. 24.
(b)	21h46m Sept. 23.	(e)	13h54m Sept. 28.
(c)	1h22m Sept. 24.	(f)	2h36m Oct. 3.

earthquake of Sept. 21, 1931, and of six rather conspicuous aftershocks of the main shock, are shown in Fig. 47 and 48. The mechanisms of the main earthquake and its aftershocks seem to be quite similar to each other.

For about four months from February to May in 1930, there occurred numerous very shallow earthquakes, swarm earthquakes, at Itô. The pattern of the condensation and rarefaction of the initial motion of the P waves of rather conspicuous earthquakes out of the swarm, are illustrated in Fig. 49. The mechanisms of these earthquakes seem also to be similar to each other. (HONDA, 1932a).

3-2 c. *Deformation of the Earth Crust Accompanying Very Shallow Earthquake.* A remarkable fault directed north and south, was observed in the North Idu earthquake of Nov. 25, 1930. The strike of the fault was nearly coincident with one of the nodal lines of the P waves. But the deformation of the crust accompanying the earthquake is not confined to the simple faulting motion. By the precise surveying performed after the earthquake, it was found that a large area surrounding the epicentral region was deformed at the earthquake. The horizontal dislocation of the earth's surface is shown by arrows in Fig. 50 (C. Tsuboi, 1939). The NE and SW parts of the region are displaced away from the epicentral region, and the NW and SE parts toward the epicentral region. The sense of the displacement coincides in general tendency with that of the initial motion of the P waves (Fig. 42). Comparing Fig. 50 with Fig. 14, we can see that the general aspect of the deformation of the crust accompanying the earthquake, is similar to the deformation of the surface of a semi-infinite elastic solid produced by the radial force which is proportional to $\sin 2\varphi$ and applied at the region surrounding the origin on the surface.

A large fault directed NW-SE, was observed at the time of the North Tango earthquake of Mar. 7, 1927. The strike of the fault coincides nearly with that of one of the nodal lines of the P waves (Fig. 40). Accompanying the earthquake, there occurred a remarkable deformation of the earth crust in the epicentral region (Fig. 51, after Tsuboi, 1939). The NE side of the fault is displaced toward NW, and the SW part toward SW. The pattern of deformation is similar to that in the lower half of Fig. 14, and the sense of dislocation is also nearly consistent with that of the initial motion of the P waves (Fig. 40). (Honda and Miura, 1935).

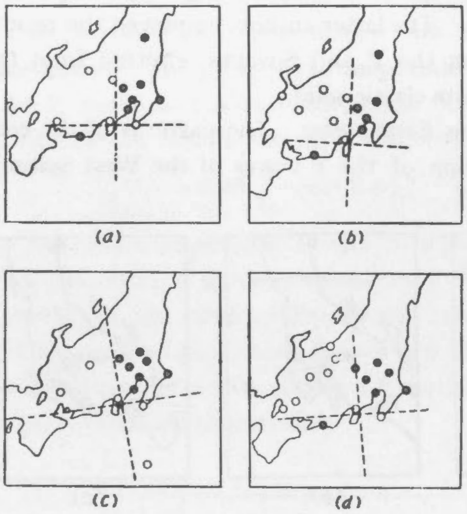


Fig. 49. The initial motion of P for the swarm earthquakes at Itô, 1930.(48),(63)
(a); 8h37m Feb. 21, 1930.
(b); 19h54m Mar. 9.
(c); 17h50m Mar. 22.
(d); 5h14m May 17.

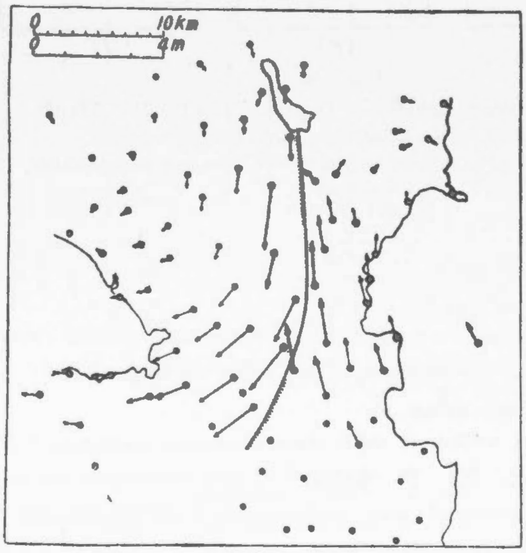


Fig. 50. The deformation of the earth's surface accompanying the North Idu earthquake of Nov. 25, 1930. (After Tsuboi, 1939.)

It is especially to be noticed that not only the distribution of the direction and magnitude of the seismic waves but also the general feature of the deformation of the earth crust accompanying very shallow earthquake, are explained theoretically by the hypothesis of the force system of the type II, even in the cases when distinct faults are observed at the earth's surface, except in the region very close to the fault. According to

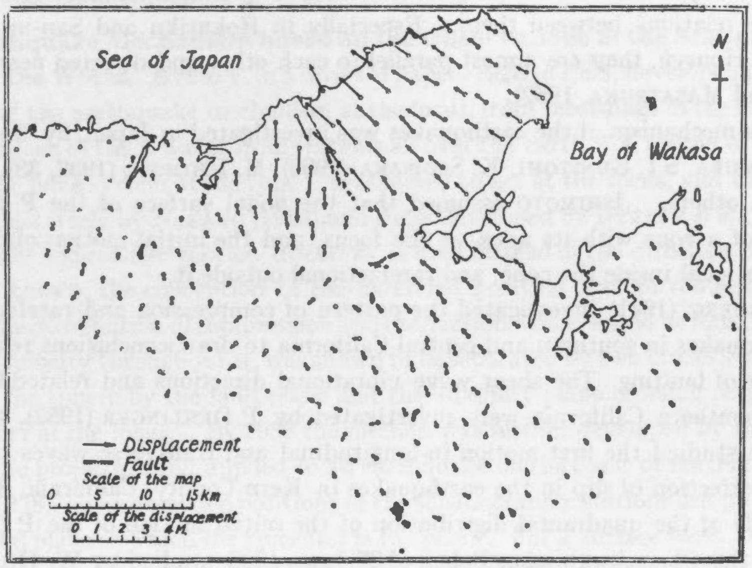


Fig. 51. The deformation of the earth's surface accompanying the North Tango earthquake of Mar. 7, 1927. (After Tsuboi, 1939.)

the theory of elasticity expressed e.g. by the equations such as $X_y = Y_x$ ...., it may be considered to be natural to suppose that the vast region in the earth is subjected to the large scale stresses corresponding to the force system of the type II, that the earthquakes occur when some faults or sudden collapses are generated by the stress, and yet that the general features of the seismic waves and the deformation of the earth crust surrounding the focal region are governed by the large scale stresses.

3–2 d. *Statistical Investigation of the Mechanism of Very Shallow Earthquakes.* The number of very shallow earthquakes occurred in or near Japan, and caused damage more or less during the period

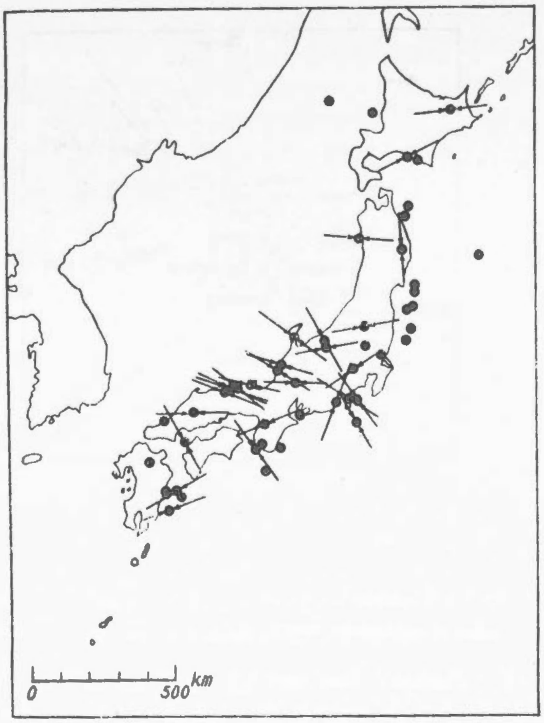


Fig. 52. The direction of the horizontal maximum pressure for the very shallow earthquakes, 1927-1949.[61]

1927 to 1949, amounted to 62. The mechanisms of 27 earthquakes out of them have been elucidated. When the directions of the horizontal maximum pressure for these 27 earthquakes are shown by arrows on a map (Fig. 52), it is seen that there exist some relations between them. Especially in Hokuriku and San-in, the Japan Sea side of Honsyû, they are almost parallel to each other and directed nearly NW-SE. (HONDA and MASATSUKA, 1952).

3-2 e. The mechanism of the earthquakes was investigated in Japan, by OMORI, SHIDA, S.T. NAKAMURA, S.I. KUNITOMI, K. SAGISAKA (1930), M. ISHIMOTO (1932, 33), H. TAKAGI (1950) and others. ISHIMOTO assumed that the nodal surface of the P waves is in the shape of a cone with its apex at the focus, and the initial motion of the P waves is condensational inside the cone, and rarefactional outside it.

GUTENBERG (1941) investigated the pattern of compression and rarefaction in the local earthquakes in southern and central California to draw conclusions respecting the mechanism of faulting. The shear wave vibrational directions and related fault movements in southern California were investigated by P. DEHLINGER (1952). GUTENBERG (1955) also studied the first motion in longitudinal and transverse waves of the main shock and direction of slip in the earthquakes in Kern County, California, during 1952. An example of the quadrantal distribution of the initial motion of the P (P_g and P_n) waves for the Oberschwäbisches Beben of 27 June, 1935, studied by W. HILLER (1953), is shown in Fig. 53. DI FILIPPO *et al.* (1949, 50) and P. CALOI *et al.* (1952, 55, 56) investigated the mechanism of the earthquakes occurred in Italy.

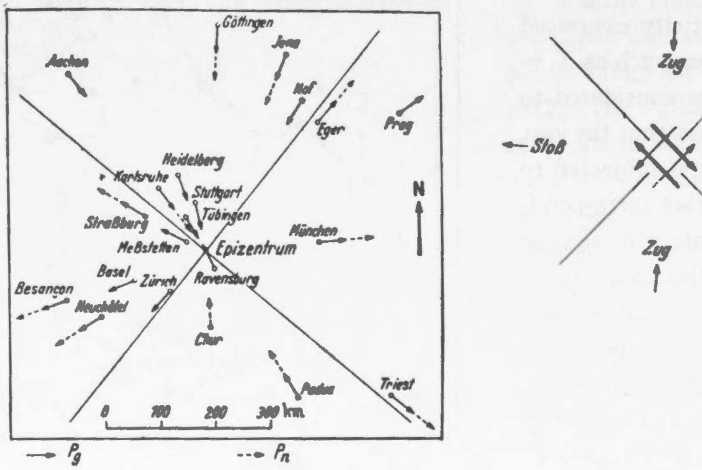


Fig. 53. The initial motion of P_g and P_n and the mechanism for the Oberschwäbisches Beben of June 27, 1935. (After HILLER, 1953.)

4 Investigation of Earthquake Mechanism based on the Observations at the Stations distributed over the World

4-1. Distant Earthquakes recorded at Individual Stations. P. E. GHERZI, O. SOMVILLE and others showed that the initial motions of the P waves recorded at individual station are condensational for distant earthquakes occurring in certain regions and rarefactional for those in other regions. BYERLY and J. F. EVERNDEN (1950) published a map for circum-Pacific epicnters, showing the nature of the initial motions of the P waves recorded at Berkeley. M. Båth (1952) made a similar investigation for Pasadena and Huancayo, and J.W. Jones (1952) for Seattle.

4-2. Earthquake Mechanism based on the Observations at the Stations distributed over the World. Byerly, in a series of papers 1926 to 1955, developed the methods for studying the earthquake mechanism at the focus, from recordings of the compressions and rarefactions of the P waves from stations all over the earth. A couple of forces with moment, the force system of the type I, is assumed to act at the focus, and the results of the theoretical study by Nakano (1923) and those developed by Byerly *et al.*, (1949) were adopted. The expression 'motion direction' is used instead of the direction of the forces. As is well known, the conception of the extended position was introduced by him in 1928, and the distribution of compression and rarefaction which would be found on a sphere of uniform velocity throughout it, was shown to be separated by two circles, which are the sections of the sphere by the fault plane and the auxiliary plane crossing perpendicularly to each other at the focus. 'By 1938 the method was further developed by the use of the stereographic projection and applied to an earthquake on the coast of northern California (Byerly, 1938). The extended positions of the seismographic stations are projected onto an equatorial plane of which the epicenter is the pole'*. For a surface focus, the extended distance is equal to $R \tan e$, where R is the radius of the earth and e the angle of emergence of the seismic ray arriving at the station (Fig. 54). 'These projected points are marked as to whether the first P wave was a compression or a rarefaction. The problem is then to draw

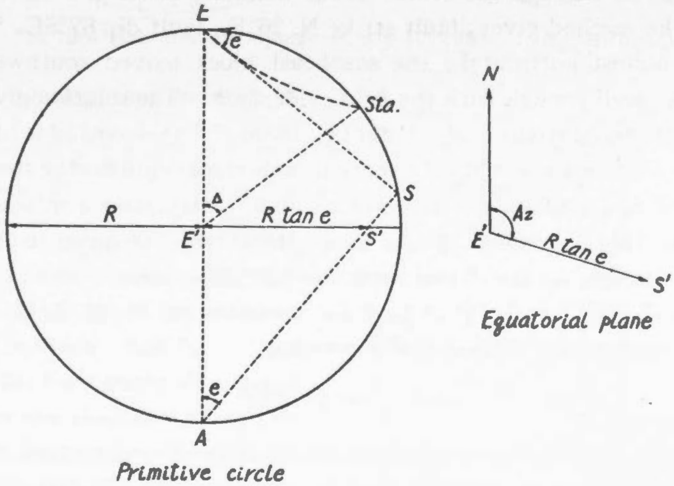


Fig. 54. The stereographic projection.
E: Epicenter. A: Anticenter. Sta: Station. S: Extended position of station. e: Angle of emergence. S': Stereographic projection of S. ---- : Seismic ray. Az: Azimuth of station from epicenter. (After Byerly, 1955.)

two circles on this equatorial plane which pass through the focus and which separate regions of compression and rarefaction'*, as the circles on the sphere project into circles on the map. The stereographic projection method was applied to the Montana earthquake of

June 28, 1925; the projection for the earthquake is shown in Fig. 55. (Byerly, 1955). 'The strike of the fault is given by the direction of a tangent drawn at the projection of the epicenter to the fault plane circle. The auxiliary plane is described by the second

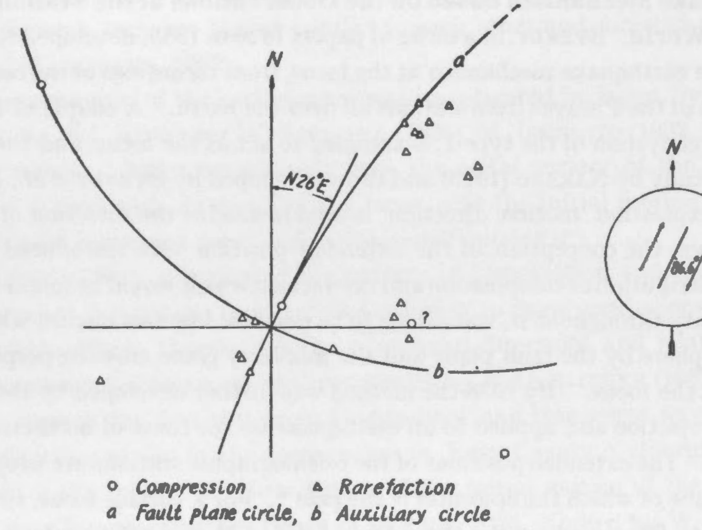


Fig. 55. The Montana earthquake of June 28, 1925. (After Byerly, 1955)

circle on the projection. The plunge of the line of motion of the fault is given by the direction of the line through the center of the auxiliary circle and the epicenter. For the example the method gives: fault strike N. 26°E., fault dip 87°SE. The motion on the fault was almost horizontal; the southeast block moved southwest. Thus the direction agrees well enough with the field evidence'*. The solution given here is one of the two possible solutions. (* ; Byerly, 1955)

Hodgson *et al.* have developed remarkably the technique for the stereographic projection method and applied the method to many earthquakes, in a series of papers published since 1951. For non-surface foucs, the earth is stripped to the focal depth, and the method is used for the virtual surface focus. The tables of the extended distances for the phases P, PKP, PcP, PP and pP for various focal depths have been produced. There holds a relationship, orthogonality criterion,

$$\cos\theta = \tan\beta/\tan\delta$$

between the angle of intersection of the two circles θ, the dip of the fault δ, and the plunge of the line of movement on the fault β. (J.D. Adkins, 1940, Hodgson *et al.*, 1951).

A fault plane solution for the New Hebrides earthquake of May 17, 1950, is shown in Fig. 56. 'The circles represent two planes, one striking approximately NS and dipping 79° to the W, the other striking approximately EW and dipping 71° to the N. There is no way of recognizing which of these planes is the fault plane and which the auxiliary plane, but the fact that the circles are almost orthogonal indicates that the movement must be almost strike-slip or *transcurrent*. For example, suppose that the NS striking plane is the fault. Then the EW plane is the auxiliary plane, which is by definition perpendicular to the direction of slipping. It follows that this direction must be approximately NS, parallel to the strike of the fault. Strike-slip faulting is therefore indicated. On the other hand, if the circles had been tangential a similar argu-

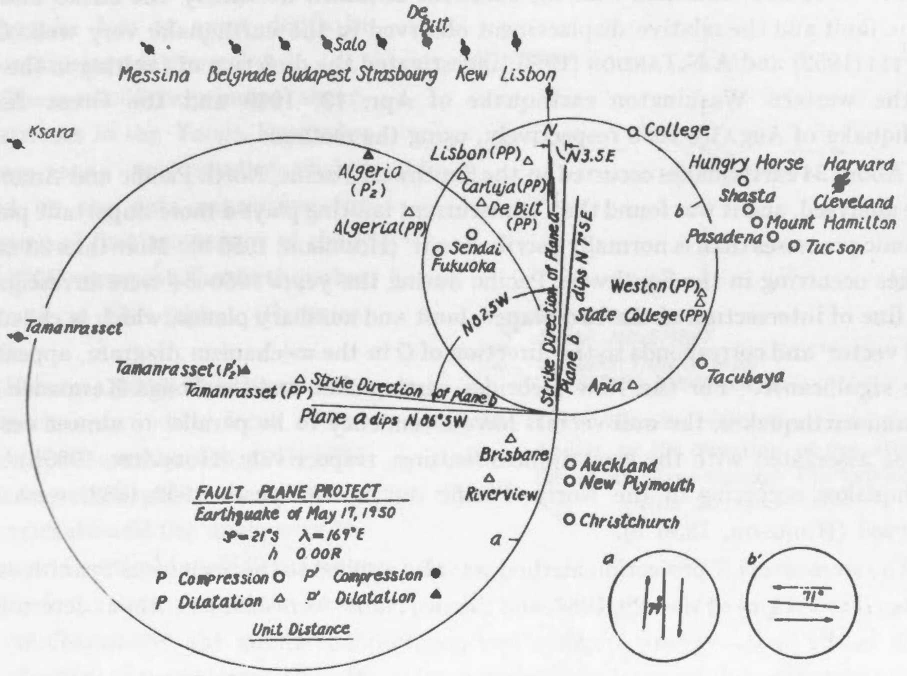


Fig. 56. The New Hebrides earthquake of May 17, 1950. (After HODGSON, 1955)

ment would show that motion must be perpendicular to the strike. In the small circular diagrams labelled *a* and *b* the two possibilities have been illustrated, the arrows representing the horizontal projection of the motion vector slightly displaced from the center of the diagram for clarity' (HODGSON, 1955 b). The mechanism of the earthquake illustrated by the small circular diagrams *a* and *b* in Fig. 56, can be shown schematically by the mechanism diagram which is explained in Sect. 3-1. Assuming that one of the nodal planes strikes approximately N4°E and dips 79° to the W, and the other one strikes N83°W and dips 71° to the N, we can obtain the directions of P_1, T_1, M_1, M_2 and Q. The mechanism diagram basing on these data is shown in

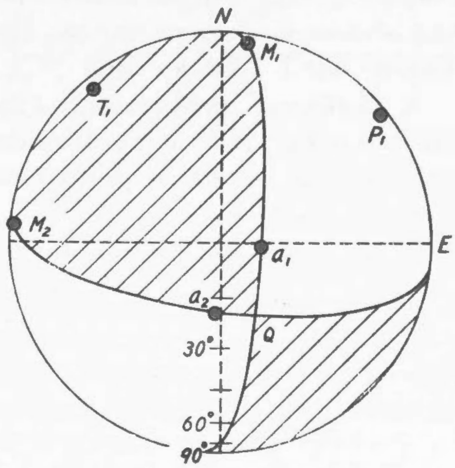


Fig. 57. The mechanism diagram for the New Hebrides earthquake of May 17, 1950.
P_1; N51°E (85°). T_1; N41°W (68°).
M_1; N 7°E (71°). M_2; N87°W (79°).
a_1; S87°E (11°). a_2; S 7°W (19°).
Q; S26°E (22°). (Slip angle)$_{1,2}$ = 20°, 12°

Fig. 57. The directions of M_1 and M_2 correspond to the supposed directions of motion illustrated by arrows in *a* and *b* of Fig. 56, respectively.

HODGSON (1955a), applied his method of analysis to the Tango earthquake, Japan, of Mar. 7, 1927, and confirmed that the solutions obtained do satisfy the strike and dip of the fault and the relative displacement observed in the earthquake very well. O.W. NUTTLI (1952) and A.N.TANDON (1955) investigated the direction of faulting in the case of the western Washington earthquake of Apr. 13, 1949 and the Great Assam earthquake of Aug. 15, 1950 respectively, using the method.

About 34 earthquakes occurred in the Southwest Pacific, North Pacific and Americas, were analysed, and it was found that 'transcurrent faulting plays a more important part in tectonic processes than is normally ascribed to it' (HODGSON, 1955 b). More than 23 earthquakes occurring in the Southwest Pacific during the years 1950–54 were investigated. The line of intersection of the two planes, fault and auxiliary planes, which is called the 'null vector' and corresponds to the direction of Q in the mechanism diagram, appears to have significance. For the New Hebrides earthquakes and the Tonga-Kermadec-New Zealand earthquakes, the null vectors have a tendency to lie parallel to almost vertical planes associated with the geographical features, respectively (HODGSON, 1956 a). 11 earthquakes occurring in the North Pacific during the years 1950–1953, were also analysed (HODGSON, 1956 b).

The stereographic projection method was also applied to the deep focus Spanish earthquake (H=650 km) of Mar. 29, 1954, and the two planes were defined without determining which is the fault. 'There are thus two possibilities. Under the first possibility the fault is approximately vertical and strikes north-south. The movement is vertical, such that the eastern side of the fault rises with respect to the western side. Under the second possibility the fault is approximately horizontal, and the movement is also horizontal, the material above the focus moving due east with respect to the material below the focus' (HODGSON and J. I. COCK, 1956).

S. Mühlhäuser (1957) determined the mechanisms for 11 earthquakes in the years 1931–1950 in the Pacific area. 'It results that there is no general rule for the mechanisms, although the strikes of the fault planes in general coincide with the circum-Pacific structural lines.'

L.P.G. KONING (1942) investigated the mechanism of the deep earthquake of June 29, 1934 occurred in the Flores Sea at a depth of 720 km. Two other deep earthquakes in the Indonesian Archipelago, one with epicenter in the Java Sea (Aug. 11, 1937. H; 610km), the other with epicenter in Mindanao (Sept. 22, 1940. H; 660 km), were investigated by A.R. RITSEMA (1953)*. 'In all these cases it has been determined that the earthquake originated by a sudden shear movement along a flat plane in the focus"* and it is 'not certain, however, about the dip of the actual shear plane because we get two possible planes of shear movement perpendicular to each other for each single earthquake'.* Fig. 58 'shows a schematic section perpendicular to the strike of the shear plane through the focus of one of the earthquakes. Only a normal dip-slip movement along one of the possible planes of shear movement can explain the distribution of the + (condensation) and - (rarefaction) areas at the earth's surface. That means the existence of a tension force in horizontal sense, or a compression force in vertical sense at the depth of the focus'.* And it is expected 'that this type of movement in earthquake foci at great depth in the archipelago is general'.*

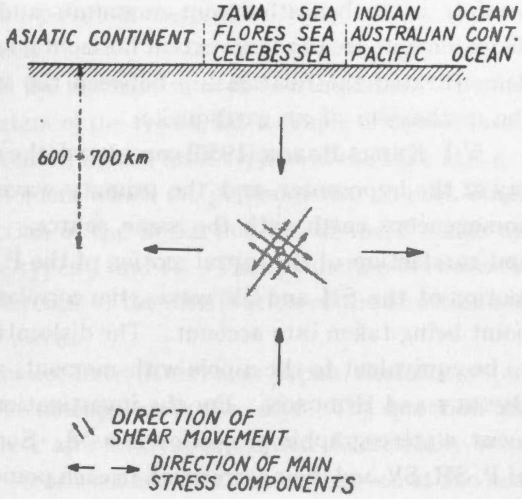


Fig. 58. The schematic vertical section perpendicular to the direction of the strike of the shear plane through the hypocenter. (After RITSEMA, 1953.)

The sense of the principal shearing stresses in the Tonga-Kermadec seismic zone was studied, being based on the data concerning the direction of first movement of the P and PKP waves of the earthquakes occurred in the region (RITSEMA, 1954).

RITSEMA (1955) investigated also the mechanism in the focus of the Hindu Kush earthquakes, 1917–1952, centering at a depth of about 220 km. The azimuth and the angle with the downward vertical in which the wave left the focus were used as the variables in illustrating the mechanism. Compression and dilatation data of the P and PKP waves were the bases of the study. It was found 'that the earthquakes are caused by a thrust fault movement in the focus. The principal stress component (greatest compression) acts about horizontal in the NW-SE azimuth, the smallest stress component (greatest stretching) about vertical somewhat inclined towards SW. The derived stress system is not in contradiction with the about NE-SW tending Hindu Kush mountain system'. Fig. 59 shows the vertical section through the focus in the NW-SE azimuth. It is noticed that the sense of the first motion of the S waves illustrated in the figure seems to be in accordance with that shown schematically in Fig. 6 (b) for the force system of the type II.

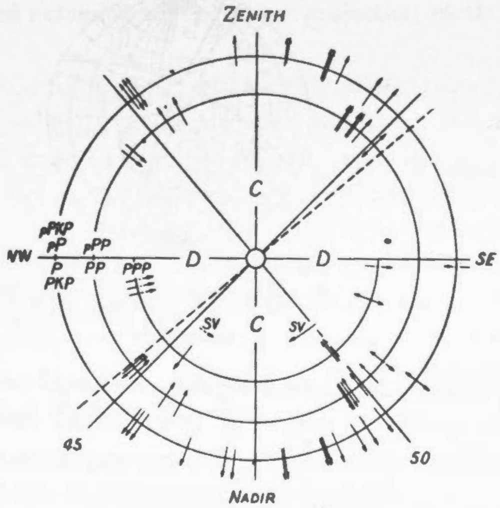


Fig. 59. The vertical section through the Hindu Kush earthquake center in the NW-SE azimuth. (After RITSEMA, 1955.)

A.E. SCHEIDEGGER (1955) collected the results of the studies of the displacements which are considered to be taking place during the occurrence of an earthquake in its focus, published by various authors, and analysed their bearing upon the physics of orogenesis.

He found that the earthquakes are localized in almost planar zones dipping at some intermediate angle beneath recent mountain and island belts, and that the differential displacements are to a large extent horizontal i.e. transcurrent. SCHEIDEGGER (1957) also demonstrated the relationship between the various methods devised for representing the mechanism of an earthquake.

V.I. KEILIS-BOROK (1956) considered 'the straight ray', semi-tangent to the seismic ray at the hypocenter, and 'the primary waves' which would be observed in a virtual homogeneous earth with the same source. He treated not only the condensation and rarefaction of the initial motion of the P waves, but also the senses of the initial motion of the SH and SV waves, the correlation of the signs of these phases for every point being taken into account. The dislocations in the source are considered as a rule to be equivalent to the dipole with moment, which is the same one as that adopted by BYERLY and HODGSON. For the investigation and illustration of the mechanism at the focus, a stereographic projection is used. Some examples of interpretation using signs of P, SH, SV and their correlation in each point, given from top to bottom, are illustrated in Fig. 60, where the points (directions of the seismic rays in the hypocenter) are plotted in a stereographic projection. The mechanisms of many earthquakes occurred in the

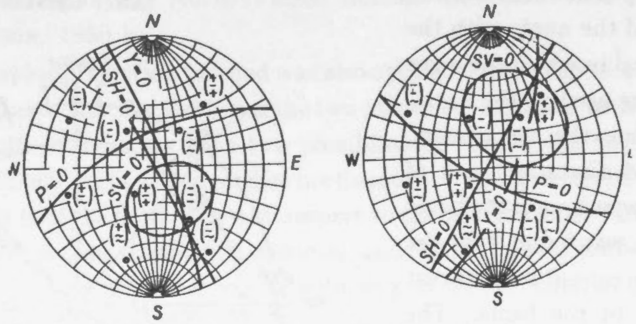


Fig. 60. Some examples of interpretation using the signs of P, SH and SV. (After KEILIS-BOROK, 1956.)

southern and eastern regions of Russia were investigated, and it was confirmed that the geological 'structures as well as the earthquakes seem to be the parallel results of general seismotectonic strains acting in vast regions.'

4-3. S and Other Waves. The initial motions of the S waves as well as other waves, have been studied by F. NEUMANN (1930), R. STONELEY (1951), K. ERGIN (1952), R.R. HEINRICH and H.K. HAILL (1952), and R.E. INGRAM (1953). INGRAM and HODGSON (1956) investigated theoretically the phase changes of PP and pP on reflection at the earth's surface, and the results are expressed for various focal depths, in terms of epicentral distances for PP and for pP between which there is no phase change on reflection.

5 Concluding Remarks

Some of the results of the investigations on the mechanism of the earthquakes by many seismologists since about 1930, have been described in foregoing chapters of the present paper. Now let us state about some points of the problem which are considered to necessitate especially further researches.

There are two kinds of assumptions on the mechanism of the earthquakes. The first one of them is represented by the force system of the type I, i.e. a couple of double forces with moment, and the second one is represented by the force system of the type II, i.e. a set of two couples of double forces with moment which are perpendicular to each other. The patterns of condensation and rarefaction of the initial motions of the P waves are similar to each other for the systems of the types I and II. The distinction between the two force systems is recognized in the difference of the distribution of the direction and magnitude of the initial motions of the S waves.

In the investigation of the earthquakes occurred in and near Japan, the force system of the type II is considered to represent the mechanism in the focus. The direction and the magnitude of the initial motions of the P and S waves calculated theoretically being based on the assumption, are shown to be in accordance with those observed at the near stations in Japan.

On the other hand, it is considered by many seismologists that the force system of the type I represents the mechanism of the earthquakes. The patterns of compressions and rarefactions of the P waves observed at the stations over the world, are explained being based on the assumption and the so-called extended stereographic projection method being used.

The force system of the type I may seem to be consistent with the elastic rebound theory. But it is to be noticed that not only the distribution of the direction and magnitude of the initial motions of the P and the S waves of deep as well as very shallow earthquakes, but also the deformation of the earth's surface accompanying some very shallow earthquakes in Japan, can be explained by the dynamical and statical force systems of the type II respectively, even when conspicuous faults are observed on the earth's surface. Further and minute investigations of the initial motion of the S waves observed at the stations over the world are desired, to be able to see which of the two assumed force systems of the types I and II, may be preferred as that representing the mechanism in the foci of the earthquakes.

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On the Focal Mechanism of Southeast Asian Earthquakes

by A. R. Ritsema,

Meteorological and Geophysical Institute, Djakarta, Indonesia.

ABSTRACT

The mechanism in the focus of about 60 southeast Asian earthquakes has been determined. Byerly's method (1938) in the form developed by the present writer is used. With the help of seismogram readings of the position of the line of polarization of S waves it was determined that in at least twelve of the shocks a single couple of forces acting along the line of fault movement was the cause of the earthquakes (Keylis-Borok, 1956). In about half of the total material, however, no conclusive evidence could be found for a choice between this type of mechanism in the focus and that of two opposite couples of forces of equal magnitude acting along lines perpendicular to each other (Honda, 1957). In the following it is assumed that these shocks also are caused by the first mentioned force system in the focus. Following and amplifying Hodgson's statement (1958), it is concluded that sufficiently reliable data for earthquake mechanism studies can be expected only from P, PKP and S waves. According to the fault movements in the focus different earthquake types are distinguished (transcurrent, clockwise and counterclockwise, normal and reversed).

In the section dealing with southeast Asian earthquake mechanism it is seen that transcurrent fault movements are about three times more common than they should be in case of a chance distribution of earthquake types. Evidence is given for small differences of earthquake mechanisms in depth and region. It is concluded that most of the fault displacements are directed perpendicular to the steeply dipping zones of seismic activity in the region. Also in the shocks in which these directions do not coincide, the plane of action still stands more or less perpendicular to this zone. This coincidence for the great majority of the earthquakes can only mean that the distribution of earthquakes in space and the fault displacements of the same probably are expressions of one and the same causal fact.

From the earthquake mechanisms shown to exist in the New Guinea-Solomons arcs it should follow that in these areas the seismic activity is concentrated in a zone steeply dipping under the Pacific Ocean side and not under the continental (i.e. Australian) side as is the case in the Sunda and the Celebes-Philippines arcs.

GENERAL PRINCIPLES OF THE METHOD

Introduction

Focal mechanism studies of earthquakes of the Sunda arc, the Celebes-Philippines arc, and the New Guinea-Solomons arcs were executed at the Seismological Department of the Meteorological and Geophysical Institute, Djakarta. Table I comprises the solutions reached. The data on which the solutions are based can be found in the publication series of the Djakarta Institute. One solution reached by Hodgson (1956) for an earthquake of the Solomon Islands group is included in the Table as earthquake number 43. The tentative determination of the direction of fault displacement of this shock is based on the S waves observed at the Indonesian stations.

The solutions reached by Veldkamp (1957) for Sumatran shocks are not included in the list. The complete solutions of these shocks will appear in the near future in the publication series of the Royal Netherlands Meteorological Institute, De Bilt.

The principle on which the study of earthquake mechanisms is based is the assumption that the initial character of the seismic waves remains the same from a small sphere around the focus to the observing stations. A compressional (or dilatational) P wave in a station means that the wave started from the focal region as a compression (or dilatation).. At the same time it is assumed that the angle α between the line of polarization of an S wave and the plane of incidence remains constant. This means that the proportion SH/SV as determined in the station is the same as that in the focal region.

Table I. The earthquake mechanisms of southeast Asia.

No.	Date G.M.T.	Epicenter	Depth Magnitude	I	II	III	IV	V	VI	Type	Evidence
1	1930 June 4 09h50m29s	6 1/2° S 128 1/2 E	0.06 R 6 3/4	53° 14	160° 50	52°	313° 36	205° 22	91° 46	P (R)	poor
2	1931 Mar. 28 12.38.37	7 S 129 1/2 E	0.01 R 7.3	50 7	144 29	30	307 60	190 15	93 26	R (P)	poor
3	1934 June 29 08.25.17	6 3/4 S 123 3/4 E	0.11 R 6.9	98 38	340 31	41	223 36	35 54	180 4	T (R)	poor
4	1935 Oct. 4 05.15.36	6 N 125 E	0.07 R 6 1/2	50 70	290 10	31	197 16	309 52	96 33	T (R)	poor
5	1936 Jan. 20 16.56.19	6 N 127 E	0.01 R 7.1	175 4	85 6	6	300 82 1/2	40 1	130 7	L (P)	fair
6	1936 Apr. 28 13.35.45	6 1/2 S 129 E	0.03 R 6 1/2	300 35	47 23	29	163 46	358 43	261 7	L (T)	poor
7	1936 May 8 09.11.34	5 3/4 S 112 3/4 E	0.09 R 6 1/2	235 9	143 15	15	355 72	98 4	190 17	L (P)	poor
8	1936 June 10 08.23.21	5 1/2 S 147 E	0.02 R 6.9	97 23	196 20	22	323 58	56 2	147 32	R (P)	fair
9	1937 Apr. 5 06.56.41	1 S 133 E	0.01 R 6.9	215 7	123 18	19	326 70	171 18	78 8	R (T)	fair
10	1937 Aug. 11 00.55.52	6 1/2 S 116 1/2 E	0.09 R 7.2	347 66	191 22	67	98 8	208 66	4 22	T (R)	poor
11	1938 Aug. 18 09.30.04	3 3/4 S 102 3/4 E	0.01 R 6.9	330 63	150 27	90	60 0	330 18	150 72	P (?)	poor
12	1938 Aug. 31 17.45.13	4 S 151 1/2 E	0.05 R 6 3/4	106 13	200 18	19	342 68	244 3	152 22	R (P)	poor
13	1938 Oct. 20 02.19.29	9 1/4 S 123 E	0.01 R 7.3	264 42	156 19	26	49 42	200 44	305 14	T (R)	fair
14	1939 Dec. 21 21.00.40	0 123 E	0.02 R 8.0	150 57	357 30	67	260 12	166 14	30 71	P (L)	fair
15	1940 June 18 13.52.33	5 1/2 N 123 E	0.08 R 6 1/2	120 50	315 39	79	218 7	224 76	122 3	T (R)	poor
16	1940 June 22 11.36.46	0 122 1/2 E	0.03 R 6 3/4	148 36	25 37	48	266 33	357 1	87 57	P (L)	fair
17	1940 Sept. 22 22.51.58	7 1/2 N 123 1/2 E	0.10 R 6 3/4	302 52	55 17	28	157 33	17 50	261 21	T (L)	fair
18	1940 Oct. 7 06.43.04	5 N 126 E	0.01 R 7.0	322 26	72 35	40	203 44	13 46	108 5	T (L)	poor
19	1941 Jan. 31 02.38.40	6 1/2 S 128 1/2 E	0.03 R 6 3/4	174 9	77 36	37	276 53	132 32	30 18	R (T)	fair
20	1941 Feb. 4 14.03.12	9 N 124 E	0.09 R 6.9	321 44	105 40	63	212 19	35 70	303 2	T (L)	fair
21	1941 Feb. 25 05.37.45	9° S 125 E	0.02 R 6.9	135 42	38 7	10	300 47	184 23	67 34	L (P)	fair
22	1941 Sept. 4 10.21.44	4 1/2 S 154 E	0.01 R 7.1	208 25	103 28	32	332 50	65 2	156 40	L (P)	fair
23	1941 Sept. 17 06.48.04	1/4 N 122 3/4 E	0.03 R 7.1	91 23	344 34	38	208 47	43 42	306 8	R (T)	fair
24	1941 Nov. 27 08.37.34	6 1/2 S 121 E	0.07 R 6 3/4	137 17	23 53	57	238 32	342 21	100 51	P (L)	fair
25	1942 May 28 01.01.48	0 124 E	0.01 R 7.5	120 15	212 8	8	329 73	167 16	75 5	L (T)	fair
26	1942 July 25 06.22.35	11 1/2 N 124 1/2 E	0.01 R 6 3/4	200 12	293 13	14	68 72	247 18	337 1/2	L (T)	fair
27	1943 June 30 10.49.02	7 S 122 E	0.11 R 6 3/4	278 20	180 20	22	49 61	318 0	228 29	L (P)	poor
28	1943 Dec. 1 06.04.55	4 1/2 S 144 E	0.01 R 7.2	171 6 1/2	80 12	12	290 76	126 13	35 3	R (T)	fair
29	1944 Mar. 22 00.43.18	8 1/2 S 123 1/2 E	0.03 R 7.5	110 25	12 16	18	252 60	152 6	59 30	L (P)	fair
30	1945 Apr. 22 09.51.18	5 N 123 E	0.10 R 6 3/4	240 10	133 60	61	335 28	211 47	83 29	T (R)	poor

Table I. The earthquake mechanismes of southeast Asia—*Concluded.*

No.	Date G.M.T.	Epicenter	Depth Magnitude	I	II	III	IV	V	VI	Type	Evidence
31	1945 May 9 03.31.13	7 1/2° S 124 E	0.08 R 6 3/4	107° 45	355° 20	30°	249° 38	40° 48	147° 15	T (R)	poor
32	1946 June 15 18.29.16	3 S 128 E	0.01 R 6 1/4	128 17	34 13	14	268 68	80 22	172 3	R (T)	poor
33	1948 Jan. 28 03.47.21	1 1/2 N 126 1/2 E	0.01 R 7.2	304 30	187 37	44	61 38	249 52	154 4	T (R)	fair
34	1949 Apr. 23 11.15.39	8 S 121 E	0.01 R 7.1	76 20	185 40	44	327 43	225 13	122 44	P (R)	poor
35	1949 Apr. 30 01.23.37	7 N 125 E	0.02 R 7.4	157 21	257 23	26	30 58	297 2	206 32	R (P)	fair
36	1950 Aug. 7 02.44.45	7 1/2 N 124 1/2 E	0.01 R 6 3/4	141 23	240 20	23	7 58	100 2	191 32	R (P)	fair
37	1950 Sept. 14 09.05.50	1/2 N 127 E	0.03 R 6 1/2	51 4	321 4	4	186 84	6 6	276 0	R (T)	poor
38	1950 Dec. 4 16.28.01	5 S 153 1/2 E	0.01 R 7	113 30	221 28	33	345 47	76 1	167 43	R (P)	fair
39	1951 Feb. 17 21.07.09	7 S 146 E	0.03 R 7 1/4	158 55	56 8	14	320 34	88 42	208 29	T (R)	fair
40	1952 Feb. 11 07.01.06	5 1/2 S 109 3/4 E	0.10 R 6.9	94 26	198 26	30	326 51	146 39	56 0	L (T)	fair
41	1952 Feb. 14 03.38.15	7 3/4 S 126 1/2 E	0.00 R 7 1/4	217 3	126 16	16	317 74	173 13	81 10	R (T)	fair
42	1952 Mar. 19 10.57.09	9 1/2 N 126 E	0.00 R 7 1/2	228 37	102 38	50	344 31	165 59	75 1	T (R)	fair
43	1952 May 9 17.47.40	6 1/2 S 155 E	0.01 R 7	308 34	206 18	22	93 50	350 10	253 38	L (P)	poor
44	1952 July 13 17.34.30	3 S 127 1/2 E	0.00 R 6 1/2	121 64	263 18	45	349 19	87 25	227 59	P (R)	fair
45	1953 Jan. 20 17.33.07	1 1/2 N 126 E	0.00 R 6 1/2	65 10	155 1	1	252 80	111 8	19 6	L (T)	fair
46	1953 Apr. 6 00.36.16	7 1/4 S 131 E	0.00 R 7	217 31	112 23	28	352 50	162 40	256 5	R (T)	fair
47	1953 June 25 10.44.57	8 1/2 S 123 1/2 E	0.00 R 7 1/4	114 3	204 2 1/2	3	330 86	69 0	159 4	R (P)	fair
48	1953 July 7 04.07.48	1 N 100 E	0.03 R 6 1/2	320 53	95 28	52	197 22	293 14	52 64	P (R)	fair
49	1953 Nov. 13 16.17.05	3 1/2 N 96 E	0.00 R 6 1/4	288 1	18 2	2	168 88	63 1/2	333 2	R (P)	poor
50	1953 Dec. 2 04.24.51	2 3/4 S 141 1/2 E	0.00 R 6 1/2	130 1	40 2	2	245 88	355 1/2	85 2	L (P)	fair
51	1954 Jan. 1 13.04.19	9 S 123 1/2 E	0.01 R 6 1/2	236 26	327 1	1	58 64	188 17	285 19	R (P)	fair
52	1954 Feb. 20 18.35.07	7 S 124 1/2 E	0.09 R 6 3/4	340 62	89 10	22	184 26	61 47	291 31	T (L)	fair
53	1954 Mar. 3 06.02.55	5 1/2 S 142 1/2 E	0.00 R 7	282 14	191 5	5	83 75	236 14	327 6	R (T)	fair
54	1954 June 6 16.50.40	3 S 135 1/2 E	0.00 R 7	249 2	346 75	75	158 15	55 41	264 44	P (R)	fair
55	1954 June 7 10.15.33	3 1/2 S 152 1/2 E	0.07 R 6 3/4	191 2	99 43	43	283 47	154 31	46 27	R (T)	fair
56	1954 July 3 22.31.25	6 1/2 S 105 1/2 E	0.01 R 6 3/4	37 24	165 54	63	295 25	198 16	78 60	P (R)	fair
57	1954 Sept. 20 00.39.28	1 1/2 S 120 1/2 E	0.00 R 6	145 52	254 14	24	354 35	100 23	217 47	P (R)	fair
58	1954 Oct. 3 23.21.35	1 1/2 S 127 1/2 E	0.00 R 6 1/4	201 3	110 10	10	307 80	65 5	155 9	L (P)	fair
59	1954 Nov. 2 08.24.10	8 S 119 E	0.00 R 6 1/2	91 3	182 16	16	352 74	228 9	135 13	R (P)	fair

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Methods

After gathering the initial motion data of P, PKP and S waves of many stations all over the world, the following procedure is pursued to arrive at a solution.

1. Determine the azimuth of the station from the epicenter, the epicentral distance, and the azimuth of the epicenter from the station. This is done using a chart published by the Dominion Observatory (Willmore and Hodgson, 1955).

2. Determine the angle i at which the wave left the focus to emerge at the station. This is done with the help of a set of graphs showing for any depth of fucus (with intervals of 0.01R) the (i, Δ)-functions. The graphs are based on the Seismological Tables of Jeffreys and Bullen, and are calculated in the usual way (Byerly, 1955; Ritsema, 1952; Hodgson and Storey, 1953). An example of such a graph is shown in Figure 1.

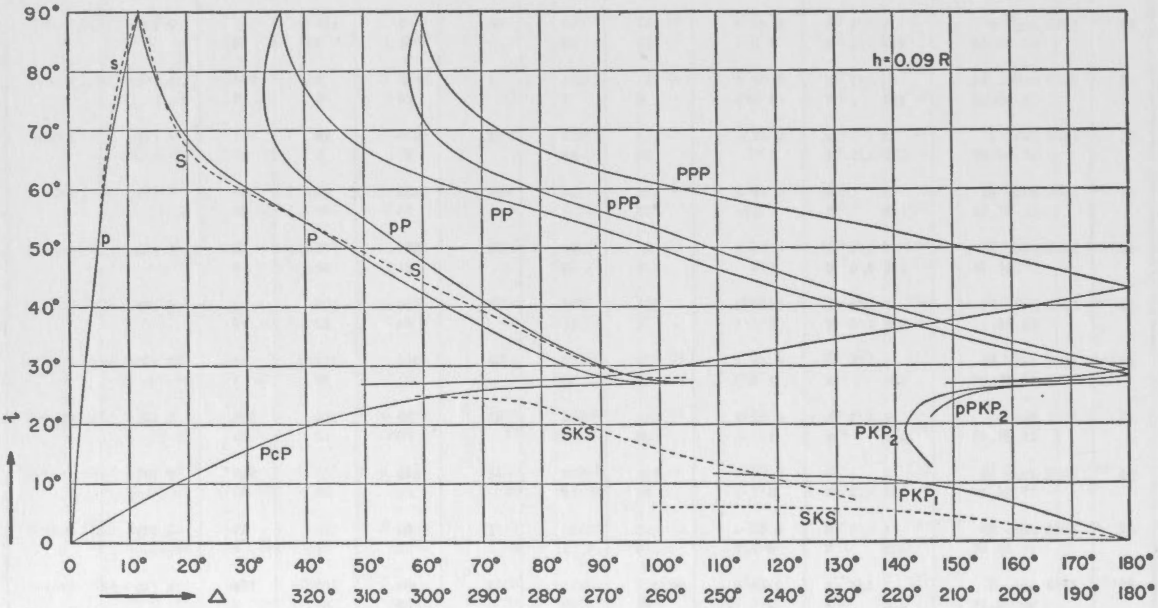

Figure 1. (i,Δ) curves for a focal depth of 0.09 R.

3. Plot the compressions and dilatations of the P and PKP waves in a diagram in the appropriate azimuth and at a distance of tan $i/2$ from the centre (*see* Figure 2).

4. Separate the compressions and dilatations by two nodal lines perpendicular to each other These lines must follow the course of a meridional line of Wulff's stereographic projection net (Figure 3). They represent the nodal planes in the focus in which no P wave is propagated.

5. Resolve S wave amplitudes in the SH and SV components with the help of the azimuth of the epicenter from the station. The angle α is determined, of which the tangent equals SH/SV.

6. Plot a vector in the diagram from the proper place of observation in a direction that makes an angle of α with the radial direction between the centre of the diagram and the station's projection. Note the sign of the initial motions, for SH either to left (L) or to right (R), and for SV either upward (U) or downward (D), (*see* Figure 4).

7. Determine which of the two types of initial S-wave motions was the actual one. In type I (*see* Keylis-Brook, 1956) with a single couple of forces in the focus acting along the line of fault movement, all S-wave vectors in the diagram must follow meridional lines that come together in the point representing the direction of fault movement (*see* Figure 5). In type II (*see* Honda, 1957) with two couples of forces of equal magnitude but opposed direction acting along the lines perpendicular to the two nodal planes for longitudinal waves in the focus, the

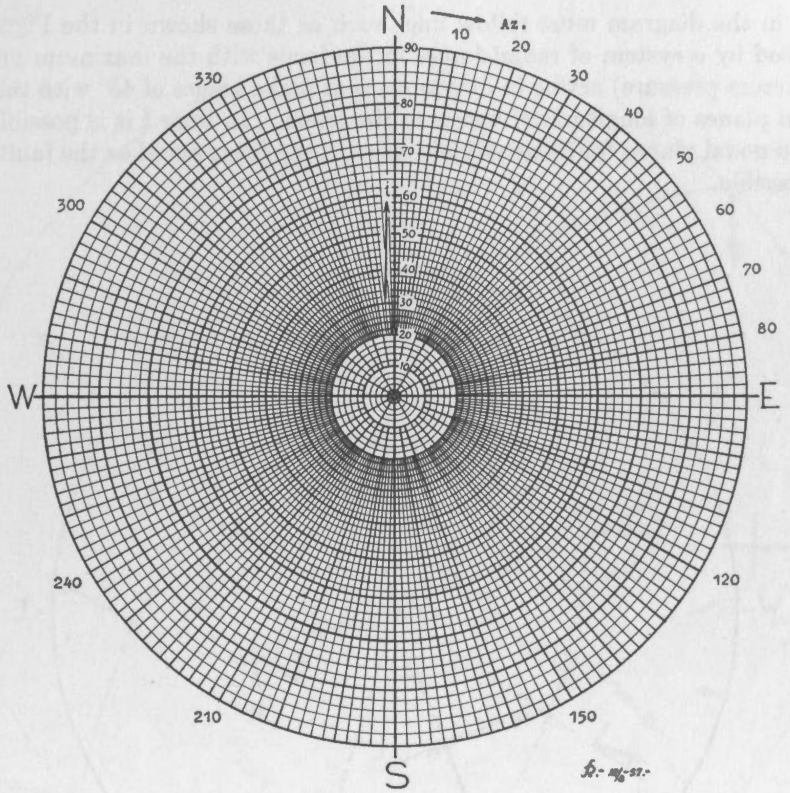

Figure 2. **(*i,Az*) diagram used for the plotting of the data.**

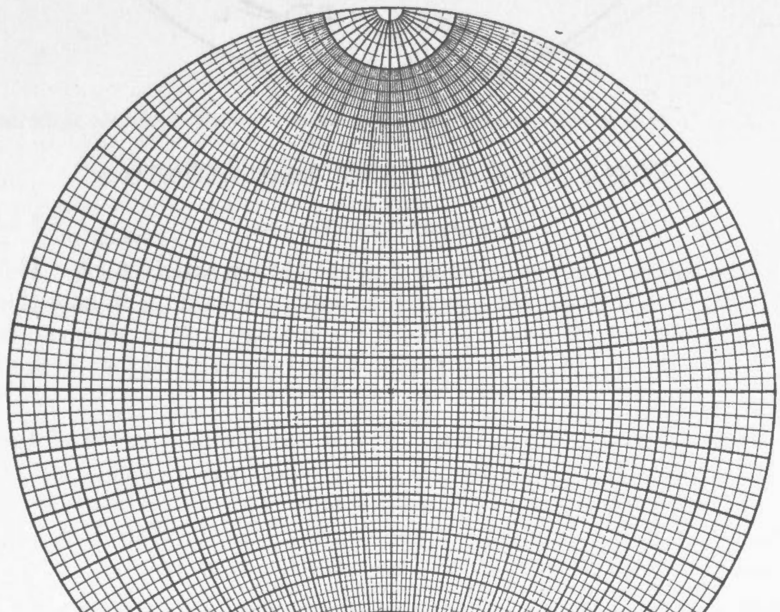

Figure 3. Wulff's stereographic projection net used for the determination of the course of the nodal lines and the direction of fault movement.

S-wave vectors in the diagram must follow lines such as those shown in the Figure 6. Case II also can be caused by a system of radial forces in the focus with the maximum pressure and the tension (or minimum pressure) acting in directions that make angles of 45° with those of the poles of the two nodal planes of longitudinal waves in the focus. In type I it is possible to determine which of the two nodal planes for longitudinal waves in the focus acted as the fault plane, in type II this is not possible.

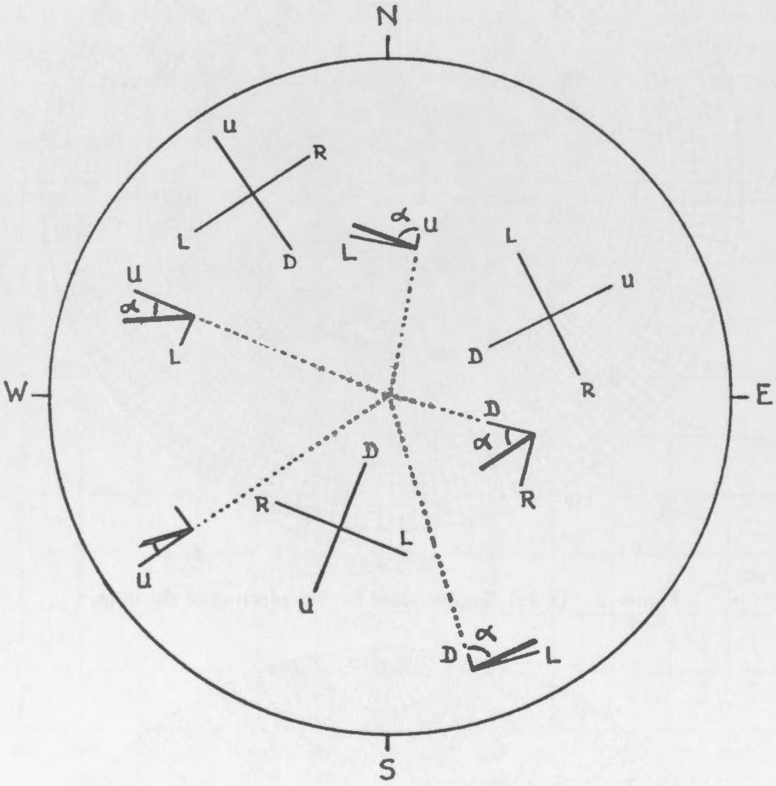

Figure 4. The plotting of S-wave data in the diagram.

Longitudinal Waves

Evidence for the solutions given in Table I is not always satisfactory. This can be caused by a scarcity of data, by a high percentage of contradictory data, or in case the position of the two nodal planes for longitudinal waves in the focus is fairly well established, by a lack of sufficiently reliable S-wave data. In Table II the earthquakes are listed for which no solution could be reached.

Numbers of consistent and inconsistent data of longitudinal waves of the earthquake of Table I are listed in Table III. These figures partly reflect the reliability of the solution, but a high number of consistent data do not implicitly mean that the solution is 'fair'. That also depends upon the distribution of the data in the diagram, and therefore it is not possible, solely on the basis of these numbers, to give the shock a classification.

It is seen from the Table that on the average 8 out of 9 P-wave data are consistent, and 7 out of 9 PKP-wave data. The percentage of the consistent data of reflected longitudinal waves is always of the order of about 2 out of 3.

S Waves and the Determination of the Type of Force System in the Focus

The actual sense of initial motion of the S wave is not implicitly needed for the choice between the two force types I and II; the position of the line of polarization is sufficient for the

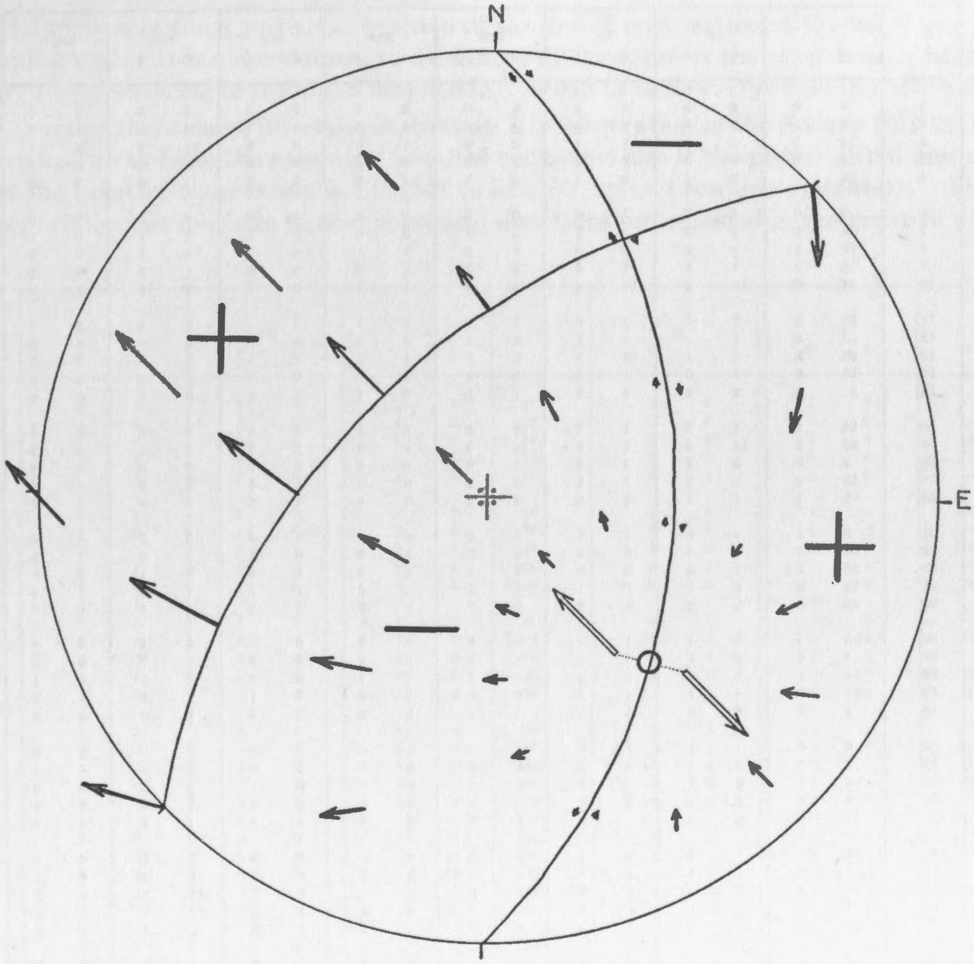

Figure 5. Theoretical course of S-wave vectors caused by force system of type I in the earthquake focus.

Table II. Earthquakes for which no solution could be reached.

Year and Date	H Time	Epicenter	Focal Depth	Magnitude
1934 October 26	14^h 44^m 29^s	6°S 124°E	0.11 R	6 3/4
1935 July 11	13 03 42	4 S 111 E	0.09 R	6
1936 February 12	09 34 30	6 S 116 E	0.09 R	6 1/2
February 27	10 04 08	7 S 127 E	0.02 R	6 3/4
May 19	07 22 26	5 1/2 S 112 1/2 E	0.09 R	6 1/2
1937 May 12	02 44 55	4 1/2 S 144 E	0.02 R	6 3/4
1938 January 18	04 20 04	4 S 101 1/2 E	0.01 R	6 1/2
April 4	21 09 03	7 S 127 E	0.06 R	6
May 8	14 40 35	6 S 124 E	0.10 R	5 3/4
1939 June 13	20 39 55	3/4 N 125 3/4 E	0.02 R	6.9
December 20	13 04 06	7 S 120 E	0.10 R	6
1941 January 2	16 49 38	3 N 122 1/2 E	0.07 R	6 1/4
March 14	16 08 18	7 S 120 E	0.08 R	6
1947 December 4	14 46 40	7 1/2 N 124 1/2 E	0.07 R	6

No.	P		pP		PP		pPP		PPP		PcP		PKP		pPKP	
	c	i	c	i	c	i	c	i	c	i	c	i	c	i	c	i
1	5	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0
2	9	1	0	4	4	0	0	0	0	0	0	1	3	1	1	0
3	14	2	1	3	1	5	2	2	1	0	0	0	11	0	0	1
4	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	13	3	0	1	0	1	0	0	1	0	0	0	2	0	0	0
6	8	0	2	0	1	0	0	0	0	0	0	0	0	0	0	0
7	6	0	4	3	2	1	2	0	0	0	0	1	3	1	0	1
8	17	1	2	2	4	0	2	0	1	1	0	0	4	0	0	0
9	15	3	1	0	7	4	0	0	1	0	0	0	1	0	0	0
10	36	6	18	4	10	8	5	8	1	3	0	2	7	0	1	0
11	22	2	7	1	8	0	1	1	0	1	0	0	6	0	1	0
12	12	0	1	1	1	3	0	0	0	0	0	1	4	0	0	0
13	25	3	8	1	13	3	6	0	2	1	2	1	8	1	0	0
14	17	6	1	0	1	0	0	0	0	0	0	0	2	0	0	0
15	21	2	9	3	2	5	1	1	0	1	0	0	0	1	0	0
16	18	2	2	2	1	2	0	0	0	1	0	0	3	2	0	0
17	33	2	14	3	9	6	14	0	1	0	3	1	6	1	0	2
18	9	0	2	1	2	0	0	0	0	0	0	0	0	0	0	0
19	13	0	2	0	3	1	0	0	0	0	1	0	2	0	0	0
20	19	2	1	1	2	0	0	0	0	0	1	0	2	0	0	0
21	8	1	0	0	0	1	0	0	0	0	1	0	2	1	0	0
22	16	2	4	0	6	2	0	0	1	0	0	1	9	3	1	0
23	29	0	7	9	9	6	5	4	4	0	1	0	5	1	1	0
24	15	0	6	0	7	1	1	1	1	0	1	1	7	0	1	0
25	22	3	0	2	6	2	0	0	2	0	0	0	4	2	0	0
26	14	2	0	1	1	2	0	0	0	0	0	0	2	1	0	0
27	5	0	0	1	0	2	1	0	0	0	0	0	2	0	0	0
28	11	1	1	2	5	3	0	0	0	1	0	0	6	3	0	1
29	11	0	4	1	4	3	0	0	0	0	0	1	9	2	0	0
30	3	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
31	6	0	1	1	1	0	0	0	0	0	0	0	3	2	0	0
32	7	0	2	1	1	5	0	0	0	0	0	0	2	0	0	0
33	9	1	0	1	1	2	0	0	0	0	0	1	2	1	0	0
34	8	0	1	2	5	2	0	0	0	0	0	0	1	0	0	0
35	24	5	2	1	4	3	0	0	1	0	0	0	4	2	0	0
36	21	4	1	1	5	4	1	0	0	0	0	0	6	1	0	0
37	6	0	0	1	4	0	0	0	0	1	0	0	1	0	0	0
38	21	3	2	2	3	6	1	0	0	0	0	0	11	6	0	2
39	24	5	4	1	6	5	0	0	0	0	1	0	12	3	0	2
40	39	6	8	0	6	3	0	0	3	2	1	0	17	4	3	4
41	24	6	1	0	19	5	0	0	2	1	0	0	14	3	0	0
42	55	10	0	0	15	6	0	0	5	1	0	0	7	4	0	0
43	24	5	1	0	6	1	0	0	0	0	0	0	22	7	1	3
44	17	3	0	0	10	3	0	0	1	0	0	0	7	4	1	0
45	22	3	0	0	10	2	0	0	4	1	1	0	12	3	0	0
46	31	2	0	0	16	7	0	0	1	0	2	1	19	6	0	0
47	30	5	0	0	13	9	0	0	1	1	0	0	22	5	0	0
48	28	5	2	2	6	1	3	0	0	0	0	0	9	5	0	0
49	24	4	0	0	4	2	0	0	0	0	0	0	12	3	0	0
50	25	6	1	0	9	4	0	0	1	0	0	0	9	3	1	0
51	15	1	3	0	7	3	1	0	0	0	2	0	11	7	1	1
52	39	4	5	4	5	2	3	0	4	0	2	0	19	7	1	1
53	35	7	0	0	22	8	0	0	7	1	0	0	28	5	0	0
54	33	7	0	0	20	7	0	0	2	1	0	0	23	4	0	0
55	42	1	8	6	9	9	0	0	1	0	1	0	14	7	0	2
56	66	3	2	0	16	12	0	0	3	1	2	0	27	8	0	0
57	17	1	0	0	10	2	0	0	0	0	2	1	7	3	0	0
58	19	1	0	0	5	2	0	0	0	0	2	0	3	1	0	0
59	22	3	0	0	12	3	0	0	2	1	1	0	11	4	0	0
Total	1187	145	141	69	359	179	49	17	54	20	27	13	448	128	14	20

Table III. Numbers of consistent (c) and inconsistent (i) data of longitudinal waves of the single earthquakes.

purpose. This position differs enough in types I and II to be able to determine which of the two was the actual one (*see* Figures 5 and 6).

This consideration is rather important, as it has been shown by HODGSON and ADAMS (1958) and also during this study that the reliability of the reading of any impulse that arrives later than P or PKP is considerably decreased. But in spite of the impossibility of a reliable reading of the initial motion of the S wave, the position of the line of polarization of the wave can be determined quite well. It is not necessary to determine this position at the exact time of beginning of the wave by a measuring of the initial amplitude. It can be done everywhere in the S-wave train.

In practice this means, for example, that an RD observation of the S wave (SH to the right, SV down and away from the epicenter) is called consistent also if the proper initial motion of the wave at the point of observation is LU (SH to left, SV up and towards epicenter). Thus, only the observations just opposite to the theoretical directions are included in the group of consistent data.

No.	Ia		Ib		II		No.	Ia		Ib		II	
	c	i	c	i	c	i		c	i	c	i	c	i
1	3	0	1	2	2	1	31	5	0	1	4	3	2
2	4	0	1	3	2	2	32	3	1	1	3	1	3
3	1	0	0	1	1	0	33	7	1	4	4	4	4
4	4	1	2	3	2	3	34	2	1	1	2	1	2
5	7	1	3	5	4	4	35	7	2	3	6	5	4
6	3	1	2	2	2	2	36	6	2	4	4	2	6
7	7	0	1	6	3	4	37	2	1	1	2	2	1
8	2	1	2	1	2	1	38	7	4	5	6	5	6
9	6	1	1	6	5	2	39	8	1	3	6	6	3
10	5	0	1	4	4	1	40	16	4	11	9	11	9
11	2	1	1	2	1	2	41	9	4	5	8	8	5
12	2	0	0	2	1	1	42	16	5	8	13	15	6
13	4	0	2	2	4	0	43	1	0	0	1	1	0
14	2	0	1	1	2	0	44	14	3	4	13	13	4
15	5	0	3	2	3	2	45	14	5	5	14	10	9
16	8	2	4	6	6	4	46	18	5	8	15	13	10
17	2	2	1	3	2	2	47	13	0	1	12	9	4
18	4	1	1	4	3	2	48	17	4	14	7	15	6
19	3	0	0	3	2	1	49	8	5	7	6	6	7
20	9	3	7	5	8	4	50	18	0	2	16	12	6
21	5	1	3	3	2	4	51	7	3	3	7	6	4
22	6	2	3	5	4	4	52	24	8	20	12	23	9
23	9	2	2	9	2	9	53	13	5	5	13	11	7
24	4	1	1	4	4	1	54	19	2	12	9	12	9
25	6	2	3	5	4	4	55	13	2	8	7	8	7
26	2	1	1	2	0	3	56	20	4	10	14	17	7
27	5	0	1	4	4	1	57	9	2	3	8	7	4
28	3	0	1	2	3	0	58	9	4	4	9	7	6
29	4	2	2	4	2	4	59	9	3	3	9	8	4
30	3	0	2	1	2	1							
							TOTAL	444	106	209	341	329	221

Table IV. Numbers of consistent (c) and inconsistent (i) S-wave data in the case of three different force systems in the focus.

In Table IV the number of consistent and inconsistent observations of S polarization are listed for each earthquake under three different assumptions. In column Ia it is assumed that a single couple acts in the focus, (type I of HONDA, 1957) and that nodal plane *a* is the fault. In column Ib it is again assumed that a single couple acts at the focus but that plane *b* represents the fault. In each case we have designated as *a* that plane giving the higher percentage of consistent data. In column II it has been assumed that two equal couples acted at right angles to each other in the focus (type II of HONDA, 1957).

Because the designation *a* has been given to that plane having the fewer inconsistencies, there is no significance in the difference between columns Ia and Ib. It is a difference between Ia and II which we must seek.

It is not always clear that there is such a difference; in nearly half of the earthquakes there is no appreciable difference between the numbers of consistent and inconsistent data. These shocks do not give sufficient evidence for the choice between the focal force systems I and II.

However it is worth noting that none of the earthquakes shows clearly better percentages for force type II than for force type Ia, whereas there are quite a few earthquakes with clearly

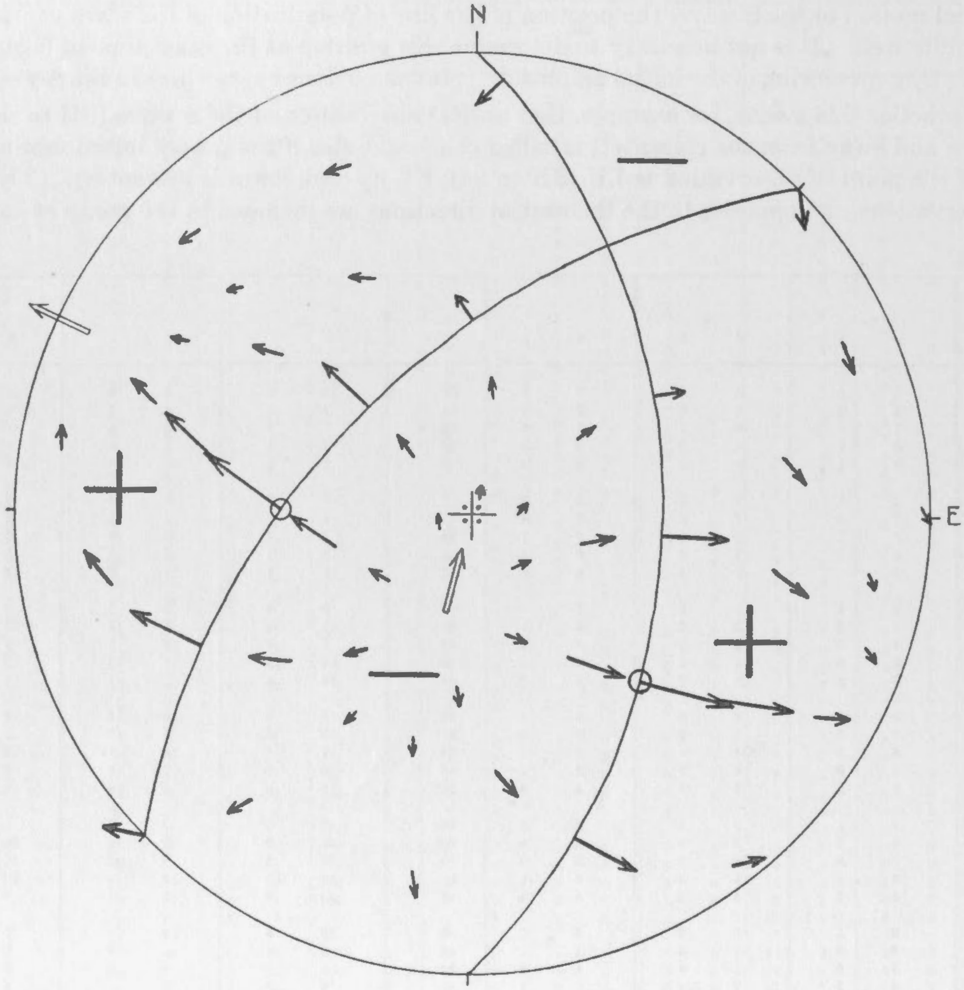

Figure 6. Theoretical course of S-wave vectors caused by force system of type II in the earthquake focus.

higher percentages of consistent data in case Ia than in case II (for example the numbers 5, 7, 21, 23, 29, 33, 36, 40, 46, 50, 54, and 55). It is clear then that a single couple of forces in the focus acting in a plane perpendicular to the fault plane and including the direction of fault movement is most likely the cause for at least part of the earthquakes of Table I.

There is no preference shown by the earthquakes, either of group Ia or II, for a particular depth level or region. The earthquakes of which the S-wave data are not conclusive are distributed at random at all depth levels and through all seismic zones.

For a unification of the material it has been assumed that all the earthquakes have been caused by a single couple acting in the focus. This procedure is possible because it is usually not very difficult to make a choice between the force types Ia and Ib.

For the total material then, the consistent and inconsistent data appear in the following percentages:

Ia-4:1; Ib-2:3; II-3:2

Thus, on the average it seems that there are 4 consistent S data out of a total of 5 if we assume that force type I is the cause of all earthquakes. If we do not include the S-wave readings that are opposite to the theoretical motions in the group of consistent data, it seems that there is a chance of only 50 per cent of a reading being consistent. This means that the data as such are useless.

It should be mentioned that the S-wave data of other stations were reported to the Djakarta Institute in the form of a motion to the N and W, or to S, E and Up, etc. In most cases no amplitude figures were included. That means that the position of the line of polarization of the wave could only be determined with an accuracy of 45° in the plane perpendicular to the direction of propagation of the wave. With this consideration in mind it was determined which observation was consistent and which inconsistent. Possibly this procedure is a cause for errors in the solutions given, but it is not likely that serious errors in the determination of the type of force system in the focus can be the result of this simplification.

Nevertheless in the next questionnaire concerning southeast Asian earthquakes that is now in preparation, special attention will be drawn to this point.

Other Waves

For SKS waves the considerations that make it possible to use S-wave data for studies concerning earthquake mechanism, are not valid. This is because SKS waves are always polarized in the plane of incidence after refraction through the earth's core, and therefore only consist of SV components. This is clearly demonstrated by the SKS data that were gathered and that show about equal percentages of consistent and inconsistent data.

It is clear from this that it is very unlikely indeed that reflected transverse waves could be of any use either. The complications caused by a reflection of a transverse wave of which only the position of the line of polarization in the station can be determined are such that it seems nearly impossible to expect reasonably reliable data for the polarization direction of the wave in the focal region.

The conclusion is that sufficiently reliable data for earthquake mechanism studies only can be expected from P, PKP and S waves (*see* also Hodgson and Adams, 1958).

This is the reason that the older solutions have been reviewed, and that some of the solutions of Table I differ somewhat from those given in the earlier publications. The solutions presented here are based on direct P, PKP and S waves only.

The Solutions

The solutions are given in the form of the figures in six columns of Table I. These columns represent respectively:

I—The direction of the pole of the fault plane (azimuth N through E, and inclination),

II—The direction of the fault displacement (azimuth and inclination),

III—The slip angle (measured between the direction of fault movement and the strike of the fault plane),

IV—The direction of the pole of the plane of action. The plane of action is that plane standing perpendicular to both nodal planes for longitudinal waves in the focus. This is the plane in which the direction of fault movement and also the principal stresses are situated. The pole of the plane of action is the null vector of Hodgson (1957),

V and VI—The azimuth and inclination of the two lines that make angles of 45° with the directions I and II. Along these lines the maximum and minimum pressure components respectively should act in case the force system II were the cause of the earthquake

It is clear that not all directions given in the table are independent of each other. In fact, only two of these directions plus the type description are sufficient for a determination of the other four factors. Figure 7 shows how the six factors of Table I are measured in Wulff's stereographic projection net in which the data were plotted. The diagram of earthquake No. 29 is used as an example.

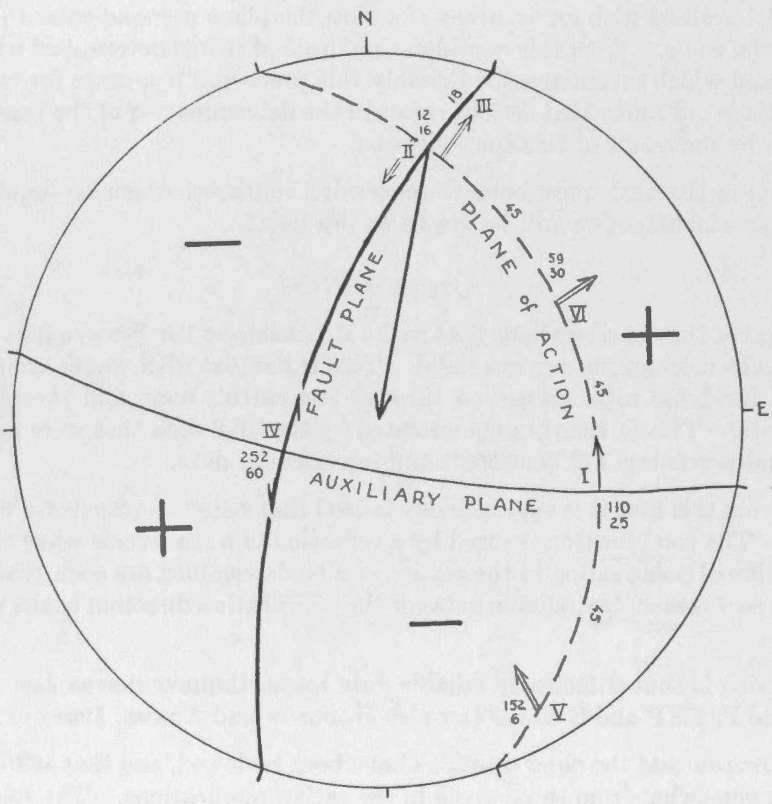

Figure 7. Example of a solution obtained with the method described in the text. Earthquake 29 has been used.

Earthquake Types

According to the following fault movements, eight different types of earthquakes are distinguished:

right lateral, partly normal	R(T)
right lateral, partly reverse	R(P)
left lateral, partly normal	L(T)
left lateral, partly reverse	L(P)
normal, partly right lateral	T(R)
normal, partly left lateral	T(L)
reverse, partly right lateral	P(R)
reverse, partly left lateral	P(L)

A right lateral, clockwise or dextral transcurrent fault movement is indicated by an R for *right*; a left lateral, counterclockwise or sinistral transcurrent fault movement by an L for *left*. A normal fault movement is indicated by a T for the *tension* (or minimum pressure) component that is the more horizontal of the two forces in case mechanism II is acting in the focus. A reverse fault movement is indicated by a P for the maximal *pressure* component that is the more horizontal of the two forces in case mechanism II is acting in the focus.

A random distribution of the different types should result in 8.3 per cent for the first four types, the mainly transcurrent fault movements, and 16.7 per cent for each of the latter four types, the normal and reverse fault movements (*see* also Ritsema, 1957c).

Distribution of Earthquake Types in Depth

Table V gives the total numbers of T, of P, of R and of L shocks at different depth levels. It is seen that at shallow and intermediate depths, clockwise transcurrent fault movements are in the majority, and normal faults at great depths.

TABLE V

Earthquake type distribution in depth

	T	P	R	L
0.00 R	1	3	6	3
0.01	3	3	7	5
0.02	.	1	2	1
0.03	1	2	3	2
0.04	.	.	.	.
0.05	.	.	1	.
0.06	.	1	.	.
0.07	1	1	1	.
0.08	2	.	.	.
0.09	3	.	.	1
0.10	2	.	.	1
0.11 R	1	.	.	1
Total	14	11	20	14

In Table VI the same numbers for shallow, intermediate and deep earthquakes are gathered for the separate regions of the Sunda arc, the Celebes-Philippines arc and the New Guinea-Solomons arcs. The groups are divided such that the earthquakes of the north and central

TABLE VI

Regional distribution of earthquake types in depth

Sunda	T	P	R	L
0.00 R	.	.	5	.
0.01–0.04 R	1	4	3	3
0.04–0.11 R	4	2	.	3
Celebes-Philippines				
0.00 R	1	2	.	2
0.01–0.04 R	2	2	5	3
0.04–0.10 R	5	.	.	.
New Guinea-Solomons				
0.00 R	.	1	1	1
0.01–0.04 R	1	.	4	2
0.04–0.07 R	.	.	2	.
Total				
0.00 R	1	3	6	3
0.01–0.04R	4	6	12	8
0.04–0.11 R	9	2	2	3

Moluccas are included in the Celebes-Philippines arc. The percentage distribution of the different types is shown in the Figure 8.

From the table and Figure 8 it seems that there are regional differences. In the Sunda and Celebes-Philippines arcs the percentage of transcurrent fault movements decreases from shallow to deep levels; in the New Guinea-Solomons arcs this seems to be reversed (*see* also Ritsema, 1957c).

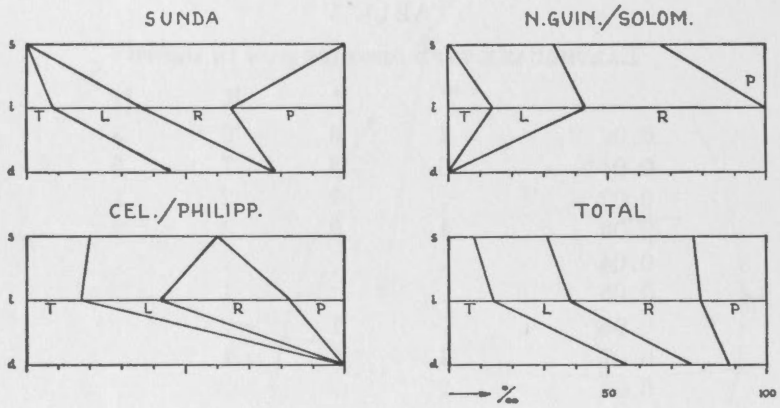

Figure 8. Earthquake type distribution in depth and in regions.

In all regions, however, transcurrent fault movements prevail in shallow and intermediate depth levels. In the Sunda arc there is a clear change from right lateral fault movements at shallow depths to left lateral at great depths. In the New Guinea-Solomon Islands arcs this seems to be reversed.

It is understood that for statistical purposes the total number of shocks investigated is still somewhat small, therefore it is possible that the percentage figures will undergo some change with the increase of data. It is remarkable, however, to note that the total figures for the 'fair' solutions only, neglecting the 'poor' ones, produce percentage figures that are almost the same as those of the total material.

Distribution of Earthquake Types in Different Magnitude Ranges

From Table VII it is clear that none of the special earthquake types is exclusively confined to the greater or to the smaller magnitude ranges. The distribution of the earthquake types is about the same in all magnitude ranges represented in the table. The excess of the transcurrent fault movements over the other types of fault movement is varying from two to four times in the different magnitude ranges.

TABLE VII

Distribution of earthquake types in different magnitude ranges

	T	P	R	L
$7\frac{1}{2}$–8	1	1	.	2
7–7.4	6	2	9	3
$6\frac{3}{4}$–6.9	6	4	6	4
6–6.7	2	3	5	5

Direction of the Pole of the Fault Plane

The mean dip of the fault plane calculated for every depth level with an interval of 0.01 R shows a rather irregular distribution. There is a tendency, however, for steeper dips at more shallow depths. The mean values for shallow, intermediate and deep earthquakes are 73°, 64° and 56° respectively. That for the total material is 64°.

Using only the 'fair' solutions, excluding the 'poor' ones, the last figure changes to 65°. There is thus no material influence of the classification of the solutions on the average figures.

There are only 12 shocks of the 59 in which the dip of the fault plane was smaller than or equal to 45°. Six of these are deep shocks, 4 are intermediate and 2 shallow. The same tendency that is valid for the mean figures shows itself in these numbers.

The average angle of inclination of the pole of the fault plane for shallow, intermediate and deep shocks thus is respectively 17°, 26° and 34°.

Diagrams were constructed that show for each of the three seismic regions the direction of the pole of the fault plane of the earthquakes with epicenter in these regions. Wulff's stereographic projection net has been used here and also for the construction of the diagrams to follow. It seems that there is no systematical distribution of these directions that are represented by the points in Figures 9, 10 and 11. The only tendency that does exist, is that most of the fault planes seem to have a strike more or less perpendicular to the general trend of the seismic zones, although there are a number of exceptions.

The arrows that are shown in the figures give for each of the earthquakes the direction in which the lower of the two fault blocks moved. (Compare the direction of earthquake 29 in Figure 9 with that indicated in point I of Figure 7).

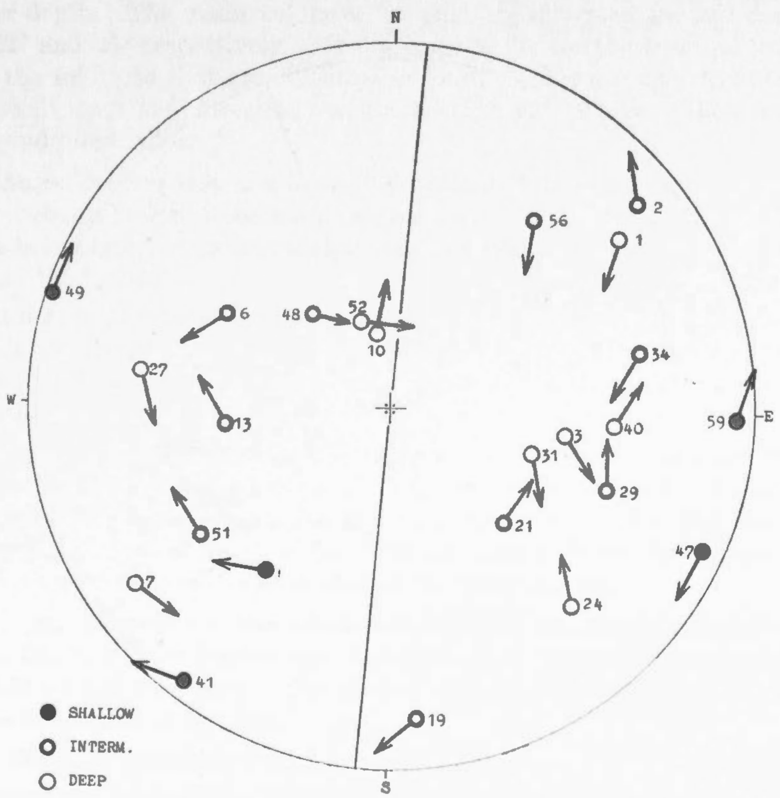

Figure 9. Directions of the fault-plane pole of Sunda arc earthquakes and the motion directions of the footwall. The solid line in Figures 9-11 is drawn perpendicular to the general trend of the seismic zone.

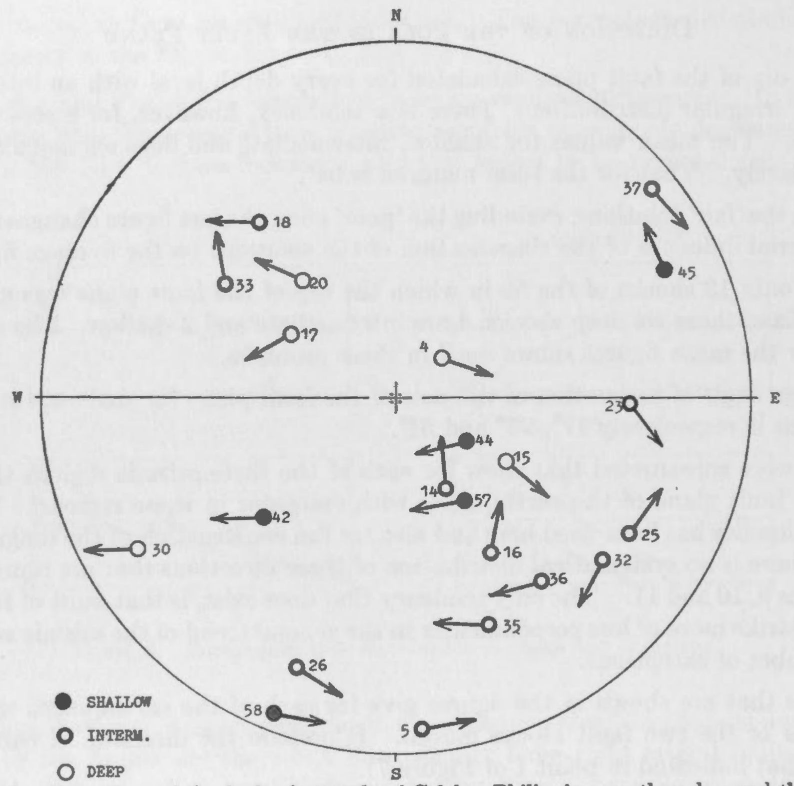

Figure 10. Directions of the fault-plane pole of Celebes-Philippines earthquakes and the motion directions of the footwall.

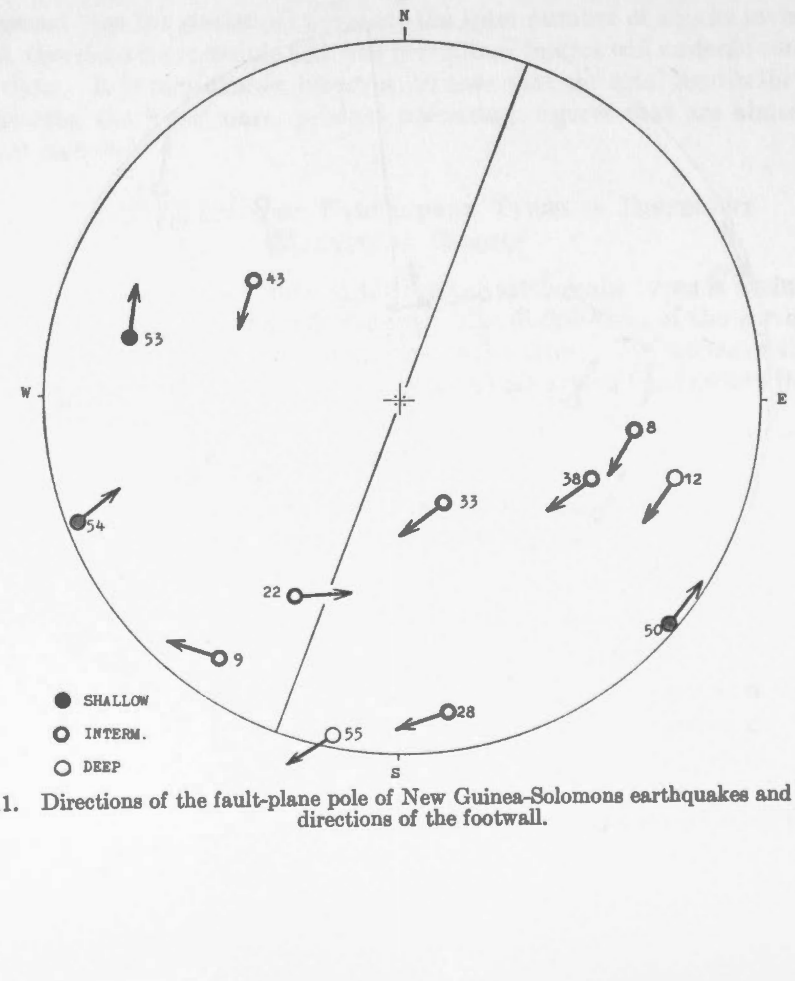

Figure 11. Directions of the fault-plane pole of New Guinea-Solomons earthquakes and the motion directions of the footwall.

In general the arrows follow meridional lines that converge in directions about perpendicular to the general trend of the zone and inclined somewhat to the S in the Sunda arc, to the E in the Celebes-Philippines arc, and to the SSW in the third region under consideration. That means that these block movements nearly always take place in a plane standing perpendicular to the zone of seismic activity that is dipping under the Asian continent for the first two regions. For the third region (Figure 11) the convergence of the arrows at the SSW side of the seismic zone could then be interpreted to mean that here the zone is dipping under the Pacific side and not under the continental (here Australian) side such as in the other two regions.

No system can be found in the distribution of the sense of the block movements. In no part of the diagrams are all arrows pointing in a single direction; always there are those pointing in the opposite direction. Not even for the earthquakes of a particular depth interval can a regular system be found.

Earthquakes with exceptional block movement directions in Figure 9 are numbers 48 (of the Sumatra salient, where the general trend of the zone is changed from about E-W to SE-NW), 3, 6, 52, and in a lesser degree also numbers 24 and 31. Of these only number 52, classified as 'fair', is rather serious.

In Figure 10 the outstanding exceptions are numbers 33, 14, 16 and 23. Of these the first one is in the Moluccas, and the other three from the N arm of Celebes where the general trend is changed from about N-S to E-W. Therefore none of these is serious.

In Figure 11 the only rather serious exception is earthquake 54, classified as 'fair'.

Azimuth and Plunge of the Fault Movement Direction

The single values of the plunge of the fault displacement direction for each depth interval of 0.01 R are rather irregular, but on the average the tendency exists for somewhat greater plunges at greater depth. The mean values of the shallow, intermediate and deep earthquake groups are 17°, 22° and 30° respectively. The average value for the total material is 23°, the same as that for the solutions that are classified as 'fair'. There are only five shocks in which the plunge of the fault movement direction was greater than 45°. Three of these are deep shocks, one intermediate and one shallow.

Except for the tendencies just mentioned no evident differences exist between the earthquakes of different depth levels of the same seismic zone. Therefore in Figures 12, 13 and 14 no distinction has been made for earthquakes of certain depth intervals. Instead the earthquake type is indicated in the figures.

It is seen that here is a tendency for a concentration of fault movement directions in azimuths about perpendicular to the seismic zone. This seems to be especially true for the earthquakes with a mainly and partly reverse fault character. Those with a mainly and partly normal fault character are distributed more at random.

In Figure 12, the diagram for the earthquakes of the Sunda arc, the most deviating fault movement directions of P and (P) earthquakes are those of numbers 51, 2 and 7. The first has a slip angle of only 1° and therefore the (P) character is very faint, and the other two are classified as 'poor'. Earthquake 48 is in the Sumatra salient of the Sunda arc and therefore its position is not directly comparable with that of the other shocks.

In Figure 13, the diagram for the Celebes-Philippines arc, earthquakes 14 and 16 have epicenters near to the N arm of Celebes and therefore are in line with the approximately E-W trend of the seismic zone at that place. The other P and (P) shocks are in line with the general N-S trend of the greater part of the zone.

In Figure 14 the only exception is earthquake number 22.

No clear system can be found in the distribution of R and L fault movement directions. Therefore diagrams of these have not been reproduced here.

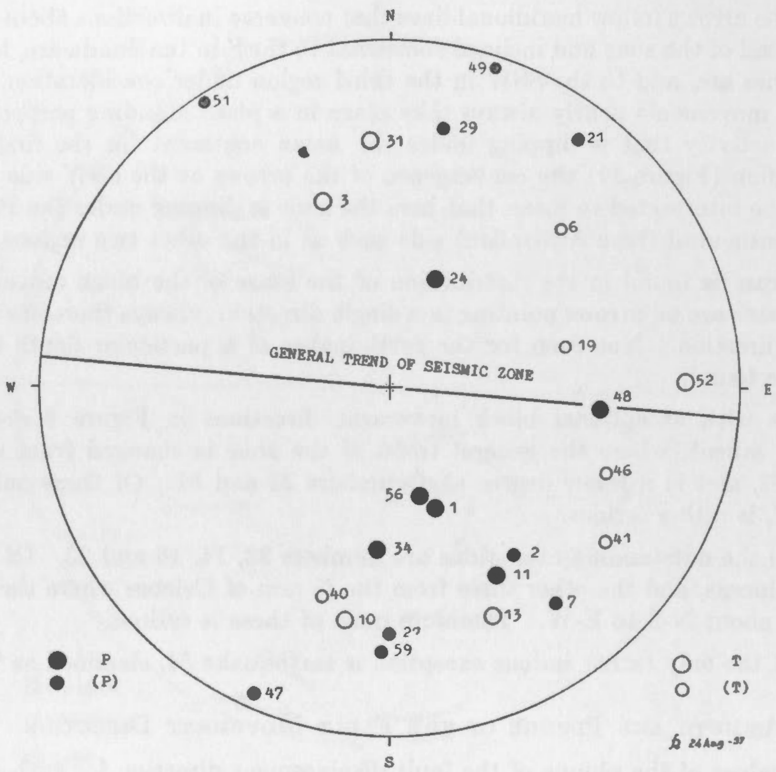

Figure 12. Fault movement directions in Sunda arc earthquakes. The solid line in Figures 12-14 represents the general trend of the seismic zone.

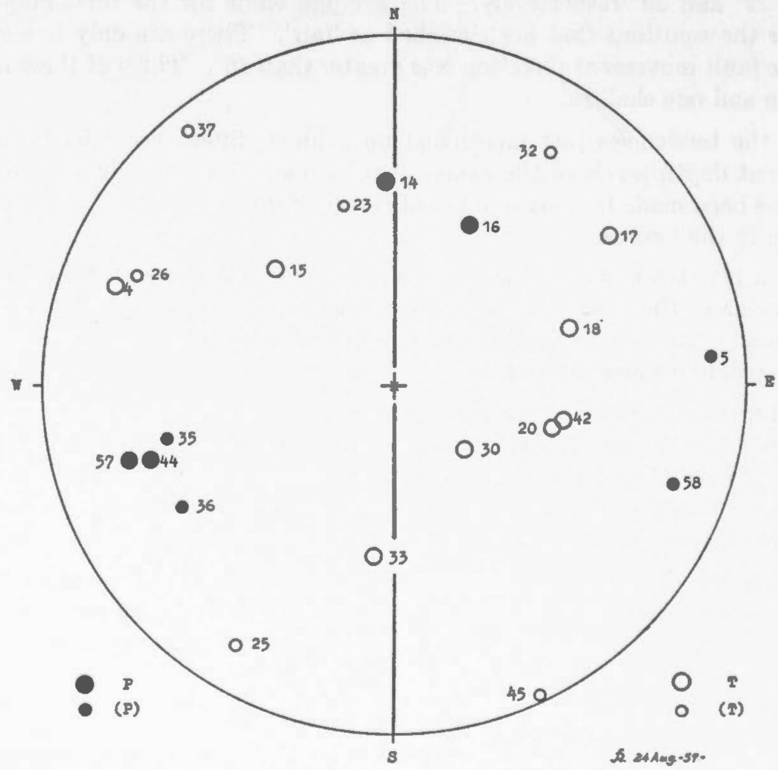

Figure 13. Fault movement directions in Celebes-Philippines earthquakes.

A remarkable tendency, however, does exist in the form of a concentration of the fault movement directions of R(T) and L(P) shocks in certain azimuths, and those of R(P) and L(T) shocks in the opposite directions. These azimuths seem to be related to the direction of the

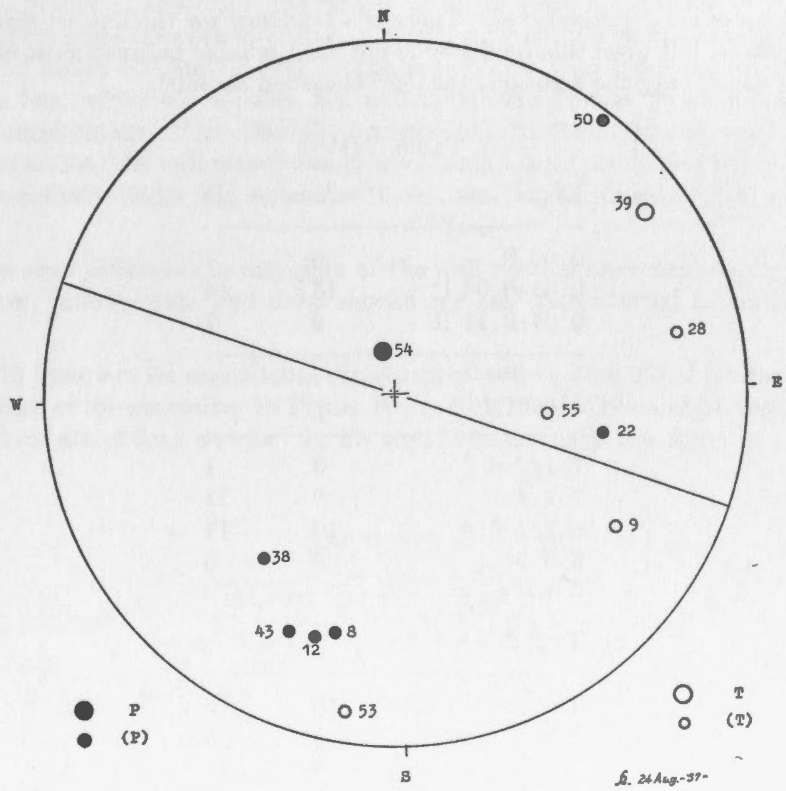

Figure 14. Fault movement directions in New Guinea-Solomons earthquakes.

seismic zone. R(T) and L(P) fault movements are directed in easterly azimuths in the approximately W-E trending Sunda arc, in northerly azimuths in the approximately S-N trending Celebes-Philippines arc, and in ESE azimuths in the New Guinea-Solomons arcs of which the greatest elongation lies in this direction. R(P) and L(T) fault movements are directed just in the opposite azimuths in the length direction of the zones.

Clear exceptions to this latter rule are numbers 2, 6 and 49 of the Sunda arc; number 49 belonging to the Sumatra salient, and both others classified as 'poor'. Number 58 of the Celebes-Philippines arc also is not in line with this rule, but this earthquake is situated in the Moluccas archipelago with its intricate structural lines. The only other exception is number 45 of the Solomons Islands arc, classified as 'poor'.

The transcurrent parts of the mainly normal and mainly reverse fault movements in general are not in accordance with the rule outlined above. Thus, until more data are available on these seismic zones, the rule should not be considered as definite.

The Plunge of the Fault Displacement and that of the Pole of the Fault Plane

The study of the initial motion of P and PKP waves results in two nodal planes, either of which may be the fault plane. The choice of the actual fault plane seems to be independent of the difference in plunge between the two poles of the nodal planes.

Table VIII shows the numbers of earthquakes for which the actual fault displacement plunges steeper, B, and less steep, A, than the direction of the pole of the fault plane. Table VIII shows that there is no preference for a fault displacement in the steepest or in the less steep nodal plane at any depth level. Table VIIIb shows that there is no preference either for one of the two possible fault planes in some special magnitude range. Finally Table VIIIc shows that the numbers of steepest and less steep possible fault movement directions are nearly the same in each group of earthquake types. There is a tendency for the flattest direction in the T group of earthquakes, but even this tendency is not very reliable because most of the difference disappears if we count only the solutions that are classified as 'fair'.

Table VIII

a) Depth	A	B
0.00 R	6	7
0.01–0.04 R	15	14
0.04–0.11 R	9	7

b) Magnitude		
7 1/2–8	3	1
7–7.4	8	11
6 3/4–6.9	10	11
6–6.7	9	5

c) Type		
T	10	5
P	5	5
R	8	11
L	7	7

Thus, it can be concluded that neither in depth, nor in magnitude or type does there exist a preference for the steepest or for the less steep possible direction of fault movement to be the actual one.

The Slip Angle at Different Depths

Although the divergencies of the mean figures are considerable, a clear tendency exists for greater slip angles at increasing depths. The mean values for shallow, intermediate and deep earthquakes are 21°, 30°, and 41° respectively. This confirms that at great depth a more important percentage of the earthquakes is normal or reversed than at shallow depths, where a far greater percentage is of the transcurrent fault type.

There are 13 slip angles greater than 45°, 6 of deep shocks, 5 of intermediate and 2 of shallow ones. The average slip angle of the total material is 31°, that of the 'fair' solutions only, 29°.

Direction of the Pole of the Plane of Action—the "Null Vector"

We recall that the plane of action has been defined as that plane perpendicular to both the nodal planes, and that the pole of this plane is the null vector of Hodgson. Although the values of the dip of the plane of action for the single depth intervals of 0.01 R are somewhat confused, on the average there is a clear increase of dip with increasing depth of focus. The mean figures for shallow, intermediate and deep shocks are respectively 29°, 39° and 54°. The average of the total material is 41°, and 40° for the 'fair' solutions only. From these figures it is clear that most shallow earthquakes are transcurrent, and most of the deep shocks are normal or reverse.

In 11 out of 16 deep shocks the plane of action had a dip greater than 45°, and in 9 out of 13 shallow shocks the dip was smaller than 45°. There is a clear gradual change in dip between the depth ranges.

Figures 15, 16 and 17 show that the directions of the pole of the plane of action are almost confined to the solid angle between two planes, with a strike in the length direction of the seismic zone, and dips of about 50° and 75°–85°. The first plane, with the smallest inclination, dips under the Java Sea, under the Celebes Sea and under the Pacific Ocean in the three seismic regions under consideration. The other plane always dips in the opposite direction. This means that the plane of action (the null plane) nearly always stands perpendicular to the steeply dipping zone of seismic activity under the Asian continent, and for the third region under the Pacific Ocean.

There is no clear difference in direction of the null vectors of certain depth intervals. The points of shallow, intermediate and deep shocks are not concentrated in certain parts of the diagram.

In Figure 15 there are six exceptional directions of null vectors, all of intermediate and deep earthquakes. Half of the exceptions in Figure 16 are of north Celebes and Moluccas earthquakes, and the other three are of deep shocks. In Figure 17 there is only one exception, earthquake 54.

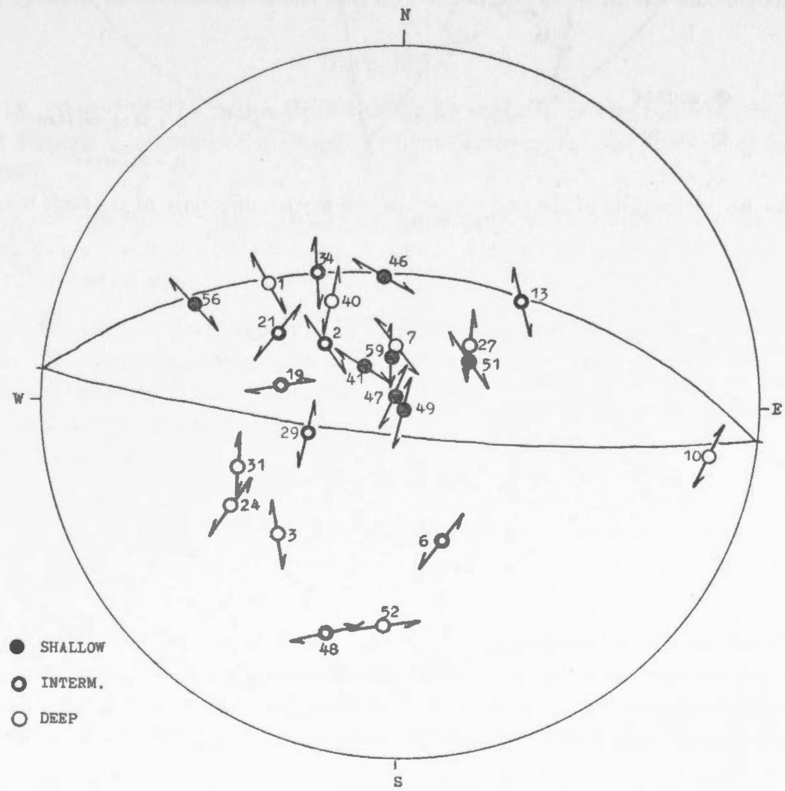

Figure 15. Directions of the null vector and the motion directions of the fault blocks in Sunda arc earthquakes.

The confinement of the directions of the null vectors to the solid angle between the planes that have been drawn in the figures for each seismic region, is not as perfect as that shown by HODGSON (1956) to exist in the Tonga-Kermadec and New Hebrides seismic zones. These latter zones, however, are very simple and straight, whereas in all of the seismic zones that are under consideration here there are bends that easily may complicate the general lines and make the diagrams less clear.

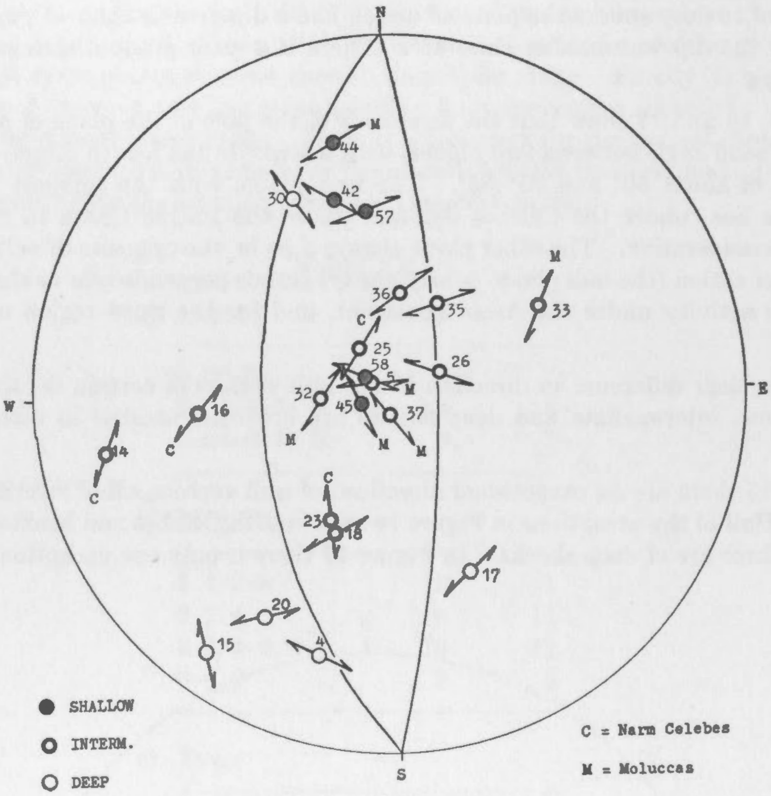

Figure 16. Directions of the null vector and the motion directions of the fault blocks in Celebes-Philippines earthquakes.

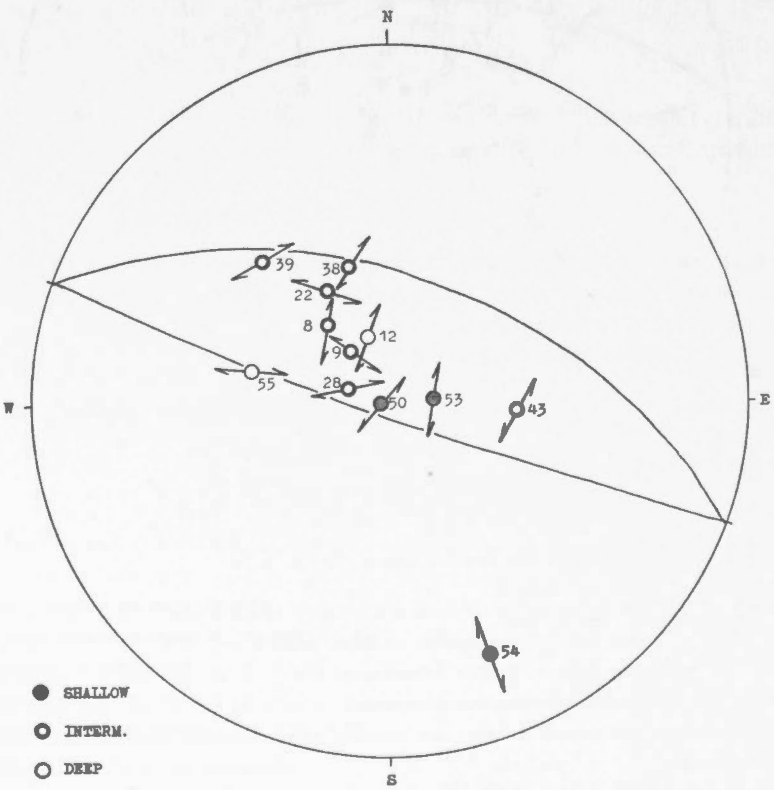

Figure 17. Directions of the null vector and the motion directions of the fault blocks in New Guinea-Solomons earthquakes.

The two half-arrows drawn through each point of observation represent the motion directions of the two adjacent fault blocks with respect to each other. (Compare the direction and the sense of the half-arrows of earthquake number 29 in Figure 15 with the same in point IV of Figure 7).

It is seen that most of the half-arrows are directed almost perpendicular to the meridional lines that come together in the direction of the general trend of the seismic zones.

More or less clear exceptions to this rule in the Sunda arc are numbers 48 (of the Sumatra salient), 52, 19, 41 and 46. The last three, however, are of the extreme eastern part of the Sunda arc where the general trend of the zone is changing from W-E to WSW-ENE. In Figure 16 more or less clear exceptions are numbers 14, 16, 23 and 25 (all of the northern arm of Celebes with its approximate E-W trend), and 32, 33, 37 and 45 (all of the Moluccas archipelago with its intricate structural lines) and numbers 4 and 15 both classified as 'poor'. Numbers 9, 22, 28 and 55 are exceptions in Figure 17, all of which are classified as 'fair'.

There is no clear indication that the distribution of the clockwise and counterclockwise motion vectors is subject to a certain rule; this in contrast to the opinion expressed earlier on the earthquakes of the Sunda arc when the solutions of only a part of the earthquakes used here were known (Ritsema, 1957b). Although several tendencies can be found to exist in the figures, no clear system in the distribution can be found, not even in the earthquakes of a certain depth interval.

The Maps

In Figures 18, 19 and 20 the azimuth of the strike and dip of the fault plane, and that of the fault movement direction, of each of the earthquakes is shown for shallow, intermediate and deep shocks respectively.

The maps stress once more the intimate connection that exists between the direction of fault displacement and the trend of the seismic zone. Almost all fault displacements are directed about perpendicular to the zone.

Clear exceptions are the deep shocks 7, 17, 52 and 55, and the intermediate shocks 6, 9, 11, 19 and 22. But all other fault displacements are almost perfectly in line with the direction perpendicular to the seismic zone at the place of the epicenter. Note for example the shift in the direction of fault displacement to SE azimuths in the extreme east of the Sunda arc (12, 41, 46) and near the north extremity of the north arm of Celebes (37, 45).

It is clear from these instances that the direction of fault displacement is neither uniform in the whole area, nor in the single regions in which the area has been divided. The directions follow more or less closely all bends and curves in the seismic zones, nearly always standing perpendicular to these.

It is apparent that for regions with intricate structural lines the direction of fault displacements as concluded to exist from earthquake mechanism studies, can be an important help in distinguishing the major structural directions. If more data are available this procedure can be used for the area of the central and northern Moluccas, where the three seismic zones come together.

APPENDIX

It is understood that the S-wave data used in the investigations are not perfect, and in the second place that in about half of all shocks these imperfect S data do not give conclusive evidence for a choice between the two types of force systems. In fact, there are only 12 earthquakes that clearly point to force type I, and about 20 shocks with a smaller preference for the same force system in the focus.

So, the evidence on which the assumption is based that all earthquakes were caused by force type I in the focus is only faint. Therefore the consequences have also been considered for

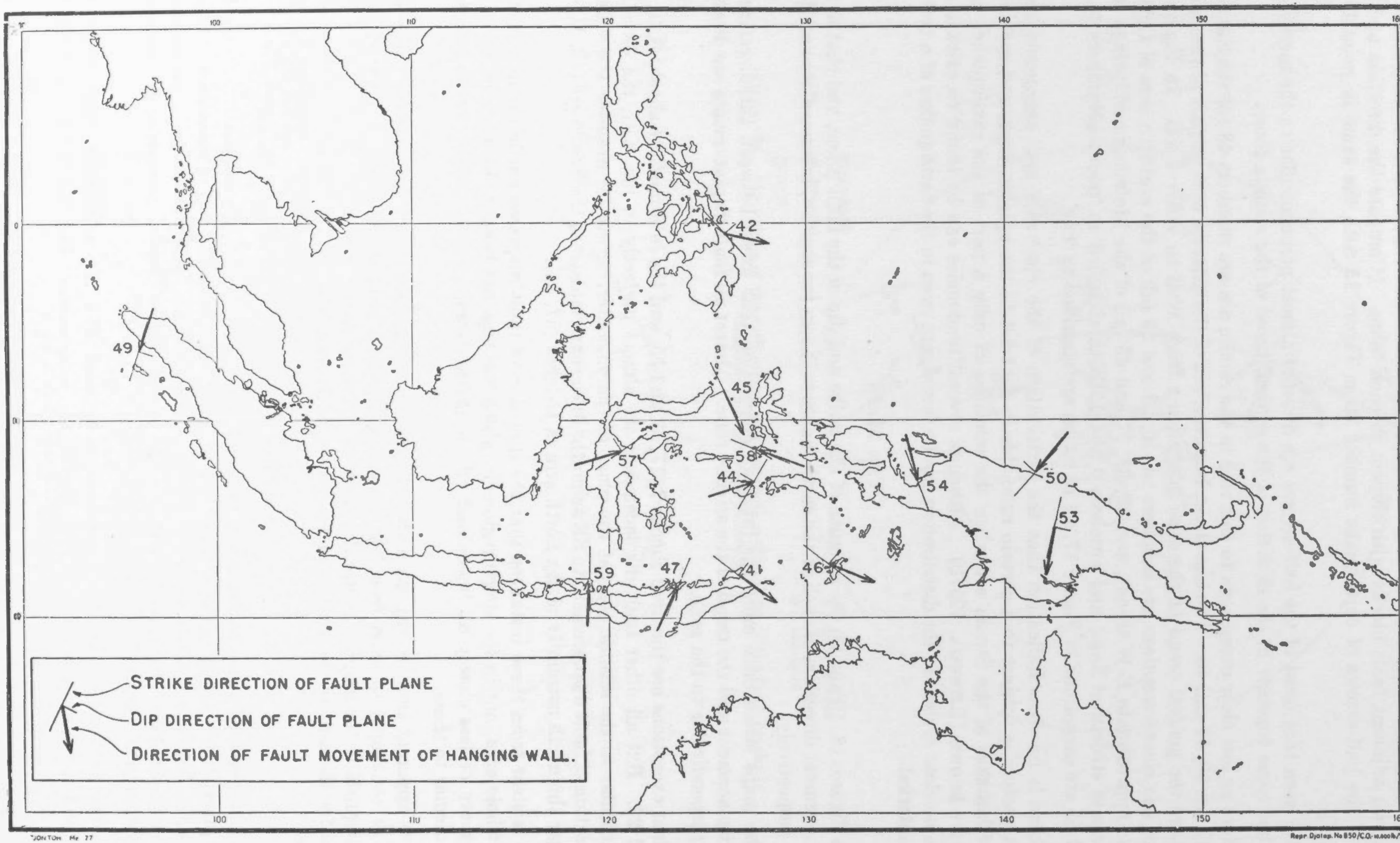

Figure 18. Epicenter map of shallow earthquakes with the azimuth of the fault movement directions and of the strike and dip of the fault planes.

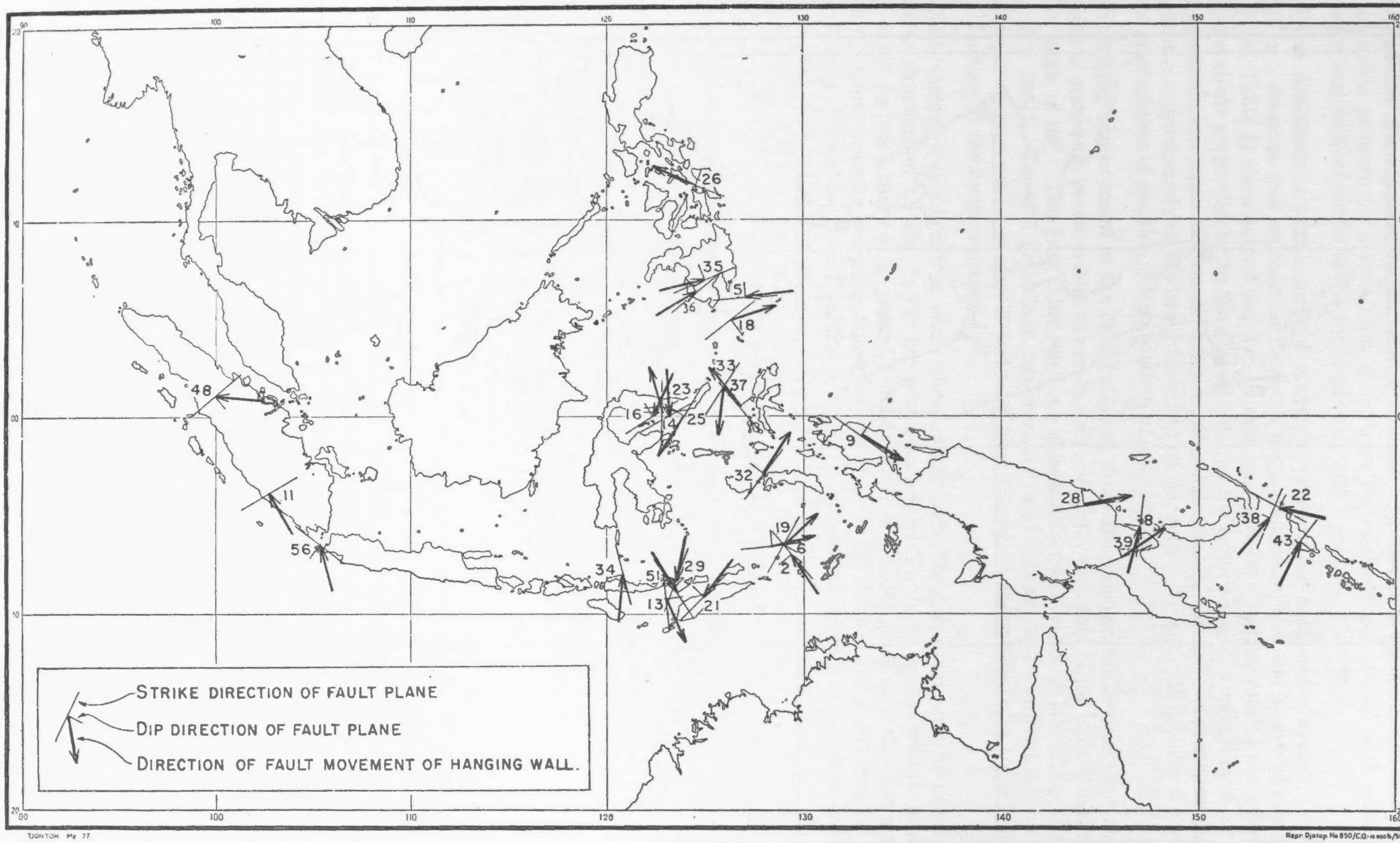

Figure 19. Epicenter map of intermediate earthquakes with the azimuth of the fault movements and of the strike and dip of the fault planes.

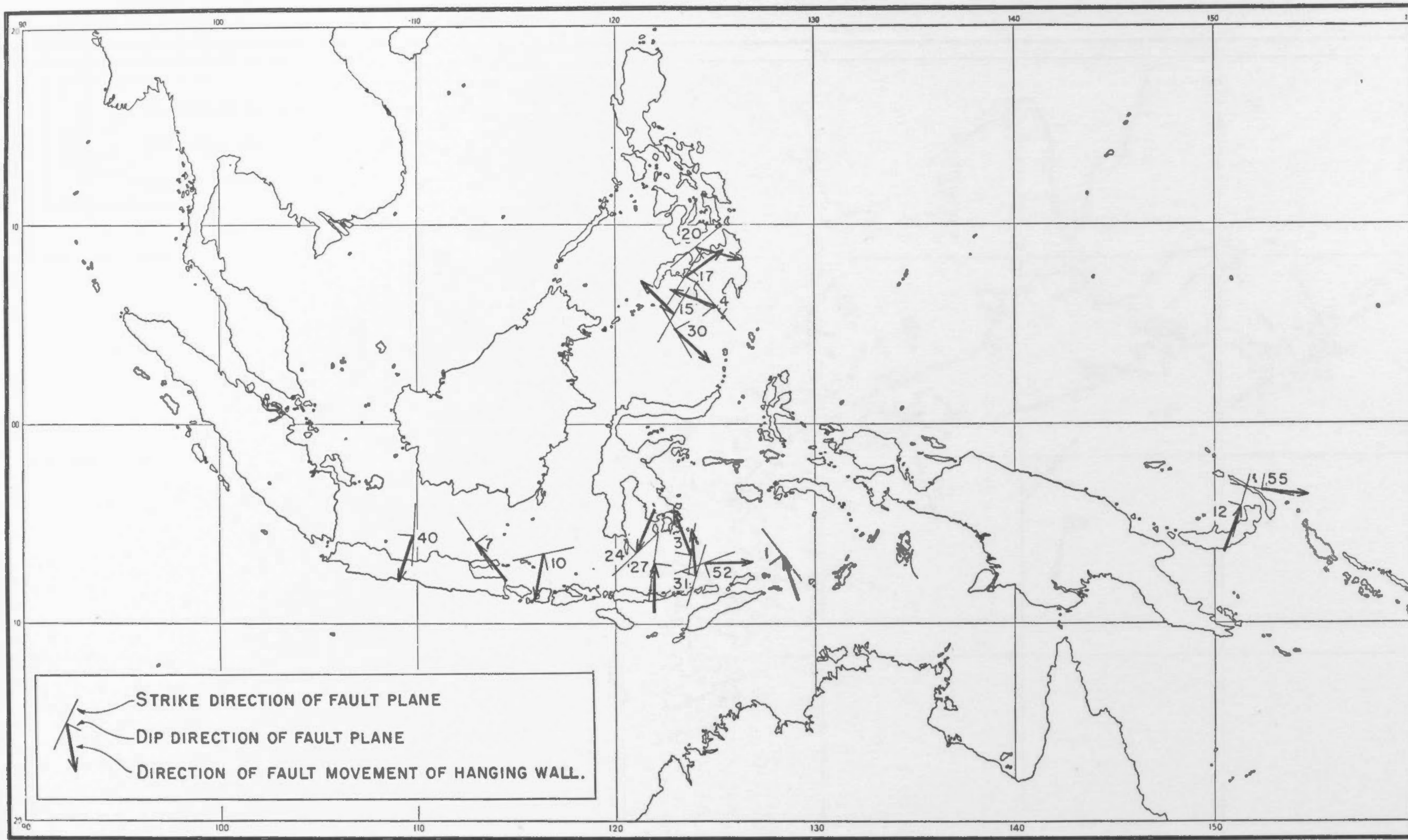

Figure 20. Epicenter map of deep earthquakes with the azimuth of the fault movement directions and of the strike and dip of the fault planes.

all earthquakes of a supposed force system of type II. In that case the directions of maximum and minimum pressure (or tension) act along lines that make angles of 45° with both nodal planes for longitudinal waves in the focus (*see* columns V and VI in Table I).

These directions of maximum and minimum pressure for each single seismic zone were plotted in a diagram (not reproduced here). The diagrams (and also the figures of columns V and VI of Table I) show a tendency for all maximum pressure components to concentrate in directions about perpendicular to the general trend of the seismic zone. The minimum pressure components show a more random distribution, although most of these components are directed in azimuths approximately in the length direction of the zone. No clear differences are evident for the earthquakes of shallow, intermediate and deep levels.

A striking improvement in the distribution of these directions occurs if we assume that the direction of maximum pressure does not make an angle of 45° with that of the fault displacement, but an angle of 30°. This last value has been chosen as a mean value of laboratory data (*see* HUBBERT, 1951). For this procedure, however, we must assume that the fault displacement direction as derived earlier is correct and with that the whole assumption of a force system of type II acting in the focus is disposed of.

Nevertheless, it is a fact that under these suppositions the maximum pressure components of the earthquakes of the Sunda arc are concentrated, with only a few exceptions, in a solid angle of 60° perpendicular to the general trend of the zone. At the same time the vast majority of the minimum pressure components are concentrated in the solid angle of 60° parallel to the general trend of the zone. It is true that in the other two seismic regions the tendencies are the same but the distribution less perfect.

CONCLUSIONS AND SUMMARY

From these considerations the following conclusions can be drawn:

1. It is most likely that force type I, a single couple of forces in the focus, is the origin of the earthquakes of the region.

2. In all magnitude ranges, and in all of the seismic zones in the region, transcurrent fault movements are about three times as frequent as they should be in case of a chance distribution. The fault movements of this type therefore are definitely the most dominating and important.

3. There are indications of small differences in the earthquake mechanisms of different depth levels and seismic zones, (for example greater percentages of normal fault type earthquakes at great depth; gradual changes in dip of the fault plane, plunge of the fault displacement direction, slip angle, and dip of the plane of action at different depth levels; greater frequency of transcurrent fault movements in Pacific regions than in Sunda and Celebes-Philippines arcs).

4. In general the fault displacements are directed perpendicular to the steeply dipping zones of seismic activity in the region. Also when this is not the case the plane of action (null plane) in which the fault movement takes place and in which the forces causing the earthquake are acting, stands about perpendicular to the seismic zone. It is clear therefore that the distribution of earthquakes in space and the mechanisms of the same are clearly related to each other, and that it is most likely that both are expressions of one and the same cause.

5. No clear system can be found in the sense of the fault displacements. The sense of the arrows in Figures 9–11 and 15–17 is not uniform, not even in part of the diagrams or for earthquakes of a certain depth level.

ACKNOWLEDGMENTS

Our special thanks go to the numerous seismologists all over the world who furnished the data on which this study is based.

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The Null Vector as a Guide to Regional Tectonic Patterns

BY JOHN H. HODGSON

Dominion Observatory, Ottawa, Canada.

ABSTRACT

The paper is a sequel to one published earlier (HODGSON, 1957) in which 75 solutions were summarized and discussed. Here 86 additional solutions are given, from various authors, making a total of 161 solutions available for discussion.

Two new areas, southeast Asia and the zone from the Marianas to Japan, have been added to the two already known in which faulting is not exclusively strike-slip. While there can be no doubt of the extreme importance of strike-slip faulting, it appears possible that a disproportionate number of solutions have come from areas in which faulting is exclusively strike-slip, and that the importance of strike-slip faulting has thereby been overemphasized in earlier papers.

Analysis of the direction of dip-slip gives no support to the contraction hypothesis, either in limited areas or in the world as a whole.

The null vectors for tectonically simple areas show simple patterns related to the geographic features. This inspires some confidence in the null vector as a diagnostic tool. So used, it suggests that in both the northeast Pacific and the northwest Pacific a double system of failures is going on, while the Aleutians, central Asia and the Mediterranean are so tectonically complex that only limited areas of them can be considered at the same time.

INTRODUCTION

In a recent paper (HODGSON, 1957) the fault-plane project of the Dominion Observatory was reviewed, a summary was provided of all the solutions by BYERLY's method then available, and the implications of these solutions to geology were discussed. The present paper is a sequel to that earlier one; it will review recent advances in theory and technique in the work of this Observatory, summarize the additional solutions which have become available, and discuss these solutions from the same point of view as that used in the earlier paper.

REVIEW OF RECENT DOMINION OBSERVATORY CONTRIBUTIONS

Comparison of Projections

Because the fault-plane work has grown up independently in several countries, different projections have been used by various investigators, and intercomparison of techniques has been made difficult by the several languages in which the papers are written. SCHEIDEGGER (1957) has gone into the question of projections very thoroughly, and has shown that the projections used in the Soviet Union, in Holland and Indonesia, and by the followers of BYERLY, are all equivalent, and that no other projection is likely to have any additional merit.

Study of Inconsistent Observations

A statistical study has been made (HODGSON and ADAMS, 1958) of the inconsistent observations in the fault-plane solutions summarized in the earlier paper. This work showed that a small number of stations were contributing a relatively high percentage of the inconsistent observations. When these stations were eliminated, the proportion of inconsistencies in P and PKP was just under 14 per cent. The percentage of inconsistencies in the reflected phases, however, was so high as to suggest that these phases were producing random observations. This matter has been investigated in two subsequent papers (HODGSON and COCK, 1957; HODGSON and STEVENS, 1958) by basing solutions solely on direct phases and then testing the data on the reflected phases by comparison with the completed solutions. It has been proven conclusively that, as reported in questionnaires, observations of reflected phases are random.

Solution Confirmed by Field Observation

In the earlier paper ten examples were given of fault-plane solutions which had received some measure of confirmation from field observations; an additional solution may now be added to this list. This is for the Baja California earthquake of February 9, 1956.

The fault-plane solution (Hodgson and Stevens, 1958) shows plane *b* striking N72°W and dipping 72° northeast. Regarding this plane as the fault, the movement is right-lateral strike-slip, with the northeast hangingwall rising slightly.

Shor and Roberts (1958) report a zone of *en echelon* faulting, the mean direction of the zone being N60°W. The fault was apparently very steep. Movement was right-lateral strike-slip with the northeast side rising. The correlation between the seismic solution and the field observations is very satisfactory.

SUMMARY AND DISCUSSION OF NEW SOLUTIONS

Summary of the Solutions

In preparing the summary of new solutions shown in Table I, the findings of Scheidegger (1957) that the various projections are all equivalent has permitted the inclusion of a large number of solutions from Ritsema. However, solutions such as those of the Japanese, which are based on observations at near stations only, have not been included because the dips of the planes are not sufficiently well defined for the purpose of the analysis to follow. In view of the doubts which surround the use of S, solutions which have been based even in part on S have been excluded from the summary. Solutions which, in the opinion of the author, have been based on inadequate data have been excluded from the summary without explanation.

Within these limits 86 additional solutions have become available, 26 of them from Ritsema (1956), 9 from Mühlhäuser (1957), 38 from this Observatory (Hodgson and Cock, 1957; Hodgson and Stevens, 1958) and 13 from various other authors as indicated in the table. The form of the table, and the significance of the various notations employed in it, are identical to those used in the equivalent table of the earlier paper (Hodgson, 1957).

Nature of the Faulting

In the earlier paper it was found that all but 8 of the 75 earthquakes there summarized were the result of strike-slip faulting. In the present listing there are 24 earthquakes in which the dip component is larger than the strike component. This is a much higher percentage than in the earlier paper, but not so large as to vitiate the conclusion that strike-slip faulting is of paramount importance in large earthquakes. Thirteen of the earthquakes in which dip-slip predominates lie in the New Guinea-Indonesia-Sumatra sector and have already been discussed by Ritsema (1956). Nine others are from the zone between the Marianas and Japan. Combining the results of the earlier paper with this one, there have been 17 earthquakes analysed for this area, in 9 of which dip-slip has predominated. In the earlier paper it was shown that in Alaska and in the Pacific coast of British Columbia and Washington the faulting was not exclusively strike-slip. It appears that Japan and Indonesia are two other such areas.

Most of the earthquakes studied have been the result of strike-slip faulting, but even in these it is possible to define the dip component as thrust or tensional. Table II examines the results of such an analysis, for various geographical areas and focal depths; the table combines results from the two papers. It seems clear that the sense of the dip components give no support to the contraction hypothesis, which would demand thrusts near the surface and tensions at depth. There is actually a slight tendency in the reverse direction. There seems again a suggestion that thrusts predominate (31 to 12) in the south Pacific and tensions in the north Pacific (16 to 9). The data are still much too scanty to allow a final conclusion in the matter.

Table I. Summary of additional fault-plane solutions.

EARTHQUAKE				PLANE a					PLANE b					Null Vector		DEXTRAL Solution	SINISTRAL Solution	REFERENCE
Date	φ	λ	Focal Depth-km.	Strike Direction	Dip Direction	Dip	Strike Component	Dip Component	Strike Direction	Dip Direction	Dip	Strike Component	Dip Component	Trend	Plunge			
New Zealand - Kermadecs - Tonga - Fiji																		
February 19, 1954	30° S	177.7° W	Normal	N 29.5° E	S 60.5° E	87°	0.985	+0.175	N 60° W	N 30° E	80°	0.999	+0.053	N 48° E	79.5°	b	a	Hodgson and Cock, 1957.
- alternative solution -				N 78.5° E	N 11.5° W	73°	0.889	+0.459	N 21° W	S 69° W	64°	0.946	+0.325	N 72° W	58°	b	a	Hodgson and Cock, 1957.
December 10, 1950	28.7°S	179° W	300	N 85° E	N 5° W	88°	0.707	+0.707	N 7° W	S 83° W	45°	0.999	+0.049	S 87° W	45°	b	a	Mühlhäuser, 1957.
January 10, 1956	25° S	176° W	Normal	N 25° E	S 65° E	82°	0.981	-0.193	N 67° W	N 23° E	79°	0.990	-0.142	N 60° E	76.4°	a	b	Hodgson and Stevens, 1958.
August 18, 1954	21.5°S	176° W	150	N 27° E	S 63° E	81°	0.932	-0.363	N 67° W	N 23° E	69°	0.986	-0.168	N 50° E	66.8°	a	b	Hodgson and Cock, 1957.
September 13, 1954	21° S	175.5° W	150	N 17° E	S 73° E	84°	0.939	-0.345	N 75° W	N 15° E	70°	0.994	-0.112	N 32° E	69.6°	a	b	Hodgson and Cock, 1957.
September 15, 1954	18° S	178.5° W	600	N 51.5° E	N 38.5° W	83°	0.864	-0.504	N 34.5° W	N 55.5°E	60°	0.990	-0.141	N 39.5°E	59.4°	b	a	Hodgson and Cock, 1957.
November 10, 1955	15° S	174° W	100	← Not defined →				+ →	N 80° W	N 10° E	87°	← + — Not defined →				a	b	Hodgson and Stevens, 1958.
New Hebrides - Solomons																		
January 5, 1955	16°S	167.5° E	Normal	N 56.5° E	S 33.5° E	56°	0.999	-0.022	N 33.5° W	N 56.5°E	89°	0.820	-0.572	S 35.5°E	55.9°	a	b	Hodgson and Cock, 1957.
October 13, 1955	9.5°S	161° E	Normal	← Not defined →				+1.	← Not defined →				+1. →			Thrust		Hodgson and Stevens, 1958.
August 16, 1955	6° S	155° E	200	N 49° E	N 41° W	81°	0.944	+0.330	N 38° W	N 52° E	71°	0.986	+0.166	N 26° E	68.9°	a	b	Hodgson and Stevens, 1958.
Marianas - Bonins - Japan - Kuriles - Kamchatka																		
February 1, 1956	19° N	145.5° E	350	← Not defined →				-1. →	← Not defined →				-1. →			Normal		Hodgson and Stevens, 1958.
May 30, 1955	24.5°N	142.5° E	600	N 70° E	N 20° W	35°	1.000	-0.000	N 20° W	S 70° W	90°	0.574	-0.819	N 21° W	35.4°	a	b	Hodgson and Cock, 1957.
February 18, 1956	30° N	137.5° E	450	N 29° E	S 61° E	56°	0.892	-0.452	N 76° W	N 14° E	68°	0.798	-0.603	N 78° E	47.7°	a	b	Hodgson and Stevens, 1958.
April 17, 1948	33° N	135.5° E	Normal	N 43° E	S 47° E	86°	0.000	+1.00	N 43° E	N 47° W	4°	0.000	+1.00	N 43° E	0°	Thrust		Mühlhäuser, 1957.
July 18, 1952	34.4°N	135.8° E	70	N 74° E	S 16° E	71°	0.918	-0.396	N 14° W	N 76° E	68°	0.936	-0.351	S 65° E	62.4°	a	b	Ichikawa, 1955.
May 14, 1954	36° N	137° E	250	N 56° E	N 34° W	68°	0.991	+0.132	N 31° W	N 59° E	83°	0.926	+0.378	N 14.5° W	66.9°	a	b	Hodgson and Cock, 1957.
May 23, 1938	36.5°N	141.6° E	Normal	N 31° W	N 59° E	84°	0.000	+1.00	N 31° W	S 59° W	6°	0.000	+1.00	N 31° W	0°	Thrust		Mühlhäuser, 1957.
November 2, 1936	38.3°N	141.9° E	Normal	N 37° E	S 53° E	75°	0.000	+1.00	N 37° E	N 53° W	15°	0.000	+1.00	N 37° E	0°	Thrust		Mühlhäuser, 1957.
March 4, 1952	42.1°N	143.9° E	40	N 16° E	N 74° W	85°	0.0	-1.0	N 16° E	S 74° E	5°	0.0	-1.0	N 16° E	0°	Normal		Ichikawa, 1955.
November 13, 1932	43.4°N	137° E	330	N 32° E	N 58° W	70°	0.628	+0.778	N 82° W	S 8° W	43°	0.865	+0.502	S 47.5°W	35.1°	b	a	Mühlhauser, 1957.
September 11, 1935	43.6°N	146° E	Normal	← Not defined →				+1. →	← Not defined →				+1. →			Thrust		Muhlhäuser, 1957.
February 28, 1950	46.2°N	143.5° E	320	N 5° E	N 85° W	69°	0.997	-0.075	N 84° W	N 6° E	86°	0.933	-0.350	N 73° W	67.7°	b	a	Ichikawa, 1955.
July 6, 1954	46.5°N	153.5° E	100	← Not defined →				+ →	N 22° W	N 68° E	62°	← + — Not defined →						Hodgson and Cock, 1957.
June 30, 1936	51° N	161.1° E	Normal	N 55° E	N 35° W	66°	←	+ — Not defined — + →										Mühlhäuser, 1957.
May 3, 1954	51.5°N	159.5° E	Normal	N 9° E	N 81° W	70°	0.938	-0.346	N 74° W	N 16° E	71°	[illegible]	-0.362	N 34° W	62.2°	b	a	Hodgson and Cock, 1957.
April 17, 1955	52° N	159.2°	Normal	N 51° E	N 39° W	84°	0.978	-0.210	N 38° W	N 52° E	78°	[illegible]	-0.107	N 25° E	76.9°	b	a	Hodgson and Cock, 1957.
Aleutians																		
June 2, 1955	51.5°N	180°	Normal	N 86° E	←	90°	← Not defined →							N 86° E	→			Hodgson and Cock, 1957.
June 20, 1955	51.5°N	180°	Normal	N 38° E	N 52° W	58°	0.752	-0.660	N 27° W	N 63° E	56°	0.769	-0.639	N 7.5° E	39.7°	b	a	Hodgson and Cock, 1957.
April 17, 1954	51.5°N	179° W	Normal	N 87.5°E	N 2.5° W	82°	0.994	-0.106	N 3° W	S 87° W	84°	0.990	-0.140	N 40° W	80.0°	a	b	Hodgson and Cock, 1957.
-alternative solution -				N 45° E	S 45° E	84°	0.965	-0.261	N 46° W	N 44° E	75°	0.994	-0.108	N 66° E	74.3°	a	b	Hodgson and Cock, 1957.
March 14, 1955	52.5°N	173.5° W	100	N 19° E	N 71° W	70°	0.979	-0.203	N 67° W	N 23° E	79°	0.938	-0.348	N 39° W	66.3°	b	a	Hodgson and Cock, 1957.
January 13, 1955	53° N	167.5° W	Normal	N 52° E	S 38° E	89°	0.961	+0.275	N 39° W	N 51° E	74°	0.999	+0.018	N 66° E	73.3°	b	a	Hodgson and Cock, 1957.
Alaska - United States - Central America - Caribbean																		
October 3, 1954	60.5°N	151° W	100	N 36° E	S 54° E	52°	0.958	-0.285	N 45.5° W	S 44.5°W	77°	0.775	-0.632	S 31° E	49.3°	b	a	Hodgson and Cock, 1957.
July 6, 1954	39.5°N	118.5°W	Normal	N 56° E	N 34° W	51°	0.963	-0.268	N 24° W	N 66° E	78°	0.765	-0.643	N 10° W	48°	b	a	Tocher, 1955.

Table I. Summary of additional fault-plane solutions—*Continued*

EARTHQUAKE				PLANE a					PLANE b					Null Vector		DEXTRAL Solution	SINISTRAL Solution	REFERENCE
Date	φ	λ	Focal Depth-km.	Strike Direction	Dip Direction	Dip	Strike Component	Dip Component	Strike Direction	Dip Direction	Dip	Strike Component	Dip Component	Trend	Plunge			
Alaska - United States - Central America - Caribbean (Cont'd)																		
August 24, 1954	39.5°N	118.5° W	Normal	N 45° E	N 45° W	51°	0.587	-0.810	N 5° W	N 85° E	51°	0.587	-0.810	N 20° E	27.7°	b	a	Tocher, 1955.
December 16, 1954	39.5°N	118° W	Normal	N 66° E	N 24° W	66°	0.858	-0.514	N 11° W	N 79° E	62°	0.887	-0.461	N 31° E	52.0	b	a	Romney, 1957.
February 9, 1956	31.5°N	116° W	Normal	N 19° E	S 71° E	85°	0.951	+0.311	N 72° W	N 18° E	72°	0.996	+0.092	N 35° E	70.9°	b	a	Hodgson and Stevens, 1958.
April 29 A, 1954.	28.5°N	113° W	Normal	N 46° E	S 44° E	88°	0.925	+0.379	N 45° W	N 45° E	68°	0.999	+0.038	N 50° E	68°	b	a	Hodgson and Cock, 1957.
April 29 B, 1954	28.5°N	113° W	Normal	N 46° E	S 44° E	88°	0.925	+0.379	N 45° W	N 45° E	68°	0.999	+0.038	N 50° E	68°	b	a	Hodgson and Cock, 1957.
July 9, 1956	20° N	73° W	100	N 13° E	S 77° E	64°	0.977	+0.213	N 82° W	N 8° E	79°	0.894	+0.447	N 77° E	61.6°	b	a	Hodgson and Stevens, 1958.
January 15, 1931	16.4°N	96.3° W	Normal	N 2° E	S 88° E	74°	0.987	+0.162	N 87° E	N 3° W	81°	0.960	+0.279	N 60° E	70.7°	b	a	Mühlhäuser, 1957.
August 28, 1955	14° N	91° W	60	N 7° E	S 83° E	73°	0.789	+0.615	N 85° E	N 5° W	54°	0.932	+0.361	N 27° E	48.6°	b	a	Hodgson and Stevens, 1958.
February 19 B, 1954	12.5°N	87.5°W	Normal	N 28.5° E	N 61.5° W	55°	0.985	-0.170	N 55° W	N 35° E	82°	0.815	-0.579	N 44° W	53.3°	b	a	Hodgson and Cock, 1957
July 18, 1934	8.2°N	82.6° W	Normal	N 79° E	N 11° W	84°	0.890	-0.456	N	E	63°	0.993	-0.117	N 69.3°E	61.4°	b	a	Mühlhäuser, 1957.
April 27, 1954	6° N	82.5° W	Normal	N 6.5° E	S 83.5° E	85°	0.970	-0.243	N 85° W	N 5° E	76°	0.996	-0.090	N 27° E	75.2°	a	b	Hodgson and Cock, 1957.
South America																		
January 8, 1956	19° S	70° W	Normal	N 18° E	N 72° W	83°	0.919	-0.393	N 69° W	N 21° E	67°	0.991	-0.132	N 2° E	65.8°	b	a	Hodgson and Stevens, 1958.
December 7, 1953	22° S	68.5° W	100	N 32° E	S 58° E	79°	0.812	-0.584	N 66° W	N 24° E	55°	0.973	-0.233	N 46° E	53.5°	a	b	Ingram, 1957.
April 19, 1955	30° S	72° W	Normal	N 35° E	N 55° W	72°	0.946	-0.325	N 49° W	N 41° E	72°	0.946	-0.325	N 6° W	64.4°	b	a	Hodgson and Cock, 1957.
December 17, 1949	53.6°S	69.9° W	Normal	← Not defined →					N 51.5° W	N 38.5° E	83°	←	→	S 65° E	← Not defined →			Rascher, 1952
South Pacific																		
November 22, 1955	24.5°S	123° W	Normal	N 2° E	N 88° W	89°	0.981	+0.197	N 88° W	N 2° E	79°	0.999	+0.018	N 1° W	78.5°	a	b	Hodgson and Stevens, 1958.
New Guinea - Indonesia - Philippines - Sumatra																		
January 31, 1956	4° S	152° E	400	← Not defined				-1.	Not defined				-1. →			Normal		Hodgson and Stevens, 1958.
March 3, 1954	5.5°S	142.5° E	Normal	N 12° E	S 78° E	76°	0.996	-0.090	N 79° W	N 11° E	85°	0.970	-0.243	N 82° E	75°	a	b	Ritsema, 1956.
December 2, 1953	2.7°S	141.5° E	Normal	N 40° E	N 50° W	89°	0.999	+0.034	N 50° W	S 40° W	88°	0.999	+0.017	S 67° W	87.7°	b	a	Ritsema, 1956.
August 21, 1955	3° S	137.5° E	Normal	N 74° E	S 16° E	60°	0.934	+0.357	N 26° W	N 64° E	72°	0.851	+0.526	S 53° E	54.0°	b	a	Hodgson and Stevens, 1958.
June 6, 1954	3° S	135.5° E	Normal	N 21° W	N 69° E	88°	0.000	+1.00	N 21° W	S 69° W	2°	0.000	+1.00	N 21° W	0°	Thrust		Ritsema, 1956.
April 6, 1953	7.3°S	131.0° E	Normal	N 22° E	N 68° W	67°	0.829	-0.560	N 53° W	N 37° E	59°	0.890	-0.456	N 8° W	49.5°	b	a	Ritsema, 1956.
January 31, 1941	6.5°S	128.5° E	200	N 78° E	N 12° W	81°	0.111	-0.994	N 40° E	S 50° E	11°	0.573	-0.820	N 77° E	8°	b	a	Ritsema, 1956.
October 3, 1954	1.5°S	127.5° E	Normal	N 20° E	N 70° W	80°	0.999	+0.053	N 70° W	N 20° E	87°	0.985	+0.175	N 52° W	79.4°	a	b	Ritsema, 1956.
July 13, 1952	3.1°S	127.4° E	Normal	N 31° E	N 59° W	26°	0.709	+0.705	N 17° W	N 73° E	72°	0.327	+0.945	N 12° W	19°	Thrust		Ritsema, 1956.
February 14, 1952	7.7°S	126.5° E	Normal	N 36° E	N 54° W	74°	0.999	-0.055	N 53° W	N 37° E	87°	0.961	-0.277	N 43° W	73.3°	b	a	Ritsema, 1956.
January 20, 1953	1.5°N	126° E	Normal	N 65° E	N 25° W	89°	0.984	-0.181	N 25° W	S 65° W	80°	0.999	-0.018	S 70° W	80°	a	b	Ritsema, 1956.
March 19, 1952	9.5°N	126° E	Normal	N 12° E	N 78° W	52°	0.645	-0.764	N 42° W	N 48° E	53°	0.637	-0.771	N 16° W	30.3°	b	a	Ritsema, 1956.
February 20, 1954	6.9°S	124.5° E	600	N 70° E	S 20° E	28°	0.929	-0.370	N 1° W	S 89° W	80°	0.443	-0.897	S 4° W	27°	b	a	Ritsema, 1956.
- alternative solution -				N 15° W	S 75° W	79°	0.535	-0.845	N 88° W	N 2° E	34°	0.940	-0.341	N 24 W	32°	b	a	Ritsema, 1956.
January 1, 1954	9.0°S	123.5° E	100	N 57° E	S 33° E	89°	0.901	+0.434	N 34° W	N 56° E	64°	0.999	+0.019	N 62° E	65°	b	a	Ritsema, 1956.
June 25, 1953	8.5°S	123.5° E	Normal	N 24° E	N 66° W	87°	0.999	+0.033	N 66° W	N 24° E	88°	0.999	+0.049	N 26° W	86.1°	a	b	Ritsema, 1956.
September 22, 1940	7.5°N	123.5° E	650	N 32° E	S 58° E	38°	0.880	-0.475	N 35° W	S 55° W	73°	0.567	-0.824	S 24° E	33°	b	a	Ritsema, 1956.
October 20, 1938	9.2°S	123.0° E	100	N 66° E	N 24° W	71°	0.706	-0.708	N 6° W	N 84° E	48°	0.899	-0.438	N 48° E	42.4°	b	a	Ritsema, 1956.
June 18, 1940	5.4°N	123.0° E	550	N 45° E	N 45° W	43°	0.000	-1.00	N 45° E	S 45° E	47°	0.000	-1.00	N 45° E	0°	Normal		Ritsema, 1956.
September 17, 1941	0.1°N	122.7° E	200	N 0° E	N 90° W	66°	0.837	-0.548	N 75° E	S 15° E	60°	0.883	-0.470	S 32° W	50°	a	b	Ritsema, 1956.
November 27, 1941	6.6°S	121.1° E	500	N 47° E	N 43° W	73°	0.550	+0.835	N 67° W	S 23° W	37°	0.874	+0.486	S 58° W	31°	b	a	Ritsema, 1956.
September 20, 1954	1.5°S	120.5° E	Normal	N 55° E	N 35° W	38°	0.919	-0.393	N 16° W	N 74° E	76°	0.583	-0.812	N 6° W	34°	a	b	Ritsema, 1956.
November 2, 1954	8.0°S	119.0° E	Normal	N 1° E	N 89° W	87°	0.961	+0.277	N 88° W	N 2° E	74°	0.999	+0.055	N 10° W	74°	a	b	Ritsema, 1956.

Table I. Summary of additional fault-plane solutions—*Concluded*

EARTHQUAKE				PLANE a					PLANE b					Null Vector		DEXTRAL Solution	SINISTRAL Solution	REFERENCE
Date	φ	λ	Focal Depth-km.	Strike Direction	Dip Direction	Dip	Strike Component	Dip Component	Strike Direction	Dip Direction	Dip	Strike Component	Dip Component	Trend	Plunge			
New Guinea - Indonesia - Philippines - Sumatra (Cont'd)																		
August 11, 1937	6.5°S	116.5°E	600	N 79° W	N 11° E	68°	0.000	-1.00	N 79° W	S 11° W	22°	0.000	-1.00	S 79° E	0°	Normal		Ritsema, 1956.
February 11, 1952	5.5°S	109.8°E	650	N 4° E	N 86° W	64°	0.873	-0.488	N 72° W	N 18° E	64°	0.873	-0.488	N 34° W	51.4°	b	a	Ritsema, 1956.
July 3, 1954	6.5°S	105.5° E	100	N 53° W	S 37° W	66°	0.000	+1.00	N 53° W	N 37° E	24°	0.000	+1.00	N 52° W	0°	Thrust		Ritsema, 1956.
August 18, 1938	3.8°S	102.8° E	100	N 60° E	N 30° W	63°	0.000	+1.00	N 60° E	S 30° E	27°	0.000	+1.00	N 60° E	0°	Thrust		Ritsema, 1956.
July 7, 1953	1.0°N	100° E	200	N 5° E	N 85° W	62°	0.426	+0.905	N 50° E	S 40° E	37°	0.626	+0.780	S 18° W	21.8°	b	a	Ritsemu, 1956.
November 13, 1953	3.5°N	96° E	Normal	N 18° E	S 72° E	89°	0.999	+0.034	N 72° W	S 18° W	88°	0.999	+0.017	S 9° E	87.8°	a	b	Ritsema, 1956.
Central Asia																		
August 15, 1950	28.5°N	98.7° E	Normal	E W	N	75°	0.000	-1.00	E W	S	15°	0.000	-1.00	E W	0°	Pure Normal		Tandon, 1954.
March 21, 1954	24.4°N	95.2° E	180	N 50° E	N 40° W	60°	0.829	+0.560	N 56° W	S 34° W	61°	0.820	+0.572	S 88° W	46.4°	b	a	Tandon and Mukherjee, 1956.
July 21, 1956	23.5°N	70.2° E	Normal	N 57° E	N 33° W	65°	0.985	-0.173	N 29° W	N 61° E	81°	0.904	-0.428	N 11° W	64°	b	a	Tandon, 1957.
Mediterranean and Azores																		
September 12, 1955	32.5°N	30° E	Normal	N 33° E	N 57° W	64°	0.783	+0.623	N 38° W	N 52° E	56°	0.849	+0.529	N 4° E	44.2°	a	b	Hodgson and Stevens, 1958
July 16, 1955	37.5°N	27° E	Normal	N 40° E	N 50° W	84°	0.995	+0.105	N 50° W	N 40° E	84°	0.995	+0.105	N 6° W	81°	a	b	Hodgson and Cock, 1957.
July 9 A, 1956	37°N	26° E	Normal	N 43° E	N 47° W	72°	0.798	-0.603	N 62° W	S 28° W	55°	0.926	-0.377	S 65° W	48.1°	a	b	Hodgson and Stevens, 1958
April 30, 1954	39°N	22° E	Normal	N 86° E	N 4° W	18°	0.998	-0.069	N 46° W	S 44° W	78°	0.954	-0.301	N 49° W	13°	a	b	Hodgson and Cock, 1957.
March 16, 1941	38.5°N	12.0° E	85	N 68° E	N 22° W	59°	1.00	0.000	N 22° W		90°	1.00	0.000	N 68° E	59°	b	a	Di Filippo, 1950 a.
November 25, 1941	37.3°N	19.0° W	Normal	N 87° E	N 3° W	90°	1.00	0.000	N 3° W	N 87° E	70°	1.00	0.000	N 87° E	70°	a	b	Di Filippo, 1950 b.

Table II. Relationship of Thrust (+) and Gravity (−) Dip Components to Focal Depth and Geographic Area.

Area	Focal Depth, km.														Total	
	Normal		100		200		300		400		500		600			
	+	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-
New Zealand to Samoa	4	3	3	-	3	-	2	1	-	-	1	-	1	1	14	5
New Hebrides, Solomon Islands	10	1	2	1	3	1	1	-	-	-	-	-	-	-	16	3
Marianas, Bonins	1	-	-	1	-	-	-	1	-	1	-	-	-	1	1	4
Japan to Kamchatka	2	8	2	-	-	1	1	1	-	-	1	-	-	-	6	10
Aleutians	3	5	-	1	-	-	-	-	-	-	-	-	-	-	3	6
Alaska to Panama	9	9	-	-	-	-	-	-	-	-	-	-	-	-	9	9
Continental North America	1	4	-	-	-	-	-	-	-	-	-	-	-	-	1	4
Caribbean	-	-	1	-	-	-	-	-	-	-	-	-	-	-	1	-
South America	1	3	1	1	-	-	-	-	-	-	-	-	1	-	3	4
New Guinea to Sumatra	8	6	3	1	1	2	-	-	-	1	1	1	-	4	13	15
Central Asia	-	3	-	-	1	1	-	-	-	-	-	-	-	-	1	4
Mediterranean	2	8	-	-	-	-	-	-	-	-	-	-	1	-	3	8
Totals	41	50	12	5	8	5	4	3	-	2	3	1	3	6	71	72

Dip Vectors and Null Vectors

A General Discussion

In the earlier paper two quantities were defined, known as the dip vector and the null vector. These terms derived logically from the techniques of the solutions. As an example the reader is referred to Figure 9 of that earlier paper (Hodgson, 1957) which shows a typical solution. In that figure, circles *a* and *b* represent planes. The direction of dip of these planes is obtained by drawing the diameters of the corresponding circles through the origin; the tangent of the dips of the planes is proportional to the length of these diameters. The direction of dip is thus given by the direction of a line and the amount of dip by its length. It is therefore logical to call the directed line segment a vector—the *dip vector*.

The line joining the points of intersection of the two circles is the projection of the line of intersection of the corresponding planes. The trend of this line of intersection is given by the azimuth of its projection, and the tangent of its plunge is proportional to the length of the projection. Again it is logical to call the directed segment a vector— the *null vector*, the term *null* deriving from the fact that the line of intersection of the two planes undergoes no displacement during the earthquake.

In the earlier paper it was suggested that the strike directions of the planes in the various circum-Pacific areas were random, but that the dip vectors and null vectors showed patterns. These patterns were demonstrated by treating the dip or null vectors as free, and drawing them from a single point by means of the projection shown in Figure 1a. If in this figure we regard PQ as the vector, then it projects into the segment OQ', or simply into the point Q'. If we regard PQ as the trace of a plane drawn perpendicular to the paper, then the plane projects into a line through Q'. Parallel planes having different dips project into parallel lines at distances from the centre proportional to the dips of the corresponding planes.

McIntyre and Christie (1957) in a discussion of that earlier paper made an important contribution to the understanding of the physical significance of the null vector. They also made a number of criticisms, most of them very helpful, one or two of them pedantic. In the latter category must be their objection to the term "vector" as used in dip vector and null vector. These terms have been defended in the foregoing paragraphs. Perhaps this in itself is pedantic; it matters little what they are called so long as their significance is understood. More pertinently McIntyre and Christie pointed out that the separate analysis of strike and dip is a serious defect in procedure, since these are two aspects of a single concept—the attitude of the plane. In structural geology it is usual to define attitude by plotting the pole of the plane in a stereographic projection. This brings us to the question of projections and to the most serious criticism of their Discussion.

Structural geologists have long been accustomed to dealing with the orientation in space of lines and planes. This has been done with the stereographic projection shown in Figure 1b. Lines are drawn from the centre of the figure to meet the lower hemisphere as at Q. This point

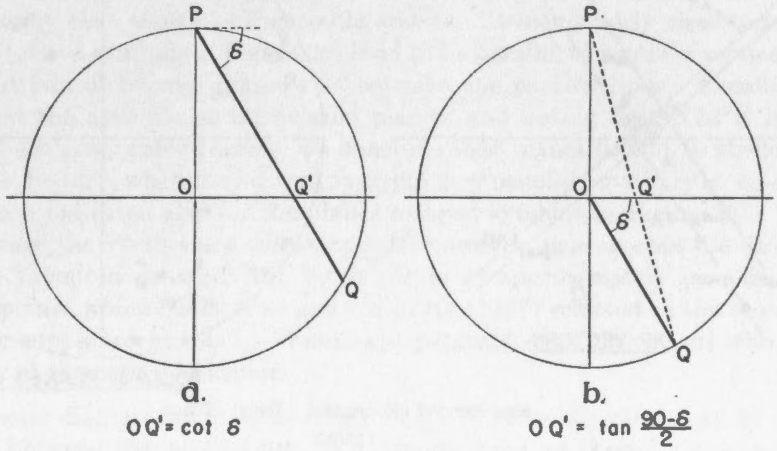

Figure 1. A comparison of the two alternate projections. In each case the heavy line is to be projected on the diametral plane drawn perpendicular to the paper through O. *a* is the projection used in the earlier paper, *b* is the projection normally used by structural geologists.

is then joined to the pole P to intersect the mapping plane at Q'. The line OQ thus projects into the line OQ', or simply into the point Q'. To plot a plane, the plane is imagined to pass through the origin and the downward normal is drawn; this is a line similar to OQ, and it is projected as before. The point Q' would be called the *pole* of a plane perpendicualr to OQ. McIntyre and Christie suggested that, since the study of the fault planes is a study in structural geology, the projection favoured by structural geologists should be used. They suggest indeed that the projection shown in Figure 1a, which was used in the earlier paper, leads to self-deception.

Before examining this criticism it should be pointed out that McIntyre and Christie have clarified the meaning of the dip vector: the dip vector defines the attitude of the fault plane, for its azimuth is perpendicular to the strike of the plane and its dip is the complement of the dip of the plane. It defines attitude just as well, although less conventionally, than the poles do. Indeed, as it turns out, it does it better.

This is shown in Figure 2, where the attitude of the planes in the New Zealand-Tonga sector are defined by dip vectors (a) and by poles (b). In b the poles lie close to the periphery of the diagram, indicating that the planes are steeply dipping, and they are drastically spread out in azimuth indicating a lack of uniformity in strike direction. It labours the very points which McIntyre and Christie sought to avoid. Figure 2a, on the other hand, shows that there is a system to the attitude of the planes—that planes which deviate from a preferred strike direction have a very steep dip.

The null vectors are plotted in the two projections in Figure 3. In the projection used in Figure 3a the distance of a point from the centre is equal to cot δ, which can vary from zero to infinity. The points are much more extended in the favoured direction than in Figure 3b where the distance of a point, being equal to tan $(90-\delta)/2$, can vary only from zero to one. This extension is not scientifically dishonest; where there is no pattern it also magnifies the confusion. But the most important point about the projection used in *a* is that parallel planes project into parallel lines instead of into arcs of circles as in *b*. This is a great convenience since we propose to search for properties related to parallel planes. I conclude that while McIntyre and Christie may properly use their favourite projection in carrying out their very valuable analysis of the fault-plane results, its advantages are not sufficiently obvious to require a change from the projection already adopted.

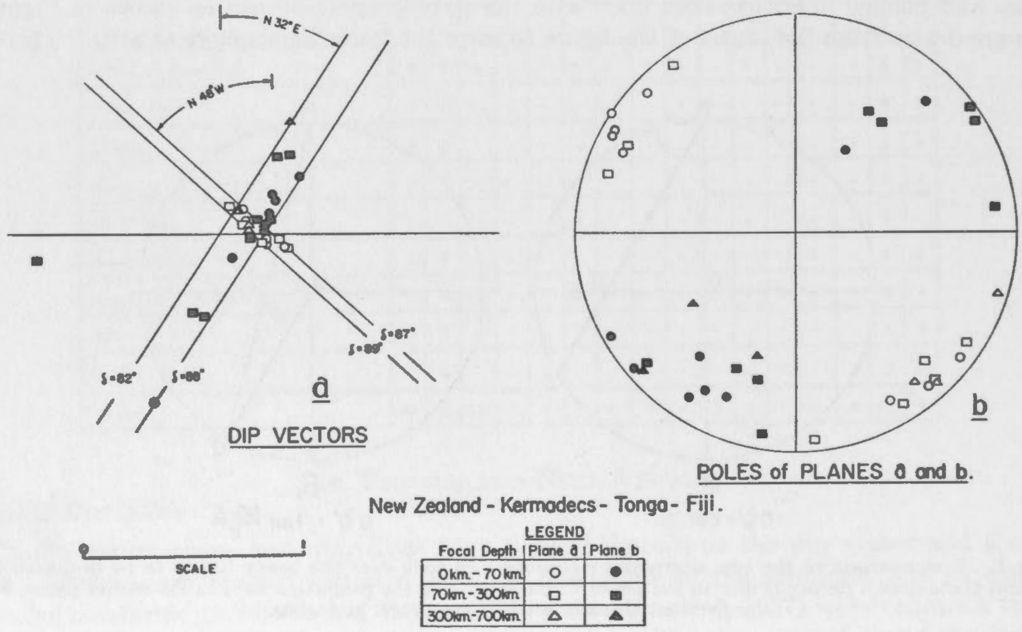

Figure 2. The attitudes of the fault planes determined in the New Zealand—Tonga sector as defined by (*a*) dip vectors and the projection of Figure 1*a* and by (*b*) poles and the projection of Figure 1*b*.

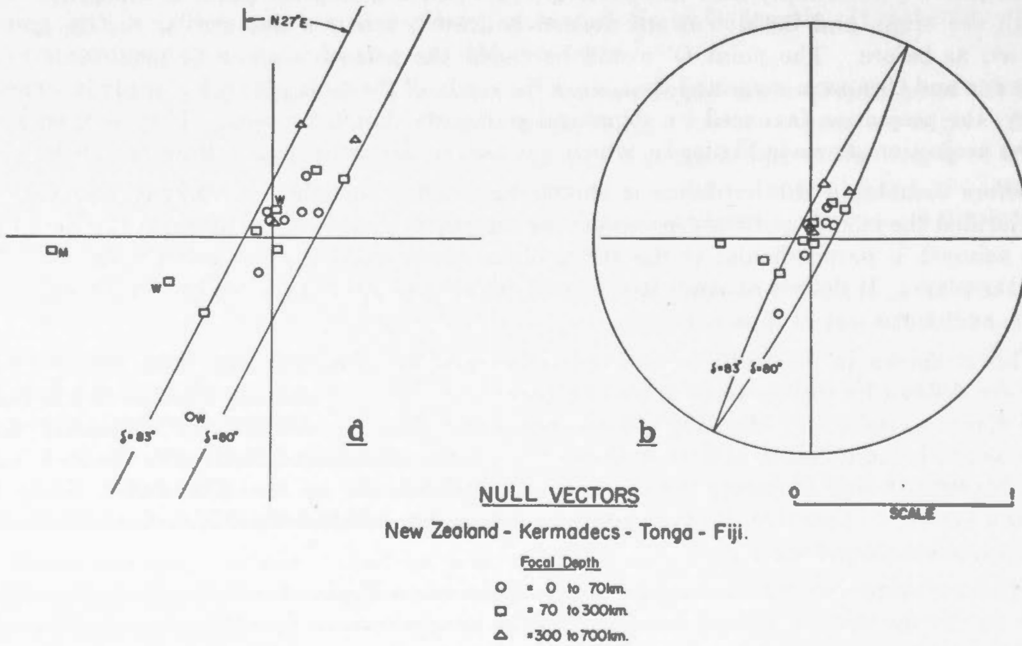

Figure 3. Null vectors and their enveloping planes as defined by (*a*) the projection of Figure 1*a* and (*b*) the projection of Figure 1*b*. Letters *M*, *W*, beside symbols indicate solutions by Mühlhäuser (1957) and Webb (1954) respectively.

Areas with Simple Null Vector Patterns

It will be a thesis of this paper, as it was of the earlier one, that the null vector has definite tectonic significance in the New Zealand-Tonga sector, in the New Hebrides, and in South America. If this can be accepted it is a most important conclusion; these areas are the most difficult ones in which to obtain solutions because of the small numbers of seismic stations within even moderate distance of the epicentres. If the results in these areas can be shown to be tectonically valid there can be little doubt that the solutions in other areas are dependable. Considering the conflict between the results of the fault-plane work and the theories of many tectonophysicists it is extremely important to establish this point.

The dip vector and null vector diagrams for the first of these areas, the New Zealand-Tonga sector, have already been shown in Figures 2*a* and 3*a*. It seems fairly clear that the dip vectors for the *b* planes (closed symbols in Figure 2*a*) tend to lie parallel to a nearly vertical plane, striking N32°E. All but two of twenty symbols lie between the parallel lines. Recalling that the dip vectors represent the attitude of the related planes, and noting that N32°E is approximately the direction of the geographic feature, we conclude that planes *b* tend to strike at right angles to the geographic feature; when they do not so strike they usually have very steep dip. A favoured direction has been indicated also for the planes *a* (open symbols in Figure 2*b*). This is not well supported, because the vectors are too steep. If, however, one accepts the direction, it would follow that the favoured direction for the *a* planes is approximately parallel to the feature. It is this set of planes which McIntyre and Christie (1957) selected as the more probable fault planes; they are supported in this by Wellman (personal communication) who is an authority on the tectonics of the area in question.

The null vector diagram for the area (Figure 3*a*) seems equally clear. All but two of nineteen null vectors lie between the parallel lines, and the direction of these lines, as was shown in the earlier paper, is approximately that of the associated geographic feature. It would certainly be desirable to establish the best direction of the lines statistically and indeed to establish that parallel lines provide the best system; these are difficult statistical problems. It must also be admitted that, whereas the typical fault in the area is a steeply dipping strike-slip one, the direction of the pattern is controlled by the distant points, and these derive from the less strongly strike-slip faults with the less steeply dipping planes. In this sense, the pattern which is being proposed as typical for the area derives from the least typical earthquakes. Despite these objections, when one considers that the points in Figure 3*a* might lie anywhere in the plane, the pattern is impressive.

The dip vector pattern for the New Hebrides is shown in Figure 4*a*, the null vector pattern in Figure 4*b*. The directions which have been suggested for the dip vector pattern are less well defined than those in the New Zealand-Tonga sector, and they are less easy to interpret. The diagram would suggest that the favoured direction for faulting is about N43°E and N66°W, and since the mean direction of the geographic feature is about N22°W, these are neither normal nor tangential to the feature. It should be pointed out that the two directions suggested in this diagram are very similar to the dip vector directions for the New Zealand-Tonga sector as shown in Figure 2*a*. This suggests the possibility that the favoured direction for the strike of the fault planes is related in the two areas.

It might be argued that a more westerly inclination to the parallel lines would fit the pattern of null vectors better than that selected. At least it seems clear that the pattern will be a NW-SE one, which is in good agreement with the strike of the geographic feature. Twelve of the fifteen points fit the pattern selected and two others come very close to doing so. This pattern is exactly parallel to the feature. Admitting the limitations of the analysis already outlined, the correlation is reasonably satisfactory.

The tectonic pattern in South America is relatively simple, but the area is so large that diagrams similar to those used in the southwest Pacific are not satisfactory. It is better to

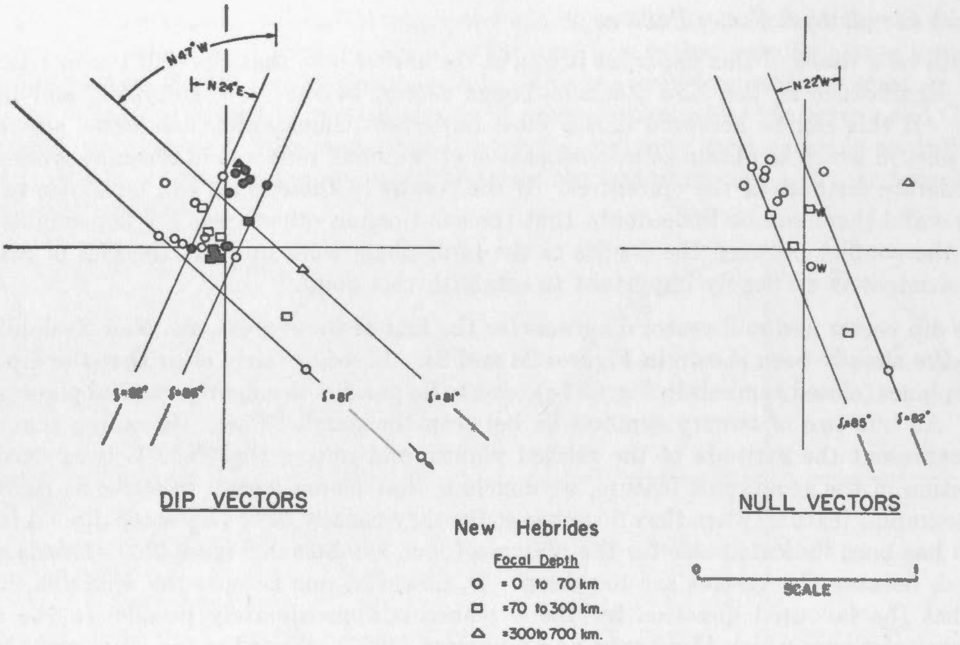

Figure 4. Dip vectors and null vectors for earthquakes in the New Hebrides. The letter *W* beside a symbol represents a solution by Webb (1954).
In the dip vector diagram open symbols refer to planes *a*, closed symbols to planes *b*.

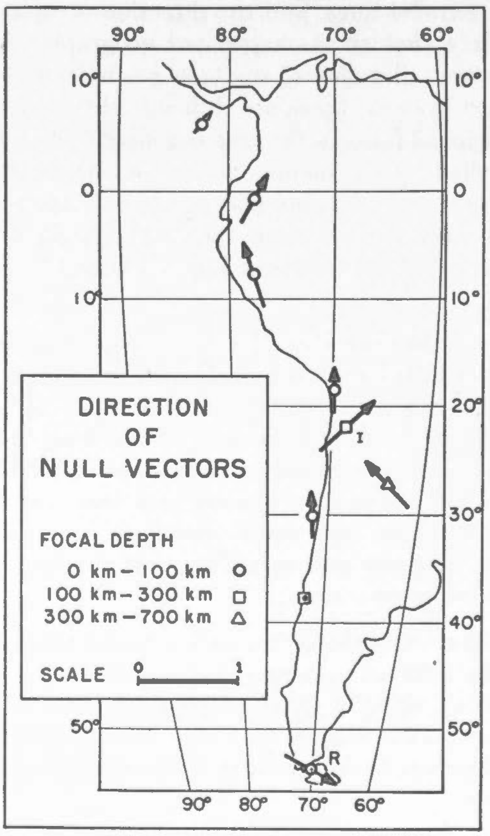

Figure 5. Null vectors for South American earthquakes. The lengths of the vectors are obtained by the projection of Figure 1*a*. The letter *I* identifies a solution by Ingram (1957), the letter *R* one by Rascher (1952).

plot the null vectors on a map. This has been done in Figure 5. With the exception of the solution by INGRAM the arrows are very satisfactorily parallel to the tectonic fabric of the country; even the swirl at the southern tip of the continent is followed by the null vector of RASCHER's solution. The solution by INGRAM is a very well defined and well supported one, and there can be no question about its accuracy. The epicentre lies at the junction of the northern and southern systems, and the null vector direction is probably significant.

This discussion of South American earthquakes concludes the most direct evidence for the significance of the null vector. It is submitted that the null vectors have shown a strong tendency to lie parallel to the tectonic pattern in the New Zealand-Tonga sector and in South America, and a less definite but still well defined tendency in the New Hebrides. It is further submitted that this cannot be an accidental matter and that, since it occurs in the regions where solutions are most difficult to obtain, the techniques of the fault-plane project must be thereby confirmed. We conclude that the null vector must have tectonic significance, and we shall use it to examine areas which are less simple tectonically.

Areas with Double Null Vector Pattern

There are two Pacific areas in which the null vectors suggest a double pattern, as if two different failure systems were in simultaneous operation. The first such area is the northwest Pacific. The dip and null vector patterns for these areas, shown in Figure 6 are considerably different than those given in the earlier paper. This has come about because of the large number of new solutions many of which, having strong dip components, have their vector points far off-scale. These off-scale points dictate the directions of the parallel lines.

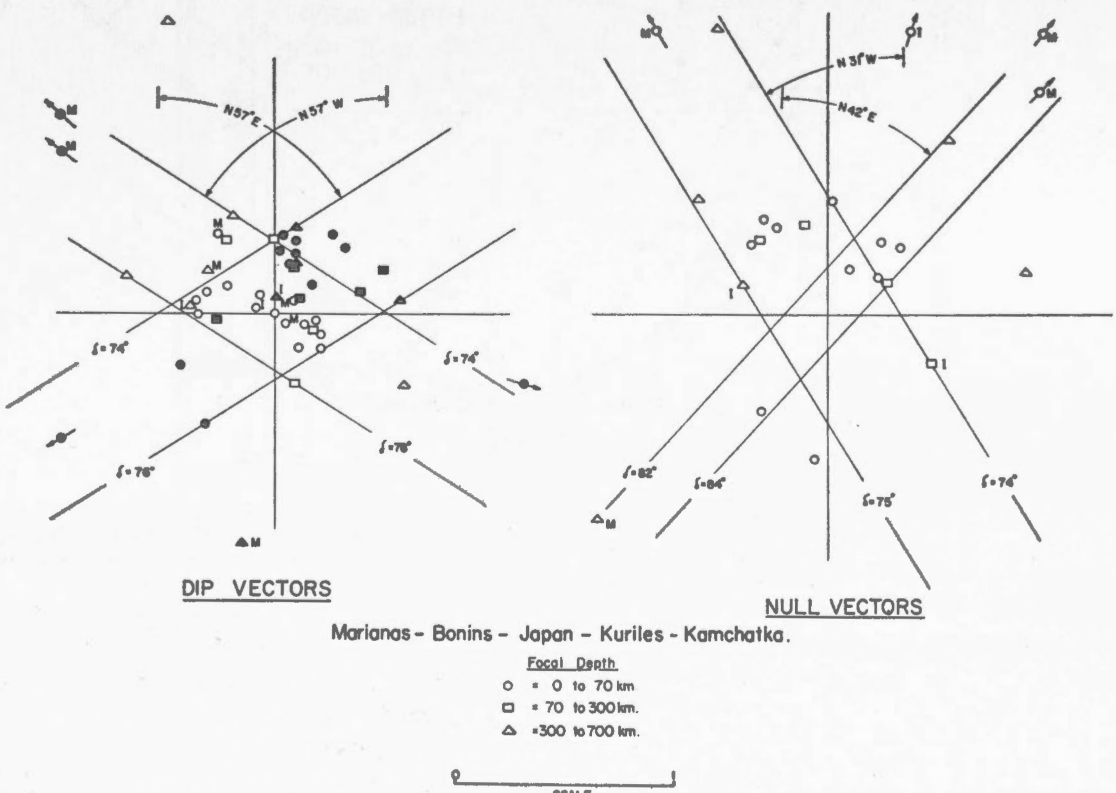

Figure 6. Dip vectors and null vectors for earthquakes in the northwest Pacific. The letter *M* identifies points from solutions by MÜHLHÄUSER (1957), the letter *I* points from solutions by ICHIKAWA (1955).

In the dip vector diagram open symbols refer to planes *a*, closed symbols to planes *b*.

The pattern selected for the dip vectors is a highly symetrical one, with deviations of about 15° from vertical planes striking 57° east and west of north. All but three of forty-nine dip vectors adhere to this pattern. This suggests that the favoured direction of faulting is either N33°W or N33°E. The former direction is inclined at 20° to the mean normal to the arc. I have elsewhere published evidence (Hodgson 1958), based largely on Russian solutions, that this is the probable direction of the faults of the area.

The null vector diagram (Figure 6*b*) suggests however that the problem is not so simple. In the southwest Pacific the null vectors defined a single direction for each arc; here two directions appear to be defined. All but three of twenty-four null vectors fit the suggested pattern, the directions of which are dictated by the off-scale points. These directions are somewhat different than those determined in the earlier paper, but they give a better fit to the geographic directions there selected (Hodgson, 1957, p. 636) of N38°E and N30°W.

A second area with an apparently dual null vector pattern is the Pacific coast of North America, the diagrams for which are shown in Figure 7; note that in this figure the scale for the null vector diagram is only one-fifth of that used in the other diagrams.

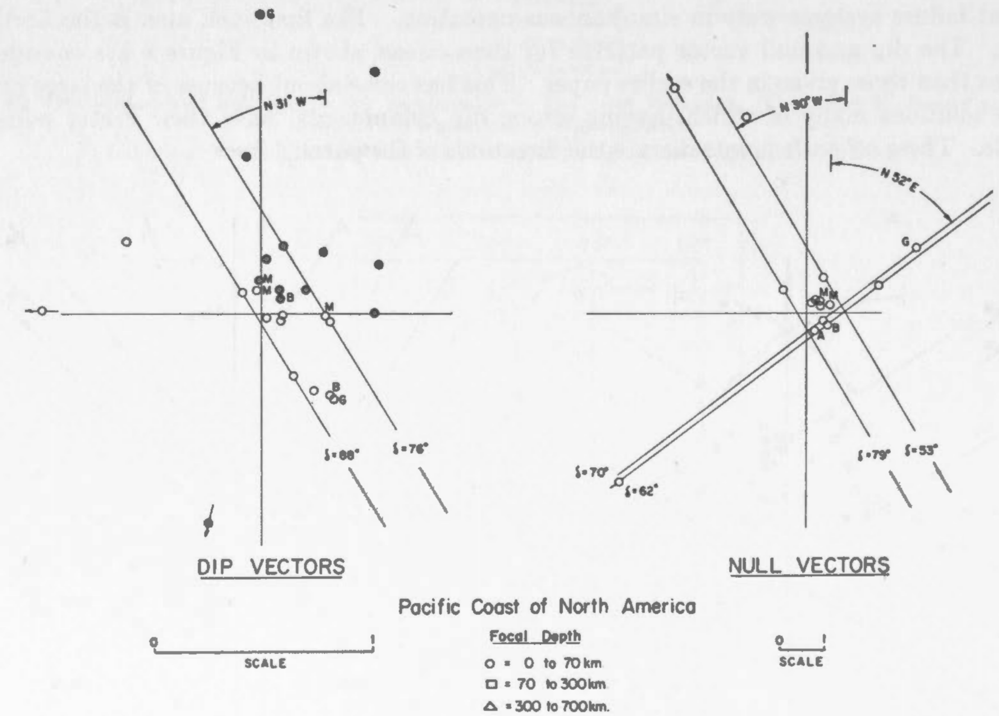

Figure 7. Dip vectors and null vectors for earthquakes on the Pacific coast of North America. Note the special scale used in the null vector diagram. The letters *A*, *B*, *G* and *M* indicate that the points come from solutions by Adkins (1940), Byerly (1938), Gutenberg (1955) and Mühlhäuser (1957) respectively.

In the dip vector diagram open symbols refer to planes *a*, closed symbols to planes *b*.

A direction N31°W has been selected as the best direction for the dip vectors of plane *a*. This is not a well defined direction, a much more westerly trend would be equally easy to defend. Indeed it may well be that there is no favoured direction for the *a* dip vectors; there is certainly no direction evident for the *b* set. There does, however appear to be some evidence for a dual pattern in the null vector diagram, even when we bear the reduced scale in mind. The significance of the two directions suggested was discussed in the earlier paper. It is worth noting that the better defined of the two planes is not vertical, but dips at about 66° to the southeast.

It is much too early to suggest the significance of the dual null vector pattern found in the two north Pacific areas. If one is prepared to accept the patterns it must follow that, in each of these vast areas, the tectonics may be considered as a whole; in the next section we shall see that in other much smaller areas this cannot be done. It must also follow that, in each area, there are two different families of earthquakes. It seems certain that these families must be regarded separately in studies such as those which McIntyre and Christie (1957) made in the southwest Pacific. It is possible that they should be considered separately also in constructing strain release diagrams.

Areas with Complex Null Vector Pattern

We now turn our attention to certain other areas in which, considering the section as a whole, no null vector pattern can be found. The first such area is the Aleutians, for which the null vectors have been shown on in Figure 8. If there is any pattern in the null vectors it seems to be quite different from that in the south Pacific, for here the more prominent vectors are perpendicular rather than parallel to the features. It is probably more significant that adjacent null vectors are nearly parallel: for example the three vectors on the Alaskan mainland are approximately parallel to each other, and so are the vectors for the next two earthquakes to the west. This suggests that in this particular area the tectonics of different small sections must be considered separately.

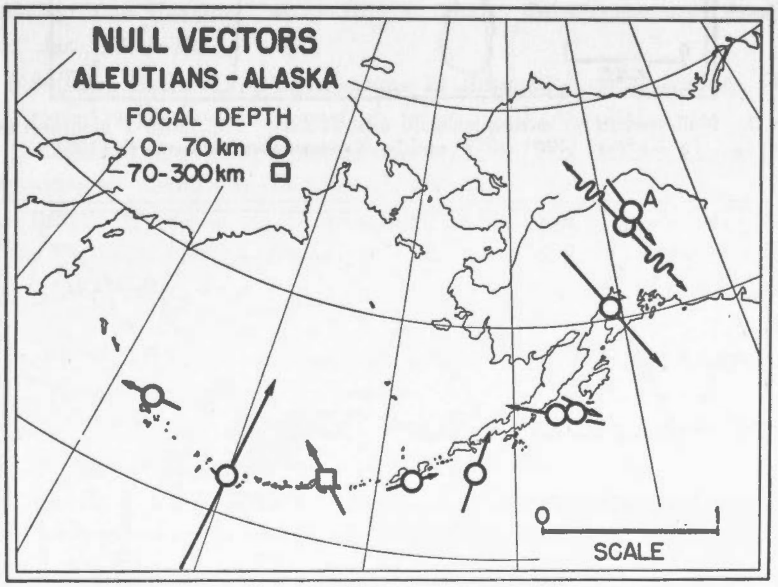

Figure 8. Null vectors for Aleutian earthquakes. The symbol designated *A* represents a solution by Adkins (1940). In this, and in subsequent diagrams, null vectors of greater than unit length have been indicated by a compressed arrow.

In the version of this paper that was read at the Meetings it was suggested that the New Guinea-Indonesia area was similar in its complexity. In his contribution to this symposium Ritsema has shown that the null vectors in the area of his interest probably have a pattern, not as simple as that in the southwest Pacific, but a good deal more regular than I had supposed. The reader is referred to his very complete discussion, to which nothing can be added here.

Null vectors for earthquakes in central Asia are shown in Figure 9, those for the Mediterranean in Figure 10. Again it seems clear that there is no over all pattern in these large areas but that these areas must be subdivided for discussions of their tectonics.

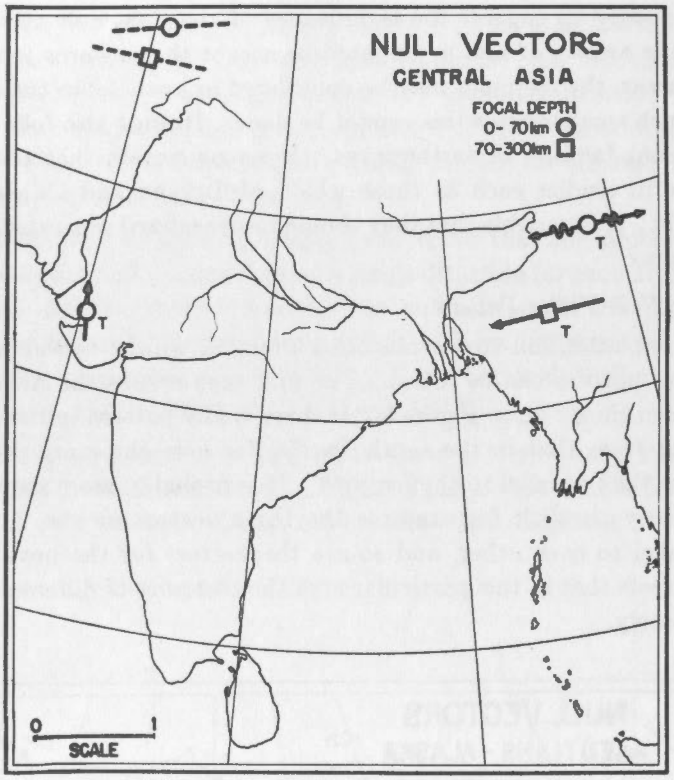

Figure 9. Null vectors for earthquakes in central Asia. The letter *T* identifies solutions by TANDON (1954, 1957) and by TANDON and MUKHERJEE (1956).

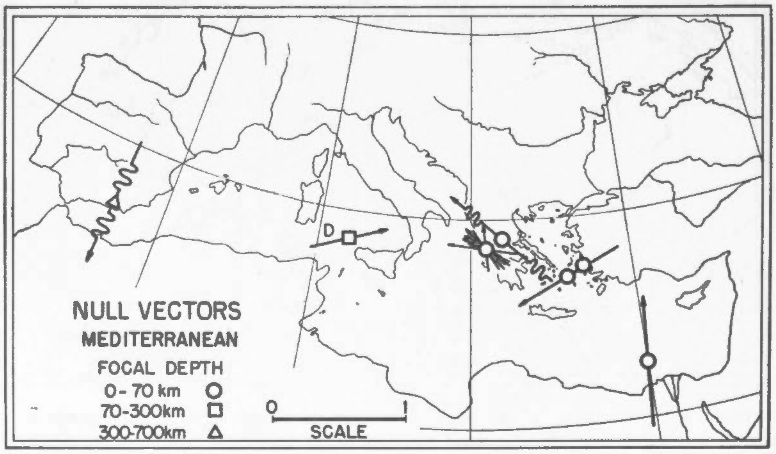

Figure 10. Null vectors for Mediterranean earthquakes. The letter *D* identifies a solution by DIFILIPPO (1950a).

SUMMARY AND CONCLUSIONS

Eighty-six fault-plane solutions, from various sources, have been listed; combining these with the 75 solutions given earlier yields 161 earthquakes for analysis.

From the combined results it appears that strike-slip faulting is by far the most common, but that there are certain areas in which the faulting in not exclusively strike-slip. Among these areas are Alaska and British Columbia, central Asia, the zone from the Marianas to Japan, and southeast Asia. The latter two are newly defined as areas in which the faulting is not exclusively strike-slip. The addition of two such large areas to the previous small list must raise the question whether the importance of strike-slip faulting has been overemphasized. It now appears possible that a disproportionate number of solutions have been made in areas in which the faulting is exclusively strike-slip.

There is no support for the contraction hypothesis from the analysis of the direction of dip-slip.

The null vectors for tectonically simple areas show simple patterns related to the geographic features. This inspires some confidence in the null vector as a diagnostic tool. So used it suggests that a double failure system has developed in the northeast and northwest Pacific, while the Aleutians, central Asia and the Mediterranean are so tectonically complex that only limited areas of them can be considered at one time.

ACKNOWLEDGEMENTS

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The Kinematics of Faulting from Seismic Data

BY DONALD B. MCINTYRE and JOHN M. CHRISTIE
Pomona College, Claremont, California.

ABSTRACT

The attitude of a fault and the nature of the slip on it can be determined from the pattern of distribution over the globe of compressional and dilatational first motions of P waves. The method as used by BYERLY and HODGSON gives two possible solutions for each earthquake. The writers have already demonstrated that in an area showing a certain type of structural homogeneity, the ambiguity might be resolved by consideration of the geometrical relations between the pairs of solutions: it was concluded that in the southwest Pacific the movement was on steep strike-slip faults striking parallel to the physiographic feature. In the present paper solutions from other areas are discussed.

On the assumption that the ambiguity of the results of a P-wave analysis can be resolved by study of the first motions of S waves, KOGAN has derived unique solutions for the northwest Pacific. It is shown that KOGAN's results for the Japan-Kamchatka area differ markedly from HODGSON's solutions for the same region and time interval based on P-wave records obtained at stations distributed all over the world. Similarly the solutions of HONDA *et al* for the same area and time interval differ markedly from the solutions of both HODGSON and KOGAN.

The value of solutions for an earthquake sequence is emphasized and an analysis of a series of Greek earthquakes (1953) is attempted.

INTRODUCTION

If an earthquake is generated by movement on a fault, and if the orientations of the fault and of the slip on it are known, then it is possible to predict the distributions of stations receiving respectively compressional and dilatational first motions of the P phase. Conversely, from an adequate distribution of data concerning the observed signs of the first motion of P, the orientation of the generating fault and the nature of the slip on it may be determined. The method, originated by BYERLY, and developed especially by HODGSON, is now well known. Unfortunately, the symmetry of the data is such that two solutions are always possible; the orientations of two planes are found, one of these is the fault and the other is the plane normal to the direction of slip. Using kinematic reference axes*, we can say that, whereas the B axis is uniquely determined as the intersection of the two planes, it is not possible to distinguish between the planes and hence between the A and C axes.

Perhaps the greatest interest in the results obtained by HODGSON and his collaborators is the unambiguous demonstration that the B axes are usually steep (MCINTYRE and CHRISTIE, 1957, Figure 1) and hence that the fault movements which give rise to major earthquakes are predominantly strike-slip. As a result of the ambiguity between A and C inherent in the method, there is uncertainty about the relative orientations of the faults and the approximately rectilinear or arcuate physiographic features with which they are associated. It has been claimed that for any area the B axes tend to lie parallel to a vertical plane having the direction of the associated feature. The fault-plane solutions give in each case two perpendicular planes, one of which is the fault plane; the present writers examined the structure resulting from one of the two sets of planes for all solutions in a single arc, and then from the other. This was done by means of β diagrams; that set of planes which gave a β maximum coinciding with the maximum of B axes for the arc was taken to represent the faults†.

*A = motion direction in the fault plane;
B = normal to A in the fault plane (equal to null vector);
C = normal to the fault plane (AB).

†One of the conditions which must be fulfilled but which was not stated explicity (MCINTYRE and CHRISTIE, 1957, p. 651), is that the planes must fall into two groups. These groups may be defined statistically but in such a case ambiguity will remain for any planes which do not belong to these groups.

It is essential that the solutions with which such an analysis is made are derived from faults which belong to a genetically related series, such as the faults constituting a movement zone like the San Andreas Rift. The selection of areas for analysis is therefore a matter of critical importance, for if an area includes two or more unrelated systems of faults, a simple result could not be expected using this technique. It seems to have been generally assumed that the long, gently-curving island arcs of the circum-Pacific region represent such simple systems. However, it is not unlikely that some of the island arcs are more complex than this, and close to the intersections of arcs complication of the kinematic picture must certainly exist. These complexities may account for the failure of our analyses in some of the areas selected, though lack of data is considered to be a more important cause. Old fault planes or other planes of weakness unrelated to the main fault system may become active during a sequence of movements if the resolved shear stress on any of these becomes sufficiently great. Solutions obtained for movements on such planes might vitiate the patterns obtained for an area.

The best results are to be expected from series of shocks belonging to a single earthquake sequence, for we consider that in a localized sequence there is the greatest likelihood of the movements being kinematically related. One such sequence (in the Greek Islands, August 1953) is analyzed below and it is shown that the data could be interpreted in terms of movement with the same sense and more or less the same direction on a group of sub-parallel planes. Eyewitness accounts indicate that at least some of the movements followed the pattern deduced. It is to be hoped that solutions will be obtained for other sequences of this type, such as the remarkable series of shocks which occurred in the Aleutians in March, 1957. Where sequences of shocks are not available, considerable advantage should be gained by subdividing the areas at present used for analysis; some of these are island arcs almost 3,000 miles long. This procedure has already been employed by Honda (1957) in his analysis of movements in the region of Japan. By separate analysis of solutions for smaller areas and shorter intervals of time it may be possible to resolve the complexity in some of the areas so far considered. An ideal case would be a number of foreshock-main shock-aftershock sequences in a limited area.

NEW ZEALAND-KERMADEC-TONGA-FIJI

When the available data were plotted on equal area projections, it was found that only for Hodgson's New Zealand-Kermadec-Tonga-Fiji group was the claim justified that in any one area the B axes defined a plane. In the other areas the number of analyses was as yet too small. In the New Zealand-Fiji area, the B axes define a vertical plane striking parallel to the trend of the feature and containing a single strong maximum (McIntyre and Christie, 1957, Figures 2–4); the A and C axes (which of course cannot be distinguished from one another) fall into two groups, normal and parallel respectively to the plane of the B axes. Whereas the group of planes which are parallel to the plane of the B axes gives a β maximum of nearly 30 per cent per 1 per cent area coinciding with the B maximum, the other planes give two much smaller β maxima which do not coincide with B. Hence it was concluded that the group of planes parallel to the physiographic feature probably represent the faults.

Dr. Hodgson has since made available to us a large number of new solutions. Four of these are from the New Zealand-Kermadec-Tonga area and they are shown in Figure 1*a*. The result of adding these new analyses to the thirteen previously available is to maintain the two groups of planes (Figure 1*b*), and to increase the strength of the β maximum for the northeast-striking planes while weakening the B maxima for the northwest-striking planes (compare Figures 1*c* and *d* with McIntyre and Christie, 1957, Figures 3 and 4).

At the time of writing our contribution to the discussion of Hodgson's paper (Hodgson, 1957), we did not have data on the sense of movement implied by our selection of a northeasterly strike for the faults. This important information has fortunately been included in the table of data accompanying the published paper (Hodgson, 1957, Table 1), and is also available for Hodgson's new analyses (personal communication). There are seventeen solutions for the New

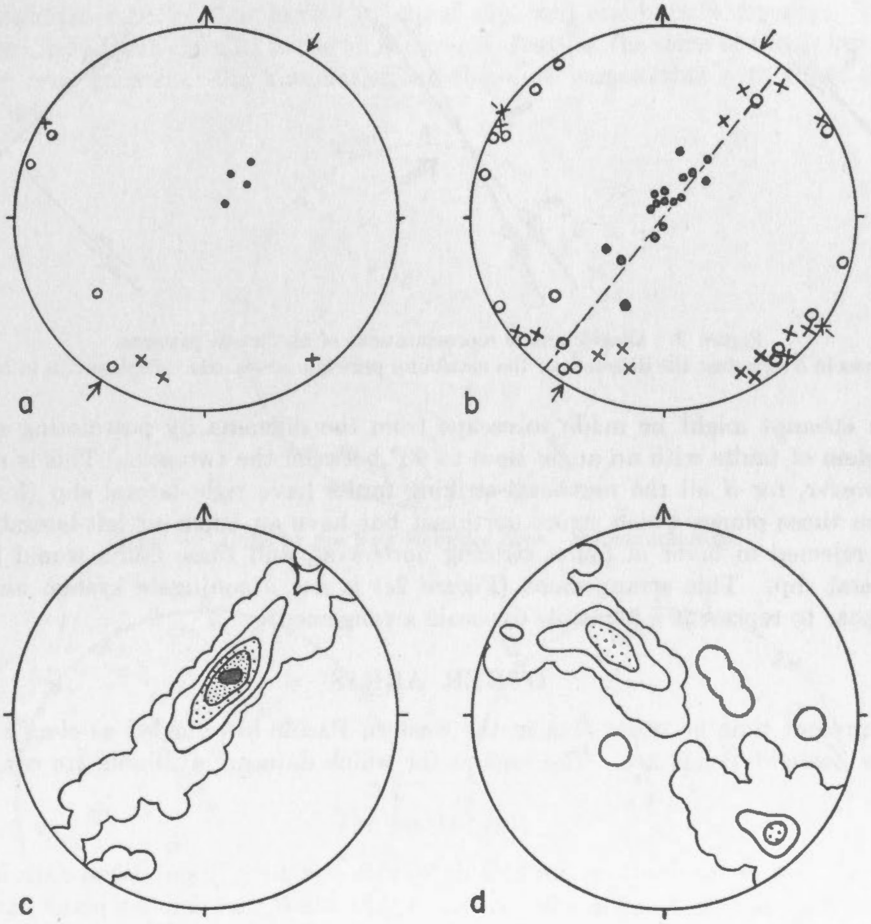

Figure 1. Data for the New Zealand-Kermadec-Tonga-Fiji arc.
a. Four new solutions.
b. Total of seventeen solutions.
c. β diagram for group of planes with northeast strike.
Contours: 30, 20, 10, 5, 3/4 per cent per 1 per cent area.
d. β diagram for group of planes with northwest strike.
Contours: 10, 5, 3/4 per cent per 1 per cent area.

The following symbols are used in all the projections except where otherwise stated:
● *B* axis.
⊗ Pole of a plane with pure dip-slip movement.
○ Pole of a plane with right-lateral strike-slip component of movement.
× Pole of a plane with left-lateral strike-slip component of movement.
Arrows indicate the mean trend of the associated physiographic feature in each area.
All data are plotted in the lower hemisphere of an equal-area projection; the primitive circle is horizontal with north at the top.

Zealand-Tonga area and of these nine have right-lateral slip and eight have left-lateral slip. There are several possible interpretations of this interesting result:

i) The large earthquakes may all result from slip on essentially parallel faults on which the sense of slip oscillates between right and left lateral (Figure 2*a*).

ii) The faults may constitute a system of two sets of slip surfaces inclined at small angles to each other and with opposite senses of slip (Figure 2*b*). This would imply a higher degree of plasticity than seems probable, and in the available data there is no indication of two such sets of faults.

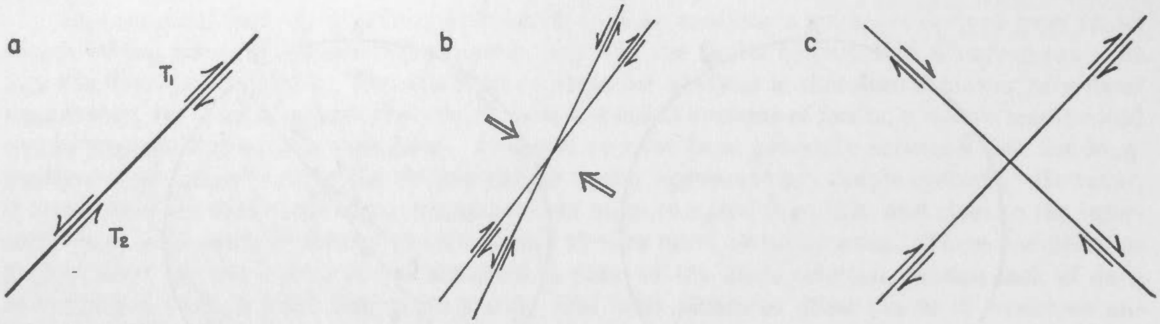

Figure 2. Diagrammatic representations of movement patterns.
Arrows in *b* represent the direction of the maximum principle stress axis. Explanation in text.

iii) An attempt might be made to escape from the dilemma by postulating a conjugate system of faults with an angle close to 90° between the two sets. This is not possible however, for if all the northeast-striking faults have right-lateral slip (for example), then those planes which strike northeast but have an apparent left-lateral slip would be rejected in favor of faults striking northwest, and these faults would have right-lateral slip. This arrangement (Figure 2*c*) is not a conjugate system and does not appear to represent a plausible dynamic arrangement.

OTHER AREAS

At the present time no other area in the western Pacific has yielded as clear a pattern as has the New Zealand-Tonga arc. The regions for which data are available are commented on briefly.

New Hebrides

Hodgson's new determinations are combined with the already published data in Figure 3. The pattern is now more in keeping with the claim that the *B* axes define a plane parallel to the physiographic feature, but the scatter is considerable and the poles of the planes do not fall into two distinct groups. The data do not fulfill the conditions previously outlined and an analysis cannot be made for this area.

Sumatra-Timor

Ritsema (1956) has published seventeen solutions for the Sumatra-Timor arc and these are shown in Figure 4*a*. The *B* axes do not define a plane and analysis of the type employed for the New Zealand-Tonga arc is not applicable in this area.

Phillipines-New Guinea

Nine solutions for this arc have been published by Ritsema (1956). Eight of the *B* axes define a plane striking north-northwest, a little oblique to the trend of the physiographic feature (Figure 4*b*). The remaining earthquake had a horizontal *B* axis nearly normal to this plane; the movement on this fault is so different from the pattern given by the other earthquakes that it has been omitted from the analysis. The poles of the planes given by the eight solutions fall into two groups, representing planes striking northwest and northeast respectively. The northwest-striking planes, which are parallel to the general trend of the feature, give a β maximum of 21 per cent per 1 per cent area coinciding with the *B* maximum (Figure 4*c*), whereas the northeast-striking planes give a weaker β maximum ($17\frac{1}{2}$ per cent) nearly normal to the *B* maximum (Figure 4*d*).

Although there is still a scarcity of data from this arc, the existing data may be interpreted in an analogous manner to those from the New Zealand-Fiji arc; the planes striking parallel to the physiographic feature appear to be the faults. It is interesting to observe that of these, three have right-lateral slip, four have left-lateral slip, and one is pure dip-slip. Thus, if the fault planes are indeed sub-parallel to the physiographic feature, the sense of slip in this movement zone has not been constant; the kinematics are therefore comparable with those of the New Zealand-Fiji arc.

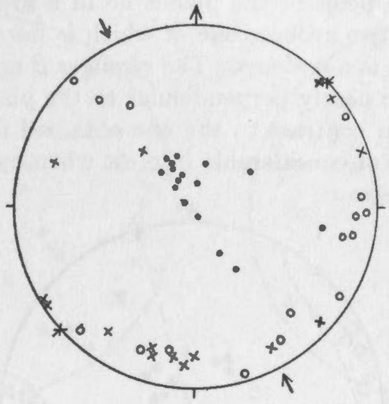

Figure 3. Data for the New Hebrides Area. Sixteen solutions.

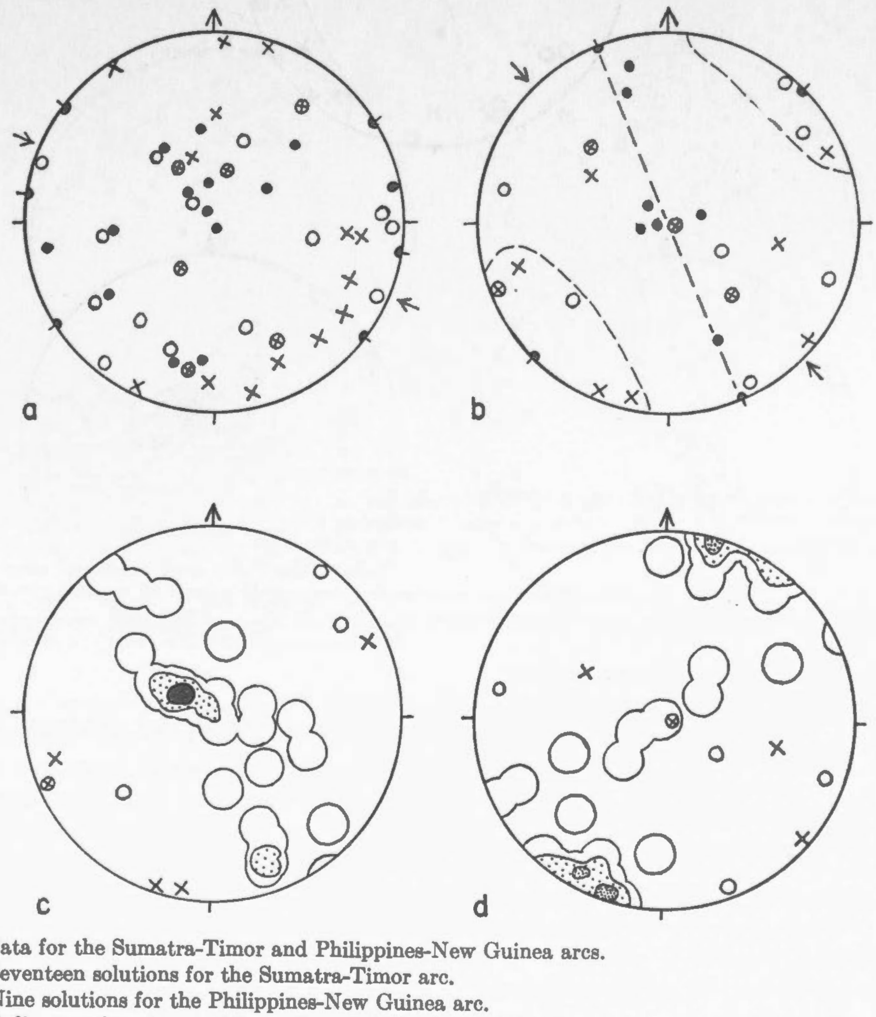

Figure 4. Data for the Sumatra-Timor and Philippines-New Guinea arcs.

a. Seventeen solutions for the Sumatra-Timor arc.
b. Nine solutions for the Philippines-New Guinea arc.
c. β diagram for planes with northwest strike (poles enclosed by broken line in b). Contours: 21, $10\frac{1}{2}$, $3\frac{1}{2}$ per cent per 1 per cent area.
d. β diagram for planes with northeast strike. Contours: $17\frac{1}{2}$, $10\frac{1}{2}$, $3\frac{1}{2}$ per cent per 1 per cent area.

Kuriles-Kamchatka

From the data now available from this arc (Figure 5*a*) it might be claimed that the B axes define a vertical plane, but the definition is very poor; the B axes tend rather to lie in a single maximum. In consequence the poles of the planes lie in a great circle about this maximum. The poles may be divided into two groups, one of which is normal to the plane of the B axes, but the separation of the groups is not sharp. The stronger β maximum (Figure 5*c*) is obtained for the planes which strike more nearly perpendicular to the plane of the B axes, and for these planes $\beta = B$. This result is in contrast to the one obtained for the areas already described. The patterns for this arc will be of considerable interest when more data are available.

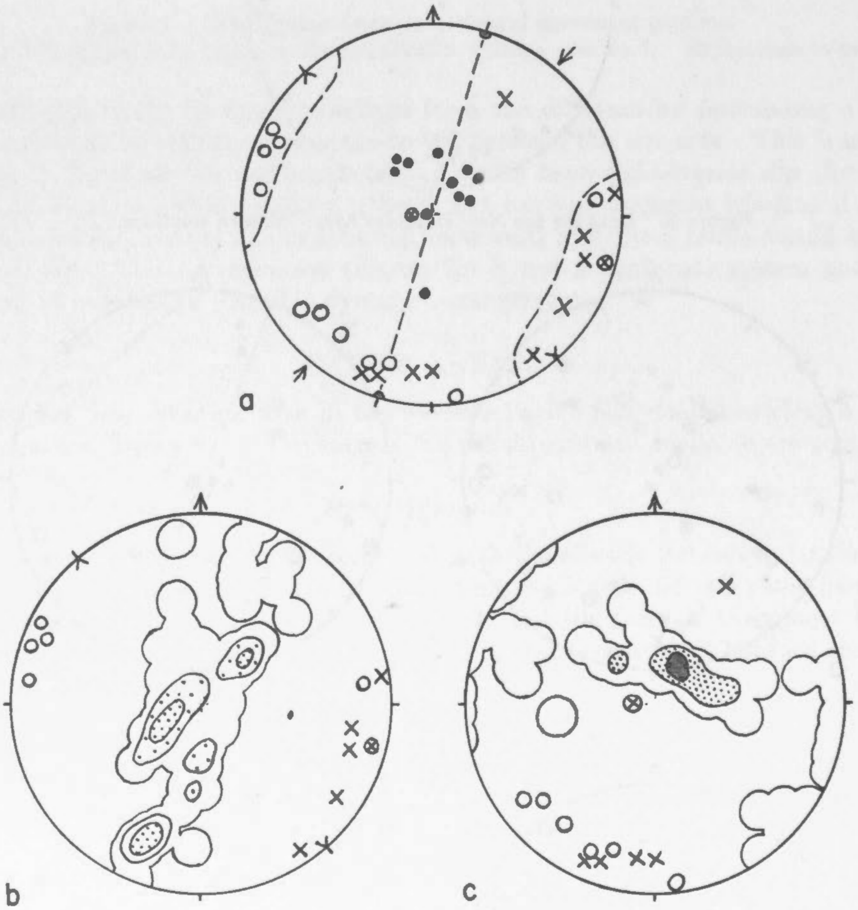

Figure 5. Data for the Kuriles-Kamchatka arc.
a. Total of twelve solutions.
b. β diagram for group of planes enclosed by broken line in a. Contours: 10, 6, $1\frac{1}{2}$ per cent per 1 per cent area.
c. β diagram for other group of planes. Contours 18, 10, $1\frac{1}{2}$ per cent per 1 per cent area.

Comparison of Solutions from Different Sources

Three groups of workers have published solutions for the Mariana-Bonin-Japan-Kamchatka area and their results are shown in Figure 6. Hodgson and co-workers (Hodgson, 1957, and unpublished data) have utilized reports, obtained in response to questionnaires, from stations with world-wide distribution. Miss Kogan, working with Dr. Keylis-Borok in Moscow (Kogan, 1954, cited by Scheidegger, 1957) made use of records from stations in the U.S.S.R. and the scanty data available in the literature for other stations. Honda and his colleagues (Honda, *et al.*, 1957) appear to have used data from Japanese stations alone.

Hodgson included thirteen solutions from the Bonins, Japan and Kamchatka in his 1957 paper and has since supplied us with seven additional solutions. These are all shown in Figure 6*a*. The pattern is characterized by steep *B* axes which do not define a plane.

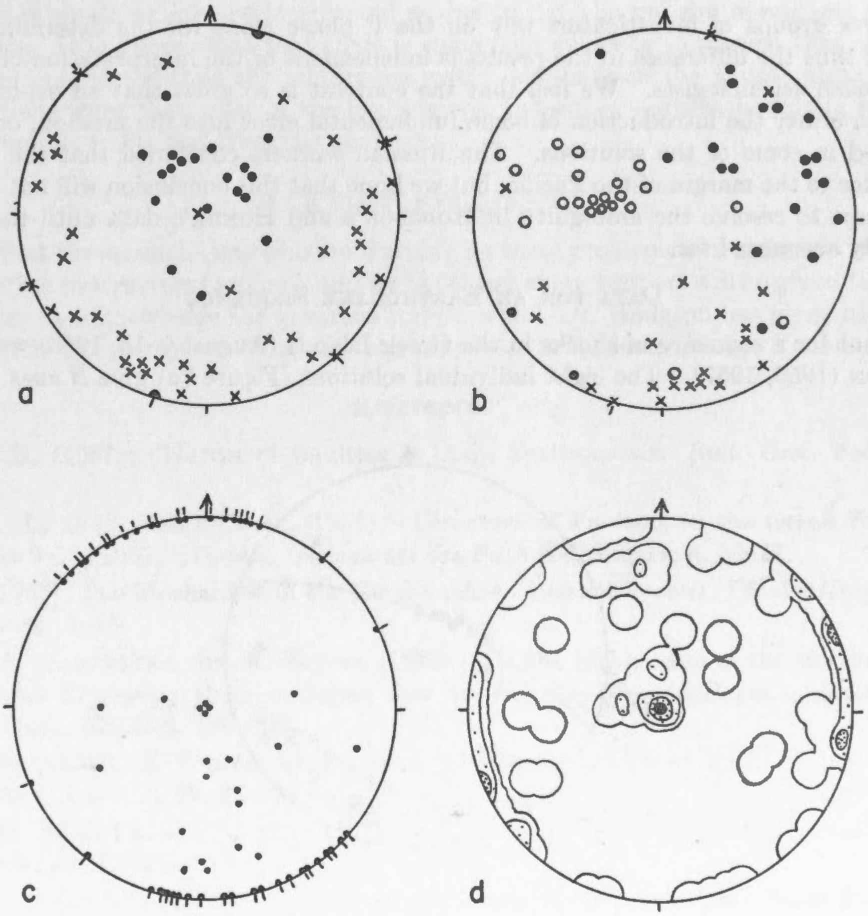

Figure 6. Comparison of data from different sources.

a. Twenty solutions by Hodgson for the Mariana-Bonin-Japan-Kamchatka area. Planes are not distinguished on the basis of type of movement: crosses represent poles of all planes (*A* and *C* axes).

b. Twenty-one solutions by Kogan for same area. Crosses represent poles of faults (*C* axes) and open circles are movement directions (*A* axes).

c. Forty-three *B* axes from solutions by Honda, *et al.*, for same area.

d. Eighty-six poles of planes (*A* and *C* axes) from the forty-three solutions represented in c. Contours: 20, 10, 5, 1½ per cent per 1 per cent area.

A number of solutions for earthquakes in this area have been determined by Kogan. The Russian workers employed the first motion of the P phase to determine the orientations of the two planes and then distinguished the fault plane from the auxiliary plane by study of the S phase. Thus, provided an adequate distribution of data regarding P was available, and the intrepretation of S is reliable, a unique solution is found for each earthquake. On Figure 6*b* are shown Kogan's twenty-one solutions for the same area as covered by Hodgson's data (Figure 6*a*).

Honda, *et al.* (1957, Table I) have listed the maximum pressure and the maximum tension which they inferred from their data. This has enabled us to determine the attitudes of the *B* axes and nodal planes for each of forty-three earthquakes in the vicinity of Japan. The *B* axes for these solutions are represented in Figure 6*c* and the poles of planes are shown in the contoured diagram (Figure 6*d*).

The contrast between the three groups of solutions is remarkable, although each group shows strong preferred orientations of *B* axes. Whereas the *B* axes determined by Hodgson are characteristically steep, those found by Kogan are gently plunging; the pattern of *B* axes of Honda and his colleagues is similar to neither of these.

All three groups of investigators rely on the P phase alone for the determination of the *B* axis, and thus the difference in the results is independent of the interpretation of the S phase by the Russian seismologists. We feel that the contrast is so great that an explanation must be sought in either the introduction of some fundamental error into the method, or inadequacy of data used in some of the solutions. The Russian workers concluded that the faults strike perpendicular to the margin of the Pacific, but we hope that this conclusion will not be employed in an attempt to resolve the ambiguity in Hodgson's and Honda's data until the contrast is satisfactorily accounted for.

Data for an Earthquake Sequence

Solutions for a sequence of shocks in the Greek Islands (August 9–13, 1953) were published by Hodgson (1956, 1957). The eight individual solutions (Figure 7*a*) give *B* axes which define

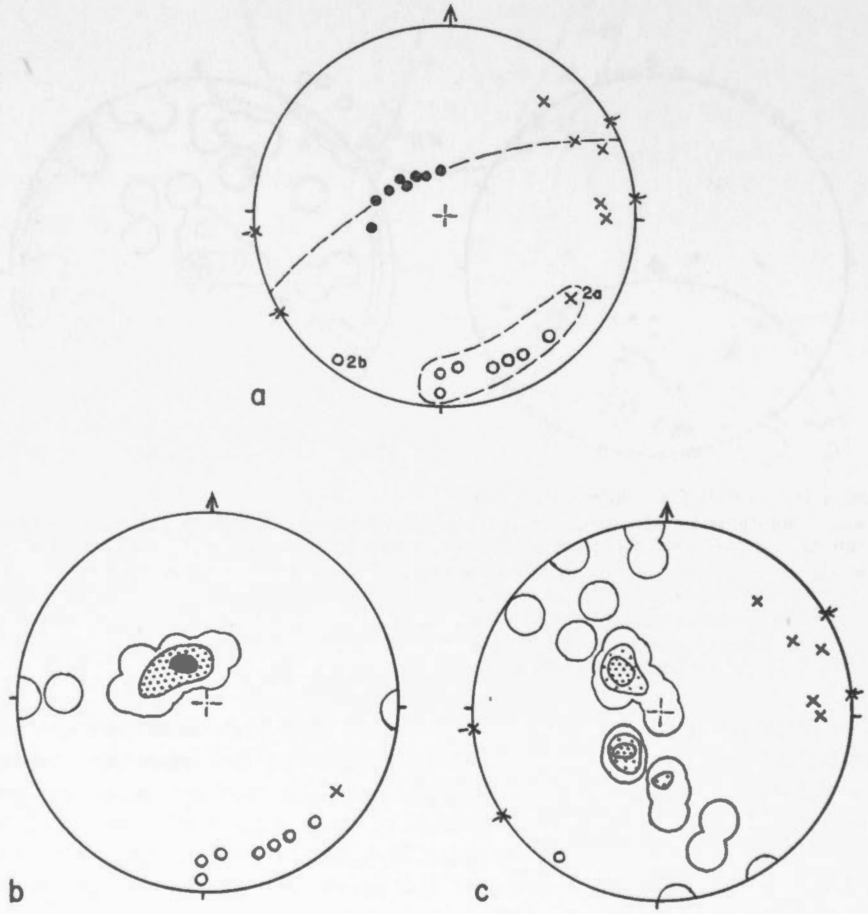

Figure 7. Analysis of the Greek earthquake sequence of August 9-13, 1953.
a. Solutions for eight shocks.
b. β diagram for planes with northeast strike (poles enclosed by broken line in a). Contours: 50 per cent, 25 per cent, $3\frac{1}{2}$ per cent per 1 per cent area.
c. β diagram for planes with northwest strike. Contours 21 per cent, $10\frac{1}{2}$ per cent, $3\frac{1}{2}$ per cent per 1 per cent area.
No linear physiographic feature is present in the area covered by the epicenters of these shocks.

a plane dipping steeply towards the northwest, and the planes can be grouped into two broad orientations, one of which strikes approximately parallel to the plane of the B axes. This group gives a β maximum $= B$, whereas there is no strong β maximum for the other group. The spread of these two groups is such that HODGSON's planes $2a$ and $2b$ could be interchanged so that all the earthquakes might be interpreted as due to right-lateral slip movement on a single group of faults. It is appreciated that there is some field evidence to suggest that the faulting may be more complicated than the picture we would deduce from the P data alone. But the field observations show that most of the faulting was indeed on northeast-striking planes, and this is the conclusion obtained from the analysis.

ACKNOWLEDGMENTS

We feel that the seismologists who are working on these problems are making a very important contribution to structural geology, and we hope that every support will be given to this work. It is a pleasure to acknowledge the generous way in which Dr. Hodgson has given us data, help and advice. The authors are working with the support of a National Science Foundation grant.

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Acknowledgements

We feel that the seismologists who are studying [illegible] have provided [illegible] a very important contribution to [illegible] geology [illegible]. It is a pleasure to acknowledge the generous way in which [illegible].

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Circum-Pacific Tectonics*

BY HUGO BENIOFF

Seismological Laboratory, California Institute of Technology.

ABSTRACT

A study of the Kamchatka aftershock sequence by BÅTH and BENIOFF provided the basis for distinguishing between the two possible fault-plane solutions for the principal shock given by HODGSON. Thus, this great earthquake was generated by a right-handed slip on a 1000-km. fault segment lying parallel to the trench. With this observation, data are now available for the direction of slip on the shallow components of nearly all the principal circum-Pacific faults. This includes Japan, Philippines, Tonga-Kermadec, New Zealand, the Aleutian Arc, Alaska, northwest Pacific, California and possibly the western coast of South America. In all of these regions the principal fault lies parallel to the coast and the slip is right-handed. Secondary faulting, such as represented by the Garlock fault in California, strikes transverse to the coast line and in many cases is left-handed. Although the principal movement is strike-slip in nature, smaller dip-slip components also occur and these are responsible for the relief which takes the form of oceanic deeps and associated mountain ranges. The circum-Pacific tectonic activity now in progress can thus be described as a tangential, clockwise rotation of the continental margins relative to the oceanic mass, together with a radial movement of the margins toward the oceanic mass. If the tangential slip is constant around the margins, with a rate equal to that of the San Andreas, the time for a complete revolution is approximately 3×10^9 years.

The observational data from which we attempt to determine the tectonic behavior patterns of the circum-Pacific marginal province are the surface geology (when accessible), the spatial and chronological distribution of earthquake foci, and the observed or calculated directions of earthquake fault slips. The problem is rendered difficult by small scale complexities of the patterns which tend to obscure or conceal the principal mass movements. Moreover, the methods for calculating the fault-slip geometry at the source from initial seismogram trace displacements are not entirely satisfactory, owing to instrumental and transmission complications or to departures of the source mechanism from the simple form assumed in the theory. In this paper an attempt is made to derive the principal tectonic patterns from the portions of the available data considered to be most reliable or pertinent.

The western marginal region of North America, extending from a point off the coast of Oregon to the southern end of the Gulf of California, is tectonically dominated by the San Andreas fault or fault system. The relative crustal movements involved in this system are horizontal, with the oceanic block moving northwestward relative to the continental mass. The fault is thus of the right-hand (dextral) strike-slip or transcurrent type. The great San Francisco earthquake of 1906 was caused by a slip on its northern segment. The visible trace extended 400 km. northward from San Juan to Point Arena and from there possibly an unknown distance under the ocean. The maximum relative displacement was 6.5 meters. In the earthquake of 1857 a segment of approximately the same length and slip displacement was active from the vicinity of San Bernardino northward. In addition to these two great earthquakes many smaller ones have occurred in the system, clearly indicating extension of the fault zone northward under the ocean to a point approximately $\phi = 44.5°$, $\lambda = 130°$, and southward under the Gulf of California to its southern limit as shown by the map of epicenters Figure 1. The epicenters are taken from GUTENBERG and RICHTER (1949). Although over most of its length the fault is quite straight, a substantial flexure occurs in the vicinity of Gorman where the southern segment appears to have been moved eastward relative to the northern segment. Near the curved region another fault, the Garlock fault, originates and extends approximately eastward for about 250 km. Although no earthquakes of consequence have taken place on this

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fault during the 100 years or so of historical time, the geological evidence indicates that it is an active strike-slip fault with left-hand polarity. The Garlock fault does not cross the San Andreas fault. However, some 8 km. north of the point of intersection, the Pine fault takes off on the western side of the San Andreas fault in a direction roughly parallel to the Garlock

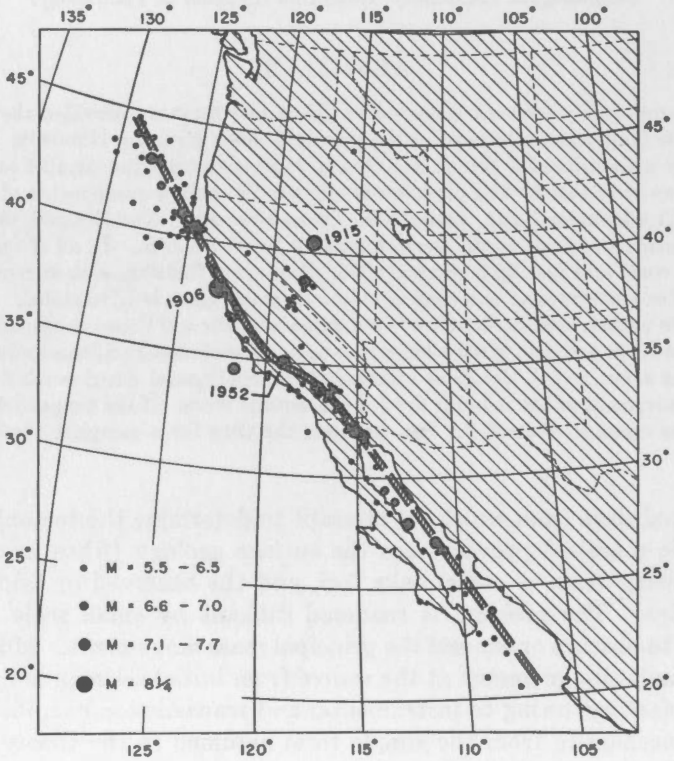

Figure 1. San Andreas fault and earthquake epicenters.

fault. It also exhibits sinestral polarity. A number of authors and more recently HILL and DIBBLEE (1953) have interpreted the San Andreas, Garlock and Pine configuration as a conjugate shear fracture pattern generated by a single horizontal north-south crustal stress acting throughout the region. This interpretation appears untenable to this writer for the following reasons:

1. The angles between the two components and the assumed direction of stress is too large.

2. The concept of conjugate fractures is derived from laboratory experiments on small homogeneous samples in which the two components break simultaneously. In a large body such as the portion of the earth's crust represented by the San Andreas system, the material cannot be sufficiently homogeneous for simultaneous conjugate fractures to occur. Owing to the existence of joints, crystal imperfections and variations in composition, the failure response to an increasing uni-directional stress can only begin as a single fracture. Once such an initial break has formed the local stress pattern becomes modified in such a way as to reduce the conjugate stress component and to prevent the formation of a conjugate fracture.

3. The curvature in the vicinity of the intersection is not compatible with a uni-directional stress.

4. HILL and DIBBLEE (1953) present arguments for a total accumulated displacement on the San Andreas fault of at least 550 km. If this is true, the Garlock and Pine faults should be offset relative to each other by this amount since the two original conjugate fractures must necessarily be simultaneous.

5. The geologic evidence indicates that movement on the Garlock-Pine faults has amounted to at least a kilometer and possibly more (Hill, Dibblee, 1953 p. 451). This movement should have offset the San Andreas fault.

It is clear that conjugate fractures can exist only as initial breaks within a very small region in a homogeneous material. Subsequent movements on both components are incompatible—one or other initial break must take over for large accumulated displacements.

Without prior knowledge as to the origin of the tectonic forces involved, it is not possible to derive the primary stress pattern from observations of the fracture pattern in fault systems such as the San Andreas. Thus a compressional stress, such as sometimes envisaged as the cause of the San Andreas system of fractures, might be produced by a horizontal gradient in viscous drag between the under surface of the crust and a subcrustal current flowing parallel to the assumed direction of the simple linear stress. On the other hand, the San Andreas fracture may just as well have been generated by a shear stress pattern produced by a subcrustal current flowing parallel to the fault having a viscous drag gradient at right angles to the direction of flow, as illustrated in Figure 2. In view of the marginal nature of the San Andreas fault, the

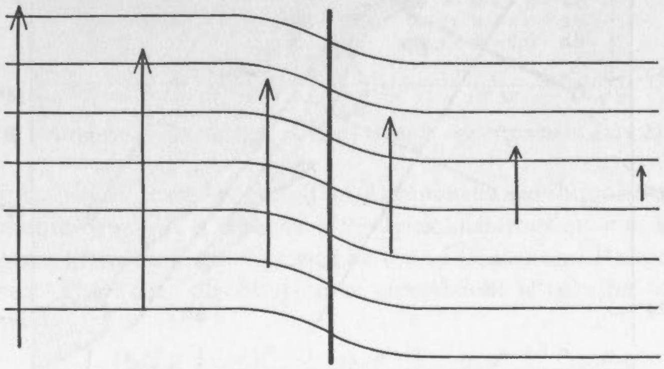

Figure 2. Plan of stress gradient normal to a fault.

generating stress might also originate in body forces acting differentially on continental and oceanic land masses. With the present state of our ignorance of the origin of tectonic forces, the writer prefers to confine considerations to observable tectonic movements, displacements and strains, rather than to attempt to derive the generating stress patterns from incomplete observational data.

The principal tectonic movements of the western continental margin from the lower limit of the Gulf of California to a position corresponding with the northern limit of the San Andreas system are, therefore, a horizontal dextral displacement parallel to the margin of the oceanic mass relative to the continental mass, and a sinistral displacement of the northern portion relative to the southern, in a direction perpendicular to the margin. These two movements are indicated by the arrows in Figure 3. It should be noted that the arrows represent velocity vectors and not stresses. The transverse movement is indicated by the Garlock-Pine fault displacements and by the curvature of the San Andreas fault. Since movements on the two faults are mutually incompatible, the San Andreas system exhibits branches in the southern part, west of the original break. Thus it appears that the San Jacinto, Elsinore and Inglewood branch-faults represent the tendency of the San Andreas fault to maintain a straight course in spite of the transverse distortion.

The White Wolf fault, on which the Kern County earthquake of 1952 occurred, is a reverse fault with a small average sinistral strike-slip component. This fault is also a result of the incompatibility of the two principal movements, (Benioff, 1955). The portion of the northeastern block of the San Andreas fault which moves along the flexure is subjected to a local distortion in the form of a north-south compression, and this accounts for the combined reverse and sinistral strike-slip characteristic of the White Wolf fault. The White Wolf fault is thus an auxiliary fracture, and its orientation and slip are not direct indicators of the regional stress system but are, instead, expressions of a small local distortion resulting from two primary components of the regional flux pattern. It may be concluded, therefore, that fault-plane solutions

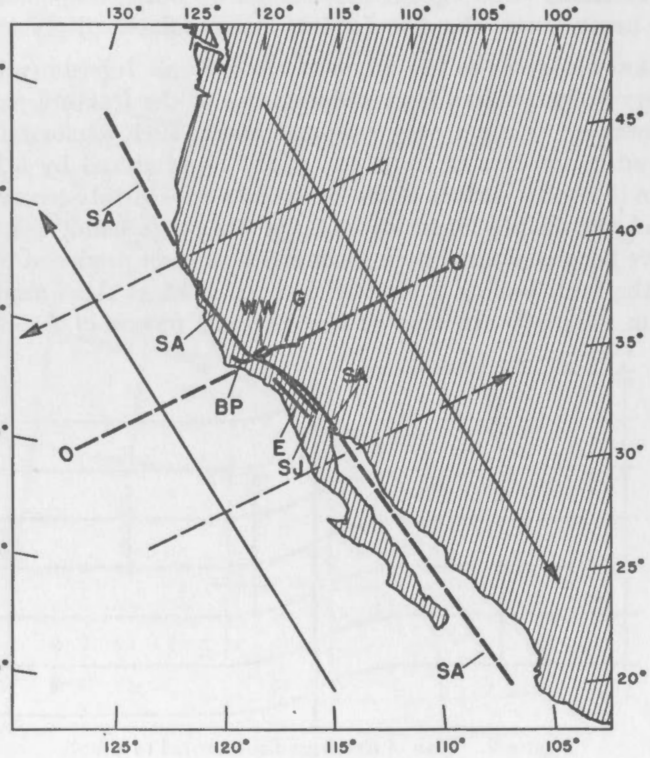

Figure 3. Large scale dynamic pattern of San Andreas province.

of earthquake fault characteristics cannot be relied upon indiscriminately for deriving the principal stress or flux patterns of a large region unless additional pattern information is available from other sources. The fault-plane evidence is reliable in great earthquakes only, since in these the extent of faulting is large enough to eliminate the effects of local distortions, and thus to indicate the character of the prevailing tectonic flux of the region. It should be noted, however, that there is no *a priori* reason for assuming that the primary stress patterns do not change with time. A pattern responsible for the generation of a given fault system may change in magnitude or direction with time. Consequently, once a fracture pattern has been established, subsequent movements on the faults may bear no simple relation to the original generating stress.

The Kern County shock of July 21, 1952 was the first earthquake in which precise epicentral locations of aftershocks were available together with visible evidence for the extent of faulting. A group of portable seismographs were rushed into the area within a few hours and these, together with the permanent network of stations of the California Institute of Technology, provided the necessary observations for precise aftershock epicenter determinations with errors not greater than about ± 1 km. as reported by C. F. Richter (1955). Figure 4 is a map of the region showing the principal shock epicenter, the observed extent of faulting and the aftershock epicenters. In this earthquake the extent of faulting coincides with the long dimension of the aftershock epicenter distribution area. That aftershocks would define the extent of faulting in the principal earthquake has long been suspected by the writer on the basis of partial evidence, but this is the first instance in which the evidence was complete. Assuming that this relationship holds generally, we can determine the extent of faulting in other earthquakes where the

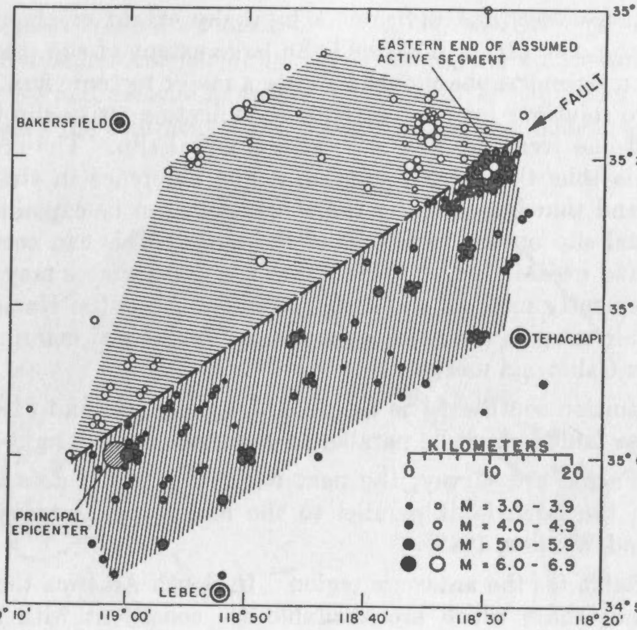

Figure 4. Aftershock distribution of Kern County earthquake of July 21, 1952.

fault is not accessible to visual observation. The Kamchatka earthquake of November 4, 1952 provided the first example in which a reliable aftershock distribution was available from which the extent of faulting in a great earthquake could be found (BÅTH and BENIOFF, 1958). Figure 5 is a map of the region. The linear distribution of aftershocks is parallel to the general coastal

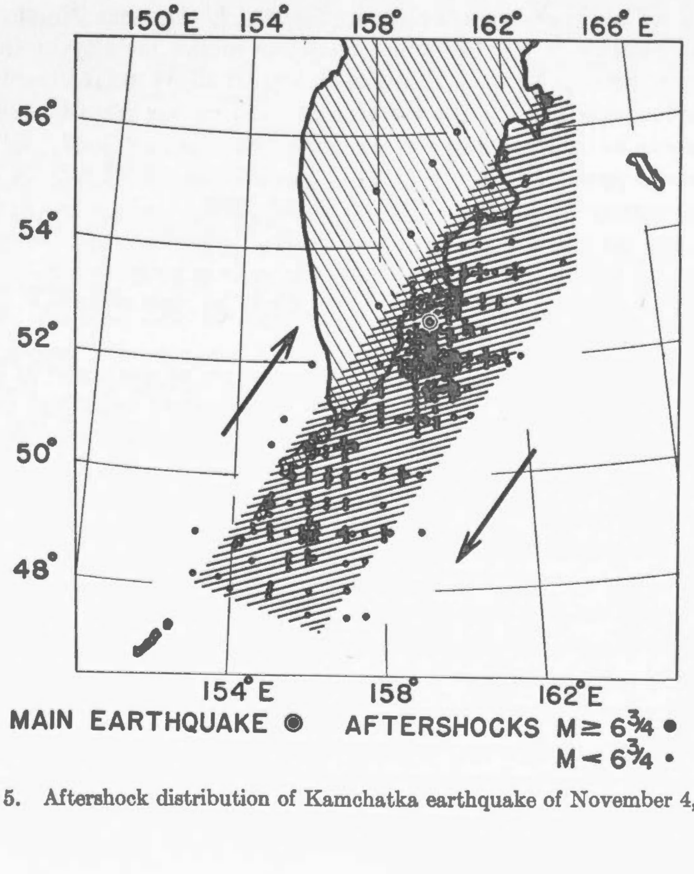

Figure 5. Aftershock distribution of Kamchatka earthquake of November 4, 1952.

trend of the principal features, and indicates a total slip extent of about 1000 km. In view of the size of the earthquake ($M = 8.25$) and the large extent of slip, the fault-plane solution from first P motions on seismographs should indicate a major tectonic flux pattern of the region. HODGSON'S (1956) two solutions for this earthquake indicate a strike-slip fault trending N10°E with dextral slip, and one trending N84°.5W with sinistral slip. The one with strike N10°E and dextral polarity is thus the correct solution. The difference in strike direction between his solution, N10°E, and that indicated by the aftershocks can be explained, partially at least, on the basis of unequal slip on the two faces of the fault. This can occur in marginal faults between continental and oceanic land masses where the two surfaces may have unequal elastic coefficients and consequently unequal slip displacements. Thus the Kamchatka arc is moving relatively to the oceanic mass in a direction parallel to the coastal margin. The slip is dextral as in the San Andreas California margin.

Directing our attention southward to the Japan segment, we find (TSUBOI—personal communication) that those faults which lie parallel to the coast exhibit right-hand strike slip also.

Continuing our Pacific arc survey, the next region for which data are available is New Zealand, where again the large fault parallel to the major axis is transcurrent with dextral polarity (WELLMAN and WILLET, 1942).

No data are available for the antarctic region. In South America the data are inadequate for final evaluation but those which are available are consistent with right-hand strike-slip movement. INGRAM (1957) derived a fault-plane solution for the Chilean earthquake of December 7, 1953 ($\phi = 22°S$, $\lambda = 68\frac{1}{2}°W$, $M = 7.1$) with one plane striking N66°W and the other N32°E. Assuming that the plane N32°E, more nearly parallel with the coast, is the fault plane, his results indicate dextral transcurrent slip. The solution for the Ancash, Peru, shock of November 10, 1946, derived by HODGSON and BREMNER (1953) and indicating principally transcurrent faulting, departs so far from the visible vertical fault displacement (SILGADO, 1951) that it cannot be trusted.

Passing over the California region already discussed, the next North American segment for which data are available is the Canadian coastline in the vicinity of the Queen Charlotte Islands. The evidence here from the earthquake of August 22, 1949 (HODGSON and MILNE, 1951) indicates dextral strike slip parallel to the margin. Also in the northern Canadian Pacific margin, Alaska, and the Aleutian arc, the geological evidence (ST. AMAND, 1957) indicates large dextral strike-slip displacement parallel to the margin. The solution of HODGSON and MILNE (1951) for the Aleutian earthquake of April 1, 1946 ($\phi = 53°$ 30N, $\lambda = 163°W$) indicates principally transcurrent slip, either on a plane striking N22° 30′E or N65°W. In this region the N22° 30′E direction is more nearly parallel with the arc and these data indicate left-hand polarity. However, since this shock is not large ($M = 7.3$) it may not be representative of the whole region, especially in view of the geological evidence.

The fault-slip characteristics of the circum-Pacific margins discussed in the preceding paragraphs are indicated on the map of Figure 6. The solid arrows represent movements believed to be reliably known: the dashed arrows refer to assumed movements for which the observations are inadequate. On the basis of the evidence here presented, it appears that the principal tectonic movement of the circum-Pacific region is a clockwise rotation of the continents relative to the enclosed oceanic mass. The observed data are not sufficient to determine which of the two structures is moving in an absolute sense relative to coordinates fixed with respect to the earth's axis of rotation. The rate of movement has been measured geodetically in one region only—California (C. A. WHITTEN, 1955)—and here it amounts to approximately 5 cm. per year. If this represents a mean constant rate applicable to the whole system, the time required for a complete relative rotation is about 10^9 years.

It was noted in an earlier paragraph that in California, in addition to the principal movement parallel to the margin, there is a second movement approximately normal to the margin. Viewed in relation to the whole circum-Pacific arc this movement is radial. The marginal segment from

California to Alaska differs from the remainder of the circum-Pacific arc in that it contains no oceanic trenches and no deep-focus earthquakes. This may be a chronological difference only. The presence of trenches and associated coastal uplift, and the dip under the continents of the marginal contact between the continental and oceanic masses, as defined by the foci of the deep

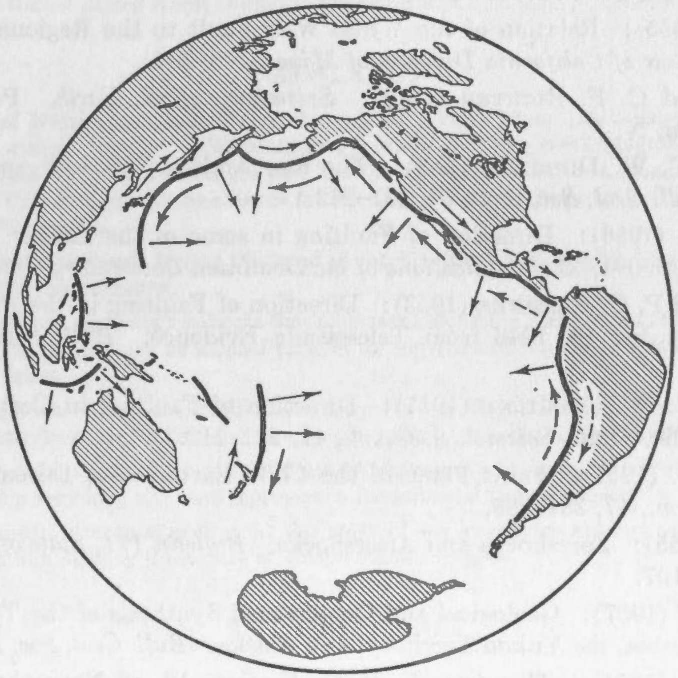

Figure 6. Principal fault slip pattern of the circum-Pacific margins.

earthquakes, have been taken as evidence for radial motion (BENIOFF, 1954) at the margin. It was assumed that since the continental mass is less dense than the oceanic mass, the radial movement causes the former to override the latter at the margins. The oceanic mass is thus forced downward to form the trench and the continental mass is uplifted to form the mountains. The amount of radial movement required to form the marginal relief is small compared with tangential movements which have been suggested on the basis of geological evidence—560 km. for the San Andreas fault (HILL and DIBBLEE, 1953) and 240 km. for the Alaskan faults (ST. AMAND, 1957). This corresponds with HODGSON's fault-plane data which indicate that the total amount of dip slip is small; the dip-slip faults are few in number and the strike-slip faults have small dip components. The energy required in dip-slip movements to produce relief is very much larger than that required for equal strike-slip tectonic displacements. Neglecting the elastic energy contribution, the energy required to produce, against gravity, an oceanic trench and associated uplift of 1000 km. extent and 5 km. departure from sea level, is of the order of 10^{30} ergs, about equivalent to the elastic energy of 10^6 magnitude 8 earthquakes. Thus assuming an average of 2 meters slip per earthquake, the energy required to produce the relief of an average trench and mountain chain against gravity could produce a total horizontal slip of about 1000 km. if expended in strike-slip faulting. In the light of these considerations, radial movement of the continental margins relative to the ocean mass continues to be a reasonably satisfactory hypothesis for the origin of the circum-Pacific marginal relief. As mentioned earlier (BENIOFF, 1954, p. 396) the movement which generates the relief originally may not continue indefinitely. In time, reverse or other movements may occur tending to restore the original level contours, or bring about other modifications.

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Circum-Pacific Orogeny

BY PIERRE ST. AMAND

United States Naval Ordnance Test Station, China Lake, California.

ABSTRACT

The Pacific coast of North America is fringed by a series of right lateral faults sub-parallel to the coastline. The San Andreas fault extends from Baja California to a point off the Oregon-Washington coast. Near this point, the Alaskan fault complex begins and continues past the Queen Charlotte Islands, along the coast and inland to join the Denali fault. This zone of faulting extends for more than 2100 km. from Lynn Canal, by the north face of Mt. McKinley, to the Bering Sea.

Faulting on the Alaska peninsula having the trend of the Aleutian Island arc has been mapped as right lateral faulting with concomitant overthrusting.

First motion results from seismology indicate that movement along the Aleutian arc, the Kamchatka-Kurile arc and elsewhere around the Pacific may be aligned parallel to the strike of the island arcs or mountain chains, and is often of right lateral sense.

The conclusion is presented that the Pacific basin from at least Baja California to a point beyond the Kurile Islands is rotating counterclockwise. The rest of the Pacific basin is probably also rotating in the same sense.

The Rocky Mountain Trench and sub-parallel features between it and the coast indicate that this type of movement has been going on a very long time and represents a fundamental type of orogeny.

The results of field and structural geology at this stage of our knowledge support the basic work of BYERLY and of HODGSON, and aid in defining the nature of circum-Pacific orogeny.

INTRODUCTION

STATEMENT OF INTENT

For several years seismologists have been reporting that many earthquakes are produced by lateral movements on faults. These investigators have been courageously flying in the face of geological and geophysical tradition. They have contended that a predominant portion of present day tectonic activity has been due to lateral faulting and some of them have even expressed surprise that this much lateral faulting exists. Although lateral faults have been recognized in California, Canada, Alaska, Scotland and elsewhere, the importance of these faults has scarcely been appreciated by geologists and largely ignored by geophysicists. Recently, however, HILL and DIBLEE (1953), MOODY and HILL (1956), and ALBERDING (1957) have published papers showing the importance of lateral faulting. In this discussion I wish to assemble a few of the main facts pertaining to the distribution of faulting around the northern and eastern edges of the Pacific basin and to demonstrate as best I can that this faulting forms a consistent pattern and that this pattern is consistent with the observations of seismologists. In order to do this it will be necessary to discuss the subjects of geology and geomorphology to some extent. The object of the fault-plane work is to discover the nature of the present day mountain building processes and that is a geologic goal.

RECOGNITION OF LATERAL FAULTS

General Remarks

It is difficult to recognize a lateral fault in the field, unless one has learned a few diagnostic geomorphic criteria essential to the recognition of such features. An actual proof of lateral movement on a fault is even more difficult. ANDERSON's work (1942) on the Great Glenn fault forms one of the finest examples of such a demonstration. In most cases the lateral component of motion cannot be shown from stratigraphic evidence. Often the stratigraphic evidence has

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been explained away by assuming vertical movement to have been responsible for all the displacement. The San Andreas fault of California and Baja California is now considered by all geologists to be primarily strike-slip in nature but it is doubtful if the lateral habit would have been recognized if the fault had not actually slipped several times in recorded history. Once the lateral nature of faulting was known, it was easy to distinguish those geomorphic criteria by which lateral faults may be recognized.

The most striking property of large lateral faults is the consistent straightness, or the smooth and gradual curvature, of the strike of the feature. Another, not always present, is the occurrence of a trough along the strike of the fault. This trough is found along portions of the San Andreas, Garlock, Great Glenn and Denali faults, to name a few. The troughs have a comparatively straight trend, are usually filled with alluvium and are often not recognized as being the locus of a fault. Small scale features attributable to smaller scale faulting are often found within the trough; examples are the upthrusting of minor fault slices or the formation of small grabens. There have been instances where geologists have mapped such minor features in considerable detail and have made desperate attempts to understand the stratigraphy without ever recognizing the fact that they were working in a large fault zone.

The trough may be developed by erosion of crushed rock in the zone of the fault, or in some instances, such as the Koehn Valley trough of the Garlock fault by development of a graben through normal faulting on both sides of a lateral fault. Such troughs may also develop along the sides of thrust faults associated with lateral faulting, as is the case of a portion of the White Wolf fault. The width of the trough along the course of a lateral fault may be several tens of miles.

Such faults often exhibit many branches and it is frequently difficult to tell if there is a main fault. An example is to be found in the San Andreas in the southernmost part of California where ALLEN (1957) has remarked that the entire area, over 50 miles in width between the Elsinore fault on the west and the eastern edge of the Salton depression should properly be called the San Andreas fault zone.

Other geomorphic features often cited are shutter ridges, formed by the displacement of one part of a ridge with respect to another so that a ridge blocks the drainage of an established stream. Upthrusting of fault slices may also produce ridges lying athwart the drainage of a major mountain mass. This situation gives rise to offset streams and these are a commonly cited criterion. Offset streams commonly occur also in the trough of the fault, and the direction of offset is often taken as being indicative of the direction of displacement on the fault. This is not a reliable indication unless one is able to establish that a major valley has been offset.

The extent of a lateral fault is often underestimated because the faulting has been recognized by apparent vertical offset along one portion of the fault, and the fault considered to be terminated, when actually there are other evidences of faulting of a less spectacular nature. There is a small lateral fault near Little Lake, California, at least 30 miles long, yet it cannot be followed for more than a few thousand feet by any one criterion. A few of the features along the fault will be cited. This fault intersects the main body of the Sierra Nevada at an oblique angle with but little change in the general slope of the mountain front. The fault is noticeable by a series of oases aligned along the trace and by an occasional small col and butt. A few thousand feet south it may be seen in a road cut, a little farther along it is marked by some ridges in a lava flow, a small cinder cone, a series of sag ponds in the surface of a basaltic lava bed, and eventually a scarp produced by a flexure in some lake bed sediments, compressed in a direction parallel to the strike of the fault. Hereafter the fault is lost beneath the alluvium for several miles but reappears to form a trough-like valley across a minor mountain block. This fault has been active since the end of the ice age and yet if a geologist were to look at any one part of it, it is unlikely that he would recognize it as a fault, much less an important lateral fault.

I will not discuss this sort of geomorphology in detail, and cite these examples only to show that the problem of recognizing lateral faults is not a simple one. In my opinion, any fault having a straight trace more than a few miles in length has undergone lateral movement. The reason that the prevalence of lateral faulting surprises seismologists, particularly from elsewhere than California, is because geologists have not recognized this type of faulting often enough.

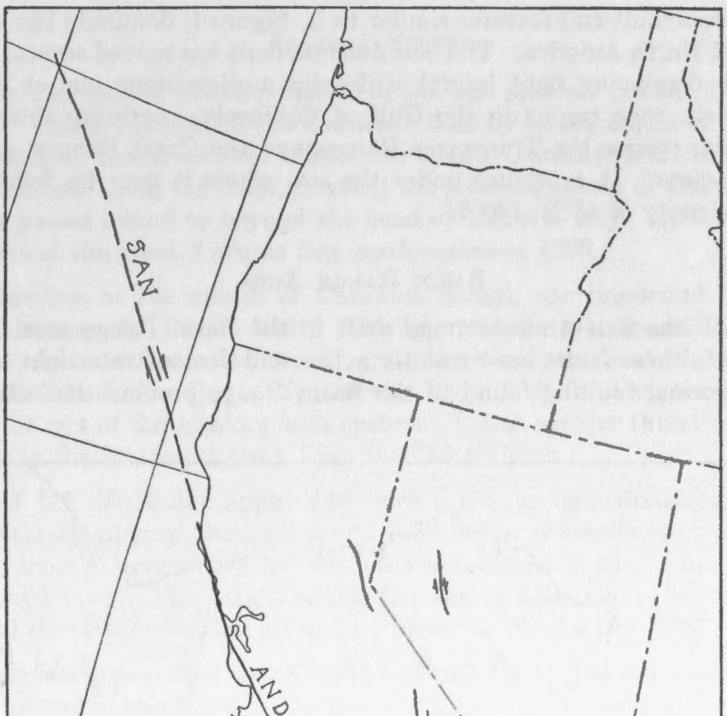

Figure 1. The path of the San Andreas fault across California, with a few of the more important active or recent faults shown. The path of the San Andreas in the ocean is deduced from seismological evidence.

DISCUSSION OF REGIONAL STRUCTURAL GEOLOGY OF THE PACIFIC COAST OF NORTH AMERICA

What is now known of the faulting around a portion of the Pacific margin will be discussed, and on the basis of regional geology an attempt will be made to understand the nature of the orogeny. We will begin with the San Andreas fault zone and work our way around the Pacific to the north and west.

San Andreas Fault

The San Andreas fault and features similar to it, Figure 1, dominate the structural geology of the west coast of North America. The San Andreas fault has moved several times in recorded history, each time displaying right lateral strike-slip motion along one or more of its many branches. The main zone begins in the Gulf of California, continues through the Imperial Valley of California, crosses the Transverse Ranges and the Coast Ranges, and enters the sea north of San Francisco. It continues under the sea, where it may be followed by a line of epicenters to the vicinity of 45°N, 130°W.

Basin Range Area

Structures with the San Andreas trend exist in the Basin Range area. In the southern part of this province these faults are currently active and demonstrate right lateral movement. The magnificent normal faulting found in the Basin Range province has distracted attention

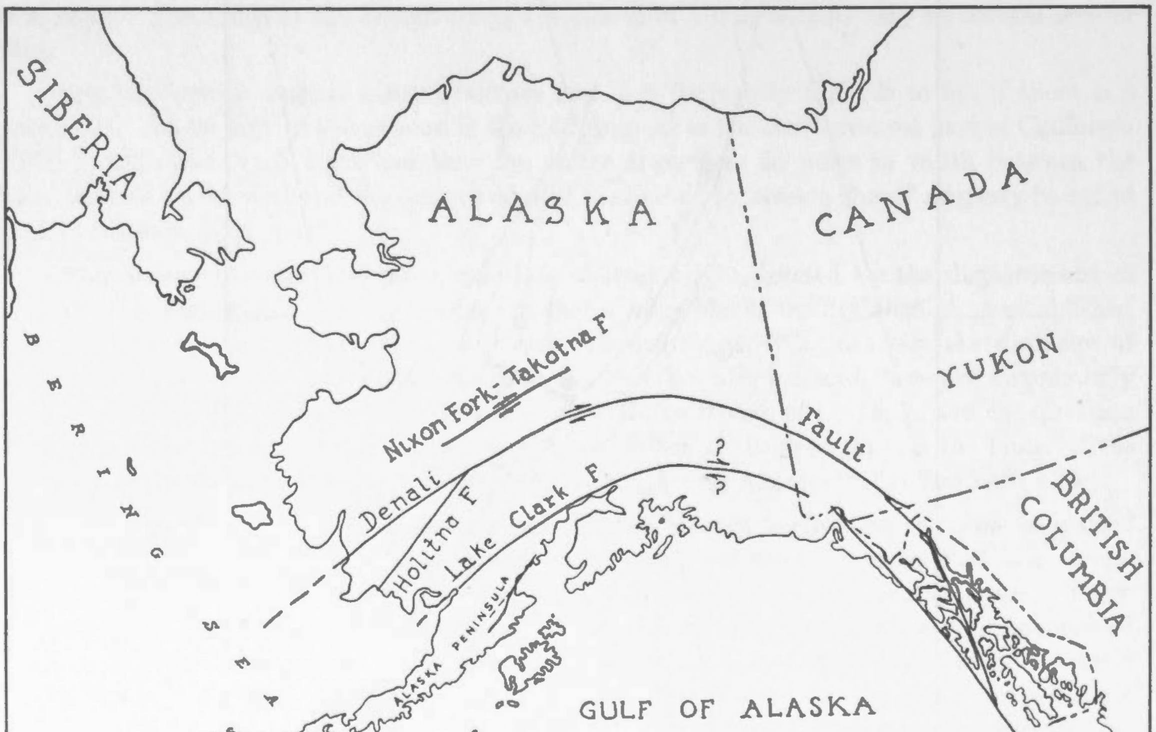

Figure 2. The principal faults in the southern part of Alaska and British Columbia.

from the lateral faulting. This region has been, and is being, deformed as if it were undergoing dextral shear by a couple aligned roughly east-west, the western end of which is being pulled north.

An example that might be cited is the Fairview Peak earthquake of 1954, where a fault displayed a right lateral displacement of about 10 feet. Lateral movement accompanied the great earthquake of 1872 in Owens Valley, but unfortunately it seems impossible to decide the sense of the main faulting from the printed accounts. It does appear that the movement was right lateral and of the order of 18 feet, both horizontally and vertically.

Alaskan System

To the north and east of the termination of the San Andreas system, the Alaskan system (Figure 2) begins. This is traceable under the ocean floor by an alignment of epicenters reaching to the Alaskan coast on the oceanward side of the Queen Charlotte Islands. The main line of activity runs northward along the coast, forming the seaward shores of Baranof and Chichagof Islands, and then passes inland to beyond the head of Yakutat Bay. This fault was probably the causative agent of the great Yakutat Bay earthquakes of 1899.

The fault branches at the mouth of Christian Sound, one important branch passing up Lynn Canal and joining the Denali fault. This gigantic feature, somewhat circular in plan, extends from the region of Lake Dezadeash, past the northern front of Mt. McKinley, and reaches the shores of the Bering Sea in Kuskokwim Bay. This fault appears to be right lateral in habit, as does the rest of the Alaskan fault system. It has a major thrust branch, the Holitna fault, that strikes to the southwest away from the Denali fault.

The massif of Mt. McKinley appears to have been upraised along gigantic thrust faults lying along the eastern edge of the massif and oriented in a southwesterly direction. These thrusts appear to have undergone a great deal of lateral displacement, although the sense of the displacement is not known. The details of this faulting in Alaska have been explored in a preliminary way, and the documentation given, in a paper by St. Amand (1957).

There is a second major fault south of the Denali fault, and sub-parallel thereto. This fault seems to be lateral in habit, but nothing can be told of the sense of movement as yet. This is called the Lake Clark fault zone because Lake Clark lies in the trough of this fault.

Displacement on Alaskan System

The evidence upon which the sense of the displacement of the Denali fault is based is scant. The Mt. McKinley massif appears to have been offset, along the Denali fault, from the Mt. Hess-Mt. Hayes massif by about 150 miles. A tectonic map by Cady, Wallace, Hoare and Webber (1956) shows that the division between the rocks of the primary and secondary geosyncline of the Kuskokwim region are offset 150 miles along the Denali fault. While a large part of this displacement may be due to vertical movements, it is interesting and probably significant that the same dividing line is offset another 150 miles in a right lateral sense across the Nixon Fork-Iditarod alignment—another huge fault displaying all the geomorphic and stratigraphic relations commonly found on lateral faults.

Aleutian Islands

Knappen (1929) describes the structure of the Alaskan peninsula in the Katmai region. Here he finds the predominate faulting to be right lateral with concomitant overthrusting. The lateral faulting is aligned at a slight angle to the Aleutian arc. The volcanoes in this region appear to have been developed along conjugate tensional shears where these intersect other fractures. The geology of the rest of the Aleutian Islands is not known well, but it has been proposed by Gibson and Nichols (1953) that a continuous fracture runs the full length of the

Island chain. The maps of the Aleutians show many faults, some of which are aligned parallel to the strike of the islands. It is difficult to tell if the faults have undergone lateral displacement or not. Indeed, it is almost impossible to recognize lateral faulting in a volcanic terrain.

Fault-Plane Solutions and Fault Movement

The seismic evidence for displacement on these faults, to be found in the papers of Hodgson and others, indicates that the major movement is lateral. One of the two solutions for most of the earthquakes indicates a right lateral movement aligned along the general trend of the fault. Usually, the motion makes a slight angle with the arc or with the most prominent nearby geologic structure. Benioff and Båth (1958) have recently demonstrated that the major Kamchatka faulting was parallel to the arcuate structure, and this permits making a choice as to one of Hodgson's solutions for this earthquake. This has been pointed out by Benioff in another paper in this symposium.

ROTATIONAL MOVEMENT AS A SOLUTION

Consistent Right Lateral Displacement

The consistent movement from the Mexican coastal region, along the San Andreas system, including the great Basin faults, the Alaskan system, the Aleutian arc and the Kurile-Kamchatka system, clearly indicates that the ocean basin is rotating counterclockwise (Figure 3) with respect to the continents for at least that far. The work of Wellman (1955) in New Zealand also indicates the right lateral nature of the faulting in that area. It hence appears as a possible solution that the whole of the Pacific basin is rotating counterclockwise. These conclusions have also been reached independently by Benioff and by St. Amand (1957).

It will be necessary to study in detail the geology of Kamchatka, the Kuriles, Japan, the Pacific islands and South America in order to establish that the rest of the Pacific is so rotating. There are other fault systems in the Pacific area, some of which are left lateral in nature. These are usually associated with the fracture zones beneath the Pacific as described by Menard (1955) and form the transverse ranges of North America.

Movement in the Past

There are on the North American continent a number of features similar to the San Andreas and Denali fault systems. The most prominent of these is the Rocky Mountain Trench. Although the matter of movement and the nature of this feature, or of the several parallel to it and the western coast, has not been clearly demonstrated it seems likely that they are lateral faults. Should the movement on these prove to have been right lateral, then it is clear that the Pacific rotational orogeny has been going on for a very long time indeed.

It appears, further, that the orogenic zone on the eastern side of the Pacific may have moved westward as time went by, abandoning former planes of movement as they became too stiff to displace, or as the agency producing the force moved westward.

POSSIBLE CAUSE OF THE OROGENIC FORCES

Convection Currents

At this stage, one can only guess as to the source of the movements and forces causing them. A possible source of the orogenic forces is a convergent sub-crustal current moving from the continents toward the oceans. This should produce a Coriolis force of the same sense as is observed. Objections to this hypothesis are that it is contrary to ideas developed from heat-flow measurements and evidence as discussed by Menard (1957).

It is also possible that some sort of magneto-hydrodynamic forces are producing the rotation.

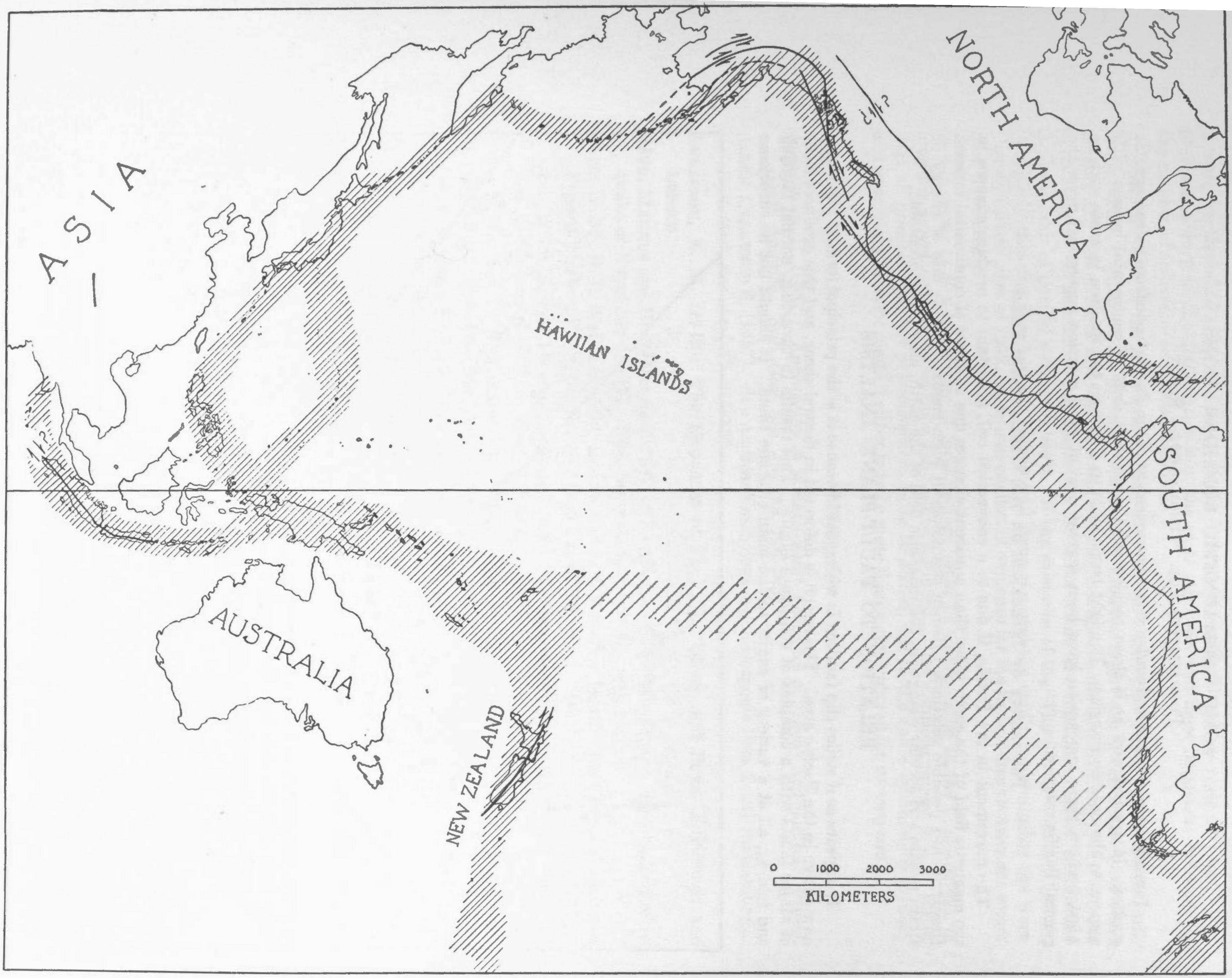

Figure 3. Circum-Pacific orogenic zone, the hatched portions representing seismically active areas. It is felt that the orogenic zone in the southern half is spread between a zone through Antarctica and the Easter Island zone nearer the equator. It appears as if the whole ocean basin on both sides of the equator is rotating in the same sense, counter-clockwise with respect to the continents. It appears also as if the portion north of the equator has been shoved west with respect to that half south of the equator. Such a movement would agree with the movement on the transverse ranges of the North American coast.

SOME GEOMAGNETIC CONSIDERATIONS

Possibilities For Paleomagnetic Study

It might be possible to find evidence for the movement of the Pacific basin from paleomagnetic studies. It appears now as if these require some large scale drift of continental masses with respect to the oceanic margins. It might be possible to check on the rotation in areas such as Alaska where there appears to have been a great deal of local rotation superposed upon the general Pacific rotation.

Possibility of Influence on the Geomagnetic Field

The movement in the Pacific, if due to a convection cell, is certain to produce changes in the magnetic field of the earth other than apparent changes due to drifts of continental masses. Research into possible relations between seismological phenomena, such as rate of energy or strain release and secular changes in the magnetic field of the earth, may prove profitable.

RELATION TO FAULT-PLANE ANALYSIS

It appears as if strike-slip faulting is widespread because it is the principal form of distortion now active in the Pacific area. The region is deformed in dextral shear, and this produces a set of major faults with a complex of conjugate shears. This results in thrusting, normal faulting and folding, all at a variety of angles to the main orogenic trend. It should not be surprising

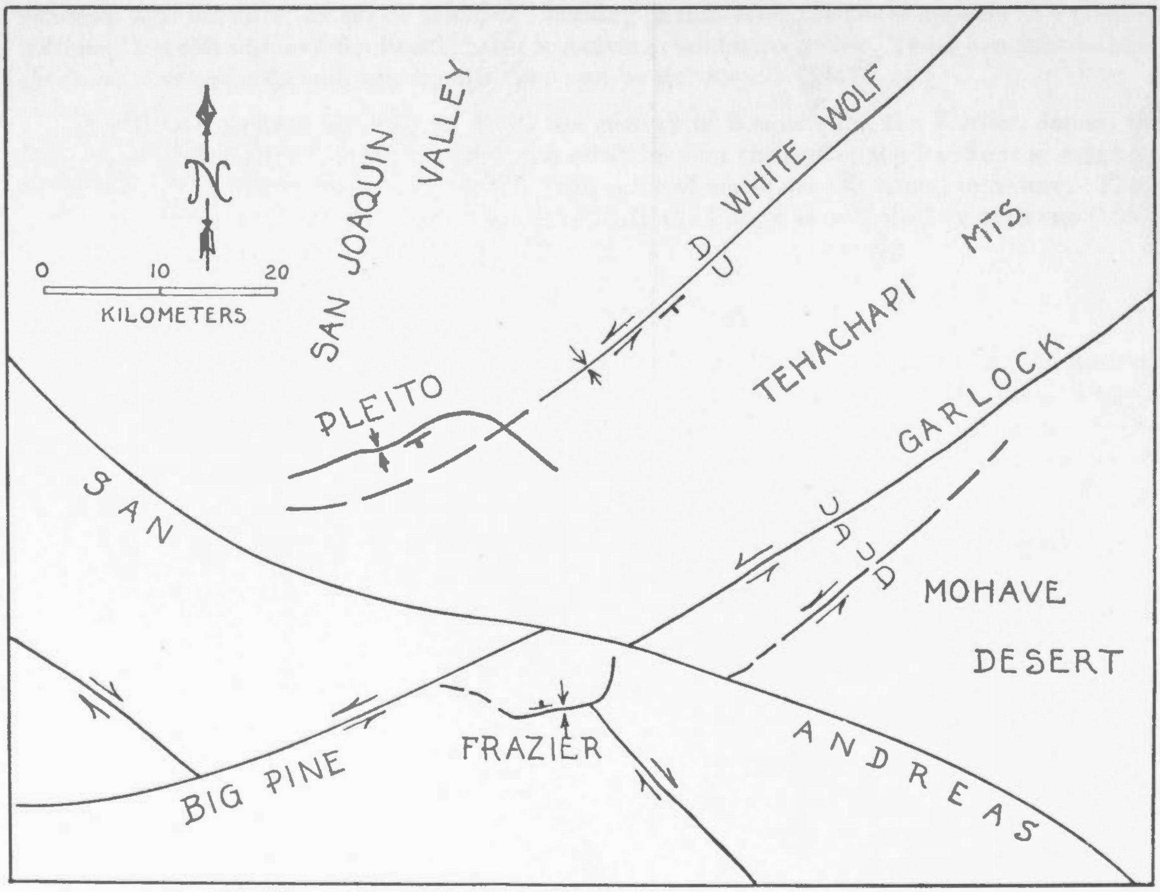

Figure 4. The plexus of faults near the intersection of the San Andreas and Garlock systems. Any of the faults shown are capable of producing large earthquakes. Conclusions based on fault-plane work in this area would lead to possible erroneous conclusions if the structural geology were not known.

if many earthquakes appear to be on faults difficult of explanation on a regional basis. The previous history of the deformation and the local structure will have important influence in the manner of failure in individual localities.

The existence of the left lateral fracture zones in the transverse ranges, such as the Garlock fault, further complicate the picture. An example that one might cite is the White Wolf fault (Figure 4). The strike of this feature is almost at right angles to the San Andreas, the movement is an oblique, left lateral, reverse displacement. This occurs in a region dominated by the San Andreas fault of dextral strike-slip habit. If the existence of the White Wolf were not known, it is likely that the San Andreas fault would have received the credit for producing the Kern County earthquakes of 1952. A serious conflict of evidence for the San Andreas movement would then have arisen.

It seems as if a knowledge of local geology must be incorporated in the final analysis of orogenic movements, as based upon fault-plane solutions. The solutions should first be made, if at all possible, without preconceptions as to structure, but in the end a synthesis of geology and seismology must be made if either is to be more than a game played for its own end.

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Current Status of Fault-Plane Studies—A Summing Up

BY JOHN H. HODGSON

Dominion Observatory, Ottawa, Canada.

ABSTRACT

The paper attempts to state the present position of the fault-plane work, as defined by the contributions to this Symposium. The conclusions are:

1. There is a fundamental disagreement about mechanism which must be solved before the results may be interpreted unambiguously. The disagreement involves the interpretation of S.

2. Assuming a fault mechanism, faulting is predominantly strike-slip except in limited areas. Where unambiguous solutions have been obtained they usually suggest displacement perpendicular to the feature.

3. Assuming the alternative force mechanism, the principal forces appear to act normal to the geographic feature in most areas.

4. The most pressing need of the fault-plane work is agreement on the interpretation of S. This should be sought through detailed studies in theoretical and model seismology and by the careful examination of many seismograms.

During the past few years the study of the mechanism of earthquakes has been increasingly occupying seismologists. Four principal "schools" have grown up, one in Japan, one in Holland, one in the Soviet Union and one, of broad geographical distribution, made up of followers of BYERLY. These different groups have worked independently of each other, and comparison of techniques and results has been difficult. The present volume is the first to contain contributions from each of these groups, as well as papers interpreting the fault-plane results in terms of tectonophysics. In order to define areas of agreement and disagreement between the several authors and to give direction to future work, it seemed desirable to provide a summary of these papers, a task that could best be performed by the Editor. The review has been criticized in manuscript by all of the contributors; it is hoped that it has thereby gained in objectivity.

THEORY

At the outset we must record a disagreement between various investigators in the fundamental matter of assumed mechanism. Two alternative mechanisms have been mentioned repeatedly throughout this volume. They may conveniently be referred to in the notation of HONDA*: type I a single couple, type II a pair of perpendicular coplanar couples. These mechanisms both yield a pair of planes in which the P amplitude becomes zero, but the pattern for S waves is different in the two cases. For type I the magnitude of S is a maximum in the auxiliary plane and a minimum in the fault plane, in type II both nodal planes represent maxima in the magnitude of S waves. It should therefore be possible to decide which mechanism is appropriate from a study of the S waves.

This volume shows complete disagreement in the results of such studies. HONDA, working with records obtained close to the epicentre, finds that a mechanism of type II is demanded by Japanese earthquakes of all focal depths. KEYLIS-BOROK reports that Soviet seismologists, working with more than 300 earthquakes both near to and distant from their stations, find that almost without exception these are due to a mechanism of type I. RITSEMA, instead of using the first motion of S, determines the line of polarization of the S waves from questionnaires from distant stations and the records of nearby ones. He reports that twelve of the earthquakes which he studied were clearly due to type I; results for the remainder were inconclusive.

*Where no specific paper is mentioned, the reference is to the particular author's contribution to this Symposium.

How are we to account for these conflicting findings? It is possible, although improbable, that different mechanisms are active in different parts of the world. The model studies of Press, in which the S waves fail to produce a node on the fault plane, even when the fault has been carefully cemented, seem to point to a more logical explanation. If the nodal plane for shear waves is displaced from that for P waves by as much as 35°, and if a maximum thereby appears on the fault plane, it would be very easy to confuse the pattern with that expected from a model of type II. It may be objected that the model used by Press is too simple; the excellent agreement between the model studies and the theory for the P amplitudes argues against this. In any event the work suggests that the theory for S amplitudes should be re-examined.

If the failure of different investigators to agree on mechanism is due to the inadequate understanding of the S waves, the possibility must be considered that studies which have been based to any considerable extent on S may be in error. In the present state of knowledge it appears desirable to define the nodal lines by use of P data only, and to use the S data to distinguish the fault plane from the auxiliary plane. Even this process of selection must be suspect in the light of the findings of Press and the equivalent work of Kato and Takagi (1957).

The paper by Byerly and Stauder suggests that North American seismologists, influenced by the San Francisco earthquake, have accepted a mechanism of type I without question. This is certainly true of those of us who have been followers of Byerly. We have been content to accept the mechanism and to search for confirmation of our fault-plane solutions in observed faulting. I have listed elsewhere (Hodgson, 1957) ten solutions in which the fault strike was confirmed by field observation; my paper in the present volume lists an eleventh. As Byerly and Stauder have stated, this agreement would not be expected under a mechanism of type II, for in that case the fault would be inclined to the nodal plane at an angle of 20° or more. In this connection it is interesting to note that Honda lists two earthquakes, the North Idu earthquake of Nov. 25, 1930, and the North Tango earthquake of March 7, 1927, in which the observed faulting is almost coincident with one of the P nodal planes. This suggests a type I mechanism, yet even in these cases Honda says the general features of the geodetic deformations, in the region not very close to the fault, are best explained by type II mechanism. North American seismologists would regard the fault as the basic concept, the surface distortion as a secondary effect in which the basic displacement is influenced by surface material, topography, and elastic afterworking.

It seems clear that this problem of mechanism, and the associated problem of the reliability of S waves, is the most pressing matter currently facing investigators. The theory of the S amplitudes should be re-examined, experimental studies using more sophisticated models should be encouraged and, in the words of Honda, "further and minute investigations of the initial motion of the S waves observed at stations over the world are desired".

TECHNIQUE

In discussing technique one must recognize two classes of solutions, those based on data from nearby stations only and those based principally on data from distant stations. In the former case the information is usually plotted on ordinary maps, in the latter case some special projection must be used. The matter of projections has been competently discussed by Scheidegger (1957). Whether one uses the Wulff projection or the Byerly projection the results are the same and the amount of work involved is comparable. So far as projection is concerned one may combine all results based on observations at distant stations into a single catalogue; indeed there is no theoretical reason why all solutions, whether they are based on near or on distant stations, should not be combined.

In practice the results from the different groups of investigators do not seem to be strictly comparable, as has been pointed out by McIntyre and Christie. Ottawa solutions, largely for earthquakes from the circum-Pacific zone, have shown a preponderance of strike-slip faulting on steeply dipping planes. Ritsema, working with earthquakes of the East Indies, found a much smaller percentage of strike-slip faults. In the area from Japan to Kamchatka, in which the Ottawa group has found so many examples of strike-slip faulting on steeply dipping planes, Soviet studies (Kogan, 1954) have also shown strike-slip faulting but on less steeply dipping planes. Japanese solutions, on the other hand, generally show nodal planes very steeply dipping. The amount of strike-slip motion is a very important matter in the interpretation of the fault-plane results, and these differences should not go unmentioned.

The Ottawa group has obtained only five solutions in the area from the Solomons to New Guinea, probably too few to permit a valid comparison with Ritsema's results. Of these five, one indicated normal faulting, one thrust faulting, one strike-slip faulting, and two strike-slip faulting with a strong thrust component. These results are sufficiently similar to Ritsema's to suggest that our techniques are probably consistent, and that Ritsema is working in an area in which the mechanics of failure differ somewhat from the Pacific zone.

I had thought at first that the difference between Kogan's solutions and my own was due to the fact that she was using S extensively. Dr. Keylis-Borok tells me that this is not so, that the nodal lines were defined largely by the P waves and that the S waves were used only to select the fault plane. He suggests another reason. When the Soviets were developing their techniques, Kogan examined the Soviet records, covering a very long period of time, for all earthquakes in the north Pacific, but was able to obtain solutions only for a small percentage of these earthquakes. Keylis-Borok suggests that this selection favoured the less steeply-dipping planes for some reason. This seems probable, and I am able to suggest a reason. Kogan was dependent largely on the records of Soviet stations, with limited help from bulletins. Planes which were dipping so steeply as to be defined in the PKP range or at the greater distance of the P range would lie beyond the range of the Soviet stations and so escape her notice. She would therefore obtain a preponderance of solutions in which the circles were defined at intermediate distances.

An analogous reason explains the very steep dips found by the Japanese. With their close networks of stations near to the epicentre they can define the quadrants very accurately and so obtain a good definition of strike. With only nearby stations however they cannot define the curvature of the nodal lines; any steeply dipping plane will appear to define a straight line on the surface, and all steeply dipping planes will be called vertical for want of definition. This does not seriously vitiate the conclusions from such studies, but renders exact comparison unprofitable.

From the foregoing it appears probable, but by no means certain, that the work of the various "schools" is comparable. It is sometimes suggested that each group working in fault-plane studies should be assigned an area for which they will be responsible and on which other investigators will not encroach. At the present time this does not seem to be desirable. It is better for each group to work independently until, by comparison of results, the equivalence of technique is established beyond question. In the meantime one is probably justified in combining results for most sorts of studies. It must always be remembered that any investigator may occasionally produce an erroneous solution. The data are never as complete as one would like, and in making the best fit to an incomplete set of data, errors must occasionally occur.

So much for the larger aspects of technique. It is interesting that these major aspects have become generally accepted and that it is the refinements which are now coming in for study. Ingram's paper, which looks forward to the time when fault-plane studies will be less of an art and more of a science, is a case in point. We in Ottawa have examined the reliability of secondary arrivals as reported in questionnaires and have found this to be unsatisfactory (Hodgson and Adams, 1958). Ritsema gives somewhat analagous evidence. But in neither case is there any evidence that past use of secondary phases has caused solutions to be seriously in error. Soviet seismologists have examined the effects of refracting boundaries close to the source, of crustal layers including low-velocity layers, and of materials which are not perfectly elastic. From a practical point of view they find that these effects are likely to be serious only for near earthquakes or for certain phases such as PcP in the event that the core is not perfectly elastic. SUTTON and BERG (1958) have examined the effect of crustal structures of various degrees of complexity on some solutions published by the Ottawa group. They find that the effect of allowing for the crust would be to increase the strike-slip component of the solutions. Since the solutions have been criticized for having too high a strike-slip component the results of the refinement have not been in the desired direction. To sum up, it appears that the refinements and the critical examination of details have not vitiated any of the main conclusions of the fault-plane work.

RESULTS AND INTERPRETATION

From the time when fault-plane solutions became available in many parts of the world it has been apparent that strike-slip faulting has a larger importance in tectonics than had been anticipated. This conclusion is so inconsistent with existing theories that many tectonophysicists have refused to accept it. We have already seen that the papers of the present volume give no reason to doubt the theory or techniques of the method. Do the results taken as a whole justify the conclusion?

It should first be stressed that the conclusion depends on the assumption of a mechanism of type I. If a mechanism of type II is assumed instead the nodal plane is no longer a fault, and one thinks in terms of the forces bisecting the angles between the nodal planes. In Japan, as HONDA has shown, these pressures lie approximately normal to the trends of the deep and intermediate earthquake zones. RITSEMA also finds that, assuming a mechanism of type II, there is "a tendency for all maximum pressure components to concentrate in directions about perpendicular to the general trend of the seismic zone". It seems probable that if the results of other investigators were treated in the same way similar conclusions might be reached. Since most theories of mountain building or of island arc formation require forces normal to the feature, most tectonophysicists would be happier with the assumption of a mechanism of type II.

Returning to the fault interpretation, all studies seem to point to the great importance of strike-slip faulting. Normal faults become important at great depths in the East Indies, dip-slip faults occur profusely in the Hindu Kush and in the Pamir Knot area and occasionally in the Bonins and off the coast of British Columbia. Elsewhere strike-slip faulting does appear to be the rule. How is this fact to be reconciled with the crustal shortening evident in island arcs and mountain ranges? There are many variations of thought on these matters, many of them heard in discussion rather than read in print, but most thinking seems to derive from one or other of two models.

The first model is the San Andreas fault. This is a strike-slip fault parallel to the continental boundary; by inference one group of thinkers would argue that the strike-slip faults found in the fault-plane work should lie parallel to the continental margin or to the island arc. Where fault-plane solutions are based on P waves only, and so are ambiguous, it is usually possible to select one plane which approximately fits this criterion. WELLMAN, in several private communications, has favoured this interpretation of the fault-plane results in the southwest Pacific; his interpretation is based on an intimate knowledge of the geology of the area rather than on philosophical arguments. MCINTYRE and CHRISTIE arrive at a similar conclusion from interpretation of the null vector. Two of the interpretive papers in the present volume, those by BENIOFF and by ST. AMAND, have been along these lines; both these papers have been based only partly on fault-plane results and have depended more on large-scale evidence and on detailed knowledge of the regional geology.

The "San Andreas" model has difficulty in producing adequate crustal shortening. BENIOFF has overcome this by postulating a second movement radial to the Pacific, by which the ocean basin underthrusts the continents. Others, following ANDERSON (1942), have suggested that strike-slip faults are usually hinged and that there is enough vertical motion involved to account for deeps and mountains. However the problem does bring us to the second model.

The second model is the ordinary island arc. There is a vast literature on island arcs, in most of which it is implicit that they are the product of pressures normal to themselves. If strike-slip faulting develops from such a force ti should be inclined at a small angle, perhaps 30°, to the normal to the feature. Where fault-plane solutions are ambiguous one may usually select a plane which fits this requirement. With planes so selected, the direction of material transport is approximately in the direction of the normal, that is in the direction of the postulated major force.

The fault-plane literature, including that in the present volume, is inclined in favour of this second model. Soviet solutions are based on S and so are unambiguous. In the Pacific those solutions favour faulting approximately perpendicular to the arcs (KOGAN, 1954). RITSEMA, who has used S, finds that strike-slip faults tend to be perpendicular, and dip-slip faults parallel, to the seismic zones so that, in his own words, "almost all fault displacements are directed approximately perpendicular to the (seismic) zone". I have shown elsewhere (HODGSON, 1958) that my own results in the northwest Pacific may be interpreted to give displacements normal to the arc in almost exactly the same direction as KOGAN'S, and that the solutions in the south Pacific may be similarly interpreted. HONDA, while admitting that other possible interpretations of his data exist, says that there "seems to exist the general tendency for the Pacific side to be relatively forced downward and toward the Asiatic continental side."

The second model seems to present the least difficulty in interpreting the fault-plane results. We postulate a force normal to the feature, so that folds, troughs and similar features will have axes parallel to the feature. In some areas this force gives rise to dip-slip faults striking parallel to the feature but more usually it causes strike-slip faults inclined at small angles to the normal to the feature. There is nothing in this inconsistent with conventional geological theories on the failure of material. We even, as I have shown in the paper already referred to, get dextral and sinistral faults developed in about equal numbers, so that by interfingering we obtain the necessary crustal shortening. MCINTYRE and CHRISTIE have discussed the difficulties posed by the development of dextral and sinistral faults in about equal numbers. These difficulties are much less severe in the second model.

The papers by BENIOFF and by ST. AMAND in the present volume present evidence for the first, or "San Andreas" model, but little of this evidence is from the fault-plane work. Where the seismic solutions are ambiguous they have selected the solution best fitted to the other evidence, and they have ignored the evidence of the unambiguous solutions that displacement is perpendicular to the geographic features. BENIOFF has given some thought-provoking reasons to justify this. He suggests that fault-plane solutions should not be used by themselves to derive the principal stresses in a region, because they may only be expressions of small local distortion. Only the fault-plane solutions for the largest earthquakes, in which the extent of faulting is large enough to eliminate local effects, are to be depended upon and even here the movement may be along fractures established under an earlier system of forces. DIX has suggested other reasons why fault planes determined from first motion may not always coincide with actual faulting. These arguments are extremely discouraging to the fault-plane seismologists, and most of us would repudiate them where a statistical number of solutions are involved. Nevertheless we must make it clear that a large gulf still exists between the findings of the fault-plane seismologists and the theories of the tectonophysicists.

Finally we must mention the contribution of MCINTYRE and CHRISTIE, who have brought the disciplines of structural geology to the interpretation of the null vector. The null vector was originally introduced as evidence that the fault-plane solutions were self-consistent and related to the topography. While MCINTYRE and CHRISTIE have not accepted this conclusion in all areas, they have given a geological interpretation to the null vector and have used it as a basis for selecting the fault plane. Unless the use of S can be established beyond question, so that unambiguous solutions become available, their technique will become very important. Solely on the basis of this evidence they have been independently led to the "San Andreas" model in those areas where their results are definite.

Clearly, no final conclusions on interpretation can yet be drawn. Seismologists must devote much more effort to the study of the S waves, so that they may come to an agreement on the fundamental mechanism and eliminate the ambiguity of the fault-plane solutions. In the meantime tectonophysicists should not ignore those solutions from which the ambiguity has already been eliminated, but should seek some interpretation of the available data which is acceptable to both disciplines.

CONCLUSIONS

1. There is disagreement on the fundamental mechanism of energy release. Efforts to resolve this disagreement have not been successful. Studies in model seismology suggest that this may be due to inadequacy of the theory. This is the most important problem facing fault-plane seismologists at the present time, and it should be attacked as energetically as possible.

2. On the fault hypothesis faulting is strike-slip in most areas; exceptions are deep-focus earthquakes in the East Indies, and earthquakes of various focal depths in the Hindu Kush, the Pamir Knot, the Bonins and off the coast of British Columbia. Refinements of technique and slight differences between different groups of investigators do not alter this conclusion. On the alternative hypothesis (type II), forces generally act normal to the associated feature.

3. Enough differences exist between the results of the several "schools", that no effort should be made to limit duplication of effort. Only by duplication can comparison be obtained.

4. Where unambiguous solutions have been obtained they suggest that displacement is perpendicular to the associated feature in most areas. This may be accomplished by having dip-slip faults striking parallel to the feature or strike-slip faults striking perpendicular to it. Ambiguous results may be given a similar interpretation.

5. When agreement has been obtained on the interpretation of S, uniquely defined solutions should be aimed at.

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