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OTTAWA

Vol. XVIII, No. 1

Gravity Measurements Over the Cumberland Basin, N. S.

By

G. D. Garland

Reprinted from
The Canadian Mining and Metallurgical Bulletin, Vol. 48, 1955

Gravity Measurements over the Cumberland Basin, Nova Scotia

*By G. D. GARLAND**

(*Transactions, Volume LVIII,* 1955, pp. 90-98)

Introduction

ALTHOUGH the presence of rock salt in the Carboniferous basin of northern Nova Scotia has been known for at least one hundred and twenty years, and salt has been mined at Malagash continuously since 1919, certain characteristics of the deposits make exploration by drilling or surface examination difficult. The surface rocks of the basin are, in general, of Pennsylvanian age, while the salt occurs in the Mississippian Windsor group. The latter rocks are brought to the surface only along anticlinal folds, or as irregular fault blocks. Because of the limited areal extent of these Windsor exposures, and their complicated internal structure, geophysical surveys, especially gravimetric, can be of considerable aid in outlining the more favourable areas.

The present paper describes the results of recent investigations by the Dominion Observatory, in cooperation with the Nova Scotia Department of Mines. It includes a regional study of that section of the Cumberland basin lying between Springhill and Malagash (Figure 1), and a much more detailed survey of the immediate vicinity of the Malagash deposit itself. This deposit had been studied by Miller (6, 7) with the torsion balance nearly twenty years before, and a direct comparison between the results given by the two types of instruments is therefore possible.

Geology of the Area

The region to be studied forms part of the extensive Cumberland basin of Carboniferous deposition. It is well covered by the one mile to the inch map series of the Geological Survey of Canada, and is described fully by Bell (1) and Norman (8). This outline, which is drawn largely from publications of the Geological Survey, is intended only to present the general nature of the formations and the structural relationships that are to be dealt with in the interpretations of the gravity anomalies.

Table of Formations

Pennsylvanian	Pictou Series	Sandstone, shale, conglomerate
	Cumberland Series	Sandstone, conglomerate, shale
	Riversdale Series	Boss Point formation: sandstone, shale. Claremont formation: conglomerate, sandstone, shale.
Mississippian	Middleborough form'n	Sandstone, shale
	Windsor group	Shale, sandstone, gypsum, limestone, salt
Pre-Carboniferous		Complex of sedimentary and volcanic rocks intruded by granite, etc.

The Cumberland basin lies between the exposed pre-Carboniferous ridge that forms the Cobequid mountains to the south, and the concealed extension, inferred from previous gravity observations (3), of the Caledonian mountains to the north. The general sequence of rocks in the area, with the lithological nature of each series or formation, is given in the accompanying Table.

The thicknesses of the various series are rather variable over the area, but the total thickness of the Pennsylvanian strata alone is several thousands of feet. The Middleborough formation, which lies immediately above the Windsor group,

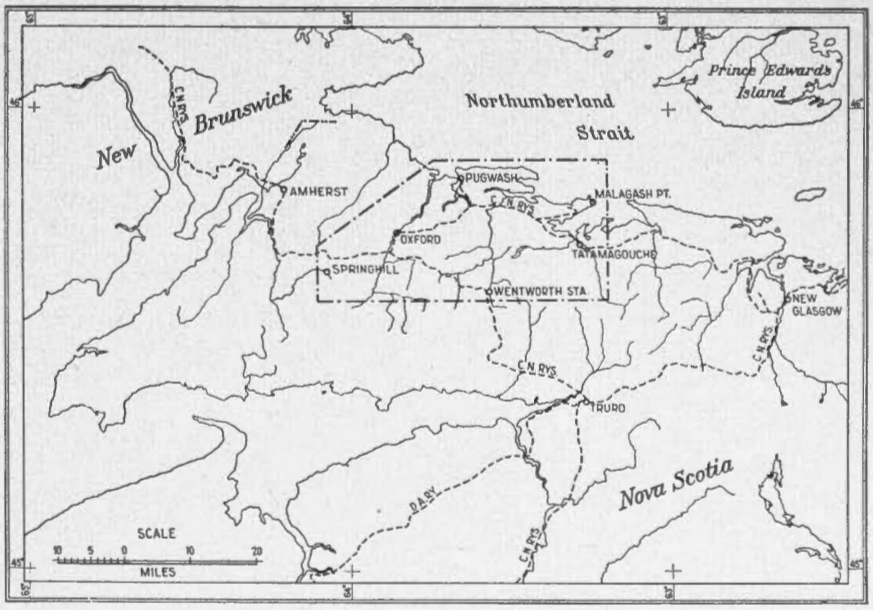


Figure 1.—Outline of the area of northern Nova Scotia covered by the regional gravity survey.

*Dominion Observatory, Department of Mines and Technical Surveys, Ottawa.

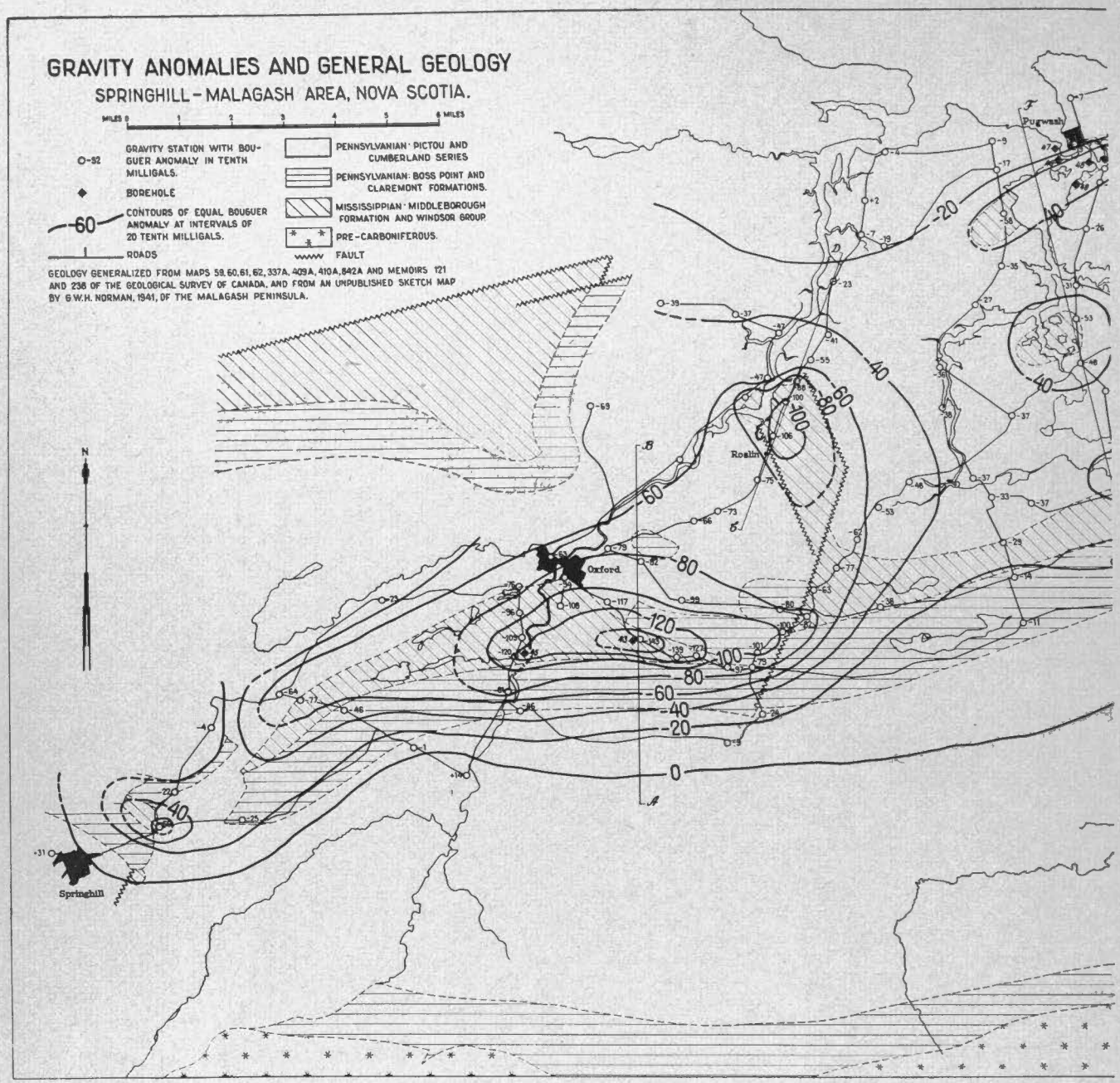


Figure 2.—Bouguer gravity anomalies and generalized geology of a portion of the Cumberland basin.

ranges in thickness from a few hundred to about three thousand feet.

A generalized section of the Windsor group itself in the area is given by Bell (1), as follows:

Red sandstone, siltstone, etc..	400 ft.
Calcareous member: limestone, etc.....	125 ft.
Red shale, mudstone, etc.....	800 ft.
Gypsum-anhydrite-salt member.....	500+ft.

The lowest member of the group offers little resistance to erosion, and where it has been brought to the surface the actual rock exposures are characteristically poor. Very often, its presence can only be inferred from topographical features, such as 'sinks' and ponds, produced by solution. Where the structure of the Windsor areas can be deduced, the strata are in general found to be steeply dipping and highly contorted.

Overlying formations up to and including the Boss Point appear to have been deformed by major forces acting before the deposition of the Pictou series. Thus, although the Windsor exposures lie along the axes of anticlinal folds in this series, the dips of the Pictou strata are much more regular and gentle than those of the pre-Pictou rocks.

The actual contact relationships between the Windsor group and younger rocks are quite varied among the different exposures. At places along the Claremont anticline, which extends from near Springhill to Malagash point (Figure 2), the Windsor beds are found to lie conformably beneath the Middleborough formation. More often, however, the areas of Windsor rocks are in fault contact with rocks as young as the Pictou series. In the case of the exposure south of Pugwash, the Windsor group is apparently bounded on all sides by overlap of the Pictou strata, and the relationships with formations older than the Pictou are not known.

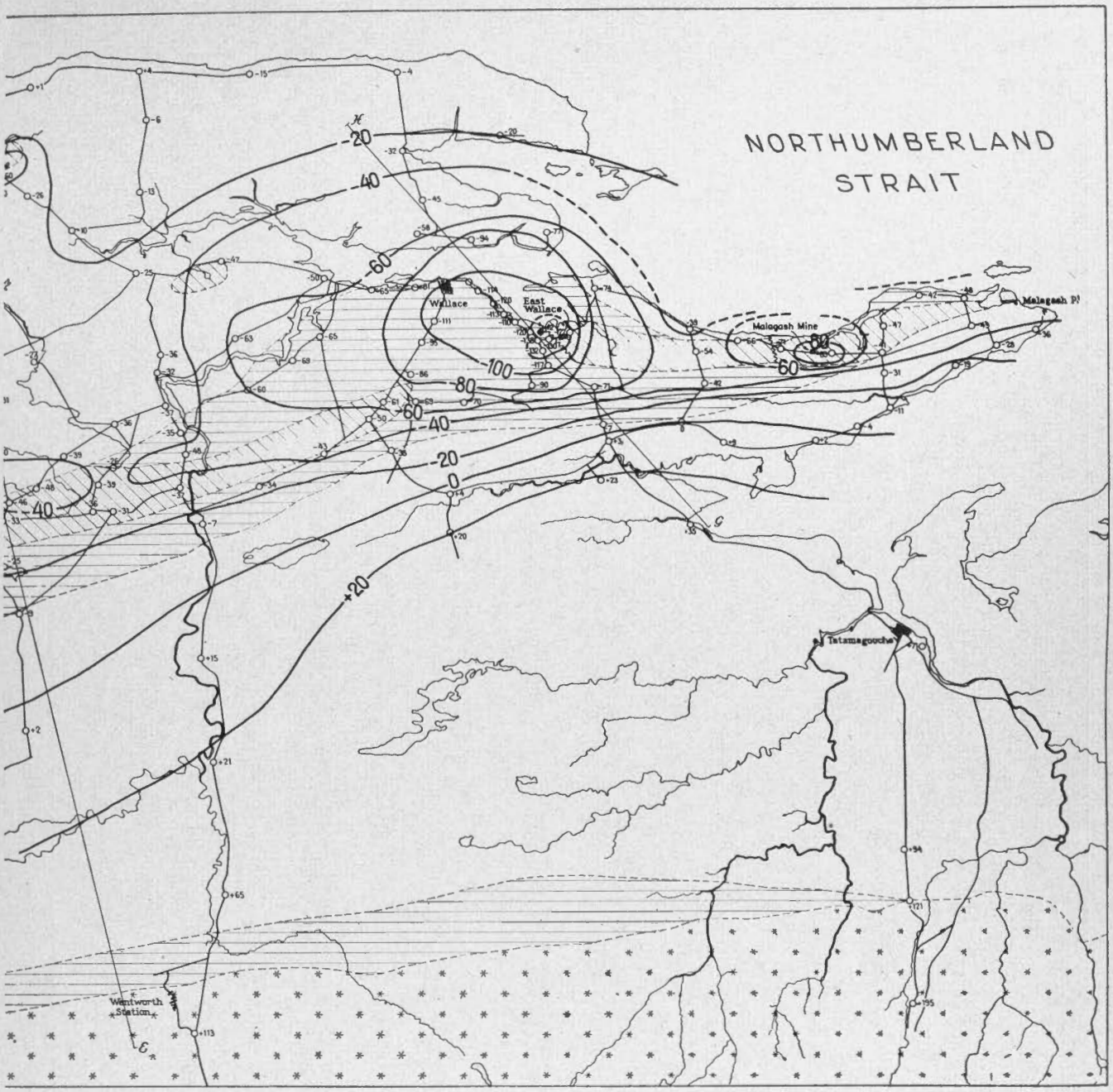


Figure 2. (For caption, see page opposite)

For the interpretation of the gravity anomalies, a knowledge of the densities of the rocks involved is of prime importance. The data available, which include values measured by Miller (6) and by the writer, are summarized in Table I.

Although the range in density between lithological units of a formation may appear to be greater than the difference between formations, certain generalities may be noted. The Boss Point formation, which is fairly thick (2,000 to 4,000 feet) throughout the area, is on the whole probably less dense than the overlying Pictou series. The Windsor group on the average is less dense than the majority of the younger formations, as the dense limestone member it contains is quite thin. It is apparent that local concentrations of gypsum, and especially of salt, will largely control the exact density of the Windsor. These relationships suggest that the gravity observations may be applied to the problem of outlining the various Windsor exposures, and, on a more detailed scale, to the detection of salt concentrations within these areas.

The Observations

Quite different field procedures were employed on the regional and detailed surveys. For the former, stations were spaced at intervals of about half a mile along the available roads through the area. The gravity readings were taken with a North American instrument, whose scale constant was 0.2315 milligals per division. All observations were made relative to bases at Tatamagouche, Pugwash, or Oxford, which were in turn connected to a previously established main base at Amherst (3). The elevations of the majority of the stations were obtained by readings with two aneroid barometers. As control points in the form of bench marks and map elevations were plentiful throughout the area, the station elevations are probably reliable to about five feet,

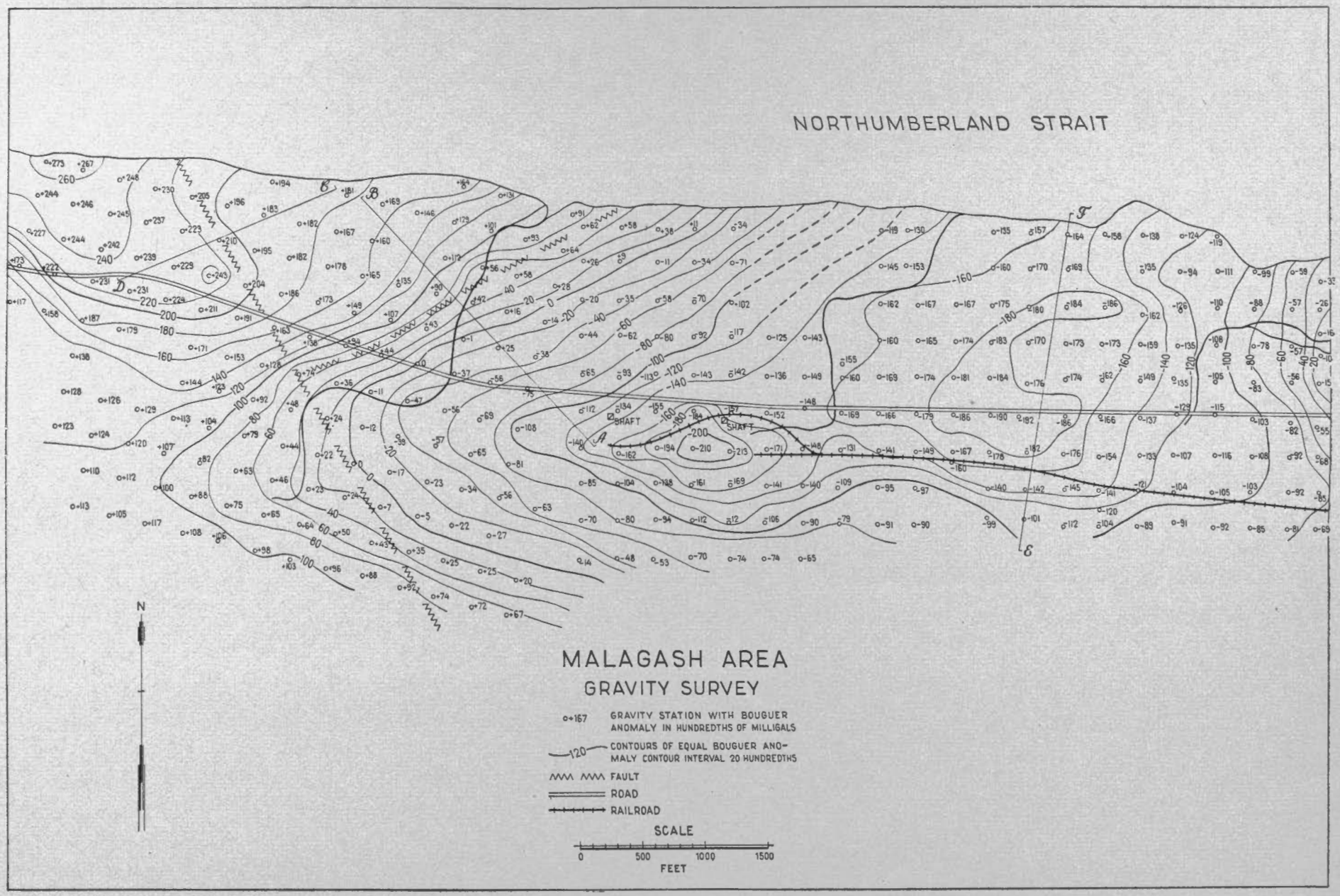


Figure 3.—Bouguer gravity anomalies of the Malagash area

TABLE I.— DENSITIES OF CARBONIFEROUS ROCKS OF THE CUMBERLAND BASIN

ROCK TYPE	DENSITY Gm. per cc.	OBSERVER
PICTOU:		
Sandstone.....	2.48	G.D.G.
Sandstone.....	2.45	A.H.M.
Conglomerate..	2.36	A.H.M.
BOSS POINT:		
Sandstone.....	2.35	G.D.G.
Sandstone.....	2.33	A.H.M.
Red shale.....	2.56	A.H.M.
CLAREMONT:		
Conglomerate..	2.42	G.D.G.
MIDDLEBOROUGH:		
Shale.....	2.44	G.D.G.
Sandstone.....	2.47	G.D.G.
WINDSOR:		
Red shale.....	2.42	G.D.G.
Red shale.....	2.50	A.H.M.
Yellow shale...	2.17–2.30	A.H.M.
Anhydrite.....		G.D.G.
Gypsum.....	2.3	(Smithsonian Tables)
Salt.....	2.16	A.H.M.
Limestone.....	2.69	G.D.H.

and the error from this cause in the Bouguer 'anomalies' is about 0.5 milligals (*i.e.*, 5 parts in the last figure of the quantities plotted on the map, Figure 3). In computing these anomalies, a density of 2.67 was adopted for the rocks above sea-level, so that the values would be directly comparable to those on the gravity map of the Maritime Provinces (3). It is apparent that this density is rather high for the particular region, but very few of the stations are as much as 200 feet above sea-level, and the resulting uncertainty for these highest stations is not greater than 0.5 milligals. The Bouger anomalies are plotted on the map in units of 0.1 milligal (0.0001 cm. per sec.^{2}), and are contoured at intervals of twenty of these units.

In the case of the detailed survey of the Malagash area, a rectangular grid of 300 feet was used (Figure 3). Gravity observations were taken with a Worden gravimeter, scale constant 0.1114 milligals per division. The observations were made on short loops out from base stations distributed along the main east-west road. They are believed, on the basis of repeat observations at certain stations, to be accurate to about 0.02 milligals. Elevations for all stations were obtained by spirit levelling with a Zeiss auto-level. The mean closure error on levelling circuits was about 0.05 foot. The Bouguer anomalies were computed for a density of the surface material of 2.0 grams per cubic centimeter. This figure was adopted as a mean between the soil density of 1.7 and the rock densities of 2.3 to 2.4. The land surface is fairly level over much of the area, except for minor undulations in the glacial drift. Toward the southern limit of the survey, however, it rises gradually to about 150 feet above the sea. Since a rise in the bed-rock surface is assumed beneath this higher ground, a density intermediate between that of rock and soil was adopted.

The topography, as mentioned above, is flat or gently rolling over most of the area. However, the western section of the coastline is in the form of an almost vertical cliff, rising forty to fifty feet above the sea. Terrain corrections were applied to stations in the vicinity of this feature by calculating the effect, at various distances, of a vertical, 50-foot scarp of infinite strike length. These corrections became quite negligible at a distance of 200 feet from the cliff, and only at about ten stations did the corrections significantly change the contouring. This method of treating terrain features was suggested by Hubbert (6). The final Bouguer anomalies are plotted on the map in units of 0.01 milligal (0.00001 cm. per sec.^{2}), and are contoured at intervals of twenty of these units.

DISCUSSION OF THE RESULT OF THE REGIONAL STUDY

The accompanying map (Figure 2) indicates that the Bouguer anomalies range from +113 units at the extreme south of the area to −143 in the vicinity of Oxford. The positive values along the southern border are due to the dense pre-Carboniferous rocks of the Cobequid complex. There is a fairly rapid decrease in anomaly near the edge of the Carboniferous basin, but from a few miles north of the basin edge to the shores of Northumberland Strait any effect of the pre-Carboniferous basement rocks must be very small and slowly varying in comparison with the sharper effects of near-surface density variations. The most striking feature of this region is the series of negative anomalies along the axis of the Claremont anticline and over the Windsor exposures near Roslin and Pugwash. This correlation of negative anomalies with the uplifted areas confirms the hypothesis that the Windsor and possibly other pre-Pictou formations are less dense than the overlying Pictou series.

The different Windsor areas will now be examined in detail, in order to suggest what may be deduced from the gravity field regarding the structural relations and internal composition of these areas.

Oxford Area

The largest single exposure of Windsor strata within the region studied is that which occupies the axial portion of the Claremont anticline from near Springhill to the transverse fault about five miles east of Oxford. Traverses across the western section of the area indicate a rather broad area of lower anomaly, conforming to the boundaries of the Windsor series with the overlying, denser formations. East of Oxford, however, there is a narrower, more intense negative anomaly, suggestive of a concentration of low-density material within the Windsor rocks. The nature of the anomaly, as indicated by the profile along the line *AB*, Figure 4, suggests that the effect of a local, near-

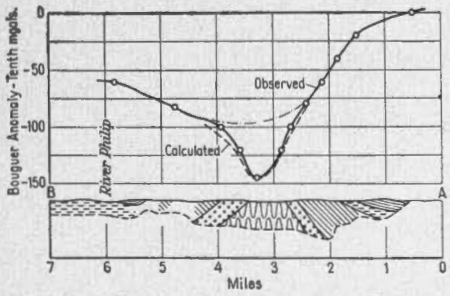
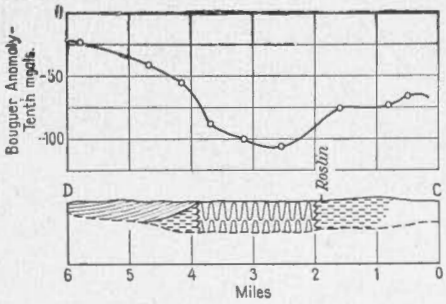


Figure 4.—Gravity anomaly profile and geological section along the line *AB*, Figure 2. (Regional survey)



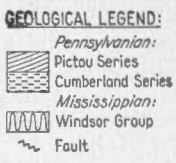


Figure 5.—Gravity anomaly profile and geological section along the line *CD*, Figure 2. (Regional survey)

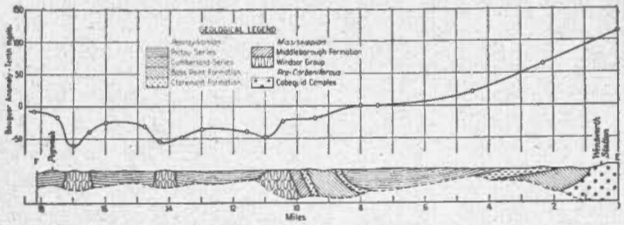


Figure 6.—Gravity anomaly profile and geological section along the line *EF*, Figure 2. (Regional survey)

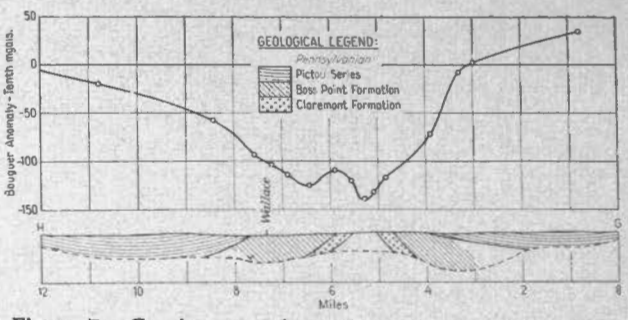


Figure 7.—Gravity anomaly profile and geological section along the line *GH*, Figure 2. (Regional survey)

surface structure is superimposed on the broader negative anomaly caused by the general anticlinal structure. For comparison, the illustration includes the calculated anomaly due to a shallow, horizontal cylinder, with a radius of 2,500 feet, and a density deficiency of 0.2 grams per cubic centimeter. One interpretation would be that a concentration of low-density material, including salt strata, could be present along the axis of the anticline between Phillip river and the fault mentioned above.

However, the results of recent drilling suggest that any body of commercial salt must be rather restricted in size. The log of borehole 43 (Figure 2) of the Malagash Salt Company indicated steeply dipping red clay or soft shale from the surface to a depth of about 250 feet. From there to about 380 feet, both red and green shale containing stringers and crystals of coloured salt, with a few bands of clear salt, were encountered. Below 380 feet, to the end of the hole at 412 feet, the salt content was found to decrease. Similar conditions were found in borehole 45 at the opposite side of the anomaly peak. These findings do not entirely rule out the possibility of there being a dome-like concentration of salt in the area between the drill holes.

The negative anomaly ends abruptly at the transverse fault east of Oxford, although Windsor or Middleborough rocks continue to occupy the axial region of the anticline. Only near Wallace river, some eight miles to the east, does a pronounced negative reappear over the anticline. It appears safe to conclude that the intervening area holds little promise of important near-surface salt accumulations.

Roslin Area

The block of Windsor rocks near Roslin forms an interesting structure, as it is apparently bounded on three sides by faults and on the fourth side by an overlap of Pictou strata (Bell 1944 and G.S.C. Map 842A). The Windsor group is highly distorted and steeply dipping, and is known to contain gypsum at several localities. Its gravitational effect is clearly seen on the anomaly map as a closed negative anomaly decreasing to about −100 units. An oblique profile across the block is shown in Figure 5. Although the negative anomaly is quite pronounced, it is less intense than that considered above, and it appears to result from the block as a whole, rather than from any concentration within it.

A more detailed network of stations over the area might give quite a different picture, but for the present no specific deposit can be pointed out. One interesting feature that may be seen from the anomaly map is the steep gradient northwest of the block, just inside the overlapping Pictou strata. This suggests that the contact between the Windsor group and younger pre-Pictou strata, presumably along a fourth fault, is not far northwest of the actual exposure.

Wentworth-Pugwash Profile

In Figure 6 is shown a profile extending from near Wentworth Station, on the pre-Carboniferous rocks, to the coast of Northumberland strait, near Pugwash. The profile indicates that, apart from the rise toward the southern edge of the basin, the anomaly level over areas of Pictou rocks is quite uniform. Three areas of Windsor strata produce negative anomalies, although none of these is very intense. However, it should be pointed out that the distribution of stations over the two northern areas is rather sparse, as they are difficult of access. The Windsor exposures near Pugwash are largely covered by an inlet of Northumberland strait, while the central area on the profile, known as the Canfield Creek area, is low-lying and traversed by few roads. In the three cases, the Windsor rocks are exposed on the axes of anticlinal structures in the Pictou series, but the Mississippian formations are characteristically more severely folded than the Pictou.

On the basis of magnitude of anomaly only, none of the Windsor areas on this profile would appear as favourable as those near Oxford or East Wallace. However, this criterion alone is hardly satisfactory, as the most intense negative anomalies may indicate areas of extreme crumpling and piling up of the light Mississippian strata, in which bands of relatively pure salt cannot be satisfactorily traced. In any case, preliminary drilling of the more moderate anomaly near Pugwash suggests that it is underlain by a somewhat less distorted block of Windsor strata, containing definite salt horizons. Borehole 48 is apparently located near the axis of the structure, for it passed immediately into gypsum and anhydrite, intersecting salt between about 360 and 540 feet. The northern limit of the Winsdor rocks is either a fault or a steeply dipping unconformity passing between boreholes 46 and 47. In the former hole, the salt was found at a depth of somewhat over 600 feet, while the total depth of the latter hole, almost one thousand feet, lay in Pictou strata. The steep nature of this northern boundary is indicated also by the gravity gradient over it.

Wallace Area

In the vicinity of East Wallace, the axis of the Claremont anticline changes rather abruptly from northeasterly to east-west. Here, also, the north limb of the anticline is more gently dipping, in contrast to the overturned north limb, which may be observed a few miles to the east, near Malagash. Over this section of the structure, which is evidenced on the map by the wide exposure of the Boss Point formation, there is a broad area of low gravity, extending roughly as far west as Wallace river. Superimposed on this

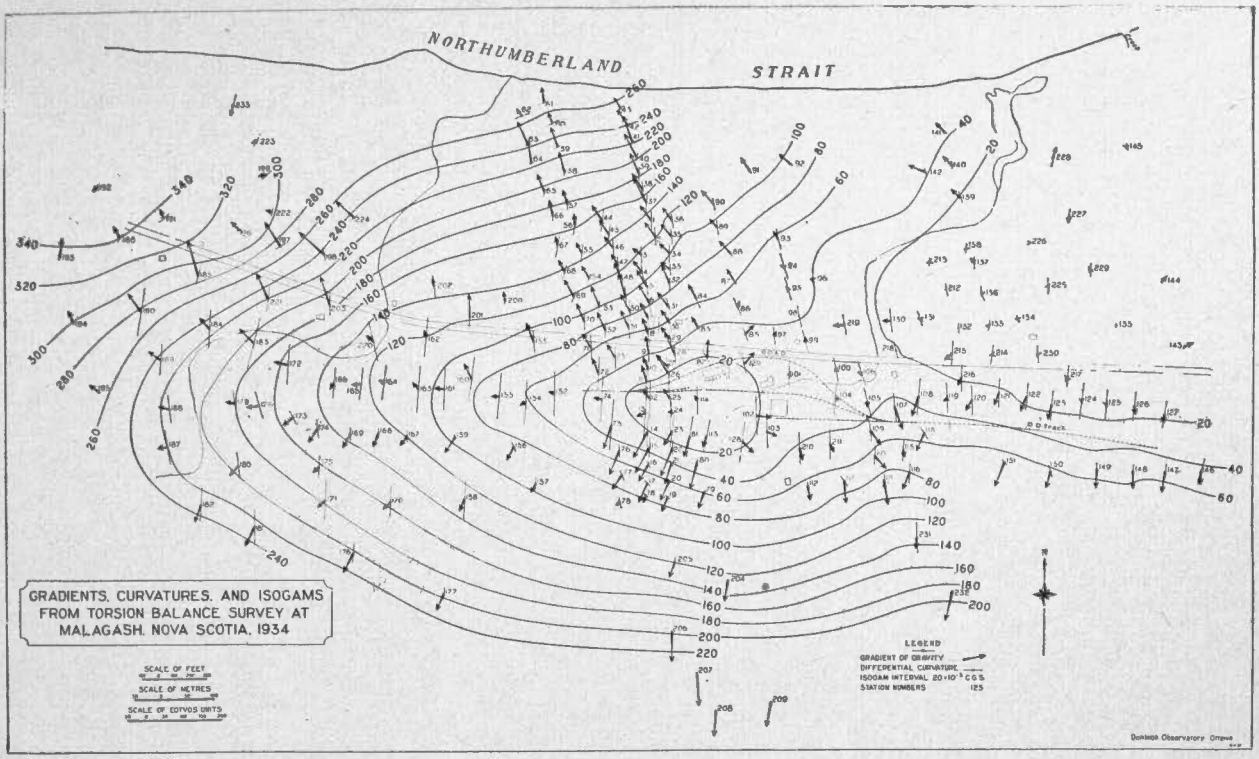


Figure 8.—Torsion balance survey of the Malagash mine area.

broad effect is a sharp circular negative anomaly near East Wallace. The general low area may be a reflection of the wider exposure of pre-Pictou (less dense) formations (*e.g.*, the Boss Point) on the north side of the anticline, or it may indicate a deep concentration of evaporite. In any case, the local anomaly near East Wallace must be due to a relatively shallow body, and is therefore of importance. The general relation between the anomaly profile and the geological section is shown in Figure 7. Comparisons with calculated profiles suggest that the anomaly could be caused by a structure in the form of a vertical cylinder with upper surface near the earth's surface, if the radius of the cylinder is taken as 1,000 feet and the density contrast with the surroundings as 0.2 grams per cubic centimeter. Actually, the rocks exposed along the axis of the anticline within the area of the anomaly are Claremont strata (Bell 1944, p. 38), the nearest Windsor exposures lying about 1,200 feet to the northeast.

However, the Windsor group, according to Bell (1944), is there contained between two thrust faults, and, if the more southerly of these is of low angle, the Windsor group could be expected at a moderate depth beneath the centre of the anomaly. Gussow (4) has described several cases of salt accumulation in New Brunswick, some of which apparently are related to thrust faulting. This fact, together with the intensity of the East Wallace anomaly, and its location over a possible deep accumulation of salt, suggested that the area was worthy of further investigation.

A drill hole, number 42 as shown on Figure 2, was put down near the centre of the anomaly by the Malagash Salt Company. This hole passed through steeply dipping, soft, red shale, with many zones of gouge-like material, suggestive of faulting. Some gypsum was encountered between 591 and 614 feet. From 614 feet to the bottom of the hole at 655 feet the strata consisted of shale containing numerous small cubical cavities from which salt had been leached, together with larger cavities which caused the drill stem to drop several feet at a time. It was concluded that most of the salt originally present had been leached by water circulating through the fault zone. The effect of the cavities would, of course, be to decrease the density of the rocks, and this may contribute to the pronounced local anomaly. The single drill hole does not conclusively indicate that salt is not present within the anomalous zone, but it does suggest that much of the area would be unsuitable for mining operations in any case, because of the broken, faulted strata.

To the east of the feature described above, the course of the Claremont anticline is marked only by a rather weak gravity minimum, except in the immediate vicinity of Malagash. The detailed examination of the conditions there will form the subject of the following section.

Detailed Study of the Malagash Area

The Malagash salt deposit has been described in detail by Hayes (5), Norman (8), and others. In 1934, a torsion-balance survey of the area was conducted by A. H. Miller of the Dominion Observatory (7 and 8), the results of his survey being reproduced in Figure 8. A comparison between this map and the results of the present survey (Figure 3) shows a remarkable similarity. Even though the terrain correction for the torsion balance averaged 25 per cent of the measured gradients, that instrument appears to have outlined the main deposit as faithfully as the gravimeter.

As the rock exposures in the area are limited to the shore of Northumberland strait and to the mine workings, the precise boundaries of the Windsor block containing the deposit were not known before the gravity survey. A fault, with downthrow to the west, was known to exist at the shore west of the mine, and its extension was believed to form the western limit of the Windsor group. The northerly boundary was believed to be formed by fault contact with younger strata (Bell

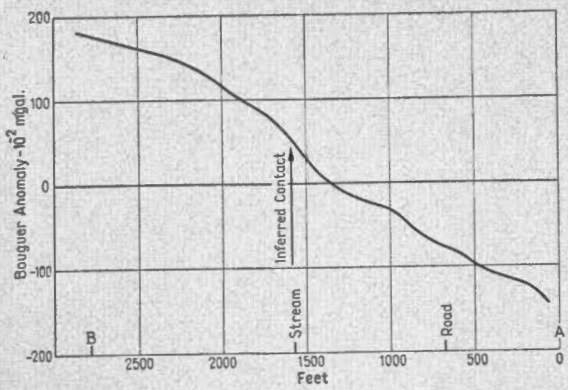


Figure 9.—Gravity anomaly profile along the line *AB*, Figure 3.
(Detailed survey)

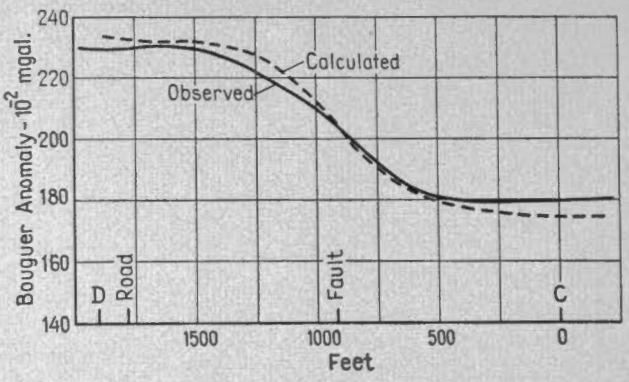


Figure 10.—Gravity anomaly profile along the line *CD*, Figure 3.
(Detailed survey)

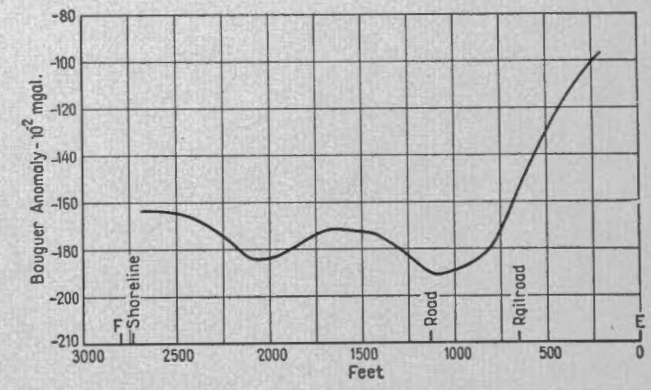


Figure 11.—Gravity anomaly profile along the line *EF*, Figure 3.
(Detailed survey)

1944, p. 36), along the line indicated on Figure 3. The southern and eastern boundaries were also thought to be faults.

The gravity map indicates a broad area of low gravity, bounded on the northwest by a steep gradient near the presumed fault and on the southwest by a similar gradient. This area of low gravity extends almost to the eastern limit of the surveyed area. The eastern boundary of the low-density rocks would appear, from the gravity contours, to be along a north-south line, about 4,500 feet east of the main shaft. Within these limits, the broad area of low gravity is assumed to indicate the presence of the salt-bearing Windsor member, that is, interbedded salt, gypsum, anhydrite, and low-density shales. Concentrations of salt within this member should be indicated by more local gravity minima within the general low area.

The profile shown in Figure 9, taken along the line *AB* on the map, extends from the region of the main deposit northwesterly to the shore, crossing the northern boundary of the Windsor block. The main contact would appear to be indicated by the steepest portion of the curve, which coincides with the line of the assumed fault shown on the map. North of this line, the strata presumably belong to the Claremont, and, nearer the shore, to Boss Point formations. The major fault, which trends southeasterly from the shore, would appear to be evidenced on the gravity map in two ways. Near the shore, rocks of the Pictou series to the west are down-faulted against the Boss Point formation. The profile of Figure 10, along the line *CD*, shows the anomaly produced by this relationship. For comparison, the calculated effect of a vertical fault at 500 feet displacement, and density contrast 0.1 grams per cubic centimeter, is also shown. The good agreement between the curves indicates that the assumed density differential between the Boss Point and Pictou strata is consistent with Norman's (8) estimate of the throw on the fault. Farther south, the western extremity of the area of low gravity appears to be displaced southward along the line of the same fault. This would suggest that the horizontal displacement on the fault is to the south on the west side, a hypothesis consistent with Hayes' (5) observations at the shore line.

Turning to the examination of local minima within the favourable area, it is seen that the anomaly over the known deposit is much the most prominent. However, the appearance of this feature, which might seem to suggest the presence of a circular salt dome, is probably misleading. The anomaly undoubtedly owes much of its form and prominence to its location near the beginning of the steep gradients due to the boundaries of the Windsor block, and to the mass deficiency caused by the removal of material from the upper levels of the mine workings. Actually, the salt beds at the mine occur as steeply dipping strata, striking generally east-west, but contorted into a number of cross-folds. The dip of the beds is toward the south, and becomes more gentle with depth. A total thickness of about 300 feet of salt strata is present, but salt of commercial quality is limited to a relatively few seams, which are thickest along the axes of the cross-folds. The mine workings extend for about 1,000 feet down the dip of the beds, and for about the same distance along the strike, between the two shafts (Figure 3).

The torsion balance survey extended about 2,500 feet east of the main shaft, and indicated the extension of the broad area of low gravity in this direction. The gravimeter observations show two partially merged minima within this area, one on strike with the known deposit, and a similar one about nine hundred feet north of the first. These local minima are rather weak but, as the entire area is believed to be underlain by low-density strata, any lowering of the general anomaly level must be considered significant. A profile across the two features is shown in Figure 11. The fact that the effects along the line of the profile are quite distinct puts a definite upper limit on the depth of the source, for any structures deeper than about 800 feet would not have produced resolvable anomalies (Elkins and Hammer 1938). Actually, the bodies responsible for the minima are probably much shallower, judging from the form of the curves. These two anomalies, apart from the known deposit,

would appear to be the only promising areas within the block of Windsor rocks.

Conclusion

The regional gravity survey has been found to indicate the presence of lower-density Mississippian rocks upfolded or upthrust into the overlying Pennsylvanian formations. In particular, the Claremont or Malagash anticline has been traced from near Springhill to Malagash point. Along the axis of the anticline, intense negative anomalies were indicated near Oxford and East Wallace, but the latter of these occurs over a fault zone where the Windsor strata are badly broken and leached of salt. By contrast, a more regular structure, with better possibilities for development, has been indicated by drilling beneath the moderate anomaly near Pugwash.

The detailed investigation of the Malagash area has shown that the anomaly over the main deposit, as measured with the gravimeter, agrees very closely with the results of the torsion balance survey of 1934. The area covered by the gravimeter was extended to include the presumed boundaries of the upfaulted Windsor block in which the salt occurs (except the northern boundary, concealed beneath Northumberland strait), and these limits have been confirmed by the gravity anomalies. Two possible areas of salt-bearing strata have been indicated to the east of the known deposit. However, in view of the findings at the Malagash mine that salt of commercial grade forms only a small percentage of the total deposit, it must be remembered that gravimetric surveys can only be expected to suggest favourable areas for more detailed, sub-surface investigation. There is a good possibility that some, at least, of the anomalies discussed are due to accumulations of salt-bearing rocks, but of the detailed chemical and physical nature of the salt nothing can be told.

Acknowledgments

The detailed investigation of the Malagash area was undertaken at the request of the Nova Scotia Department of Mines. With the co-operation of Mr. J. P. Messervey, Deputy Minister of Mines of Nova Scotia, surveyors of that Department located the positions of the stations for the detailed survey. This very materially aided the progress of the gravity work. Officials of the Malagash Salt Company, namely, Messrs. J. L. Cavanaugh, John MacQuarrie, and C. M. Thurgood, provided many kindnesses to the party in the field. All observations with the Worden gravimeter were made by Mr. J. A. Robinson, while the elevations were determined by Mr. W. P. Eames and Mr. D. F. Young.

I should like also to express my thanks to the Malagash Salt Company for permission to outline the results of recent drilling, and to Mr. L. H. Cole, consultant to the Company, for helpful discussions.

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GRAVITY IN THE SUDBURY BASIN AND VICINITY

BY

A. H. Miller and M. J. S. Innes

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Gravity in the Sudbury Basin and Vicinity

A. H. Miller and M. J. S. Innes

ABSTRACT

The results of some 500 measurements of gravity over an area of about 2,000 square miles in the Sudbury district are presented. Although a more complete network of stations is desirable, the principal trends and major features of the gravity field are believed to have been established.

It has been shown that most of these features are largely controlled by surface densities of the rock formations. The anomalies, for instance, are quite variable over the Killarney granites and gneisses and were found to be directly related to density changes within these masses.

A gravity high that persists along the southern boundary of the basin is the most prominent feature of the anomaly pattern and is largely due to the noritic phase of the irruptive and to the Stobie formation. The steep gradient over the Mississagi quartzites is interpreted as reflecting a thinning of this formation to the north.

Evaluation of the gravity data over the basin suggests that the structure of the Sudbury irruptive and overlying Whitewater sediments is similar to one deduced by Collins and Kindle from geological considerations. The measurements deny the existence of large underground channels near the centre of the basin, but provide some support to the theory that the rise of the magma was controlled by faulting along the south side of the basin.

INTRODUCTION

The shape of the Sudbury Nickel irruptive has long been the subject of considerable debate and enquiry, because some of the world's richest nickel-copper ore deposits are located near its margins and are believed to be genetically related to it. The irruptive outcrops as an oval ring (*see* Figure 1) approximately 37 miles long and 17 miles across. Norite, the basic phase of the irruptive, forms the outer part of the ring while micropegmatite, the granitic phase, forms the inner portion; a comparatively narrow transition zone lies between the two. The outcrop of the intrusive varies in width from about 1 mile on the north to a maximum of 3·6 miles to the south. Diamond drilling and mining operations[1] have shown that the lower contact of the norite dips toward the centre of the structure at angles* varying from 30 to 50 degrees.

Overlying the irruptive and wholly within its ring is a comformable series of sedimentary rocks and volcanic tuffs known as the Whitewater series. Its formations outcrop concentrically with the irruptive and are disposed in a broad synclinal structure with gentle dips prevailing throughout the central parts. In a general way the series is considered to be conformable with the underlying irruptive.

From these facts it has been inferred, and accepted by most geologists, that the nickel irruptive is a thick basin-shaped sheet or sill‡ that lies between the contact of the Whitewater series and the older rocks below. Not so certain, however, is the configuration of the intrusive at depth, and in 1947 Dr. H. J. Fraser of Falconbridge Mines, Limited,

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[1] Knight, C. W., Report of Royal Ontario Nickel Commission, Ontario Dept. Mines, 1917.

* In some places the norite contact with the underlying formations is nearly vertical or dips outward, but such instances are believed due to faulting. *See:* Cooke H.C., "Structural Geology of Canadian Ore Deposits", *Bull. Can. Inst. Min. Met., 1948.*

‡It is still open to question whether the irruptive was folded into a syncline, along with the Whitewater series, or was intruded after the syncline had formed.
See: Cooke, H. C., "Structural Geology of Canadian Ore Deposits", *Bull. Can. Inst. Min. Met.*, p. 588, 1948.
Yates, A. B., "Structural Geology of Canadian Ore Deposits", *Bull. Can. Inst. Min. Met.*, p. 601, 1948.

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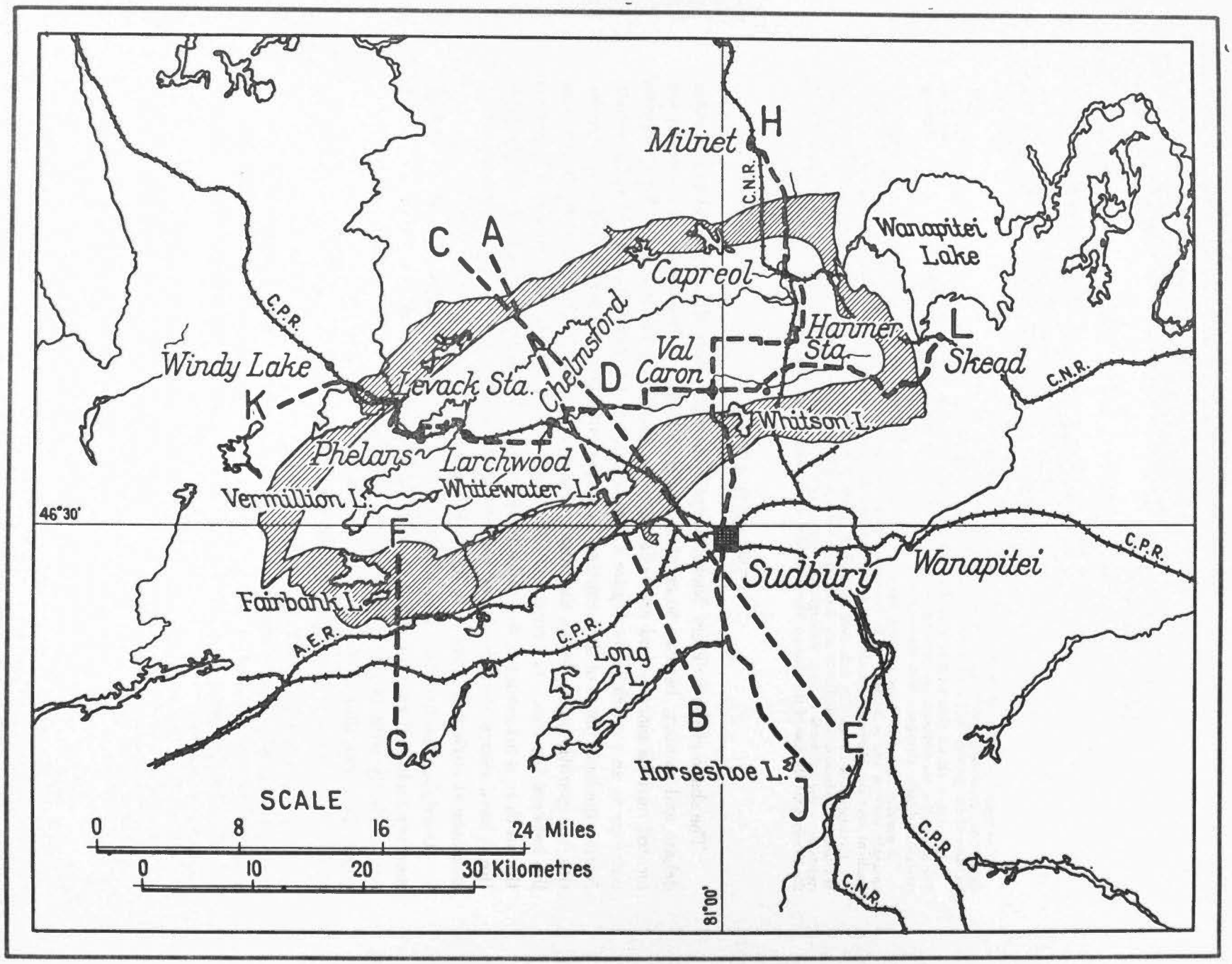


FIGURE 1. Location Map.

suggested to the newly established committee on Research in the Geological Sciences† that geophysical surveys, gravimetric and seismic, might profitably be employed to throw some light on the problem.

In agreement with this proposal the Dominion Observatory made some 340 gravity measurements in the area during the summer of 1948. Since then, in connection with other gravimeter programs, other observations were taken to increase the total number of stations to about 500. The stations are distributed over an area of about 2,000 square miles. The greatest density of stations is in the vicinity of the basin; here automobile transport was used and measurements were taken at $\frac{1}{2}$-mile intervals along most of the passable roads. About 20 gravimeter stations were established in the outlying regions using aircraft transportation. Through the courtesy of the superintendents of the Canadian Pacific and Canadian National railways, measurements were taken at sites along all railway lines radiating from Sudbury. Transportation was by train and "way" freights which stopped for three to five minutes at various railway stations along the way. Complete coverage of the area so far has not been possible and a much denser network is required to outline with certainty the smaller features of the gravitational field. Nevertheless, the existing distribution provides a general knowledge of the major trends and will serve as a basis for more detailed study in the future.

In the following section the results of the gravity measurements are presented and the more pronounced anomalies examined in relation to the larger geological formations. The gravity anomalies for certain hypothetical geological sections of the basin are given and compared with the observed anomalies.

COMPUTATION OF THE GRAVITY ANOMALIES

The principal facts for the gravity stations are tabulated in the Appendix. Although both Bouguer and Free Air anomalies are listed, only the former have been used in the geological interpretation which follows. The Free Air anomalies have been included for their use in geoidal and isostatic investigations. The Bouguer anomalies shown on the accompanying maps and profiles are based upon an adopted value* of 980·684 cm. per sec^2 for gravity at the Sudbury pendulum station and for the gravimeter station just outside the building (the Technical High School). In the Table of Principal Facts, however, the observed values of gravity and the anomalies have been adjusted to agree with recent gravimeter comparisons‡ which give 980·6860 cm. per sec^2 for Sudbury. Accordingly the anomalies in the Table are all 2 milligals greater than those shown on the gravity maps, but such systematic differences will have no bearing on the geological interpretation of the results.

The anomalies are based upon the International Formula of 1930 for normal gravity, γ_0, at sea level.

$$\gamma_0 = 978\cdot049\ (1 + 0\cdot0052884 \sin^2 \phi - 0\cdot0000059 \sin^2 2\phi$$

where ϕ is the latitude. The Bouguer correction for the height of the station is given by

$$(0\cdot09406 - 0\cdot0128\ \sigma)\ \text{H.mgls.},$$

† *Bull. Can. Inst. Min. Met., 1946.*
* Miller, A. H., *Publications of the Dominion Observatory*, Vol. XI, No. 4, p. 96. 1936.
‡ Innes, M. J. S., and Thompson, L. G. D., *Publications of the Dominion Observatory*, Vol. XVI, No. 8, 1953.

where σ is the mean density of the rock in gms per cm³ and H is the height of the station in feet above mean sea level. Consistent with other regional investigations a constant average value of 2·67 gms per c.c. has been assumed for the rock density for the entire area. It is shown in the next section that there is considerable variation in density among the rock types present and that the mean density may be closer to 2.74 gms per c.c. If so, the resulting error in the Bouguer anomalies would be about 0·8 milligals. The greater part of such an error, however, is systematic, as the heights of stations vary from about 600 to 1,300 feet with a mean height of 850 feet.

The accuracy of the anomalies also depends upon the accuracy of the gravity measurements and how well the position and heights of stations have been determined. Repeated measurements have shown that the observed gravity values are reliable to one-tenth of a milligal. The elevations were obtained whenever possible from bench marks and railway elevations. For most of the stations, however, aneroid altimeters were employed. Repeated observations have indicated that errors in elevation are not likely to exceed 8 feet, which is equivalent to an error of about 0·5 milligals. The position of the gravity stations were, for the most part, scaled from maps with scales of one mile and two miles to an inch, and errors from this source are estimated to be less than 0·1 milligal. Apart from possible systematic errors mentioned above it is believed that the maximum error from all sources does not exceed 0·7 milligals.

The map enclosed at end of paper shows the gravity stations and Bouguer anomalies in units of 1×10^{-4} C.G.S., or tenths of milligals. Contours are drawn at intervals of 25 of these units, or 2·5 milligals, where the gravity stations are more dense, otherwise a contour interval of 10 milligals has been chosen.

DENSITY OF ROCK FORMATIONS

To interpret the variations of the Bouguer anomaly the densities of the underlying rock formations must be known with fair accuracy. During the course of the gravity measurements 160 rock samples were gathered from outcrops near the sites of the gravity stations. Their densities, which were later measured in the laboratory, are summarized in Table 1.

Although much care was taken to obtain a representative selection of unweathered samples from each formation, there is considerable variation among the densities within each group. The standard deviation of the mean value for each formation is included in the table and provides a measure of the uncertainty in applying these measurements of density. The sedimentary formations provide the most consistent sets with deviations ranging from 0·03 to 0·06 gms/cm³. Although not altogether unexpected, the volcanic rocks, basic intrusives and the Killarney granites and gneisses show quite large variations in density, with deviations ranging from 0·07 to 0·12 gms/cm³. The large variations in the density of the granites (from 2·54 to 3·15 gms per c.c.) from this district have previously been reported by Garland*.

Examination of the table shows that the mean densities of the formations fall roughly into three density ranges. The lowest density group, 2·60 to 2·70 gms per c.c., consists of the Chelmsford and Onwatin formations of the Whitewater series, the Cobalt and

* Garland, G. D., *Publications of the Dominion Observatory*, Vol. XVI, No. 1, p. 48.

Bruce sediments with the exception of the McKim formation and some of the sediments of the Stobie group. Included also in this group of low density rocks are specimens of the early Precambrian granites (Birch Lake and Levack granite) which lie to the north and northwest of the basin.

TABLE 1

SUMMARY OF DENSITY MEASUREMENTS

Formation		Mean Density	Standard Deviation of Mean	Number of Determinations
		gm/cm³	gm/cm³	
Quartz Diorite		2·83	—	1
Granite and Granite Gneiss (Killarney, Creighton)		2·74	0·12	42
Norite Irruptive	*(a)* Micropegmatite	2·72	0·04	7
	(b) Transition zone	2·92	0·03	3
	(c) Norite	2·87	0·09	10
Whitewater Series	*(a)* Chelmsford formation	2·65	0·05	5
	(b) Onwatin formation	2·61	0·03	5
	(c) Onaping formation	2·74	0·08	11
Nipissing Diabase		2·84	0·09	9
Cobalt Series	*(a)* Lorraine Quartzite	2·83	—	1
	(b) Gowganda formation	2·68	0·06	5
Bruce Series	*(a)* Serpent Quartzite	2·62	—	1
	(b) Espanola formation	2·65	—	1
	(c) Mississagi Quartzite	2·62	0·04	17
	(d) McKim formation	2·74	0·03	6
	(e) Copper Cliff Rhyolite	2·61	0·07	4
Granite and Granite Gneiss (Levack, Birch Lake)		2·66	0·04	10
Stobie Group	*(a)* Greywacke and Quartzite	2·68	0·06	3
	(b) Basic lavas	2·90	0·11	17

The next density range, 2·70 to 2·80 gms. per c.c. includes the Onaping and McKim formations, the micropegmatite member of the Sudbury irruptive and the granitic rocks (Creighton granite, Killarney granite and gneisses) found to the southeast of the basin. The highest density range, 2·8 gms. per c.c. and greater, includes the norite and transition zone rocks of the Nickel irruptive, the Nipissing diabase and the basic lavas of the Stobie group lying along the south side of the basin.

A graphical representation of the data in Table 1 is given in Figure 2. The mean density of each formation is plotted along with the corresponding mean Bouguer anomaly, and clearly shows that the anomalies are largely due to the rocks which outcrop.

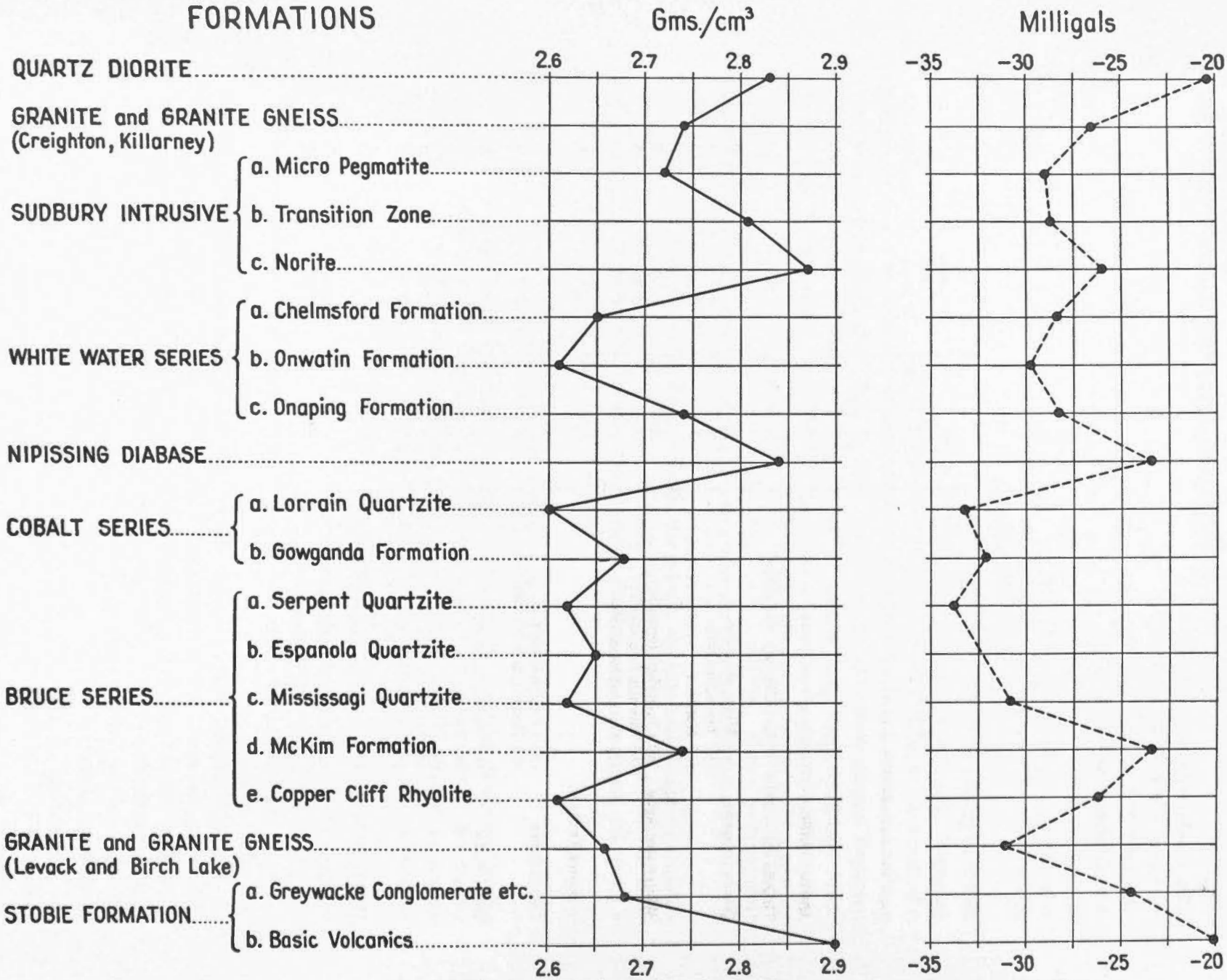
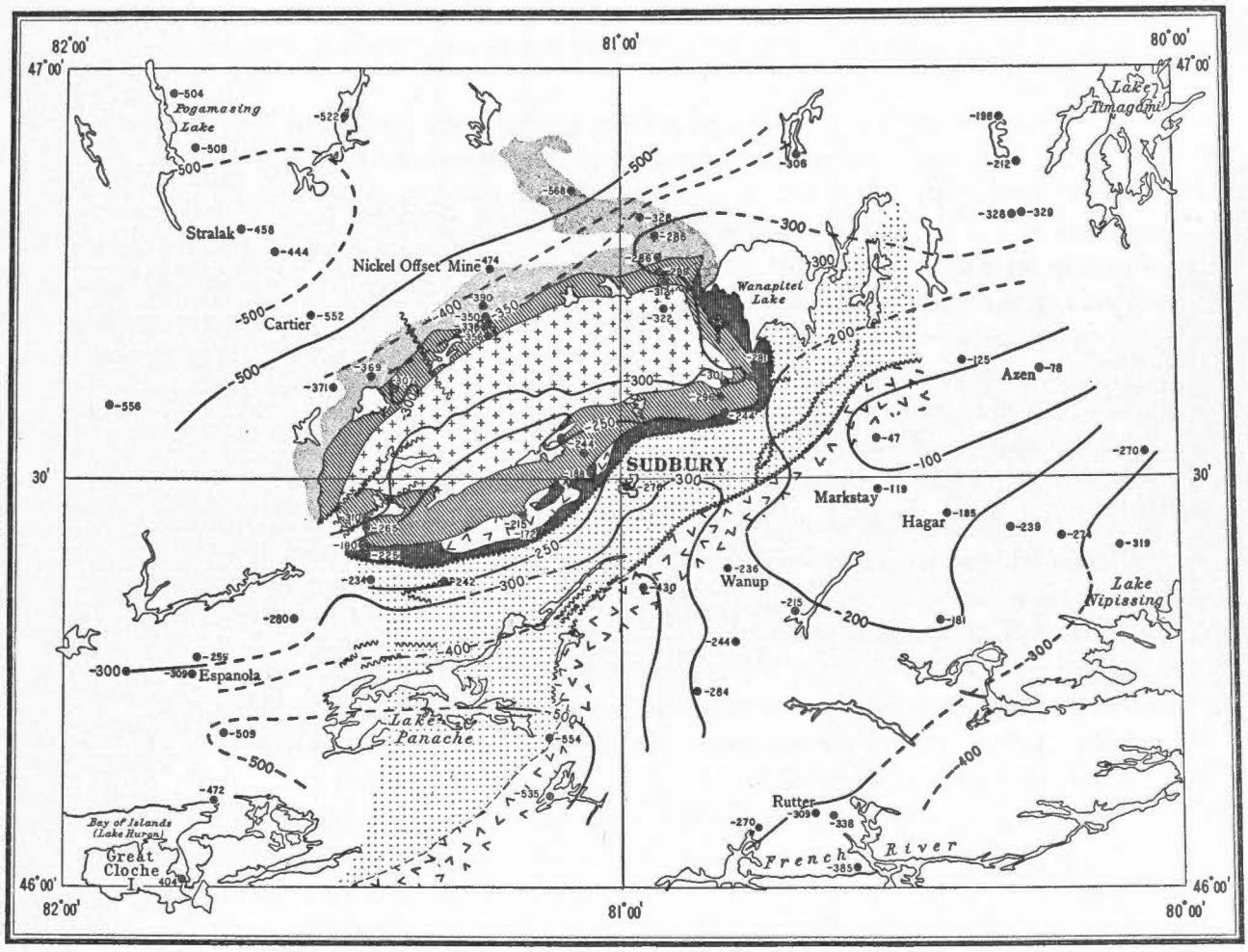


FIGURE 2. Graphical representation of mean gravity anomalies and mean formation densities at 160 stations in the vicinity of Sudbury.

GENERAL FEATURES OF THE GRAVITY FIELD

Figure 3 is a geological sketch map of the surveyed area, and on it contours of the Bouguer anomalies are drawn at 10 mgl. intervals (100 gravity units of 1×10^{-4} C.G.S.). The anomalies have a range of about 53 mgls. over the area and if the variable density distribution of stations is considered the mean anomaly is not very different from -32 mgls.



GRAVITY ANOMALIES and GENERAL GEOLOGY

in the

VICINITY OF SUDBURY

ONTARIO

SCALE OF MILES

8 4 0 8 16 24 32

LEGEND

- .....Later Granite
- Sudbury Irruptive
- .....Whitewater Series
- .....Huronian (Cobalt, Bruce)
- .....Granite

LEGEND

- Stobie Group.....
- Fault .....
- Gravity Station and Bouguer Anomaly in Units of 1×10^{-4} c.g.s. ....●-341
- Gravity Contours —250

FIGURE 3. Sketch map of Sudbury area showing general geology and gravity anomalies.

The whole area can be roughly divided into four sections corresponding to different anomaly ranges that for the most part are directly related to the surface densities. The largest variations in the anomalies from their general average are for stations outside of the basin. To the northwest the anomalies are all generally low ranging from −40 near the northern side of the basin to −57 mgls. farther north. The prevailing rocks are the Birch Lake and Levack granites and gneisses† which are found to have densities lower than the average for the whole district (*see* Table 1). The slightly greater anomalies for two stations in the area near Stralak are believed due to a narrow belt of underlying basic volcanic rocks.

Killarney granite and granite gneiss form a large body south and southeast of the fault which limits the southeastern boundary of the Huronian rocks. In this region the gravity anomalies are quite variable and range from −50 mgls. in the west to a maximum amplitude of −5 mgls. about four miles north of the village of Markstay. This high was previously reported by Garland* and, on the assumption of a uniform density for Precambrian granites and gneisses, was interpreted as the gravitational effect of a deep-seated anticline at the base of the granitic layer. However, some forty specimens of granite rocks from this area (*see* Table 1) showed wide variations in density ranging from 2·59 to 3·15 gms. per c.c. which can be directly correlated with the variation of the Bouguer anomaly. Analysis shows that about 70 per cent of the variance in the anomalies can be accounted for by differences in the densities within these granite masses.

The Bouguer anomalies to the southwest near Lake Panache have amplitudes of about −50 mgls. These, as can better be seen from the closely spaced contours on the gravity map, increase uniformly over a distance of about 10 miles towards the southern edge of the basin. In this region the surface exposures are chiefly Mississagi quartzite of low (2·63 gms. per c.c.) density and scattered sill-like masses of Nipissing diabase. The latter, although of comparatively high density (2·87 gms. per c.c.) appears to have little control over the general trend of the anomalies and the steep gradient of gravity persists to the north regardless of its distribution.

The mean Bouguer anomaly for the basin and proximity is about −30 mgls., not much different from the mean anomaly for the whole survey. Probably the most significant feature of the anomaly pattern is that the contours tend to parallel the general strike of the geological formations with higher values of gravity to the south due to the greater thickness of the norite and to the basic volcanics of the Stobie group which form a band about 2 miles wide along the south side of the basin. These and other relationships are discussed in more detail in the following sections.

CALCULATED ANOMALIES ACROSS THE BASIN

To help in the analysis of the observed anomalies, the attraction was calculated for a hypothetical northwest-southeast section of the basin, corresponding to its minor axis. The structure assumed was according to Collins'** conception, which is the one generally

† *Geol. Surv., Canada,* Map Sheet 871A.

* Garland, G. D., *Publications of the Dominion Observatory,* Vol. XVI, No. 1, pp. 1-58, 1950.

** Collins, W. H., and Kindle, E. D., "The Life History of the Sudbury Nickel Irruptive II", *Trans. Roy. Soc. Can.,* pp. 27-38, 1935.

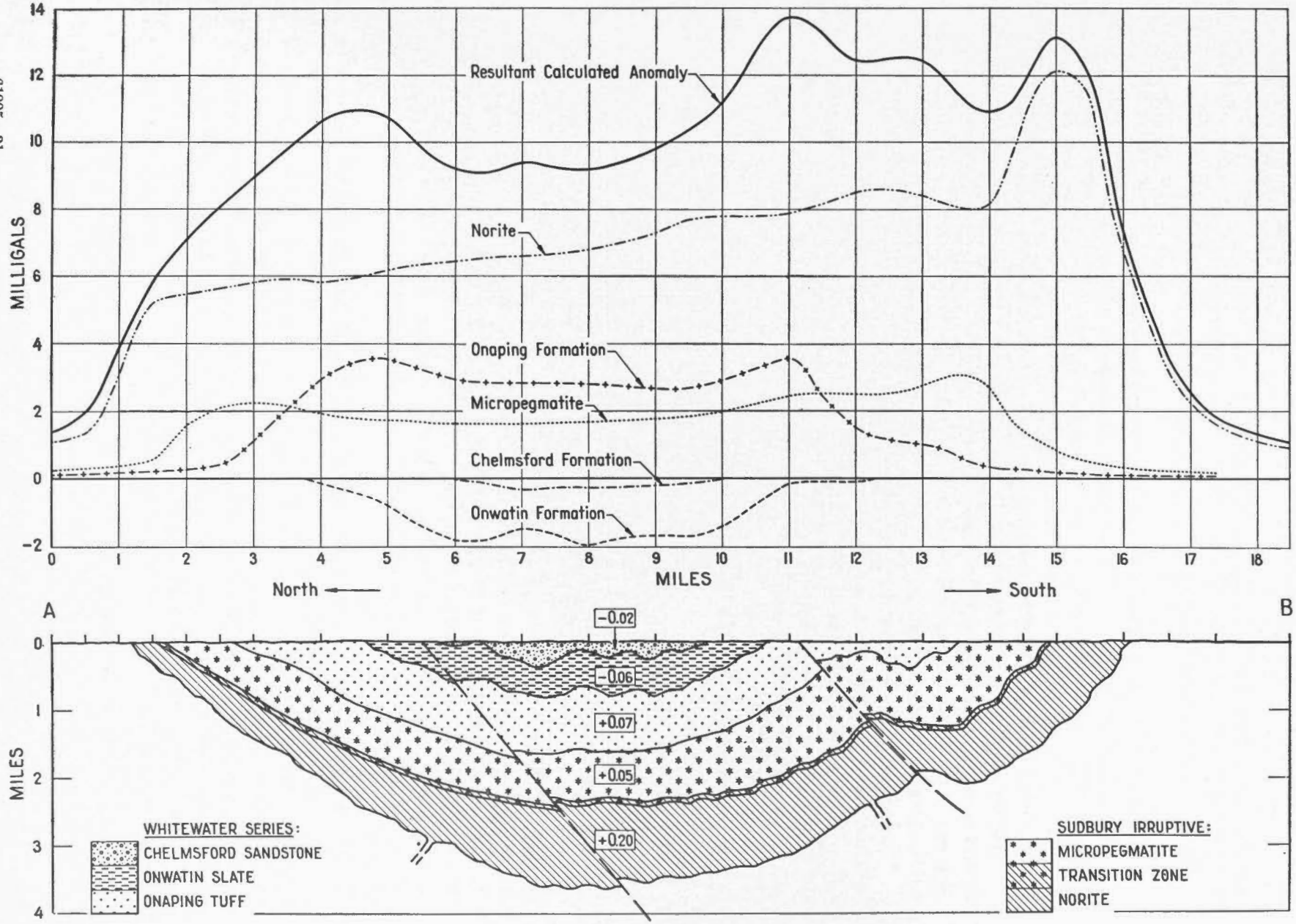


FIGURE 4. Vertical cross-section of Sudbury Nickel irruptive and overlying Whitewater series (after Collins and Kindle) along section line (A-B) shown in Figure 1. The gravitational attraction of each formation and the resultant attraction of the whole section is illustrated.

accepted by most geologists*. Along with his section (line A-B, location map Figure 1) which is reproduced in Figure 4, the calculated values of gravity are given for each phase of the irruptive, for each formation of the Whitewater series, and for the structure as a whole.

The densities employed in the calculations are indicated for each formation and are relative to an assumed value of 2·67 gms. per c.c. for the rocks underlying and surrounding the basin. This value was estimated from the densities in Table 1 and corresponds to the mean density found for the Huronian rocks (the Cobalt and Bruce series) and the Levack and Birch Lake granites, roughly weighted according to their distribution.

Inspection of the curves shows that the norite largely controls the amplitude and general trend of the resultant calculated anomalies. The highs due to its emergence at each end of the section are apparent, as well as the gradual increase in amplitude due to a thickening of the norite from north to south.

The Onaping volcanics produce nearly twice the gravitational effect that the micropegmatite does, not only because of its slightly greater density, but chiefly because the formation as a whole is not as deep. The near surface effects of the Onaping formation are conspicuous in the resultant curve between Miles 4 and 5 and at Mile 11; here the gravity anomalies reach peak values, while the general decrease in gravity over the central portion of the basin is due to the near surface Chelmsford and Onwatin formations, both having densities lower than the other formations.

DISCUSSION OF RESULTS

(a) *Comparison of Observed and Calculated Anomalies*

The observed and calculated gravity anomalies, and geological section† for the profile C-D-E are shown in Figure 5. This profile lies about 2 miles to the east and is nearly parallel to Collins' section shown in Figure 4. The zero or normal value of the computed anomaly curve has been assumed equivalent to a normal value of −40 mgls. on the observed anomaly curve, since the latter reaches this value for stations over the granite masses at both the north and south ends of the profile. The curve I-II-III is the anomaly profile calculated for the irruptive and overlying Whitewater series while I-II-IV includes an estimate of the attraction of the series of formations lying south of the norite between Miles 19 and 23.

There is a striking similarity in the form and amplitude of the computed and observed anomaly profiles, which strongly suggests that the anomaly producing body is similar in form and dimensions to that deduced by Collins from geological considerations. To the north (Mile 3) both observed and calculated curves rise sharply to equal heights over the norite. They diverge over the next few miles and merge again at Mile 10 near the centre of the basin. This departure (a maximum of 4 mgls.) may be due partially to the displacement of the formations by the Sandcherry Creek fault that parallels the gravity profile between Miles 3 and 7 and intersects it near Mile 5. Over the central portion of the

* Cooke, H. C., "Structural Geology of Canadian Ore Deposits", *Bull. Can. Inst. Min. Met.*, p. 585, 1948.

†The geological sections shown in Figures 5, 6, 7 and 8, are somewhat generalized. Although the formations to the south of the norite may have dips somewhat different than shown, they are all steeply dipping. Contacts of the formations were taken from *Geol. Surv., Canada*, Maps 292A, 871A, 872A, and from Collins, W. H., *Bull. Geol. Soc. Am.*, Vol. 47, 1936.

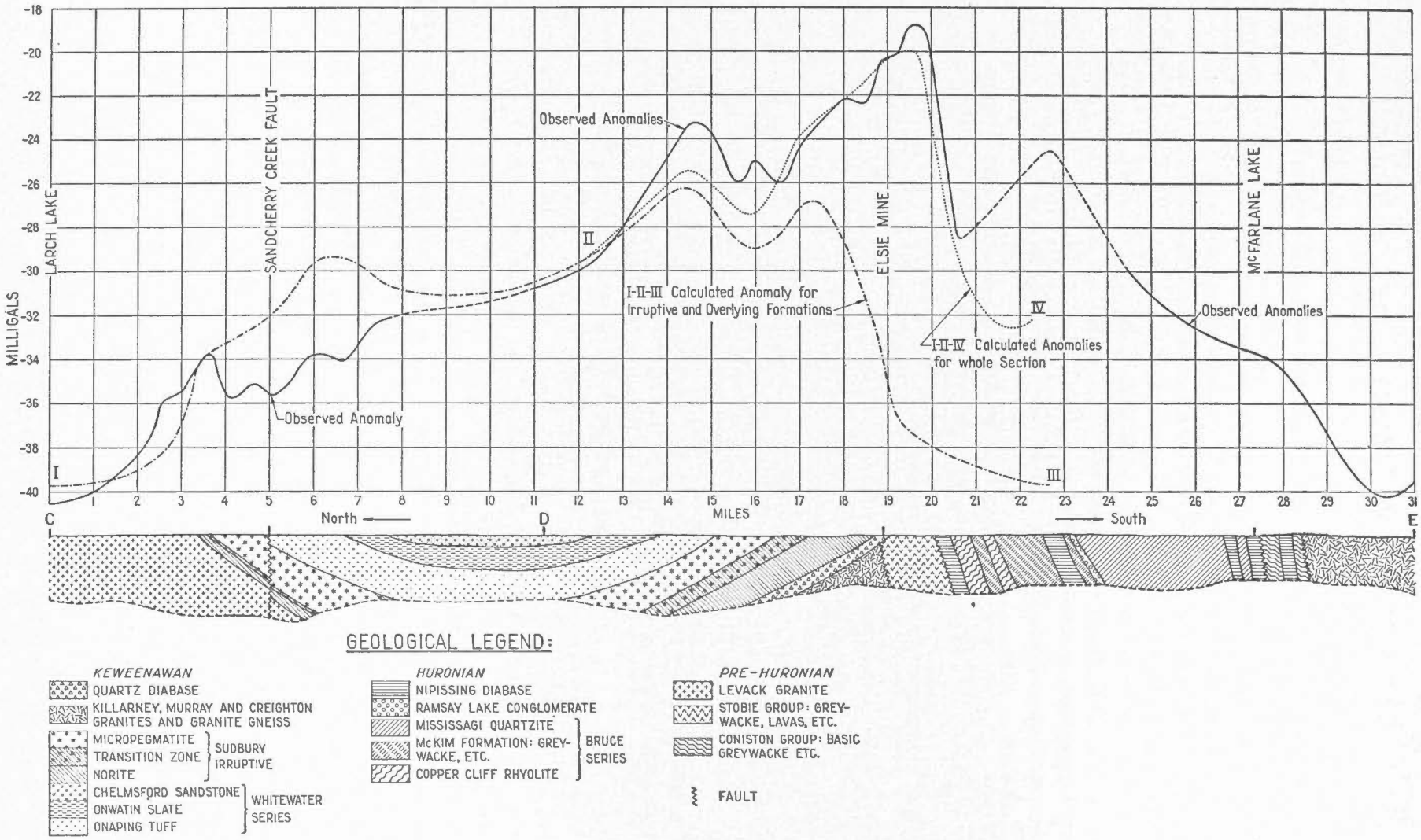


Figure 5. Generalized geological section and observed and computed anomalies along section line C-D-E shown in Figure 1.

basin the curves have the same general trend and amplitude and both reach peak values coincident with the Onaping formation between Miles 14 and 15. Continuing to the south the anomaly curves both decrease over the micropegmatite (Mile 16) and both rise again over the norite at Mile 17.

Here the similarity between the observed anomalies and those calculated for the irruptive and overlying formation ends. The latter decreases to zero amplitude while the former continues to rise to a maximum over the Stobie group of sediments and basic volcanics between Miles 19 and 20. The profile I, II, IV shows the anomalies calculated for the whole geological section south to Mile 23, assuming the dips as illustrated and densities from Table 1. To bring the calculated profile into near coincidence with the observed anomalies, as shown, it was necessary to assume depths of 12,000 feet for the Stobie formation and the Nipissing diabase, and 7,000 feet for the McKim and Copper Cliff formation.

(*b*) *The Shape of the Irruptive at Depth*

These calculations show that the peak observed anomaly over the Stobie formation can be fully accounted for by what may be reasonable assumptions for the depth of the Stobie and for other formations to the south. The calculations, however, do not deny other possible interpretations. While there is little doubt that the greater part of the peak anomaly is due to the Stobie formation, part of the effect may be due to a greater thickness of the intrusive than has been assumed, or the expression of large underground channels through which the irruptive rose.

Indeed there is much to be said for the latter possibility. Cooke* concludes that faulting along the whole southern boundary has brought the Stobie rocks from depth into their present position. Although this faulting post-dates the intrusion of the norite, it may be that an earlier break along this zone played a major role in controlling the rise of the irruptive.

There is little evidence from the gravity measurements to support Coleman's conception of the configuration of the nickel irruptive at depth. He suggested that the irruptive was intruded as a large laccolithic sheet and that its present form resulted from collapse following the intrusion. He supposed that "the source of the magma was immediately beneath the longer axis of the area . . . " and that "the fissure from which the molten rock came was probably somewhat curved, being concave to the northwest . . . " (*see* coloured frontispiece, Coleman†, 1905). In the frontispiece referred to, this fissure is only vaguely defined and of indefinite dimensions, but appears to be a few miles in width. Assuming that below the main norite mass as shown in Figure 4, the channel through which the irruptive rose is a wedge-shaped fissure extending along the main axis, and tapers to a width of a fraction of a mile at great depth, such a configuration for the irruptive would produce about twice the anomaly over the basin than has been observed. Alternatively a funnel-shaped body 5 miles in diameter at the base of the main norite body and tapering to a stock or neck 1 mile in diameter at a depth of 7 miles would produce an additional anomaly of about 5 mgls. The gravity measurements would reveal either of these possibilities if they existed.

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*Cooke, A. H., "Structural Geology of Canadian Ore Deposits", *Bull. Can. Inst. Min. Met.*, p. 587, 1948.
†Coleman, A. P., *Ont. Bur. Mines*, vol. XIV, Pt. III, p. 12 ,1905, and *J. Geol.*, vol. XV, p. 763, 1907.

On the other hand if the magma rose through a single channel in the form of a cylindrical neck or plug 1 mile in diameter, and extending to great depth below the main body of the intrusive, the effect of such a body at the surface would be less than one-half a milligal and indistinguishable from other effects.

It may therefore be concluded, that although gravity measurements are incapable of outlining conduits below the main body of the irruptive should they have diameters of 1 mile or less, they deny the existence of a fissure or neck having the dimensions suggested by Coleman and others. The most probable location of the channel through which the irruptive rose would seem to be along the southern boundary.

Finally it should be emphasized that good agreement between observed and computed effects is not always conclusive evidence for the reality of the structure assumed for the calculations. Uniqueness of gravity interpretation depends upon the number of auxiliary aids available. In this investigation, we have a fair knowledge of the surface densities, the position of the geological contacts and the dips of the formations. While these all provide some measure of control and limit the number of possible solutions, they are insufficient to permit unique interpretation.

It is clear from Figure 4 that within the limits imposed by the controls just mentioned, an overall change in the magnitude of the resultant anomaly curve could result from variations in the thicknesses of any one of the formations. It is therefore impossible from the existing data to refine the estimate already given for the configuration of the irruptive at depth. On the other hand, a seismic profile across the basin, if sufficient velocity contrast between the formations is found to exist, might provide the necessary control to remove some of the ambiguity from this interpretation of the gravity measurements.

OTHER RELATIONSHIPS

No further quantitative analysis of the anomalies has been attempted. Referring again to Figure 5, to the south of the Stobie, the observed values drop sharply over the less dense Copper Cliff formation and rise to a secondary peak near Mile 23, presumably due to the Nipissing diabase. From here to the fault separating the Huronian rocks from the Coniston group and the Killarney granites and gneisses, the anomalies decrease; south of the fault the gradient is somewhat steeper and the anomalies reach their minimum value in a distance of 2 miles.

As mentioned in a previous section the magnitude of the anomalies over the Mississagi formation is greater than one would expect considering its lower than average density. However, the steep gradient to the north over the Mississagi, persists the full length of the basin; this is clearly demonstrated by the closely spaced contours in Map 1, and by Figure 6 which is a north-south profile to the west, over nearly the same succession of rocks as shown in Figure 5. Although the gradient could be the reflection of heavy masses at great depths to the south of the norite, it can be fully accounted for by the McKim and Ramsay Lake conglomerate formations, should they be underlying and dipping to the south at a somewhat smaller angle than illustrated. This interpretation which is synonymous with the statement that the Mississagi formation thins to the north is in agreement with Collins'* description of the Mississagi and with Cooke** who described the general

*Collins, W. H., *Geol. Surv., Canada Mem. 143*, p. 44, 1925.
**Cooke, H. C., *Geol. Surv., Canada Bull. 3*, p. 37, 1945.

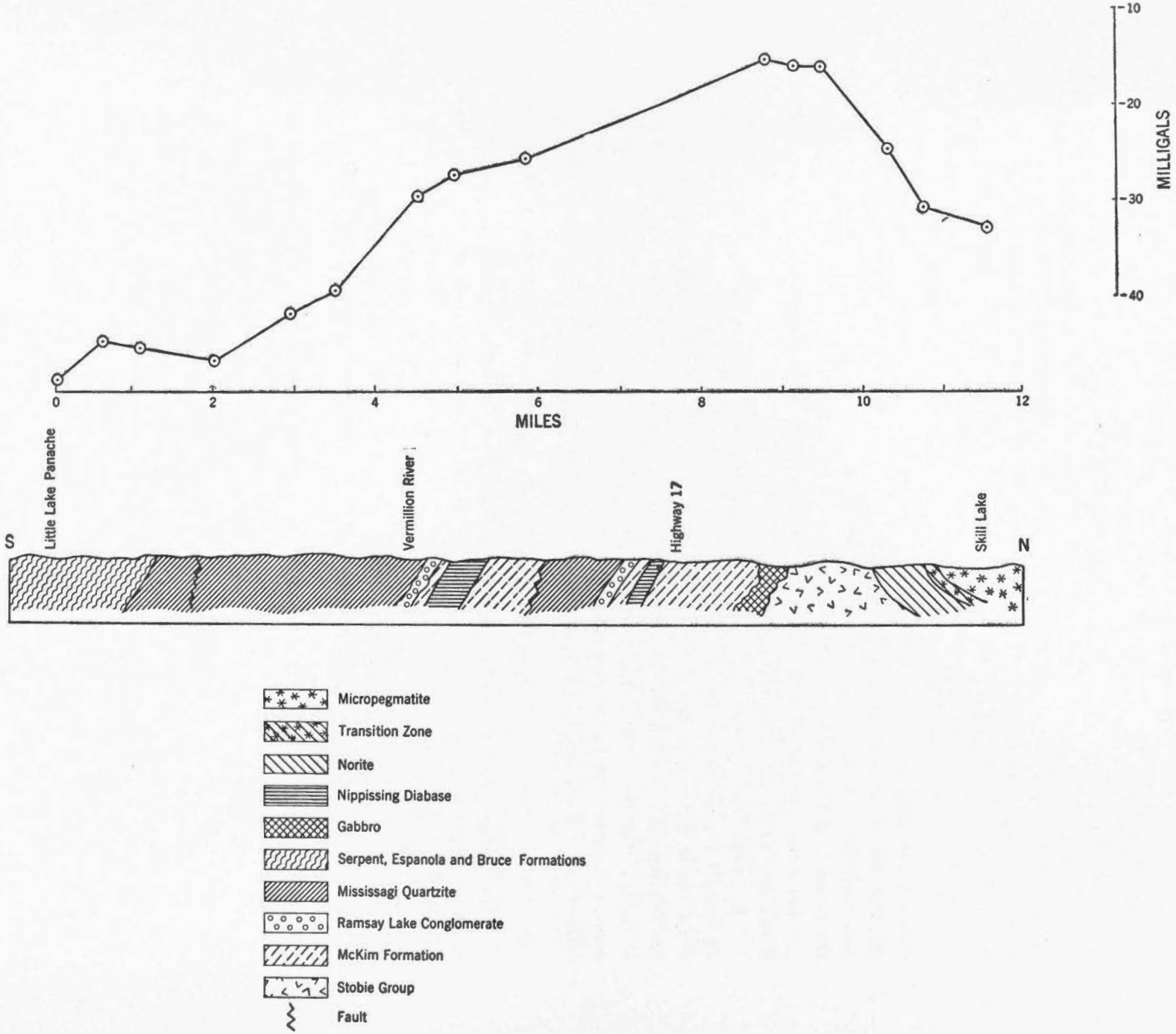

FIGURE 6. Gravity anomalies and geological section for the traverse (F-G) shown in location map.

structure of the McKim formation as that of a homocline facing to the south or southeast. From Lake Panache, to the north, the average change in gravity over the Mississagi is about 15 mgls. and for a density contrast of 0·1 gms. per c.c. could represent a thinning to the north of about 10,000 feet.

Figure 7 shows the observed gravity anomalies from observations along the highway between Milnet to the northeast of the basin and Sudbury and along the road south of Sudbury to Horseshoe Lake. The general trend of the anomalies is much the same as before with maximum values to the south. More conspicuous, however, is the low over the centre of the basin near Mile 24 where the anomalies are about four mgls. lower than over the corresponding position along the section on Figure 5. It may also be observed from Map 1 that about 3 miles north of this location the anomalies are smaller still with a minimum amplitude of about −38 mgls. While a general decrease in the anomalies could be the expression of an overall thinning of the irruptive, these variations occur over relatively short distances which suggests a more shallow origin.

The structure of the Whitewater sediments, usually referred to as a basin-shaped syncline, is more aptly described as a complex synclinorium.† Coleman†† describes the Chelmsford sandstone‡ as forming a succession of anticlines parallel to the principal axis of the main structure, and that "the synclines between the anticlinal hills are always buried so that a complete fold is never seen". For one location he estimates the total height of the fold (from trough to crest) to measure 400 to 500 feet, which implies a depth of over 200 feet of drift* between the anticlinal ridges. The gravity minima referred to in the previous paragraph are in a drift covered area partly underlain by Chelmsford sandstones and partly by Onwatin slates. They may reasonably be interpreted as reflecting the combined effect of the folding described above and the varying thicknesses of overburden, since 200 feet of drift, suitably distributed, can produce an anomaly of more than 2 mgls.

Finally, it will be noticed that the gravity maximum over the norite to the north is both higher and broader than over the corresponding portion of the section shown in Figure 5. These differences are believed due to the greater thickness of the norite on this section (seven-tenths of a mile compared to three-tenths of a mile in the section of Figure 5) and to the variation in density within the granite masses to the north of the norite. These granites have variable densities (*see* Figure 7) which increase all the way from Milnet, south to the norite contact.

Figure 8 is an east-west profile over the basin between Skead to the east through Hanmer, Chelmsford and Larchwood to Levack to the west. The variation in the gravity anomalies are for the most part what one would expect from the relationships developed in the previous sections. The anomaly curve rises sharply from a minimum over the granite to the west of Levack with peak values over the norite and Onaping formations. With minor variations higher values occur across the full length of the basin. Since this profile follows the highway, the variations from the general trend are largely due to the

†Yates, A. B., "Structure of Canadian Ore Deposits", *Bull. Can. Inst. Min. Met.*, pp. 596-617, 1948.

††Coleman, A. P., *Ont. Bur. Mines*, vol. XIV, pp. 96-99, 1905.

‡Burrows, A. G. and Rickaby, H. C., *Ont. Dept. Mines*, vol. XXXVIII, Pt. III, 1929.

*Interpretation of geophysical results showed that the depth of glacial drift at Falconbridge ranges from 80 to 180 feet.—Slichter, L. B., *Geophysical Prospecting*, 1929.

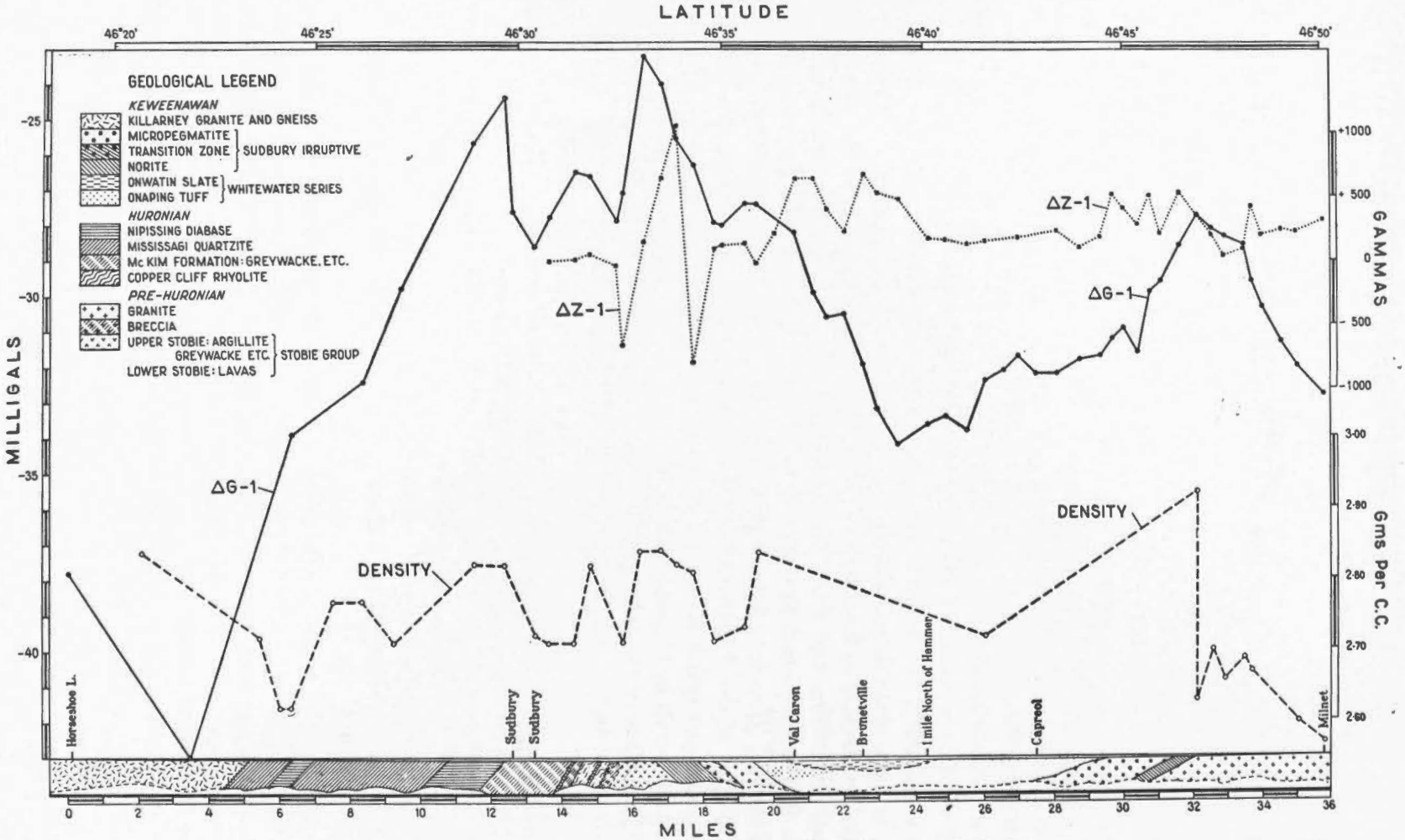

FIGURE 7. Gravity anomalies (△G) and vertical magnetic anomalies (△Z), for the north-south traverse (H-J) along the highway between Milnet and Sudbury and on the road south to Horseshoe Lake.

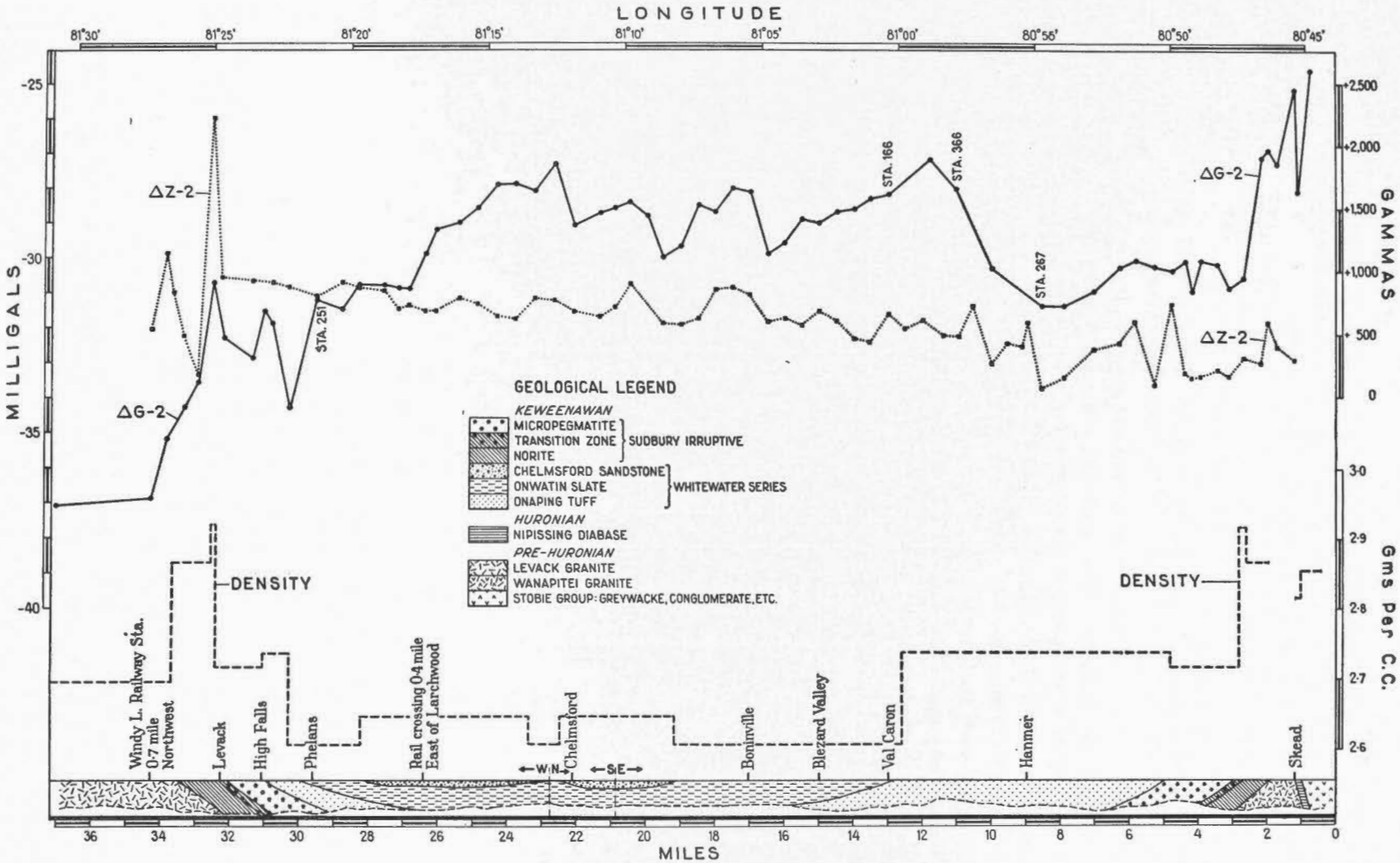

FIGURE 8. Gravity anomalies (ΔG) and vertical magnetic anomalies (ΔZ), along the highway traverse (K-L) between Levack to the east and Skead to the west.

relative proximity of the Stobie-norite masses to the south. The high to the east is believed to be controlled by large inclusions of metamorphosed Stobie rocks within the Wanapitei granite* which forms a large body to the east of the norite.

MAGNETIC MEASUREMENTS

Observations of the vertical magnetic intensity over the basin were limited to the two profiles illustrated in Figures 7 and 8. The observations were made in 1948 by G. D. Garland, with an Askania magnetometer and are referred to the Dominion Observatory magnetic station at Sudbury. The maximum anomalies on both profiles occur over outcrops of the irruptive, the greatest peak occurring near Levack (*see* Figure 8) and having an amplitude of nearly 2,200 gammas. Lesser anomalies occur over the Onaping formation. Still smaller anomalies but amounting to as much as 500 gammas, a considerable anomaly, occur over the Onwatin and Chelmsford formations. Apart from these variations, whose steep gradients suggest a surface, or near surface origin for the anomaly producing bodies, there is little or no evidence from the magnetic results to indicate the kind of structure one would expect from geological considerations of the area.

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*Cooke, H. C., *Geol. Surv., Canada, Bull. 3*, p. 51, 1946.

APPENDIX

PRINCIPAL FACTS FOR GRAVITY STATIONS

Station		Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name							Free Air	Bouguer
		°	′	°	′	Ft.			
1	Hagar	80	25·0	46	27·3	691	980·7028	0·0071	−0·0164
2	Sudbury	81	00·0	46	29·8	881	·6860	·0044	− ·0256
3		80	59·1	46	29·6	874	·6893	·0074	− ·0224
4		80	59·3	46	30·7	845	·6893	·0030	− ·0258
5		80	59·0	46	31·3	876	·6897	·0054	− ·0245
6		80	59·2	46	31·7	910	·6881	·0064	− ·0246
7		80	58·8	46	32·3	913	·6875	·0052	− ·0259
8		80	58·9	46	32·5	948	·6866	·0072	− ·0251
9		80	58·9	46	33·0	967	·6900	·0117	− ·0212
10		80	59·0	46	33·4	978	·6892	·0113	− ·0220
11		80	59·1	46	33·8	965	980·6891	0·0094	−0·0235
12		80	59·3	46	34·2	969	·6886	·0087	− ·0243
13		80	59·6	46	34·7	993	·6864	·0080	− ·0259
14		81	00·3	46	34·9	982	·6872	·0075	− ·0260
15		81	00·6	46	35·4	976	·6889	·0079	− ·0254
16		81	00·4	46	35·7	1,005	·6876	·0089	− ·0254
17		81	00·5	46	36·1	940	·6918	·0063	− ·0258
18	Val Caron	81	00·5	46	36·6	931	·6927	·0056	− ·0262
19		81	00·5	46	37·1	927	·6919	·0037	− ·0279
20		81	00·5	46	37·3	925	·6916	·0029	− ·0286
21		81	00·5	46	37·8	930	980·6922	0·0032	−0·0285
22		81	00·5	46	38·2	939	·6909	·0021	− ·0299
23		81	00·5	46	38·6	940	·6901	·0008	− ·0312
24		81	00·5	46	39·2	955	·6891	·0003	− ·0322
25		80	59·9	46	39·2	957	·6897	·0011	− ·0315
26		80	59·2	46	39·2	960	·6894	·0011	− ·0316
27		80	58·5	46	39·2	955	·6894	·0007	− ·0319
28		80	57·9	46	39·2	957	·6903	·0017	− ·0309
29		80	57·3	46	39·2	985	·6895	·0035	− ·0300
30		80	58·9	46	31·3	863	·6906	·0051	− ·0243
31		80	58·4	46	31·3	866	980·6896	0·0043	−0·0252
32		80	57·8	46	31·3	868	·6996	·0046	− ·0250
33		80	57·1	46	31·3	872	·6889	·0043	− ·0254
34		80	56·5	46	31·3	875	·6883	·0039	− ·0259
35		80	56·7	46	39·2	973	·6906	·0036	− ·0296
36		80	56·1	46	39·0	971	·6902	·0033	− ·0298
37	Hanmer Station	80	55·5	46	39·1	969	·6919	·0046	− ·0284
38		80	55·5	46	39·6	975	·6891	·0016	− ·0316
39		80	55·3	46	39·9	976	·6895	·0017	− ·0316
40		80	55·2	46	40·3	975	·6903	·0018	− ·0314
41		80	55·0	46	40·9	985	980·6903	0·0018	−0·0318
42	Capreol	80	55·8	46	42·6	1,004	·6932	·0040	− ·0302
43		80	55·1	46	41·3	992	·6918	·0034	− ·0304
44		80	55·1	46	41·8	1,004	·6922	·0041	− ·0301
45		80	55·2	46	42·1	1,013	·6924	·0048	− ·0297
46		80	55·8	46	43·1	1,020	·6930	·0045	− ·0302

PRINCIPAL FACTS FOR GRAVITY STATIONS—*Continued*

Station		Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name							Free Air	Bouguer
		°	′	°	′	Ft.			
47	.....	80	55·5	46	43·7	1,039	·6932	·0056	− ·0298
48	.....	80	55·6	46	44·1	1,046	·6935	·0059	− ·0297
49	.....	80	55·8	46	44·4	1,022	·6959	·0057	− ·0292
50	.....	80	55·8	46	44·8	1,021	·6968	·0059	− ·0289
51	.....	80	55·8	46	45·1	1,036	980·6957	0·0057	−0·0296
52	.....	80	55·8	46	45·3	1,037	·6977	·0075	− ·0279
53	.....	80	55·7	46	46·2	1,018	·7015	·0081	− ·0266
54	.....	80	55·4	46	46·6	1,040	·7016	·0097	− ·0257
55	.....	80	55·6	46	47·3	1,061	·7008	·0099	− ·0263
56	.....	80	55·8	46	45·7	1,019	·6996	·0062	− ·0276
57	.....	80	55·6	46	46·9	1,058	·7005	·0099	− ·0261
58	.....	80	55·8	46	47·7	1,063	·7010	·0096	− ·0266
59	.....	80	56·1	46	47·9	1,059	·7006	·0085	− ·0276
60	.....	80	56·8	46	48·2	1,049	·7009	·0074	− ·0283
61	.....	80	57·1	46	48·7	1,070	980·6994	0·0071	−0·0293
62	.....	80	57·2	46	49·0	1,080	·6999	·0082	− ·0286
63	.....	80	57·6	46	49·1	1,081	·6986	·0068	− ·0300
64	Milnet.....	80	57·8	46	49·8	1,082	·6988	·0060	− ·0308
65	.....	80	55·5	46	39·3	971	·6912	·0038	− ·0293
66	.....	81	01·1	46	36·6	937	·6922	·0056	− ·0263
67	.....	81	01·7	46	36·6	934	·6920	·0052	− ·0266
68	.....	81	02·3	46	36·5	932	·6919	·0050	− ·0267
69	Blezard Valley.....	81	03·0	46	36·5	932	·6916	·0047	− ·0270
70	.....	81	03·7	46	36·5	927	·6920	·0046	− ·0269
71	.....	81	04·3	46	36·5	922	980·6916	0·0038	−0·0276
72	.....	81	04·9	46	36·5	923	·6912	·0035	− ·0279
73	.....	81	05·6	46	36·5	926	·6909	·0035	− ·0280
74	.....	81	05·6	46	36·0	905	·6927	·0041	− ·0268
75	Boninville.....	81	05·6	46	35·6	908	·6926	·0049	− ·0261
76	.....	81	06·2	46	35·6	911	·6925	·0051	− ·0260
77	.....	81	06·8	46	35·6	902	·6924	·0041	− ·0267
78	.....	81	07·5	46	35·6	906	·6923	·0044	− ·0265
79	.....	81	08·1	46	35·6	902	·6914	·0030	− ·0277
80	.....	81	08·5	46	35·6	903	·6910	·0027	− ·0280
81	.....	81	09·2	46	35·6	905	980·6920	0·0040	−0·0268
82	.....	81	09·8	46	35·6	898	·6929	·0042	− ·0264
83	Chelmsford.....	81	12·0	46	35·0	885	·6920	·0030	− ·0271
84	.....	81	10·4	46	35·6	900	·6926	·0040	− ·0266
85	.....	81	11·0	46	35·6	902	·6922	·0038	− ·0269
86	.....	81	11·0	46	34·9	898	·6916	·0039	− ·0267
87	.....	81	11·9	46	34·4	885	·6924	·0043	− ·0258
88	.....	81	11·9	46	34·1	888	·6924	·0050	− ·0252
89	.....	81	12·6	46	34·1	880	·6929	·0047	− ·0253
90	.....	81	13·3	46	34·1	885	·6918	·0041	− ·0261
91	.....	81	14·1	46	34·1	890	980·6916	0·0044	−0·0259
92	.....	81	14·7	46	34·1	889	·6916	·0044	− ·0259
93	.....	81	15·4	46	34·2	885	·6914	·0036	− ·0266
94	.....	81	16·0	46	34·2	885	·6910	·0032	− ·0270
95	.....	81	16·9	46	34·2	923	·6885	·0043	− ·0272

PRINCIPAL FACTS FOR GRAVITY STATIONS—*Continued*

Station		Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name							Free Air	Bouguer
		°	′	°	′	Ft.			
96	.....	81	17·2	46	34·3	880	·6905	·0021	− ·0279
97	.....	81	17·8	46	34·8	879	·6904	·0011	− ·0289
98	.....	81	18·2	46	35·2	879	·6910	·0011	− ·0289
99	.....	81	18·8	46	35·2	889	·6905	·0015	− ·0288
100	.....	81	19·5	46	35·2	892	·6903	·0016	− ·0288
101	.....	81	20·1	46	35·2	887	980·6898	0·0007	−0·0295
102	.....	81	21·0	46	35·2	889	·6875	− ·0015	− ·0318
103	Phelans.....	81	21·1	46	34·6	905	·6882	·0016	− ·0292
104	.....	81	22·0	46	34·6	954	·6821	·0002	− ·0323
105	.....	81	22·6	46	34·9	966	·6843	·0031	− ·0299
106	.....	81	23·0	46	35·4	1,001	·6833	·0046	− ·0295
107	.....	81	22·9	46	36·1	1,015	·6828	·0043	− ·0303
108	.....	81	23·3	46	36·4	1,047	·6806	·0048	− ·0309
109	Levack (Railway Station).....	81	24·4	46	36·1	1,088	·6783	·0067	− ·0303
110	.....	81	24·4	46	36·6	1,174	·6741	·0099	− ·0301
111	.....	81	24·7	46	37·0	1,218	980·6735	0·0128	−0·0287
112	.....	81	24·8	46	37·3	1,164	·6759	·0096	− ·0300
113	.....	81	27·1	46	37·5	1,199	·6691	·0059	− ·0349
114	.....	81	26·4	46	37·3	1,170	·6723	·0066	− ·0332
115	.....	81	26·0	46	37·1	1,113	·6763	·0056	− ·0323
116	.....	81	25·3	46	37·2	1,198	·6721	·0092	− ·0316
117	.....	80	55·5	46	38·5	956	·6901	·0025	− ·0301
118	.....	80	55·5	46	38·1	952	·6899	·0025	− ·0299
119	.....	80	54·9	46	38·1	967	·6895	·0035	− ·0294
120	.....	80	54·1	46	38·1	966	·6896	·0035	− ·0294
121	.....	80	53·0	46	38·1	968	980·6898	0·0040	−0·0290
122	.....	80	52·0	46	38·1	969	·6905	·0047	− ·0283
123	.....	80	52·1	46	38·1	971	·6906	·0050	− ·0281
124	.....	80	50·8	46	37·9	988	·6891	·0054	− ·0283
125	.....	80	50·2	46	37·8	998	·6882	·0056	− ·0284
126	.....	80	49·7	46	37·4	1,006	·6875	·0113	− ·0281
127	.....	80	49·5	46	37·0	992	·6867	·0048	− ·0290
128	.....	80	49·2	46	36·7	1,005	·6865	·0062	− ·0281
129	.....	80	48·5	46	36·7	1,107	·6902	·0095	− ·0282
130	.....	80	48·1	46	37·0	1,112	·6796	·0090	− ·0289
131	.....	80	47·5	46	37·3	1,118	980·6800	0·0095	−0·0286
132	.....	80	46·9	46	37·2	1,121	·6833	·0131	− ·0251
133	.....	80	46·6	46	37·4	1,130	·6832	·0136	− ·0249
134	.....	80	46·2	46	37·8	1,083	·6861	·0115	− ·0254
135	.....	80	45·6	46	38·0	1,056	·6903	·0128	− ·0231
136	Skead Station.....	80	45·4	46	39·3	956	·6952	·0064	− ·0261
137	.....	80	55·7	46	31·3	862	·6887	·0030	− ·0263
138	.....	80	54·8	46	31·3	872	·6904	·0057	− ·0240
139	.....	80	54·1	46	31·4	875	·6897	·0051	− ·0247
140	.....	80	52·9	46	30·9	877	·6894	·0058	− ·0241
141	.....	80	52·3	46	31·0	866	980·6866	0·0018	−0·0277
142	.....	80	50·4	46	30·7	841	·6864	− ·0003	− ·0289
143	.....	80	50·4	46	29·5	822	·6874	·0007	− ·0273
144	Coniston.....	80	51·0	46	29·1	817	·6831	− ·0035	− ·0313

PRINCIPAL FACTS FOR GRAVITY STATIONS—*Continued*

Station No.	Station Name	Longitude ° ′	Latitude ° ′	Elevation Ft.	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
145	.....	80 58·0	46 30·0	897	·6888	·0084	− ·0222
146	.....	80 56·2	46 29·4	852	·6850	·0012	− ·0278
147	.....	80 54·2	46 29·1	908	·6777	− ·0003	− ·0312
148	.....	80 54·2	46 28·2	912	·6749	− ·0014	− ·0325
149	.....	80 54·2	46 29·6	885	·6827	·0018	− ·0284
150	.....	80 52·4	46 29·1	845	·6820	− ·0019	− ·0307
151	.....	80 56·3	46 30·3	899	980·6881	0·0074	−0·0232
152	Garson Junction.....	80 54·9	46 31·9	888	·6885	·0044	− ·0259
153	.....	80 54·8	46 32·2	901	·6893	·0060	− ·0247
154	.....	80 54·2	46 32·5	918	·6882	·0061	− ·0252
155	.....	80 52·5	46 33·0	954	·6851	·0056	− ·0269
156	.....	80 51·7	46 33·0	958	·6835	·0044	− ·0283
157	.....	80 51·7	46 33·1	970	·6842	·0060	− ·0270
158	.....	80 51·7	46 33·3	975	·6870	·0090	− ·0242
159	.....	80 50·9	46 34·3	974	·6899	·0103	− ·0229
160	.....	80 50·9	46 34·7	961	·6906	·0091	− ·0236
161	.....	80 50·9	46 35·1	954	980·6871	0·0044	−0·0281
162	.....	80 50·5	46 35·5	965	·6867	·0044	− ·0285
163	.....	80 49·8	46 35·9	1,017	·6850	·0070	− ·0276
164	Garson.....	80 51·7	46 33·8	953	·6908	·0100	− ·0225
165	.....	80 51·2	46 32·1	905	·6881	·0053	− ·0255
166	.....	80 50·4	46 31·5	861	·6864	·0037	− ·0290
167	.....	80 50·2	46 30·2	821	·6837	− ·0041	− ·0321
168	Wanapitei Station.....	80 46·9	46 29·2	797	·6908	·0022	− ·0249
169	Sudbury.....	81 00·9	46 29·5	902	·6827	·0035	− ·0272
170	.....	81 01·7	46 29·5	893	·6837	·0037	− ·0267
171	.....	81 03·0	46 30·1	925	980·6895	0·0116	−0·0199
172	.....	81 03·5	46 30·8	967	·6897	·0148	− ·0182
173	.....	81 03·8	46 31·1	982	·6871	·0131	− ·0203
174	.....	81 04·1	46 31·7	970	·6867	·0106	− ·0224
175	.....	81 05·3	46 32·5	885	·6915	·0062	− ·0240
176	Azilda Station.....	81 06·2	46 33·1	890	·6924	·0067	− ·0237
177	.....	81 02·5	46 29·5	900	·6835	·0042	− ·0265
178	.....	81 03·4	46 30·4	944	·6920	·0154	− ·0168
179	.....	81 03·7	46 31·0	991	·6884	·0153	− ·0184
180	.....	81 04·8	46 32·2	916	·6908	·0089	− ·0223
181	.....	81 05·5	46 33·1	889	980·6931	0·0073	−0·0230
182	.....	81 05·5	46 33·7	881	·6936	·0061	− ·0239
183	.....	81 05·5	46 34·1	900	·6936	·0074	− ·0233
184	.....	81 05·5	46 34·9	902	·6950	·0077	− ·0230
185	.....	81 05·5	46 37·7	914	·6907	·0003	− ·0308
186	.....	81 01·7	46 35·7	1,012	·6873	·0091	− ·0254
187	.....	81 03·0	46 35·7	929	·6927	·0067	− ·0249
188	.....	81 04·2	46 35·7	902	·6933	·0049	− ·0259
189	.....	81 06·8	46 37·7	919	·6902	·0003	− ·0310
190	.....	81 06·8	46 38·6	931	·6900	− ·0001	− ·0318
191	.....	81 06·7	46 36·6	911	980·6901	0·0011	−0·0299
192	.....	81 08·0	46 36·5	907	·6920	·0028	− ·0281
193	.....	81 08·0	46 34·7	905	·6933	·0066	− ·0242

PRINCIPAL FACTS FOR GRAVITY STATIONS—*Continued*

Station		Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name							Free Air	Bouguer
		°	′	°	′	Ft.			
194	.....	81	08·0	46	33·9	894	·6941	·0076	− ·0229
195	.....	81	08·0	46	33·1	889	·6941	·0083	− ·0220
196	.....	81	07·0	46	33·9	905	·6949	·0094	− ·0214
197	.....	81	06·9	46	34·8	909	·6933	·0069	− ·0241
198	.....	81	09·0	46	34·7	903	·6933	·0064	− ·0243
199	.....	81	10·1	46	34·7	904	·6926	·0058	− ·0250
200	.....	81	00·1	46	31·8	977	·6836	·0081	− ·0252
201	.....	81	00·4	46	31·4	989	980·6825	0·0087	−0·0250
202	.....	81	00·4	46	30·9	1,004	·6794	·0077	− ·0265
203	.....	81	00·5	46	30·3	915	·6837	·0046	− ·0266
204	Clarabelle Station.....	81	03·3	46	29·9	945	·6892	·0135	− ·0187
205	.....	81	03·8	46	29·6	940	·6897	·0140	− ·0181
206	.....	81	04·2	46	29·3	962	·6836	·0104	− ·0223
207	Copper Cliff.....	81	04·2	46	28·6	857	·6887	·0067	− ·0225
208	Copper Cliff Station.....	81	04·5	46	27·7	860	·6869	·0065	− ·0228
209	.....	81	05·9	46	26·7	862	·6861	·0074	− ·0219
210	.....	81	07·2	46	25·8	864	·6865	·0094	− ·0201
211	.....	81	08·5	46	25·2	820	980·6860	0·0056	−0·0224
212	.....	81	08·9	46	26·3	909	·6894	·0157	− ·0152
213	Creighton.....	81	10·8	46	27·5	999	·6815	·0145	− ·0195
214	Creighton Shaft.....	81	11·2	46	27·8	1,008	·6824	·0157	− ·0186
215	.....	81	09·1	46	26·8	946	·6840	·0131	− ·0192
216	.....	81	09·9	46	27·2	973	·6814	·0124	− ·0208
217	.....	80	59·0	46	36·5	935	·6932	·0066	− ·0252
218	.....	80	58·0	46	36·5	1,001	·6885	·0081	− ·0260
219	.....	80	58·0	46	37·3	938	·6910	·0036	− ·0284
220	.....	80	56·7	46	37·4	941	·6911	·0037	− ·0283
221	.....	80	55·5	46	37·3	947	980·6902	0·0036	−0·0287
222	.....	80	56·7	46	38·2	963	·6898	·0033	− ·0295
223	.....	80	57·9	46	38·2	960	·6899	·0031	− ·0296
224	.....	80	59·2	46	38·2	956	·6894	·0022	− ·0303
225	.....	81	07·7	46	33·4	890	·6940	·0079	− ·0225
226	.....	81	09·6	46	33·9	888	·6939	·0068	− ·0234
227	.....	81	11·0	46	33·9	889	·6931	·0061	− ·0242
228	.....	81	08·9	46	33·9	893	·6940	·0074	− ·0230
229	.....	81	11·0	46	33·0	887	·6948	·0089	− ·0213
230	.....	81	11·0	46	32·3	970	·6884	·0114	− ·0217
231	.....	81	12·2	46	33·1	879	980·6942	0·0075	−0·0225
232	.....	81	13·5	46	33·2	883	·6935	·0070	− ·0231
233	.....	81	15·0	46	33·3	890	·6924	·0064	− ·0239
234	.....	81	16·0	46	33·4	885	·6919	·0053	− ·0249
235	.....	81	16·0	46	32·5	881	·6915	·0058	− ·0242
236	.....	81	17·2	46	32·5	866	·6910	·0039	− ·0256
237	.....	81	18·8	46	32·5	863	·6903	·0029	− ·0265
238	.....	81	01·8	46	39·1	948	·6882	·0051	− ·0334
239	.....	81	01·8	46	38·2	940	·6896	·0009	− ·0311
240	.....	81	03·1	46	38·2	941	·6900	·0014	− ·0306
241	.....	81	04·1	46	38·2	938	980·6900	0·0011	−0·0308
242	.....	81	03·1	46	37·3	940	·6905	·0033	− ·0288

PRINCIPAL FACTS FOR GRAVITY STATIONS—*Continued*

Station		Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name							Free Air	Bouguer
		°	′	°	′	Ft.			
243	.....	81	04·3	46	37·3	938	·6901	·0026	− ·0294
244	.....	80	53·0	46	38·9	970	·6904	·0035	− ·0295
245	.....	80	53·0	46	39·8	972	·6915	·0034	− ·0297
246	.....	80	51·5	46	39·0	973	·6916	·0049	− ·0283
247	.....	80	54·2	46	39·0	964	·6910	·0034	− ·0295
248	.....	80	56·8	46	39·8	972	·6890	·0030	− ·0322
249	.....	80	56·7	46	41·1	964	·6913	·0005	− ·0323
250	.....	81	00·5	46	40·0	969	·6892	·0005	− ·0325
251	.....	81	00·6	46	41·2	963	980·6923	0·0013	−0·0315
252	.....	81	00·6	46	41·8	930	·6906	− ·0044	− ·0361
253	.....	80	59·2	46	40·1	964	·6888	− ·0005	− ·0333
254	.....	80	59·2	46	40·8	959	·6890	− ·0018	− ·0344
255	.....	80	54·2	46	39·8	971	·6908	·0026	− ·0305
256	.....	80	58·1	46	40·0	966	·6892	·0003	− ·0326
257	.....	81	01·8	46	37·3	945	·6905	·0037	− ·0285
258	.....	81	10·0	46	36·4	906	·6911	·0019	− ·0289
259	.....	80	56·7	46	32·1	891	·6894	·0053	− ·0250
260	.....	80	55·5	46	33·0	903	·6902	·0059	− ·0249
261	.....	80	54·2	46	33·0	927	980·6887	0·0066	−0·0250
262	.....	80	53·5	46	33·0	922	·6892	·0067	− ·0247
263	Falconbridge.....	80	49·1	46	34·6	1,088	·6840	·0146	− ·0224
264	.....	81	12·3	46	35·9	897	·6917	·0025	− ·0281
265	.....	81	12·8	46	37·0	916	·6911	·0020	− ·0292
266	.....	81	13·4	46	37·7	903	·6917	·0004	− ·0304
267	.....	81	14·7	46	38·6	908	·6920	− ·0003	− ·0312
268	.....	81	13·5	46	39·1	934	·6904	− ·0002	− ·0320
269	.....	81	14·7	46	37·7	888	·6911	− ·0017	− ·0319
270	Rutter.....	80	39·6	46	06·2	679	·6593	− ·0058	− ·0289
271	.....	81	16·0	46	37·7	896	980·6901	−0·0020	−0·0325
272	.....	81	17·2	46	36·9	882	·6901	− ·0021	− ·0321
273	.....	81	18·5	46	36·9	884	·6915	− ·0005	− ·0306
274	.....	81	18·5	46	36·0	883	·6896	− ·0010	− ·0311
275	.....	81	18·8	46	33·5	902	·6884	− ·0032	− ·0275
276	Larchwood Station.....	81	17·7	46	34·3	890	·6902	·0027	− ·0276
277	.....	81	19·1	46	34·3	865	·6905	·0007	− ·0288
278	.....	81	20·4	46	34·3	883	·6903	·0021	− ·0280
279	.....	81	22·3	46	33·4	863	·6905	·0018	− ·0276
280	.....	81	23·6	46	33·4	865	·6867	− ·0018	− ·0313
281	.....	81	24·6	46	33·4	867	980·6886	+0·0003	−0·0293
282	.....	81	13·0	46	39·7	927	·6916	− ·0005	− ·0321
283	.....	81	15·2	46	42·9	1,078	·6824	− ·0003	− ·0370
284	.....	81	15·0	46	42·2	1,082	·6842	+ ·0029	− ·0339
285	.....	81	15·1	46	42·0	1,181	·6789	+ ·0072	− ·0330
286	.....	81	15·1	46	41·8	1,164	·6792	+ ·0062	− ·0334
287	.....	81	15·0	46	41·6	1,151	·6905	+ ·0066	− ·0326
288	.....	81	14·9	46	41·4	1,122	·6828	·0064	− ·0318
289	.....	81	14·6	46	40·8	1,035	·6858	·0022	− ·0331
290	.....	81	14·8	46	41·2	1,051	·6848	·0021	− ·0337

PRINCIPAL FACTS FOR GRAVITY STATIONS—*Continued*

Station		Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name							Free Air	Bouguer
		°	′	°	′	Ft.			
291	.....	81	14·6	46	41·0	1,043	980·6852	0·0020	−0·0335
292	.....	81	13·4	46	40·0	969	·6895	·0009	− ·0322
293	.....	81	14·2	46	40·4	1,022	·6855	·0012	− ·0336
294	Kirk.....	80	12·6	46	26·0	678	·6927	− ·0023	− ·0254
295	.....	80	25·0	46	25·7	766	·6929	+ ·0067	− ·0194
296	Appelby Corner.....	80	25·0	46	24·4	750	·6911	·0053	− ·0202
297	.....	80	25·0	46	22·7	745	·6892	·0055	− ·0199
298	.....	80	26·0	46	19·8	687	·6922	·0074	− ·0161
299	.....	80	26·3	46	18·4	657	·6880	·0025	− ·0199
300	.....	80	26·0	46	15·0	673	·6780	− ·0010	− ·0239
301	.....	80	26·0	46	13·2	686	980·6726	−0·0024	−0·0258
302	.....	80	26·0	46	11·5	682	·6654	− ·0074	− ·0306
303	.....	80	26·0	46	09·7	658	·6592	− ·0131	− ·0355
304	Noelville.....	80	26·0	46	08·5	709	·6521	− ·0137	− ·0378
305	.....	80	26·0	46	06·3	723	·6463	− ·0148	− ·0394
306	.....	80	28·2	46	06·3	717	·6483	− ·0134	− ·0378
307	.....	80	29·5	46	06·3	724	·6491	− ·0120	− ·0366
308	.....	80	32·3	46	06·3	717	·6501	− ·0116	− ·0361
309	.....	80	33·3	46	06·3	634	·6548	− ·0147	− ·0363
310	.....	80	34·7	46	06·1	609	·6542	− ·0173	− ·0381
311	.....	80	36·6	46	06·3	694	980·6524	−0·0115	−0·0351
312	.....	80	38·3	46	06·3	609	·6608	− ·0111	− ·0318
313	Bigwood.....	80	35·8	46	02·2	634	·6484	− ·0149	− ·0365
314	French River.....	80	34·2	46	01·3	630	·6464	− ·0160	− ·0374
315	.....	80	35·8	46	04·2	661	·6498	− ·0141	− ·0366
316	.....	80	22·8	46	06·3	680	·6471	− ·0181	− ·0412
317	.....	81	00·2	46	27·0	871	·6802	+ ·0018	− ·0278
318	.....	80	59·6	46	26·1	902	·6744	·0003	− ·0304
319	.....	80	55·1	46	25·9	756	·6801	− ·0074	− ·0331
320	Wanup.....	80	48·8	46	23·6	745	·6889	+ ·0038	− ·0216
321	Burwash.....	80	47·8	46	18·6	727	980·6816	0·0023	−0·0224
322	McVitties.....	80	50·9	46	16·9	695	·6784	− ·0013	− ·0250
323	.....	80	52·7	46	24·7	792	·6838	+ ·0015	− ·0255
324	Whitefish.....	81	19·2	46	22·7	809	·6830	·0053	− ·0221
325	Worthington.....	81	27·1	46	22·9	775	·6862	·0050	− ·0214
326	Turbine.....	81	30·8	46	22·3	710	·6866	·0002	− ·0240
327	Cartier.....	81	33·7	46	42·2	1,378	·6472	− ·0062	− ·0532
328	Benny.....	81	37·8	46	47·0	1,267	·6719	+ ·0008	− ·0424
329	.....	81	30·4	46	36·5	1,363	·6577	·0113	− ·0351
330	.....	81	34·9	46	37·6	1,259	·6499	− ·0079	− ·0508
331	Levack Mine.....	81	22·2	46	39·2	1,110	980·6820	+0·0078	−0·0300
332	Levack.....	81	23·6	46	38·1	1,058	·6841	·0067	− ·0294
333	Warren.....	80	18·6	46	26·5	690	·6960	·0014	− ·0221
334	River Valley.....	80	11·0	46	35·0	788	·7139	·0158	− ·0111
335	Desaulniers.....	80	06·7	46	33·0	787	·6970	·0018	− ·0250
336	Field.....	80	01·7	46	31·4	752	·6885	− ·0076	− ·0332
337	Sudbury.....	80	59·1	46	28·9	810	·6908	+ ·0039	− ·0237
338	Nepewassi Lake.....	80	41·5	46	20·3	656	·6913	·0352	− ·0195

PRINCIPAL FACTS FOR GRAVITY STATIONS—*Continued*

Station		Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name							Free Air	Bouguer
		°	′	°	′	Ft.			
339	West Bay	80	12·7	46	13·8	640	·6767	− ·0035	− ·0253
340	Wawiashkashi Lake	80	17·6	46	48·8	851	·7111	− ·0018	− ·0308
341	Wanapitei Lake	80	45·3	46	39·9	880	980·6999	+0·0031	−0·0269
342	Onaping Lake	81	30·4	46	56·0	1,350	·6726	− ·0042	− ·0502
343	Shakwa Lake	81	58·7	46	46·9	1,387	·6508	− ·0088	− ·0561
344	Acheson Lake	81	54·9	46	35·3	1,070	·6549	− ·0172	− ·0536
345	Windy Lake	81	26·8	46	37·0	1,060	·6794	+ ·0038	− ·0323
346	South East Bay	80	40·7	46	54·0	1,034	·7102	·0067	− ·0286
347	Bigwood Lake	81	05·7	46	51·0	1,211	·6688	− ·0136	− ·0548
348	Annie Lake	81	08·1	46	11·0	769	·6367	− ·0272	− ·0534
349	Lake Panache	81	30·1	46	13·6	725	·6488	− ·0231	− ·0478
350	Gough Lake	81	58·2	46	19·0	844	·6620	− ·0068	− ·0356
351	McGregor Lake	81	43·3	46	03·8	582	980·6498	−0·0210	−0·0408
352	Tyson Lake	81	07·8	46	06·9	660	·6389	− ·0290	− ·0515
353		81	21·4	46	16·9	792	·6575	− ·0131	− ·0401
354		81	20·0	46	21·9	763	·6823	+ ·0015	− ·0245
355		81	20·0	46	21·4	790	·6785	·0010	− ·0259
356		81	21·7	46	17·4	898	·6548	− ·0066	− ·0371
357		81	21·5	46	17·8	807	·6601	− ·0104	− ·0379
358		81	21·3	46	18·6	736	·6647	− ·0137	− ·0388
359		81	21·0	46	19·4	776	·6671	− ·0087	− ·0352
360		81	20·6	46	19·8	741	·6715	− ·0082	− ·0335
361		81	19·7	46	20·4	761	980·6737	−0·0051	−0·0310
362		81	19·9	46	22·1	770	·6843	+ ·0038	− ·0224
363		81	19·8	46	22·2	803	·6839	·0064	− ·0210
364		81	29·4	46	21·0	806	·6741	− ·0013	− ·0288
365	Nairn	81	34·9	46	20·0	722	·6804	− ·0014	− ·0260
366		81	28·6	46	22·7	748	·6861	+ ·0027	− ·0228
367		81	29·0	46	20·3	763	·6741	− ·0049	− ·0309
368		81	28·1	46	19·5	791	·6704	− ·0042	− ·0311
369		81	31·3	46	18·9	682	·6750	− ·0089	− ·0322
370		81	30·4	46	19·9	769	·6736	− ·0037	− ·0298
371		81	32·4	46	19·4	689	980·6799	−0·0041	−0·0276
372		81	33·4	46	19·8	690	·6832	− ·0013	− ·0248
373		81	34·3	46	19·9	766	·6793	+ ·0018	− ·0243
374		81	27·8	46	23·0	769	·6865	·0046	− ·0216
375		81	28·0	46	23·9	736	·6895	·0031	− ·0219
376		81	28·1	46	24·6	790	·6887	·0064	− ·0205
377		81	28·1	46	25·2	969	·6824	·0160	− ·0170
378		81	27·9	46	26·0	941	·6801	·0099	− ·0222
379		81	27·7	46	26·3	1,000	·6747	·0096	− ·0245
380	(Fairbank Lake)	81	27·6	46	27·3	970	·6735	·0040	− ·0290
381	Espanola	81	46·1	46	15·9	672	980·6739	−0·0065	−0·0293
382	Webbwood	81	52·7	46	16·0	661	·6759	− ·0056	− ·0282
383	Verner	80	07·6	46	24·7	670	·6867	− ·0071	− ·0299
384	Lavigne	80	10·2	46	19·6	641	·6850	− ·0037	− ·0257
385		80	14·9	46	21·8	677	·6898	+ ·0011	− ·0220
386		80	21·3	46	21·8	658	·6919	·0015	− ·0211
387	Hagar	80	25·0	46	27·3	691	·7028	·0071	− ·0165

PRINCIPAL FACTS FOR GRAVITY STATIONS—*Continued*

Station No.	Station Name	Longitude ° ′	Latitude ° ′	Elevation Ft.	Observed Gravity	Gravity Anomalies Free Air	Gravity Anomalies Bouguer
388	Hugel	80 17·5	46 29·6	728	·7035	·0078	− ·0170
389		80 14·8	46 33·2	799	·7096	·0152	− ·0120
390	River Valley	80 11·0	46 35·5	793	·7147	·0163	− ·0107
391	Azen	80 14·8	46 38·0	764	980·7252	+0·0203	−0·0057
392	Glen Afton	80 17·8	46 38·9	766	·7240	·0179	− ·0081
393		80 17·0	46 42·7	849	·7042	·0002	− ·0287
394		80 18·1	46 45·2	866	·7028	− ·0033	− ·0328
395	Brightwater River	80 16·8	46 49·2	886	·7095	− ·0008	− ·0309
396		80 17·1	46 53·2	962	·7227	+ ·0136	− ·0192
397		80 18·6	46 56·4	1,057	·7232	·0182	− ·0178
398	Rivière Veuve	80 25·2	46 32·2	756	·7147	·0178	− ·0080
399	Markstay	80 32·6	46 29·6	707	·7118	·0142	− ·0099
400		80 32·7	46 33·0	866	·7146	·0268	− ·0027
401		80 32·6	46 35·4	875	980·7176	0·0270	−0·0028
402	Sudbury	81 00·0	46 29·8	881	·6860	·0044	− ·0256
403		80 52·2	46 21·7	738	·6840	·0011	− ·0240
404	Paddy Creek	80 54·0	46 20·9	754	·6744	− ·0058	− ·0314
405	Horseshoe Lake	80 54·7	46 18·9	718	·6692	− ·0113	− ·0358
406		81 00·4	46 26·1	930	·6759	+ ·0045	− ·0272
407		81 00·6	46 24·8	862	·6761	·0002	− ·0291
408	Rheault	80 59·5	46 24·4	766	·6784	− ·0059	− ·0320
409		81 02·2	46 23·5	866	·6723	− ·0012	− ·0307
410		81 04·0	46 22·8	895	·6690	− ·0008	− ·0312
411		80 57·9	46 22·2	827	980·6624	−0·0128	−0·0410
412		80 50·1	46 20·6	728	·6831	+ ·0010	− ·0238
413		80 48·9	46 15·7	700	·6772	− ·0002	− ·0241
414	Burwash C.N.R.	80 51·9	46 14·5	692	·6736	− ·0028	− ·0264
415	Burwash	80 54·0	46 13·3	663	·6682	− ·0091	− ·0317
416	Wanup C.P.R.	80 48·8	46 23·6	745	·6889	+ ·0038	− ·0215
417		80 46·3	46 26·4	797	·6945	+ ·0101	− ·0179
418	Worthington	81 27·4	46 23·1	775	·6862	·0047	− ·0217
419	Espanola	81 45·9	46 15·7	672	·6740	− ·0061	− ·0289
420		81 42·7	46 11·5	722	·6447	− ·0243	− ·0489
421	Whitefish Falls	81 43·7	46 06·7	597	980·6487	−0·0248	−0·0452
422	Birch Island	81 46·6	46 04·1	590	·6511	− ·0192	− ·0393
423	McGregor Bay	81 46·8	46 01·1	592	·6474	− ·0182	− ·0384
424	Chelmsford	81 11·9	46 35·2	886	·6918	+ ·0026	− ·0276
425		81 13·4	46 39·3	935	·6910	·0002	− ·0316
426		81 14·3	46 43·8	1,184	·6770	·0029	− ·0375
427	Nickel Offset Mine	81 14·4	46 45·5	1,331	·6627	− ·0001	− ·0454
428		81 15·9	46 36·9	871	·6927	− ·0005	− ·0301
429		81 14·4	46 36·9	923	·6913	+ ·0030	− ·0284
430		81 12·9	46 37·0	911	.6910	.0014	− ·0296
431	Chudleigh	80 23·2	46 38·5	792	980·7196	0·0166	−0·0105
432	Washagami	80 26·6	46 38·5	789	·7193	·0160	− ·0109
433	Crerar	80 32·9	46 37·8	851	·7079	·0115	− ·0175
434	Sudbury Junction	80 54·1	46 31·4	875	·6897	·0051	− ·0247
435	Anstice	81 03·0	46 54·2	1,185	·6794	− ·0102	− ·0506
436	Raphoe	81 07·5	46 59·4	1,241	·6741	− ·0181	− ·0604

PRINCIPAL FACTS FOR GRAVITY STATIONS—*Continued*

Station		Longitude	Latitude	Elevation	Observed Gravity	Gravity Anomalies	
No.	Name					Free Air	Bouguer
		° ′	° ′	Ft.			
437	St. Cloud	80 48·0	46 24·0	749	·6916	+ ·0063	− ·0192
438	Waterfall	80 50·1	46 19·3	709	·6901	− ·0019	− ·0260
439	Romford	80 52·4	46 29·1	845	·6820	− ·0019	− ·0307
440	Geneva	81 33·5	46 45·1	1,381	·6521	− ·0050	− ·0524
441	Stralak	81 42·4	46 48·5	1,351	980·6677	+0·0023	−0·0438
442	Pogamising	81 46·5	46 54·7	1,158	·6836	− ·0094	− ·0488
443	Fluorite	81 49·0	46 58·6	1,195	·6876	− ·0077	− ·0484
444	Bayswater Station	80 45·2	46 05·2	647	·6637	− ·0029	− ·0250
445	Hartley Bay Station	80 45·5	46 01·9	619	·6568	− ·0075	− ·0286
446	Pickerel River Station	80 43·6	46 00·3	638	·6508	− ·0093	− ·0311
447	Delamere	80 42·4	46 10·1	655	·6725	− ·0007	− ·0230
448	Paget	80 44·4	46 13·9	689	·6766	+ ·0008	− ·0226
449	Porlock	80 49·1	46 11·5	593	·6715	− ·0097	− ·0299
450		81 00·4	46 30·5	955	·6824	+ ·0067	− ·0258
451		80 50·1	46 34·2	1,013	980·6901	+0·0143	−0·0202
452		80 45·0	46 39·6	949	·6997	·0097	− ·0226
453		81 08·4	46 25·2	817	·6860	·0053	− ·0226
454		81 08·2	46 26·7	944	·6882	·0172	− ·0149
455		81 06·7	46 27·2	884	·6903	·0129	− ·0173
456		81 08·4	46 26·3	920	·6870	·0144	− ·0170
457		81 09·0	46 26·3	895	·6899	·0149	− ·0156
458		81 09·0	46 25·6	884	·6867	·0117	− ·0184
459		81 09·6	46 25·6	883	·6888	·0137	− ·0163
460		81 08·8	46 25·4	816	·6892	·0081	− ·0197
461		81 08·4	46 25·4	815	980·6876	0·0064	−0·0213
462		81 10·0	46 23·0	778	·6902	− ·0009	− ·0274
463		81 11·2	46 21·5	774	·6757	− ·0035	− ·0298
464		81 11·5	46 20·5	757	·6746	− ·0047	− ·0305
465		81 07·8	46 24·5	830	·6818	+ ·0033	− ·0249
466		81 07·0	46 23·2	780	·6773	− ·0039	− ·0305
467		81 11·7	46 27·3	997	·6833	+ ·0163	− ·0176
468		81 12·4	46 26·9	944	·6868	·0155	− ·0167
469		81 13·5	46 26·5	915	·6859	·0124	− ·0187
470		81 14·7	46 26·1	859	·6849	·0068	− ·0225
471		81 05·2	46 25·4	828	980·6824	0·0025	−0·0257
472		81 04·7	46 24·1	853	·6747	− ·0010	− ·0300
473		81 05·3	46 23·2	813	·6727	− ·0054	− ·0330
474		81 03·5	46 26·4	834	·6842	+ ·0033	− ·0251
475		81 02·9	46 25·6	854	·6811	·0033	− ·0258
476		81 02·6	46 25·2	859	·6759	− ·0008	− ·0301
477		81 02·5	46 24·4	751	·6802	+ ·0040	− ·0310
478		81 22·7	46 23·4	824	·6864	·0091	− ·0190
479		81 22·6	46 24·5	886	·6879	·0147	− ·0155
480		81 23·3	46 25·3	977	·6832	·0174	− ·0159
481		81 23·7	46 25·9	1,024	980·6748	+0·0126	−0·0223
482		81 23·7	46 26·2	1,024	·6907	·0080	− ·0269
483		81 23·4	46 26·9	968	·6738	·0047	− ·0283
484	Mond Station	81 23·3	46 24·9	905	·6870	·0150	− ·0158
485		81 22·3	46 21·9	840	·6790	·0054	− ·0232

PRINCIPAL FACTS FOR GRAVITY STATIONS—*Concluded*

Station		Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name							Free Air	Bouguer
		°	′	°	′	Ft.			
486	.....	81	23·5	46	21·2	752	·6821	·0013	− ·0244
487	.....	81	22·8	46	20·8	749	·6800	− ·0005	− ·0260
488	McKerrow Station.....	81	45·4	46	17·1	685	·6804	− ·0006	− ·0239
489	.....	81	44·8	46	18·6	828	·6807	+ ·0110	− ·0173
490	.....	81	46·0	46	19·3	852	·6795	·0110	− ·0181
491	.....	81	45·9	46	20·2	960	980·6744	0·0148	−0·0180
492	.....	81	54·0	46	17·1	663	·6728	− ·0103	− ·0328
493	.....	81	52·6	46	17·5	668	·6755	− ·0077	− ·0304
494	.....	81	48·7	46	18·4	764	·6793	+ ·0039	− ·0222

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Canadian West Coast Earthquakes, 1954

BY

W. G. Milne

EDMOND CLOUTIER, C.M.G., O.A., D.S.P.,
QUEEN'S PRINTER AND CONTROLLER OF STATIONERY
OTTAWA, 1955

600—1955

Canadian West Coast Earthquakes, 1954

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ABSTRACT

This report continues a series, already published, dealing with earthquakes on the west coast of Canada. During 1954 there were 178 earthquakes recorded on the network of seismograph stations in southwestern British Columbia, and of these epicentral determinations were possible for 67. The earthquakes located are plotted on an accompanying map of the area. A list of the few earthquakes recorded on the Crowsnest Pass seismographs is included.

Instrumental changes at the Horseshoe Bay station late in 1954 are described.

INTRODUCTION

The seismological network set up in southwestern British Columbia in 1951 has continued to operate during 1954. The Victoria station, which dates back to 1899, is the central station. The records of the Alberni and Horseshoe Bay stations are combined with those of Victoria for the purpose of locating many of the small local earthquakes occurring in the immediate area. Three temporary units in the southeastern Rocky Mountain region were added at Fernie, Coleman, and Turner Valley. A discussion of the seismograph records obtained during 1954 at the six stations, is presented in this paper as a continuation of the series of reports on seismic activity in British Columbia given for 1951[1], 1952[2], and 1953[3].

DESCRIPTION OF STATIONS

At the Dominion Astrophysical Observatory near Victoria, the new seismological station continues to be the centre of the network. The three-component short-period Benioff seismographs, of variable reluctance type, record the local earthquakes. In addition the Victoria station is equipped with Milne-Shaw seismographs for recording teleseisms. A standard chronometer is used to place time marks on the record, and accurate time control is obtained from automatically recorded NPG (San Francisco) time signals whenever available. A more detailed description of this station is given in the report for 1953.

The Alberni station, which is serviced by a local operator, is equipped with short-period Willmore-Sharpe seismometers. These drive Turner galvanometers, which in turn record on a Sprengnether microseismic recorder at the paper speed of 60 mm/min. Time control is supplied once a day by automatically recorded Dominion Observatory time signals.

Until December 1st, 1954, the Horseshoe Bay seismographs were identical with those at Alberni. During 1953 a new ferry service was inaugurated between Horseshoe Bay and Nanaimo to add to the two services already operating from the dock, a few hundred yards from the seismograph. Because of the very short-period design of the Willmore-Sharpe seismometers, the record was disturbed for a period of two to five minutes when

[1] W. G. Milne and F. Lombardo, "Canadian West Coast Earthquakes, 1951", *Publications of the Dominion Observatory*, Vol. XVI, No. 3, 1952.

[2] W. G. Milne, "Canadian West Coast Earthquakes, 1952", *Publications of the Dominion Observatory*, Vol. XVI, No. 9, 1953.

[3] W. G. Milne, "Canadian West Coast Earthquakes, 1953", *Publications of the Dominion Observatory*, Vol. XVI, No. 13, 1955.

62346—1½

the ferry docked and departed. The Willmore-Watt seismometers, with periods of the order of one second, were substituted for the Willmore-Sharpe units. One galvanometer was installed with a period of 0·25 sec., and the other galvanometers with periods approximately 0·03 sec. The longer period unit eliminates most of the ferry and traffic noise, but brings the system into the frequency range of microseisms. Many teleseisms as well as all the local tremors appear on the records from the 0·25 sec. galvanometer. On the system with the 0·03 sec. galvanometers, traffic noise still persists, but the record is much less disturbed by microseisms and the earthquakes are more clearly seen. The new galvanometers have a very short focal length so the Sprengnether method of placing time marks on the records was changed. Instead of using chronometer contacts to move a prism in the light path and so shift the light spot, the contacts now close a circuit which supplies a small voltage directly to the galvanometer. The spot is thus moved with a minimum of relay stages in the system. As in the past, time corrections are obtained daily from automatically recorded Dominion Observatory time signals.

Seismograph stations established late in 1953 in the Rocky Mountain area along the southern British Columbia-Alberta border, have been used to investigate the rockburst activity in the coal mines of the Crowsnest Pass. These stations have recorded a few local tremors although their sensitivity is not high. At Fernie and Coleman the recorders are in the mine offices. Willmore-Watt seismometers and recorders are used. T_s is approximately 1 sec. and T_g is 0·25 sec. Standard chronometers are used and CBC radio time signals are recorded when available. The Turner Valley station in Alberta is equipped with similar seismographs.

The co-ordinates of the stations are given in Table I.

TABLE I

Station	Latitude			Longitude		
	°	′	″ N	°	′	″ W
Victoria	48	31	09·9	123	24	55·1
Alberni	49	16	14	124	49	18
Horseshoe Bay	49	22	39	123	16	33
Fernie	49	29·0		114	58·6	
Coleman	49	38·1		114	31·2	
Turner Valley	50	39	52	114	16	44

METHOD OF LOCATING EPICENTRES

When an earthquake is of sufficient strength to record on three seismographs, an epicentre can be determined. Preliminary co-ordinates are obtained by using differences in arrival times of P waves at pairs of stations. This position is adjusted to obtain the best possible fit for the three stations, again using only the P phase. The distance to each station, scaled from a map, is checked against the S-P distance to eliminate any major error in the position of the epicentre. For all this work the travel-time curves for the Canadian Shield[4] are used; curves more appropriate to the area have not yet been determined. Epicentres a considerable distance out of the triangle, and epicentres out of the

[4] John H. Hodgson, "A Seismic Survey in the Canadian Shield", *Publications of the Dominion Observatory*, Vol. XVI, No. 5, 1953.

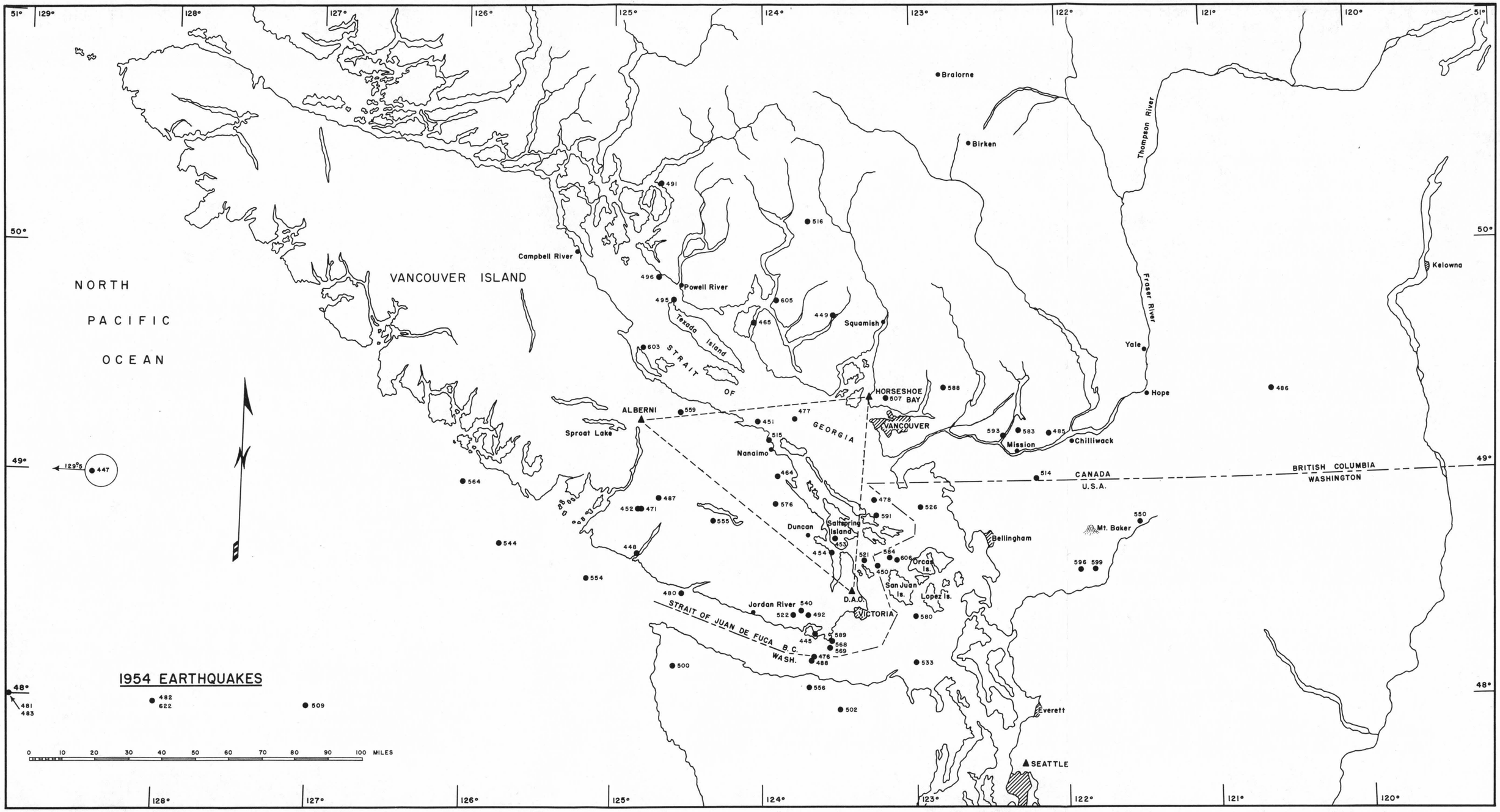
1954 EARTHQUAKES
NORTH PACIFIC OCEAN
VANCOUVER ISLAND
STRAIT OF GEORGIA
STRAIT OF JUAN DE FUCA
B.C.
WASH.
CANADA
U.S.A.
BRITISH COLUMBIA
WASHINGTON
Thompson River
Fraser River
Texada Island
Saltspring Island
San Juan Is.
Orcas Is.
Lopez Is.
Campbell River
Powell River
Squamish
Bralorne
Birken
Yale
Hope
Chilliwack
Mission
Kelowna
Mt. Baker
Bellingham
Everett
SEATTLE
VANCOUVER
HORSESHOE BAY
ALBERNI
Sproat Lake
Nanaimo
Duncan
Jordan River
D.A.O.
VICTORIA
0 10 20 30 40 50 60 70 80 90 100 MILES

TABLE II—1954 EARTHQUAKES

No.	Date	Origin Time GMT	Lat. N.	Long. W.	Intensity	Arrival Times of P-Phase, GMT			Distance			Remarks
						Victoria	Horseshoe Bay	Alberni	V	HB	A	
			° ′	° ′			h m	h m s		kms		
444	Jan. 14	.....	.....	.....	I	.....	05 43 50·5	.....	.....			Very close to Horseshoe Bay.
445	Jan. 15	06 33 26	48 20	123 40	II	S-P=3ˢ5	.....	06 33 48·2	28		135	Probable location southwest of Victoria.
446	Jan. 15	23 39 20	.....	.....	III	No record	23 39 27·0	23 39 44·5	15		155	Northeast of Horseshoe Bay, approx. 15 kms.
447	Jan. 16	.....	49	129·5	IV	S-P=37ˢ	22 46 18·4	22 43 00·1	.....			Off west coast of Vancouver Island.
448	Jan. 20	08 28 24	48 41	124 51	II	S-P=9ˢ5	08 28 44·9	08 28 33·0			65	On west coast of Vancouver Island.
449	Jan. 20	11 57 35	49 44	123 32	II	.....	11 57 29·0	11 57 52·2			107	Northeast of Horseshoe Bay.
450	Jan. 24	17 49 20	48 38	123 15	II	S-P=ˢ·1	17 49 35·4	17 49 43·5		91	137	Gulf Islands.
451	Jan. 26	23 10 55	49 16	123 02	III	23 11 11	23 11 05	23 11 05·0		49	60	North of Nanaimo.
452	Fef. 3	16 17 26	48 53	124 50	II	16 17 44·0	(16 17 47·5)	16 17 33·0	120		43	South of Alberni.
453	Feb. 7	10 40 39	48 45	123 32	III	10 40 43·5	10 40 51·5	10 40 57·8	27	75	112	West of Saltspring Island.
454	Feb. 20	23 42 19	48 41	123 33	II+	23 42 22·5	23 42 33·1	23 42 38·0	21	85	116	Southern Vancouver Island.
455	Feb. 22	.....	.....	.....	I	.....	.....	18 22 05	.....			
456	Feb. 23	.....	.....	.....	I	.....	.....	22 35 51·1	.....			
457	Feb. 23	.....	.....	.....	II	23 16 18	.....	.....	.....			Off west coast of Vancouver Island.
458	Feb. 24	.....	.....	.....	I	.....	.....	19 12 49·0	.....			
459	Feb. 24	.....	.....	.....	I	.....	.....	21 29 06·2	.....			
460	Feb. 25	.....	.....	.....	I	.....	.....	01 08 35·3	.....			
461	Mar. 2	.....	.....	.....	I	.....	.....	19 15 02·2	.....			Very close to Alberni.
462	Mar. 3	.....	.....	.....	I	.....	.....	16 14 22·7	.....			Very close to Alberni.
463	Mar. 4	.....	.....	.....	I	.....	.....	18 34 54·6	.....			
464	Mar. 7	.....	49 02	123 54	II	S-P=7ˢ9	23 28 44·9	23 28 47·1	62	65	72	Southern Vancouver Island.
465	Mar. 8	.....	49 42	124 04	II	.....	13 09 40·6	13 09 41·5		71	71	Sechelt Peninsula.
466	Mar. 10	.....	.....	.....	II	00 35 07·0	00 35 21	.....	95			Horseshoe Bay is likely an S reading. Direction is southeast of Victoria.
467	Mar. 11	.....	.....	.....	I	.....	.....	19 42 56·6	.....			
468	Mar. 12	.....	.....	.....	I	04 17 19·4	.....	.....	70			
469	Mar. 12	.....	.....	.....	II	14 35 48·4	.....	.....	.....			(Seattle 14:35:47), probably off Coast of Washington.
470	Mar. 12	.....	.....	.....	II	20 38 45·8	20 38 43·7	.....	120			Probably in Mission area.
471	Mar. 13	00 04 50	48 53	124 49	II+	00 05 08·8	00 05 11·0	00 04 57·3	112	126	43	South of Alberni.
472	Mar. 16	.....	.....	.....	IV	15 56 44·0	15 56 55·8	15 57 04	.....			South of Seattle (Seattle 15:56:29).
473	Mar. 18	.....	.....	.....	I	21 36 04·7	.....	.....	.....			

TABLE II—1954 EARTHQUAKES—*Continued*

No.	Date	Origin Time GMT	Lat. N.	Long. W.	Intensity	Arrival Times of P-Phase, GMT			Distance			Remarks
						Victoria	Horseshoe Bay	Alberni	V	HB	A	
			° ′	° ′			h m s	h m s		kms		
474	Mar. 22	.....	.....	.....	II	22 46 06·5	.....	.....	.....			Probably off west coast.
475	Mar. 25	.....	.....	.....	.....	17 40 04·0	17 40 07·5	.....	131			Probably east of Bellingham.
476	Mar. 25	21 16 35	48 14	123 40	III	21 16 40·9	21 16 56·4	21 16 58·2	36	131	140	Southwest of Victoria.
477	Mar. 25	21 31 00	49 17	123 45	III	21 31 15·1	21 31 06·8	21 31 13·2	90	37	78	Gulf of Georgia.
478	Mar. 30	05 29 18	48 55	123 16	III	05 29 25·3	05 29 27·1	05 29 37·5	46	51	120	Gulf Islands.
479	April 3	.....	.....	.....	I	.....	15 54 47	.....	.....			
480	April 4	12 42 29	48 31	124 32	III	12 42 42·8	12 42 51·0	12 42 43·6	84	133	87	Entrance to Juan de Fuca Strait.
481	April 5	.....	48	129	VI	19 26 55	.....	19 26 46	.....			U.S.C.G.S. epicentre.
482	April 5	.....	48	128	V	19 35 53	.....	19 35 45	.....			U.S.C.G.S. epicentre.
483	April 5	.....	48	129 (?)	IV	19 48 37	.....	19 48 29	.....			Off west coast.
484	April 9	.....	.....	.....	I	00 58 03·2	.....	.....	20			Southwest of Victoria.
485	April 12	.....	49·2	122·1	III	23 32 10·6	23 32 05·2	23 32 21·5	125	91	199	East of Vancouver, epicentre only approximate.
486	April 15	.....	49 22	120 35	IV	19 20 10·2	19 20 08·8	19 20 24·4	222	197	320	South of Princeton, B.C. (using S-P values). Seattle readings fit well and this tremor was recorded at Butte.
487	April 15	.....	48 56	124 42	II	23 30 47·5	.....	23 30 36·3	107		38	South of Alberni.
488	April 22	.....	48 13	123 41	II	19 28 49·6	19 29 04·9	19 29 06·4	27	131	143	Strait of Juan de Fuca.
489	May 5	.....	.....	.....	IV	01 43 53·7	.....	.....	150			Felt in Tacoma, Wash. (Seattle P=01:42:40·0).
490	May 6	.....	.....	.....	I	record fogged	.....	15 15 23·5	.....			
491	May 10	.....	50·3	124·7	III	.....	05 11 19·4	05 11 15·0		142	116	North of Powell River.
492	May 14	.....	48 25	123 42	II	19 06 19·9	.....	19 06 37·8	20	130	115	South Vancouver Island.
493	May 15	.....	47·4	122·5	VI	13 02 32·9	13 02 45·2	13 02 52·1	.....			Puget Sound epicentre computed by Professor Neumann.
494	May 15	.....	.....	.....	II	17 39 29·0	.....	.....	127			
495	May 19	.....	49·8	124·6	II	.....	18 39 55·2	18 39 47·8		108	63	Texada Island.
496	May 19	.....	49·9	124·7	II	.....	23 02 46·0	23 02 39·0			76	North Strait of Georgia.
497	May 20	.....	.....	.....	I	22 56 21·7	.....	.....	.....			Very near Victoria.
498	May 21	.....	.....	.....	I	14 00 44·3	.....	14 00 17·9	.....			These seem to be the same event, but their arrival times do not permit an epicentral determination.
499	May 21	.....	.....	.....	II	17 04 31·5	.....	.....	.....			

500	May 22	.....	48·2	124·6	III	12 47 29·7	12 47 40·2	12 47 33·8	97	160	116	In Olympic Mountains.
501	May 26	.....	.....	.....	I	22 34 22·6	.....	.....	.....			Very near Victoria.
502	June 3	.....	48·0	123·5	III	07 58 48·4	07 59 00·3	07 59 03·8	49	155	175	South of Port Angeles.
503	June 10	.....	.....	.....	II	.....	.....	21 19 34·0	.....		60	
504	June 18	.....	.....	.....	III	15 10 01·7	15 10 13·6	15 10 20·2		195		Felt in Seattle (Seattle 15:09:51).
505	June 20	.....	.....	.....	III	19 20 49·0	19 20 59·1	19 21 07·2	145	250	300	(Seattle 19:20:34). Epicentre near Seattle?
506	June 22	.....	.....	.....	I	.....	.....	01 43 25·5			205	
507	June 22	20 08 58	49 22	123 11	II	20 09 13·4	20 09 00·2	20 09 18·6	97	12	119	Very close to Horseshoe Bay; perhaps a blast along the Capilano River.
508	June 23	.....	.....	.....	II	.....	.....	23 17 25·6			62	
509	July 5	.....	48	127	III	01 13 07·5	.....	01 13 00·7	.....			Off west coast.
510	July 11	.....	.....	.....	IV	04 56 36·1	.....	04 56 19·2	.....			Off west coast (Seattle 04:56:47).
511	July 12	.....	.....	.....	II	.....	.....	16 38 43·9			95	
512	July 13	.....	.....	.....	II	.....	.....	06 01 49·1			182	
513	July 15	13 24 35	54	138	IV	13 26 32	.....	.....	.....			Queen Charlotte Islands (U.S.C. G.S.).
514	July 15	.....	49·0	122·2	III	21 43 14·1	21 43 12·3	21 43 27·9	110	95	225	Abbotsford area.
515	July 16	19 40 37	49 11	123 58	III	19 40 51·4	19 40 46·6	19 40 47·6	86	56	62	Near Nanaimo.
516	July 21	02 17 35	50 09	123 42	III	02 18 03·9	02 17 49·7	02 17 55·7	200	93	127	North of Sechelt Peninsula.
517	July 28	.....	.....	.....	I	.....	.....	19 59 27·2			80	
518	July 29	.....	.....	.....	I	.....	.....	21 05 34·4			55	
519	July 29	.....	.....	.....	I	.....	.....	22 09 14·4			95	
520	July 30	.....	.....	.....	I	.....	.....	13 28 45·5			26	
521	Aug. 1	17 21 59	48 39	123 20	III	17 22 02·8	17 22 12·8	17 22 20·6	15	83	129	Gulf Islands.
522	Aug. 2	07 23 53	48 25	123 48	III	07 23 58·2	07 24 11·5	07 24 12·3	31	112	118	South Vancouver Island.
523	Aug. 2	.....	.....	.....	II	.....	.....	16 03 40·1			85	
524	Aug. 3	.....	.....	.....	I	03 25 32·7	.....	.....	.....			Very close to Victoria.
525	Aug. 3	.....	.....	.....	II	05 13 13	.....	05 12 54·3			150	Northwest of Alberni.
526	Aug. 5	10 26 56	48 53	122 57	III	10 27 05·5	10 27 06·0	10 27 19·6	55	58	143	South Gulf of Georgia.
527	Aug. 11	.....	.....	.....	I	.....	.....	18 37 52·4			78	
528	Aug. 19	.....	.....	.....	I	.....	05 04 33·2	.....		32		Very near Horseshoe Bay.
529	Aug. 20	.....	.....	.....	I	12 16 14·4	12 16 20·7	.....	50			Probably in the Gulf Islands area.
530	Aug. 25	.....	.....	.....	II	14 25 33·7	S-P=11^{s}7	14 25 51·0	20	90		Probably in Gulf Islands area, very weak records.
531	Aug. 27	.....	.....	.....	II	04 56 11	.....	04 55 50·8	.....			Northwest of Alberni.
532	Aug. 31	.....	.....	.....	I	05 58 18·6	.....	.....	65			
533	Sept. 1	.....	48·2	123·0	III	12 42 24·1	12 42 38·7	12 41 45·7	55			Seattle 12:42:27, epicentre under Strait of Juan de Fuca between Victoria and Port Townsend.
534	Sept. 1	.....	.....	.....	I	22 28 25·0	.....	.....	72			
535	Sept. 2	.....	.....	.....	I	13 50 18·5	.....	.....	76			

TABLE II—1954 EARTHQUAKES—*Continued*

No.	Date	Origin Time GMT	Lat. N.	Long. W.	Intensity	Arrival Times of P-Phase, GMT			Distance			Remarks
						Victoria	Horseshoe Bay	Alberni	V	HB	A	
			° ′	° ′			h m s	h m s		kms		
536	Sept. 3	.....	.....	.....	I	17 58 22·8	.....	.....	15			
537	Sept. 3	.....	.....	.....	II	20 39 41·7	.....	.....	75			
538	Sept. 3	.....	.....	.....	II	20 40 52·5	.....	.....	.....			
539	Sept. 3	.....	.....	.....	II	23 00 50·5	.....	23 01 11·5	65		220	Southeast of Victoria.
540	Sept. 4	.....	48 26	123 45	II	01 16 24·4	.....	01 16 39·0	27		122	South Vancouver Island.
541	Sept. 4	.....	.....	.....	II	07 13 34·0	.....	07 13 53·3	65		220	Southeast of Victoria.
542	Sept. 4	.....	.....	.....	I	07 15 36·0	.....	.....	.....			
543	Sept. 4	.....	.....	.....	I	20 15 42·0	20 15 55·7	.....	33	105		Gulf Islands area.
544	Sept. 4	.....	48 44	125 45	III	21 49 23·3	.....	21 49 11·1	175		92	Off Barkley Sound.
545	Sept. 5	.....	.....	.....	I	16 17 08·2	.....	.....	35			Probably two earthquakes.
546	Sept. 7	.....	.....	.....	I	08 52 28·4	.....	.....	65			
547	Sept. 11	.....	.....	.....	I	05 41 55·2	.....	.....	75			
548	Sept. 11	.....	.....	.....	I	.....	.....	08 27 50·2			52	
549	Sept. 13	.....	.....	.....	II	20 53 50·7	.....	20 54 06·7	63		170	Probably south of Port Angeles, in Washington.
550	Sept. 15	.....	48·8	121·5	III	03 37 34·0	03 37 34·9	.....	148	152		East of Mount Baker.
551	Sept. 16	.....	.....	.....	I	06 53 26·8	.....	06 53 46·7	65			Probably south in Washington.
552	Sept. 17	.....	.....	.....	I	.....	.....	20 38 14·7			33	
553	Sept. 17	.....	.....	.....	II	.....	.....	21 53 29·6			55	
554	Sept. 20	.....	48 35	125 11	II	03 23 40·3	.....	03 23 32·2	130		82	Off Barkley Sound.
555	Sept. 20	.....	48 50	124 20	II	07 07 10·7	.....	07 07 06·9	75		62	South central Vancouver Island.
556	Sept. 21	.....	48·1	123·7	II	22 32 27·2	.....	22 32 43·6	55		135	There seem to be at least three and perhaps four local shocks within the space of a minute. The first only is located.
557	Sept. 24	.....	.....	.....	I	.....	.....	17 28 45·4	.....			
558	Sept. 24	.....	.....	.....	III	.....	20 50 13·3	20 50 06·9		120	93	Victoria recorder stopped; No epicentre location is possible.
559	Sept. 25	.....	49 19	124 32	III	08 18 16·2	08 18 11·5	08 17 59·5	123	95	35	Northeast of Alberni.
560	Sept. 25	.....	.....	.....	II	.....	.....	22 02 10·5	.....			Felt in Alberni.
561	Sept. 30	.....	.....	.....	I	18 06 26·0	.....	.....	85			
562	Oct. 2	.....	.....	.....	I	.....	.....	19 30 25·8	.....			
563	Oct. 4	.....	.....	.....	I	.....	.....	23 21 51·4	.....			

564	Oct.	5	.....	49·0	126·0	III	13 01 07·1	.....	13 00 49·2		100	Horseshoe Bay record very weak. Epicentre probably off Barkley Sound.
565	Oct.	6	.....	.....	.....	I	.....	.....	11 37 41·9	.....		
566	Oct.	7	.....	.....	.....	II	.....	.....	14 14 19·7		165	
567	Oct.	11	.....	.....	.....	I	.....	.....	02 52 29·8		55	
568	Oct.	13	.....	48 17	123 34	II	19 33 23·8	(19 33 43·6)	19 33 41·3	32 125	145	Strait of Juan de Fuca.
569	Oct.	13	.....	48 17	123 34	II	21 49 09·7	(21 49 28·9)	21 49 27·2	32 125	145	Same as No. 568.
570	Oct.	15	.....	.....	.....	II	.....	.....	18 15 05·2	.....		
571	Oct.	16	.....	.....	.....	III	02 26 03·3	.....	02 25 44·2		155	Probably off west coast.
572	Oct.	19	.....	.....	.....	II	.....	.....	21 03 53·1		80	
573	Oct.	24	.....	.....	.....	II	.....	.....	06 50 30·8		65	Very sharp on Alberni record.
574	Oct.	27	.....	.....	.....	II	19 55 30·3	.....	.....	120		
575	Oct.	28	.....	.....	.....	I	.....	.....	23 14 50·4	.....		
576	Nov.	1	06 33 53	48 54	123 55	II	06 34 02·0	06 34 04·5	06 34 05·3	57 73	77	South central Vancouver Island.
577	Nov.	2	.....	.....	.....	II	01 52 00·9	.....	.....	102		
578	Nov.	2	.....	.....	.....	II	07 44 05·5	07 43 54·1	07 43 40·1		155	Victoria P very weak. Probably off west coast.
579	Nov.	2	.....	.....	.....	II	.....	.....	23 54 29·7		80	
580	Nov.	3	.....	48·4	123·0	III	05 35 26·0	05 35 38·5	05 35 46·2	40 115	200	South of Gulf Islands.
581	Nov.	4	.....	.....	.....	II	10 54 40·0	10 54 53·2	.....	70 162		Probably in Puget Sound area.
582	Nov.	6	.....	.....	.....	I	01 29 17·3	.....	.....	15		
583	Nov.	6	.....	49·3	122·3	II	16 39 48·7	16 39 39·2	.....	115 60		Victoria record weak. Epicentre probably between Pitt Lake and Stave Lake.
584	Nov.	8	02 52 29	48 40	123 11	III	02 52 31·7	02 52 40·6	02 52 49·8	16 87	135	Gulf Islands area.
585	Nov.	9	.....	.....	.....	II	00 20 52·4	00 21 10·8	00 21 13·4	92		Records are weak, except for Victoria.
586	Nov.	9	.....	.....	.....	I	23 56 36·1	.....	.....	19		
587	Nov.	11	.....	.....	.....	III+	22 15 31·2	.....	22 15 44·0	174	270	Seattle 22:15:43. Felt at Raymond, Wash. Seattle reading probably S.
588	Nov.	12	.....	49·4	122·8	II+	21 59 54·6	21 59 42·4	22 00 00·7	114 39	152	Directly east of Horseshoe Bay.
589	Nov.	12	.....	48 18	123 33	III	23 31 17·4	23 31 32·3	23 31 35·7	30 125	144	Southwest of Victoria.
590	Nov.	13	.....	.....	.....	II	08 25 42·9	08 26 10·2	.....	.....		
591	Nov.	20	.....	48 51	123 15	III	10 13 08·5	10 13 07·2	10 13 21·0	41 58	124	Gulf Islands area.
592	Nov.	26	.....	.....	.....	I	20 30 49·1	.....	.....	35		Very close to Victoria.
593	Nov.	29	.....	49·2	122·4	II	14 48 24·6	14 48 18·8	.....	94 71		Probably south of Stave Lake.
594	Nov.	30	.....	.....	.....	II	02 23 17·7	.....	.....	107		
595	Nov.	30	.....	.....	.....	II	03 38 22·3	.....	.....	38		
596	Dec.	1	.....	48·6	121·9	II	22 54 47·7	22 54 50·6	.....	125		East of Bellingham.
597	Dec.	2	.....	.....	.....	I	08 24 03·8	.....	.....	80		
598	Dec.	2	.....	43·5	125	III	09 06 12·1	09 06 23·8	.....	.....		Off coast of Oregon.

TABLE II—1954 EARTHQUAKES—*Concluded*

No.	Date	Origin Time GMT	Lat. N.	Long. W.	Intensity	Arrival Times of P-Phase, GMT			Distance			Remarks
						Victoria	Horseshoe Bay	Alberni	V	HB	A	
			° ′	° ′			h m s	h m s		kms		
599	Dec. 2	.....	48·6	121·8	II	22 50 54·1	22 50 56·0	.....	.....			East of Bellingham.
600	Dec. 3	.....	.....	.....	III	02 18 16·5	02 18 26·1	.....	.....			Probably same area as No. 601 below.
601	Dec. 3	08 46 02	44	127	IV+	08 47 26·0	08 47 35·9	08 47 31·7	.....			Off coast of Oregon.
602	Dec. 3	19 09 02	67·5	136	.....	.....	.....	.....	.....			Yukon (not recorded).
603	Dec. 5	.....	49·6	124·8	I	.....	00 01 43·8	00 01 23·8		116	55	Not very reliable epicentre.
604	Dec. 5	.....	.....	.....	I	.....	01 49 33·3	01 49 30·9		67	33	Probably northwest of Nanaimo.
605	Dec. 7	.....	49·8	123·9	I	.....	22 08 04·2	22 08 09·6		62		Jervis Inlet area.
606	Dec. 8	.....	48 39	123 07	II	18 39 58·4	18 40 07·1	18 40 16·8	27	84	105	Gulf Islands area.
607	Dec. 11	.....	.....	.....	I	10 37 52·7	10 38 00·8	.....	.....			
608	Dec. 11	.....	.....	.....	I	10 58 47·7	10 59 02·3	.....	.....			
609	Dec. 11	.....	.....	.....	I	11 00 53·2	11 01 09·9	.....	.....			
610	Dec. 11	.....	.....	.....	I	11 11 04·5	.....	.....	.....			
611	Dec. 11	.....	.....	.....	I	11 42 01·9	.....	.....	.....			
612	Dec. 11	.....	.....	.....	I	12 01 21·3	12 02 28·5	.....	.....			
613	Dec. 11	.....	.....	.....	I	12 15 02·7	12 15 11·0	.....	.....			
614	Dec. 11	.....	.....	.....	I	12 27 43·5	12 27 51·1	.....	.....			
615	Dec. 11	.....	.....	.....	I	13 06 36·4	13 06 30·8	.....	.....			
616	Dec. 11	.....	.....	.....	I	13 08 10·9	13 08 17·3	.....	.....			
617	Dec. 11	.....	.....	.....	II	16 05 13·8	16 06 21·7	.....	.....			
618	Dec. 13	.....	.....	.....	II	00 31 08·0	00 31 17·5	.....	40			
619	Dec. 17	.....	.....	.....	II	12 03 46·7	12 04 02·9	12 04 00·4	.....			Probably south in Washington, very weak.
620	Dec. 20	.....	.....	.....	I	12 36 52·8	12 37 08·5	.....	.....			Very small.
621	Dec. 21	.....	.....	.....	.....	.....	18 00 52·5	18 01 08·9		62	172	
622	Dec. 25	.....	48	128	III	01 32 30·1	S-P = 43^{s}·6	01 32 16·4	372	438	310	Off west coast.

triangle but close to any one station are not precisely located, and in these cases the epicentral co-ordinates are given only to 0·1 minute of arc. Epicentres termed "off the west coast" fall into this category as well.

In a few cases, co-ordinates have been given for epicentres where only two stations have recorded the disturbance and no trace of the earthquake can be found on the record of the third station. From the records of two seismograph stations only, there are two possible epicentres for one event. Of the two, that epicentre more distant from the third station, at which no disturbance was recorded, is listed as the true origin.

Seattle readings, supplied by Professor Neumann in his regular bulletin, are often combined with data from the stations of the southwest British Columbia network to obtain an epicentre. Hungry Horse readings, supplied directly through the co-operation of the United States Coast and Geodetic Survey and the Bureau of Reclamation, are used to supplement the readings of the Crowsnest Pass stations. Dr. Nile at Butte frequently contributes his readings for stronger tremors. Provision of these data, which make epicentral determinations possible, is greatly appreciated.

Table II lists all the earthquakes recorded on the southwestern British Columbia network during 1954. The co-ordinates of the epicentres that have been located are shown in detail on a map of the area. Table III lists those few tremors recorded at the Crowsnest Pass stations. In no instance were the stations well enough placed with respect to the tremors to permit epicentral determinations.

The values of intensity given in Table II are only approximate. They are intended to follow as closely as possible the Modified Mercalli Intensity Scale of 1931, given here as Table III. For the earthquakes that are felt, the value of intensity given is reliable. For those earthquakes that have a magnitude listed on the epicentre card, the intensity at the origin can be determined. For all other earthquakes, the intensities are estimated by comparing the amplitudes recorded on the Benioff seismograms with those recorded for earthquakes that have been felt. Personal observation indicates that such estimated intensities tend to be too low.

TABLE III

MODIFIED MERCALLI INTENSITY SCALE[5]

(Abridged)

I Not felt except by a very few under especially favorable circumstances. (I Rossi-Forel Scale)

II Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing. (I to II Rossi-Forel Scale)

III Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration like passing truck. Duration estimated. (III Rossi-Forel Scale)

IV During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls make creaking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably. (IV to V Rossi-Forel Scale)

V Felt by nearly everyone; many awakened. Some dishes, windows, etc. broken; a few instances of cracked plaster; unstable objects overturned. Disturbances of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop. (V to VI Rossi-Forel Scale)

VI Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight. (VI to VII Rossi-Forel Scale)

VII Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motor cars. (VIII Rossi-Forel Scale)

VIII Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Disturbs persons driving motor cars. (VIII+ to IX Rossi-Forel Scale)

IX Damage considerable in specially designed structures; well designed frame structures thrown out of plumb: great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken. (IX+ Rossi-Forel Scale)

X Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks. (X Rossi-Forel Scale)

XI Few, if any, (masonry) structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipe lines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.

XII Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into the air.

DETAILS OF PARTICULAR EARTHQUAKES

Princeton, April 15, 1954

An earthquake, strong enough to have been recorded as far distant as Butte, Montana, was centred south of Princeton, British Columbia, on April 15. There were no reports that the earthquake was felt, probably because the area is sparsely settled. The epicentre reported in Table II has been computed from the Butte, Hungry Horse, and Seattle readings together with those of the Canadian stations. Its intensity is listed as IV.

Victoria, May 15, 1954

A few residents of Victoria and surrounding municipalities felt an earthquake at 5:02 a.m. PST on May 15th. The maximum intensity felt at Victoria was estimated at II. No damage was reported. There is no indication that the tremor was felt on the mainland

[5] H. O. Wood and F. Neumann, "Modified Mercalli Intensity Scale of 1931", *Bull. Seism. Soc. Am.*, 21, 277-283.

south of Vancouver. Professor Frank Neumann, of the University of Washington, in a letter places the epicentre in the Vashon Island area southwest of Seattle. His estimate of the focal depth is 50 to 60 km.

Victoria, September 24, 1954

One person in Victoria felt a very slight earthquake in the city at 12:50 p.m. PST on September 24th. It is likely that this corresponds to earthquake number 588 of Table II. The epicentre is probably under the Strait of Juan de Fuca, southwest of Victoria. On the following day, one very slight shock was felt at Alberni at 14:02 p.m. PST.

Crowsnest

The local earthquakes recorded at Coleman and Fernie for the last few months of 1954 are listed in Table IV. Prior to September the instruments were running at a reduced sensitivity, and part of the time they were not operating due to mechanical difficulties. The few earthquakes that occurred during the period are all very small, probably of the order of II or III on the intensity scale. The epicentres lie a few miles either northwest or southeast of Coleman; quite close to the high ridge of the Rocky Mountain range. A few were strong enough to have been recorded on the Benioff seismographs at Hungry Horse.

TABLE IV

CROWSNEST EARTHQUAKES

Date	Time (GMT)			Station	Distance	Remarks
	h	m	s		kms	
Sept. 9	18	07		Coleman	220	Possibly northwest of Coleman
Sept. 10	20	28·8		Coleman	40	
Sept. 24	07	30	35	Coleman	27	Hungry Horse 07:30:54; epicentre north of Coleman
Sept. 24	23	02	13	Coleman	15	Hungry Horse 23:02:40; epicentre south of Coleman
Sept. 28	20	19	49	Coleman	31	Epicentre near Fernie?
Oct. 20	13	41	16	Coleman	9	
Oct. 21	00	16	54	Coleman	8	
Oct. 29	05	22	52	Coleman	31	Hungry Horse 05:23:16; epicentre north of Coleman
Nov. 4	21	38	34	Coleman	31	Fernie, distance 40 km; epicentre northwest of Coleman
Nov. 20	22	19	17	Coleman	19	Hungry Horse, distance 106 km.

Off the West Coast

In reports on earthquakes in British Columbia many of the epicentres are placed "off the west coast". Some of these epicentres are just a few kilometers west of Vancouver Island at approximately 126°W and 49°N. There are also many more, and apparently stronger tremors around the area at 130°W and 49°N. Many of these are reported on the United States Coast and Geodetic Survey epicentre cards. For the years these reports have been published the general trend of such epicentres is along a line striking some 40°

west of north. It appears that this line of epicentres is in itself a zone of activity quite separate from those epicentres near Vancouver Island. Projected to the south this line passes near the many epicentres off the coast of northern California, and projected to the north it passes through the origin of many of the strong tremors associated with the Queen Charlotte Islands.

DISCUSSION OF EPICENTRES

The earthquake epicentres for 1954 seem to fall within the regions where activity has been reported for the previous three years. One of the most striking features appears on the map on which the epicentres for the four years have been plotted. A line of origins extends from Nanaimo slightly southeast to the Strait of Juan de Fuca. Although this line is well defined, it is not in agreement with the direction of faulting in the area, as indicated on the diagram.

Again the Gulf Islands area is very active, but for small shocks only, during 1954. A few of the epicentres are scattered into the Gulf of Georgia whereas in the past they were all very near the Islands. These two regions make up the area into which the majority of epicentres listed in this report fall.

The three seismographs have recorded several shocks whose origins are under the Olympic Mountain range, an area of very rugged peaks some 40 miles south of the Victoria station.

Off the west coast of Vancouver Island, two lines of epicentres seem well marked. Three tremors were recorded off Barkley Sound, in an area which was the epicentre of a strong tremor in 1918. Two epicentres lie in the general area of the June 23, 1946 tremor in the north Gulf of Georgia, the first to be recorded in that area since that date. The absence of shocks for the years 1951-1953 is surprising for the 1946 tremor was very strong and its aftershocks could be expected to continue for many years.

The Powell River-Jervis Inlet area again has been the origin of a number of small tremors. Several small earthquakes have origins in the mountains lying north of the Fraser River and extending from the coast to the Fraser Canyon. The Abbotsford-Huntington area was active in 1954, but the tremors are smaller than in the past. One shock south of Princeton, although the first recorded from that region since this network of seismographs was installed in 1951, is in an area which was believed to have been active early in the century.

The number of earthquakes recorded during 1954 is consistent with the results of the previous three years. The intensities seem to be less for those tremors based within the populated area of the province. Again, the strongest earthquakes are those some distance off the west coast. No tremors were felt generally over any considerable area, although the one earthquake of May 15th was reported as being felt by many persons in Victoria.

Dominion Astrophysical Observatory,
Victoria, B.C.,
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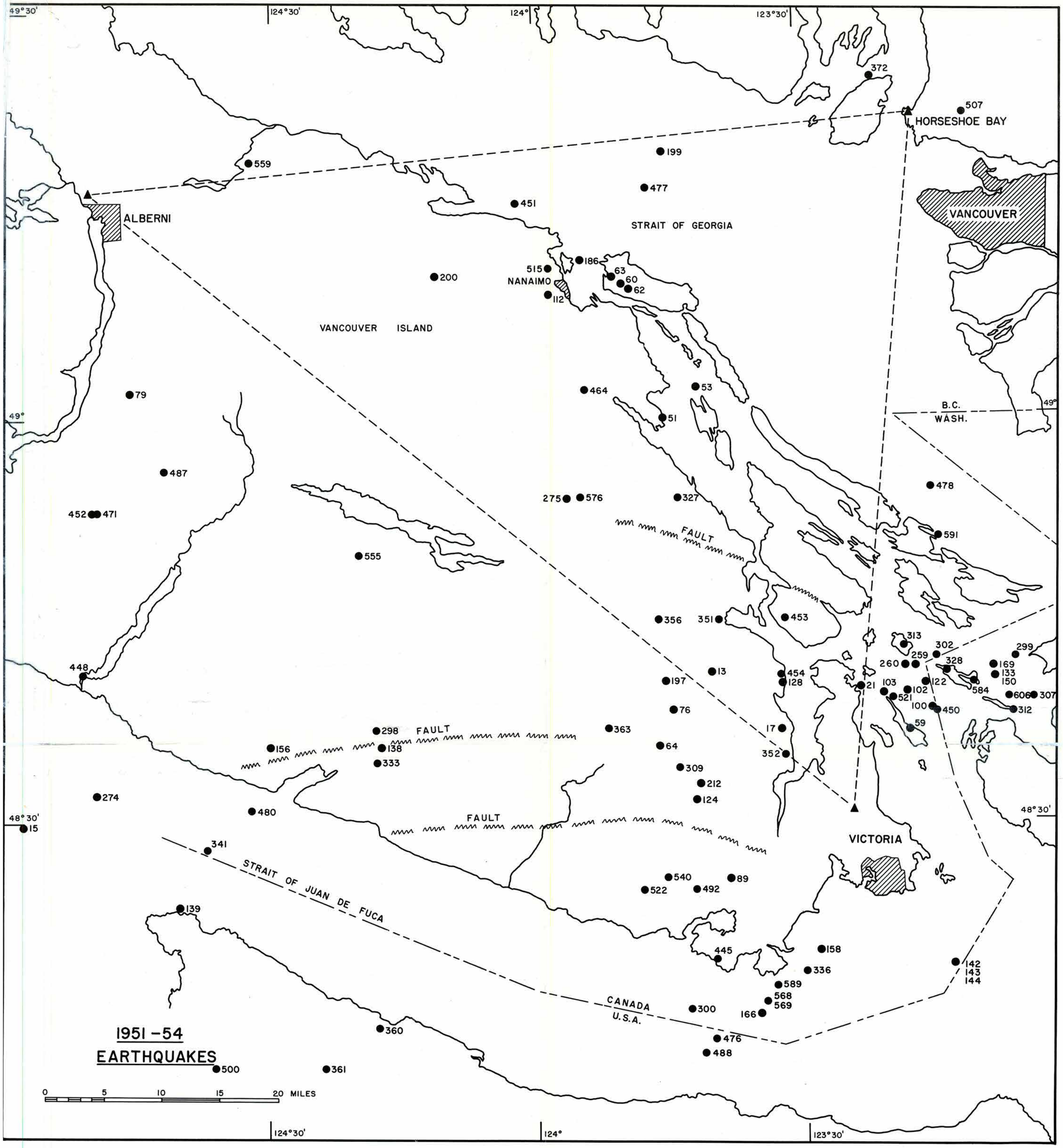

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A Profile Study of the New Quebec Crater

BY

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FIGURE 1. An early photograph of the New Quebec Crater, No. 2086L-8216, taken by the U.S. Air Force on June 20, 1943.

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INTRODUCTION

The New Quebec Crater*, located in the Ungava peninsula in northern Quebec, is one of the most interesting topographical features of the Canadian north. Thanks to two expeditions (1,2), led by Dr. V. Ben Meen in 1950 and 1951 respectively, general information concerning this crater has now been made available both to interested scientific institutions and to the general public.

Since no complete history concerning the recognition of the crater has yet appeared it seems appropriate to record this briefly here. Apart from the occasional visits of Eskimos, whose old camp sites have been found on the crater rim, the crater seems first to have been noted on the trimetrogon survey photographs of the U.S. Army Air Forces, taken on their operations over the Ungava peninsula during the summer of 1943 (*see* Figure 1). Because of its striking appearance the crater was a useful navigation landmark in a wilderness of irregular lakes and rocky barrens. It was first plotted on the Wakeham Bay Sheet (111D), AAF Preliminary Base, scale 1:500,000, an AAF Aeronautical Chart printed in February 1945 for restricted use. The feature appeared on this map as a circular lake about 2 miles in width, with a fine-stipple ruling, surrounded by closely spaced radiating hachures and designated with the word "Crater". Since then it has appeared on all large-scale topographical maps of this area published in both Canada and the United States (*see* Appendix A).

In the summer of 1946 the Geodetic Survey of Canada had several field parties in northern Ungava for the purpose of establishing astronomic control points. The Royal Canadian Air Force transported these parties and in the course of these flights the crater became a well-known landmark. F/L (now S/L) Jake F. Drake mentions sighting the crater on July 20, 1946, and taking pictures, but ice conditions prevented a landing on that date. Later, on July 28, F/L (now W/C) William K. Carr landed in the crater to avoid a line squall and tied up to the northeast shore (3). It was on this occasion that some empty tin cans were left on the shores of Crater Lake. One of these was later found by Dr. Meen's first expedition.

As far as can be ascertained the first published reference to a possible origin for the crater appears in a book by Nicholas Polunin (4). The author, in describing the Ungava operations of 1946, makes the following reference to the crater:—

> "The next morning, 14th August, we were up at daybreak for the start, but the weather on this occasion (and it was by no means the first) prevented us from moving—at least for the time being. There was a thick wet mist and at the same time not a little wind. As we rather

* Previously referred to elsewhere as the Ungava Crater and the Chubb Crater.

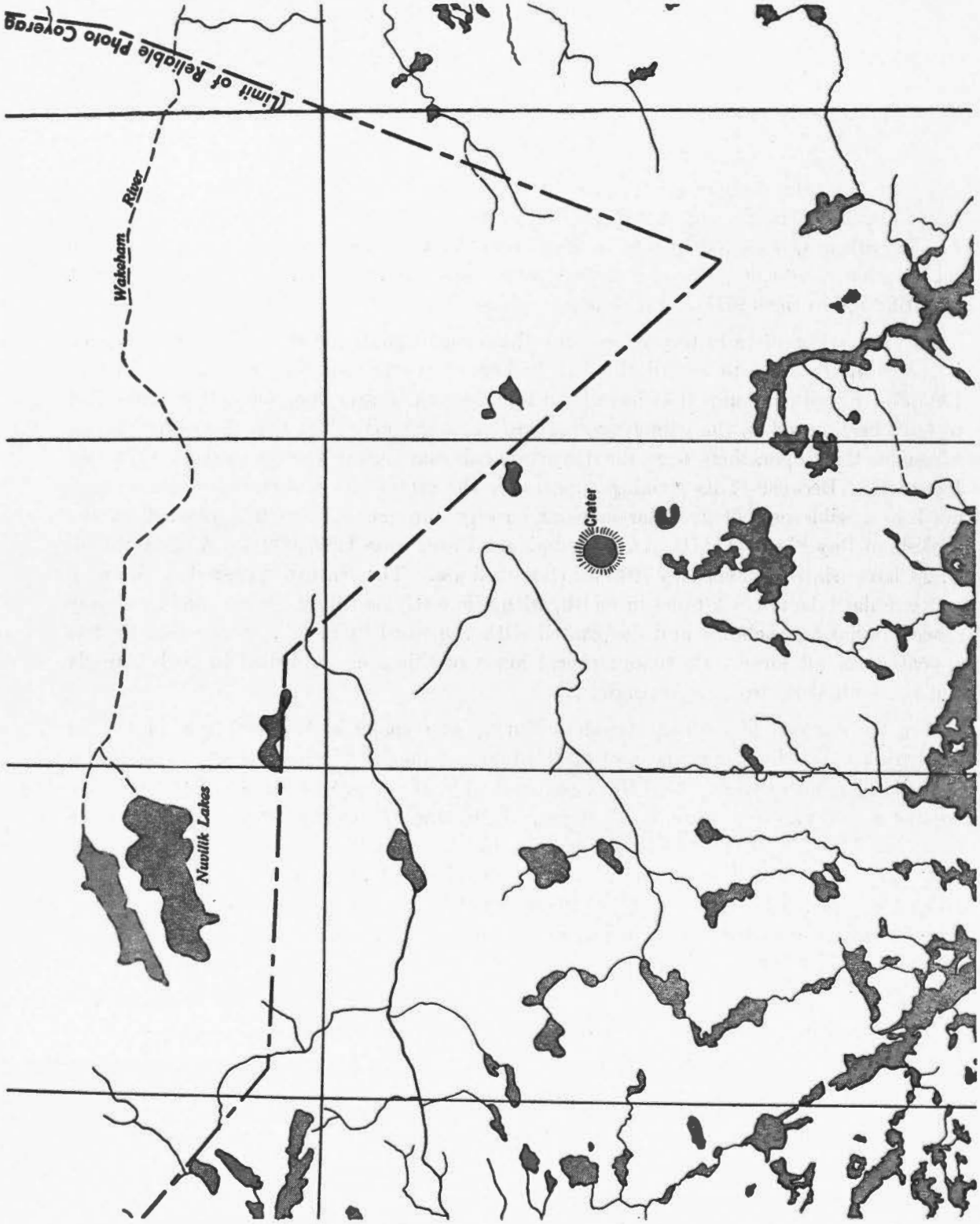

FIGURE 2. The first appearance of the New Quebec Crater on a topographic map; a portion of the Wakeham Bay Sheet (111), AAF Preliminary Base, printed in February 1945.

miserably and disgustedly went back to bed, Jake told me of a 'crater' he had flown over and photographed a few days previously in north-eastern Ungava, near the headwaters of the Povungnituk River. It was the better part of three miles across, had a considerable lake in the centre, and looked as though it had been caused by some vast explosion or at least impact."

In July, 1948, the crater was again photographed in the course of the trimetrogon survey of Ungava carried out by the R.C.A.F. As a result of these photographs C. B. Bassett of Legal Surveys, Ottawa, wrote the Geological Survey of Canada on June 2, 1949, asking for an interpretation of the feature. The following memorandum from Dr. Fortier appears on the files of the Geological Survey:—

"To Chief Geologist Date June 6, 1949.

Subject—Letter from Mr. Bassett re interpretation of Air Photographs

One of the pictures submitted by Mr. Bassett had already been chosen for our collection as an example of a meteorite crater. Comparison of these pictures with those shown in the chapter on meteorite craters, especially in Arizona, in Lobeck's textbook on 'Geomorphology' will convince anyone of the similarities of the features at the two localities. Such a crater to be of volcanic origin would have to be of recent formation, which is not likely in the Canadian Shield.

Y. O. Fortier,
Bureau of Geology and Topography."

In 1949 Professor G. V. Douglas and Mary C. V. Douglas prepared a comprehensive report on Ungava for the Arctic Institute of North America. This has not been published but it may be of interest to quote here from page 442 of Volume III of this report:—

"*The Crater*, (61° 18′ N. Lat., 73° 40′ W. Long.) (Fig. 187) is thought to be meteoric in origin. However, this crater has never been examined on the ground and the theory is based on a study of aerial photographs. If the crater is meteoric in origin it fell nearly vertically, for the elevations on all sides are about the same. It is thought to be post glacial but that it fell at least 10,000 years ago, as the material on the rim has been smoothed out or the rim welt has been susceptible to frost action. The smoothing out can be seen clearly on the right hand of the rim. The circular section and the very steep internal slopes also indicate a meteoric origin."

The photograph included in the above report is R.C.A.F. Photo REA 470-14, taken on July 20, 1948. A copy of this appeared on the front cover of *Sky and Telescope* for November, 1951 (5).

Early in 1950 the prospector, F. W. Chubb, approached Dr. V. B. Meen, Director of the Royal Ontario Museum of Geology and Mineralogy, and called his attention to this crater, thinking possibly it might contain diamonds as do some extinct volcanoes in South Africa (1). Because of the commercial possibilities plans for investigating the

crater were not announced to the public and the "Chubb Crater Exploration Syndicate" was formed and accepted for filing by the Ontario Securities Commission on July 13, 1950 (6). An expedition was jointly financed by the *Globe and Mail* newspaper in Toronto and a group of interested businessmen. As a result of this exploration of the crater, July 21-26, 1950, Dr. Meen became convinced of its meteoritic origin. A second more extensive expedition under the auspices of the Royal Ontario Museum and the National Geographic Society, Washington, was organized by Dr. Meen in 1951 and from July 25 to August 21 detailed studies were made in and around the crater, including a measurement of the depth of the almost circular lake (2). The details of the scientific results secured on this last expedition have not yet been published.

In spite of the early history of the crater outlined above, the staff at the Dominion Observatory were unaware of its existence until the account of Dr. Meen's first expedition appeared in the columns of the *Globe and Mail* on the morning of August 7, 1950. Dr. B. R. MacKay of the Geological Survey of Canada, and the author of this paper visited Dr. Meen on August 15, 1950, and received a first-hand account of his findings. The weight of evidence in favour of this being a genuine meteor crater seemed strong. It was considered that one of the most urgent needs in connection with further scientific study was a detailed air survey of the area in and around the crater. At the request of the Dominion Observatory the R.C.A.F. issued an Operation Order for the necessary photography on August 25, 1950. However, the season available for satisfactory photographic coverage in northern Ungava is short and various circumstances prevented completion of the vertical air photography until the summer of 1953.

In July and August of 1953 Dr. J. M. Harrison of the Geological Survey of Canada spent some time at the crater (7). He supports the meteoritic origin but disagrees with Meen's statement that there is no sign of glaciation in and around the crater. Harrison considers the evidence for the crater being pre-glacial as "overwhelming". Harrison also disagrees with Hoffleit's suggestion (8) that "fossil glacial ice" might have been a major factor in forming the crater.

Dr. Meen recommended that the crater be named "Chubb" in honour of the man who instigated the 1950 investigation. This has not been done, however, since Mr. Chubb did not discover the crater nor did he suggest its meteoritic origin. On June 3, 1954, the Canadian Board on Geographical Names, meeting in Ottawa, accepted the names adopted earlier by the Quebec Geographic Board. These are:—

New Quebec Crater
Crater Lake
Lac Laflamme

The last name is that given to the lake which served as a base of operations for the two expeditions led by Dr. Meen and which was earlier called Museum Lake.

NEW QUEBEC CRATER MAP

During August 1953, a complete air photo coverage of an area 11½ by 10 miles centred on the crater was secured by the Royal Canadian Air Force. The vertical line overlap photography was carried out at a height of 9,400 ft. above sea level, giving a scale on the

FIGURE 3. Montage made from two prints, Nos. REA 659-10 and 659-11 taken by the RCAF on July 15, 1952. This is a view looking slightly east of south across the crater.

original negatives of approximately 1,280 ft. to the inch. A portion of the uncorrected photo mosaic resulting from this survey is reproduced as Figure 4. Several lines across the crater were also flown at a height of 5,540 ft. above sea level, giving photographs of approximately twice the above scale, or 640 ft. to the inch.

Unfortunately the ground control points required for producing an accurate topographical map were not available. Since there might be some years' delay in securing these, and because of the very general scientific interest in the crater, it was decided to produce a map (*see* map pocket) on which the relative positions of the topographical features were correctly shown but where there was an unavoidable uncertainty as to the exact values of both the horizontal and the vertical scales.

The elevations above sea level of 1,700 ft. for both Crater Lake and Lac Laflamme were adopted, as determined by Harrison in 1953 from barometer readings. These values are very close to those found by Meen in 1950 (1).

As a guide to the horizontal scale we have the lake diameter, 9,100 ft., and the rim diameter, 11,500 ft., given by Meen as a result of the 1951 expedition (2). The latter value seemed to agree with the trimetrogon survey material better than the other and the scale (1:25,000) of the printed map accompanying this paper was set on the basis of Meen's rim diameter. It now remains to check this approximate value by any independent methods available in the hope of arriving at a more exact estimate of the true scale of the map.

The results of this procedure, carried out by actual measures on the map after it was printed, are given in Table 1. The first column lists the method used, the second the resulting scale determined, and the third an estimate of the expected percentage probable error. The mile-to-the-inch acetate master used in producing the eight-miles-to-the-inch topographic map (Povungnituk River Sheet) was loaned to the author by the Surveys and Mapping Branch and proved to be the most reliable material available for scale determination. The last three values of scale listed in Table 1 were determined by the two most satisfactory methods and agree reasonably well among themselves. They

TABLE 1

SCALE DETERMINATION FOR PRINTED CRATER MAP

Method	Scale	p.e.
Assuming rim diameter of 11,500 ft	1 : 24,900	
Assuming lake diameter of 9,100 ft	1 : 23,700	
Assuming coordinates of magnetic stations as given on map	1 : 26,400	>5 %
Comparison with topographic 8 miles/inch series, Povungnituk River sheet	1 : 24,260	1 %
Using listed height for air survey flights and measures on original air photos	1 : 24,470	<1 %
Comparison with 1 mile/inch acetate master drawn from trimetrogon survey:—		
10 comparison lines	1 : 24,450	0·3 %
20 comparison lines	1 : 24,520	0·2 %
Adopted true scale of printed map	1 : 24,500	± 0·5 %

were the only ones used in arriving at a final average. It is considered that a scale of 1:24,500 for the printed map is the best that can be adopted, pending the establishment of accurate ground control points near the crater. The probable error of 0·5 per cent is, if anything, estimated on the large side.

The orientation of the printed map must also be considered. Here again, the acetate master map can be used. The bearings of various features visible both on the acetate master and the printed map were compared. From this investigation it has been concluded that the true bearing of the side of the printed map is 354°0 with an uncertainty of half a degree or less. The geographical position of the centre of Crater Lake, as measured on the acetate master, is Lat. 61° 17′0 N, Long. 73° 40′2 W. This position agrees well with that determined from the mean of the magnetic station coordinates.

Since no ground control was available the vertical scale for the contour intervals on the map may have an error independent of the horizontal scale. The establishment of this scale depends on a knowledge of the true height of the aircraft carrying out the survey. The absolute error in measures over a range of 500 ft. above the adopted lake level of 1,700 ft. is probably not more than 3 per cent and may be considerably less. In Table 1 the horizontal scale determined from the recorded height of the aircraft agrees well with that found independently, and this indicates that the listed height of the aircraft cannot be very much in error.

THE PROFILE STUDY OF THE CRATER

This material, in preliminary form, was presented at the meeting of the Royal Society of Canada, June, 1954(9). On the basis of the adopted horizontal scale of 1:24,500 the mean lake diameter is 9,430 ft. and the mean rim diameter 11,290 ft., giving a rim to lake ratio of 1·197. The above figures were found by taking 16 uniformly spaced diameters for both lake and rim and averaging them. Since neither rim nor lake is a perfect circle the individual values of diameter scatter about the mean. The average deviation from the mean in the diameter for a single measure is ±100 ft. for the lake and ±140 ft. for the rim. The centre of the rim is offset from the centre of the lake by 280 ft. in a direction 61° true bearing. This is directly toward the highest point on the rim.

For a study of details of the crater contours the master map used in the production of the printed map was available and was kindly loaned to the author by the Topographical Survey. This is metal backed and is drawn on a scale 1·58 times the printed map. It is hence more suitable for the measurement of fine detail. All measurements of the crater reported below were made on this large scale master map and reduced to feet or degrees by the appropriate scale factors. The unavoidable limitations of the air survey of this area, mentioned earlier, must be born in mind here. Undoubtedly a certain amount of revision in the crater measurements will be necessary when accurate ground surveys become available.

To record the general profile of the crater, unbiased by small local irregularities in the topography, detailed measurements were made along 16 equally spaced radii originating from a point adopted as the best mean position for the centre of Crater Lake. These radii were spaced at intervals of 22·5 degrees from the highest point on the rim, located

FIGURE 4. A portion of the uncorrected photo mosaic made from photographs taken by the R.C.A.F. on August 25, 1953.

in a direction 61° true bearing from the lake centre. It is evident, from a casual examination of the map contours, that one side of the rim is considerably higher on the average than the other. This was reported by Meen (1) as a result of his first expedition to the crater. The measured radii were divided into two groups, those on the high side and those on the low side of the crater, and for identification were lettered from a to p (*see* Figure 8). Since the lowest point on the rim was not exactly opposite the highest point, measures were also made along an additional radius passing through this lowest point. This radius was designated as x. Measurements along it were not averaged in with those along the other equally spaced radii.

The results of these detailed profile measurements are listed in Table 2. The first column gives the radius identification, the eight radii on the high side being listed first. Radius d passes through the highest point on the rim. In addition to general averages,

TABLE 2

PROFILE STUDIES ALONG STANDARD RADII

Designation	True Bearing of Radius from Adopted Lake Centre	Distances from Adopted Lake Centre (in feet)				Inclination to Horizontal		Height Above Lake Level (in feet)		True Bearing of Rim Position from Rim Centre
		To Edge of Lake	To Highest Point on Rim	To Discontinuity in Outer Slope	To Point on Outer Slope at Lake Level	Inner Slope	Outer Slope	Highest Point on Rim	Discontinuity in Outer Slope	
a	353°·5	4,660	5,780	7,180	13,600	34°·3	10°·4	420	175	351°·0
b	16·0	4,700	5,830	7,580	16,200	30·8	7·3	370	175	14·0
c	38·5	4,770	5,950	7,810	16,700	31·4	7·9	395	175	37·5
d	61·0	4,760	5,950	9,190	13,800	31·9	9·4	530	70	61·0
e	83·5	4,940	5,820	6,840	19,600	27·2	8·4	370	230	84·5
f	106·0	4,860	6,060	7,810	(30,000)	33·3	6·8	435	245	108·0
g	128·5	4,690	5,770	6,840	>37,000	30·4	9·5	455	295	131·0
h	151·0	4,570	5,990	6,950	(30,000)	30·1	9·0	400	255	154·0
Means for High Side		4,740	5,890	7,530	21,500	31·2	8·6	420	200	
i	173·5	4,650	5,570	7,010	16,700	32·8	7·0	345	190	176·0
j	196·0	4,740	5,450	6,490	11,900	36·7	10·9	285	120	198·0
k	218·5	4,990	5,420	6,780	12,800	30·9	7·1	220	90	219·5
l	241·0	4,660	5,530	6,430	25,400	32·4	7·5	330	200	241·0
m	263·5	4,620	5,380	5,860	(28,000)	30·9	15·3	295	175	262·5
n	286·0	4,560	5,460	6,430	(31,000)	30·0	5·9	260	135	284·0
o	308·5	4,800	5,670	7,470	31,200	24·8	6·3	290	110	306·0
p	331·0	4,770	5,720	7,240	14,700	29·7	8·2	385	160	328·0
Means for Low Side		4,720	5,530	6,710	21,500	31·0	8·5	300	150	
General Means		4,730	5,710	7,120	21,500	31·1	8·6	360	175	
x	268·5	4,620	5,030			32·2		170		267·0

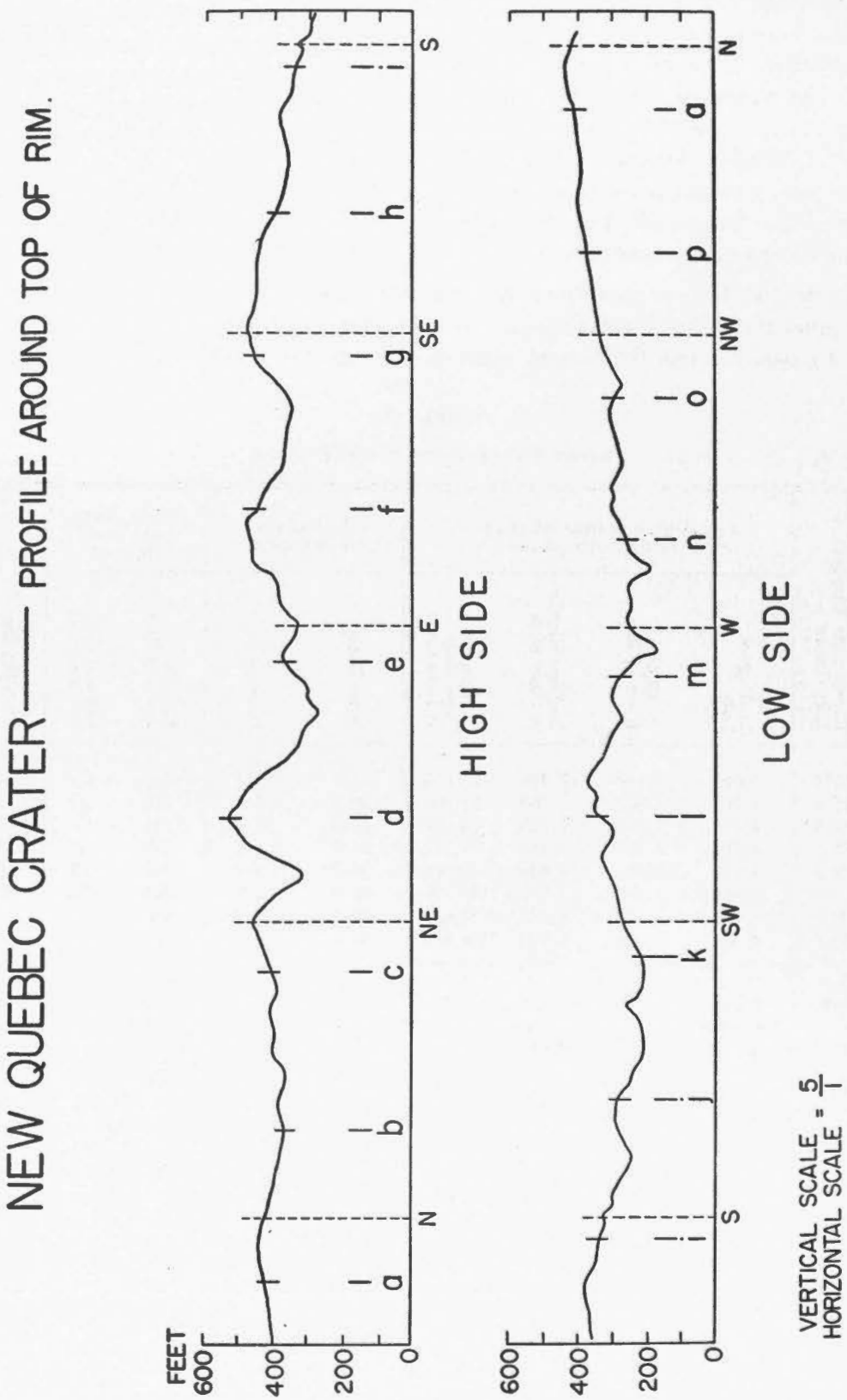

FIGURE 5. The variation in height around the crater taken at the crest of the rim.

separate averages for the high and low sides have been listed. The second column gives the true bearing of each radius from the adopted lake centre. These values were determined by assuming the orientation of the printed map determined above.

The next four columns give horizontal distances in feet from the lake centre to specified points along the radius; 1—the shore of the lake, 2—the highest point on the rim, 3—a point where the fairly steep and regular outer slope seems to break and alter to a much more gradual and irregular descent, 4—a point where the topography seems to have reached the level of 1,700 ft. above sea level adopted as standard for Crater Lake and Lac Laflamme. It should be noted here that often the ground rises again from this 1,700 ft. level as we move farther out from the crater. Hence, as pointed out later, the basic level of the topography around the crater may be some tens of feet higher than 1,700 ft. above sea level. The seventh and eighth columns give measurements of the inclinations to the horizontal of the inner and outer rim slopes. These were determined graphically from profiles plotted on a large scale. The tabulated values correspond to the portions of the rim profiles which approximate straight lines, and not to the well-rounded portions near the top of the rim. The outer rim slope given is for the steeper part, that inside the discontinuity mentioned above.

The ninth column lists the elevation of the top of the rim above the lake level and the tenth column gives the same value for the discontinuity on the outer slope. Finally, the last column gives the true bearings of the points where the standard radii cut the mean rim position, taken from the mean rim centre. Since, as noted above, this is displaced somewhat from the lake centre these bearings will differ from those in the second column.

Let us now examine in turn these measured features of the crater profile. The lake radius shows no significant difference on the high and the low side, which is as it should be if the adopted centre is well chosen. On the other hand the mean rim radius on the high side is 360 ft. greater than on the low side, a natural result of the rim centre being offset from the lake centre. It will be noted that the general means for lake radius, 4,730 ft., and rim radius, 5,710 ft., given in Table 2, are not exactly half the lake and rim diameters given earlier. The discrepancy results from the difference in the methods of finding the listed values. In the first case 16 diameters were measured, taken as straight lines across the features. In the second 16 radii were measured from a fixed point and this point, while centre for the lake, was not the centre of the rim.

Along most of the radii it was not too difficult to select a point where the outer slope of the rim flattened markedly. There is far more variation in the position of this discontinuity than in either the lake edge or the top of the rim. It is systematically further out on the high side by about 800 ft. when compared with the low side.

The most irregular value of all is the position where the general level of the ground reaches the 1,700 ft. contour. Along some of the radii this had to be extrapolated and the figure is very uncertain and is included in brackets. In spite of this, however, it is felt that the tabulation of this quantity is of value and it is interesting to note that both the high and low sides give approximately the same average distance, i.e., $4\frac{1}{2}$ times the lake radius. Allowing for the difference between the high and low sides the average

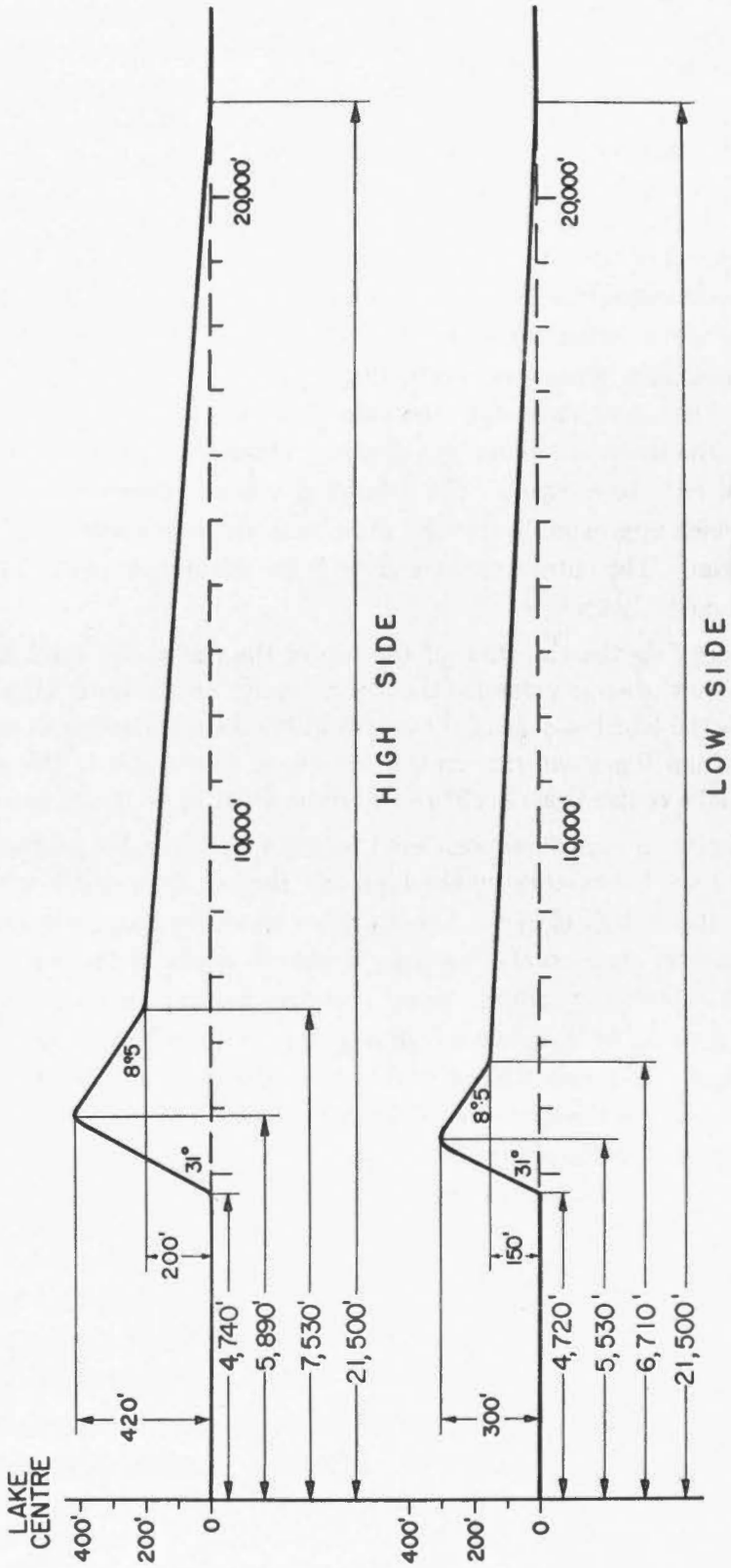

FIGURE 6. Schematic plot of mean values for the high and low sides of the crater, taken from Table 2.

deviation of a single measured value from the mean is 2 per cent for the lake and rim radii, 7 per cent for the radius of the discontinuity in the outer slope, and just over 30 per cent in the distance to lake level on the outer slope.

In the case of the inner and outer rim slopes there is no indication of any systematic difference between the high and the low sides. The average deviation of the individual values from the mean is 1·8 degrees for the inner slope and 1·6 degrees for the outer. Considering the inherent errors present in measuring these slopes this agreement is good. However, it is difficult to reconcile these values with the slopes published by Meen who in 1950 gave 45° inner slope, 25° outer slope (1)*, and in 1952 gave 40°–45° for the inner slope (2). Measurement of the inner slope from photographs on pages 6 and 29 of this latter paper, where a point with vision tangent to the lake edge can be chosen, gives 33° and 31° respectively, which seem to agree with those listed in Table 2. Meen does not indicate how his slopes were determined and they would appear to be only rough visual estimates. The eye normally exaggerates the angle of any slope, particularly if it is viewed from above.

There is considerable variation of height around the rim, and the high side averages 120 ft. higher than the low side. The average deviation of individual measurements from the means for the high and low sides is 40 ft. The height of the discontinuity on the outer slope also varies by about this same amount. It is 50 ft. up on the high side as compared with the low. The highest portions of the rim average 200 to 300 ft. higher than those diametrically opposite to them and, since the inner slopes are roughly uniform all the way round the crater, this automatically offsets the rim centre from the lake centre by the measured amount.

To give a picture of the variation in elevation around the top of the rim the height of the crest was measured in relation to true bearings taken from the rim centre. These values have been plotted in Figure 5, the vertical scale being expanded over the horizontal by a ratio of approximately 5 to 1. The positions where the 16 standard radii cross the rim crest have been indicated.

The mean values for the high and the low sides of the crater, taken from Table 2, are summarized schematically in Figure 6.

The 16 individual profiles measured along the standard radii are plotted in Figure 7. The vertical scale has been expanded to 5·18 times the horizontal so that the various features of the profiles can be studied to better advantage. It is unfortunate that we have so little knowledge of the crater profile below the water line of the lake. Meen has published one value only, a depth of 825 ft. for the lake centre (2), and this has been plotted to scale in relation to profile d. The smooth inner slope of the rim has been continued as a dotted line in the figure but its correct position must remain uncertain until additional lake depths have been published.

The 16 profiles reproduced in Figure 7 have been averaged for the high side and for the low side and the final means given in Table 3. In taking these means the steepest portions of every profile, i.e. the slope from the water level up, were placed in coincidence

* In discussing this point with Dr. Meen he pointed out that their party had climbed over the rim at a location between radii "a" and "p" and in Figure 7 it is seen that these profiles are above average in steepness at the top of the outer slope.

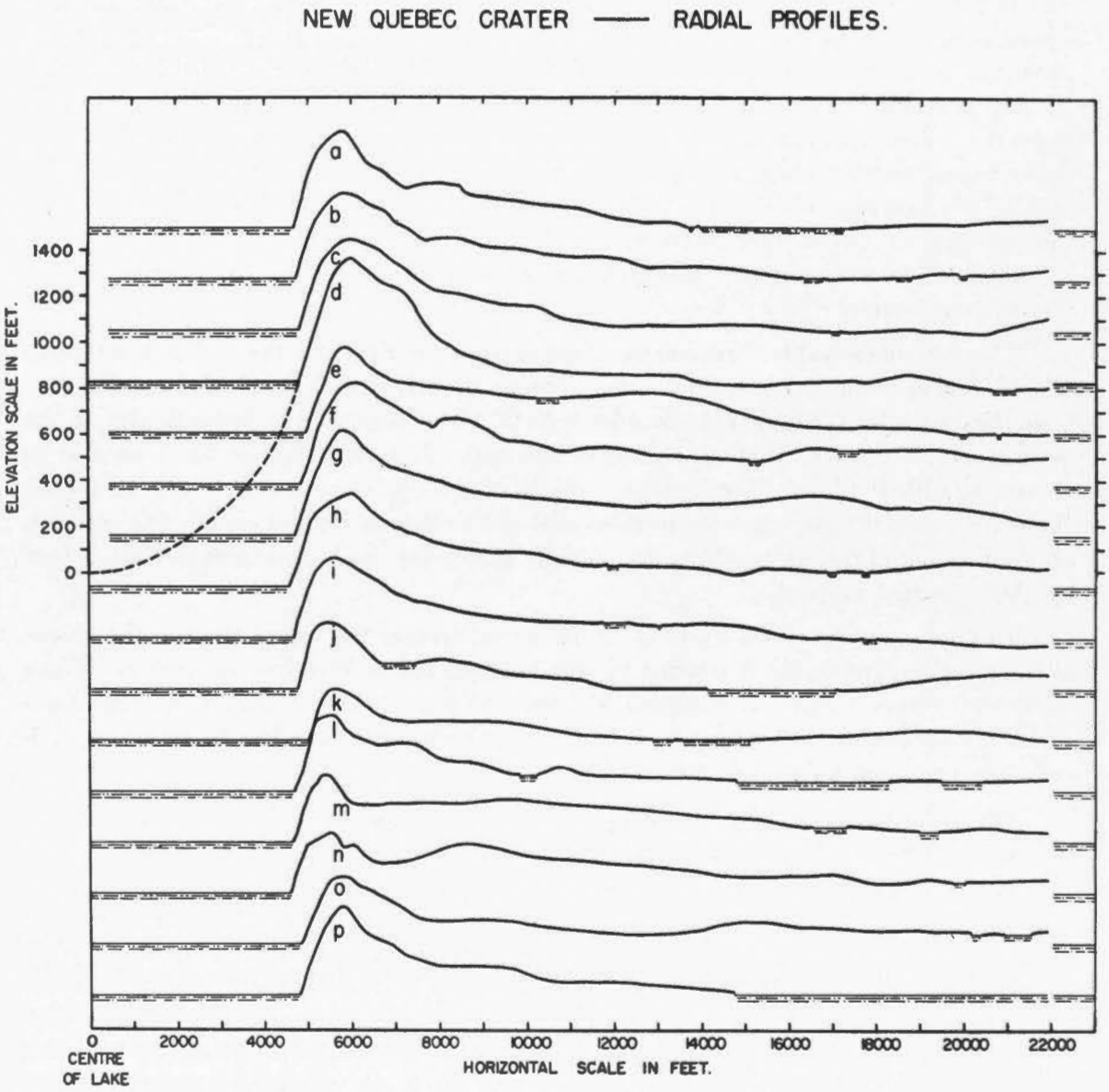

FIGURE 7. Profiles of the New Quebec crater measured along the 16 standard radii. Vertical scale 5·18 times the horizontal.

as otherwise the process of taking means would give an artificially low slope. When these mean profiles are plotted to scale we find a tendency to flatness on the upper portion of the inner slope, before it rounds off for the crest. This gives a 10 to 12 degree incline above the 31-degree drop to the lake level. The feature can be seen on several of the individual profiles in Figure 7. The figures of Table 3 do not reproduce exactly the means of Table 2 because of the difference in the methods of reduction. For example, the crests of the mean profiles are lower in both cases than the means for the ninth column of Table 2. In Table 2 the highest points on each profile are brought together and averaged but when taking the mean profiles for Table 3 the highest points are not all at exactly the same distance from the lake shore and so do not fall over each other and are not averaged together. Other differences may be explained in a similar way.

TABLE 3

MEAN PROFILES FOR HIGH AND LOW SIDES

High Side				Low Side			
Distance from Lake Centre	Height Above 1700′	Distance from Lake Centre	Height Above 1700′	Distance from Lake Centre	Height Above 1700′	Distance from Lake Centre	Height Above 1700′
(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)
4,740	0	9,340	140	4,720	0	9,320	113
4,855	68	9,900	129	4,835	68	9,900	96
4,970	140	10,500	113	4,950	139	10,500	84
5,085	206	11,600	94	5,065	206	11,600	68
5,200	267	12,800	78	5,180	244	12,800	54
5,315	315	13,900	64	5,295	267	13,900	49
5,430	353	15,100	49	5,410	287	15,100	40
5,545	379	16,200	52	5,525	297	16,200	30
5,660	400	17,400	50	5,640	293	17,400	29
5,775	411	18,500	53	5,755	275	18,500	29
5,890	415	19,700	49	5,870	254	19,700	27
6,005	409	20,800	41	5,985	235	20,800	25
6,120	395	22,000	49	6,100	223	22,000	23
6,235	378	23,100	51	6,215	209	23,100	22
6,350	358	24,300	51	6,330	196	24,300	18
6,465	340	25,400	66	6,445	185	25,400	7
7,040	274	26,600	75	7,020	150	26,600	9
7,610	215	27,700	66	7,590	137	27,700	5
8,190	193	28,900	51	8,170	132	28,900	8
8,760	162			8,740	128		

Examination of the map shows little evidence of the concentric ridges surrounding the crater, mentioned by Meen on page 10 of (1). However, the contour interval of 25 feet is too large to show very much detail of this nature. An examination of the mean profiles shows that there is no general tendency for concentric ridges at fixed distances outside the main rim.

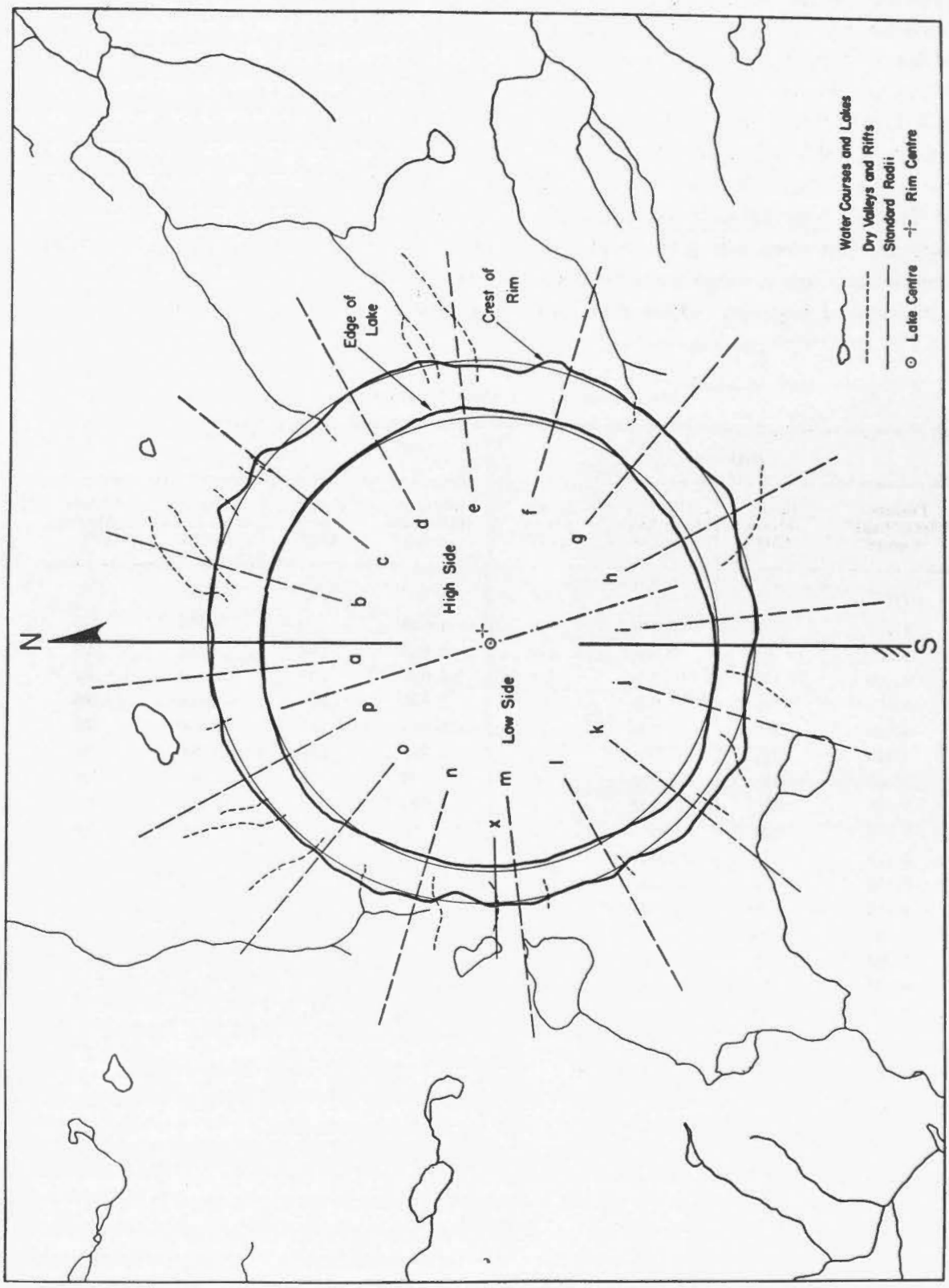

FIGURE 8. Scale plot showing the relation between the rim crest and the lake shore. The radial rifts and valleys and the locations of the standard radii have also been plotted.

As noted by Meen there are a number of rifts or valleys which cross the rim in a generally radial direction. Over 20 of these can be picked out from the map and their position has been plotted in Figure 8, together with the contours of the lake edge and the crest of the rim. For ease in reference the standard radii have also been plotted. Harrison (7) has pointed out that these valleys have been considerably modified by the direction of glacial drift. The glacial groovings and striae can be seen in the photomosaic of Figure 4, particularly on the northeast side of the crater. Evidence of their presence can also be seen in the water courses and valleys plotted in Figure 8. On the average the glacial striae lie along a bearing from 233°–53° true. The valleys intersect the crest of the rim at angles ranging all the way from 0° to 40° to the radial direction, with a mean angle of 15°. On the outer slope of the rim the valleys deviate still further from the radial line.

The magnetic observations recorded on the map were made by W. L. W. Hannaford, Division of Geomagnetism, Dominion Observatory. A standard electrical magnetometer, designed at the Observatory, was used, and the observations were taken as part of the regular magnetic coverage of the Canadian north. In this work no attempt was made to study in detail any magnetic features around the crater, nor to detect possible magnetic anomalies connected with the crater. The magnetic values found are normal for the region. The geographical coordinates listed were derived in the course of azimuth determinations and are not of the accuracy of those for precise geodetic control points.

GENERAL DISCUSSION OF CRATER PROFILES

It is of interest now to examine the mean profile of the New Quebec crater in the light of the general characteristics of explosion craters, both lunar and terrestrial. Baldwin (10) has found empirically two formulae giving relations among the three quantities — rim diameter, rim height, and total depth — for explosion craters. These are:—

$$D = 0 \cdot 1083d^2 + 0 \cdot 6917d + 0 \cdot 75$$
$$E = -0 \cdot 097D^2 + 1 \cdot 542D - 1 \cdot 841$$

where

D is log diameter (feet)
d is log depth (feet)
E is log rim height (feet)

From Table 3 we may conclude that the general average elevation of the terrain outside the crater is approximately 30 ft. above the lake level, or 1,730 ft. above sea level. We can then adopt the following as the best averages for the measurements of the New Quebec crater:—

diameter	11,290 ft.
depth	1,185 ft.
rim height	330 ft.

Using the value $D = \log 11{,}290 = 4 \cdot 0526$ in Baldwin's equations we find that for a typical explosion crater with this diameter the corresponding depth is 1,535 ft. and the rim height 655 ft. The depth of the New Quebec crater does not agree exactly with Baldwin's curve as it is just 77 percent of the average value. Still, this difference is only $0 \cdot 11$ in

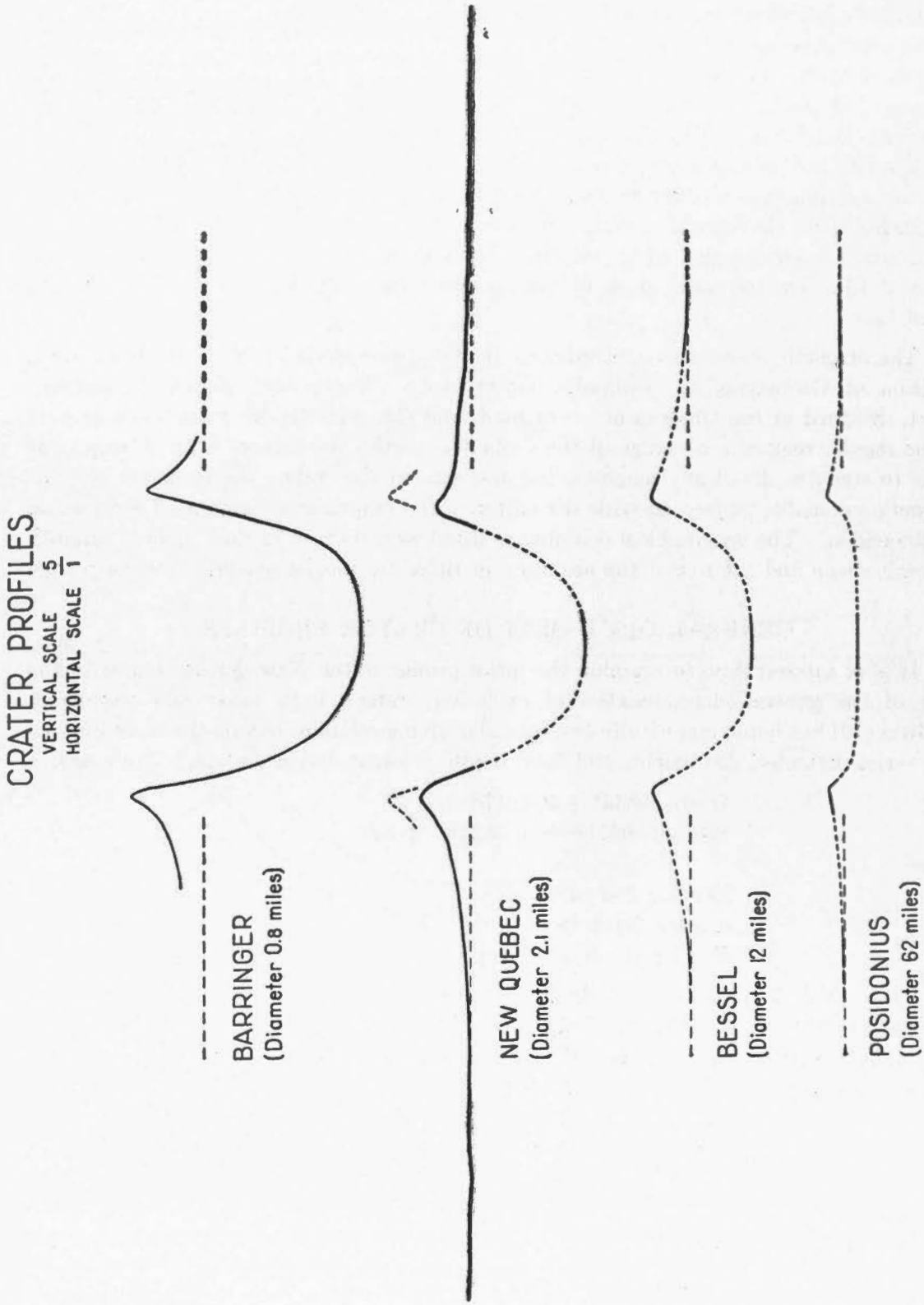

FIGURE 9. Comparison of the profiles of two terrestrial craters and two lunar craters. The measured portions of the profiles are indicated by the solid lines.

the log and is well within the general scatter in Baldwin's Figure 12 on page 132, *loc. cit.* The observed rim height shows a greater divergence from the standard, being barely 50 percent of the computed value.

However, a more basic figure than the above is the true depth of the crater below average ground level. This is found by subtracting rim height from the depth and is 1,535 − 655 = 880 ft. for the standard crater profile. The measured quantities are 1,185 − 330 = 855 ft., a very good agreement with the predicted value. It is obvious then that the New Quebec crater differs from the average explosion crater of corresponding size chiefly in the rim height, which is about half the expected value. Reference has already been made to the evidence of glaciation which has taken place since this crater was formed. It is likely that the rim height has been considerably reduced by this agency.

In Figure 9 the profiles of four craters are plotted for comparison purposes. The horizontal scales have been adjusted so that the craters as plotted have a uniform diameter. The vertical scales are in each case five times the horizontal scales. The Barringer crater profile was measured from a contour map prepared by Roswell Miller, III, and N. C. Harding in 1951, and kindly forwarded to the author by D. Moreau Barringer, Jr. The New Quebec crater profile was plotted from the two mean profiles listed in Table 3 of this paper. The values for the two lunar craters were taken from MacDonald's lists (11).

In comparing the New Quebec crater with the Barringer crater the well-rounded rim of the former is evident and leaves little doubt that it has been considerably ground down by glacial action. The tendency to flatness on the upper part of the inner slope, mentioned earlier, also supports this view. The rim height for the standard crater, taken from Baldwin's formula, has been plotted as a dotted line above the observed profile. The highest point on the rim is at true bearing 61° from the centre and the average of the high side is at true bearing 72°. The bearing of the glacial groovings is 53° true and Harrison (7) has given the direction of glacial drift as from the southwest towards the northeast quadrant. It is probably not coincidence that the low side of the rim is in the direction from which the glacial drift has come. Harrison suggests that as the glacial age developed the water in the crater would freeze and form a solid surface over and around which the glacial ice would flow. Relatively little in the form of glacial debris would then be trapped in the crater itself. The correctness of this view is supported by the close agreement between computed and measured depth of the crater below the general ground level. On the other hand the abnormally low and rounded rim would indicate that much of the original rim material was carried around and over the crater by glacial action and deposited to the northeast of the feature. In view of the above discussion it is felt that any connection between the high and low sides of the crater, and the direction of travel of the meteoric mass which may have formed the feature, is rather doubtful. The uniform inside slope around the rim and the nearly circular shape would also indicate that the crater-forming explosion acted symmetrically in all directions. The offset position of the rim with respect to the lake is a necessary consequence of the rim being higher on one side than on the other.

If the crater rim ever did extend to a height corresponding to the average for explosion craters it means that a depth of several hundred feet of rim was carried away by glaciation.

This could only have been in the form of broken rock fragments as it is difficult to imagine the basic layers of granite being worn away to this extent. Since this crater was formed in ancient granitic gneisses and since most of the comparison craters were formed in softer and lighter material, it is possible that the original rim height for New Quebec differed from the average given by Baldwin's equation.

The underwater profile for the New Quebec crater is drawn in Figure 9 for illustrative purposes and is very uncertain, as only the depth at the centre of the lake is known. Taking the entire crater profile as drawn, a very rough calculation gives a greater volume of material in the rim than is the total volume of the crater below the adopted ground level. This takes no account of the material removed by glaciation and if this is added to the rim volume the discrepancy becomes even greater. It is possible that the underwater profile, as drawn, is too shallow and that hence the calculation of the crater volume under the water is too small. What has a much greater effect is the choice of the average ground level which existed at the spot prior to the formation of the crater. Owing to the uneven nature of the surface in the neighbourhood, and to the uncertainties resulting from the absence of accurate geodetic ground control, it is difficult to make a good estimate. It seems evident that the average ground level chosen above is too low and that it should be raised, perhaps by as much as 50 ft. If this were done the discrepancy would disappear. It does not seem profitable to make detailed computations on this point or to pursue the matter further until geodetic ground control has been established and until more is known concerning the profile of the lake bottom.

Let us now consider the question of the slopes on the inside and the outside of the crater rim. The theoretical study of the slope at which any given type of material may be expected to lie is a complicated one, as can be seen by reference to such works as Terzaghi's "Theoretical Soil Mechanics" (12). It is not proposed to discuss this phase of the subject here. We can, however, examine the information available concerning other explosion-type craters.

For 113 lunar craters, with diameters from 1 to 18 miles, Fauth (13) finds a mean inner slope of 33°.5, with no tendency within this group for the average slope to vary with crater diameter. For larger lunar craters Fauth's mean slopes are considerably less. On the earth, where surface changes are continually taking place, the slopes found in a crater should vary more than on the moon, as they will be dependent upon the age and the type of weathering to which the crater has been exposed. In general these changes will tend to decrease the original slopes present when the crater was first formed. The steepest part of the inner slope for the Barringer crater, measured from the profile in Figure 9, is 49° for the high side, 36° for the low side. From pictures of the Wolf Creek crater, published by C. H. Holmes (14), the inner slope seems to average between 25° and 30°. For the two Odessa craters the slopes of the rock walls, apart from the sand fill, are 37° and 26° as measured on diagrams in an unpublished report by Sellards and Evans (15). The inner slopes of the Talemzane crater (16) vary from 22° to 30°, those of the Aouelloul crater attain 20° to 30° (17). Measurements of the plotted profiles of the largest Estonian crater at Ösel (18) give an average inner slope of 28°. From the profiles published for four of the Campo del Cielo craters (19) mean inner slopes of 12°,

12°, 16° and 8° respectively are measured. From the above brief summary it will be seen that the 31° inner slope of the New Quebec crater lies between those found in the relatively recent and well-preserved Barringer crater and the slopes of other terrestrial craters which in general have been modified to a greater extent by weathering. The inner slope for New Quebec is close to but slightly less than the average for craters of similar size on the moon.

A range of values from 1° to 8° has been given for the outer slopes of the lunar craters by Neison (20) and Schmidt (21). The Barringer crater profile has an average outer slope of about 15°, and 5° to 15° is the range given for the outer slope of the Aouelloul crater (17). Outer slopes for the large Estonian crater average about 12° (18). Little other quantitative information is readily available concerning the outer slopes of terrestrial craters. Some have no appreciable outer slopes but wherever one exists it is always described as considerably less than the inner slope. The mean slope of 8°.5 measured for the top of the outer rim wall at the New Quebec crater is equal to the maximum of the outer slopes reported for the moon and is probably near the centre of the range for outer slopes of terrestrial craters.

SUMMARY

To summarize the above profile study we find that the New Quebec crater agrees well with the standard form of explosion craters of comparable size. It has a nearly circular outline, the depth of the crater below ground level is normal and the inner and outer slopes of the rim are what we might expect from a study of other craters. Only in the rim height is there very much divergence from the standard profile and the well-rounded rim crest, together with ample evidence of glaciation at the crater, will explain this. There has been nothing in the present investigation to negative the theory of meteoric origin for this feature. In fact, it is felt that the close agreement between the New Quebec crater and the normal series of explosion craters, considerably strengthens the meteoric theory and, in the absence of any other satisfactory suggestions, leaves a meteoritic origin as the best explanation for the presence of this large symmetrical depression in the Precambrian rocks of the Canadian north.

ACKNOWLEDGMENTS

In conclusion it is desired to thank A. A. Larocque of the Map Compilation and Reproduction Division for his assistance in the determination of the scale of the printed map. Among a number of both service and civilian personnel who supplied the writer with details concerning the early history of the crater particular mention should be made of W/C W. K. Carr, R.C.A.F., and of Dr. B. R. MacKay, formerly of the Geological Survey of Canada. The Office of Research and Liaison, U.S.A.F. Aeronautical Chart and Information Centre, Washington, was very helpful in checking the early appearances of the crater on their maps. Discussions with Drs. Morris Innes and J. A. Rottenberg and with other members of the Observatory staff are gratefully acknowledged, and finally, the author's sincere thanks go to Dr. C. S. Beals for his constant advice and encouragement throughout the course of the investigation, and generally in all problems dealing with the study of explosion craters.

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APPENDIX A

NOTES ON THE APPEARANCE OF THE NEW QUEBEC CRATER ON MAPS OF THE UNGAVA PENINSULA

Date of Map	Series and Sheet in Series	Scale	Source	Plotting of the Crater
1942	Regional Aeronautical Chart, UNGAVA BAY	1:1,000,000	USAAF	No crater plotted
1942	National Topographic Series, POVUNGNITUK RIVER (35 S.E.)	1:506,880	Mines and Resources	No crater plotted
1944, May	AAF Aeronautical Chart, HUDSON STRAIT (111)	1:1,000,000	USAAF	No crater plotted
1945, Feb.	AAF Preliminary Base, WAKEHAM BAY (111D)	1:500,000	USAAF	Plotted with word "crater"
1945, Aug.	AAF Aeronautical Chart HUDSON STRAIT (111) Base No. 2	1:1,000,000	USAAF	Plotted with word "crater"
1946	National Topographic Series, POVUNGNITUK RIVER (35 S.E.)	1:506,880	Mines and Resources	Plotted with word "crater"
1949	World Aeronautical Chart, IACO KOVIK RIVER (2109)	1:1,000,000	Mines and Tech. Sur.	Plotted
1949	National Topographic Series, POVUNGNITUK RIVER (35 S.E.)	1:506,880	Mines and Tech. Sur.	Plotted with word "crater"

APPENDIX B

Official Air Photographs of the New Quebec Crater

Date	Source	Photo Reference Numbers	Remarks
1943, June 20	AAF	1 — 2086 L — 8212 — 8213 — 8214 — 8216	trimetrogon survey, first photos of the crater
1946	RCAF	REA 360 — 18	oblique, distant view
1948, July 3	RCAF	T 193 R — 85 — 86 — 87 — 88 — 89 — 90 — 190 — 191 — 192 — 193 — 194 — 195 — 196 — 197	trimetrogon survey, crater from east trimetrogon survey, crater from west
1948, July 20	RCAF	REA 470 — 14 — 15 — 16 — 17 — 18 — 19	obliques, mostly close-up views of the crater
1952, July 15	RCAF	REA 659 — 7 — 8 — 9 — 10 — 11 — 12 — 13	obliques, mostly close-up views of the crater
1953, Aug. 9	RCAF	A 13842 — (1—39)	39 vertical photographs at 9920′
Aug. 25	RCAF	A 13841 — (1—124)	124 vertical photographs at 5540′
Aug. 25	RCAF	A 13780 — (47—191, 327—349)	168 vertical photographs at 9400′

Note:—Prints of the RCAF photographs listed above may be purchased from the National Air Photographic Library, Department of Mines and Technical Surveys, Ottawa, Ont.

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TABLES OF EXTENDED DISTANCES FOR PPP, pPP, pPKP AND FOR P AT VERY SHORT DISTANCES

BY

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ABSTRACT

The paper presents tables of extended distances for several secondary phases which are occasionally useful in fault-plane solutions, and extends earlier tables for P to very short distances. The tables are given for surface focus and for focal depths ranging from 0·00R to 0·12R in steps of 0·01R. They are consistent with earlier tables of extended distances so that the several phases can be used in a single solution.

INTRODUCTION

In recent years this Observatory has carried out a program to determine the direction of faulting in large earthquakes. The solutions are based on direction of motion data supplied by co-operating stations through the medium of questionnaires. Collaborators are urged to supply direction of motion data not only for the first phase but also for secondary P phases where the direction of motion can be read with confidence. Tables of extended distances for the secondary phases PcP, PP and pP have already been published[1,2]. The present paper presents tables of extended distances for some other secondary phases which have been reported frequently enough to suggest that the tables would be of value.

Earlier tables of extended distances for P[3] were left incomplete at very short distances pending the completion of tables of extended distances for PKP. The missing entries are obtained automatically in the course of obtaining extended distances for pPKP and are presented in tabular form.

DERIVATION OF THE TABLES

There is one important basic principle underlying the derivation of these tables It has been discussed in earlier papers, but will bear repetition. In Figure 1, F is supposed to represent the focus of an earthquake. The technique of deriving tables of extended

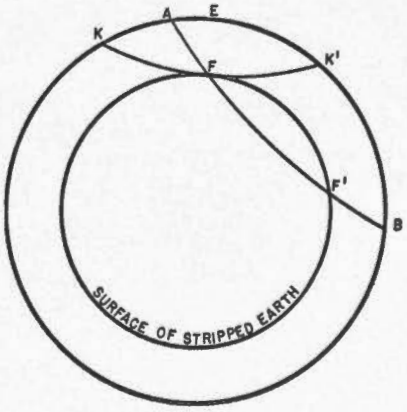


Figure 1.

[1] J. H. Hodgson and J. F. J. Allen, "Tables of Extended Distances for PKP and PcP", *Publications of the Dominion Observatory*, Vol. XVI, No. 10, 1954.

[2] J. H. Hodgson and J. F. J. Allen, "Tables of Extended Distances for PP and pP", *Publications of the Dominion Observatory*, Vol. XVI, No. 11, 1954.

[3] J. H. Hodgson and R. S. Storey, "Tables Extending Byerly's Fault-Plane Techniques to Earthquakes of Any Focal Depth", *Bull. Seism. Soc. Am.*, 43, 49-61, 1953.

distances for deep-focus earthquakes has been to strip the earth to the depth of focus. Stations such as A, lying in the zone KK′ and receiving their impulse from an upward rising ray, are thus lost to analysis.

In an earlier paper[3] it was shown that if AFB is a continuous ray, such that an earthquake at A would give rise to the ray AFB, then the point A and the point B would receive the same initial impulse, either both compressions, or both dilatations. Thus information obtained at a station A in the stripped zone need not be lost but may be used to infer the motion at F′, the stripped earth equivalent of the point B. A and B are, of course, at exactly opposite azimuths, so that the extended distances of points such as A were given as equal to the extended distance of their related point F′ but with a negative sign.

The tables[3] of extended distances for P may thus be used to obtain sets of related points, that is pairs of epicentral distances whose extended distances are equal in magnitude but opposite in sign. For example the extended distance at 0·12R for 4° is −1·341. By interpolation, the extended distance for 76°.1 is +1·341. 4° and 76°.1 are related distances.

Now refer to Figure 2, in which A and B are related points, so that the extended distance of A is the negative of the extended distance of B. The ray FB gives rise, by reflection, to a PP ray emergent at C and to a PPP ray emergent at D. Since extended distance is a function only of the angle at which the generating ray leaves the focus, all these rays will have the same extended distance. Similarly a P phase recorded at A, a pP ray recorded at E and a pPP ray recorded at G will all have the same value, but with a negative sign.

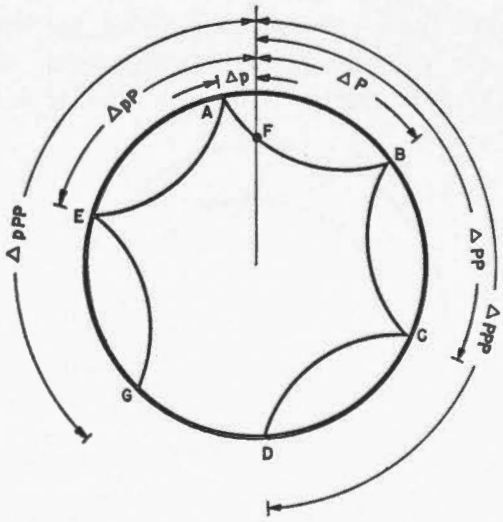


FIGURE 2.

By examination of the figure, and in the notation there defined, we have

$$\triangle PPP = 3\triangle P + 2\triangle p, \tag{1}$$

$$\triangle pPP = 2\triangle P + 3\triangle p. \tag{2}$$

By putting a pair of related values $\triangle$P and $\triangle$p into these equations we will obtain values of $\triangle$PPP and $\triangle$pPP having numerically the same extended distance. For example, we have already seen that, for a focal depth of O.12R, 4° and 76°.1 are related points with extended distance 1·341. Then

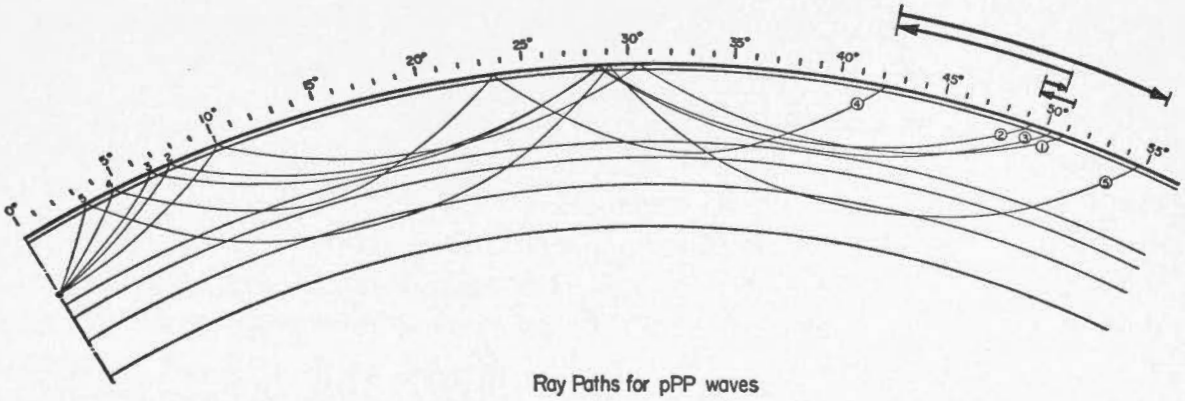
$$\triangle PPP = 3(76^\circ.1) + 2(4^\circ.0) = 236^\circ.3,$$
$$\triangle pPP = 2(76^\circ.1) + 3(4^\circ.0) = 164^\circ.2,$$

so that the extended distance of PPP at 236°.3 is 1·341 while that of pPP at 164°.2 is −1·341.

By taking a number of pairs of related points, one rapidly obtains corresponding values of $\triangle$PPP and $\triangle$pPP. By plotting these against extended distance and reading off at even values of $\triangle$, the required tables are obtained.

Table I (pages 89 to 92) gives extended distances for PPP, while Table II (pages 93 to 96) gives those for pPP.

In an earlier paper[2] in which extended distances were given for PP and pP, it was found that the extended distances for pP did not approach zero smoothly. This was found to be due to a complicated cusp arrangement on pP. This cusp has since been demonstrated graphically by one of us[4] and has been discussed analytically by Bullen[5]. An analagous cusp of course exists on pPP, and again prevents a smooth approach to zero. As an example, the ray diagram is shown in Figure 3 for a focal depth of 0·05R. The double cusp is clearly shown. The corresponding multiple values of extended distance have not been shown in the tables since the several sections of the cusp have not been observed in practice. Only the largest value of extended distance has been given in each case.



Ray Paths for pPP waves
Focal Depth 0·05 R

FIGURE 3.

We now turn our attention to obtaining extended distances for the phase pPKP. Consider Figure 4, which shows ray paths for PKP and for pPKP. Once again A and B are related points, and the extended distance of a P wave emergent at A and of a pPKP

[4] P. L. Willmore and J. H. Hodgson, "Charts for Measuring Azimuth and Distance and for Tracing Seismic Rays through the Earth", Publications of the Dominion Observatory, Vol. XVI, No. 14, 1955.

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ray emergent at C are equal to each other and to the negative of the extended distance of a PKP wave emergent at B. In the notation of the figures:

$$\triangle pPKP = \triangle PKP + 2\triangle p. \tag{3}$$

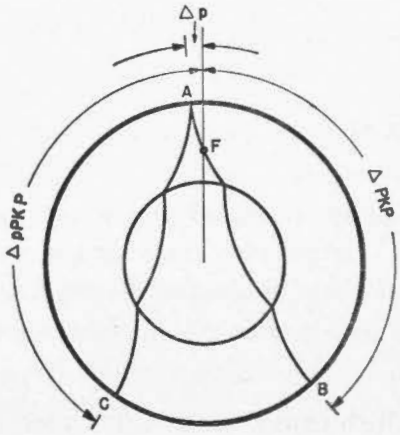

FIGURE 4.

Unfortunately the original tables of extended distances for P do not give values of $\triangle p$ corresponding to values of PKP, so that it is not possible to obtain sets of related points from those tables. However, values of $\triangle p$ were obtained in deriving the tables of extended distances for PKP, although they were given a different symbol. If the reader will refer to Figure 3 and the accompanying text of that earlier paper[1] it will be seen that the angle which is here called $\triangle p$ was there designated θ. Table II of that paper is typical of tables which were developed in that earlier work, in which values of i_d, the angle at which the ray leaves the focus of depth d, are related to values of θ_{sd}, the angle corresponding to $\triangle p$. These original tables are still available in storage and were used in the present work.

The method of procedure can probably best be illustrated by an example based on Table II of the earlier paper, although it happens to present a rather uninteresting case. That table gives values corresponding to a focal depth of 0·00R. For this focal depth and for an epicentral distance of 145°, the extended distance of PKP_2 is 3·69. Then $i_d(=i_o$ in this case) is $\cot^{-1} 3{\cdot}69$, or 15°.2. By the table, the corresponding value of θ_{so} is 0°.08. Hence $\triangle p$ = 0°.08 and $\triangle PKP_2$ = 145° are a pair of related points having the same numerical value of extended distance 3·69. By equation (3), this same value would apply to

$$\triangle pPKP_2 = 145° + 2(0{\cdot}08) = 145°.2$$

Hence, for a focal depth of 0·00R the extended distance of a P wave emergent at 0°.08 and that of a $pPKP_2$ wave emergent at 145°.2 are both −3·69. Selecting other values of $\triangle PKP$ one computes the corresponding values of $\triangle p$ and of $\triangle pPKP$ and so builds up the required tables.

Extended distances for $pPKP_1$ are given in Table III (pages 97 and 98) of $pPKP_2$ in Table IV (page 99) and for P at short distances in Table V (page 100).

TABLE I

Extended Distances for PPP

Δ°	Depth h =												
	0·00	0·01	0·02	0·03	0·04	0·05	0·06	0·07	0·08	0·09	0·10	0·11	0·12
9	0·041	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
10	0·063	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
11	0·084	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
12	0·107	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
13	0·130	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
14	0·151	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
15	0·173	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
16	0·194	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
17	0·216	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
18	0·236	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
19	0·256	0·032	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
20	0·275	0·058	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
21	0·294	0·079	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
22	0·313	0·096	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
23	0·332	0·112	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
24	0·350	0·124	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
25	0·368	0·138	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
26	0·385	0·152	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
27	0·403	0·165	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
28	0·422	0·178	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
29	0·440	0·192	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
30	0·458	0·204	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
31	0·476	0·216	0·035	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
32	0·495	0·227	0·073	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
33	0·504	0·239	0·103	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
34	0·532	0·251	0·128	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
35	0·549	0·263	0·149	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
36	0·566	0·275	0·170	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
37	0·583	0·286	0·187	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
38	0·599	0·297	0·205	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
39	0·615	0·309	0·220	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
40	0·631	0·321	0·236	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
41	0·657	0·333	0·250	0·095	.....	.....	.....	.....	.....	.....	.....	.....	.....
42	0·663	0·345	0·263	0·130	.....	.....	.....	.....	.....	.....	.....	.....	.....
43	0·679	0·358	0·276	0·157	.....	.....	.....	.....	.....	.....	.....	.....	.....
44	0·694	0·372	0·288	0·180	.....	.....	.....	0·025	.....	.....	.....	.....	.....
45	0·711	0·387	0·299	0·202	.....	.....	.....	0·074	.....	.....	.....	.....	.....
46	0·726	0·403	0·312	0·220	0·051	.....	.....	0·114	.....	.....	.....	.....	.....
47	0·742	0·420	0·324	0·238	0·095	.....	.....	0·142	.....	.....	.....	.....	.....
48	0·757	0·438	0·337	0·253	0·127	.....	.....	0·167	.....	.....	.....	.....	.....
49	0·772	0·456	0·352	0·268	0·155	.....	0·034	0·192	.....	.....	.....	.....	.....

TABLE I *(Continued)*

Extended Distances for PPP

Δ°	*Depth h* =												
	0·00	0·01	0·02	0·03	0·04	0·05	0·06	0·07	0·08	0·09	0·10	0·11	0·12
50	0·786	0·474	0·367	0·282	0·182	.....	0·368	0·213	.....	.....	.....	.....	.....
51	0·800	0·491	0·386	0·298	0·205	.....	0·417	0·233	.....	.....	.....	.....	.....
52	0·815	0·509	0·404	0·319	0·225	0·043	0·449	0·253	.....	.....	.....	.....	.....
53	0·830	0·529	0·425	0·346	0·252	0·489	0·472	0·275	.....	.....	.....	.....	.....
54	0·845	0·548	0·449	0·375	0·321	0·538	0·495	0·295	.....	.....	.....	.....	.....
55	0·858	0·566	0·480	0·422	0·562	0·560	0·515	0·316	0·092	.....	.....	.....	.....
56	0·872	0·584	0·606	0·556	0·610	0·580	0·530	0·337	0·128	.....	.....	.....	.....
57	0·884	0·604	0·705	0·613	0·643	0·597	0·546	0·357	0·164	.....	.....	.....	.....
58	0·897	0·624	0·756	0·653	0·667	0·613	0·561	0·376	0·195	.....	.....	.....	.....
59	0·910	0·645	0·784	0·690	0·681	0·629	0·575	0·393	0·223	.....	.....	.....	.....
60	0·923	0·665	0·806	0·722	0·703	0·643	0·588	0·411	0·251	0·000	.....	.....	.....
61	0·936	0·686	0·825	0·750	0·720	0·656	0·599	0·427	0·278	0·099	.....	.....	.....
62	0·949	0·708	0·843	0·777	0·733	0·669	0·610	0·442	0·303	0·137	.....	.....	.....
63	0·962	0·729	0·859	0·800	0·748	0·681	0·621	0·458	0·324	0·176	.....	.....	.....
64	0·975	0·750	0·875	0·817	0·761	0·692	0·633	0·473	0·346	0·206	.....	.....	.....
65	0·988	0·772	0·892	0·832	0·772	0·703	0·645	0·487	0·361	0·230	.....	.....	.....
66	1·001	0·794	0·906	0·846	0·784	0·714	0·657	0·502	0·376	0·254	.....	.....	.....
67	1·009	0·816	0·923	0·858	0·795	0·724	0·668	0·517	0·392	0·277	0·111	.....	.....
68	1·017	0·838	0·934	0·870	0·806	0·734	0·679	0·530	0·408	0·295	0·163	.....	.....
69	1·026	0·860	0·947	0·881	0·815	0·744	0·690	0·541	0·422	0·312	0·191	.....	.....
70	1·034	0·882	0·958	0·892	0·824	0·754	0·701	0·553	0·436	0·327	0·218	.....	.....
71	1·043	0·904	0·969	0·902	0·833	0·764	0·710	0·564	0·449	0·343	0·235	.....	.....
72	1·051	0·925	0·981	0·912	0·842	0·773	0·719	0·575	0·459	0·357	0·252	.....	.....
73	1·060	0·947	0·993	0·922	0·849	0·783	0·727	0·587	0·471	0·369	0·267	0·083	.....
74	1·069	0·969	1·004	0·933	0·857	0·792	0·735	0·597	0·484	0·380	0·281	0·124	.....
75	1·078	0·990	1·014	0·943	0·864	0·801	0·743	0·607	0·496	0·391	0·293	0·157	.....
76	1·087	1·010	1·025	0·952	0·871	0·810	0·751	0·616	0·505	0·402	0·304	0·179	.....
77	1·096	1·031	0·034	0·962	0·876	0·818	0·759	0·625	0·515	0·412	0·315	0·197	0·039
78	1·104	1·052	1·043	0·971	0·882	0·826	0·767	0·634	0·525	0·421	0·326	0·215	0·072
79	1·113	1·073	1·052	0·979	0·887	0·834	0·774	0·643	0·534	0·430	0·336	0·233	0·103
80	1·122	1·095	1·061	0·987	0·892	0·842	0·782	0·651	0·543	0·438	0·346	0·248	0·128
81	1·131	1·116	1·069	0·995	0·897	0·851	0·789	0·659	0·552	0·448	0·355	0·261	0·151
82	1·140	1·134	1·077	1·003	0·902	0·858	0·796	0·667	0·561	0·455	0·364	0·273	0·171
83	1·149	1·153	1·086	1·010	0·907	0·865	0·803	0·675	0·569	0·462	0·372	0·285	0·192
84	1·158	1·172	1·094	1·017	0·912	0·871	0·810	0·682	0·577	0·470	0·381	0·295	0·207
85	1·166	1·189	1·102	1·024	0·917	0·878	0·817	0·690	0·584	0·477	0·389	0·304	0·220
86	1·174	1·206	1·110	1·031	0·922	0·884	0·824	0·696	0·592	0·484	0·396	0·313	0·232
87	1·183	1·223	1·118	1·038	0·928	0·890	0·831	0·702	0·598	0·491	0·403	0·321	0·243
88	1·192	1·241	1·126	1·045	0·934	0·896	0·840	0·707	0·605	0·498	0·411	0·329	0·254
89	1·201	1·256	1·134	1·051	0·939	0·901	0·848	0·712	0·611	0·505	0·418	0·337	0·264
90	1·210	1·271	1·142	1·058	0·944	0·906	0·855	0·717	0·617	0·511	0·425	0·344	0·273
91	1·219	1·286	1·149	1·064	0·949	0·911	0·861	0·722	0·622	0·517	0·431	0·352	0·282
92	1·228	1·301	1·156	1·071	0·954	0·916	0·868	0·726	0·628	0·523	0·437	0·358	0·290
93	1·236	1·317	1·163	1·077	0·959	0·921	0·874	0·730	0·634	0·528	0·443	0·365	0·298
94	1·245	1·332	1·170	1·083	0·964	0·926	0·880	0·733	0·639	0·534	0·449	0·372	0·305

TABLE I *(Continued)*

Extended Distances for PPP

Δ°	Depth h =												
	0·00	0·01	0·02	0·03	0·04	0·05	0·06	0·07	0·08	0·09	0·10	0·11	0·12
95	1·253	1·347	1·176	1·089	0·968	0·931	0·886	0·736	0·645	0·540	0·455	0·378	0·313
96	1·262	1·361	1·183	1·095	0·973	0·935	0·892	0·739	0·650	0·545	0·461	0·385	0·320
97	1·271	1·373	1·189	1·101	0·978	0·940	0·898	0·742	0·655	0·549	0·467	0·391	0·328
98	1·280	1·386	1·195	1·106	0·983	0·944	0·905	0·745	0·660	0·555	0·472	0·397	0·335
99	1·289	1·399	1·201	1·113	0·988	0·948	0·910	0·747	0·665	0·560	0·477	0·403	0·343
100	1·297	1·411	1·206	1·119	0·993	0·952	0·916	0·750	0·670	0·565	0·482	0·408	0·350
101	1·306	1·423	1·212	1·125	0·999	0·956	0·921	0·752	0·675	0·570	0·487	0·413	0·357
102	1·315	1·435	1·217	1·131	1·004	0·960	0·926	0·754	0·679	0·575	0·493	0·418	0·364
103	1·323	1·448	1·223	1·137	1·010	0·963	0·932	0·755	0·684	0·579	0·498	0·423	0·371
104	1·332	1·460	1·229	1·143	1·015	0·967	0·938	0·757	0·689	0·584	0·503	0·428	0·377
105	1·341	1·472	1·235	1·149	1·021	0·971	0·944	0·759	0·693	0·589	0·508	0·433	0·383
106	1·350	1·483	1·241	1·155	1·028	0·975	0·950	0·761	0·698	0·594	0·513	0·438	0·389
107	1·359	1·494	1·247	1·161	1·034	0·978	0·955	0·763	0·703	0·599	0·518	0·443	0·396
108	1·368	1·505	1·252	1·167	1·040	0·981	0·960	0·766	0·707	0·604	0·523	0·448	0·402
109	1·377	1·515	1·258	1·172	1·046	0·984	0·965	0·769	0·711	0·609	0·528	0·453	0·407
110	1·386	1·525	1·264	1·177	1·052	0·987	0·971	0·772	0·715	0·613	0·533	0·457	0·413
111	1·394	1·534	1·270	1·183	1·059	0·990	0·976	0·775	0·719	0·618	0·537	0·462	0·418
112	1·403	1·543	1·276	1·188	1·066	0·993	0·981	0·779	0·723	0·623	0·542	0·467	0·423
113	1·412	1·552	1·282	1·193	1·071	0·996	0·986	0·782	0·727	0·628	0·547	0·472	0·429
114	1·421	1·560	1·288	1·198	1·077	0·999	0·989	0·785	0·732	0·633	0·551	0·477	0·434
115	1·430	1·569	1·294	1·203	1·083	1·002	0·992	0·789	0·736	0·637	0·556	0·482	0·440
116	1·439	1·577	1·300	1·208	1·089	1·005	0·996	0·794	0·740	0·642	0·561	0·487	0·446
117	1·448	1·585	1·306	1·213	1·096	1·008	1·000	0·800	0·744	0·647	0·565	0·492	0·451
118	1·456	1·594	1·312	1·217	1·102	1·010	1·003	0·805	0·747	0·651	0·570	0·497	0·457
119	1·465	1·601	1·318	1·222	1·108	1·013	1·006	0·812	0·751	0·656	0·574	0·501	0·462
120	1·474	1·608	1·324	1·226	1·114	1·015	1·009	0·820	0·755	0·661	0·579	0·506	0·468
121	1·482	1·613	1·329	1·231	1·121	1·018	1·012	0·826	0·758	0·666	0·584	0·511	0·473
122	1·491	1·620	1·335	1·236	1·127	1·022	1·015	0·832	0·762	0·671	0·589	0·516	0·478
123	1·500	1·626	1·342	1·241	1·134	1·026	1·017	0·839	0·766	0·676	0·594	0·522	0·484
124	1·508	1·633	1·347	1·246	1·141	1·031	1·020	0·846	0·770	0·681	0·600	0·527	0·490
125	1·517	1·640	1·353	1·251	1·148	1·035	1·023	0·852	0·774	0·686	0·605	0·532	0·495
126	1·526	1·646	1·358	1·256	1·154	1·038	1·026	0·859	0·778	0·691	0·610	0·537	0·501
127	1·534	1·652	1·365	1·261	1·161	1·042	1·030	0·866	0·783	0·696	0·616	0·543	0·507
128	1·544	1·658	1·371	1·266	1·168	1·046	1·034	0·873	0·788	0·701	0·621	0·550	0·513
129	1·552	1·664	1·377	1·271	1·175	1·051	1·037	0·879	0·793	0·706	0·627	0·556	0·519
130	1·561	1·671	1·382	1·276	1·182	1·056	1·042	0·886	0·798	0·711	0·632	0·562	0·525
131	1·570	1·678	1·388	1·281	1·188	1·061	1·046	0·892	0·803	0·716	0·638	0·568	0·531
132	1·579	1·684	1·394	1·285	1·196	1·067	1·050	0·899	0·808	0·722	0·644	0·574	0·537
133	1·587	1·691	1·400	1·290	1·202	1·073	1·055	0·906	0·814	0·727	0·650	0·580	0·543
134	1·596	1·698	1·405	1·295	1·209	1·080	1·060	0·912	0·820	0·733	0·656	0·586	0·549
135	1·604	1·704	1·412	1·300	1·216	1·086	1·065	0·919	0·826	0·738	0·662	0·592	0·556
136	1·613	1·711	1·418	1·305	1·223	1·092	1·071	0·926	0·832	0·743	0·668	0·598	0·562
137	1·622	1·717	1·424	1·310	1·229	1·099	1·077	0·932	0·838	0·749	0·675	0·605	0·568
138	1·631	1·723	1·430	1·315	1·235	1·106	1·082	0·939	0·844	0·754	0·682	0·612	0·575
139	1·640	1·730	1·436	1·319	1·242	1·113	1·088	0·946	0·850	0·760	0·688	0·618	0·582

TABLE I *(Concluded)*

Extended Distances for PPP

Δ°	*Depth h* =												
	0·00	0·01	0·02	0·03	0·04	0·05	0·06	0·07	0·08	0·09	0·10	0·11	0·12
140	1·648	1·737	1·441	1·324	1·248	1·120	1·094	0·953	0·856	0·766	0·694	0·625	0·588
141	1·657	1·743	1·447	1·329	1·255	1·127	1·100	0·960	0·862	0·773	0·701	0·631	0·595
142	1·665	1·750	1·453	1·333	1·262	1·135	1·106	0·966	0·868	0·780	0·707	0·638	0·601
143	1·674	1·756	1·459	1·338	1·270	1·142	1·111	0·973	0·874	0·787	0·713	0·644	0·608
144	1·683	1·762	1·465	1·342	1·277	1·149	1·116	0·980	0·880	0·794	0·720	0·650	0·614
145	1·691	1·769	1·471	1·347	1·284	1·157	1·122	0·987	0·886	0·801	0·726	0·658	0·621
146	1·700	1·775	1·477	1·351	1·290	1·165	1·127	0·990	0·892	0·807	0·733	0·665	0·628
147	1·709	1·781	1·483	1·355	1·296	1·174	1·132	1·002	0·898	0·813	0·739	0·672	0·635
148	1·718	1·788	1·489	1·360	1·302	1·182	1·138	1·009	0·904	0·820	0·746	0·679	0·642
149	1·726	1·794	1·495	1·364	1·309	1·191	1·143	1·016	0·910	0·827	0·752	0·687	0·649
150	1·735	1·801	1·501	1·369	1·315	1·200	1·148	1·023	0·917	0·834	0·758	0·694	0·657
151	1·744	1·808	1·507	1·373	1·322	1·208	1·153	1·030	0·925	0·841	0·765	0·702	0·664
152	1·752	1·814	1·513	1·378	1·328	1·216	1·159	1·037	0·932	0·847	0·773	0·709	0·671
153	1·761	1·820	1·518	1·384	1·335	1·225	1·165	1·045	0·939	0·854	0·780	0·717	0·678
154	1·770	1·827	1·525	1·388	1·342	1·233	1·172	1·052	0·946	0·860	0·787	0·724	0·685
155	1·779	1·833	1·531	1·394	1·348	1·242	1·180	1·060	0·954	0·867	0·795	0·732	0·692
156	1·787	1·840	1·536	1·400	1·354	1·250	1·188	1·067	0·961	0·874	0·802	0·739	0·700
157	1·796	1·846	1·542	1·406	1·360	1·258	1·196	1·074	0·969	0·881	0·810	0·747	0·707
158	1·804	1·852	1·548	1·411	1·367	1·267	1·204	1·081	0·976	0·887	0·817	0·754	0·714
159	1·813	1·859	1·554	1·417	1·375	1·276	1·213	1·088	0·984	0·894	0·824	0·762	0·722
160	1·822	1·865	1·560	1·422	1·382	1·284	1·221	1·095	0·992	0·901	0·832	0·769	0·729
161	1·831	1·871	1·566	1·428	1·389	1·292	1·230	1·102	0·999	0·908	0·839	0·777	0·737
162	1·840	1·878	1·572	1·434	1·396	1·301	1·238	1·110	1·006	0·915	0·847	0·784	0·744
163	1·849	1·884	1·578	1·440	1·402	1·309	1·247	1·117	1·014	0·922	0·854	0·792	0·752
164	1·857	1·891	1·584	1·447	1·409	1·318	1·255	1·125	1·022	0·929	0·861	0·800	0·759
165	1·866	1·898	1·589	1·453	1·416	1·326	1·263	1·131	1·029	0·937	0·868	0·807	0·767
166	1·874	1·904	1·595	1·460	1·423	1·335	1·271	1·139	1·036	0·944	0·876	0·814	0·774
167	1·883	1·910	1·601	1·467	1·430	1·343	1·279	1·146	1·043	0·951	0·883	0·822	0·782
168	1·892	1·917	1·607	1·473	1·437	1·351	1·287	1·153	1·051	0·958	0·891	0·829	0·789
169	1·900	1·923	1·613	1·479	1·445	1·359	1·295	1·160	1·058	0·966	0·898	0·837	0·797
170	1·909	1·930	1·620	1·486	1·452	1·368	1·303	1·167	1·066	0·974	0·906	0·845	0·804
171	1·918	1·936	1·626	1·493	1·460	1·376	1·311	1·175	1·073	0·982	0·913	0·853	0·812
172	1·926	1·942	1·631	1·500	1·467	1·385	1·319	1·182	1·080	0·989	0·920	0·861	0·819
173	1·935	1·949	1·637	1·506	1·475	1·393	1·327	1·190	1·087	0·997	0·928	0·868	0·826
174	1·944	1·955	1·643	1·513	1·482	1·402	1·335	1·197	1·095	1·004	0·935	0·876	0·833
175	1·952	1·961	1·649	1·521	1·489	1·412	1·343	1·204	1·102	1·012	0·943	0·883	0·841
176	1·961	1·968	1·655	1·528	1·496	1·421	1·351	1·212	1·109	1·020	0·950	0·891	0·848
177	1·970	1·974	1·661	1·536	1·503	1·431	1·360	1·220	1·117	1·027	0·957	0·898	0·856
178	1·979	1·981	1·667	1·543	1·511	1·439	1·368	1·228	1·125	1·034	0·965	0·906	0·863
179	1·987	1·988	1·673	1·551	1·519	1·449	1·376	1·236	1·132	1·041	0·973	0·913	0·871
180	1·996	1·994	1·679	1·559	1·527	1·458	1·384	1·243	1·140	1·049	0·980	0·921	0·879

TABLE II

Extended Distances for pPP

Δ°	Depth h =												
	0·00	0·01	0·02	0·03	0·04	0·05	0·06	0·07	0·08	0·09	0·10	0·11	0·12
8	−0·054	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
9	−0·079	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
10	−0·105	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
11	−0·131	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
12	−0·157	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
13	−0·182	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
14	−0·207	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
15	−0·233	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
16	−0·259	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
17	−0·285	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
18	−0·310	−0·050	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
19	−0·337	−0·098	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
20	−0·363	−0·126	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
21	−0·388	−0·152	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
22	−0·414	−0·176	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
23	−0·440	−0·199	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
24	−0·465	−0·218	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
25	−0·491	−0·238	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
26	−0·516	−0·257	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
27	−0·541	−0·276	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
28	−0·567	−0·296	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
29	−0·593	−0·315	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
30	−0·619	−0·335	−0·124	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
31	−0·645	−0·358	−0·187	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
32	−0·670	−0·388	−0·213	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
33	−0·696	−0·419	−0·252	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
34	−0·722	−0·450	−0·279	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
35	−0·748	−0·480	−0·302	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
36	−0·774	−0·510	−0·327	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
37	−0·800	−0·542	−0·352	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
38	−0·826	−0·573	−0·380	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
39	−0·852	−0·603	−0·429	−0·210	.....	.....	.....	.....	.....	.....	.....	.....	.....
40	−0·877	−0·634	−0·480	−0·258	.....	.....	.....	.....	.....	.....	.....	.....	.....
41	−0·903	−0·665	−0·664	−0·300	.....	.....	.....	.....	.....	.....	.....	.....	.....
42	−0·930	−0·695	−0·787	−0,686	.....	.....	.....	.....	.....	.....	.....	.....	.....
43	−0·955	−0·726	−0·809	−0·736	−0·619	−0·508	.....	.....	.....	.....	.....	.....	.....
44	−0·980	−0·757	−0·825	−0·768	−0·673	−0·577	−0·471	−0·103	.....	.....	.....	.....	.....
45	−1·007	−0·788	−0·839	−0·796	−0·702	−0·608	−0·518	−0·168	.....	.....	.....	.....	.....
46	−1·028	−0·819	−0·852	−0·815	−0·725	−0·634	−0·548	−0·224	.....	.....	.....	.....	.....
47	−1·046	−0·850	−0·864	−0·831	−0·747	−0·660	−0·576	−0·278	.....	.....	.....	.....	.....
48	−1·065	−0·880	−0·876	−0·845	−0·767	−0·681	−0·598	−0·324	.....	.....	.....	.....	.....
49	−1·084	−0·911	−0·888	−0·858	−0·786	−0·702	−0·620	−0·367	.....	.....	.....	.....	.....

TABLE II *(Continued)*

Extended Distances for pPP

Δ°	Depth h =												
	0·00	0·01	0·02	0·03	0·04	0·05	0·06	0·07	0·08	0·09	0·10	0·11	0·12
50	−1·101	−0·942	−0·900	−0·870	−0·804	−0·719	−0·640	−0·409	.....	.....	.....	.....	.....
51	−1·119	−0·974	−0·912	−0·881	−0·820	−0·737	−0·659	−0·442	.....	.....	.....	.....	.....
52	−1·138	−1·004	−0·923	−0·892	−0·835	−0·753	−0·678	−0·470	.....	.....	.....	.....	.....
53	−1·157	−1·036	−0·933	−0·902	−0·848	−0·768	−0·695	−0·500	−0·204	.....	.....	.....	.....
54	−1·175	−1·067	−0·944	−0·911	−0·861	−0·783	−0·711	−0·527	−0·318	.....	.....	.....	.....
55	−1·194	−1·099	−0·955	−0·920	−0·873	−0·797	−0·726	−0·551	−0·362	.....	.....	.....	.....
56	−1·213	−1·110	−0·966	−0·930	−0·885	−0·812	−0·740	−0·571	−0·400	.....	.....	.....	.....
57	−1·232	−1·122	−0·977	−0·939	−0·898	−0·826	−0·753	−0·590	−0·432	.....	.....	.....	.....
58	−1·251	−1·134	−0·988	−0·949	−0·912	−0·840	−0·765	−0·607	−0·456	.....	.....	.....	.....
59	−1·269	−1·146	−0·999	−0·958	−0·925	−0·852	−0·778	−0·622	−0·478	−0·285	.....	.....	.....
60	−1·288	−1·159	−1·009	−0·968	−0·937	−0·863	−0·790	−0·637	−0·500	−0·330	.....	.....	.....
61	−1·307	−1·171	−1·019	−0·977	−0·949	−0·872	−0·802	−0·651	−0·518	−0·359	.....	.....	.....
62	−1·325	−1·183	−1·030	−0·987	−0·960	−0·881	−0·813	−0·665	−0·535	−0·383	.....	.....	.....
63	−1·344	−1·196	−1·041	−0·997	−0·971	−0·890	−0·824	−0·677	−0·552	−0·404	.....	.....	.....
64	−1·362	−1·208	−1·051	−1·006	−0·982	−0·898	−0·835	−0·687	−0·565	−0·425	−0·255	.....	.....
65	−1·380	−1·220	−1·062	−1·015	−0·992	−0·906	−0·845	−0·698	−0·578	−0·440	−0·292	.....	.....
66	−1·398	−1·232	−1·073	−1·025	−1·001	−0·915	−0·854	−0·709	−0·589	−0·453	−0·317	.....	.....
67	−1·414	−1·244	−1·084	−1·034	−1·011	−0·923	−0·861	−0·719	−0·600	−0·465	−0·336	.....	.....
68	−1·432	−1·256	−1·095	−1·044	−1·020	−0·931	−0·868	−0·728	−0·610	−0·478	−0·358	.....	.....
69	−1·449	−1·268	−1·106	−1·053	−1·030	−0·939	−0·875	−0·737	−0·620	−0·491	−0·374	.....	.....
70	−1·467	−1·279	−1·116	−1·062	−1·040	−0·947	−0·881	−0·746	−0·629	−0·503	−0·388	.....	.....
71	−1·482	−1·291	−1·127	−1·072	−1·049	−0·955	−0·888	−0·755	−0·638	−0·511	−0·401	−0·240	.....
72	−1·498	−1·303	−1·138	−1·081	−1·058	−0·963	−0·895	−0·764	−0·646	−0·521	−0·414	−0·279	.....
73	−1·412	−1·315	−1·149	−1·090	−1·067	−0·970	−0·902	−0·772	−0·654	−0·530	−0·427	−0·304	.....
74	−1·527	−1·328	−1·160	−1·100	−1·076	−0·978	−0·909	−0·780	−0·662	−0·540	−0·438	−0·321	.....
75	−1·541	−1·340	−1·170	−1·110	−1·085	−0·986	−0·916	−0·787	−0·669	−0·549	−0·448	−0·339	.....
76	−1·556	−1·352	−1·181	−1·119	−1·094	−0·994	−0·923	−0·794	−0·675	−0·558	−0·458	−0·352	.....
77	−1·572	−1·364	−1·192	−1·128	−1·103	−1·002	−0·930	−0·801	−0·682	−0·568	−0·468	−0·365	−0·200
78	−1·589	−1·376	−1·203	−1·137	−1·111	−1·010	−0·937	−0·808	−0·689	−0·577	−0·477	−0·378	−0·243
79	−1·604	−1·388	−1·214	−1·147	−1·118	−1·018	−0·944	−0·814	−0·696	−0·583	−0·486	−0·389	−0·271
80	−1·622	−1·400	−1·225	−1·157	−1·126	−1·026	−0·951	−0·820	−0·702	−0·591	−0·495	−0·400	−0·290
81	−1·638	−1·413	−1·235	−1·166	−1·133	−1·034	−0·958	−0·827	−0·709	−0·598	−0·503	−0·410	−0·310
82	−1·653	−1·426	−1·246	−1·176	−1·139	−1·042	−0·965	−0·834	−0·716	−0·606	−0·511	−0·420	−0·327
83	−1·669	−1·438	−1·257	−1·185	−1·145	−1·050	−0·971	−0·840	−0·722	−0·613	−0·519	−0·428	−0·342
84	−1·684	−1·449	−1·268	−1·194	−1·150	−1·058	−0·978	−0·847	−0·729	−0·621	−0·527	−0·437	−0·356
85	−1·700	−1·461	−1·278	−1·204	−1·155	−1·066	−0·986	−0·854	−0·735	−0·629	−0·534	−0·445	−0·368
86	−1·714	−1·473	−1·289	−1·213	−1·160	−1·074	−0·993	−0·860	−0·742	−0·636	−0·541	−0·453	−0·380
87	−1·728	−1·485	−1·300	−1·222	−1·166	−1·082	−1·001	−0·867	−0·749	−0·644	−0·549	−0·461	−0·392
88	−1·742	−1·497	−1·311	−1·232	−1·171	−1·090	−1·008	−0·874	−0·756	−0·652	−0·557	−0·469	−0·403
89	−1·756	−1·509	−1·321	−1·241	−1·176	−1·099	−1·016	−0·881	−0·762	−0·659	−0·565	−0·477	−0·413
90	−1·769	−1·522	−1·332	−1·251	−1·181	−1·109	−1·025	−0·888	−0·769	−0·669	−0·572	−0·485	−0·423
91	−1·781	−1·534	−1·343	−1·260	−1·193	−1·118	−1·033	−0·895	−0·777	−0·677	−0·580	−0·493	−0·433
92	−1·794	−1·545	−1·354	−1·270	−1·204	−1·128	−1·042	−0·902	−0·784	−0·685	−0·589	−0·502	−0·442
93	−1·808	−1·558	−1·365	−1·279	−1·214	−1·138	−1·052	−0·910	−0·791	−0·693	−0·598	−0·510	−0·451
94	−1·822	−1·570	−1·376	−1·288	−1·225	−1·148	−1·061	−0·917	−0·799	−0·702	−0·607	−0·518	−0·461

TABLE II *(Continued)*

Extended Distances for pPP

Δ°	Depth h =												
	0·00	0·01	0·02	0·03	0·04	0·05	0·06	0·07	0·08	0·09	0·10	0·11	0·12
95	−1·837	−1·582	−1·387	−1·298	−1·236	−1·158	−1·070	−0·924	−0·808	−0·710	−0·616	−0·526	−0·470
96	−1·851	−1·594	−1·398	−1·307	−1·247	−1·168	−1·078	−0·932	−0·816	−0·719	−0·625	−0·535	−0·480
97	−1·866	−1·606	−1·409	−1·317	−1·258	−1·178	−1·087	−0·940	−0·824	−0·727	−0·633	−0·544	−0·490
98	−1·880	−1·619	−1·420	−1·326	−1·269	−1·188	−1·097	−0·948	−0·832	−0·735	−0·642	−0·553	−0·500
99	−1·893	−1·631	−1·430	−1·335	−1·280	−1·198	−1·106	−0·956	−0·841	−0·744	−0·651	−0·563	−0·510
100	−1·906	−1·642	−1·441	−1·344	−1·291	−1·209	−1·116	−0·964	−0·850	−0·752	−0·661	−0·573	−0·520
101	−1·918	−1·654	−1·451	−1·353	−1·302	−1·219	−1·126	−0·973	−0·860	−0·760	−0·671	−0·583	−0·530
102	−1·931	−1·667	−1·462	−1·362	−1·313	−1·229	−1·136	−0·982	−0·869	−0·769	−0·681	−0·595	−0·540
103	−1·943	−1·679	−1·473	−1·371	−1·324	−1·239	−1·146	−0·991	−0·878	−0·780	−0·691	−0·607	−0·551
104	−1·956	−1·692	−1·484	−1·380	−1·335	−1·249	−1·155	−1·001	−0·888	−0·791	−0·701	−0·618	−0·562
105	−1·968	−1·706	−1·496	−1·395	−1·346	−1·260	−1·165	−1·013	−0·898	−0·802	−0·712	−0·629	−0·573
106	−1·980	−1·720	−1·506	−1·408	−1·357	−1·270	−1·175	−1·023	−0·910	−0·813	−0·723	−0·640	−0·585
107	−1·992	−1·731	−1·517	−1·421	−1·368	−1·280	−1·185	−1·034	−0·922	−0·824	−0·734	−0·651	−0·597
108	−2·004	−1·741	−1·528	−1·435	−1·379	−1·290	−1·194	−1·045	−0·933	−0·834	−0·745	−0·662	−0·609
109	−2·017	−1·751	−1·538	−1·449	−1·390	−1·300	−1·204	−1·055	−0·945	−0·845	−0·757	−0·675	−0·620
110	−2·030	−1·764	−1·548	−1·462	−1·401	−1·310	−1·214	−1·066	−0·957	−0·857	−0·768	−0·688	−0·632
111	−2·042	−1·776	−1·559	−1·475	−1·412	−1·320	−1·225	−1·077	−0·969	−0·867	−0·779	−0·700	−0·644
112	−2·055	−1·788	−1·570	−1·489	−1·423	−1·330	−1·236	−1·088	−0·981	−0·878	−0·791	−0·712	−0·655
113	−2·069	−1·800	−1·580	−1·503	−1·434	−1·340	−1·249	−1·100	−0·993	−0·889	−0·803	−0·724	−0·667
114	−2·081	−1·812	−1·591	−1·516	−1·445	−1·350	−1·261	−1·112	−1·005	−0·900	−0·815	−0·737	−0·680
115	−2·094	−1·824	−1·602	−1·530	−1·456	−1·360	−1·274	−1·124	−1·016	−0·911	−0·827	−0·750	−0·693
116	−2·106	−1·836	−1·612	−1·544	−1·467	−1·370	−1·287	−1·135	−1·028	−0·922	−0·839	−0·761	−0·705
117	−2·120	−1·849	−1·623	−1·557	−1·478	−1·380	−1·300	−1·147	−1·040	−0·934	−0·852	−0·774	−0·718
118	−2·134	−1·861	−1·634	−1·570	−1·489	−1·390	−1·312	−1·159	−1·052	−0·945	−0·865	−0·788	−0·731
119	−2·148	−1·873	−1·645	−1·584	−1·500	−1·400	−1·325	−1·172	−1·064	−0·957	−0·877	−0·801	−0·743
120	−2·161	−1·885	−1·655	−1·598	−1·510	−1·412	−1·337	−1·184	−1·076	−0·969	−0·888	−0·813	−0·756
121	−2·173	−1·898	−1·666	−1·611	−1·521	−1·425	−1·349	−1·197	−1·088	−0·981	−0·900	−0·826	−0·769
122	−2·186	−1·910	−1·676	−1·625	−1·532	−1·439	−1·361	−1·209	−1·099	−0·992	−0·913	−0·839	−0·782
123	−2·198	−1·922	−1·687	−1·639	−1·543	−1·453	−1·374	−1·221	−1·110	−1·004	−0·925	−0·852	−0·794
124	−2·211	−1·934	−1·698	−1·652	−1·554	−1·467	−1·386	−1·233	−1·122	−1·015	−0·937	−0·865	−0·807
125	−2·223	−1·946	−1·711	−1·665	−1·565	−1·481	−1·399	−1·245	−1·134	−1·027	−0·949	−0·877	−0·819
126	−2·235	−1·958	−1·725	−1·679	−1·476	−1·496	−1·411	−1·257	−1·146	−1·039	−0·961	−0·889	−0·832
127	−2·247	−1·970	−1·740	−1·692	−1·587	−1·510	−1·424	−1·270	−1·158	−1·052	−0·972	−0·902	−0·845
128	−2·259	−1·982	−1·754	−1·706	−1·598	−1·524	−1·436	−1·282	−1·170	−1·064	−0·984	−0·914	−0·858
129	−2·270	−1·994	−1·769	−1·719	−1·609	−1·538	−1·449	−1·294	−1·182	−1·076	−0·996	−0·926	−0·871
130	−2·281	−2·007	−1·783	−1·733	−1·620	−1·551	−1·461	−1·306	−1·194	−1·089	−1·008	−0·939	−0·884
131	−2·292	−2·020	−1·797	−1·747	−1·631	−1·565	−1·474	−1·318	−1·206	−1·101	−1·020	−0·951	−0·896
132	−2·303	−2·031	−1·811	−1·760	−1·642	−1·580	−1·486	−1·330	−1·218	−1·114	−1·032	−0·962	−0·909
133	−2·315	−2·043	−1·825	−1·774	−1·656	−1·593	−1·499	−1·342	−1·230	−1·126	−1·044	−0·974	−0·921
134	−2·327	−2·055	−1·839	−1·788	−1·670	−1·608	−1·512	−1·355	−1·241	−1·138	−1·056	−0·985	−0·934
135	−2·339	−2·068	−1·853	−1·801	−1·687	−1·622	−1·524	−1·368	−1·253	−1·150	−1·068	−0·997	−0·947
136	−2·352	−2·080	−1·868	−1·815	−1·702	−1·636	−1·536	−1·379	−1·265	−1·162	−1·080	−1·009	−0·960
137	−2·365	−2·092	−1·883	−1·828	−1·718	−1·650	−1·549	−1·391	−1·278	−1·175	−1·092	−1·021	−0·972
138	−2·377	−2·105	−1·897	−1·841	−1·734	−1·664	−1·561	−1·404	−1·290	−1·188	−1·104	−1·032	−0·985
139	−2·389	−2·117	−1·911	−1·855	−1·750	−1·678	−1·574	−1·416	−1·302	−1·200	−1·115	−1·044	−0·998

TABLE II *(Concluded)*

Extended Distances for pPP

Δ°	Depth h =												
	0·00	0·01	0·02	0·03	0·04	0·05	0·06	0·07	0·08	0·09	0·10	0·11	0·12
140	−2·401	−2·129	−1·925	−1·868	−1·766	−1·692	−1·587	−1·428	−1·313	−1·213	−1·127	−1·055	−1·010
141	−2·413	−2·141	−1·939	−1·882	−1·783	−1·706	−1·601	−1·441	−1·326	−1·225	−1·139	−1·067	−1·022
142	−2·425	−2·153	−1·953	−1·896	−1·799	−1·720	−1·618	−1·456	−1·340	−1·237	−1·152	−1·079	−1·035
143	−2·437	−2·166	−1·967	−1·909	−1·815	−1·734	−1·634	−1·471	−1·354	−1·250	−1·165	−1·091	−1·048
144	−2·449	−2·178	−1·981	−1·922	−1·832	−1·748	−1·650	−1·486	−1·368	−1·264	−1·178	−1·104	−1·061
145	−2·461	−2·190	−1·995	−1·936	−1·849	−1·762	−1·667	−1·501	−1·382	−1·278	−1·192	−1·117	−1·075
146	−2·472	−2·202	−2·010	−1·949	−1·865	−1·776	−1·683	−1·516	−1·397	−1·292	−1·205	−1·130	−1·088
147	−2·483	−2·214	−2·024	−1·963	−1·881	−1·790	−1·700	−1·531	−1·411	−1·305	−1·218	−1·143	−1·101
148	−2·494	−2·227	−2·038	−1·976	−1·898	−1·804	−1·718	−1·546	−1·425	−1·319	−1·232	−1·155	−1·114
149	−2·505	−2·240	−2·052	−1·990	−1·915	−1·818	−1·733	−1·561	−1·440	−1·332	−1·245	−1·168	−1·127
150	−2·516	−2·252	−2·066	−2·004	−1·932	−1·832	−1·749	−1·575	−1·453	−1·346	−1·259	−1·181	−1·140
151	−2·528	−2·263	−2·080	−2·017	−1·949	−1·846	−1·765	−1·590	−1·468	−1·360	−1·272	−1·193	−1·153
152	−2·539	−2·275	−2·094	−2·031	−1·966	−1·860	−1·781	−1·605	−1·482	−1·374	−1·286	−1·206	−1·166
153	−2·551	−2·288	−2·109	−2·044	−1·983	−1·874	−1·798	−1·620	−1·496	−1·388	−1·299	−1·219	−1·180
154	−2·562	−2·300	−2·123	−2·060	−1·999	−1·888	−1·814	−1·636	−1·510	−1·401	−1·313	−1·232	−1·194
155	−2·573	−2·312	−2·137	−2·080	−2·016	−1·902	−1·831	−1·651	−1·525	−1·415	−1·326	−1·246	−1·208
156	−2·584	−2·324	−2·151	−2·100	−2·033	−1·916	−1·847	−1·667	−1·539	−1·429	−1·340	−1·261	−1·223
157	−2·596	−2·336	−2·165	−2·119	−2·050	−1·930	−1·863	−1·682	−1·554	−1·442	−1·355	−1·276	−1·237
158	−2·608	−2·348	−2·180	−2·138	−2·067	−1·944	−1·880	−1·697	−1·568	−1·456	−1·369	−1·291	−1·252
159	−2·619	−2·361	−2·194	−2·156	−2·084	−1·960	−1·896	−1·712	−1·583	−1·470	−1·384	−1·306	−1·266
160	−2·630	−2·373	−2·208	−2·175	−2·101	−1·978	−1·913	−1·728	−1·597	−1·485	−1·399	−1·322	−1·280
161	−2·640	−2·385	−2·222	−2·193	−2·118	−1·995	−1·929	−1·743	−1·612	−1·500	−1·415	−1·338	−1·295
162	−2·651	−2·397	−2·236	−2·210	−2·135	−2·014	−1·945	−1·758	−1·626	−1·516	−1·430	−1·353	−1·309
163	−2·662	−2·406	−2·250	−2·225	−2·152	−2·032	−1·961	−1·773	−1·639	−1·531	−1·445	−1·368	−1·323
164	−2·673	−2·415	−2·265	−2·239	−2·169	−2·051	−1·978	−1·788	−1·653	−1·547	−1·460	−1·384	−1·338
165	−2·684	−2·425	−2·279	−2·251	−2·186	−2·069	−1·994	−1·803	−1·666	−1·562	−1·475	−1·399	−1·352
166	−2·695	−2·435	−2·293	−2·263	−2·203	−2·088	−2·011	−1·818	−1·679	−1·577	−1·490	−1·414	−1·366
167	−2·706	−2·445	−2·307	−2·275	−2·219	−2·107	−2·027	−1·834	−1·692	−1·592	−1·505	−1·429	−1·380
168	−2·717	−2·455	−2·321	−2·287	−2·236	−2·126	−2·043	−1·849	−1·705	−1·608	−1·520	−1·444	−1·394
169	−2·727	−2·466	−2·335	−2·298	−2·252	−2·144	−2·060	−1·866	−1·718	−1·622	−1·535	−1·460	−1·408
170	−2·737	−2·477	−2·350	−2·308	−2·268	−2·164	−2·076	−1·884	−1·731	−1·638	−1·550	−1·470	−1·423
171	−2·747	−2·489	−2·364	−2·318	−2·285	−2·183	−2·092	−1·900	−1·744	−1·654	−1·565	−1·479	−1·437
172	−2·756	−2·500	−2·379	−2·328	−2·301	−2·200	−2·109	−1·918	−1·757	−1·669	−1·580	−1·488	−1·451
173	−2·766	−2·510	−2·393	−2·337	−2·318	−2·218	−2·125	−1·935	−1·770	−1·684	−1·595	−1·496	−1·465
174	−2·776	−2·520	−2·408	−2·345	−2·334	−2·234	−2·141	−1·952	−1·783	−1·699	−1·610	−1·505	−1·479
175	−2·786	−2·531	−2·422	−2·354	−2·351	−2·250	−2·157	−1·969	−1·796	−1·714	−1·627	−1·513	−1·493
176	−2·797	−2·542	−2·436	−2·362	−2·367	−2·265	−2·174	−1·985	−1·809	−1·729	−1·643	−1·522	−1·507
177	−2·807	−2·554	−2·450	−2·370	−2·383	−2·279	−2·187	−2·000	−1·823	−1·744	−1·659	−1·530	−1·521
178	−2·817	−2·566	−2·464	−2·377	−2·397	−2·292	−2·200	−2·015	−1·836	−1·760	−1·671	−1·539	−1·535
179	−2·827	−2·578	−2·478	−2·384	−2·412	−2·304	−2·213	−2·030	−1·849	−1·775	−1·683	−1·547	−1·549
180	−2·837	−2·590	−2·492	−2·391	−2·425	−2·316	−2·226	−2·042	−1·862	−1·790	−1·695	−1·555	−1·563

TABLE III

Extended Distances for $pPKP_1$

Δ°	Depth h =												
	0·00	0·01	0·02	0·03	0·04	0·05	0·06	0·07	0·08	0·09	0·10	0·11	0·12
109	.....	.....	−6·68	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
110	−7·17	−6·93	−6·69	−6·45	−6·22	−6·00	−5·79	−5·40	.....	.....	.....	.....	.....
111	−7·19	−6·94	−6·70	−6·46	−6·23	−6·01	−5·80	−5·41	−5·11	−4·87	−4·68	−4·53	.....
112	−7·20	−6·96	−6·71	−6·47	−6·25	−6·03	−5·81	−5·42	−5·12	−4·88	−4·69	−4·54	−4·38
113	−7·22	−6·97	−6·73	−6·49	−6·26	−6·04	−5·82	−5·43	−5·13	−4·90	−4·70	−4·55	−4·39
114	−7·23	−6·99	−6·74	−6·50	−6·27	−6·05	−5·84	−5·44	−5·14	−4·91	−4·71	−4·56	−4·40
115	−7·25	−7·00	−6·76	−6·52	−6·29	−6·06	−5·85	−5·45	−5·15	−4·92	−4·72	−4·57	−4·41
116	−7·27	−7·02	−6·77	−6·53	−6·30	−6·08	−5·86	−5·46	−5·17	−4·93	−4·73	−4·58	−4·42
117	−7·28	−7·04	−6·79	−6·55	−6·31	−6·09	−5·88	−5·48	−5·18	−4·94	−4·74	−4·59	−4·43
118	−7·30	−7·05	−6·80	−6·56	−6·33	−6·11	−5·89	−5·49	−5·19	−4·95	−4·75	−4·60	−4·44
119	−7·32	−7·07	−6·82	−6·58	−6·34	−6·12	−5·90	−5·50	−5·20	−4·96	−4·77	−4·61	−4·45
120	−7·34	−7·08	−6·83	−6·60	−6·36	−6·14	−5·92	−5·51	−5·22	−4·97	−4·78	−4·62	−4 46
121	−7·36	−7·10	−6·85	−6·61	−6·37	−6·15	−5·93	−5·53	−5·23	−4·99	−4·79	−4·63	−4·47
122	−7·37	−7·12	−6·87	−6·63	−6·39	−6·17	−5·95	−5·54	−5·24	−5·00	−4·80	−4·64	−4·49
123	−7·39	−7·14	−6·89	−6·64	−6·41	−6·18	−5·96	−5·56	−5·26	−5·01	−4·81	−4·65	−4·50
124	−7·41	−7·16	−6·90	−6·66	−6·42	−6·20	−5·98	−5·57	−5·27	−5·02	−4·83	−4·67	−4·51
125	−7·43	−7·18	−6·92	−6·68	−6·44	−6·21	−6·00	−5·59	−5·29	−5·04	−4·84	−4·68	−4·52
126	−7·45	−7·20	−6·94	−6·70	−6·46	−6·23	−6·01	−5·60	−5·30	−5·05	−4·86	−4·70	−4·54
127	−7·47	−7·22	−6·96	−6·72	−6·48	−6·25	−6·03	−5·62	−5·32	−5·07	−4·87	−4·71	−4·55
128	−7·49	−7·24	−6·98	−6·74	−6·50	−6·27	−6·05	−5·63	−5·33	−5·08	−4·88	−4·72	−4·56
129	−7·52	−7·26	−7·00	−6·76	−6·52	−6·29	−6·07	−5·65	−5·35	−5·09	−4·90	−4·74	−4·58
130	−7·54	−7·29	−7·03	−6·78	−6·54	−6·31	−6·09	−5·67	−5·37	−5·11	−4·91	−4·75	−4·59
131	−7·57	−7·31	−7·05	−6·80	−6·57	−6·33	−6·11	−5·69	−5·39	−5·13	−4·93	−4·76	−4·61
132	−7·60	−7·33	−7·08	−6·82	−6·59	−6·35	−6·13	−5·71	−5·40	−5·15	−4·94	−4·78	−4·62
133	−7·63	−7·36	−7·11	−6·85	−6·62	−6·38	−6·15	−5·73	−5·42	−5·17	−4·96	−4·80	−4·64
134	−7·66	−7·39	−7·14	−6·88	−6·64	−6·40	−6·18	−5·75	−5·45	−5·19	−4·98	−4·81	−4 66
135	−7·70	−7·43	−7·17	−6·92	−6·67	−6·43	−6·21	−5·78	−5·47	−5·21	−5·01	−4·84	−4·68
136	−7·74	−7·47	−7·21	−6·96	−6·71	−6·46	−6·24	−5·81	−5·50	−5·24	−5·03	−4·86	−4·70
137	−7·79	−7·52	−7·25	−7·00	−6·74	−6·50	−6·27	−5·84	−5·52	−5·27	−5·06	−4·89	−4·73
138	−7·84	−7·57	−7·30	−7·04	−6·79	−6·55	−6·31	−5·88	−5·56	−5·30	−5·09	−4·92	−4·75
139	−7·89	−7·62	−7·35	−7·09	−6·84	−6·60	−6·36	−5·92	−5·60	−5·34	−5·12	−4·95	−4·79
140	−7·95	−7·68	−7·41	−7·15	−6·89	−6·65	−6·41	−5·97	−5·65	−5·38	−5·16	−4·99	−4·83
141	−8·02	−7·74	−7·47	−7·21	−6·95	−6·71	−6·46	−6·02	−5·70	−5·43	−5·20	−5·03	−4·86
142	−8·10	−7·82	−7·54	−7·27	−7·02	−6·77	−6·52	−6·07	−5·75	−5·48	−5·25	−5·08	−4·91
143	−8·18	−7·90	−7·62	−7·35	−7·08	−6·83	−6·59	−6·14	−5·80	−5·53	−5·31	−5·12	−4·96
144	−8·27	−7·99	−7·71	−7·43	−7·17	−6·90	−6·66	−6·20	−5·87	−5·59	−5·37	−5·18	−5·01
145	−8·38	−8·09	−7·80	−7·52	−7·25	−6·99	−6·74	−6·27	−5·94	−5·66	−5·43	−5·24	−5·07
146	−8·50	−8·20	−7·91	−7·63	−7·36	−7·09	−6·83	−6·36	−6·02	−5·73	−5·50	−5·31	−5·13
147	−8·63	−8·32	−8·03	−7·75	−7·47	−7·20	−6·93	−6·45	−6·11	−5·82	−5·58	−5·39	−5·21
148	−8·77	−8·46	−8·17	−7·88	−7·59	−7·31	−7·04	−6·56	−6·20	−5·91	−5·67	−5·48	−5·29
149	−8·94	−8·63	−8·32	−8·02	−7·73	−7·46	−7·18	−6·68	−6·31	−6·02	−5·77	−5·57	−5·38

TABLE III *(Concluded)*

Extended Distances for $pPKP_1$

Δ°	*Depth h =*												
	0·00	0·01	0·02	0·03	0·04	0·05	0·06	0·07	0·08	0·09	0·10	0·11	0·12
150	−9·13	−8·81	−8·49	−8·19	−7·89	−7·60	−7·32	−6·81	−6·44	−6·14	−5·88	−5·68	−5·48
151	−9·34	−9·01	−8·69	−8·37	−8·07	−7·77	−7·48	−6·97	−6·59	−6·28	−6·01	−5·80	−5·60
152	−9·57	−9·23	−8·90	−8·58	−8·26	−7·96	−7·66	−7·14	−6·75	−6·43	−6·16	−5·95	−5·74
153	−9·82	−9·48	−9·13	−8·80	−8·48	−8·17	−7·87	−7·32	−6·92	−6·59	−6·32	−6·10	−5·89
154	−10·1	−9·74	−9·38	−9·05	−8·72	−8·40	−8·08	−7·53	−7·12	−6·78	−6·49	−6·26	−6·05
155	−10·4	−10·0	−9·67	−9·33	−8·98	−8·66	−8·32	−7·74	−7·33	−6·98	−6·68	−6·45	−6·22
156	−10·8	−10·4	−10·0	−9·62	−9·26	−8·93	−8·59	−8·01	−7·56	−7·20	−6·90	−6·65	−6·42
157	−11·1	−10·7	−10·3	−10·0	−9·58	−9·24	−8·89	−8·28	−7·82	−7·44	−7·14	−6·88	−6·62
158	−11·6	−11·1	−10·7	−10·4	−9·93	−9·58	−9·23	−8·60	−8·11	−7·73	−7·41	−7·14	−6·84
159	−12·1	−11·6	−11·2	−10·8	−10·4	−9·97	−9·60	−8·95	−8·45	−8·05	−7·71	−7·43	−7·17
160	−12·6	−12·1	−11·7	−11·2	−10·9	−10·4	−10·0	−9·35	−8·84	−8·40	−8·05	−7·78	−7·48
161	−13·2	−12·7	−12·3	−11·8	−11·4	−10·9	−10·5	−9·81	−9·25	−8·80	−8·44	−8·15	−7·85
162	−13·9	−13·3	−12·9	−12·4	−11·9	−11·5	−11·1	−10·3	−9·73	−9·25	−8·86	−8·56	−8·27
163	−14·7	−14·1	−13·6	−13·1	−12·6	−12·2	−11·7	−10·9	−10·3	−9·76	−9·35	−9·03	−8·72
164	−15·6	−15·0	−14·4	−13·9	−13·4	−12·9	−12·4	−11·5	−10·9	−10·4	−9·93	−9·59	−9·25
165	−16·6	−16·0	−15·4	−14·8	−14·3	−13·7	−13·2	−12·3	−11·6	−11·0	−10·6	−10·3	−9·86
166	−17·8	−17·2	−16·5	−15·9	−15·4	−14·8	−14·2	−13·2	−12·5	−11·9	−11·4	−11·0	−10·6
167	−19·2	−18·5	−17·8	−17·1	−16·6	−15·9	−15·3	−14·2	−13·5	−12·8	−12·2	−11·9	−11·4
168	−20·8	−20·0	−19·3	−18·6	−17·9	−17·2	−16·6	−15·5	−14·6	−13·8	−13·2	−12·9	−12·3
169	−22·6	−21·9	−21·1	−20·3	−19·6	−18·8	−18·1	−16·9	−15·9	−15·1	−14·5	−14·2	−13·5
170	−24·9	−24·0	−23·2	−22·3	−21·6	−20·7	−20·0	−18·5	−17·6	−16·7	−15·9	−15·4	−14·9
171	−27·7	−26·8	−25·8	−24·9	−24·0	−23·1	−22·3	−20·7	−19·6	−18·6	−17·8	−17·1	−16·6
172	−31·2	−30·1	−29·1	−28·0	−27·0	−26·0	−25·0	−23·3	−22·1	−21·0	−20·1	−19·3	−18·6
173	−35·6	−34·4	−33·2	−32·0	−30·9	−29·8	−28·6	−26·7	−25·2	−24·1	−23·0	−22·2	−21·3
174	−41·6	−40·3	−38·6	−37·4	−36·1	−34·7	−33·5	−31·1	−29·5	−28·1	−26·9	−26·0	−25·0
175	−49·9	−48·3	−46·4	−44·9	−43·3	−41·7	−40·1	−37·2	−35·5	−33·7	−32·5	−31·2	−30·3
176	−62·8	−60·4	−58·1	−56·1	−54·0	−52·1	−50·3	−46·6	−44·4	−42·2	−40·7	−39·2	−38·0
177	−83·8	−80·7	−77·6	−75·6	−72·7	−70·0	−67·2	−62·2	−59·6	−56·7	−54·9	−52·9	−51·2
178	−126	−123	−118	−115	−110	−107	−102	−94·9	−90·5	−85·8	−83·7	−80·9	−77·8
179	−254	−246	−237	−232	−224	−218	−212	−196	−185	−176	−170	−164	−158
180	−∞	−∞	−∞	−∞	−∞	−∞	−∞	−∞	−∞	−∞	−∞	−∞	−∞

TABLE IV

Extended Distances for $pPKP_2$

Δ°	Depth h =												
	0·00	0·01	0·02	0·03	0·04	0·05	0·06	0·07	0·08	0·09	0·10	0·11	0·12
144	−4·03	−3·96	−3·87	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
145	−3·73	−3·64	−3·55	−3·45	−3·38	−3·30	.....	−3·05	−2·93	.....	.....	.....	.....
146	−3·57	−3·46	−3·35	−3·26	−3·17	−3·07	−2·99	−2·81	−2·69	−2·61	−2·53	.....	−2·46
147	−3·48	−3·36	−3·25	−3·14	−3·04	−2·94	−2·85	−2·66	−2·56	−2·43	−2·35	−2·32	−2·27
148	−3·41	−3·29	−3·18	−3·08	−2·97	−2·86	−2·77	−2·58	−2·44	−2·33	−2·25	−2·18	−2·14
149	−3·36	−3·24	−3·13	−3·02	−2·91	−2·81	−2·72	−2·52	−2·38	−2·27	−2·18	−2·11	−2·05
150	−3·32	−3·20	−3·09	−2·98	−2·87	−2·77	−2·67	−2·48	−2·34	−2·22	−2·13	−2·06	−1·99
151	−3·29	−3·17	−3·06	−2·95	−2·84	−2·73	−2·64	−2·44	−2·31	−2·18	−2·10	−2·02	−1·96
152	−3·26	−3·15	−3·03	−2·92	−2·81	−2·71	−2·61	−2·41	−2·28	−2·16	−2·07	−2·00	−1·93
153	−3·24	−3·12	−3·01	−2·90	−2·79	−2·69	−2·58	−2·39	−2·25	−2·14	−2·05	−1·97	−1·90
154	−3·21	−3·10	−2·99	−2·88	−2·78	−2·66	−2·56	−2·37	−2·23	−2·12	−2·03	−1·95	−1·88
155	−3·20	−3·09	−2·97	−2·86	−2·76	−2·65	−2·55	−2·36	−2·22	−2·11	−2·01	−1·93	−1·86
156	−3·18	−3·08	−2·96	−2·85	−2·74	−2·63	−2·54	−2·34	−2·21	−2·09	−2·00	−1·92	−1·85
157	−3·17	−3·06	−2·94	−2·83	−2·73	−2·62	−2·52	−2·33	−2·19	−2·07	−1·98	−1·91	−1·84
158	−3·16	−3·05	−2·93	−2·82	−2·72	−2·61	−2·51	−2·32	−2·18	−2·06	−1·97	−1·90	−1·82
159	−3·14	−3·04	−2·92	−2·81	−2·71	−2·60	−2·50	−2·31	−2·17	−2·05	−1·96	−1·89	−1·81
160	−3·13	−3·03	−2·91	−2·80	−2·70	−2·59	−2·49	−2·30	−2·16	−2·04	−1·95	−1·88	−1·80
161	−3·12	−3·02	−2·90	−2·79	−2·69	−2·58	−2·48	−2·29	−2·15	−2·03	−1·94	−1·87	−1·79
162	−3·11	−3·01	−2·89	−2·78	−2·68	−2·57	−2·47	−2·28	−2·14	−2·03	−1·93	−1·86	−1·78
163	−3·10	−3·00	−2·88	−2·77	−2·67	−2·56	−2·46	−2·27	−2·14	−2·02	−1·93	−1·85	−1·78
164	−3·10	−2·99	−2·88	−2·76	−2·66	−2·55	−2·46	−2·27	−2·13	−2·01	−1·92	−1·85	−1·77
165	−3·09	−2·98	−2·87	−2·76	−2·65	−2·55	−2·45	−2·26	−2·12	−2·01	−1·91	−1·84	−1·76
166	−3·08	−2·97	−2·86	−2·75	−2·65	−2·54	−2·44	−2·25	−2·12	−2·00	−1·91	−1·83	−1·76
167	−3·08	−2·97	−2·85	−2·74	−2·64	−2·54	−2·44	−2·25	−2·11	−1·99	−1·90	−1·83	−1·75
168	−3·07	−2·96	−2·85	−2·74	−2·64	−2·53	−2·43	−2·24	−2·11	−1·99	−1·90	−1·82	−1·75
169	−3·07	−2·96	−2·85	−2·74	−2·63	−2·53	−2·43	−2·24	−2·10	−1·99	−1·89	−1·82	−1·74
170	−3·07	−2·95	−2·84	−2·73	−2·63	−2·52	−2·42	−2·24	−2·10	−1·98	−1·89	−1·82	−1·74
171	−3·06	−2·95	−2·84	−2·73	−2·63	−2·52	−2·42	−2·23	−2·10	−1·98	−1·89	−1·81	−1·74
172	−3·06	−2·95	−2·84	−2·73	−2·62	−2·52	−2·42	−2·23	−2·09	−1·98	−1·88	−1·81	−1·74
173	−3·06	−2·95	−2·83	−2·72	−2·62	−2·52	−2·42	−2·23	−2·09	−1·98	−1·88	−1·81	−1·73
174	−3·06	−2·94	−2·83	−2·72	−2·62	−2·51	−2·41	−2·23	−2·09	−1·98	−1·88	−1·80	−1·73
175	−3·05	−2·94	−2·83	−2·72	−2·62	−2·51	−2·41	−2·22	−2·09	−1·97	−1·88	−1·80	−1·73
176	−3·05	−2·94	−2·83	−2·72	−2·61	−2·51	−2·41	−2·22	−2·09	−1·97	−1·88	−1·80	−1·73
177	−3·05	−2·94	−2·83	−2·72	−2·61	−2·51	−2·41	−2·22	−2·08	−1·97	−1·87	−1·80	−1·73
178	−3·05	−2·94	−2·82	−2·72	−2·61	−2·51	−2·41	−2·22	−2·08	−1·97	−1·87	−1·80	−1·73
179	−3·05	−2·93	−2·82	−2·71	−2·61	−2·51	−2·41	−2·22	−2·08	−1·97	−1·87	−1·80	−1·72
180	−3·05	−2·93	−2·82	−2·71	−2·61	−2·51	−2·40	−2·22	−2·08	−1·97	−1·87	−1·80	−1·72

TABLE V

Extended Distances for P for Short Epicentral Distances

Δ°	Depth h =													
	Surface	0·00	0·01	0·02	0·03	0·04	0·05	0·06	0·07	0·08	0·09	0·10	0·11	0·12
0·5	0·021	−1·0	−2·4	−2·8	−3·85	−4·90	−5·89	−6·87	−7·58	−8·39	−9·27	−9·98	−10·96	−12·03
1·0	0·042	−0·039	−1·10	−1·70	−2·05	−2·37	−2·92	−3·40	−3·75	−4·18	−4·60	−5·06	−5·52	−5·98
1·5	0·061	0·008	−0·347	−0·77	−1·38	−1·64	−1·95	−2·17	−2·33	−2·76	−3·04	−3·34	−3·65	−3·97
2·0	0·077	0·031	−0·191	−0·498	−0·805	−1·18	−1·41	−1·59	−1·85	−2·02	−2·175	−2·48	−2·71	−2·96
2·5	0·093	0·052	−0·107	−0·371	−0·592	−0·87	−1·08	−1·24	−1·44	−1·625	−1·795	−1·985	−2·15	−2·34

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TABLES OF EXTENDED DISTANCES FOR S, SS and sS

BY

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Tables of Extended Distances for S, SS and sS

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ABSTRACT

Tables of extended distances, consistent with those already published for the P phases, are presented for those S phases which are likely to be useful in fault-plane studies. As in earlier papers, the extended distances are given for surface focus, and for focal depths from 0·00R to 0·12R in steps of 0·1R.

INTRODUCTION

For the past several years this Observatory has been studying the direction of faulting in earthquakes. To date these studies have made use only of P waves or their derivatives, and for this reason unique solutions have not been obtained. Instead the solutions define a pair of orthogonal planes, without indicating which of these represents the fault.

It has long been recognized that this ambiguity could be resolved through the use of shear waves. The difficulties in this work are several. It is frequently very difficult to identify the beginning of S with certainty, and even if this can be done it is often impossible to determine the direction of first motion. Nevertheless, considering the interest which attaches to the result, one often wishes to attempt the use of shear waves. The tables of extended distances for S, SS and sS here presented should facilitate these experiments. It seems doubtful that waves with more complicated history will be useful due to the uncertainty of the phase relationships on reflection.

THEORY

Extended Distances for S

The work of this section is closely analagous to that of an earlier paper (Hodgson and Allen, 1954a) in which extended distances were obtained for PKP. In that earlier paper the formula was developed:

$$\sin i_d = \frac{r_s}{r_d} \cdot \frac{v_d}{111 \cdot 11} \cdot \frac{dt}{d\Delta} ; \tag{1}$$

where

i_d = angle between ray and radius vector at the focus, such that extended distance = cot i_d,

r_s = radius of the earth, measured in km.,

r_d = radius of an earth stripped to focus of depth d, measured in km.,

v_d = velocity of wave propagation at focus of depth d, measured in km/sec.

$dt/d\Delta$ = slope of the travel time wave, measured in seconds/1°.

63256—1½

In the earlier application of this formula $dt/d\Delta$ was determined from the surface focus curve at an epicentral distance $\delta + \Delta$ (*see* Figure 1). It was then necessary to determine the value of δ, which was very complicated. It is clear that we may work much more simply in applying formula (1) by evaluating $dt/d\Delta$ at distance Δ on the travel time curve appropriate to depth d.

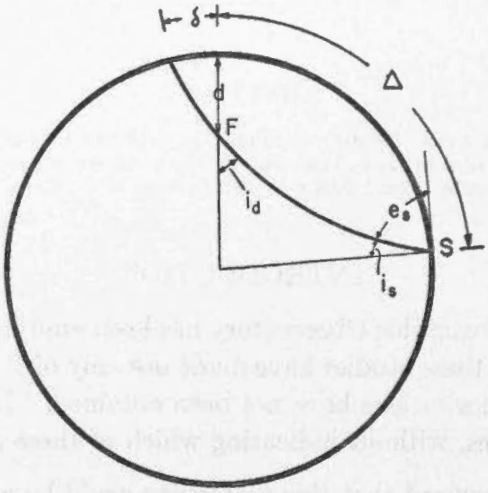

FIGURE 1

In evaluating equation (1) the radii and velocities shown in Table I have been used. These have been taken from Jeffreys (1939). $dt/d\Delta$ have been determined from the appropriate curves of the Jeffreys-Bullen tables (1940).

TABLE I

Depth	Radius (km)	Velocity (km/sec.)
Surface	6371	4·35
0·00	6338	4·353
0·01	6275	4·444
0·02	6211	4·539
0·03	6148	4·638
0·04	6084	4·741
0·05	6021	4·850
0·06	5958	4·962
0·07	5894	5·227
0·08	5831	5·463
0·09	5768	5·670
0·10	5704	5·850
0·11	5641	6·002
0·12	5577	6·125

Extended distances for S will be found in Table II, (pages 106 to 108). As is usual in these tables a negative extended distance indicates that the ray reaching that point is a rising one. Such stations are plotted at an azimuth exactly opposite to their true one.

Extended Distances for SS and sS

The method used in deriving extended distances for these phases is exactly the same as that used in the case of PP and pP, (Hodgson and Allen, 1954b). Sets of related points A, B at epicentral distances Δs, ΔS, must first be determined from the S tables of extended distance, such that they have extended distances numerically identical but

opposite in sign. Then the sums

$$\Delta SS = 2\Delta S + \Delta s$$

and

$$\Delta sS = \Delta S + 2\Delta s \quad ,$$

are formed. The extended distance of an S at ΔS is the same as that of an SS at ΔSS; the extended distance of an S at Δs and of an sS at ΔsS is the negative of this.

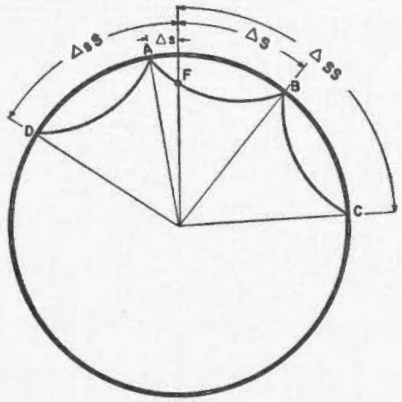

FIGURE 2

Each extended distance selected yields a set of related points and associate distances ΔSS and ΔsS. By selecting enough points curves are constructed which may be entered at even values of ΔSS, ΔsS.

The results of this work will be found in Table III, pages 109 to 113, which gives extended distances for SS, and in Table IV, pages 114 to 116, which gives extended distance for sS. In the latter case, since sS derives from an upward rising ray, the extended distances are all negative.

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TABLE II

Extended Distances for S

Δ	Depth h =													
	Surface	0·00	0·01	0·02	0·03	0·04	0·05	0·06	0·07	0·08	0·09	0·10	0·11	0·12
0·0	0·000	− ∞	− ∞	− ∞	− ∞	− ∞	− ∞	− ∞	− ∞	− ∞	− ∞	− ∞	− ∞	− ∞
0·5	0·033	−0·740	−1·600	−2·733	−3·655	−4·548	−5·850	−6·612	−7·207	−7·700	−9·357	−10·02	−10·39	−11·20
1·0	0·059	−0·408	−0·851	−1·303	−1·819	−2·300	−2·840	−3·312	−3·732	−3·867	−4·705	−4·915	−5·193	−5·671
1·5	0·081	−0·198	−0·575	−0·839	−1·230	−1·600	−1·881	−2·205	−2·488	−2·619	−3·060	−3·251	−3·511	−3·812
2·0	0·097	−0·045	−0·272	−0·603	−0·885	−1·142	−1·397	−1·651	−1·834	−1·980	−2·225	−2·402	−2·660	−2·888
2·5	0·112	−0·024	−0·112	−0·449	−0·669	−0·875	−1·095	−1·299	−1·433	−1·576	−1·732	−1·921	−2·116	−2·322
3·0	0·125	0·013	−0·061	−0·358	−0·532	−0·711	−0·894	−1·069	−1·175	−1·294	−1·407	−1·588	−1·732	−1·897
3·5	0·137	0·051	−0·035	−0·296	−0·420	−0·584	−0·737	−0·894	−0·983	−1·084	−1·183	−1·327	−1·450	−1·576
4·0	0·149	0·085	−0·019	−0·240	−0·342	−0·471	−0·625	−0·754	−0·833	−0·916	−1·014	−1·126	−1·235	−1·347
4·5	0·160	0·111	−0·005	−0·176	−0·281	−0·392	−0·534	−0·649	−0·703	−0·776	−0·875	−0·969	−1·069	−1·183
5·0	0·169	0·132	0·024	−0·128	−0·235	−0·337	−0·456	−0·587	−0·589	−0·657	−0·759	−0·842	−0·933	−1·057
5·5	0·180	0·148	0·056	−0·089	−0·194	−0·291	−0·386	−0·496	−0·499	−0·552	−0·647	−0·737	−0·827	−0·952
6·0	0·189	0·162	0·077	−0·056	−0·158	−0·247	−0·325	−0·410	−0·418	−0·471	−0·550	−0·644	−0·737	−0·863
6·5	0·200	0·175	0·096	−0·028	−0·121	−0·205	−0·275	−0·348	−0·352	−0·404	−0·468	−0·563	−0·654	−0·778
7·0	0·209	0·187	0·114	0·000	−0·079	−0·166	−0·229	−0·294	−0·294	−0·340	−0·394	−0·499	−0·577	−0·700
7·5	0·218	0·200	0·130	0·040	−0·028	−0·128	−0·189	−0·253	−0·246	−0·279	−0·329	−0·431	−0·507	−0·618
8·0	0·229	0·213	0·146	0·072	0·024	−0·095	−0·153	−0·216	−0·203	−0·224	−0·272	−0·346	−0·437	−0·538
8·5	0·239	0·225	0·162	0·096	0·058	−0·061	−0·103	−0·182	−0·164	−0·175	−0·224	−0·272	−0·382	−0·452
9·0	0·250	0·238	0·176	0·117	0·080	−0·031	−0·062	−0·148	−0·125	−0·132	−0·180	−0·216	−0·342	−0·378
9·5	0·260	0·251	0·193	0·135	0·102	0·000	−0·022	−0·114	−0·084	−0·095	−0·144	−0·176	−0·300	−0·323
10·0	0·272	0·264	0·205	0·153	0·117	0·028	−0·019	−0·079	−0·042	−0·061	−0·112	−0·142	−0·235	−0·281
10·5	0·284	0·277	0·220	0·169	0·133	0·058	0·056	−0·042	0·000	−0·031	−0·082	−0·110	−0·153	−0·244
11·0	0·297	0·291	0·235	0·185	0·149	0·084	0·096	0·000	0·042	0·000	−0·054	−0·080	−0·114	−0·211
11·5	0·310	0·304	0·249	0·200	0·166	0·110	0·137	0·164	0·082	0·035	−0·026	−0·054	−0·082	−0·180
12·0	0·324	0·319	0·264	0·216	0·180	0·133	0·193	0·231	0·125	0·070	0·000	−0·026	−0·052	−0·151
12·5	0·338	0·333	0·279	0·233	0·198	0·158	0·236	0·277	0·166	0·103	0·037	0·000	−0·026	−0·123
13·0	0·352	0·346	0·296	0·249	0·214	0·182	0·275	0·313	0·205	0·137	0·072	0·028	0·000	−0·096
13·5	0·367	0·362	0·313	0·266	0·233	0·203	0·311	0·344	0·244	0·167	0·107	0·058	0·023	−0·070
14·0	0·384	0·378	0·329	0·283	0·251	0·225	0·348	0·376	0·279	0·200	0·139	0·086	0·047	−0·047
14·5	0·400	0·392	0·346	0·302	0·272	0·247	0·384	0·404	0·313	0·231	0·169	0·112	0·070	−0·023
15·0	0·416	0·408	0·366	0·321	0·291	0·268	0·427	0·435	0·346	0·259	0·198	0·137	0·093	0·000
15·5	0·433	0·424	0·384	0·338	0·313	0·289	0·466	0·462	0·378	0·287	0·227	0·160	0·114	0·017
16·0	0·450	0·441	0·404	0·360	0·338	0·380	0·501	0·490	0·408	0·315	0·255	0·184	0·135	0·035
16·5	0·466	0·458	0·424	0·382	0·368	0·552	0·534	0·518	0·439	0·342	0·281	0·205	0·157	0·052
17·0	0·484	0·475	0·447	0·406	0·414	0·582	0·566	0·547	0·468	0·370	0·308	0·225	0·175	0·068
17·5	0·502	0·492	0·471	0·433	0·557	0·610	0·594	0·575	0·494	0·396	0·333	0·246	0·193	0·086
18·0	0·518	0·510	0·499	0·516	0·632	0·640	0·622	0·603	0·518	0·422	0·354	0·264	0·209	0·102
18·5	0·532	0·527	0·534	0·608	0·682	0·669	0·649	0·632	0·541	0·445	0·374	0·283	0·224	0·117
19·0	0·548	0·545	0·584	0·682	0·713	0·700	0·677	0·657	0·561	0·466	0·394	0·300	0·236	0·132
19·5	0·569	0·566	0·698	0·745	0·748	0·729	0·705	0·680	0·582	0·486	0·410	0·317	0·249	0·146
20	0·612	0·695	0·784	0·801	0·778	0·756	0·732	0·700	0·601	0·503	0·424	0·333	0·262	0·158
21	0·838	0·882	0·875	0·863	0·836	0·810	0·778	0·737	0·632	0·536	0·452	0·362	0·283	0·185
22	0·953	0·952	0·942	0·920	0·888	0·842	0·818	0·770	0·662	0·561	0·475	0·390	0·302	0·203
23	1·024	1·018	1·000	0·966	0·929	0·888	0·848	0·798	0·687	0·587	0·496	0·408	0·317	0·216
24	1·094	1·080	1·046	1·000	0·962	0·923	0·875	0·821	0·708	0·606	0·512	0·422	0·329	0·231

TABLE II—*Continued*

Extended Distances for S

Δ	Depth h =													
	Surface	0·00	0·01	0·02	0·03	0·04	0·05	0·06	0·07	0·08	0·09	0·10	0·11	0·12
25	1·140	1·134	1·087	1·032	0·990	0·952	0·897	0·842	0·727	0·622	0·527	0·435	0·340	0·249
26	1·172	1·171	1·118	1·061	1·011	0·972	0·916	0·860	0·743	0·637	0·538	0·441	0·348	0·266
27	1·202	1·200	1·146	1·091	1·028	0·983	0·933	0·875	0·756	0·647	0·547	0·452	0·360	0·283
28	1·228	1·222	1·167	1·111	1·046	0·997	0·942	0·885	0·767	0·654	0·557	0·460	0·374	0·300
29	1·249	1·244	1·183	1·126	1·065	1·007	0·949	0·894	0·776	0·662	0·568	0·473	0·392	0·319
30	1·266	1·257	1·196	1·142	1·080	1·018	0·959	0·900	0·781	0·667	0·577	0·486	0·410	0·338
31	1·280	1·271	1·205	1·154	1·091	1·028	0·969	0·910	0·790	0·677	0·589	0·499	0·429	0·358
32	1·292	1·285	1·213	1·163	1·103	1·039	0·979	0·920	0·795	0·687	0·601	0·516	0·447	0·380
33	1·302	1·294	1·226	1·171	1·111	1·050	0·990	0·929	0·804	0·700	0·615	0·534	0·464	0·400
34	1·310	1·299	1·235	1·183	1·122	1·061	1·003	0·939	0·816	0·716	0·630	0·550	0·481	0·420
35	1·315	1·308	1·248	1·192	1·134	1·072	1·014	0·952	0·830	0·732	0·642	0·566	0·499	0·439
36	1·321	1·317	1·257	1·205	1·146	1·087	1·028	0·966	0·845	0·748	0·657	0·582	0·514	0·456
37	1·330	1·327	1·271	1·217	1·159	1·099	1·043	0·983	0·860	0·765	0·672	0·598	0·527	0·475
38	1·347	1·342	1·285	1·230	1·175	1·111	1·057	0·997	0·879	0·781	0·685	0·615	0·543	0·492
39	1·363	1·356	1·299	1·244	1·188	1·126	1·072	1·011	0·894	0·795	0·700	0·630	0·559	0·507
40	1·389	1·371	1·313	1·257	1·205	1·142	1·087	1·025	0·910	0·810	0·716	0·647	0·573	0·523
41	1·398	1·387	1·332	1·275	1·222	1·159	1·099	1·043	0·923	0·824	0·729	0·662	0·587	0·538
42	1·414	1·402	1·347	1·294	1·235	1·175	1·115	1·057	0·939	0·839	0·745	0·677	0·603	0·552
43	1·432	1·418	1·366	1·303	1·248	1·188	1·130	1·072	0·952	0·851	0·759	0·690	0·618	0·568
44	1·448	1·433	1·376	1·317	1·262	1·205	1·146	1·084	0·966	0·866	0·773	0·705	0·632	0·582
45	1·466	1·450	1·392	1·332	1·275	1·222	1·159	1·099	0·979	0·879	0·787	0·719	0·647	0·596
46	1·481	1·466	1·407	1·347	1·294	1·235	1·175	1·115	0·993	0·891	0·801	0·732	0·662	0·610
47	1·497	1·488	1·423	1·361	1·308	1·248	1·188	1·126	1·007	0·907	0·816	0·748	0·677	0·625
48	1·512	1·505	1·439	1·376	1·322	1·262	1·205	1·142	1·021	0·920	0·830	0·762	0·692	0·640
49	1·527	1·517	1·455	1·397	1·337	1·275	1·217	1·154	1·036	0·933	0·845	0·776	0·705	0·654
50	1·541	1·534	1·471	1·412	1·351	1·289	1·230	1·167	1·050	0·946	0·860	0·790	0·721	0·669
51	1·556	1·546	1·483	1·428	1·366	1·303	1·248	1·183	1·065	0·959	0·875	0·804	0·737	0·685
52	1·572	1·564	1·499	1·444	1·381	1·317	1·262	1·196	1·080	0·972	0·888	0·818	0·751	0·700
53	1·589	1·582	1·517	1·460	1·397	1·332	1·275	1·209	1·095	0·990	0·904	0·833	0·767	0·716
54	1·605	1·600	1·534	1·477	1·412	1·347	1·289	1·226	1·111	1·003	0·920	0·851	0·784	0·735
55	1·622	1·613	1·552	1·494	1·428	1·361	1·303	1·239	1·126	1·018	0·936	0·866	0·801	0·751
56	1·639	1·632	1·570	1·505	1·444	1·376	1·322	1·257	1·142	1·036	0·952	0·882	0·818	0·767
57	1·656	1·651	1·582	1·522	1·460	1·397	1·337	1·271	1·159	1·054	0·969	0·897	0·836	0·784
58	1·673	1·671	1·600	1·540	1·477	1·412	1·351	1·289	1·175	1·072	0·986	0·913	0·854	0·804
59	1·692	1·684	1·619	1·558	1·494	1·433	1·371	1·308	1·188	1·087	1·003	0·929	0·869	0·821
60	1·712	1·704	1·638	1·576	1·517	1·450	1·387	1·322	1·205	1·107	1·021	0·946	0·888	0·839
61	1·732	1·725	1·658	1·594	1·534	1·471	1·407	1·342	1·222	1·126	1·039	0·966	0·907	0·857
62	1·752	1·746	1·678	1·613	1·552	1·488	1·428	1·361	1·239	1·146	1·057	0·983	0·923	0·875
63	1·771	1·767	1·698	1·632	1·576	1·511	1·444	1·381	1·257	1·163	1·076	1·000	0·942	0·894
64	1·794	1·789	1·725	1·658	1·594	1·534	1·466	1·402	1·275	1·183	1·095	1·018	0·962	0·913
65	1·819	1·811	1·746	1·678	1·619	1·552	1·488	1·423	1·299	1·200	1·115	1·036	0·979	0·929
66	1·844	1·834	1·767	1·698	1·638	1·570	1·511	1·444	1·317	1·222	1·134	1·054	0·997	0·949
67	1·868	1·857	1·789	1·725	1·664	1·594	1·534	1·466	1·337	1·244	1·150	1·076	1·018	0·969
68	1·889	1·881	1·819	1·753	1·691	1·619	1·558	1·488	1·361	1·262	1·171	1·095	1·036	0·990
69	1·909	1·905	1·842	1·775	1·711	1·638	1·576	1·511	1·381	1·285	1·192	1·115	1·057	1·007

TABLE II—*Concluded*

Extended Distances for S

Δ	Depth h =													
	Surface	0·00	0·01	0·02	0·03	0·04	0·05	0·06	0·07	0·08	0·09	0·10	0·11	0·12
70	1·930	1·929	1·865	1·797	1·732	1·664	1·600	1·534	1·407	1·303	1·209	1·134	1·076	1·028
71	1·956	1·954	1·889	1·827	1·760	1·684	1·625	1·558	1·428	1·322	1·230	1·159	1·095	1·050
72	1·985	1·980	1·913	1·849	1·782	1·711	1·651	1·582	1·450	1·342	1·248	1·179	1·115	1·069
73	2·016	2·006	1·937	1·873	1·811	1·732	1·671	1·607	1·471	1·366	1·271	1·205	1·138	1·091
74	2·046	2·032	1·963	1·897	1·834	1·760	1·698	1·625	1·494	1·387	1·294	1·226	1·159	1·111
75	2·076	2·059	1·988	1·929	1·857	1·789	1·718	1·651	1·517	1·407	1·317	1·248	1·179	1·134
76	2·108	2·087	2·014	1·954	1·881	1·811	1·746	1·678	1·540	1·428	1·342	1·275	1·205	1·154
77	2·140	2·116	2·041	1·980	1·905	1·842	1·767	1·704	1·564	1·455	1·371	1·299	1·226	1·179
78	2·168	2·145	2·069	2·006	1·937	1·873	1·797	1·725	1·594	1·483	1·397	1·327	1·253	1·205
79	2·197	2·174	2·106	2·032	1·963	1·897	1·827	1·753	1·619	1·511	1·423	1·356	1·280	1·226
80	2·228	2·204	2·135	2·069	1·988	1·929	1·857	1·782	1·651	1·540	1·455	1·387	1·308	1·253
81	2·256	2·246	2·174	2·097	2·023	1·963	1·889	1·811	1·678	1·570	1·483	1·412	1·337	1·285
82	2·287	2·278	2·204	2·135	2·059	1·997	1·921	1·849	1·711	1·600	1·511	1·444	1·366	1·313
83	2·324	2·311	2·246	2·174	2·097	2·032	1·954	1·881	1·746	1·632	1·546	1·471	1·397	1·342
84	2·360	2·356	2·289	2·204	2·135	2·069	1·988	1·921	1·775	1·664	1·576	1·499	1·428	1·371
85	2·399	2·391	2·322	2·246	2·174	2·106	2·023	1·963	1·811	1·698	1·607	1·528	1·460	1·402
86	2·442	2·426	2·367	2·289	2·215	2·145	2·059	1·997	1·849	1·732	1·638	1·558	1·494	1·433
87	2·489	2·475	2·414	2·333	2·257	2·184	2·106	2·032	1·881	1·760	1·671	1·588	1·522	1·466
88	2·533	2·526	2·463	2·379	2·300	2·225	2·145	2·069	1·921	1·789	1·698	1·619	1·552	1·494
89	2·584	2·565	2·513	2·414	2·344	2·267	2·184	2·106	1·963	1·827	1·725	1·645	1·576	1·517
90	2·638	2·619	2·565	2·463	2·379	2·300	2·225	2·145	1·988	1·849	1·753	1·671	1·600	1·540
91	2·688	2·660	2·605	2·500	2·426	2·333	2·257	2·174	2·014	1·881	1·775	1·691	1·619	1·558
92	2·711	2·703	2·633	2·539	2·463	2·367	2·289	2·204	2·041	1·913	1·797	1·711	1·638	1·570
93	2·747	2·733	2·660	2·565	2·488	2·402	2·311	2·225	2·059	1·937	1·819	1·732	1·651	1·581
94	2·795	2·762	2·689	2·592	2·513	2·414	2·333	2·246	2·078	1·954	1·834	1·746	1·664	1·594
95	2·821	2·778	2·718	2·619	2·526	2·438	2·344	2·257	2·097	1·963	1·849	1·753	1·671	1·600
96	2·844	2·808	2·733	2·633	2·552	2·450	2·356	2·267	2·106	1·971	1·857	1·760	1·678	1·607
97	2·859	2·824	2·733	2·646	2·565	2·463	2·367	2·278	2·116	1·980	1·865	1·767	1·684	1·613
98	2·868	2·840	2·747	2·660	2·565	2·475	2·379	2·289	2·125	1·988	1·873	1·767	1·691	1·619
99	2·873	2·856	2·762	2·675	2·578	2·488	2·391	2·300	2·125	1·988	1·881	1·775	1·698	1·625
100	2·880	2·872	2·762	2·675	2·578	2·500	2·402	2·300	2·135	1·997	1·881	1·782	1·698	1·625
101	2·889	2·872	2·778	2·689	2·592	2·500	2·402	2·311	2·135	1·997	1·889	1·782	1·703	1·631
102	2·896	2·888	2·778	2·689	2·592	2·500	2·402	2·311	2·145	2·006	1·889	1·782	1·703	1·631
103	2·902	2·888	2·778	2·689	2·592	2·500	2·409	2·311	2·145	2·006	1·889	1·788	1·703	1·631
104	2·908	2·888	2·793	2·703	2·605	2·500	2·409	2·311	2·145	2·006	1·889	1·788	.....	.....
105	2·910	2·888	2·793	2·703	2·605	2·500	2·409	2·311	2·145	2·006	.....	.....	.....	.....
106	2·910	2·888	2·793	2·703	2·605	2·500	.....	.....	.....	.....	.....	.....	.....	.....
107	2·910	2·888	2·793	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....

TABLE III

Extended Distances for SS

Δ	Depth h =													
	Surface	0·00	0·01	0·02	0·03	0·04	0·05	0·06	0·07	0·08	0·09	0·10	0·11	0·12
0·0	0·000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
0·5	0·019	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
1·0	0·033	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
1·5	0·047	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
2·0	0·059	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
2·5	0·071	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
3·0	0·081	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
3·5	0·089	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
4·0	0·097	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
4·5	0·106	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
5·0	0·112	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
5·5	0·119	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
6·0	0·125	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
6·5	0·132	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
7·0	0·137	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
7·5	0·143	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
8·0	0·149	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
8·5	0·154	0·006	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
9·0	0·160	0·051	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
9·5	0·165	0·069	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
10·0	0·169	0·089	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
10·5	0·175	0·101	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
11·0	0·180	0·115	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
11·5	0·185	0·126	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
12·0	0·189	0·136	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
12·5	0·194	0·145	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
13·0	0·200	0·152	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
13·5	0·204	0·160	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
14·0	0·209	0·168	0·052	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
14·5	0·214	0·175	0·068	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
15·0	0·218	0·181	0·082	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
15·5	0·224	0·187	0·094	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
16·0	0·229	0·193	0·104	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
16·5	0·234	0·200	0·113	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
17·0	0·239	0·206	0·122	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
17·5	0·245	0·213	0·132	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
18·0	0·250	0·220	0·140	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
18·5	0·255	0·226	0·148	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
19·0	0·260	0·232	0·156	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
19·5	0·266	0·239	0·165	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
20	0·272	0·246	0·172	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
21	0·284	0·259	0·189	0·000	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
22	0·297	0·273	0·203	0·080	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
23	0·310	0·287	0·217	0·115	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
24	0·324	0·300	0·233	0·137	0·051	.....	.....	.....	.....	.....	.....	.....	.....	.....

TABLE III—*Continued*

Extended Distances for SS

Δ	Depth h =													
	Surface	0·00	0·01	0·02	0·03	0·04	0·05	0·06	0·07	0·08	0·09	0·10	0·11	0·12
25	0·338	0·315	0·248	0·158	0·080	.....	.....	.....	.....	.....	.....	.....	.....	.....
26	0·352	0·328	0·264	0·177	0·108	.....	.....	.....	.....	.....	.....	.....	.....	.....
27	0·367	0·344	0·280	0·194	0·128	.....	.....	.....	.....	.....	.....	.....	.....	.....
28	0·384	0·359	0·298	0·212	0·147	0·000	.....	.....	.....	.....	.....	.....	.....	.....
29	0·400	0·376	0·315	0·230	0·168	0·028	.....	.....	.....	.....	.....	.....	.....	.....
30	0·416	0·392	0·332	0·250	0·184	0·079	0·052	.....	.....	.....	.....	.....	.....	.....
31	0·433	0·408	0·352	0·269	0·208	0·118	0·130	.....	.....	.....	.....	.....	.....	.....
32	0·450	0·424	0·370	0·290	0·233	0·156	0·243	0·262	0·042	.....	.....	.....	.....	.....
33	0·466	0·442	0·392	0·313	0·255	0·188	0·342	0·324	0·125	0·000	.....	.....	.....	.....
34	0·484	0·457	0·408	0·336	0·280	0·216	0·372	0·366	0·205	0·075	.....	.....	.....	.....
35	0·502	0·475	0·431	0·360	0·306	0·247	0·411	0·404	0·270	0·140	.....	.....	.....	.....
36	0·518	0·495	0·454	0·385	0·337	0·285	0·473	0·439	0·322	0·188	0·000	.....	.....	.....
37	0·532	0·513	0·480	0·423	0·377	0·568	0·514	0·473	0·364	0·233	0·101	.....	.....	.....
38	0·548	0·529	0·512	0·501	0·389	0·599	0·555	0·506	0·405	0·270	0·160	0·028	.....	.....
39	0·569	0·558	0·552	0·590	0·655	0·630	0·589	0·540	0·442	0·308	0·208	0·092	0·000	.....
40	0·612	0·640	0·639	0·703	0·698	0·663	0·622	0·572	0·478	0·342	0·248	0·133	0·043	.....
41	0·764	0·750	0·764	0·774	0·734	0·700	0·653	0·606	0·507	0·376	0·284	0·179	0·083	.....
42	0·838	0·860	0·839	0·818	0·771	0·731	0·684	0·644	0·533	0·408	0·318	0·201	0·114	.....
43	0·920	0·908	0·875	0·848	0·803	0·760	0·716	0·671	0·557	0·439	0·347	0·228	0·144	.....
44	0·953	0·942	0·911	0·880	0·833	0·789	0·745	0·694	0·582	0·466	0·370	0·252	0·167	.....
45	0·985	0·980	0·946	0·909	0·860	0·815	0·769	0·716	0·603	0·488	0·394	0·273	0·188	0·000
46	1·024	1·012	0·978	0·935	0·888	0·832	0·793	0·736	0·620	0·507	0·412	0·293	0·205	0·028
47	1·063	1·040	1·004	0·960	0·912	0·851	0·714	0·754	0·635	0·526	0·427	0·312	0·222	0·055
48	1·094	1·066	1·028	0·980	0·932	0·876	0·830	0·772	0·652	0·541	0·442	0·330	0·236	0·081
49	1·121	1·103	1·051	0·996	0·948	0·898	0·847	0·788	0·665	0·556	0·456	0·348	0·250	0·106
50	1·140	1·131	1·071	1·012	0·964	0·916	0·860	0·801	0·679	0·569	0·469	0·364	0·263	0·127
51	1·156	1·149	1·091	1·029	0·979	0·932	0·873	0·813	0·692	0·583	0·481	0·380	0·276	0·144
52	1·172	1·168	1·109	1·044	0·993	0·946	0·885	0·824	0·703	0·594	0·492	0·393	0·287	0·160
53	1·187	1·183	1·123	1·059	1·003	0·959	0·897	0·834	0·713	0·604	0·502	0·403	0·297	0·178
54	1·202	1·197	1·137	1·072	1·012	0·969	0·907	0·845	0·723	0·613	0·510	0·411	0·307	0·193
55	1·216	1·208	1·150	1·088	1·021	0·977	0·917	0·855	0·732	0·621	0·518	0·418	0·315	0·202
56	1·228	1·220	1·160	1·100	1·029	0·981	0·926	0·864	0·740	0·628	0·525	0·425	0·323	0·210
57	1·239	1·231	1·169	1·110	1·039	0·988	0·934	0·871	0·748	0·637	0·532	0·431	0·328	0·217
58	1·249	1·242	1·177	1·119	1·049	0·995	0·939	0·877	0·754	0·643	0·537	0·436	0·335	0·225
59	1·257	1·249	1·185	1·125	1·059	1·001	0·943	0·883	0·760	0·648	0·541	0·440	0·340	0·234
60	1·266	1·256	1·192	1·133	1·068	1·005	0·946	0·887	0·766	0·651	0·547	0·444	0·344	0·244
61	1·273	1·262	1·197	1·140	1·075	1·012	0·950	0·891	0·770	0·654	0·552	0·449	0·349	0·254
62	1·280	1·269	1·201	1·148	1·082	1·017	0·954	0·895	0·774	0·658	0·557	0·454	0·355	0·264
63	1·286	1·276	1·206	1·153	1·088	1·021	0·960	0·889	0·778	0·662	0·562	0·459	0·362	0·273
64	1·292	1·283	1·211	1·160	1·092	1·027	0·965	0·902	0·780	0·664	0·568	0·464	0·368	0·283
65	1·297	1·289	1·216	1·162	1·099	1·033	0·971	0·907	0·784	0·667	0·573	0·472	0·377	0·292
66	1·302	1·293	1·221	1·166	1·105	1·038	0·975	0·913	0·788	0·672	0·578	0·479	0·387	0·302
67	1·307	1·296	1·228	1·169	1·109	1·043	0·980	0·918	0·792	0·678	0·584	0·485	0·398	0·312
68	1·310	1·298	1·232	1·175	1·112	1·049	0·985	0·924	0·795	0·682	0·593	0·492	0·408	0·324
69	1·312	1·302	1·237	1·182	1·118	1·054	0·991	0·928	0·799	0·688	0·597	0·499	0·418	0·333

TABLE III—*Continued*

Extended Distances for SS

Δ	Depth h =													
	Surface	0·00	0·01	0·02	0·03	0·04	0·05	0·06	0·07	0·08	0·09	0·10	0·11	0·12
70	1·315	1·307	1·244	1·186	1·124	1·060	0·998	0·932	0·803	0·693	0·604	0·507	0·428	0·345
71	1·318	1·312	1·249	1·191	1·130	1·065	1·004	0·937	0·809	0·701	0·609	0·517	0·438	0·456
72	1·321	1·316	1·255	1·197	1·136	1·071	1·010	0·943	0·815	0·708	0·616	0·526	0·448	0·468
73	1·325	1·321	1·260	1·204	1·142	1·078	1·017	0·949	0·822	0·717	0·624	0·536	0·457	0·480
74	1·330	1·325	1·266	1·210	1·149	1·086	1·023	0·956	0·830	0·726	0·632	0·544	0·466	0·491
75	1·338	1·332	1·273	1·216	1·155	1·092	1·030	0·964	0·837	0·735	0·640	0·553	0·474	0·501
76	1·347	1·340	1·280	1·223	1·162	1·098	1·037	0·972	0·845	0·743	0·646	0·561	0·484	0·512
77	1·355	1·347	1·288	1·229	1·169	1·104	1·045	0·980	0·853	0·752	0·653	0·570	0·492	0·523
78	1·363	1·354	1·294	1·236	1·177	1·110	1·052	0·988	0·861	0·760	0·660	0·578	0·503	0·532
79	1·370	1·361	1·301	1·244	1·183	1·117	1·060	0·996	0·870	0·768	0·668	0·587	0·511	0·542
80	1·379	1·370	1·309	1·250	1·191	1·126	1·067	1·003	0·880	0·776	0·676	0·596	0·517	0·551
81	1·388	1·377	1·317	1·257	1·200	1·133	1·075	1·009	0·888	0·784	0·682	0·604	0·524	0·560
82	1·398	1·385	1·326	1·266	1·209	1·142	1·082	1·017	0·895	0·792	0·689	0·613	0·532	0·570
83	1·406	1·392	1·335	1·275	1·217	1·150	1·090	1·024	0·903	0·800	0·697	0·621	0·541	0·580
84	1·414	1·400	1·343	1·285	1·225	1·159	1·095	1·033	0·912	0·807	0·705	0·628	0·549	0·589
85	1·424	1·408	1·351	1·295	1·231	1·166	1·103	1·041	0·918	0·814	0·713	0·637	0·558	0·598
86	1·432	1·416	1·360	1·299	1·238	1·175	1·111	1·050	1·005	0·822	0·722	0·647	0·566	0·605
87	1·441	1·423	1·369	1·303	1·244	1·181	1·119	1·057	1·013	0·829	0·728	0·655	0·573	0·613
88	1·448	1·431	1·374	1·309	1·250	1·189	1·126	1·064	1·041	0·839	0·737	0·663	0·580	0·622
89	1·457	1·439	1·380	1·317	1·258	1·197	1·135	1·072	1·048	0·844	0·744	0·671	0·588	0·629
90	1·466	1·447	1·388	1·323	1·265	1·206	1·142	1·078	1·054	0·850	0·751	0·679	0·596	0·638
91	1·473	1·456	1·397	1·332	1·272	1·214	1·150	1·084	1·060	0·857	0·759	0·685	0·605	0·645
92	1·481	1·464	1·403	1·339	1·280	1·223	1·156	1·091	1·069	0·864	0·767	0·691	0·613	0·653
93	1·489	1·474	1·409	1·346	1·289	1·229	1·163	1·100	1·076	0·871	0·774	0·698	0·620	0·560
94	1·497	1·485	1·417	1·353	1·299	1·235	1·171	1·108	1·082	0·878	0·780	0·707	0·627	0·569
95	1·505	1·493	1·426	1·361	1·305	1·241	1·179	1·116	1·088	0·884	0·788	0·721	0·634	0·577
96	1·512	1·502	1·434	1·368	1·312	1·248	1·185	1·121	1·096	0·890	0·796	0·728	0·641	0·584
97	1·520	1·510	1·442	1·376	1·319	1·255	1·194	1·127	1·103	0·898	0·802	0·736	0·650	0·592
98	1·527	1·516	1·450	1·388	1·326	1·263	1·202	1·135	1·111	0·906	0·809	0·744	0·657	0·600
99	1·534	1·524	1·454	1·399	1·334	1·269	1·210	1·143	1·018	0·913	0·817	0·744	0·666	0·606
100	1·541	1·532	1·467	1·405	1·341	1·276	1·215	1·148	1·025	0·920	0·824	0·752	0·674	0·613
101	1·549	1·539	1·474	1·413	1·348	1·282	1·221	1·156	1·032	0·927	0·832	0·759	0·681	0·620
102	1·556	1·545	1·480	1·420	1·355	1·290	1·228	1·161	1·040	0·934	0·840	0·766	0·689	0·628
103	1·565	1·553	1·487	1·429	1·362	1·297	1·236	1·168	1·048	0·940	0·848	0·773	0·697	0·636
104	1·572	1·561	1·495	1·436	1·371	1·304	1·246	1·176	1·055	0·945	0·856	0·781	0·704	0·644
105	1·580	1·571	1·503	1·445	1·379	1·310	1·254	1·184	1·063	0·952	0·864	0·788	0·712	0·651
106	1·589	1·580	1·512	1·453	1·386	1·319	1·261	1·191	1·070	0·960	0·871	0·795	0·720	0·660
107	1·597	1·589	1·521	1·461	1·394	1·326	1·267	1·198	1·078	0·966	0·878	0·802	0·728	0·667
108	1·605	1·598	1·529	1·470	1·402	1·334	1·274	1·204	1·086	0·974	0·885	0·810	0·737	0·675
109	1·613	1·606	1·539	1·478	1·409	1·340	1·280	1·212	1·093	0·982	0·892	0·817	0·744	0·684
110	1·622	1·611	1·547	1·487	1·417	1·349	1·288	1·220	1·101	0·992	0·900	0·824	0·752	0·692
111	1·630	1·620	1·556	1·495	1·425	1·356	1·294	1·228	1·108	0·999	0·909	0·833	0·760	0·700
112	1·639	1·630	1·565	1·500	1·433	1·362	1·301	1·234	1·116	1·005	0·918	0·841	0·769	0·708
113	1·648	1·640	1·573	1·505	1·441	1·369	1·310	1·244	1·125	1·012	0·926	0·851	0·778	0·717
114	1·656	1·649	1·580	1·513	1·449	1·379	1·320	1·252	1·133	1·020	0·934	0·858	0·787	0·726

TABLE III—*Continued*

Extended Distances for SS

Δ	Depth h =													
	Surface	0·00	0·01	0·02	0·03	0·04	0·05	0·06	0·07	0·08	0·09	0·10	0·11	0·12
115	1·665	1·658	1·586	1·523	1·457	1·389	1·328	1·260	1·141	1·030	0·941	0·867	0·796	0·737
116	1·673	1·668	1·596	1·532	1·465	1·399	1·336	1·267	1·151	1·040	0·950	0·875	0·805	0·745
117	1·683	1·676	1·606	1·541	1·475	1·407	1·343	1·274	1·159	1·048	0·958	0·884	0·813	0·753
118	1·692	1·683	1·614	1·550	1·484	1·415	1·350	1·284	1·166	1·057	0·967	0·891	0·821	0·762
119	1·702	1·692	1·624	1·559	1·492	1·425	1·360	1·294	1·175	1·066	0·976	0·899	0·831	0·770
120	1·712	1·702	1·632	1·568	1·503	1·436	1·371	1·304	1·181	1·075	0·985	0·909	0·841	0·778
121	1·722	1·713	1·642	1·577	1·514	1·444	1·379	1·312	1·188	1·083	0·994	0·915	0·850	0·789
122	1·732	1·723	1·650	1·585	1·524	1·453	1·387	1·319	1·196	1·092	1·003	0·922	0·858	0·800
123	1·742	1·733	1·663	1·596	1·532	1·464	1·397	1·327	1·206	1·101	1·011	0·931	0·867	0·810
124	1·752	1·744	1·673	1·604	1·541	1·474	1·407	1·337	1·213	1·112	1·021	0·940	0·875	0·818
125	1·762	1·755	1·684	1·613	1·550	1·482	1·417	1·348	1·223	1·122	1·031	0·950	0·886	0·828
126	1·771	1·765	1·694	1·623	1·560	1·492	1·428	1·357	1·231	1·132	1·040	0·960	0·895	0·838
127	1·782	1·776	1·705	1·633	1·573	1·504	1·436	1·367	1·240	1·142	1·049	0·969	0·905	0·847
128	1·794	1·787	1·717	1·647	1·584	1·515	1·444	1·377	1·249	1·152	1·058	0·978	0·915	0·857
129	1·806	1·796	1·729	1·659	1·592	1·526	1·456	1·388	1·258	1·160	1·068	0·986	0·923	0·866
130	1·819	1·808	1·740	1·669	1·604	1·538	1·467	1·398	1·268	1·169	1·078	0·995	0·932	0·876
131	1·831	1·820	1·751	1·679	1·616	1·546	1·478	1·408	1·277	1·180	1·087	1·005	0·942	0·885
132	1·844	1·831	1·761	1·689	1·627	1·555	1·489	1·419	1·288	1·189	1·097	1·014	0·952	0·896
133	1·856	1·843	1·773	1·701	1·636	1·564	1·500	1·434	1·300	1·198	1·107	1·023	0·963	0·905
134	1·868	1·855	1·785	1·713	1·648	1·576	1·512	1·440	1·310	1·208	1·118	1·033	0·972	0·915
135	1·879	1·868	1·797	1·727	1·662	1·588	1·524	1·451	1·320	1·219	1·128	1·042	0·980	0·923
136	1·889	1·880	1·812	1·740	1·676	1·601	1·536	1·462	1·330	1·231	1·136	1·052	0·989	0·932
137	1·899	1·892	1·826	1·755	1·689	1·613	1·547	1·474	1·341	1·243	1·144	1·062	1·000	0·943
138	1·909	1·903	1·837	1·767	1·700	1·624	1·559	1·486	1·353	1·252	1·154	1·073	1·009	0·953
139	1·920	1·914	1·848	1·776	1·711	1·633	1·568	1·497	1·365	1·261	1·164	1·084	1·020	0·964
140	1·930	1·927	1·860	1·788	1·720	1·644	1·578	1·508	1·375	1·272	1·176	1·094	1·029	0·975
141	1·941	1·939	1·872	1·800	1·730	1·656	1·589	1·520	1·386	1·284	1·185	1·103	1·040	0·986
142	1·956	1·951	1·884	1·814	1·744	1·668	1·602	1·532	1·398	1·293	1·196	1·114	1·051	0·996
143	1·971	1·965	1·896	1·828	1·760	1·679	1·614	1·544	1·411	1·303	1·204	1·124	1·060	1·005
144	1·985	1·979	1·908	1·840	1·772	1·691	1·628	1·556	1·422	1·312	1·216	1·134	1·070	1·014
145	2·000	1·992	1·920	1·853	1·782	1·704	1·641	1·568	1·433	1·322	1·225	1·146	1·080	1·026
146	2·016	2·004	1·932	1·864	1·797	1·717	1·653	1·580	1·444	1·332	1·234	1·160	1·090	1·038
147	2·032	2·016	1·944	1·876	1·811	1·728	1·664	1·593	1·455	1·343	1·244	1·169	1·100	1·050
148	2·046	2·030	1·956	1·888	1·823	1·740	1·675	1·606	1·464	1·355	1·253	1·180	1·111	1·060
149	2·061	2·044	1·970	1·901	1·834	1·754	1·688	1·616	1·476	1·367	1·266	1·192	1·122	1·069
150	2·076	2·057	1·983	1·917	1·845	1·768	1·701	1·625	1·488	1·376	1·278	1·206	1·133	1·080
151	2·092	2·070	1·995	1·933	1·857	1·783	1·710	1·637	1·501	1·388	1·290	1·217	1·145	1·092
152	2·108	2·084	2·008	1·945	1·868	1·796	1·722	1·651	1·512	1·397	1·302	1·228	1·156	1·102
153	2·124	2·100	2·023	1·958	1·881	1·807	1·737	1·664	1·524	1·409	1·314	1·240	1·167	1·113
154	2·140	2·114	2·036	1·970	1·892	1·820	1·750	1·678	1·536	1·420	1·327	1·253	1·177	1·124
155	2·154	2·128	2·050	1·983	1·905	1·836	1·761	1·691	1·547	1·432	1·340	1·267	1·189	1·136
156	2·168	2·143	2·063	1·996	1·921	1·853	1·773	1·704	1·560	1·444	1·355	1·280	1·203	1·148
157	2·182	2·157	2·080	2·010	1·938	1·868	1·788	1·715	1·573	1·458	1·369	1·292	1·215	1·158
158	2·197	2·172	2·097	2·022	1·950	1·882	1·803	1·727	1·589	1·472	1·384	1·304	1·227	1·171
159	2·212	2·187	2·115	2·037	1·964	1·894	1·817	1·740	1·603	1·487	1·397	1·320	1·240	1·185

TABLE III—*Concluded*

Extended Distances for SS

Δ	*Depth h =*													
	Surface	0·00	0·01	0·02	0·03	0·04	0·05	0·06	0·07	0·08	0·09	0·10	0·11	0·12
160	2·228	2·202	2·128	2·056	1·976	1·908	1·833	1·755	1·615	1·501	1·410	1·333	1·253	1·200
161	2·242	2·222	2·145	2·072	1·990	1·924	1·849	1·768	1·630	1·516	1·423	1·349	1·267	1·211
162	2·256	2·244	2·165	2·088	2·006	1·940	1·865	1·783	1·648	1·530	1·439	1·364	1·281	1·221
163	2·270	2·260	2·182	2·102	2·024	1·960	1·881	1·798	1·660	1·545	1·456	1·380	1·296	1·235
164	2·287	2·276	2·198	2·121	2·042	1·978	1·897	1·813	1·675	1·561	1·469	1·393	1·311	1·248
165	2·305	2·292	2·216	2·141	2·060	1·994	1·913	1·829	1·690	1·576	1·484	1·407	1·325	1·264
166	2·324	2·309	2·239	2·162	2·079	2·011	1·929	1·848	1·707	1·592	1·500	1·422	1·340	1·280
167	2·343	2·331	2·260	2·180	2·098	2·028	1·945	1·866	1·725	1·608	1·515	1·439	1·355	1·296
168	2·360	2·353	2·283	2·194	2·116	2·048	1·962	1·885	1·743	1·624	1·531	1·453	1·372	1·311
169	2·378	2·372	2·300	2·212	2·136	2·065	1·979	1·905	1·758	1·640	1·549	1·467	1·387	1·327
170	2·399	2·388	2·317	2·232	2·156	2·085	1·997	1·928	1·773	1·657	1·564	1·481	1·403	1·342
171	2·420	2·407	2·337	2·255	2·178	2·104	2·015	1·948	1·792	1·675	1·580	1·495	1·418	1·356
172	2·442	2·424	2·359	2·276	2·198	2·124	2·033	1·968	1·811	1·692	1·595	1·510	1·434	1·372
173	2·466	2·447	2·383	2·296	2·220	2·143	2·051	1·985	1·829	1·708	1·612	1·526	1·451	1·388
174	2·489	2·472	2·407	2·318	2·240	2·161	2·073	2·000	1·849	1·724	1·628	1·540	1·469	1·404
175	2·511	2·496	2·430	2·341	2·261	2·182	2·096	2·019	1·864	1·740	1·645	1·556	1·487	1·420
176	2·533	2·523	2·455	2·365	2·281	2·204	2·119	2·037	1·881	1·754	1·661	1·572	1·502	1·437
177	2·557	2·543	2·480	2·385	2·304	2·224	2·139	2·056	1·902	1·769	1·677	1·588	1·517	1·453
178	2·584	2·564	2·504	2·402	2·326	2·245	2·158	2·076	1·924	1·785	1·690	1·604	1·532	1·471
179	2·612	2·588	2·530	2·423	2·348	2·267	2·177	2·094	1·945	1·802	1·704	1·619	1·548	1·485
180	2·638	2·616	2·556	2·448	2·366	2·283	2·196	2·113	1·965	1·822	1·718	1·631	1·561	1·497

TABLE IV

Extended Distances for sS

Δ	Depth h =												
	0·00	0·01	0·02	0·03	0·04	0·05	0·06	0·07	0·08	0·09	0·10	0·11	0·12
7·5	−0·051	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
8·0	−0·101	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
8·5	−0·137	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
9·0	−0·156	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
9·5	−0·171	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
10·0	−0·187	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
10·5	−0·200	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
11·0	−0·213	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
11·5	−0·228	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
12·0	−0·244	−0·114	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
12·5	−0·260	−0·136	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
13·0	−0·274	−0·156	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
13·5	−0·288	−0·173	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
14·0	−0·303	−0·194	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
14·5	−0·322	−0·208	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
15·0	−0·339	−0·226	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
15·5	−0·356	−0·245	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
16·0	−0·372	−0·264	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
16·5	−0·388	−0·284	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
17·0	−0·420	−0·303	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
17·5	−0·426	−0·319	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
18·0	−0·446	−0·338	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
18·5	−0·464	−0·360	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
19·0	−0·483	−0·380	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
19·5	−0·504	−0·400	−0·162	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
20	−0·524	−0·421	−0·195	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
21	−0·695	−0·480	−0·262	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
22	−0·911	−0·584	−0·360	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
23	−0·982	−0·875	−0·770	−0·117	.....	.....	.....	.....	.....	.....	.....	.....	.....
24	−1·056	−0·956	−0·863	−0·739	−0·582	.....	.....	.....	.....	.....	.....	.....	.....
25	−1·112	−1·019	−0·933	−0·823	−0·700	.....	.....	.....	.....	.....	.....	.....	.....
26	−1·159	−1·062	−0·980	−0·888	−0·768	−0·622	.....	.....	.....	.....	.....	.....	.....
27	−1·189	−1·103	−1·015	−0·934	−0·830	−0·732	−0·481	.....	.....	.....	.....	.....	.....
28	−1·213	−1·137	−1·049	−0·968	−0·888	−0·792	−0·669	.....	.....	.....	.....	.....	.....
29	−1·235	−1·159	−1·082	−0·999	−0·947	−0·842	−0·728	−0·534	.....	.....	.....	.....	.....
30	−1·253	−1·177	−1·107	−1·018	−0·964	−0·869	−0·778	−0·609	.....	.....	.....	.....	.....
31	−1·266	−1·192	−1·122	−1·037	−0·976	−0·897	−0·808	−0·649	−0·460	.....	.....	.....	.....
32	−1·280	−1·202	−1·140	−1·057	−0·987	−0·920	−0·832	−0·680	−0·527	.....	.....	.....	.....
33	−1·290	−1·209	−1·152	−1·075	−1·001	−0·936	−0·855	−0·708	−0·561	−0·224	.....	.....	.....
34	−1·297	−1·220	−1·161	−1·087	−1·012	−0·944	−0·872	−0·731	−0·598	−0·442	.....	.....	.....
35	−1·303	−1·231	−1·169	−1·098	−1·024	−0·952	−0·885	−0·748	−0·617	−0·475	−0·252	.....	.....
36	−1·313	−1·244	−1·180	−1·108	−1·033	−0·963	−0·894	−0·760	−0·633	−0·504	−0·322	.....	.....
37	−1·323	−1·255	−1·191	−1·120	−1·045	−0·972	−0·900	−0·769	−0·647	−0·520	−0·372	.....	.....
38	−1·335	−1·268	−1·203	−1·132	−1·057	−0·983	−0·910	−0·778	−0·654	−0·535	−0·404	−0·186	.....
39	−1·350	−1·283	−1·215	−1·144	−1·068	−0·995	−0·920	−0·786	−0·662	−0·546	−0·420	−0·236	.....

TABLE IV—*Continued*

Extended Distances for sS

Δ	Depth h =												
	0·00	0·01	0·02	0·03	0·04	0·05	0·06	0·07	0·08	0·09	0·10	0·11	0·12
40	−1·365	−1·296	−1·227	−1·156	−1·082	−1·008	−0·931	−0·793	−0·667	−0·557	−0·435	−0·278	.....
41	−1·380	−1·309	−1·244	−1·171	−1·096	−1·022	−0·943	−0·800	−0·678	−0·570	−0·444	−0·302	.....
42	−1·396	−1·327	−1·257	−1·185	−1·107	−1·038	−0·957	−0·813	−0·690	−0·580	−0·454	−0·324	.....
43	−1·410	−1·343	−1·275	−1·205	−1·126	−1·054	−0·974	−0·830	−0·706	−0·594	−0·465	−0·340	.....
44	−1·425	−1·361	−1·294	−1·222	−1·142	−1·069	−0·992	−0·845	−0·724	−0·610	−0·483	−0·350	−0·195
45	−1·443	−1·374	−1·303	−1·235	−1·159	−1·087	−1·005	−0·864	−0·744	−0·625	−0·499	−0·370	−0·220
46	−1·459	−1·390	−1·317	−1·248	−1·175	−1·099	−1·021	−0·884	−0·765	−0·642	−0·521	−0·399	−0·255
47	−1·478	−1·404	−1·332	−1·262	−1·191	−1·115	−1·040	−0·901	−0·781	−0·657	−0·546	−0·425	−0·283
48	−1·499	−1·420	−1·347	−1·278	−1·208	−1·134	−1·057	−0·918	−0·798	−0·675	−0·566	−0·451	−0·319
49	−1·513	−1·435	−1·361	−1·297	−1·225	−1·149	−1·072	−0·934	−0·813	−0·690	−0·586	−0·473	−0·344
50	−1·526	−1·451	−1·376	−1·310	−1·237	−1·161	−1·086	−0·950	−0·830	−0·708	−0·606	−0·494	−0·380
51	−1·540	−1·471	−1·400	−1·324	−1·250	−1·177	−1·102	−0·963	−0·845	−0·726	−0·626	−0·514	−0·406
52	−1·556	−1·483	−1·415	−1·340	−1·265	−1·195	−1·118	−0·979	−0·860	−0·743	−0·647	−0·532	−0·433
53	−1·574	−1·499	−1·431	−1·354	−1·279	−1·210	−1·133	−0·993	−0·873	−0·759	−0·666	−0·555	−0·456
54	−1·591	−1·517	−1·446	−1·372	−1·295	−1·222	−1·146	−1·009	−0·888	−0·776	−0·683	−0·573	−0·479
55	−1·608	−1·534	−1·463	−1·387	−1·309	−1·238	−1·160	−1·024	−0·907	−0·792	−0·698	−0·591	−0·500
56	−1·624	−1·552	−1·480	−1·402	−1·323	−1·257	−1·173	−1·039	−0·920	−0·808	−0·716	−0·611	−0·518
57	−1·642	−1·570	−1·496	−1·418	−1·337	−1·270	−1·189	−1·056	−0·936	−0·824	−0·732	−0·629	−0·528
58	−1·662	−1·582	−1·508	−1·435	−1·352	−1·283	−1·204	−1·071	−0·949	−0·841	−0·753	−0·647	−0·556
59	−1·679	−1·600	−1·526	−1·449	−1·369	−1·298	−1·220	−1·088	−0·961	−0·857	−0·765	−0·662	−0·575
60	−1·696	−1·619	−1·543	−1·467	−1·388	−1·314	−1·235	−1·104	−0·980	−0·877	−0·782	−0·680	−0·583
61	−1·716	−1·638	−1·561	−1·488	−1·407	−1·333	−1·252	−1·121	−0·994	−0·888	−0·799	−0·698	−0·608
62	−1·736	−1·658	−1·580	−1·508	−1·425	−1·350	−1·270	−1·139	−1·011	−0·908	−0·815	−0·716	−0·625
63	−1·759	−1·678	−1·601	−1·528	−1·443	−1·371	−1·289	−1·159	−1·032	−0·926	−0·833	−0·737	−0·643
64	−1·780	−1·698	−1·620	−1·545	−1·463	−1·387	−1·308	−1·175	−1·052	−0·944	−0·851	−0·755	−0·661
65	−1·802	−1·725	−1·641	−1·566	−1·484	−1·407	−1·325	−1·188	−1·072	−0·963	−0·870	−0·775	−0·681
66	−1·824	−1·746	−1·667	−1·587	−1·506	−1·428	−1·345	−1·208	−1·087	−0·981	−0·888	−0·796	−0·700
67	−1·848	−1·770	−1·687	−1·612	−1·529	−1·444	−1·365	−1·226	−1·111	−1·003	−0·906	−0·815	−0·721
68	−1·872	−1·794	−1·709	−1·634	−1·548	−1·473	−1·384	−1·244	−1·130	−1·021	−0·924	−0·836	−0·742
69	−1·895	−1·823	−1·737	−1·659	−1·570	−1·492	−1·408	−1·264	−1·150	−1·042	−0·942	−0·857	−0·762
70	−1·919	−1·847	−1·761	−1·686	−1·594	−1·515	−1·431	−1·284	−1·170	−1·062	−0·966	−0·878	−0·784
71	−1·942	−1·869	−1·783	−1·707	−1·619	−1·540	−1·452	−1·306	−1·192	−1·083	−0·983	−0·901	−0·813
72	−1·972	−1·893	−1·809	−1·728	−1·638	−1·562	−1·477	−1·330	−1·213	−1·104	−1·004	−0·923	−0·835
73	−2·001	−1·918	−1·837	−1·760	−1·664	−1·585	−1·501	−1·353	−1·235	−1·128	−1·024	−0·942	−0·857
74	−2·026	−1·942	−1·864	−1·782	−1·690	−1·608	−1·524	−1·379	−1·259	−1·148	−1·044	−0·967	−0·880
75	−2·052	−1·967	−1·888	−1·811	−1·715	−1·633	−1·552	−1·401	−1·285	−1·171	−1·066	−0·987	−0·904
76	−2·080	−1·993	−1·915	−1·834	−1·737	−1·661	−1·578	−1·428	−1·303	−1·192	−1·090	−1·006	−0·926
77	−2·108	−2·018	−1·945	−1·857	−1·765	−1·686	−1·601	−1·450	−1·322	−1·213	−1·115	−1·031	−0·948
78	−2·140	−2·047	−1·971	−1·811	−1·795	−1·712	−1·625	−1·471	−1·347	−1·233	−1·134	−1·057	−0·974
79	−2·168	−2·076	−1·996	−1·905	−1·818	−1·739	−1·651	−1·498	−1·370	−1·253	−1·161	−1·076	−0·998
80	−2·197	−2·112	−2·022	−1·943	−1·855	−1·763	−1·678	−1·521	−1·392	−1·279	−1·186	−1·100	−1·020
81	−2·237	−2·142	−2·056	−1·967	−1·883	−1·791	−1·704	−1·545	−1·415	−1·304	−1·211	−1·120	−1·050
82	−2·272	−2·180	−2·087	−1·994	−1·909	−1·821	−1·729	−1·574	−1·440	−1·336	−1·240	−1·148	−1·069
83	−2·307	−2·213	−2·123	−2·029	−1·945	−1·857	−1·759	−1·604	−1·476	−1·364	−1·268	−1·170	−1·095
84	−2·345	−2·261	−2·168	−2·066	−1·982	−1·889	−1·787	−1·633	−1·505	−1·397	−1·295	−1·198	−1·120

TABLE IV—*Concluded*

Extended Distances for sS

Δ	*Depth h =*												
	0·00	0·01	0·02	0·03	0·04	0·05	0·06	0·07	0·08	0·09	0·10	0·11	0·12
85	−2·384	−2·302	−2·198	−2·106	−2·017	−1·921	−1·819	−1·664	−1·533	−1·423	−1·327	−1·226	−1·148
86	−2·417	−2·336	−2·236	−2·143	−2·054	−1·954	−1·856	−1·696	−1·570	−1·460	−1·361	−1·253	−1·179
87	−2·466	−2·382	−2·280	−2·189	−2·096	−1·988	−1·900	−1·732	−1·600	−1·489	−1·393	−1·287	−1·209
88	−2·515	−2·432	−2·325	−2·229	−2·139	−2·024	−1·944	−1·766	−1·637	−1·524	−1·424	−1·321	−1·232
89	−2·556	−2·480	−2·368	−2·273	−2·175	−2·066	−1·983	−1·801	−1·673	−1·562	−1·457	−1·352	−1·268
90	−2·608	−2·533	−2·407	−2·316	−2·218	−2·093	−2·017	−1·849	−1·712	−1·595	−1·491	−1·391	−1·305
91	−2·652	−2·580	−2·452	−2·358	−2·267	−2·154	−2·060	−1·881	−1·744	−1·632	−1·520	−1·422	−1·342
92	−2·694	−2·616	−2·492	−2·396	−2·300	−2·191	−2·098	−1·930	−1·773	−1·664	−1·556	−1·460	−1·376
93	−2·728	−2·644	−2·539	−2·425	−2·333	−2·231	−2·138	−1·967	−1·810	−1·692	−1·588	−1·500	−1·408
94	−2·756	−2·672	−2·565	−2·477	−2·367	−2·265	−2·174	−1·995	−1·840	−1·725	−1·619	−1·530	−1·451
95	−2·778	−2·700	−2·592	−2·504	−2·402	−2·296	−2·204	−2·020	−1·873	−1·753	−1·652	−1·563	−1·481
96	−2·802	−2·724	−2·619	−2·520	−2·414	−2·320	−2·225	−2·049	−1·906	−1·775	−1·676	−1·588	−1·512
97	−2·820	−2·734	−2·633	−2·541	−2·438	−2·338	−2·246	−2·067	−1·932	−1·803	−1·699	−1·612	−1·535
98	−2·836	−2·743	−2·646	−2·560	−2·450	−2·349	−2·257	−2·084	−1·954	−1·822	−1·720	−1·631	−1·558
99	−2·853	−2·752	−2·660	−2·567	−2·463	−2·360	−2·267	−2·100	−1·963	−1·838	−1·739	−1·648	−1·570
100	−2·869	−2·762	−2·670	−2·574	−2·475	−2·371	−2·278	−2·110	−1·971	−1·852	−1·750	−1·662	−1·581
101	−2·881	−2·771	−2·679	−2·580	−2·488	−2·383	−2·289	−2·120	−1·980	−1·859	−1·756	−1·670	−1·594
102	−2·888	−2·776	−2·685	−2·585	−2·500	−2·394	−2·300	−2·126	−1·988	−1·867	−1·764	−1·677	−1·600
103	−2·888	−2·781	−2·689	−2·590	−2·500	−2·402	−2·307	−2·131	−1·992	−1·876	−1·769	−1·683	−1·607
104	−2·888	−2·787	−2·693	−2·596	−2·500	−2·402	−2·311	−2·136	−1·997	−1·880	−1·774	−1·689	−1·614
105	−2·888	−2·793	−2·699	−2·601	−2·500	−2·405	−2·311	−2·140	−2·001	−1·887	−1·777	−1·696	−1·620
106	−2·888	−2·793	−2·703	−2·605	−2·500	−2·409	−2·311	−2·144	−2·006	−1·889	−1·781	−1·700	−1·626
107	−2·888	−2·793	−2·703	−2·605	−2·500	−2·409	−2·311	−2·145	−2·006	−1·889	−1·784	−1·702	−1·629
108	.....	.....	.....	.....	−2·500	.....	−2·311	−2·145	−2·006	−1·889	−1·786	−1·703	−1·631
109	.....	.....	.....	.....	.....	.....	.....	.....	−2·006	.....	−1·788	−1·703	−1·631

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Seismic Activity in Canada, West of the 113th Meridian 1841 - 1951

BY

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QUEEN'S PRINTER AND CONTROLLFR OF STATIONERY

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ABSTRACT

From a search of available data, a list of the earthquakes felt or centred in the western mountain region of Canada has been prepared. From December of 1841 to August of 1951, a total of 242 earthquakes were located in this general area. These vary in intensity from very weak shocks to the Queen Charlotte Islands earthquake of magnitude 8·0. A description is given for the major tremors. An additional list contains those tremors recorded at Victoria after the sensitive seismograph was installed in 1948 but for which epicentres could not be determined. A map is included to show the area studied; it does not contain a complete record of the earthquakes.

INTRODUCTION

Seismological study in British Columbia began in 1899 when the first seismograph was installed at Victoria. From that date there has been a seismograph in continuous operation at Victoria, except for a brief period in 1938-39. The original instruments and their later replacements were not designed to record small earthquakes occurring near the station; hence their contribution to studies of the early seismological history of British Columbia is limited. In 1948 a sensitive seismograph was added to the Victoria station, and in 1951 two additional sensitive stations were established in south-western British Columbia for a more detailed investigation of the seismicity of that area.

The data from the network seismographs have been published in other issues of these *Publications*.[1,2,3,4] In order to make the picture as complete as possible, in this publication an attempt is made to list all the tremors occurring from the time of the earliest records in British Columbia to August of 1951. The report includes the earthquakes that have been centred or felt in British Columbia or in its coastal waters, in western Alberta, in the southern Yukon Territory area, and off the coast of the Alaskan panhandle. All available sources of information for compiling such a list have been thoroughly checked, and the results are presented in this paper. If other sources of data that may later become available reveal additional information, a supplementary report will be published.

INSTRUMENTS

Before discussing the earthquakes occurring in British Columbia prior to 1951, it is of interest to record the early history of seismograph stations in the province, a history that is centred about one place, for until 1951 Victoria was the sole seismograph station in British Columbia.

At the suggestion of the British Association for the Advancement of Science, two seismographs were purchased by the Dominion Government Meteorological Service at

[1] W. G. Milne and F. Lombardo, "Canadian West Coast Earthquakes, 1951", *Publications of the Dominion Observatory*, Vol. XVI, No. 3, 1952.

[2] W. G. Milne, "Canadian West Coast Earthquakes, 1952", *Publications of the Dominion Observatory*, Vol. XVI, No. 9, 1954.

[3] W. G. Milne, "Canadian West Coast Earthquakes, 1953", *Publications of the Dominion Observatory*, Vol. XVI, No. 13, 1955.

[4] W. G. Milne, "Canadian West Coast Earthquakes, 1954", *Publications of the Dominion Observatory*, Vol. XVIII, No. 3, 1956.

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Toronto, one of which was installed at Toronto in 1897 and the other at Victoria in the basement of the Customs Building at Government and Humbolt Streets, where it began to operate on January 1, 1899. The Victoria instrument, of the Milne horizontal type, was number ten of the original group of seismographs of this design. The paper speed of the instrument was 250 mm. per hour, the static magnification was quoted as six, and the period was approximately 19 seconds. Needless to say, the recordings of such an instrument could contribute little to the study of small local earthquakes. The instrument was operated by the Meteorological Service under the supervision of Mr. Baynes Reid, and later, of Mr. F. Napier Denison.

In 1907 Mr. Denison designed and put into operation a second similar seismograph, and, in 1914, a Wiechert, 80 kgm., vertical seismograph was added.

In 1916 the Gonzales observatory was built by the Meteorological Service near Ross Bay along the Strait of Juan de Fuca. The three instruments mentioned above were then installed on piers in the basement of the observatory and orientated to record east-west, north-south, and vertical motion. It is told in Victoria that Mr. Denison would amaze visitors to the observatory by showing them that the building moved up and down with the rise and fall of the tides. Certainly the location was not ideal for a tiltmeter-type seismograph. In January 1923 two Milne-Shaw seismographs replaced the original Milne instrument. The latter remains on its pier at the Gonzales observatory as a present-day museum-piece, apparently still in operating condition.

In 1936 the Meteorological Office was placed under the Department of Transport, and as a part of the re-organization, the seismographs were transferred to the Dominion Observatory of the Department of Mines and Resources. However the latter Department had at that time no space available at Victoria for the instruments and their operation continued at the Gonzales observatory. Late in the summer of 1939 a vault was constructed at the Dominion Astrophysical Observatory on Little Saanich Mountain and the instruments were transferred to this location, being out of operation for a few months during the transfer. At the Dominion Astrophysical Observatory the instruments were in charge of one of the astronomers, Dr. K. O. Wright, with the records being studied in Ottawa by members of the Seismological Service of the Dominion Observatory. The use of the Wiechert vertical instrument was discontinued early in 1946, but the two Milne-Shaw seismographs are still in operation. Early in 1948, a short-period vertical Benioff seismograph ($T_s = 1 \cdot 0$ second, $T_g = 0 \cdot 2$ second) was installed, probably as a direct result of interest created by the strong tremor of June 23, 1946. The great number of local earthquakes recorded by this instrument led to the installation in 1951 of two additional stations at Horseshoe Bay (near Vancouver) and at Alberni (on Vancouver Island) to make it possible to compute epicentres. At the same time seismologists were stationed at the Astrophysical Observatory to care for the instruments and to investigate the local seismicity of British Columbia. Two further improvements have been the transfer of the seismographs to a vault in the new office building of the Dominion Astrophysical Observatory, and the addition of the other two components to the vertical Benioff instrument. Complete details of station changes since August, 1951 are contained in the publications noted on page 119.

One of the most important features of any good seismograph station is an accurate time control on the records. It is assumed that prior to 1939, as is known to be the case since that year, time marks were placed on the records from calibrated standard chronometers with good rates. From 1939 to 1948 time signals were received by radio from the CBC radio station, and the chronometer correction was noted daily. Since the installation of the Benioff seismograph in 1948, CBC radio time signals have been automatically recorded daily.

SOURCES OF INFORMATION

Data on earthquakes in western Canada is given in two tables, Table 1 listing located epicentres, Table 2 giving unlocated earthquakes recorded in the Benioff seismograph at Victoria prior to the beginning of the enlarged program in August, 1951. The data for these tables have been gathered from many sources during a period of several years. The publications consulted have been referred to in the following discussion in the order of their use as sources of information. Newspaper files were subsequently checked for additional information on the earthquakes.

The basic source of information was a paper by Townley and Allen[5] containing a catalogue of earthquakes occurring on the Pacific Coast of the United States during the years 1769 to 1928; the chapter entitled "Earthquakes in Washington, 1833 to 1928" was most useful. The authors point out that the information on earthquakes from 1769 to 1897 was taken from a catalogue by Edward S. Holden,[6] published by the Smithsonian Institution of Washington, and that on earthquakes from 1897 to 1906 from a catalogue by Alexander G. McAdie[7] published by the same Institution. Neither of these original catalogues was available to the author. Only the earthquakes that were known to have been centred or felt in British Columbia are included in Tables 1 and 2.

The International Seismological Summary contains an index of epicentres for the years since 1913, and these indexes were searched for earthquakes occurring in the area covered by this report. Many of the epicentres and magnitudes for the years 1904 to 1946 were obtained from Gutenberg and Richters' "Seismicity of the Earth".[8] For the years 1946 to 1951, the cards issued by the United States Coast and Geodetic Survey were used as a source of information for epicentres and magnitudes. Pasadena magnitudes are those usually quoted.

Dr. A. F. Buckham, formerly of the Geological Survey of Canada, generously permitted the author the use of material he had collected. Buckham's early data were obtained from a paper by D. C. Bradford[9] on the seismic history of the Puget Sound Basin up to the year 1934, and Bradford in turn quotes largely from the paper of Townley and Allen, mentioned above. Again only those earthquakes that were centred or felt in British Columbia have been included.

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[5] Sidney D. Townley and Maxwell W. Allen, "Descriptive Catalog of Earthquakes of the Pacific Coast of the United States 1769 to 1928", *Bull. Seism. Soc. Am.*, Vol. 29, No. 1, 1939.

[6] Edward S. Holden, "Catalogue of Earthquakes of the Pacific Coast from 1769 to 1897", *Smithsonian Miscellaneous Collections, No. 1087.*

[7] Alexander G. McAdie, "Catalogue of Earthquakes of the Pacific Coast, from 1897-1906", *Smithsonian Miscellaneous Collections, No. 1721.*

[8] B. Gutenberg and C. F. Ritcher, "Seismicity of the Earth and Associated Phenomena", Princeton University Press, 1949.

[9] D. C. Bradford, "Seismic History of the Puget Sound Basin", *Bull. Seism. Soc. Am.*, Vol. 25, 1935.

F. Napier Denison, while in charge of the seismographs at the Gonzales observatory, clipped from various newspapers many articles on the earthquakes that were recorded at his station. This scrap-book was loaned to the author by the present meteorologist, W. H. Mackie, so that newspaper reference to earthquakes in British Columbia might be included in this report. Dr. E. A. Hodgson, while in charge of the Division of Seismology at the Dominion Observatory, also kept a scrap-book of newspaper articles concerning earthquakes. This has proven very useful as his collection includes articles from many Canadian newspapers. As well, use was made of the file on seismology at the Dominion Astrophysical Observatory, that contains letters and clippings on British Columbia earthquakes, the most important being those relating to the Bella Coola earth tremors from 1940 to 1943.

When the list was complete, each event on it was checked with available British Columbia newspapers for that date to determine to what extent the tremor was felt and reported upon. The Victoria *British Colonist* was the first newspaper in British Columbia, beginning publication in December, 1858, and with the permission of the Provincial Archivist, Willard Ireland, the copies of this newspaper in his files were searched for references to earthquakes in the years 1858 to 1872. Other newspaper files, in the library of the Provincial Parliament Buildings at Victoria, were made available to the author. In addition, a careful search of newspapers was made for each earthquake already listed. One daily newspaper of Victoria and one daily newspaper of Vancouver were consulted for each earthquake, and if they made reference to the event, the newspapers for the surrounding area, both daily and weekly, were scanned for more information. Usually the daily or weekly newspapers of such cities as Nanaimo, Chilliwack and Vernon supplied a great deal of information to add to that obtained from the Victoria and Vancouver newspapers. As well, the earthquakes of the Queen Charlotte Islands were usually mentioned in the Prince Rupert daily papers.

Table 2 contains information on earthquakes recorded on the Benioff vertical seismograph at Victoria. These are all within the distance range of local earthquakes, but there may be many of them whose epicentres are not in British Columbia. With only one sensitive seismograph it is not possible to obtain the location of an epicentre; however in order that the list may be complete all the recorded earthquakes are included.

Other sources of information on local earthquakes are scientific publications discussing the more severe tremors. E. A. Hodgson published an account of the June 23, 1946 tremor,[10] and F. Napier Denison wrote articles on the 1918[11] and 1920[12] earthquakes. Information from all three reports has been used in this compilation.

The author wishes to thank the institutions and persons mentioned above for their assistance in supplying information. It is hoped that the tables are reasonably complete and accurate, but if any reader has additional information pertaining to these or any other British Columbia earthquakes, it would be most gratefully received by the author.

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[10] E. A. Hodgson "British Columbia Earthquake, June 23, 1946", *J. Roy. Astron. Soc. Can.*, Vol. 40, 1946.

[11] F. Napier Denison, "The British Columbia Earthquake of December 6, 1918", *Bull. Seism. Soc. Am.*, Vol. 9, 1919.

[12] F. Napier Denison, "The British Columbia Earthquake of January 23, 1920", *Bull. Seism. Soc. Am.*, Vol. 10, 1920.

INTENSITIES OF EARTHQUAKES

In Table 1 the roman numerals immediately following the time of the earthquake are the author's estimation of the intensity near the origin of the tremor. These intensities are related to the Modified Mercalli Intensity Scale of 1931, shown below. In British Columbia it is very difficult to assign an intensity to an earthquake because, particularly for the early tremors, the areas immediately adjacent to the earthquake were quite often uninhabited. Ratings are assigned wherever possible but they may be in error by at least one scale division. The scale is published so that a reader may if he wishes attach an intensity value to any of the earthquakes listed in Table 1 that he has experienced.

MODIFIED MERCALLI INTENSITY SCALE OF 1931

(ABRIDGED)

I. Not felt except by a very few under especially favourable circumstances. (I Rossi-Forel Scale)

II. Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing. (I to II Rossi-Forel Scale)

III. Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration like passing truck. Duration estimated. (III Rossi-Forel Scale)

IV. During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls make creaking sound. Sensation like heavy truck striking building. Standing motor cars rock noticeably. (IV to V Rossi-Forel Scale)

V. Felt by nearly everyone; many awakened. Some dishes, windows, etc. broken; a few instances of cracked plaster; unstable objects overturned. Disturbances of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop. (V to VI Rossi-Forel Scale)

VI. Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight. (VI to VII Rossi-Forel Scale)

VII. Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motor cars. (VIII Rossi-Forel Scale)

VIII. Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Disturbing to persons driving motor cars. (VIII+ to IX Rossi-Forel Scale)

IX. Damage considerable in specially designed structures; well designed frame structures thrown out of plumb: great damage in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken. (IX+ Rossi-Forel Scale)

X. Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks. (X Rossi-Forel Scale)

XI. Few, if any, (masonry) structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipe lines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.

XII. Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into the air.

DISCUSSION OF EARTHQUAKES

A map is included to show that area of Canada covered in this report, and to help the reader identify the locality of the earthquakes. Some epicentres are marked on the map, particularly those listed by Gutenberg. However it should be pointed out that the number of earthquakes plotted on the map is incomplete, first, because many small tremors cannot be located, and secondly, because prior to the 1918 earthquake many of the strong earthquakes were not assigned epicentral co-ordinates. Furthermore, many of the early epicentres are not accurate.

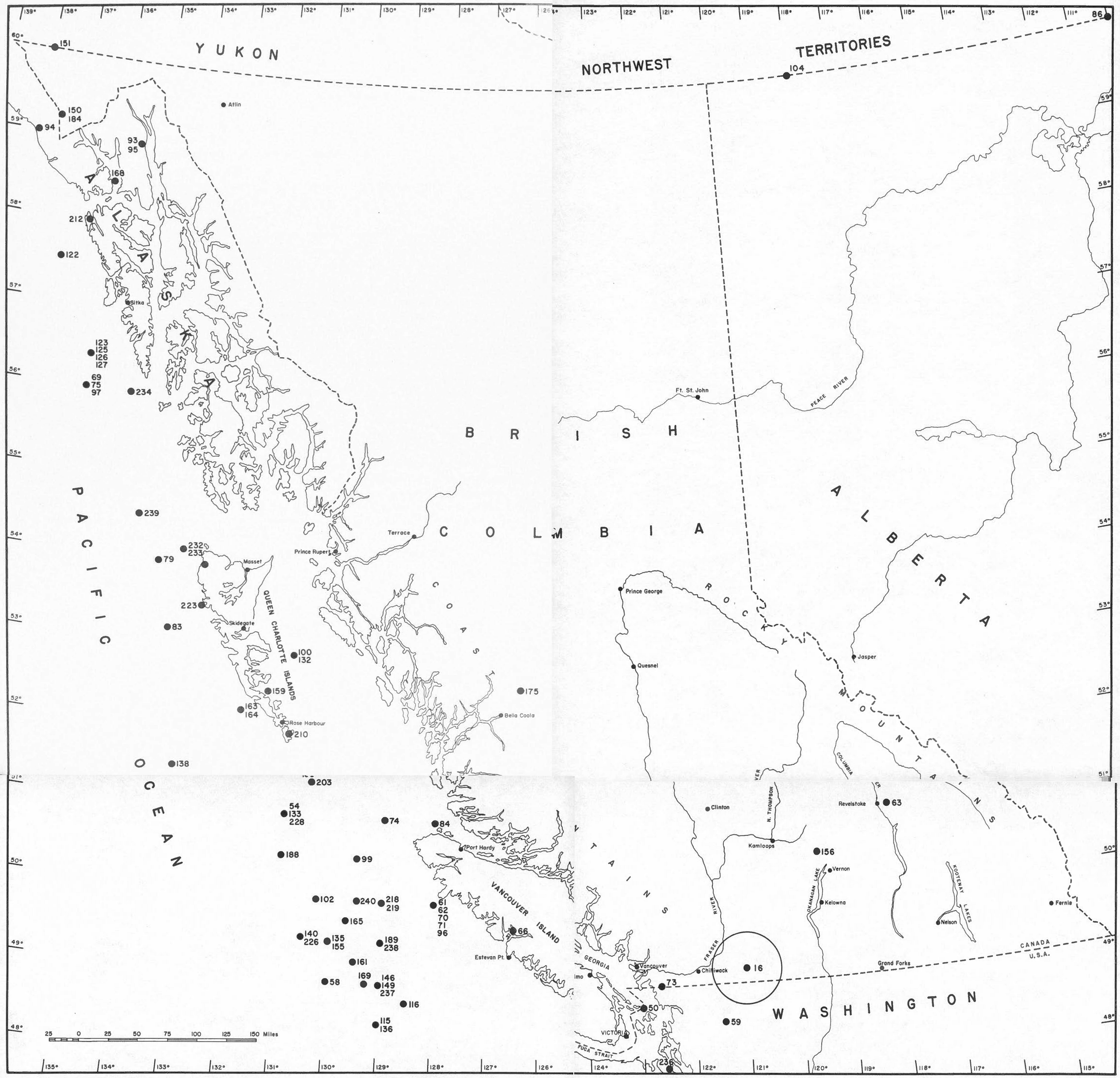
It is not proposed that Table 1 be used for a statistical study of earthquakes in British Columbia. For example, it would be misleading to divide the number of earthquakes of a certain intensity by the number of years covered by this report, and on the basis of the result state that an earthquake of that intensity will occur every so many years.

During the early years covered by this report the province was largely uninhabited, and even today an earthquake of intensity IV or V may occur unnoticed in many parts of British Columbia. The report is probably reasonably complete for the Victoria-Vancouver area for earthquakes of intensity greater than IV. For any other part of the province the report is probably complete only for those earthquakes greater than intensity VII to VIII. Many small shocks off the coast were probably unnoticed during the period covered by this report, small local shocks having been located only since the establishment of the seismograph network in 1951. The absence of data on oceanic earthquakes constitutes another good reason for not using Table 1 for statistical study, because although they have little to do with the seismicity of the inhabited areas of British Columbia, it may be argued that if strong earthquakes occur under the ocean, the stresses on the land areas may be modified.

The following abbreviations, principally for the names of periodicals and other sources of information, have been used in Tables 1 and 2.

M magnitude (Gutenberg and Ritcher scale).

BSSA *Bulletin of the Seismological Society of America*, Vol. 29, No. 1, 1939.


YUKON
NORTHWEST TERRITORIES
BRITISH COLUMBIA
ALBERTA
WASHINGTON
PACIFIC OCEAN
ALASKA
QUEEN CHARLOTTE ISLANDS
COAST MOUNTAINS
ROCKY MOUNTAINS
VANCOUVER ISLAND
GEORGIA STRAIT
JUAN DE FUCA STRAIT
PEACE RIVER
FRASER RIVER
N. THOMPSON RIVER
COLUMBIA RIVER
OKANAGAN LAKE
KOOTENAY LAKES
CANADA
U.S.A.
Atlin
Sitka
Masset
Skidegate
Rose Harbour
Prince Rupert
Terrace
Bella Coola
Port Hardy
Estevan Pt.
Ft. St. John
Prince George
Quesnel
Jasper
Clinton
Kamloops
Revelstoke
Vernon
Kelowna
Nelson
Fernie
Grand Forks
Vancouver
Chilliwack
Victoria
Imo
25 0 25 50 75 100 125 150 Miles

JAGS *Journal of the American Geographical Society of New York*, 1873.

Diary Diary of Martha Cheney Ella (courtesy of Provincial Archives, Victoria).

Br. Col. *British Colonist*, Victoria.

Col. *Daily Colonist*, Victoria.

Br. D. C. Bradford[9].

Times *Daily Times*, Victoria.

G. B. Gutenberg and C. F. Richter, "Seismicity of the Earth".

D. Scrapbook of F. Napier Denison.

ISS International Seismological Summary.

SB Scrapbook of E. A. Hodgson.

Province *Daily Province*, Vancouver.

USC and GS United States Coast and Geodetic Survey epicentre cards.

* An asterisk indicates that there is some doubt of the location of the origin of the earthquake since the location indicated by the official co-ordinates for the epicentre does not agree with that of the felt area. Such earthquakes are not plotted on the map.

TABLE 1

EARTHQUAKES IN BRITISH COLUMBIA. DECEMBER 2, 1841 TO JULY 31, 1951

1. 1841 DECEMBER 2. 4 p.m. Duffot de Mofras, apparently an early explorer, describes a report of earthquakes felt at Fort Vancouver by a Mr. Yale: "We had two that might have attracted the attention of the geologist. Both occurred after the eruption of Mount Baker. The first was tremulous, and caused some dilapidation of tottering things; but its greatest peculiarity was perhaps the loud report that preceded or attended it, and the roaring noise, which continued for some time. The adjacent mountains, being composed of tremendous masses of solid rock, we almost expected to behold them and ourselves sinking into an abyss. The other was undulatory, and did some injury to the foundation of our house. It seemed to have come from the westward, and to have left in its trail a cold, disagreeable, smoky vapour. Both occurred in winter. That of December 26 was felt here, but I believe slightly, having escaped my perception." *JAGS*

2. 1853 NOVEMBER 25. 5 p.m. "Shook whole of house, and nearly took us off our feet." *Diary*

3. 1856 DECEMBER 26. An early explorer's letter states of this earthquake: "This last one of December 26, 1856, was very perceptible at Port Townsend, where I then was, jarring the house like the fall of some heavy body. It was felt by Mr. Warbass at Widbey's Island and the Indians told him, in reply to his inquiry if they knew what it was, that the earth was rising." *JAGS*

4. 1859 JUNE 22. 3 p.m. III to IV. Oscillation from west to east of two or three seconds duration at Victoria. *Br. Col.*

5. 1859. JUNE 22. 5:30 p.m. Rumbling at Victoria. *Br. Col.*

6. 1860 MARCH 26. 3 p.m. Felt at Old Langley. Oscillation seemed to be from east to west. Some people rushed from their homes. *Br. Col.*

7. 1860 DECEMBER 12. 8:40 p.m. Severe from Victoria to Portland.

8. 1863 SEPTEMBER 26. 1:30 p.m. A rather severe shock was felt at Vancouver.

9. 1863 OCTOBER 9. 2:53 a.m. In Victoria three shocks were felt. The first two followed each other by a few seconds, and they were followed by another in 10 minutes. Bottles fell off shelves and some people ran out of doors. *Br. Col.*

10. 1864 SEPTEMBER 26. 12:45 a.m. In Victoria the duration was estimated as 10 seconds. The shock was felt at Port Townsend also, where there was more rumbling. *Br. Col.*

11. 1864 OCTOBER 29. 6:10 p.m. VI Victoria. Felt severely in Victoria, New Westminster, Vancouver. Holden describes it as the severest shock recorded to that time. In New Westminster doors rattled, and in Vancouver at least one chimney was knocked down. At Plumber Pass large trees were felled. It would appear that the epicentre was in the Gulf Islands area, but the absence of felt reports from communities in the United States indicates that the epicentre was at the northern end of the Gulf Islands group. *BSSA*

12. 1865 JUNE 12. Holden reports several shocks at Victoria and on Vancouver Island.

13. 1865 AUGUST 25. 9 p.m. VI Victoria. Heavy shock on Vancouver Island lasting two minutes, followed later by two more shocks. *BSSA*

14. 1870 MARCH 16. 2:03 a.m. Slight shock in Victoria, like a heavy gun. *Br. Col.*

15. 1870 DECEMBER 20. 3:30 p.m. IV Victoria. This tremor lasted about 12 seconds at Victoria. Motion was from east to west. *Br. Col.*

16. 1872 DECEMBER 14. 9:40·5 p.m. This was one of the major earthquakes of the Pacific coast region of British Columbia. It has been reported as being felt quite strongly as far north as Quesnel and Soda Creek in the Cariboo and as far south as Eugene, Oregon. If Neumann's curves of intensity versus distance[13] are used, the intensity at the origin of this earthquake must have been VIII or IX on the Modified Mercalli Scale. A corresponding magnitude reading would be $7\frac{1}{2}$, although some of the reports outlined below indicate an even higher value. There were few towns in British Columbia at this time, and fewer newspapers to print accounts of the event, so data are very scarce. Any information available is presented below.

Yale: Doors were rattled, bells rang, and floors of buildings were made to wave "like the decks of a vessel in a light sea".

Chilliwack: The houses oscillated and there were waves on the ground. A report in a 1915 newspaper states that a big slice of Mount Cheam (near

[13] Frank Neumann, "Earthquake Intensity and Related Ground Motion", University of Washington Press, 1954.

Chilliwack) dropped 1000 feet during the earthquake. This was likely a landslide, but it indicates that Chilliwack was quite close to the epicentre.

Vernon: A report in 1936 from this city states that 60 years ago (probably in 1872) the Indians reported a very bad earthquake. It was strong enough to knock people from their feet, and buildings and tepees came down with the vibrations.

Clinton: The earthquake awakened many people, and staggered others off their feet, causing general excitement and alarm.

Victoria: The motion seemed to be from the east to the west. Bells were rung and crockery was knocked from the shelves. People ran out on to the streets. There are reports of the earthquake being felt very strongly at Matsqui, all along the Fraser River, and at Race Rocks. In the United States there are accounts from Olympia, from Seattle where dishes were broken, from Portland and Delles, from Wallulu and Walla Walla and all along the lower Columbia River. The felt area of this tremor seems to have covered about 500,000 square miles, part of which was at sea.

To fix an epicentre for such a tremor, using only scanty macroseismic reports and no instrumental records, is a great problem. Taking the area where waves were seen on the ground as an indication of the epicentral region, then Yale and Chilliwack seem to be very near the origin. On the map the origin has been shown as being within a circle whose radius is 30 miles, and whose centre is at 49° 10′ N.lat. and 121° 00′ W.long. No estimate can be made of the accuracy of this epicentre, and it is presented merely as an attempt to fix approximately the origin of the tremor. Certainly it was east of Vancouver, north of Seattle, and probably south of Clinton. The absence of reports from further east than Vernon indicates that the centre was west of that city, and probably west of Okanagan Lake.

Following the earthquake, many tremors were reported from various places in British Columbia and northwestern Washington, which were probably aftershocks of the main disturbance. These are listed here to make the record as complete as possible, but there is the likelihood that some listed as aftershocks may well be unrelated events.

17. 1872 DECEMBER 14. 9:46 p.m. VII in Puget Sound area. This may be the main shock, with the time incorrectly reported.

18. 1872 DECEMBER 14. 10:00 p.m.

19. 1872 DECEMBER 14. 11:00 p.m.

20. 1872 DECEMBER 15. 3:00 a.m.

21. 1872 DECEMBER 15. 5:00 a.m.

22. 1872 DECEMBER 16. 9:17 a.m. VI Victoria. Very strong at Victoria and on Vancouver Island.

23. 1872 DECEMBER 19. 5:38 a.m. IV Victoria. Two slight but distinct shocks at Victoria which shook doors and windows.

24. 1873 DECEMBER 17. 11-12 p.m. Bradford lists an earthquake of intensity IV at Victoria, but the newspapers make no mention of it.

25. 1880 AUGUST 22. 1:25 p.m. South Vancouver Island and northwest Washington generally felt this shock. In Victoria the rumbling motion seemed to be from south to north. Plaster was cracked, loose bricks fell, and some persons ran into the street. At 9 a.m. on the same day a slight jolt was felt in Victoria. The main earthquake was felt in Saanich and Esquimalt. At Cowichan the boats were shaken but at Nanaimo the tremor was not felt. Port Townsend and Seattle, like Victoria, felt the earthquake and at Somenos there were two gun-like shocks although Somenos appears to be north of the main area of the disturbance. *Col.*

26. 1880 AUGUST 22. 2:10 p.m. Felt at Victoria. *Col.*

27. 1880 AUGUST 22. 2:19 p.m. Felt at Victoria. *Col.*

28. 1880 DECEMBER 12. 8:40 p.m. VII in the Puget Sound basin. Felt from Victoria to Portland. *BSSA*

29. 1882 APRIL 30. 10:45 p.m. IV-V in Victoria, where the motion seemed to be from northeast to southwest. Some crockery was thrown down, and some loose plaster fell, but the earthquake was not felt by all persons in Victoria. It was felt as far south as Portland. *Col.*

30. 1883 MAY 10. 6:55 p.m. A slight earthquake was felt at Victoria. *Br.*

31 1885 DECEMBER 8. 10:12 p.m. V in the Puget Sound basin. Felt at both Victoria and New Westminster. *Br.*

32. 1891 SEPTEMBER 22. 3:40 a.m. Bradford lists, and newspapers report, an earthquake at Victoria, Port Angeles, and Port Townsend at this time, of intensity VI. At Victoria some plaster was cracked, and dishes were shaken but no major damage was done. The *BSSA* reports this same earthquake for September 21st. *Col.*

33. 1891 NOVEMBER 29. 3:14 p.m. An earthquake which was quite strong in the lower Puget Sound basin was felt only slightly in Victoria. *Col.*

34. 1893 FEBRUARY 16. Residents of Sidney report a slight tremor. *Br.*

35. 1894 JANUARY 14. Bradford reports that pictures swayed and dishes rattled on their shelves at Vancouver during an earthquake. Newspapers make no mention of the event.

36. 1891 APRIL 16. 12:00 a.m. (midnight). In Victoria the motion appeared to be from east to west, and an earthquake was generally felt. It seems to have been much stronger at Port Townsend. *Times*

37. 1895 JULY 2. 7:00 p.m. At Nanaimo some crockery was broken, but the tremor was not felt at Victoria. *Col.*

38. 1895 NOVEMBER 30. At Kyugot on the northwest shore of Vancouver Island Indian houses were shaken from their foundations, and trees swayed. *Br.*

39. 1896 JANUARY 3. 10:30 p.m. An earthquake was felt strongly at Port Angeles and Turn Point Light House. In Victoria and Esquimalt it was generally felt but no damage was reported. *Times*

40. 1896 MARCH 15. A Vancouver newspaper account for this date reads in part as follows: "One of the Burrard Mountains is believed to have been in a state of eruption last night. Dense smoke and flames poured from the mountain. Several earth shocks were felt recently." *Br.*

41. 1900 JANUARY 30. p.m. An earthquake was felt slightly in Vancouver, New Westminster, and Aldergrove. *Col.*

42. 1900 NOVEMBER 18. Afternoon. A slight earthquake was felt at Vancouver. *Col.*

43 1904 MARCH 16. 8:21 p.m. $\phi = 47°$ N; $\lambda = 124°$ W. *BSSA.* A shock was felt in the region from Seattle to Victoria, and in the Olympic Peninsula west of Puget Sound. In Victoria clocks were stopped, but no serious damage was reported. The tremor was not felt at Nanaimo. *BSSA, Col.*

44. 1906 JANUARY 3. 5:42 a.m. Felt at Nelson, where plaster was knocked down, hanging pictures were displaced, and articles fell from shelves. Rossland and Trail seem to have suffered to the same extent. At Revelstoke windows rattled, and at Grand Forks buildings trembled. *Col., BSSA*

45. 1906 MAY 14. The Vancouver *Province* reports an earthquake in the Kootenay Mountains for this date.

46. 1907 JULY 28. 2:20 a.m. In Victoria many people were awakened. The Port Townsend area seems to have been disturbed an equal amount. *Col.*

47. 1908 MAY 15. 12:31·6 a.m. $\phi = 59°$ N; $\lambda = 141°$ W; M = 7·0. *G.*

48. 1908 NOVEMBER 30. Afternoon. At Skidegate, on the Queen Charlotte Islands, two Indian shacks were knocked to the ground. The wave seemed to pass from north to south. Furniture vibrated at Lawnhill, a few miles north of Skidegate. This earthquake was strong enough to have recorded on the seismographs at Ottawa. *Queen Charlotte News*

49. 1908 DECEMBER 1. 3 a.m. An aftershock of the above event was felt at Lawnhill.

50. 1909 JANUARY 11. 3:44 p.m. A tremor, whose origin seems to have been in the Gulf Islands between Victoria and Bellingham, was felt over an area greater than 25,000 square miles. The intensity near the origin was of the order of VI.

At Victoria, where the vibration lasted from 10 to 20 seconds, the most serious damage reported was that of broken crockery. At Blaine walls were cracked; Bellingham reported sidewalks twisted; and at Anacortes the piers were damaged. Ladysmith, Nanaimo, and Alberni felt the tremor quite distinctly. Reports indicate that the earthquake was felt at Comox, Pachena Point, Bamfield, Sumas, Chilliwack, Hammond, Everett, Lopez, Port Townsend, Tacoma, and south to Portland, but was not felt as far east as Kelowna, Princeton or Vernon. It appears that placing the epicentre in the Gulf

Islands area is as good an approximation as is possible, for no instrumental recording of the origin is available. *Col., BSSA*

51. 1909 MAY 17. 9:20 a.m. Vancouver newspapers report a strong vibration was felt over all the western provinces at this time. Information comes from Winnipeg, Regina, and strangely enough from Prince Rupert. No major tremor was recorded at this time which could have been felt over such a wide area. It is suggested that little weight be placed upon these reports.

52. 1911 JULY 4 or 5. 10:23 p.m. Victorians felt a slight earthquake. *Br.*

53. 1911 SEPTEMBER 28. 6:45 p.m. A tremor frightened many people at Bellingham. In Victoria the motion seemed to be from northwest to southeast. Nothing was felt at Seattle, hence it appears that the epicentre was in the Gulf Islands area. *Col.*

54. 1912 MARCH 11. 2:17·5 a.m. $\phi = 51°$ N; $\lambda = 131°$ W; M = 6½. *G.* The Victoria seismograph indicated the distance to the origin of this earthquake as 300 to 400 miles. The disturbance was felt at Triangle Island off the northwest tip of Vancouver Island. *Col.*

55. 1912 AUGUST 18. Newspaper reports indicate an earthquake was felt at Salmon Arm near Clowhan Lake, also at Sechelt, Deserted Bay, and up to the head of Jervis Inlet. *D*

56. 1912 NOVEMBER 21. Newspapers reported an earthquake in the Lynn Valley and Blenkinsop Bay in south central British Columbia. *D*

The Vancouver *Times* reported an earthquake was felt from the Fraser River to the end of Burrard Inlet on the same day at 4:47 p.m. The Victoria seismograph recorded an earthquake occurring at this time at a distance of 100 to 200 miles. Another tremor was recorded at 5:15 p.m. but it was not felt.

57. 1913 OCTOBER 18. The south end of Graham Island in the Queen Charlotte Islands was shaken. *D*

58. 1914 JULY 21. 2:31·3 p.m. $\phi = 49°$ N; $\lambda = 130°$ W; M = 6½. *G.* Not felt.

59. 1915 AUGUST 18. 6:05 a.m. $\phi = 48° 32'$ N; $\lambda = 121° 26'$ W. *Br.* An earthquake was felt from Seattle to Enderby, and from Victoria to the Okanagan Valley. At Victoria the S-P time on the seismograph was 17 seconds, indicating a distance of 91 miles. The tremor was felt at Penticton, Yale, Summerland, Harrison, Bellingham (where doors rattled), Kelowna, Chilliwack (where it was quite violent), and Enderby. At Marblemount an aftershock was felt at 10:00 a.m. *Col., BSSA*

60. 1916 JUNE 19. 5:50 a.m. III. Nanaimo residents generally felt a tremor. *Col.*

61. 1917 JULY 1. $\phi = 50°.0$ N; $\lambda = 128°.0$ W. *BSSA*

62. 1917 DECEMBER 23. $\phi = 50°.0$ N; $\lambda = 128°.0$ W. *BSSA*

63. 1918 FEBRUARY 4. 12:35. $\phi = 51°.0$ N; $\lambda = 118°.0$ W. *ISS.* An earthquake was generally felt at Revelstoke, and felt slightly at Alvert Canyon, Beaver-

mouth, Malakwa and Vernon. The seismograph at Victoria recorded the tremor. *D.*, *SB*

64. 1918 FEBRUARY 13. 5 a.m. Very slight at Victoria. *Col.*

65. 1918 AUGUST 22. 8:21 a.m. Felt slightly in Victoria and at Cordova Bay. *Col.*

66. 1918 DECEMBER 6. 00:41 a.m. $\phi = 49\frac{3}{4}°$ N; $\lambda = 126\frac{1}{2}°$ W; M = 7. *G.* Estevan lighthouse on the west shore of Vancouver Island was the place closest to the epicentre of this earthquake, and considerable mercury was spilled out of the lighthouse lamp due to the tremor. One report stated that the lighthouse itself swayed. At Alberni, 117 miles from the official epicentre, the intensity was rated as IV or V. At both Nanaimo and Ladysmith the earthquake was compared to an explosion. Buildings rocked, and people were violently awakened. The earthquake was felt at Victoria, Vancouver, Kelowna and Seattle, but not at Vernon, Penticton, Chilliwack or Armstrong in the interior. A detailed report was written by F. Napier Denison.[11] *Col.*

67. 1918 DECEMBER 7. About ten aftershocks of the December 6 tremor were felt at Alberni and Estevan.

68. 1918 DECEMBER 16. 5:09 a.m. A strong aftershock of the December 6 tremor was felt at Alberni.

69. 1919 MAY 18. $\phi = 56°.0$ N; $\lambda = 136°.0$ W. *ISS.*

70. 1919 JULY 1. $\phi = 50°.0$ N; $\lambda = 128°.0$ W. *ISS.*

71. 1919 JULY 10. $\phi = 50°.0$ N; $\lambda = 128°.0$ W. *ISS.*

72. 1919 OCTOBER 10. $\phi = 49°.0$ N; $\lambda = 124°.0$ W. *ISS**. This may be in error for no tremor was felt.

73. 1920 JANUARY 23. 11:10 p.m. $\phi = 49°$ N; $\lambda = 122°\ 40'$ W. *Br.* The epicentre was again near the Gulf Islands, although the position cannot be very precise since there were few seismographs near the origin. At Victoria there was a severe shaking. Windows were broken at Anacortes, and plaster was cracked at Bellingham. One report states that boulders were shaken off Crown Mountain near Vancouver, and some windows were broken in the city itself. At New Westminster people were alarmed and ran into the streets. Some chimneys were cracked and furniture was moved in houses. (See *BSSA*, Vol. 10, pp. 46-48) *Col.*, *BSSA.*

74. 1920 MARCH 28. 9:08 p.m. $\phi = 51°$ N; $\lambda = 129°$ W; M = $6\frac{1}{2}$. *G.*

75. 1920 MAY 8. $\phi = 56°.0$ N; $\lambda = 136°.0$ W. *ISS.*

76. 1920 JULY 20. 8:07 p.m. Felt in Victoria. *Br.*

77. 1920 NOVEMBER 28. 3:30 a.m. $\phi = 50°.0$ N; $\lambda = 128°.0$ W. *ISS.* This epicentre may be in error for the tremor was felt in southern Washington, and in northern Oregon.

78. 1921 FEBRUARY 21 $\phi = 52°.0$ N; $\lambda = 125°.0$ W. *ISS.** The newspapers make no mention of this earthquake.

79. 1921 April 10. 5:40 a.m. $\phi = 54°$ N; $\lambda = 134°$ W; M = 6½. *G.* An earthquake was felt at Masset on the Queen Charlotte Islands. No damage was reported, although pictures on the wall were made to swing.

80. 1921 April 10. 11 a.m Aftershock of preceding tremor at Masset.

81. 1921 April 11. 7 am. Aftershock at Masset.

82. 1921 April 11. 7:30 a.m Aftershock at Masset.

83. 1921 April 12. $\phi = 53°.2$ N; $\lambda = 133°.7$ W. *ISS.*

84. 1921 May 28. 12:55 p.m. $\phi = 48°.0$; $\lambda = 127°.5$. *ISS.** The localities of Alert Bay and Bull Harbour on northern Vancouver Island felt the tremor. Estevan did not. The seismograph record at Victoria indicated a distance of 200 miles. The felt area and the official epicentre are about 250 miles apart, and on the map the former position is indicated.

85. 1921 June 25. $\phi = 49°.0$ N; $\lambda = 124°.0$ W. *ISS.** Not reported from any area.

86. 1922 April 13 $\phi = 60°.0$ N; $\lambda = 110°.0$ W. *ISS.* This epicentre is east of any active area in western Canada.

87. 1922 May 15. 9:30 a.m. Felt in Vancouver. *Col.*

88. 1922 December 27. 6:30 p.m. Denison suggested that the epicentre was under Haro Strait. The tremor was felt in Victoria and Vancouver but no damage was reported *Col.*

89. 1923 January 10. 8:27 p.m. Felt slightly at Victoria. *D*

90. 1923 February 12. 10:20 a.m. The Bellingham area, where plaster was cracked, seems to have been the hardest hit. At Victoria the earthquake was felt but slightly. *Col., BSSA*

91. 1923 March 12. Felt slightly in the Gulf Islands region, but not at Victoria. *BSSA*

92. 1923 April 13. 2-26 a.m. Gonzales seismograph indicated a distance of 110 miles, but this does not necessarily place the origin in British Columbia. *D*

93. 1923 April 24. $\phi = 59°.0$ N; $\lambda = 135°.5$ W. *ISS.*

94. 1923 April 25. 11:32 a.m. $\phi = 59°$ N; $\lambda = 138°$ W; M = 5¾. *G.*

95. 1923 April 29. $\phi = 59°.0$ N; $\lambda = 135°.5$ W. *ISS.*

96. 1923 May 2. 8:24 a.m. $\phi = 50°.0$ N; $\lambda = 128°.0$ W. *ISS.* At Victoria the seismograph indicated a distance of 170 miles.

97. 1923 June 22. $\phi = 56°.0$ N; $\lambda = 136°.0$ W. *ISS.*

98. 1923 July 13-14. 9:30 a.m. At Dead Tree Point on the Queen Charlotte Islands an earthquake was felt.

99. 1923 October 13. $\phi = 50°.5$ N; $\lambda = 129°.5$ W. *ISS.*

100. 1923 November 16. $\phi = 53°.0$ N; $\lambda = 131°.0$ W. *ISS.*

101. 1923 November 22. 7:04 p.m. Victoria and Saanich areas, generally, felt a rumbling earthquake. *Col.*

102. 1924 MARCH 29. 4:09 p.m. $\phi = 50°$ N; $\lambda = 130\frac{1}{4}°$ W; M = 6. *G.*

103. 1924 AUGUST 8. 3: a.m. III. A report from Chilliwack stated that an area about 6 miles square in the Sumas district felt a slight tremor. A Victoria newspaper report mentioned persons being awakened by the tremor in that city and in Bellingham. The epicentre was probably in the Sumas district. *D*

104. 1924 OCTOBER 17. $\phi = 60°.0$ N; $\lambda = 118°.0$ W. *ISS.*

105. 1924 NOVEMBER 4. 3:19 a.m. An earthquake was felt slightly in Victoria. *Col.*

106. 1924 DECEMBER 18. 3:10 a.m. III. Vancouver was the only area to feel the tremor strongly, although it was noticeable in Duncan and Victoria. *D*

107. 1925 FEBRUARY 10. 2:32 a.m. A tremor was felt slightly in Victoria. *D*

108. 1925 JUNE 28. 5:20 p.m. This has been identified as the Montana earthquake, but it is included here for a tremor was felt in some parts of British Columbia, particularly at Nelson.

109. 1925 AUGUST 1. 12:50 p.m. The Victoria area felt a tremor slightly, but the epicentre appears to be south, in the Olympic mountain range. *D*

110. 1925 AUGUST 10. 8:20 p.m. Newspaper reports indicated an earthquake was felt at Lethbridge, Coutts, Taber, and Milk River in southern Alberta.

111. 1925 NOVEMBER 26. 1:40 a.m. III. The distance from the Victoria seismograph station to the origin of this earthquake was estimated as 6 miles, although it is likely the epicentre was under Haro Strait. Bellingham and Victoria both report a rumbling noise accompanying the tremor. No tremor was felt at Vancouver or New Westminster. *Col.*

112. 1926 MARCH 10. $\phi = 66°.5$ N; $\lambda = 130°.0$ W. *ISS.* Yukon area.

113. 1926 SEPTEMBER 17. $\phi = 49°.0$ N; $\lambda = 124°$ W. *ISS.** There are no reports to indicate that the tremor was felt, although the epicentre fell in a populated area.

114. 1926 SEPTEMBER 22. $\phi = 49°.0$ N; $\lambda = 124°.0$ W. *ISS.**

115. 1926 OCTOBER 30. 11:41 a.m. $\phi = 48\frac{1}{2}°$ N; $\lambda = 129°$ W; M = 6. *G.*

116. 1926 OCTOBER 31. 11:29 p.m. $\phi = 48\frac{3}{4}°$ N; $\lambda = 128\frac{1}{2}°$ W; M = $6\frac{1}{2}$. *G.*

117. 1926 DECEMBER 4. 3 a.m. The Shawnigan Lake district felt a slight tremor, identified by Denison as a foreshock of the following earthquake.

118. 1926 DECEMBER 4. 6 a.m. IV. An earthquake was generally felt throughout the Victoria area, northwest to Alberni, northeast to New Westminster and south to Port Townsend. There were no reports of serious damage, although some goods were toppled from shelves at Bellingham, and at Friday Harbour on San Juan Island the tremor was felt as a severe explosion. The epicentre was probably in the Gulf Islands area, although if the 3 a.m. jolt was a foreshock the epicentre could have been on southern Vancouver Island. *Col.*, *BSSA*, *SB*

119. 1927 MARCH 6. 1:57 p.m. An earthquake was felt at Bull Harbour, Alert Bay and Ocean Falls off the north tip of Vancouver Island. *D*

120. 1927 MAY 8. 2 p.m. $\phi = 49^\circ.0$ N; $\lambda = 124^\circ.0$ W. *ISS.** Again Bull Harbour, Alert Bay, and Ocean Falls as well as Port Hardy felt a tremor. The *ISS* epicentre is some 2° south of the felt area, in a populated region where the tremor was not felt. *D*

121. 1927 MAY 27. 1:58 p.m. Estevan, Bull Harbour, Alert Bay and Ocean Falls all felt an earthquake. The epicentre is probably just off the northwest tip of Vancouver Island.

122. 1927 OCTOBER 24. 7:59 p.m. $\phi = 57\frac{1}{2}^\circ$ N; $\lambda = 137^\circ$ W; M = 7. *G.*

123. 1927 OCTOBER 25. $\phi = 56^\circ.4$ N; $\lambda = 136^\circ.0$ W. *ISS.*

124. 1927 OCTOBER 29. An earthquake was felt generally in Vancouver and in the communities directly east of there. It was not felt at Victoria, nor was it recorded on the seismographs.

125. 1927 NOVEMBER 12. $\phi = 56^\circ.4$ N; $\lambda = 136^\circ.0$ W. *ISS.*

126. 1927 NOVEMBER 21. $\phi = 56^\circ.4$ N; $\lambda = 136^\circ.0$ W. *ISS.*

127. 1927 DECEMBER 31. $\phi = 56^\circ.4$ N; $\lambda = 136^\circ.0$ W. *ISS.*

128. 1928 JANUARY 24. 9:45 a.m. III. The Abbotsford-Hunglington area felt an earthquake. Maple Falls, Glacier, Sumas and Deming in the general region also felt the tremor slightly, but Bellingham did not. *D*

129. 1928 FEBRUARY 9. 3:04 a.m. IV. The Victoria seismograph indicates an epicentre about 100 miles northwest of the city. Alberni, Bamfield, and Pachena Point felt the tremor most severely. At Alberni it was like a loud report, and near Bamfield small tidal waves were reported. Vancouver and Nanaimo reported the tremor as very slight. It was also felt at Abbotsford, Duncan, Cowichan, Victoria, Port Renfrew, Tatoosh and Destruction Islands. The epicentre was probably in the region of the Alberni canal. *D, Prov.*

130. 1929 MARCH 1. 11:31 p.m. $\phi = 51\frac{1}{2}^\circ$ N; $\lambda = 130\frac{3}{4}^\circ$ W; M = 6. *G.*

131. 1929 APRIL 22. Felt very slightly at Victoria. *Times*

132. 1929 MAY 26. 2:42 p.m. VI-VII. $\phi = 51^\circ$ N; $\lambda = 131^\circ$ W; M = 7. *G.* The epicentre of this tremor was between 1° and 2° south of the area of maximum damage, in a region that was not heavily populated. The earthquake was felt as far north as Ketchikan, Alaska, and Anyox, B.C. and to the east as far as Terrace, Skeena and Lakelse. Prince Rupert does not appear to have been in the area of maximum damage, but at Haysport, a short distance southeast of Prince Rupert, goods were knocked off shelves. Centres on the Queen Charlotte Islands suffered greatly. At Massett, water was splashed out of tanks, trees were reported to have swayed, and houses shook violently. The Prince Rupert paper stated that people were thrown to the ground. At Queen Charlotte City dishes were broken, clocks were stopped, and a 4-foot tidal wave was reported. Nearby at Skidgate there was a tidal wave, and there were fissures on the beach. At Sandspit 500 feet of the beach was reported to have disappeared into the sea. Further south at Lockeport the crest of a hill was dislodged, and close by at Rose Harbour chimneys were

toppled. From these reports it would appear that the major damage was along the east shore of the Queen Charlotte Islands, but this is probably because that was the only settled portion of the region. Certainly the epicentre must have been quite close to Queen Charlotte city and Skidegate, probably just west of Graham Island. Such origin is indicated on the map.

133. 1929 SEPTEMBER 17. 11:17 a.m. $\phi = 51°$ N; $\lambda = 131°$ W; M = $6\frac{1}{4}$. *G.*

134. 1929 DECEMBER 14. Severe on Graham Islands. *D*

135. 1930 APRIL 16. 6:30 a.m. $\phi = 49\frac{1}{2}°$ N; $\lambda = 130°$ W; M = $5\frac{1}{2}$. *G.*

136. 1930 MAY 31. 2:21 a.m. $\phi = 48\frac{1}{2}°$ N; $\lambda = 129°$ W; M = $5\frac{1}{2}$. *G.*

137. 1930 JUNE 26–JUNE 30. On the Queen Charlotte Islands. *D*

138. 1930 JULY 1. $\phi = 51°.5$ N; $\lambda = 133°.3$ W. *ISS.*

139. 1930 JULY 21. 3:59 a.m. Two slight tremors were felt in Victoria. Denison placed the epicentre in the Strait of Juan de Fuca. The tremor was also felt in Vancouver. *D.*

140. 1930 SEPTEMBER 17. $\phi = 49°.5$ N; $\lambda = 130°.5$ W. *ISS.*

141. 1931 APRIL 17. 8 p.m. III. A slight earthquake was felt in Vancouver, Abbotsford, Bellingham and Victoria. The Gulf Islands area was again the probable origin of this disturbance. *D., Prov.*

142. 1931 JULY 18. III. Felt slightly in Victoria and Vancouver. *Br.*

143. 1931 JULY 30. 8 a.m. IV. At Nanaimo the earthquake sounded like an explosion. Houses in Kitsilano, a section of Vancouver, were rocked. Victorians did not report feeling the tremor. *Prov.*

144. 1932 JANUARY 26. 2:12 a.m. $\phi = 52°.0$ N; $\lambda = 125°.0$ W. *ISS.* No earthquake was reported to have been felt.

145. 1932 JULY 18. 2:02 p.m. The Tolt River earthquake, with epicentre about 25 miles northeast of Seattle, was felt in Vancouver and Victoria.

146. 1932 AUGUST 18. 12:23 p.m. $\phi = 49°$ N; $\lambda = 129°$ W. *G.*

147. 1932 DECEMBER 21. 10:10 p.m. Felt slightly in Vancouver. *Prov.*

148. 1933 JANUARY 29. 1:42 a.m. Felt in Sidney and North Saanich. *Col.*

149. 1933 MAY 4. 8:14 p.m. $\phi = 49°$ N; $\lambda = 129°$ W; M = $5\frac{1}{2}$. *G.*

150. 1933 AUGUST 30. 6:51 p.m. $\phi = 59\frac{1}{4}°$ N; $\lambda = 137\frac{1}{2}°$ W; M = $5\frac{1}{4}$. *G.*

151. 1933 SEPTEMBER 19. 3:39 p.m. $\phi = 60°$ N; $\lambda = 138°$ W. *G.*

152. 1933 OCTOBER 5. 6:38 p.m. IV. Nanaimo residents felt this shock as an explosion, as did the area about Chemainus. The tremor was felt slightly at Comox, Victoria and Vancouver, and heavily at Parksville and Wellington. The origin is probably on Vancouver Island near Nanaimo or immediately off shore under the Strait of Georgia. *Prov., D., SB*

153. 1934 APRIL 12. 9:30 p.m. III. A tremor was felt at Port Alberni, Long Beach, Tofino, Ucluelet on the west coast of Vancouver Island. Tofino appears to have been the location of maximum intensity. No tremor was felt at Nanaimo.

154. 1934 MAY 4. 8:09 p.m. IV. The general areas of Victoria, Port Townsend, Port Angeles, Everett, Duncan and Vancouver felt the earthquake equally. Nanaimo felt it slightly less. At Vancouver some plumbing was reported damaged.

155. 1935 September 24. 2:12 p.m. $\phi = 49\frac{1}{2}°$ N; $\lambda = 130°$ W; M = $6\frac{1}{4}$. *G.*

156. 1936 MARCH 28. 1:15 a.m. V. From newspaper files and clippings an isoseismal map can be readily drawn for this earthquake. Such a map indicates an epicentre at 50°.5 N. and 119°.5 W. In Vernon dishes were broken, plaster was cracked and the earthquake was described as a dull roar lasting 5 to 10 seconds. Residents of Oyama, slightly south, heard rockslides in the mountains, and a short distance south of Sicamous, at Mara, bricks were dislodged from chimneys. At Grindrod, near Sicamous, some aftershocks were felt. Notch Hill residents reported four chimneys down. At Kamloops the main shock rattled dishes, and an aftershock at 4 a.m. was felt. At Salmon Arm, Penticton, Merritt, Lumby, Kelowna and Lavington residents generally were awakened.

157. 1936 APRIL 22. 9:53 p.m. Felt slightly in Victoria. *SB*

158. 1936 JULY 15. 11:20 p.m. Residents of Rock Creek, on the Kettle River Valley, were alarmed by an earthquake.

159. 1936 DECEMBER 21. 11:03 a.m. $\phi = 52\frac{1}{2}°$ N; $\lambda = 131\frac{1}{2}°$ W; M = 6. *G.* A tremor was felt at Dead Tree Point on the Queen Charlotte Islands.

160. 1937 On an unrecorded date an earthquake shook the north shore at Vancouver at 6 a.m. *D*

161. 1937 SEPTEMBER 29. 3:30 a.m. $\phi = 49\frac{1}{4}°$ N; $\lambda = 129\frac{1}{2}°$ W; M = $5\frac{1}{2}$. *G.*

162. 1938 FEBRUARY 19. 6:13 a.m. Felt in Vancouver, and particularly on the north shore. *Prov.*

163. 1938 MARCH 22. 7:22 a.m. $\phi = 52\frac{1}{4}°$ N; $\lambda = 132°$ W; M = $6\frac{1}{4}$. *G.* The earthquake was felt strongly on the Queen Charlotte Islands and up to the Alaskan panhandle. Dishes rattled in Prince Rupert. *Prince Rupert Daily News.*

164. 1938 MARCH 22. 2:27 p.m. $\phi = 52\frac{1}{4}°$ N; $\lambda = 132°$ W; M = $5\frac{1}{4}$. *G.*

165. 1938 APRIL 21. 8:15 p.m. $\phi = 49\frac{3}{4}°$ N; $\lambda = 129\frac{3}{4}°$ W; M = $5\frac{1}{2}$. *G.*

166. 1938 JUNE 27. An earthquake was felt in Victoria. *D.* Newspapers reported that the seismograph was out of operation while it was being transferred to the Dominion Astrophysical Observatory and that there were a few tremors about this time.

167. 1938 SEPTEMBER 19. 4:40 a.m. Slightly felt in Vancouver. *Prov.*

168. 1938 OCTOBER 14. 7:52 a.m. $\phi = 58\frac{1}{2}°$ N; $\lambda = 136°$ W; M = 5. *G.*

169. 1939 JULY 18. 7:26 p.m. $\phi = 49°$ N; $\lambda = 129\frac{1}{4}°$ W; M = $6\frac{1}{2}$. *G.*

170 1939 NOVEMBER 6. 6:30-7:30 p.m. A letter on file from a resident of Kennedy Lake reported an earthquake in that region of west central Vancouver Island.

171. 1939 NOVEMBER 24. 4:45 p.m. An earthquake was reported at Nanaimo as a dull thud.

172. 1940 JANUARY 28. 12:28 a.m. $\phi = 61\frac{3}{4}°$ N; $\lambda = 137\frac{1}{2}°$ W; M = $5\frac{1}{4}$. *G.*

173. 1940 MAY 28. 5:57 p.m. $\phi = 67°$ N; $\lambda = 135°$ W; M = $6\frac{1}{4}$. *G.* Yukon.

174. 1940 JUNE 5. 3:01 a.m. $\phi = 67\frac{1}{2}°$ N; $\lambda = 136°$ W; M = $6\frac{1}{2}$. *G.* Yukon.

175. 1940 SEPTEMBER 8. 10:20 a.m. This is the first of a series of fairly strong local shocks in the Bella Coola area of British Columbia. Residents were generally alarmed, but no serious damage was mentioned in the reports of the British Columbia Provincial Police. The following list of the tremors is in the order of their occurrence, and unless noted, all are of the same intensity.

176. 1940 SEPTEMBER 8. 10:30 a.m.; 9:20 p.m. Bella Coola.

177. 1940 SEPTEMBER 9. 5:20 a.m. Bella Coola.

178. 1940 SEPTEMBER 10. 3 a.m.; 3:10 a.m.; 8 a.m.; 8 p.m. Bella Coola.

179. 1940 SEPTEMBER 11. 8:05 a.m.; 8:15 a.m. Bella Coola.

180. 1940 SEPTEMBER 12, 13, 26, 27. Bella Coola.

181. 1940 OCTOBER 8, 9, 11, 12, 13, 23, 24. Bella Coola.

182. 1940 OCTOBER 27. 3:29 p.m. An earthquake was felt in many districts of Victoria, and in Seattle, but not in Chilliwack. A newspaper credited the earthquake with causing a landslide on highway No. 2 about 2 miles west of Hope. This appears to be unlikely. *Prov.*

183. 1940 NOVEMBER 1, 2, 3, 4, 5, 6, 23, 25. All were felt at Bella Coola.

184. 1941 AUGUST 9. 9:05 p.m. $\phi = 59\frac{1}{4}°$ N; $\lambda = 137\frac{1}{2}°$ W; M = $5\frac{1}{4}$. *G.*

185. 1941 OCTOBER 31. 4:43 p.m. An earthquake was recorded on the Victoria seismograph at a distance of 350 miles in an unknown direction.

186. 1942 JANUARY 18. 2:45 a.m. Dr. Whiting reports from Bella Coola that a stronger than normal tremor was felt.

187. 1942 JANUARY 30. 10:49 p.m. V. $\phi = 51°$ N; $\lambda = 124°$ W; M = $5\frac{1}{2}$. *G.* The epicentres obtained from seismograms and from the felt area of this earthquake agree quite well. Powell River felt the tremor most severely, and here the newsprint machines were thrown out of line. People were generally alarmed, and reports are that a foreshock was felt a few days preceding the main tremor. At Goldbridge the main shock and two aftershocks were felt. At Manson's Landing and Cortes in the northern part of the Strait of Georgia the motion appeared to be from east to west. The earthquake tilted pictures on walls at Kamloops, and was felt stronger than this at Spences Bridge. In Vancouver dishes rattled. The epicentre indicated by Gutenberg, immediately east of Powell River, appears to be a logical choice from macroseismic evidence and newspaper reports.

188. 1942 MARCH 19. 3:59 a.m. $\phi = 50\frac{1}{2}°$ N; $\lambda = 131°$ W; M = 6. *G.*

189. 1942 JUNE 9. 3:06 a.m. $\phi = 49\frac{1}{2}°$ N; $\lambda = 129°$ W; M = $5\frac{3}{4}$. *G.*

190. 1942 JUNE 11. 6:01 p.m. $\phi = 61°$ N; $\lambda = 138°$ W; M = $5\frac{3}{4}$. *G.*

191. 1942 OCTOBER 21, 22, 29, 31. These are further reports of earthquakes felt at Bella Coola.

192. 1942 NOVEMBER 1. 11:55 a.m. Residents of Creston were alarmed at this particular tremor. It was felt in Canada at Nelson and Kingsgate and as far south as Coeur d'Alene and Spokane in the United States. There were three tremors in all (8:42 a.m., 11:55 a.m. and 12:16 p.m.), that at 11:55 a.m. being most generally felt.

193. 1943 APRIL 14. 6:15 p.m. An earthquake, again strong at Bella Coola, was felt along the valley from Ocean Falls to Canoe Crossing. The motion appears to have been from west to east.

194. 1943 MAY 24. 10:35 p.m. Felt at Bella Coola.

195. 1943 MAY 26. 11:09 a.m. Felt at Bella Coola, Ocean Falls and Stuie.

196. 1943 JULY 31. 10:15 p.m. Felt at Bella Coola, Ocean Falls and Stuie.

197. 1943 JULY 31. 10:30 p.m. 11:30 p.m. Felt at Bella Coola.

198. 1943 AUGUST 1. 4:20 a.m. Felt at Bella Coola. Although this is the last available report on earthquakes felt at Bella Coola, it should not be assumed that the tremors ceased abruptly. It is probable that the absence of reported earthquakes after 1943 indicates a lack of information rather than a lack of earthquakes. There was probably a series of earthquakes for at least three years, none of which caused damage, with epicentres at one location near Bella Coola. No field investigation was made, other than a search of police reports.

199. 1943 NOVEMBER 29. 4:30 a.m. A slight earthquake was felt at Vancouver, and at Seattle. The Victoria records indicated the epicentre as being 200 miles north-east of Victoria. *Prov.*

200. 1944 FEBRUARY 3. 4:15 a.m. $\phi = 60\frac{1}{2}°$ N; $\lambda = 137\frac{1}{2}°$ W; M = $6\frac{1}{2}$. *G.* The Whitehorse (Yukon Territory) Meteorological Office reported that clocks were stopped and doors were seen to swing with the vibration. The duration was quoted as three minutes. At Aishihik and Teslin the tremor was also felt.

201. 1944 AUGUST 8. 1:00 a.m. Sister's Island lighthouse was damaged by this earthquake, apparently centered off the northern tip of Vancouver Island.

202. 1944 AUGUST 8. 4:50 a.m. An aftershock of the above earthquake was felt.

203. 1944 AUGUST 9. 5:53 p.m. $\phi = 51°.4$ N; $\lambda = 130°.5$ W. *USC and GS.*

204. 1944 SEPTEMBER 7. 11:20 p.m. Felt at Bella Coola.

205. 1945 MAY 14. Residents of Prince George reported feeling four light tremors in two days about this time. *SB*

206. 1945 MAY 22. 1:12 a.m. An earthquake was felt slightly in Victoria.

207. 1945 JUNE 15. 3:24 p.m. III. A tremor was felt slightly in Victoria and Vancouver. At Nanaimo goods were toppled from shelves. *Col.*

208. 1945 AUGUST 2. 12:45 p.m. $\phi = 54°$ N; $\lambda = 133°$ W; M = $6\frac{1}{4}$. *G.*

209. 1945 OCTOBER 15. 00:01 a.m. $\phi = 59°.0$ N; $\lambda = 140°.0$ W. *USC and GS.*

210. 1945 OCTOBER 29. 2:54 a.m. $\phi = 52°$ N; $\lambda = 131°$ W. *USC and GS.*

211. 1945 NOVEMBER 12. 9:05 p.m. An earthquake was felt slightly in Victoria. *Times.*

212. 1945 NOVEMBER 16. 10:02 a.m. $\phi = 58°$ N; $\lambda = 136\frac{1}{2}°$ W. *G.*

213. 1946 FEBRUARY 15. 7:16 p.m. An earthquake, probably centred in the southern Puget Sound area, was generally felt in Victoria. *Col.*

214. 1946 MARCH. A resident of Hornby Island in the northern Strait of Georgia reported that he felt tremors covering the period of a week.

215. 1946 JUNE 23. 9:13 a.m. $\phi = 49°\ 52'$ N; $\lambda = 124°\ 55'$ W; M = 7·3. *Milne.* This is generally referred to as the British Columbia earthquake, mentioned earlier in this report as having been discussed in detail by E. A. Hodgson.[10] Since his publication no further details of damage have become available.

216. 1946 JULY 8. 8 p.m. Felt at Courtenay near the epicentre of the previous earthquake.

217. 1946 JULY 9. A letter on file from a resident of the Great Central Lake region reports a tremor in that area. This and the July 8 event are the only reported or recorded aftershocks of the main tremor of June 23.

218. 1946 JULY 17. 10:07 p.m. $\phi = 50°$ N; $\lambda = 129°$ W; M = $6\frac{1}{2}$. *USC and GS.*

219. 1946 JULY 17. 11:16 p.m. $\phi = 50°$ N; $\lambda = 129°$ W; M = $6\frac{1}{2}$. *USC and GS.*

220. 1947 APRIL 5. 5:51 p.m. III. The *Prince George Citizen* reported that an earthquake was felt in that area, similar to the noise of a passing truck.

221. 1947 MAY 8. 3:53 p.m. $\phi = 61°$ N; $\lambda = 139°$ W. *USC and GS.*

222. 1947 AUGUST 11. 3:55 a.m. A letter on file indicates that an earthquake was felt both at Milne's Landing and near Mill Bay on South Vancouver Island.

223. 1948 FEBRUARY 27. 5:58 p.m. $\phi = 53\frac{1}{2}°$ N; $\lambda = 133°$ W; M = $6\frac{1}{2}$. *USC and GS.* An earthquake was felt at Prince Rupert and on the Queen Charlotte Islands *Col.*

224. 1948 JUNE 9. 11:05 a.m. An earthquake was felt on Read Island in the northern Strait of Georgia.

225. 1948 JUNE 24. On this date the short-period Benioff seismograph was installed at Victoria. Many earthquakes were recorded during the next three years, and the following are those that were felt or were located by means of seismograph recordings. Table 2 lists the remainder that were recorded by the seismograph but not felt nor located.

226. 1948 JULY 22. 12:05 p.m. $\phi = 49\frac{1}{2}°$ N; $\lambda = 130\frac{1}{2}°$ W. *USC and GS.* Recorded at Victoria at 12:06:55.

227. 1948 OCTOBER 1. 1:44 a.m. Felt slightly at Kamloops, B.C. and recorded at Victoria at 1:45:34.

228. 1948 DECEMBER 30. 3:49 p.m. $\phi = 51°$ N; $\lambda = 131°$ W. *USC and GS.* Recorded at Victoria at 3:51:14.

229. 1949 FEBRUARY 4. An earthquake was felt at Summerland and Peachland in south central British Columbia. *Col.*

230. 1949 April 2. 1:17 a.m. An earthquake with a rumbling noise was felt at Queen Charlotte City.

231. 1949 April 13. 11:55 a.m. $\phi = 47°.1$ N; $\lambda = 122°.7$ W; M = $6\frac{3}{4}$. *USC and GS.* This Seattle earthquake, which did extensive damage in the lower Puget Sound basin, has been included because it was felt sharply at Victoria and at Vancouver.

232. 1949 August 20. 8:03 p.m. $\varphi = 54°.2$ N; $\lambda = 133°.5$ W; M = 8·0. This tremor, known as the Queen Charlotte Islands earthquake, did some damage in populated areas near its origin, although for the most part the immediate epicentral area was very sparsely settled. Little field data are available for the earthquake, and in particular information from the main epicentral area on the Queen Charlotte Islands did not indicate that an earthquake of magnitude 8·0 had occurred. However many different seismological stations reported very strong recordings.

There is a report of a geologist working on the north-west tip of Graham Island who was unable to stand up due to the violent shaking of the ground. Two boat captains mentioned that the water near the beach at Lockport was swirling wildly, and that there were many landslides. At Delkatla the bridge "writhed like a snake", and the ground was cracked. At a lodge nearby, the horses could not be controlled even an hour before the event. The *Prince Rupert Daily News* states that just across Delkatla Slough the earth fissured, one crack 50 feet long and 6 inches across being so deep its bottom could not be seen. Many trees were felled, and in one house a piano was shifted. As far away as Prince George the people were alarmed and ran into the streets. At Cumshewa Inlet logging camp a tank containing many gallons of fuel oil was destroyed, at considerable loss to the owner. At Terrace cars rolled on the street and dishes were broken. The earthquake was felt as far east as Jasper and as far south as Portland. Using the distance to Jasper as the radius of a circle, the felt area of the tremor is of the order of 2,220,000 square miles, half of which is under the ocean. An interesting sidelight on the phenomenon of this earthquake is that at the Dominion Observatory in Ottawa observers using the meridian-circle telescope were unable to keep the cross-hair of the guiding eye-piece on the star image during the time the strong waves from this earthquake were passing Ottawa. In the Arctic area one of the Geodetic Survey party reported that while he was observing star crossings for an astronomical position it was not possible to keep the star image steady in the eye-piece, at about the time of this earthquake.

233. 1949 August 23. 12:24 p.m. $\varphi = 54°.2$ N; $\lambda = 133°.5$ W; M = 6·4. *USC and GS.* This tremor, a strong aftershock of the earthquake of August 20, was felt in the same area. Many other aftershocks were felt, most of them being included in Table 2 because their locations are not positively known. One resident of the Queen Charlotte Islands reported that up to October 1, 107 aftershocks were felt in that area.

234. 1949 OCTOBER 30. 5:42 p.m. $\varphi = 56°$ N; $\lambda = 135°$ W; M = $6\frac{3}{4}$. *USC and GS.* The epicentre was some 70 miles south of Sitka, Alaska.

235. 1949 NOVEMBER 29. 5 a.m. An earthquake was felt slightly at Victoria and in Seattle.

236. 1950 APRIL 14. 3:04 a.m. $\varphi = 48°$ N; $\lambda = 122\frac{1}{2}°$ W. *USC and GS.* An earthquake was felt in Victoria, Ladysmith, Vancouver, Chilliwack, Haney, Abbotsford and White Rock in British Columbia. *Prov.*

237. 1950 APRIL 16. 1:48 p.m. $\varphi = 49°$ N; $\lambda = 129°$ W. *USC and GS.* Recorded at Victoria at 1:48:58 p.m.

238. 1950 AUGUST 24. 6:15 p.m. $\varphi = 49\frac{1}{2}°$ N; $\lambda = 129°$ W. *USC and GS.*

239. 1950 SEPTEMBER 28. 1:47 p.m. $\varphi = 54\frac{1}{2}°$ N; $\lambda = 134\frac{1}{2}°$ W. *USC and GS.* Recorded at Victoria at 1:49:14 p.m.

240. 1950 OCTOBER 7. 11:59 a.m. $\varphi = 50°$ N; $\lambda = 129\frac{1}{2}°$ W. *USC and GS.* Recorded at Victoria at 11:59:21 p.m.

241. 1951 JUNE 2. 10:58 p.m. Slight tremor felt at Alberni.

242. 1951 JULY 20. 2:13 p.m. Slight tremor felt at Victoria.

TABLE 2. EARTHQUAKES RECORDED AT VICTORIA JULY 1948 TO JULY 1951.
(Not located, and not listed in Table 1)

Date	Time at Victoria (P.S.T.)	Distance from Victoria	Remarks
	h m s	kms.	
1948 July 2	7 37 27 p.m.	260	
July 17	2 22 23 p.m.	96	
July 27	5 41 03 p.m.	125	
July 27	6 07 09 p.m.	148	
July 28	2 11 11 a.m.	635	
July 28	2 21 40 a.m.	635	
August 2	2 05 39 a.m.	60	
August 3	3 00 01 a.m.	160	
August 5	2 36 41 a.m.	58	
August 5	4 47 14 a.m.	98	
August 5	7 44 30 a.m.	89	
August 6	3 17 39 a.m.	160	
August 6	5 12 50 p.m.	225	
August 18	12 58 51 p.m.	100	
August 27	5 42 18 p.m.	145	
September 24	2 34 22 p.m.	100	
October 19	7 02 05 a.m.	120	
October 27	4 40 27 p.m.	875	
October 28	6 19 39 a.m.	690	
October 28	6 31 37 a.m.	690	
October 29	0 17 05 a.m.	690	
November 3	8 48 40 p.m.	460	
November 11	12 30 23 p.m.	960	
November 16	5 13 48 p.m.	535	
November 18	0 54 14 a.m.	55	
November 21	7 31 26 p.m.	680	
December 1	5 26 56 a.m.	735	
December 10	3 32 39 p.m.	85	
December 13	11 08 07 a.m.	135	
	11 33 02 a.m.	135	
	11 40 57 a.m.	135	
December 14	10 19 35 a.m.	135	
	10 24 29 a.m.	135	
	11 40 10 a.m.	135	
	1 39 47 p.m.	135	
	1 43 05 p.m.	135	
	1 49 32 p.m.	135	
	1 56 43 p.m.	135	
	2 12 11 p.m.	135	
	2 16 32 p.m.	135	
	3 07 25 p.m.	135	
December 15	0 09 02 a.m.	168	
December 15	8 30 30 p.m.	155	
December 30	10 41 52 p.m.	680	
1949 April 19	10 48 53 p.m.		
April 21	10 47 35 p.m.		
May 2	8 44 33 p.m.		
May 8	8 26 18 p.m.	170	
May 11	12 26 37 p.m.	85	
May 24	6 44 43 p.m.	545	
June 14	8 31 15 a.m.	370	
June 16	2 04 25 a.m.	185	
June 18	3 51 26 a.m.	190	

TABLE 2. EARTHQUAKES RECORDED AT VICTORIA JULY 1948 TO JULY 1951.
(Not located, and not listed in Table 1)—continued

Date	Time at Victoria (P.S.T.)	Distance from Victoria	Remarks
	h m s	kms.	
1949 June 19	6 08 16 a.m.	180	
June 27	1 55 30 p.m.		
July 25	10 40 03 a.m.	55	
	10 44 29 a.m.	55	
July 28	12 16 08 p.m.	1100	
July 29	3 09 20 a.m.	290	
August 5	12 47 38 p.m.	435	
August 5	2 46 59 p.m.	90	
August 8	3 17 24 p.m.	250	
August 8	5 36 44 p.m.	173	
August 12	2 12 50 p.m.	110	
August 12	4 08 34 p.m.	127	
August 15	8 01 21 p.m.	355	
August 15	7 30 54 p.m.	100	
August 15	9 46 06 p.m.	170	
August 18	0 04 57 a.m.	180	
August 19	12 58 59 p.m.	150	
August 19	3 24 14 p.m.		
August 19	3 59 12 p.m.		
August 21	12 50 26 p.m.		Queen Charlotte aftershock
August 21	10 16 45 p.m.		Queen Charlotte aftershock
August 22	4 21 43 a.m.		Queen Charlotte aftershock
August 22	6 59 29 p.m.		
August 23	11 43 35 a.m.		
August 23	6 37 32 p.m.		
August 24	1 53 00 p.m.		Queen Charlotte Islands aftershocks
August 24	2 37 13 p.m.		
August 25	9 26 00 p.m.		
August 26	2 39 40 p.m.		
August 27	1 30 40 p.m.		
September 7	3 37 13 p.m.	112	
September 16	6 32 39 p.m.	345	
September 17	2 20 05 p.m.	185	
September 20	4 19 40 a.m.	540	
October 2	2 32 06 p.m.	975	
October 20	8 07 13 a.m.	235	
October 23	1 00 24 p.m.		Queen Charlotte Islands
October 23	6 34 56 p.m.		Queen Charlotte Islands
October 25	10 20 46 a.m.	115	
October 30	11 24 57 p.m.		
November 13	2 55 44 p.m.	175	
November 13	10 21 58 p.m.	137	
December 2	2 32 41 p.m.	532	
December 14	11 44 01 a.m.	135	
December 15	10 35 14 p.m.	112	
December 17	5 06 02 a.m.		
December 21	5 55 52 a.m.	140	
1950 January 2	2 03 46 a.m.	620	
January 4	4 19 30 p.m.	310	
January 14	7 32 17 p.m.	147	
January 27	9 19 36 a.m.	24	
	9 21 38 a.m.	24	
January 27	1 57 05 p.m.	128	

TABLE 2. EARTHQUAKES RECORDED AT VICTORIA JULY 1948 TO JULY 1951.
(Not located, and not listed in Table 1)—continued

Date	Time at Victoria (P.S.T.)	Distance from Victoria	Remarks
	h m s	kms.	
1950 February 14	10 53 02 a.m.	15	
	10 53 36 a.m.	15	
	12 49 21 p.m.	15	
	12 50 48 p.m.	15	
	1 53 20 p.m.	15	
	1 53 50 p.m.	15	
March 2	6 17 39 a.m.	70	
March 2	12 11 29 p.m.	140	
March 5	6 52 25 a.m.	25	
	7 13 54 a.m.	25	
	7 18 27 a.m.	25	
March 21	1 26 14 p.m.	80	
March 21	1 27 17 p.m.	80	
March 24	11 39 03 a.m.	120	
March 25	12 13 39 p.m.	880	Queen Charlotte Islands?
April 12	10 45 04 a.m.	210	
April 17	9 13 41 a.m.	25	
	9 21 12 a.m.	25	
	9 28 40 a.m.	25	
	10 10 36 a.m.	25	
April 28	12 37 18 p.m.	30	
	12 38 31 p.m.	15	
	12 41 48 p.m.	27	
	12 45 22 p.m.	25	
	12 52 04 p.m.	17	
	12 54 50 p.m.	24	
May 3	8 57 32 p.m.	95	
May 16	11 34 53 p.m.	66	
May 21	0 40 15 a.m.	87	
May 22	11 51 06 a.m.	585	Off west coast of Vancouver Island.
June 30	12 28 09 p.m.	50	
July 4	20 02 15 p.m.	120	
July 15	8 55 33 p.m.	60	
August 24	2 25 20 a.m.		
	2 29 54 a.m.		
August 26	9 47 06 a.m.	66	
August 31	0 02 36 a.m.	180	
September 20	5 21 06 a.m.	660	
September 21	2 25 06 p.m.	122	
September 23	5 58 51 p.m.	290	
September 28	8 35 23 p.m.	33	
September 29	6 58 29 p.m.	33	
	7 20 22 p.m.	25	
	7 21 19 p.m.	25	
September 30	1 20 02 a.m.	25	
October 1	5 07 48 a.m.	1050	Queen Charlotte Islands?
October 1	6 12 58 a.m.	1050	Queen Charlotte Islands?
October 6	10 18 38 a.m.	95	
October 13	1 48 22 a.m.	25	
October 16	11 27 22 a.m.	76	
	11 28 48 a.m.	84	
	11 32 21 a.m.	90	
	11 35 12 a.m.	80	

TABLE 2. EARTHQUAKES RECORDED AT VICTORIA JULY 1948 TO JULY 1951.
(Not located, and not listed in Table 1)—continued

Date	Time at Victoria (P.S.T.)	Distance from Victoria	Remarks
	h m s	kms.	
1950 October 16	12 04 15 p.m.	63	
October 22	9 52 07 p.m.	177	
November 16	9 28 27 a.m.	115	
November 17	3 49 08 p.m.	63	
November 18	12 06 48 p.m.	60	
December 7	12 30 29 p.m.	118	
December 11	3 24 11 p.m.	102	
December 12	2 25 05 a.m.	87	
December 31	3 19 15 a.m.	45	
1951 January 3	5 43 16 a.m.	290	
January 6	8 15 25 p.m.	90	
January 23	3 25 39 p.m.	90	
February 7	10 24 41 a.m.	172	Depth greater than normal?
February 13	4 52 17 p.m.		
February 14	2 00 35 a.m.	650	
February 14	2 18 20 a.m.	650	
March 5	4 26 06 a.m.	102	
March 5	2 27 54 p.m.	170	
March 19	3 35 49 p.m.	42	
March 29	10 20 15 a.m.	40	
April 5	9 58 25 a.m.	72	
April 10	10 05 16 a.m.	33	
	10 06 43 a.m.	40	
	10 40 59 a.m.	33	
	12 27 01 p.m.	26	
April 11	9 11 51 p.m.	88	
April 17	2 58 33 p.m.	33	
	3 00 09 p.m.	40	
	3 01 43 p.m.	40	
	3 03 13 p.m.	40	
	3 04 36 p.m.	40	
	3 05 43 p.m.	40	
April 20	11 16 34 a.m.	33	
May 30	9 26 17 a.m.		
	9 29 12 a.m.		
	9 35 55 a.m.		
	9 48 39 a.m.		
June 17	3 35 35 a.m.	107	
June 26	10 58 30 a.m.	115	
June 27	2 51 46 a.m.		
July 19	10 47 02 p.m.	87	
July 20	8 19 16 a.m.		
	9 00 10 a.m.	38	
	9 16 01 a.m.		
	9 17 01 a.m.		
	9 17 39 a.m.		
	9 29 42 a.m.		
	9 33 22 a.m.		
	10 00 07 a.m.		
	2 00 05 p.m.		
	2 13 50 p.m.		
	2 13 50 p.m.		
	2 14 23 p.m.		

TABLE 2. EARTHQUAKES RECORDED AT VICTORIA JULY 1948 TO JULY 1951.
(Not located, and not listed in Table 1)—concluded

Date	Time at Victoria (P.S.T.)	Distance from Victoria	Remarks
	h m s	kms.	
1951 July 20	3 00 05 p.m.		
July 22	2 00 06 p.m.		
July 22	5 00 06 p.m.		
July 24	11 57 51 a.m.		
July 24	2 27 52 p.m.		
	3 57 58 p.m.		
July 26	1 30 08 p.m.		
July 26	3 00 08 p.m.		

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DIRECTION OF FAULTING IN THE GREEK EARTHQUAKES OF AUGUST 9-13, 1953

BY

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ABSTRACT

The direction of faulting is determined for eight earthquakes of the sequence which damaged the Ionian Islands in August, 1953. The solutions obtained suggest that faulting occurred either on a plane striking NNW—SSE or on a plane striking ENE—WSW. Field evidence collected by GALANOPOULOS suggests that in fact faulting occurred on both these planes which constitute a conjugate system of faulting. The agreement between the solutions and the field evidence is satisfactory.

INTRODUCTION

Between August 9 and 13, 1953, the Ionian Islands were shaken by a disastrous series of earthquakes. The first shock, of magnitude 6 1/4, occurred at 7:41, G. M. T., August 9, and caused only minor damage. The second principal shock occurred with a number of small shocks intervening, at 03:33, G. M. T., August 11. It had a magnitude of 6 3/4, and did widespread damage. A number of minor shocks followed, and the main earthquake of the sequence occurred at 9:24, G. M. T., August 12. Its magnitude was 7 1/4 and it caused almost complete destruction over most of the Ionian Islands and resulted in the death of more than 400 people. This main shock was followed by a large number of aftershocks; the seismic bulletin for the Athens station lists more than 300 of them up to the end of August. A very valuable eye-witness account of the earthquakes has been given by GRANDAZZI (1954).

At the Rome meetings of the International Union of Geodesy and Geophysics a paper dealing with the principal shock was read by DI FILIPPO and MARCELLI (1954). They made a very careful determination of the epicentre and investigated the mechanism of the earthquake, concluding that it was caused by a sinking at the focus.

Dr. A. GALANOPOULOS, who had made a detailed study of the earthquake (1954, 1955 a, b) was of the opinion that the mechanism postulated by DI FILIPPO and MARCELLI was inconsistent with the field evidence. He suggested that the present authors should investigate the direction of faulting in the three principal shocks, according to the system in use by the Dominion Observatory. The present paper is the result of that suggestion.

The method of the research has been fully described in recent papers (HODGSON, 1955; HODGSON and COCK, 1956). Briefly stated, the seismograph stations of the world are plotted on a special stereographic projection, and those which received an initial push from the earthquake (compression) are sep-

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arated from those which received an initial pull (dilatation) by a pair of circles. These circles represent the intersections of the sphere of the earth with a pair of planes, one of them the fault plane, the other a plane perpendicular to the direction of motion. The strike and dip of these planes may be determined from the drawings.

A questionnaire seeking information on first motion was circulated to the seismic stations of the world in January, 1955. Information was sought not only on the three main shocks but also on nine lesser ones of the sequence. This was done in the hope that some light might be cast on the variation of mechanism throughout the sequence. The same questionnaire collected data on the deep-focus Spanish earthquake of March 29, 1954. This solution is being given elsewhere (HODGSON and COCK, 1956).

PRESENTATION OF DATA

First motion data were sought for the following earthquakes, the times given being the times of occurrence in G. M. T. as determined by the United States Coast and Geodetic Survey.

August 9, 1953 — 07:41:05
August 11, 1953 — 03:32:24
August 11, 1953 — 12:43:24
August 11, 1953 — 13:11:06
August 12, 1953 — 06:08:03
August 12, 1953 — 09:23:55
August 12, 1953 — 11:33:46
August 12, 1953 — 12:05:22
August 12, 1953 — 13:39:23
August 12, 1953 — 14:08:38
August 12, 1953 — 16:08:32
August 13, 1953 — 03:22:06

Solutions have been obtained for only eight of the twelve earthquakes attempted. In the case of the earthquakes of August 11, 12:43:24 and 13:11:06 and of August 12, 11:33:46 the earthquakes were too small to yield sufficient data for a solution. The data collected for the earthquake of August 11, 03:32:24, were very confused and could not be fitted into any pattern. Several of the more sensitive stations reported a double beginning, which appears to account for the confusion.

Direction of motion data for the eight earthquakes for which a solution has been obtained are summarized in Table I, in a simple notation. The letter C or D indicates that the P wave was recorded as a compression or dilatation respectively. For the reflected phase PP, CC indicates a compression, DD a dilatation. The core phase P'_1 is reported by C'_1 for compression, D'_1 for dilatation. Observations in parentheses are inconsistent with the published solutions.

TABLE I

Data on which the Research is Based

STATION	Epicentral Distance	Azimuth Epicentre to Station	August 9, 1953 07:41:05	August 12, 1953 06:08:03	August 12, 1953 09 23:55	August 12, 1953 12:05:22	August 12, 1953 13:39:23	August 12, 1953 14:08:38	August 12, 1953 16:08:32	August 13, 1953 03:22:06
Athens	2.2	111.0 E	(C)	(D)	D	(C)	(C)	D	(C)	(C)
Reggio Calabria	4.3	97.0 W	—	(D)	D	—	—	—	—	D
Messina	4.3	95.3 W	(D)	—	D	D	(D)	(C)	(D)	D
Belgrade	6 2	2.5 W	(D)	D	C	C	D	(D)	(D)	—
Rocca di Papa	7.1	60.9 W	D	C	D	C	—	—	—	—
Rome	7.3	60.6 W	D	C	D	C	D	D	—	D
Trieste	8.7	34.8 W	—	D	D	C	—	D	D	(C)
Florence	8.7	53.3 W	—	—	D	C	—	—	—	—
Prato	9.0	52.0 W	D	D	(C)	C	D	(C)	(C)	D
Bologna	9.2	47.9 W	—	—	(C)	—	—	—	—	—
Stara Dala	9.3	10.8 W	C	—	—	C	—	C	—	—
Vienna	10.1	17.5 W	—	D	C	C (DD)	D	(D)	D	—
Salo	10.3	44.7 W	—	—	D	—	—	—	—	—
Skalnate Pleso	10.4	2.0 W	C	—	—	C	—	C	—	—
Pavia	10.8	50.0 W	(C)	—	D	C	D	D	—	—
Chur	11.6	42.1 W	—	D	—	—	—	D	—	—
Oropa	11.7	50.2 W	D	D	—	—	(C)	D	—	D
Helwan	12.1	133.2 E	D	D	D	—	—	—	—	—
Prague	12.3	19.9 W	D	—	C	C	—	C	—	—
Zurich	12.4	41.9 W	—	—	C	—	—	—	—	—
Stuttgart	13.1	36.3 W	D	—	D	—	—	—	—	—
Strasbourg	13.6	39.3 W	—	—	—	(D)	—	—	—	—
Karlsruhe	13.6	37.2 W	D DD	—	(C)	C CC	(C) DD	D DD	D DD	D DD
Alger Univ.	14.3	92.9 W	—	C	(C)	D	—	—	—	—
Tortosa	15.9	76.1 W	D	C	—	D	(C)	—	(C)	(C)
Paris	16.6	47.1 W	—	(C)	—	C	—	—	—	—
Uccle	16.8	38.6 W	D	—	(C) DD	C	(C)	(C)	—	—
Alicante	16.8	84.2 W	C DD	C CC	(C) DD	(C) (cc)	D CC	D (cc)	—	(C) DD
Witteveen	17.1	30.2 W	—	—	C	C	—	—	—	—
De Bilt	17.2	34.1 W	D	—	—	C	—	—	—	—
Copenhagen	17.9	15.7 W	C	—	—	C	D	—	—	—
Toledo	19.4	78.8 W	—	C	D	D	D	(C)	D	(C)
Cartuja	19.4	87.2 W	C CC	C CC	(C) (cc)	D	(D) CC	D	C CC	D DD
Kew	19.6	42.3 W	D	D	D	C	—	—	—	D
Malaga	20.1	88.0 W	(D)	(D)	D	(C)	—	—	—	—
Tamanrasset	20.5	135.4 W	C	D	(D)	C	—	C	—	—
Uppsala	21.3	4.3 W	C C[1]	D	C	C	C	C	C CC	C
Durham	22.1	36.0 W	D	—	(D)	C	—	—	—	—
Coimbra	22.6	77.0 W	C	—	—	C	—	—	—	—

[1] PcP=C

STATION	Epicentral Distance	Azimuth Epicentre to Station	August 9, 1953 07:41:05	August 12, 1953 06:08:03	August 12, 1953 09:23:55	August 12, 1953 12:05:22	August 12, 1953 13:39:23	August 12, 1953 14:08:38	August 12, 1953 16:08:32	August 13, 1953 03:22:06
Lisbon	23.6	80.4 W	—	—	D	—	—	D	—	—
Rathfarnham	23.7	42.8 W	—	D DD D[1]	(D)	C	D	D	(C)	(C)
Aberdeen	23.8	31.4 W	D	—	C C[2]	C	—	(D)	—	—
Bergen	23.9	19.1 W	C	—	C	—	—	—	—	—
Kiruna	29.2	0.3 W	C	—	—	C	C	C CC	C	C
Reykjavik	35.7	30.6 W	D	—	(D)	(D)	—	—	—	—
Quetta	38.4	88.4 E	—	—	D	(C)	—	—	—	—
Resolute Bay	59.4	16.1 W	—	—	C	C	—	C	—	—
Halifax	60.7	54.6 W	—	—	—	—	—	(C)	D	(C)
Tananarive	62.5	151.5 E	—	—	D	(C)	—	—	—	—
Pretoria	64.3	172.7 E	(C)	—	C	D	D	D	D	—
Burlington	66.8	50.9 W	—	—	C CC	—	—	—	—	—
Kimberley	67.6	176.5 E	(C)	—	C	D	D	C	C	—
Ottawa	67.8	49.1 W	—	—	(D)	—	D	D	D	D
Pietermaritzberg	68.4	171.4 E	—	—	D	(C)	—	—	—	—
Kirkland Lake	68.7	44.8 W	C	—	C	C	—	C	—	D
Palisades	69.1	53.7 W	D	—	C	C	—	D	—	—
Philadelphia	70.6	54.0 W	D (DD)	—	C	—	—	—	—	—
State College	71.6	52.1 W	—	—	—	(D)	—	—	—	—
Grahamstown	71.8	175.2 E	—	—	D	D	—	—	—	—
Washington	72.3	54.1 W	—	—	C	C	(C)	(C)	—	—
Cleveland	73.5	49.9 W	D	—	C	C	D	D	(D)	D
San Juan	76.2	77.1 W	—	—	C	(D)	—	C	C	—
College	76.3	4.8 W	(D)	—	C	C	—	(D)	C	—
Cincinatti	76.6	50.3 W	C	—	C	C	—	—	—	—
Columbia	77.6	56.3 W	—	—	C	C	—	—	—	—
Sapporo	82.2	39.6 E	—	—	D	(C)	—	—	—	—
Sitka	82.4	12.6 W	—	—	C	—	—	—	—	—
Fukuoko	82.7	52.7 E	—	—	(C)	(C)	—	—	—	—
Fayetteville	84.2	47.2 W	C	—	C	C	D	C	C	D
Hungry Horse	84.4	28.2 W	C	—	—	—	—	—	C	C
Matsushiro	85.3	45.9 E	—	—	(C)	D	—	D	—	—
Bozeman	85.5	31.3 W	—	—	C	C	—	—	—	—
Butte	85.7	30.4 W	C	—	C (cc)	C (cc)	C	C	C	C
Tokyo	86.8	45.7 E	—	—	D	—	—	—	—	—
Victoria	87.6	22.6 W	—	—	C DD	(D)	—	C	D	D
Seattle	87.9	23.8 W	—	—	—	(D)	—	C	—	—
Djakarta	90.4	97.5 E	(C)	—	(C)	(C) CC	—	—	—	—
Shasta	93.7	26.7 W	C	—	C	C	C	—	C	—

[1] PPP = D [2] PPP = C

STATION	Epicentral Distance	Azimuth Epicentre to Station	August 9, 1953 07:41:05	August 12, 1953 06:08:03	August 12, 1953 09:23:55	August 12, 1953 12:05:22	August 12, 1953 13:39:23	August 12, 1953 14:08:38	August 12, 1953 16:08:32	August 13, 1953 03:22:06
Mineral	93.9	27.6 W	C	—	C	C	—	—	—	—
Boulder City	95.0	34.5 W	—	—	C	C	C	C	—	C
Tucson	96.1	39.4 W	—	—	(C)	C	—	D	—	C
Berkeley	96.4	28.4 W	—	—	C	—	—	—	—	—
Mount Hamilton	96.7	29.0 W	—	—	D	C	—	—	—	—
Palo Alto	97.0	28.5 W	—	—	D	D	—	—	—	—
Pasadena	98.1	33.2 W	—	—	D	—	—	—	—	—
Nelson	98.3	49.0 W	—	—	(C)	C	C	D	C	C
La Paz	99.4	103.3 W	—	—	(CC)	—	—	—	—	—
Tacubaya	99.5	55.6 W	—	—	C CC	C	—	—	—	—
Fresno	100.1	23.3 W	—	—	C	C	—	C	—	—
Riverview	140.0	98.8 E	—	—	D'_1	—	—	—	—	—
Wellington	159.6	105.7 E	—	—	D'_1	—	—	—	—	—

The distances and azimuths listed in Table I were measured on the chart developed for that purpose by this Observatory (WILLMORE and HODGSON, 1955). They are based on the United States Coast and Geodetic Survey epicentre ($\varphi = 38°.5$ N, $\lambda = 21°$ E), rather than on the more accurate one ($\varphi = 38°10'27''$ N, $\lambda = 20°43'13''$ E) determined by DI FILIPPO and MARCELLI, since this latter epicentre was not available to us at the time the distances and azimuths were determined. The difference in the two epicentres can have no effect except for stations very close to the epicentre.

ANALYSIS OF THE DATA

In this section we shall present the solutions obtained for each of the eight earthquakes in turn. For the benefit of those who are not familiar with the technique, the solution for the first of these will be discussed in considerable detail.

Earthquake of August 9, 1953; 07:41:05.- The solution for this earthquake is shown in Fig. 1. It will be noted first of all that the various seismograph stations recording the earthquake have been plotted, a circle being used to indicate the recording of an initial compression, a triangle to indicate the recording of an initial dilatation. The stations are plotted at their proper azimuth with respect to the epicentre but at a distance from it known as the «extended distance». This is a rather complicated function, designed to take account not only of the distance of the station from the epicentre, but also of the curvature of the seismic ray.

The problem now reduces itself to drawing two circles to separate compressions from dilatations. Since these circles represent orthogonal planes we do not have complete freedom in drawing them; they must satisfy certain «or-

thogonality criteria», which need not concern us here. The two circles designated *a* and *b*, accomplish the required separation reasonably satisfactorily. They are drawn to contain compressions, leaving the zone of overlap and the area external to the circles to contain dilatations.

It must be pointed out that the circles, as drawn, do not account for all the observations. For example, Pretoria and Kimberley, which recorded compressions, lie outside the circles and so should have recorded dilatations. Instances such as this are common. In the present example there were nine

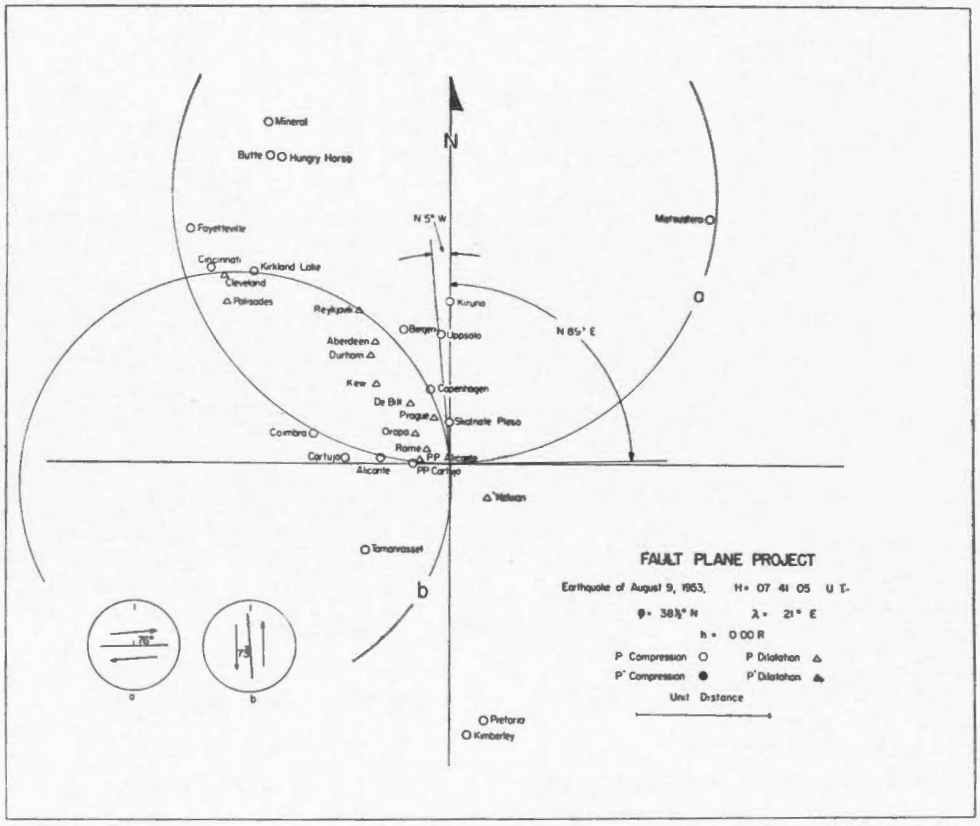

Fig. 1

inconsistent observations out of 44 observations of P, one inconsistency in four observations of PP, while one observation of pP and one of PcP were accurately accounted for. These inconsistencies are not regarded as serious. In three instances – Athens, Messina and Belgrade – the stations are so close to the epicentre that local structure may have influenced the results. In other cases the beginning may be too small to read with accuracy, and it may even happen that a galvanometer is incorrectly connected.

In Fig. 1 the observations of PP are plotted with the opposite phase to that observed at the stations. This phase change is due to the reflection. A recent paper (INGRAM and HODGSON, 1956) showed that this question of phase change on reflection of PP is related to POISSON's ratio, σ, and also to the focal

depth of the earthquake. For $\sigma > 0.2631$, PP suffers a phase change on reflection for all distances and for all focal depths. For $\sigma < 0.2631$, the situation is complicated but Table 2 of that earlier paper justifies the following remarks. For normal focal depth, and for $0.18 < \sigma < 0.25$, PP must have suffered a phase change on reflection if recorded at a distance greater than 40° or less than 4°, and must not have suffered a phase change if recorded at distances between 14° and 35°. Throughout the present paper we have assumed that $\sigma < 0.25$ and applied the above rule, for this has reduced the number of inconsistencies in PP and pP to a minimum. On the other hand, we have plotted PcP without a phase change on reflection. This is consistent with a recent paper by BATH (1954).

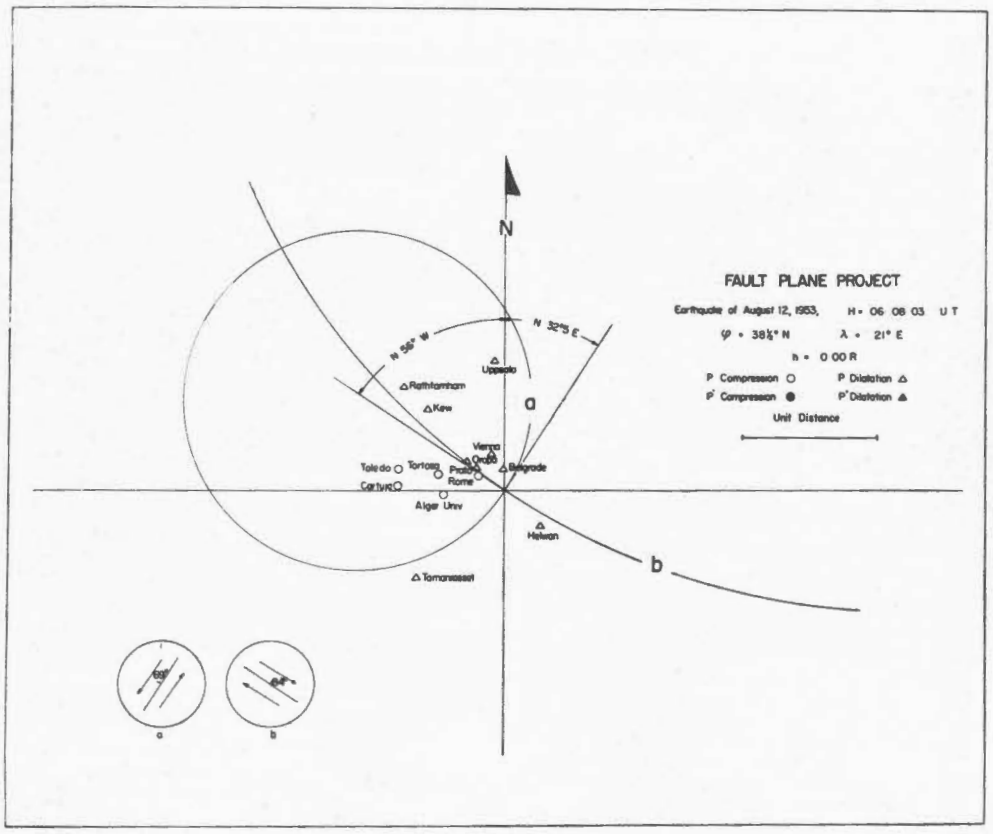

Fig. 2

There is no way of knowing which of the circles *a* or *b* represents the fault, and we must distinguish two possibilities. If circle *a* represents the fault, then the fault strikes N 89°E and dips 76° to the north. If circle *b* represents the fault, the strike is N 5° W and the dip is 73° toward the west. The two possibilities are indicated in the insert diagrams. The arrows in these diagrams indicate the direction of displacement. They are the horizontal projections of the motion vectors, displaced from the centre to make them clearly visible. Obviously, whichever circle represents the fault, the displacement is chiefly strike-slip, with a slight normal component.

Earthquake of August 11, 1953; 03:32:24.— It was mentioned in the introduction that no solution could be obtained for this earthquake because of the confused pattern. Most stations recorded compressions, the principal exceptions being those stations lying in a direction approximately N 20° W of the epicentre.

Eight stations reported a double beginning – a small initial phase followed by a very much larger phase about three seconds later. Apparently the two beginnings are being confused. The time difference of three seconds is too small to permit separation of the two earthquakes.

Earthquake of August 12, 1953; 06:08:03.— The solution shown in Fig. 2 has been carried out despite the fact that the data are few in number, because

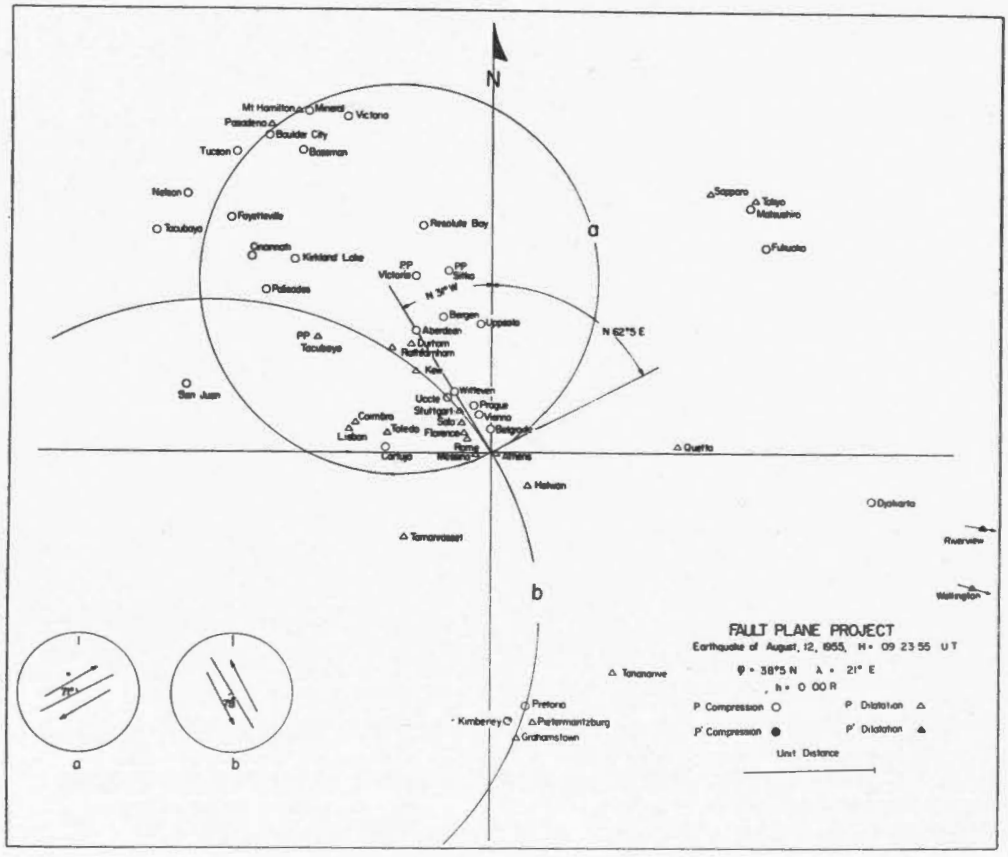

Fig. 3

it seems clear that the earthquake mechanism is different than that shown in Fig. 1.

The solution accounts for three observations of PP and one of PPP without exception, and makes four inconsistencies out of 22 observations of P. Again, as will be seen from Table 1, the inconsistencies derive principally from near stations.

The data do not limit the circles closely. The circles have been drawn

in their mean positions. Circle *a* represents a plane with a dip of $69^0 \pm 9^0$, while circle *b* represents a plane dipping $84^0 \pm 6^0$. As shown in the insert diagrams, the faulting is chiefly strike-slip, with a slight normal component.

Earthquake of August 12, 1953; 09:23:55.— This is the main earthquake of the sequence, the one which did so much damage, and the one studied by DI FILIPPO and MARCELLI. Our solution is shown in Fig. 3. It scores 20 errors out of 85 observations. These are divided as follows: 1⁻ errors out of 74 observations of P, three errors out of eight observations of PP, and no errors in two observations of P'_1 or one of PPP.

Most of the inconsistencies lie close to one or other of the circles. For

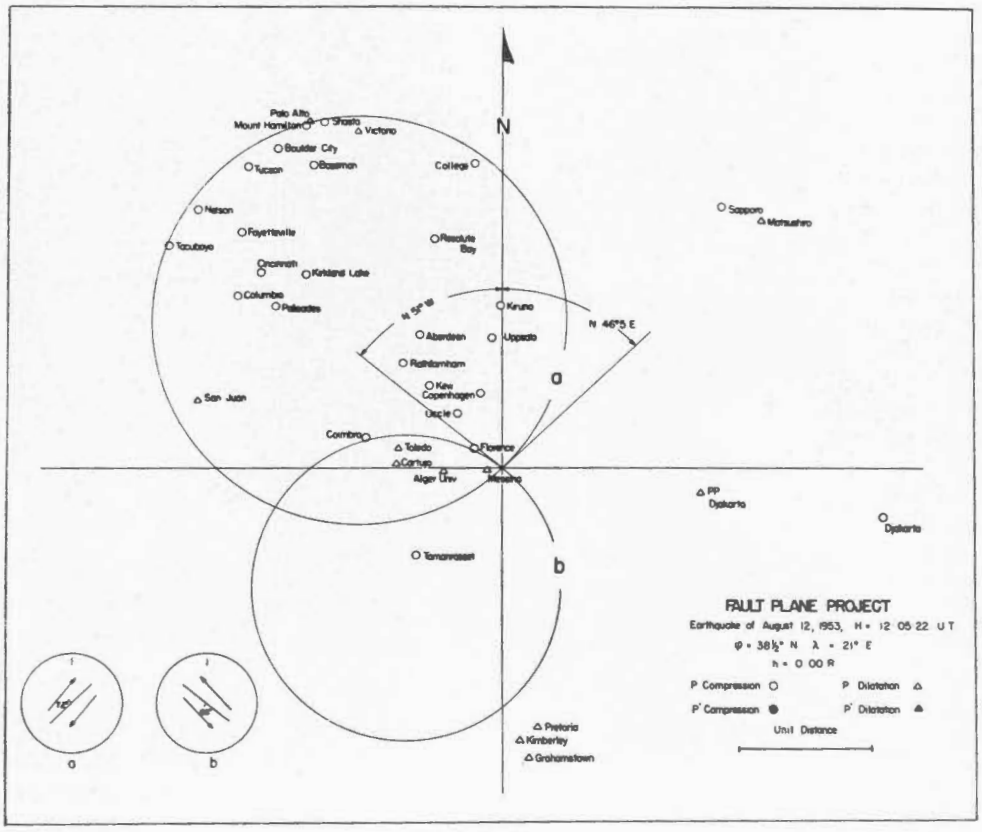

Fig. 4

example, by making circle *a* larger we could include Tacubaya, Nelson and Tucson at the expense of Pasadena and Mount Hamilton; this would only involve an increase in the dip of plane *a* of about 2°. On the other hand, by making circle *a* smaller, we might have made Cartuja and Alicante consistent. The position chosen for circle *a* represents a good compromise. Circle *b* is also in a compromise position, with the result that Uccle, Karlsruhe and Rathfarnham have been called inconsistent even though they lie very close to the line.

More serious objections are raised by the inconsistencies at Matsushiro,

TABLE 2

Comparison of the Data Published by DI FILIPPO and MARCELLI (1954) with that obtained in the Ottawa survey

STATION	Data from the Ottawa survey	Data from DI FILIPPO and MARCELLI
Athens	D	D
Reggio Calabria	D	D
Messina	D	D
Belgrade	C	D*
Rome	D	D
Trieste	D	D
Florence	D	D
Prato	(C)	D*
Bologna	(C)	D*
Vienna	C	D
Pavia	D	D
Helwan	D	D
Prague	C	C
Zurich	C	C
Chur	—	C
Neuchatel	—	C
Stuttgart	D	C
Strasbourg	—	C
Paris	—	C
Gottingen	—	C
Jena	—	C
Algeria	(C)	D
Almeria	—	D
Tortosa	—	D
Uccle	(C)	C
Alicante	(C)	D*
Cartuja	(C)	D*
Kew	D	C
Tamanrasset	(D)	C
Uppsala	C	C
Lisbon	D	D
Rathfarnham	(D)	C
Raykjavik	(D)	C
New Delhi	—	C
Kodaikanal	—	C
Ottawa	(D)	C
Palisades	C	C
Fukuoko	(C)	C
Shasta	C	C
Riverview	D'_1	C'_1

Fukuoko, Djakarta and Tamanrasset, all stations which are normally very dependable.

It has already been mentioned that DI FILIPPO and MARCELLI (1954) have made a very detailed study of this earthquake, based on the original records from a large number of stations. On page 554 of their paper they give the first motion direction of the P recorded at many of these stations. Their

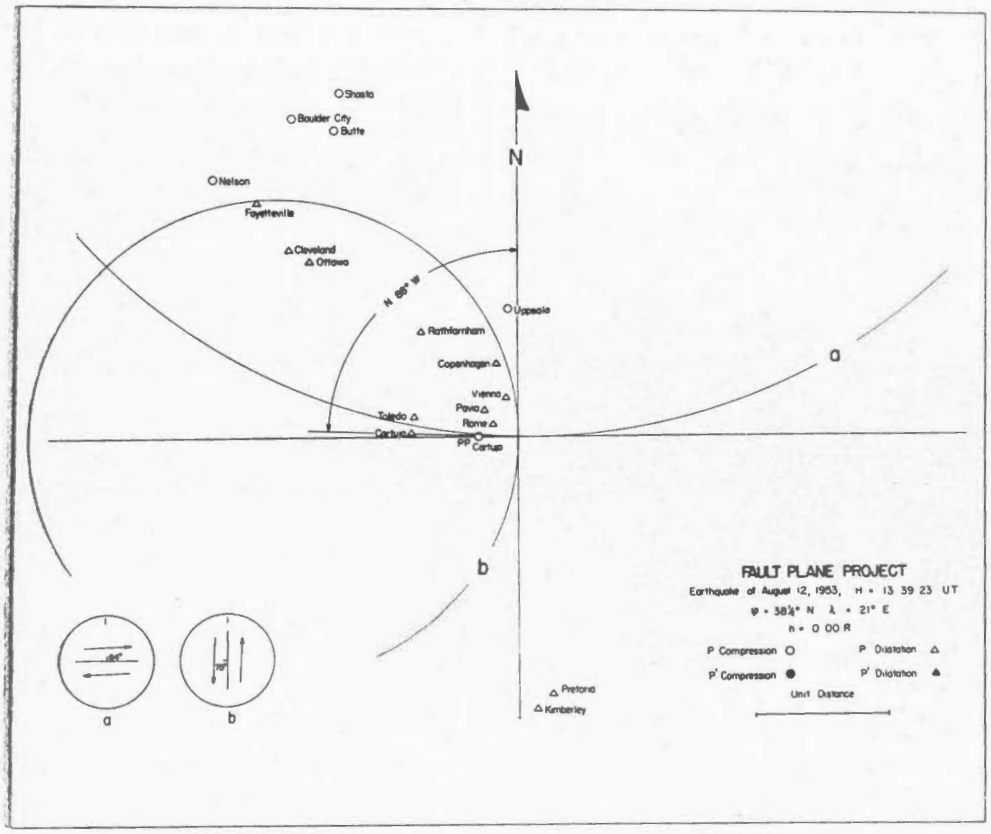

Fig. 5

data are summarized in Table 2, where they are compared with the data collected by our questionnaire. DI FILIPPO and MARCELLI did not give data for Belgrade, Prato, Bologna, Alicante or Cartuja. The observations given in Table 2 have been inferred from the map given as Fig. 2 of their paper. These observations have been indicated by an asterisk.

In comparing the data given in Table 2, the following point should be borne in mind. DI FILIPPO and MARCELLI began to collect the records shortly after the earthquake, so that many of the stations which replied to our questionnaire did not have the records available for a second reading but had to depend on the results of their preliminary reading. DI FILIPPO and MARCELLI, on the other hand, were able to study the entire group of records at one time and to compare the character of the recordings at the different stations. It

seems clear that under these circumstances their readings are likely to be the more dependable.

Table 2 lists ten stations observed by DI FILIPPO and MARCELLI and not by us. In the case of two of these stations - Kodaikanal and New Delhi - their observations are inconsistent with our solution. In the case of the remaining eight, their observations are either consistent with our solution, or lie so close to the line that they could be made consistent with a very slight shift of

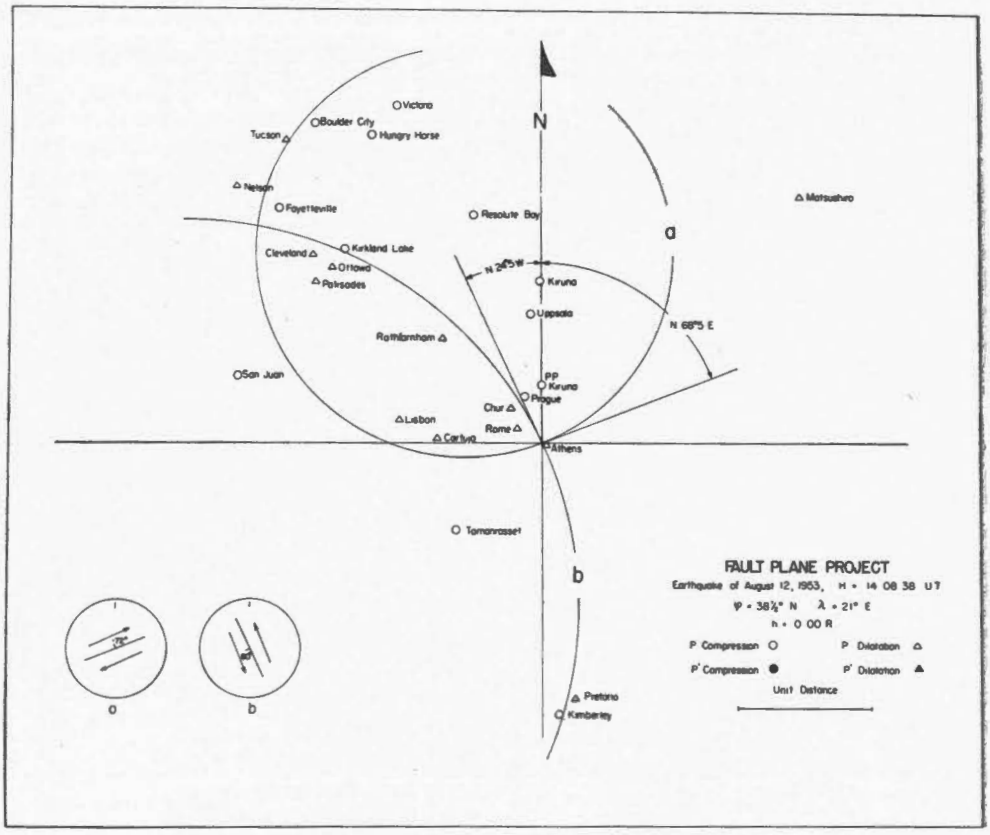

Fig. 6

it. The additional data would contribute ten additional observations with two inconsistencies.

There are thirteen cases in Table 2 where the two sets of observations differ. In three of these - Belgrade, Vienna and Riverview - their observations are inconsistent with our solution. In two other cases - Stuttgart and Kew - the stations lie so close to circle *b* as drawn that their observations cannot be said to be inconsistent with our solution. Finally it is remarkable that in eight cases - Prato, Bologna, Algeria, Alicante, Cartuja, Rathfarnham, Reykjavik and Ottawa - their observations correct inconsistencies in our solution.

We conclude that the data supplied by DI FILIPPO and MARCELLI improve the score of our solution. We would now have 84 observations of P with

14 inconsistencies in place of 74 observations with 17 inconsistencies. This reduces the percentage of inconsistencies from 23 to 17 percent.

Granted that the data published by DI FILIPPO and MARCELLI are more reliable than ours, there are many of our observations which they do not have, which would be inconsistent with their solution. For example they do not take account of the dilatations observed at Pasadena, Mount Hamilton, Sapporo, Tokyo, Tananarive, Pietermaritzburg of Grahamstown, nor of the compression recorded at Belgrade. It is probable that if the data were pooled,

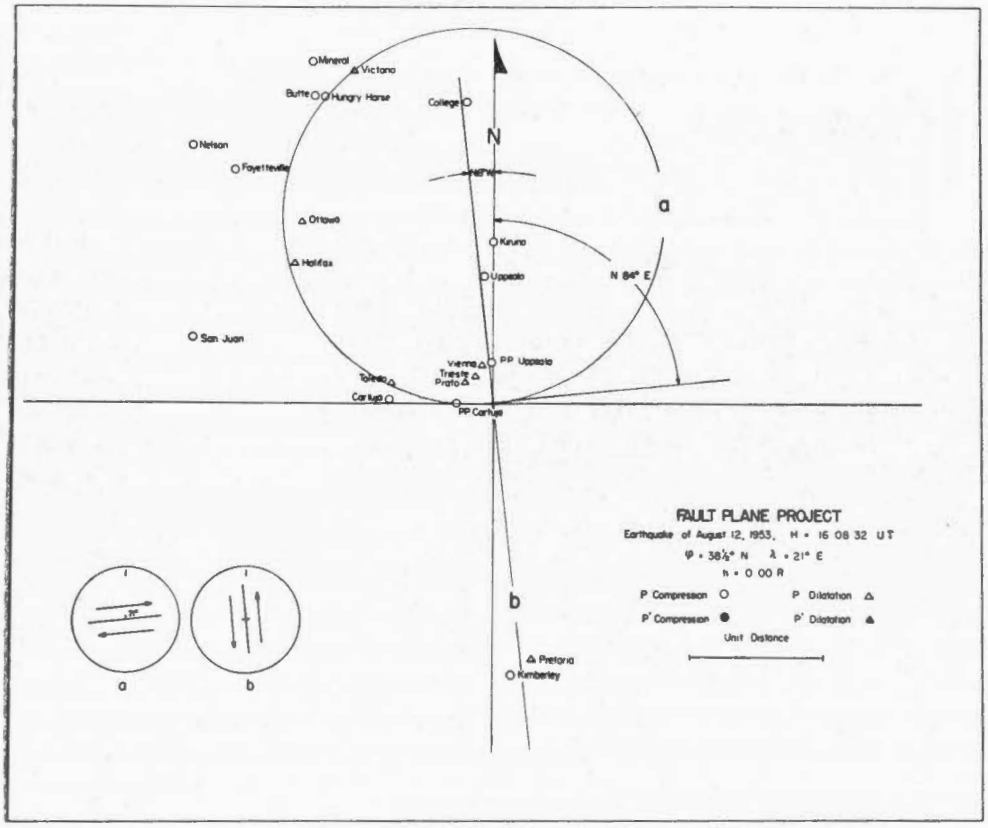

Fig. 7

their solution and ours would each score about the same percentage of inconsistencies.

Returning to Fig. 3 we note that one has to choose between a fault striking N 62°.5 E and dipping 71° to the northwest, and a fault striking N 31° W and dipping 78° to the southeast.

Earthquake of August 12, 1953; 12:05:22.— The solution for this earthquake, shown in Fig. 4, has the following score:
70 observations of P with 15 inconsistencies, five observations of PP with three inconsistencies. The solution is not very closely defined, and many of the inconsistencies lie very close to the line. For example, circle *a* might be made larger

to make Palo Alto inconsistent and Sapporo consistent, or it might be made smaller to make Victoria and San Juan consistent and College, Shasta and Mount Hamilton inconsistent. As drawn it is in a mean position, the uncertainty in the dip of plane *a* being about $\pm 5^{\circ}$. Circle *b* is fairly closely defined by Coimbra and Florence.

Earthquake of August 12, 1953; 13:39.23.— There are so few data for this earthquake that the solution, shown in Fig. 5, is presented with some dif-

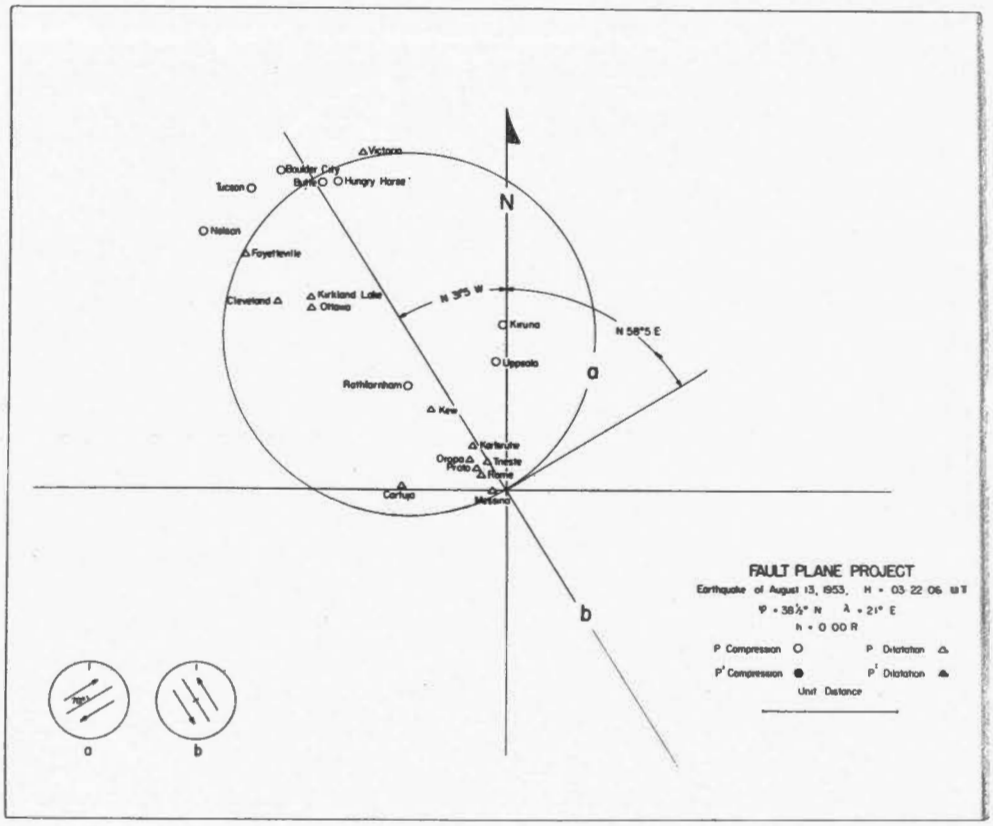

Fig. 8

fidence. The solution cannot be far from correct, and it seems desirable to obtain solutions for as many of the aftershocks as possible. There are eight inconsistent observations out of 28 observations of P, and three consistent observations of PP.

Earthquake of August 12, 1953; 14:08:38.— The solution for this earthquake is shown in Fig. 6. It accounts for 44 observations of P with 10 inconsistencies, and for three observations of PP with one inconsistency. Many of the inconsistent observations derive from stations close to the line as drawn, and many of them were qualified as questionable observations by our collaborators.

Earthquake of August 12, 1953; 16:08:32.— Again we present the solution

for an earthquake for which there are rather few data, on the grounds that the solution cannot be very far from the true one and that it contributes to our understanding of the mechanism of the aftershocks. The solution is shown in Fig. 7. It accounts for 26 observations of P with seven exceptions, and for three observations of PP without exception. The solution has been given in terms of one vertical plane; a slight variation from vertical in either direction would be tolerated by the data.

Earthquake of August 13, 1953; 03:22:06.— Again the solution, shown in Fig. 8, is in terms of one vertical plane. The solution accounts for 27 observations of P with seven inconsistencies, and for three observations of PP without inconsistencies.

DISCUSSION

To simplify this discussion the insert diagrams showing the two geological possibilities in each of the solutions have been collected together in the single diagram of Fig. 9. In examining the figure it must be borne in mind that the designation of a particular plane as *a* or *b* is purely arbitrary. There is no assurance that a plane designated *a* in one case has any relation to a plane designated *a* in another. Nevertheless, examination of Fig. 9 shows that there is a general tendency for one plane to strike somewhat north of east, and for the other to strike somewhat west of north. Indeed we may determine the following mean directions:

for plane *a* N $66^{\circ}.7 \pm 7^{\circ}.4$ E
for plane *b* N $25^{\circ}.6 \pm 7^{\circ}.4$ W

The uncertainties are standard deviations of the means.

It would appear from the low standard deviations that there is some consistency in the strike directions of planes *a* and *b*. There is almost complete consistency also in the direction of motion. With one exception, faulting on plane *a* is dextral while faulting on plane *b* is sinistral. The exception is provided by the earthquake of August 12, 06:08:03. In this earthquake the directions of motion are reversed.

Before drawing any conclusions from these facts let us consider the following remarks, taken from a letter written by Dr. A. GALANOPOULOS at the time he returned our fault-plane questionnaire.

«I am pretty sure that the first shocks of August 9 and August 11, 1953, occurred along a SSE-NNW fault (Längsbruch) separating the islands of Cephalonia and Ithaca. There are some indications * that the island of Cephalonia, i. e. the southwestern block, was moved upwards.

On the other hand, a geological consideration urges me to believe that the main earthquake of August 12, 1953, occurred along an ENE-WSW fault (Querbruch) separating the islands of Cephalonia and Zante, and that the southeastern block was moved WSW.

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* These indications have been given in detail in recent papers by GALANOPOULOS (1955) and by MÜLLER—MINY (1956).

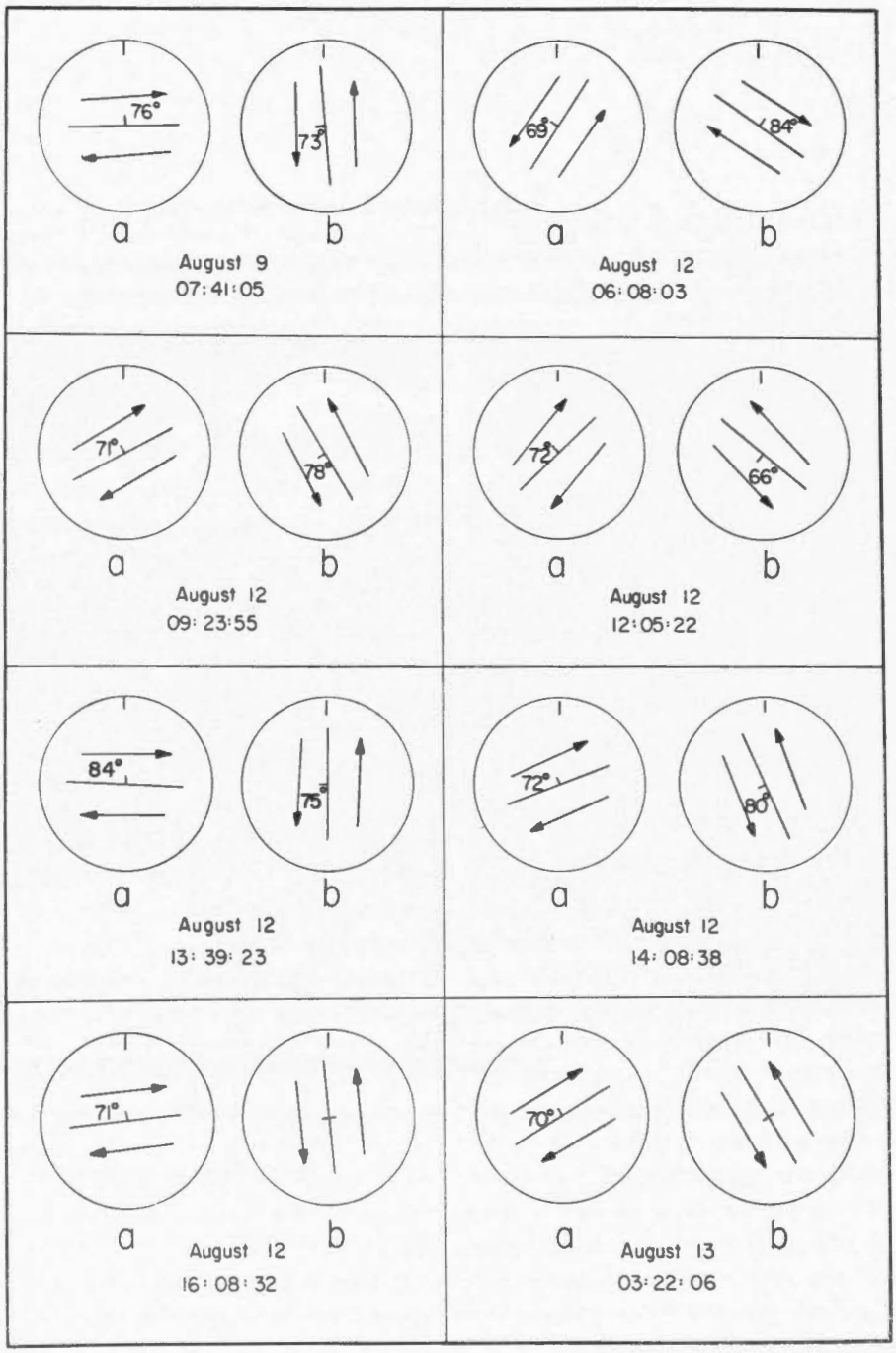

Fig. 9

Both faults are submarine; therefore there is no indication whether they are normal or reverse».

If we interpret the designation NNW exactly, the strike of the fault postulated by GALANOPOULOS for the first two earthquakes would be N 22°.5

W. We have a solution for only one of these earthquakes, that of August 9, 07:41:05. In this case the direction of plane *b*, N 5° W, was the closest to GALANOPOULOS' postulated direction, suggesting that in this case plane *b* was the fault. Similarly the direction ENE for the earthquake of August 12, 09:23:55, implies a strike direction N 67°.5 E for the fault along which the main earthquake occurred. This would compare with the direction N 62°.5 E for our plane *a*, a strong implication that in this case plane *a* represents the fault. The two directions, N 22°.5 W and N 67°.5 E, suggested by the field evidence are in even stronger agreement with our mean directions N 25°.6 W and N 66°.7 E. Without a detailed study of the shear waves, which might permit the identification of a particular plane as the fault plane, one could scarcely hope for a better correlation between the strike directions determined by the seismic methods and those found in field observations.

In the matter of direction of displacement the correlation is not so obviously satisfactory. In the earthquake of August 9 the seismic solution shows strike-slip faulting with the southwestern block dropping slightly. Field evidence suggests that this block rose, at least in certain places. This disagreement is probably not serious. ANDERSON (1942), who has made detailed studies of strike-slip faulting in Britain, finds that where the principal displacement is horizontal, the vertical displacement is apparently random, being upwards on some parts of the fault and downwards on other parts. Similar evidence is accumulating in other fault-plane studies of this Observatory. Where the faulting is chiefly strike-slip the direction of the vertical displacement is apparently random.

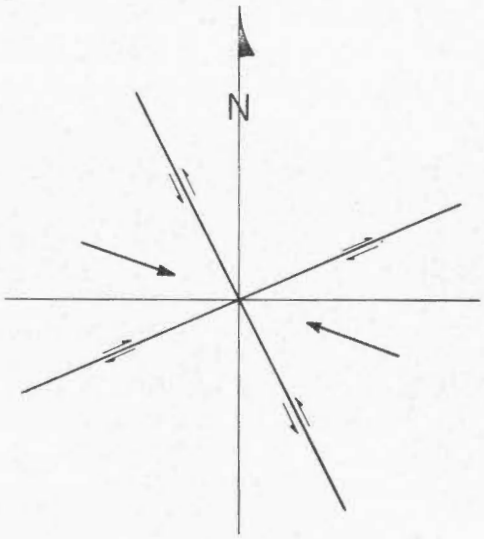

Fig. 10

In the case of the principal shock there is complete agreement on the direction of motion. GALANOPOULOS states that the southwestern block moved WSW. This is exactly what was found.

What do we learn about the relationship between the earthquakes of a sequence? Despite the consistency in the directions of planes *a* and *b*, the field results show that first one and then the other may represent the fault. In other words, they represent a conjugate system of faulting. Under ordinary theories of faulting the motivating force would be a WNW-ESE pressure, as shown in Fig. 10. The horizontal movements of all the earthquakes of the sequence, with the exception of that of August 12, 06:08:03, would be explained by this mechanism. This might suggest that the direction of pressure was consistent throughout the sequence but that occasionally the system overshot and had to recover by reverse motion.

In all of the solutions the circles have been drawn to contain compressions. It has been explained in earlier papers that this indicates that the dip component is tensional. This would be inconsistent with the compression shown in Fig. 10. The dip component is so small in this case that this is probably not a serious matter.

Finally we must raise once again the matter of the different solution obtained by DI FILIPPO and MARCELLI. It has already been pointed out that their data are more reliable than ours; indeed our solution was improved by the use of their data. The two solutions must be judged on the logic of their mechanisms and on the comparison of their results with field evidence. We leave this judgement to the reader.

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We are grateful to those many seismologists who, by completing our questionnaire, have made this study possible. We are particularly indebted to Dr. A. GALANOPOULOS who suggested the research and who has read the paper critically for us.

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DIRECTION OF FAULTING IN SOME OF THE LARGER EARTHQUAKES OF THE SOUTHWEST PACIFIC, 1950-1954

BY

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Direction of Faulting in Some of the Larger Earthquakes of the Southwest Pacific, 1950-1954

BY

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ABSTRACT

The direction of faulting is determined for 23 earthquakes occurring in the southwest Pacific during the years 1950-1954. These solutions are combined with five published earlier by Webb and two published earlier by Hodgson and Storey, to permit a study of the failure pattern in the area.

It is concluded that faulting in the southwest Pacific is principally strike-slip, on steeply dipping planes. The strike direction of the faults is not consistent nor does it show any systematic variation with latitude, depth of focus or position on the associated arcuate feature.

The solutions obtained are ambiguous in that two orthogonal planes are determined, and it is not known which of these planes represents the fault. Whichever plane represents the fault, the line of intersection of the two planes is a line uniquely determined by the solution. The line, which is here called the "null vector" appears to have great significance. For the New Hebrides earthquakes the null vectors lie closely parallel to a vertical plane striking N 22° W, that is, to a vertical plane having the direction of the associated feature. Similarly the null vectors of earthquakes associated with the Tonga-Kermadec-New Zealand feature lie nearly parallel to a vertical plane striking N 24° E, the mean direction of that feature.

The physical significance of these correlations has not yet been determined, but it seems clear that the association cannot be accidental. Under the circumstances the techniques of the fault-plane project must receive a considerable degree of confirmation.

INTRODUCTION

During the past several years this Observatory has produced a series of papers[1,2,3,4] dealing with the direction of faulting in earthquakes. The present paper will present solutions for an additional 23 earthquakes, all from the southwest Pacific. Data for these solutions derive from two sets of questionnaires, one circulated in November 1951, the other in March, 1954.

An explanation is due to our collaborators for the delay in bringing the results of the 1951 questionnaire to publication. Nine solutions were obtained as a result of this questionnaire, and these solutions were prepared for publication in summary form, without the solution diagrams and without a tabulation of the data. This was done with the thought that the method had by now been established. However, so many of the solutions represent transcurrent faulting, contrary to existing tectonophysical theories, that it was suggested that the complete solutions should be published so that critics of the method might have an opportunity of examining them. The paper which had been prepared was therefore not published. In the meantime the second questionnaire had been circulated, and it was decided to postpone publication of the first group of analyses until the second had been completed. The results of the first group, consisting of nine 1950 earthquakes, have

[1] J. H. Hodgson and W. G. Milne, "Direction of Faulting in Certain Earthquakes of the North Pacific", *Bull. Seism. Soc. Am.*, 41, 221-242, 1951.

[2] J. H. Hodgson and P. C. Bremner, "Direction of Faulting in the Ancash, Peru, Earthquake of November 10, 1946, from Teleseismic Evidence", *Bull. Seism. Soc. Am.*, 43, 121-125, 1953.

[3] J. H. Hodgson and R. S. Storey, "Direction of Faulting in some of the Larger Earthquakes of 1949", *Bull. Seism. Soc. Am.*, 44, 57-83, 1954.

[4] J. H. Hodgson, "Fault Plane Solution for the Tango, Japan, Earthquake of March 7, 1927", *Bull. Seism. Soc. Am.*, 45, 37-41, 1955.

already been included in a summary paper[5], read before the Association of Seismology of the International Union of Geodesy and Geophysics at the Rome meetings, September 1954.

It will be assumed that the reader is familiar with the methods of the research, which have been fully described in earlier papers[1,6,7,8] of the series.

[5] J. H. Hodgson, "Direction of Faulting in Pacific Earthquakes", *Geofisica Pura e Applicata*, 32, 31-42, 1955.
[6] J. H. Hodgson and R. S. Storey, "Tables Extending Byerley's Fault-Plane Techniques to Earthquakes of Any Focal Depth", *Bull. Seism. Soc. Am.*, 43, 49-61, 1953.
[7] J. H. Hodgson and J. F. J. Allen, "Tables of Extended Distances for PKP and PcP", *Publications of the Dominion Observatory*, 16, 327-348, 1954.
[8] J. H. Hodgson and J. F. J. Allen, "Tables of Extended Distances for PP and pP", *Publications of the Dominion Observatory*, 16, 349-362, 1954.

TABLE 1

LIST OF EARTHQUAKES CONSIDERED

Date	H (G.M.T.)	Epicenter		Focal Depth	Magnitude	Source
		φ	λ			
Earthquakes for which the data were too few to permit a solution						
July 23, 1950	15:50:06	16°S	165°E	0·00R	—	U.S.C. and G.S.
Sept. 10, 1950	15:16:08	15½°S	167°E	0·01R	7·1	Pasadena
Oct. 5, 1950	00:41:07	18½°S	170°E	0·00R	—	U.S.C. and G.S.
Dec. 2, 1950	19:51:49	18¼°S	167½°E	0·01R	7·7	Pasadena
Dec. 3, 1950	07:47:33	17½°S	167°E	0·00R	6·5	U.S.C. and G.S.
June 7, 1951	22:59:00	27½°S	176°W	0·00R	6·7	U.S.C. and G.S.
Aug. 13, 1953	09:23:23	21½°S	170°E	0·02R	6·8	U.S.C. and G.S.
Sept. 17, 1953	21:11:48:	20½°S	174°W	0·01R	6·8	U.S.C. and G.S.
Earthquakes for which the data were sufficient but inconsistent						
May 21, 1951	08:27:21	6°S	154½°E	0·02R	7·0	U.S.C. and G.S.
Dec. 6, 1952	10:41:14	8°S	157°E	0·00R	7·1	U.S.C. and G.S.
Feb. 26, 1953	11:42:26	11°S	164½°E	0·00R	7·2	U.S.C. and G.S.
Nov. 4, 1953	03:49:04	12½°S	166½°E	0·00R	7·3	U.S.C. and G.S.
Earthquakes for which a solution has been obtained						
May 17, 1950	18:13:13	21°S	169°E	0·00R	7·0	Pasadena
May 19A, 1950	02:38:10	20½°S	169°E	0·00R	6·8	U.S.C. and G.S.
May 19B, 1950	07:05:31	20½°S	169°E	0·00R	6·5	U.S.C. and G.S.
May 26, 1950	01:17:25	20¼°S	169¼°E	0·00R	7·1	Pasadena
May 27, 1950	12:39:43	20°S	168°E	0·03R	6·5	U.S.C. and G.S.
May 28, 1950	01:36:44	20°S	169°E	0·00R	6·5	U.S.C. and G.S.
June 21, 1950	06:55:37	20¼°S	169¼°E	0·00R	6·9	Pasadena
June 24, 1950	22:25:34	20½°S	169½°E	0·00R	7·2	Pasadena
July 17, 1950	20:17:50	20½°S	171°E	0·01R	—	U.S.C. and G.S.
July 21, 1950	20:32:01	15½°S	168½°E	0·00R	6·8	U.S.C. and G.S.
July 22, 1950	23:08:00	14°S	167°E	0·00R	—	U.S.C. and G.S.
Feb. 13, 1951	11:55:50	15°S	175°W	0·03R	7	U.S.C. and G.S.
March 23, 1951	21:38:54	31°S	180°	0·04R	7·1	U.S.C. and G.S.
Aug. 28, 1951	16:31:11	27°S	178°E	0·09R	—	U.S.C. and G.S.
Feb. 25, 1952	01:17:00	17°S	173½°W	0·00R	6·9	U.S.C. and G.S.
May 9, 1952	17:47:41	6½°S	155°E	0·01R	7·0	Pasadena
July 13, 1952	11:58:34	18½°S	169½°E	0·05R	7·0	U.S.C. and G.S.
July 27, 1952	08:23:22	20½°S	179°W	0·07R	—	U.S.C. and G.S.
Sept. 11, 1952	22:26:41	29°S	177°W	0·00R	6·8	U.S.C. and G.S.
July 2, 1953	06:56:51	18½°S	169°E	0·03	7·7	U.S.C. and G.S.
Sept. 14, 1953	00:26:36	18½°S	178½°E	0·00	6·7	U.S.C. and G.S.
Sept. 29, 1953	01:36:45	36½°S	177°E	0·04	7·2	U.S.C. and G.S.
Jan. 13, 1954	00:13:06	49°S	165°E	0·00R	7·2	U.S.C. and G.S.

PRESENTATION OF THE DATA

The epicentral data on the earthquakes considered are given in Table I. It is probable that the epicentres are not more accurate than $\pm\frac{1}{2}$ degree, nor the depths than ± 50 km. In the words of Gutenberg and Richter[9] "Location of shocks in this region has always been difficult; it is complicated by the occurrence of shocks in the whole range of shallow and intermediate focus".

It will be noted that in Table I the earthquakes are listed in three groups. For earthquakes in the first group too few data were received to make a solution possible. One of the earthquakes of this group, that of December 2, 1950, has been successfully treated by Webb[10] who worked from original records.

A second group of earthquakes listed in Table I presented sufficient but inconsistent data. Readers familiar with the earlier papers of this series will recall that most solutions have numerous inconsistent observations. These normally do not cause serious difficulty since they fall in among consistent observations in such a way that no mechanism could account for them. The four earthquakes listed in the second group of Table I had large groups of observations consistent among themselves but inconsistent with other groups. No solutions could be obtained and it appears possible that some mechanism other than failure under a couple may be active. It is perhaps significant that all the earthquakes of this group are from the Solomon Islands region.

In order that others may study the mechanism of these shocks all the first-motion data collected are given in Table II, together with distance and azimuth of each contributing station from each of the four epicentres.

The third group of earthquakes consists of those for which solutions have been obtained. These solutions are discussed in the following section; the data on which the solutions depend are given in Table III.

The notation used in Tables II and III is the same as that used in earlier papers. The letters C or D, upper or lower case, are used to indicate a recorded compression or dilatation respectively in place of the letter P in the designation of the phase. Thus a P phase recorded as a dilatation would be reported as "D", a pP_1' phase recorded as a compression would be listed as "cC_1'", and so on. This system works very well except in reporting the phase PcP, where the letter c in the phase designation is confusing. In this case the observation is reported simply by writing "PcP=" in the tables. The phase designations given in the tables are those observed at the stations; reflected phases are plotted with a phase change due to reflection.

Two of the earthquakes listed in Table I occurred on the same day, May 19, 1950. To simplify reference to these two shocks in other tables the dates have been called May 19A and May 19B.

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[9] B. Gutenberg and C. F. Richter, *Seismicity of the Earth*, (Princeton, Princeton University Press) p. 48.

[10] J. P. Webb, "A Seismological Study of the Tectonics of a Portion of the Southwest Pacific", Doctoral Dissertation, Saint Louis University, 1954.

TABLE II

Distance, Azimuth and First Motion Data for Four Solomon Islands Earthquakes

A negative sign indicates an azimuth measured west of north.

Earthquake	May 21, 1951			December 6, 1952			February 26, 1953			November 4, 1953		
Station	Dist.°	Az.°	Motion	Dist.°	Az.°	Motion	Dist.°	Az.°	Motion	Dist.°	Az.°	Motion
Aberdeen				128·4	−14·4	DD				134·7	−8·7	DD
Alger Unis				142·9	−35·8	D_1' CC	149·4	−30·2	C_1'			
Alicante	140·6	−31·6	C_1' DD	143·6	−30·5	C_1' CC	149·7	−23·8	C_1' CC	151·8	−22·0	C_1' CC
Almeria	142·8	−31·3	D_1' DD	145·8	−30·0	C_1'	151·8	−22·5	C_1' CC	153·9	−20·4	D_1' DD
Apia				31·2	103·3	D dD				21·2	95·7	C
Arcata	87·5	48·6	D dD									
Athens				128·5	−47·3	D_1'				138·3	−46·0	D_1'(?) DD(?)
Auckland				32·9	153·2	D(?) DD				25·3	164·3	C
Bandung				48·9	−92·1	cC	56·2	−90·9	D	58·2	−90·3	D
Basel	129·9	−28·8	C_1' CC				138·8	−23·8	D_1'	140·9	−22·8	C_1'(?) CC
Belgrade				127·5	−38·1	D_1'	134·4	−35·8	C_1'	136·8	−35·5	C_1'
Berkeley	88·3	51·8	C cC	87·6	51·4	C	83·8	49·7	C	83·3	49·0	C
Bermuda-Columbia							130·1	56·9	CC	129·3	58·4	C_1' CC
Bogota	131·6	89·2	DD	129·2	90·6	C_1'						
Bombay	84·1	−70·3	D	87·1	−70·6	C						
Bozeman							94·0	44·4	C			
Brisbane	21·4	−176·4	C(?)	19·7	−169·5	D	19·6	−148·2	D	19·5	−141·6	D DD
Budapest	123·9	−35·0	DD(?)				133·5	−32·0	D_1'(?) CC	135·8	−31·6	D_1' CC
Butte							93·0	43·8	D(?)	92·8	43·6	C
Calcutta	70·6	−63·7	C	73·7	−63·8	C	81·7	−65·1	C			
Cartuja	143·1	−29·8	C_1' DD cC_1'	146·1	−28·4	C_1' DD cC_1'	151·9	−20·4	D_1'	153·9	−18·2	C_1'
Chicago							110·6	49·5	DD			
Chinchina										118·3	91·1	DD
Christchurch	40·6	159·7	D	37·9	161·4	C	33·1	169·2	D	31·3	171·4	C
Cincinnati	117·6	48·8	C_1' dD_1'	117·1	50·1	DD(?)				112·5	52·7	D(?)
Cleveland							115·2	49·4	DD			

TABLE II—*Continued*

Distance, Azimuth and First Motion Data for Four Solomon Islands Earthquakes—*Continued*

A negative sign indicates an azimuth measured west of north.

Earthquake	May 21, 1951			December 6, 1952			February 26, 1953			November 4, 1953		
Station	Dist.°	Az.°	Motion	Dist.°	Az.°	Motion	Dist.°	Az.°	Motion	Dist.°	Az.°	Motion
Cobb River	38·5	157·7	C	35·7	159·5	C				28·9	170·2	C
Coimbra							150·3	−11·0	D_1'			
College	82·4	21·2	D	83·4	20·7	D						
Collmberg	124·7	−28·4	C_1'	127·7	−27·8	D_1' CC				135·8	−23·7	D_1' DD
Copenhagen	122·0	−24·3	C_1'	124·9	−23·6	C_1	130·4	−20·4	D_1'	132·5	−19·6	D_1' CC
De Bilt			CC									
Djakarta				49·8	−91·2	C dD dDD	57·2	−90·2	C DD	59·1	−89·7	D CC
Firenze										142·3	−29·8	C_1'
Fresno	90·1	53·2	C	89·4	52·9	C	85·4	51·3	C	84·8	50·7	C
Fukuoko	45·6	−28·5	C	48·5	−30·0	D	55·0	−34·9	D	57·4	−35·8	C
Halifax										126·8	43·2	D_1'
Helwan				124·8	−59·3	D_1'				135·1	−60·2	D_1'
Hiroshima										56·8	−33·6	C
Hong Kong				51·7	−53·4	C	59·5	−55·9	D	61·9	−56·2	C
Honolulu	54·1	58·4	C	53·1	55·8	C	49·0	49·0	D			
Hungry Horse	95·4	42·1	C cC				92·6	41·3	C	92·4	41·0	D
Hyderabad	78·6	−70·9	C	81·6	−71·0	C	89·6	−72·2	C	91·9	−72·7	C
Karapiro				34·1	153·4	C DD	28·5	161·5	C DD	26·5	163·8	D
Karlsruhe	128·5	−28·0	D_1 DD	131·4	−27·2	C_1' CC	137·3	−23·2	CC	139·4	−22·2	D_1' DD
Kew				132·8	−19·2	C_1'						
Kiamata	39·3	160·1	D	36·6	162·0	D	31·9	170·3	D	30·1	172·8	C cC CC
Kiruna				113·7	−16·5	C_1'						
Kobe										55·6	−31·3	C
Kochi				47·0	−27·0	D	53·3	−32·4	D			
Kodaikanal	78·4	−78·3	C	81·2	−78·3	D	89·1	−79·5	C	91·3	−79·9	C
La Paz				129·1	118·8	C_1' CC	121·2	117·0	D_1' DD	118·7	116·8	C_1' CC
Lincoln				107·6	49·8	CC				103·3	50·7	C
Lisbon				147·0	−20·1	C_1'	151·9	−10·6	C_1'			

TABLE II—*Continued*

Distance, Azimuth and First Motion Data for Four Solomon Islands Earthquakes—*Continued*

A negative sign indicates an azimuth measured west of north.

Earthquake	May 21, 1951			December 6, 1952			February 26, 1953			November 4, 1953		
Station	Dist.°	Az.°	Motion	Dist.°	Az.°	Motion	Dist.°	Az.°	Motion	Dist.°	Az.°	Motion
Malaga	143·9	−29·4	D_1' DD	146·8	−27·9	C_1'						
Manilla				42·2	−57·9	D	50·1	−60·4	D	52·5	−60·5	D
Matsushiro				47·7	−20·5	C				55·7	−27·5	C
Messina				134·1	−43·1	C_1'						
Mineral	89·2	49·5	C				85·1	47·5	C	84·7	46·8	C
Mount Hamilton	88·8	52·4	C cC DD	88·0	52·0	C CC	84·1	50·3	C CC	83·6	49·7	C
Mount Wilson	91·3	55·9	C									
Nemuro										58·8	−17·7	C
New Delhi				85·0	−60·3	D						
New Plymouth				34·5	156·2	D CC	29·2	164·6	D CC	27·2	167·1	D
Osaka										55·4	−31·1	C
Ottawa	121·5	39·4	C_1'	121·4	41·1	D_1'				118·3	45·1	CC
Palomar	92·1	56·9	C				86·7	55·3	C			
Pasadena	91·1	56·0	C	90·2	55·7	C	85·9	54·2	C	85·2	53·6	C
Pierce Ferry	94·7	54·3	C									
Prague				127·8	−29·7	D_1'	133·9	−26·5	CC	136·2	−25·8	C_1'
Pretoria				120·0	−125·8	C_1'						
Quetta				94·0	−60·2	C						
Rathfarnham				132·9	−13·6	C_1'	137·2	−8·1	C_1'	138·9	−6·6	C_1' CC
Reno	90·5	50·5	C	89·9	50·2	C DD	86·2	48·7	C	85·7	48·1	C PcP=C
Resolute Bay	101·2	14·7	C dD DD	102·5	15·0	C CC						
Reykjavik	122	−1·9	D_1'									
Riverside	91·8	56·2	C	90·8	55·9	D	86·5	54·5	C	85·8	54·0	C
Riverview	27·8	−174·0	C cC	26·2	−169·0	D CC	25·7	−153·8	D dD PcP=D	25·3	−149·1	C cC
Rome	130·9	−37·4	C_1'	134·0	−37·0	C_1'						
Salt Lake City							92·4	49·1	DD			
San Juan	138·6	69·1	C_1'	136·9	71·8	C_1'(?)						
Santa Clara	88·5	52·4	C dD	87·8	52·0	D	83·9	50·2	D	83·4	49·6	C

TABLE II—*Concluded*

Distance, Azimuth and First Motion Data for Four Solomon Islands Earthquakes—*Concluded*

A negative sign indicates an azimuth measured west of north.

Earthquake	May 21, 1951			December 6, 1952			February 26, 1953			November 4, 1953		
Station	Dist.°	Az.°	Motion	Dist.°	Az.°	Motion	Dist.°	Az.°	Motion	Dist.°	Az.°	Motion
Sapporo							57·9	−19·9	C PcP=C	60·0	−21·1	C
Saskatoon				100·2	38·5	C						
Scoresby-Sund	115·6	−1·3	CC									
Seattle	89·8	42·2	C									
Sendai	45·9	−14·9	D	48·5	−17·0	C	53·8	−23·0	C	56·0	−24·2	D
Seven Falls										121·2	42·2	D_1'
Shasta	88·7	49·0	C dD									
Sitka	84·4	31·1	D dD									
Stuttgart	128·3	−28·7	C_1'(?)									
Suva										12·8	117·1	D
Tamanrasset	145·8	−57·7	D_1' CC									
Tananarive							111·1	−115·3	C_1'(?)			
Tinemaha	91·4	53·0	C				86·6	51·4	C	86·0	50·8	C
Tokyo	43·8	−17·4	C	46·4	−19·4	C(?)	52·0	−25·6	C(?)	54·3	−26·8	C DD
Trieste				131·0	−33·8	C_1' CC(?)				139·7	−29·8	C_1'(?)
Tuai	38·5	151·1	C	35·6	152·5	C						
Tucson	97·1	58·3	C dD				91·4	57·6	C	90·5	57·2	C
Uccle										139·2	−17·3	D_1'
Ukiah				87·2	50·0	D						
Uppsala	117·2	−22·8	CC	120·0	−22·3	DD						
Victoria							86·7	39·3	D	86·6	38·8	D DD
Wellington	39·5	155·8	D	36·7	157·4	D	31·4	165·1	D	29·5	167·3	D
Weston							122·5	46·6	D_1'	122·0	47·7	D_1'
Witteveen				129·3	−22·8	D_1'						
Zurich				132·5	−28·9	C_1'(?)				140·7	−23·8	D_1'(?)

TABLE III

Data on which the Solutions are Based

STATION	May 17, 1950	May 19A, 1950	May 19B, 1950	May 26, 1950	May 27, 1950	May 28, 1950	June 21, 1950	June 24, 1950	July 17, 1950	July 21, 1950	July 22, 1950	Feb. 13, 1951	March 23, 1951	August 28, 1951	Feb. 25, 1952	May 9, 1952	July 13, 1952	July 27, 1952	Sept. 11, 1952	July 2, 1953	Sept. 14, 1953	Sept. 29, 1953	Jan. 13, 1954
Aberdeen	—	(D_1') CC	—	(D_1')	—	—	(D_1')	(D_1')	—	—	—	(dD_1')	—	—	CC	—	—	DD	—	—	(D_1')	C_1' dD_1' DD	DD
Algers Univ.	(D_1') D_2' CC	D_2'	—	DD	—	—	—	C_1' DD	C_2'	(D_1') (CC)	(D_1') (D_2')	eC_1'	—	(D_1') (C_2')	D_1' (DD)	—	C_1' CC	D_1' (DD)	(D_1')	—	—	—	—
Alicante	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	C_1'	C_1' DD	D_1' (DD)	(D_1') CC	—
Almeria	C_1'	D_1'	—	—	—	—	—	—	—	—	—	D_1'	D_1'	D_1'	—	(D_1')	C_1'	C_1'	C_1'	C_1'	(C_1')	C_1'	—
Apia	D	—	—	—	—	D	—	—	—	D	—	(D)	C	—	D	—	(D)	(C)	—	C	C	C	—
Arapuni	C (CC)	(D)	—	C DD	—	(D)	C	—	(C)	C	—	—	—	—	—	—	—	—	—	—	—	—	—
Arcata	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	(C)	—	—	—	—	—	—	—
Athens	C_1'	D_1'	—	C_1'	—	—	—	C_1'	—	—	—	—	(D_1')	—	C_1' C_2'	C_1' (eC_1')	C_1'	—	—	C_1'	D_1'	(C_1')	C_1'
Auckland	C	C	C	—	D	C	C	C	D	C	(D)	—	D	(C)	D	D	D	—	C	D dD	D	D	—
Basel	C_1'	(D_1')	—	C_1' (DD)	(D_1')	D_1'	—	—	C_1'	C_1' CC	—	D_1' eC_1'	D_1' C_2'	C_1'	C_1' CC	C_1' (CC)	C_1'	D_1'	C_1'	C_1' eC_1'	D_1' (DD)	(D_1') eC_1'	C_1' D_2' (DD)
Belgrade	C'	(C_1')	—	(D_1')	—	D_1'	C_1'	C_1'	—	(D_1')	—	—	C_1'	—	—	—	(D_1')	(C_1')	C_1'	(D_1')	D_1'	D_1'	—
Berkeley	C	D	D	C	C	(C)	C	C	C	(D)	D	D	D	—	—	D	C CC	C eC	C	C DD eC	—	C dD	CC
Bermuda	—	—	—	CC	—	—	(CC)	(CC)	—	CC	—	—	—	—	—	C_1'	—	—	—	C_1' (CC)	—	C_1' CC	D_1' CC
Besançon	—	—	—	—	—	—	—	—	—	—	—	(dD_1')	—	—	—	—	—	—	—	—	—	—	—
Bidston	—	—	—	—	—	—	—	—	—	—	—	—	—	—	C_1'	C_1'	—	—	—	—	—	—	—
Bogota	—	DD	—	DD	—	—	—	(CC)	—	(CC)	—	—	—	—	(C)	C_1'	—	—	—	C_1'	—	(DD)	—
Bologna	C_1'	C_1'	—	C_1'	—	—	C_1'	C_1'	C_1'	(D_1')	—	—	—	—	(D_2')	C_1'	—	—	—	—	—	—	—

Bombay	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	(C_1')	—	—	—	(C_1')	—
Boulder City	C	C	C	C	C	D	C	C	C	C	—	—	—	—	—	—	—	—	—	—	—	—	—
Bozeman	—	—	—	—	—	—	—	—	—	(D)	—	—	—	—	—	—	C	C	—	(D)	C	C	—
Brisbane	D	—	D	D	(D)	D (DD)	D	—	D	C	C	—	D	C	C	(D)	—	D	C	D	C	D	C
Budapest	C_1'	D_1'	—	C_1'	—	D_1'	(D_1')	(D_1')	—	—	—	D_1'	—	—	C_1' (D_2')	—	—	(C_1')	—	—	D_1'	D_1'	D_2'
Butte	—	—	—	—	—	—	—	—	—	—	—	—	—	(dD)	C	—	C	C	(D)	C	D	—	—
Calcutta	—	—	—	—	—	—	—	—	—	—	—	—	—	—	(CC)	C	—	—	—	C	—	—	—
Cartuja	C_1' CC	DD	—	(D_1') CC	(D_1') DD	—	(D_1') DD	(D_1') (DD)	(D_1') CC	C_1' CC	D_1' DD	C_1' (DD) eC_1'	D_1' D_2' (DD) eC_1'	—	—	C_1' DD dD_1'	C_1' (DD) dD_1'	C_1' CC (eC_1')	D_1' C_2'	(D_1') C_2' (dD_1') (CC)	D_1' (C_2') CC	C_1' (D_2') eC_1' (eC_2') DD	—
Cheb	—	—	—	—	—	—	—	—	—	—	—	D_1'	—	—	—	—	(D_1') dD_1'	—	—	—	D_1' (C_1')	—	—
Chicago-Loyola	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	DD	—	—	—	—	—	—
Chicago-U.S.C.G.S.	—	—	—	—	—	—	—	C_1'	—	—	—	—	—	—	—	—	DD	C CC	—	—	—	DD	—
China Lake	—	—	—	—	—	D	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Chinchina	—	—	—	—	—	—	—	—	—	—	—	C	CC	—	DD	C_1'	—	—	—	—	—	—	—
Christchurch	C	—	C (CC)	C	C	C	C	C	D (DD)	C CC	—	D	C	C	—	C	D	—	—	(C)	D	C	C
Chur	—	—	—	—	—	—	—	—	—	—	—	D_1'	—	—	—	C_1'	C_1'	D_1'	—	C_1'	D_1'	—	—
Cincinnati	—	—	—	—	—	(C)	—	—	—	C CC	—	C (dD)	D_1'	—	D	CC	—	C	(CC)	C DD eC	—	(D_1') eC_1'	—
Cleveland	(D) C_1'	—	—	C CC (D_1')	—	—	CC	C_1' CC	—	CC	(DD)	C	D_1' dD	—	—	(D_1')	C_1'	—	—	C (D_1')	DD	C_1' DD eC_1'	—
Cobb River	C	(D)	—	—	—	—	(D)	—	(C)	(D) CC	—	D	C	C	(C)	C	D	C	—	D	(C)	C	C
Coimbra	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	C_1' (D_2')	—	D_1' (CC)	—
College	C	C	D	D	(D)	D	C	D	D	D	D	(C)	C	D (dD)	D	—	D	D	D	—	—	—	—
Collmberg	—	—	—	—	—	—	—	—	—	—	—	D_1' (C_2')	C_1' DD eC_1'	D_1' D_2' eC_1'	—	C_1' DD	(D_1') (DD)	—	(C_2')	C_1' DD	D_1' D_2' (DD)	C_1' DD	C_1' C_2' CC

TABLE III—*Continued*

Data on which the Solutions are Based

STATION	May 17, 1950	May 19A, 1950	May 19B, 1950	May 26, 1950	May 27, 1950	May 28, 1950	June 21, 1950	June 24, 1950	July 17, 1950	July 21, 1950	July 22, 1950	Feb. 13, 1951	March 23, 1951	August 28, 1951	Feb. 25, 1952	May 9, 1952	July 13, 1952	July 27, 1952	Sept. 11, 1952	July 2, 1953	Sept. 14, 1953	Sept. 29, 1953	Jan. 13, 1954
Colombo	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	C	—	—	D	—	—	—
Copenhagen	(D_1')	(D_1')	CC	C_1'	(D_1')	—	—	—	C_1	—	—	D_1'	C_1' C_2' (CC)	—	—	—	—	D_1'	—	—	C_1' eC_1'	(D_2')	—
De Bilt	C_1' CC	C_1' CC	C_1'	C_1' CC	C_1'	D_1'	C_1'	C_1' CC	—	(D_1')	(C_1')	D_1' (dD_1')	—	—	—	—	—	—	—	—	—	—	—
Djakarta	—	—	—	—	—	—	—	—	C	—	—	—	—	—	—	C	—	D	—	D DD dD	(D)	C CC eC	D CC
Fayetteville	—	—	—	—	—	—	—	—	—	—	—	—	—	—	C	—	—	C	—	C	—	—	—
Finger Bay	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	D	—	—	—	—
Florence	—	—	—	—	—	—	—	—	—	—	—	D_1'	—	—	C_1'	—	—	—	(D_1')	—	(C_1') (dD_1')	C_1' CC dD_1'	—
Fresno	—	—	—	—	—	—	—	—	—	—	—	(C)	D	C eC	C	C	C	C	C dD	C DD	—	—	—
Fukuoko	C	—	—	C	—	—	D	C	—	—	—	C	—	—	—	D	(C)	—	—	C	—	C	C
Grahamstown	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	(C_1')	—	—	C
Halifax	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	C_1'	C_1' eC_1'	—	C_1'	D_1'
Harvard	C_1'	C_1' CC	CC	C (D_1')	C_1'	D_1' (DD)	C_1' CC	C_1' DD	—	CC	—	—	—	—	—	C_1'	—	—	—	—	—	—	—
Helwan	—	—	—	C_1'	—	—	C_1'	C_1'	D_1'	(D_1')		C_1'	—	—	(D_1')	—	—	(C_1')	—	C_1'	—	—	—
Hiroshima	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	C	—	—	—
Hong Kong	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	C	—	—	—	C	—	(C) (dD) CC	—
Honolulu	(C)	(C)	—	D	—	—	—	(C)	—	(C)	—	D	C	—	D	D	D	D	D	C	—	C	—

Hungry Horse	C	C	—	C	—	—	—	(D)	(D)	C	—	D	D	—	C	—	C	(D)	—	C	(C)	—	—
Hyderabad	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	(D)	—	—	—	—	(C)	CC
Ivigtut	(D_1')	D_1'	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Kalocsa	(D_1')	—	—	—	—	—	—	(D_1')	—	—	—	—	—	—	—	C'	—	(C_1')	—	—	—	—	—
Karapiro	—	—	—	—	—	—	—	—	—	—	—	—	—	D	D	(C)	—	(D)	C	D	D (DD)	C	C
Karlsruhe	—	—	—	C_1'	—	D_1'	C_1'	—	—	—	—	D_1' dD_1'	D_1'	—	(D_1') CC	(eC_1')	(D_1') CC	—	—	C_1' eC_1'	D_1' (dD_1')	(D_1') C_2'	(D_1') D_2' CC
Kecskemet	—	—	—	—	—	—	C_1' CC	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Kew	C_1'	C_1'	(D_1') DD	C_1' CC	(D_1')	D_1'	—	C_1' (DD)	—	D_1'	—	—	—	—	C_1'	—	C_1'	—	—	—	C_1'	—	—
Kiamata	(D)	C	C	(D)	—	—	—	C	D	C	—	D	C	C	D	(D)	D	D	D	D	D	—	C
Kimberley	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	C_1'	C_1'	—	—	(C_1')	—	—	—
Kirkland Lake	—	—	—	—	—	—	—	—	—	—	—				D_1'	(D_1')	(D_1')	(DD)				C_1'	C_1'
Kiruna	—	—	—	—	—	—	—	—	—	—	—	—	—	CC	C_1' CC	C_1'	CC	—	—	C_1'	—	C_1'	C_1'
Kodaikanal	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	D	—	—	—
Koti	C	—	—	(D)	—	—	D	C	—	C	—	—	—	—	—	D	—	D	—	C	—	(D)	—
Ksara	C_1'	D_1' (DD)	D_1'	(D_1') CC	D_1'	C_1' CC	C_1'	C_1'	D_1'	(D_1')	CC	—	—	—	C_1'	—	—	—	—	—	—	—	—
La Paz	(CC)	C (CC)	C (CC)	C DD	D CC	(DD)	(D) (CC)	C (CC)	—	C (CC)	—	—	D (DD)	—	(DD)	(D_1')	—	(CC)	—	C CC	C DD	(C) CC	CC
La Plata	—	—	—	—	—	—		—	—	—	—	—	CC	—	—	—	—	—	—	D_1'	—	—	PcP=C
Lincoln	—	—	—	—	—	—	—	—	—	—	—	C	—	—	—	—	C	—	—	—	—	—	—
Lisbon	C_1' CC	—	—	C_1' CC	—	—	C_1' CC	C_1' CC	—	—	—	—	D_1' D_2'	—	D_1'	C_1' (D_2')	—	—	—	C_1' (D_2') (dD_1') eC_2'	C_1' D_2'	C_1' D_2' eC_1' (dD_2')	C_2'
Lwiro	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	C_1' CC
Malaga	—	—	—	—	—	—	—	—	—	—	—	C_1' CC	—	(C_1') (C_2')	D_1' CC	C_1' DD	(D_1')	C_1' CC	D_1' DD	—	—	—	—
Manilla	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	(D)	D	—	(D)	C	D	—
Matsushiro	—	—	—	—	—	—	—	—	—	—	—	—	—	—	D	(C)	D DD	DD	—	C	C	C	C DD

TABLE III—*Continued*

Data on which the Solutions are Based

STATION	May 17, 1950	May 19A, 1950	May 19B, 1950	May 26, 1950	May 27, 1950	May 28, 1950	June 21, 1950	June 24, 1950	July 17, 1950	July 21 1950	July 22, 1950	Feb. 13, 1951	March 23, 1951	August 28, 1951	Feb. 25, 1952	May 9, 1952	July 13, 1952	July 27, 1952	Sept. 11, 1952	July 2, 1953	Sept. 14, 1953	Sept. 29, 1953	Jan. 13, 1954
Messina	C_1'	—	—	C_1'	—	—	—	C_1'	—	—	C_1'	—	—	—	(D_1')	—	—	—	—	C_1'	—	—	—
Mineral	—	—	—	—	—	—	—	—	—	—	—	D	(C)	D	—	—	C DD (eC)	C eC	C dD	C DD	D	C	CC
Mount Hamilton	C	D	C	C	C	D	C	C	C	C CC	D	D (DD)	D	C eC	C	C	C (CC)	C (dD)	(D) dD	C DD eC	C	C	—
Mount Wilson	—	—	—	—	—	—	—	—	—	—	—	D	D	C	C	C	C	C		C	—	C	—
Nagoya	C	—	—	C	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Nemuro	—	—	—	—	—	—	—		—	—	—	—	—	—	—	—	—	D	—	—	—	—	—
New Plymouth	C	C	—	—	—	—	—	—	—	(D)	—	D	D	(D)	—	D	C	D	—	(C)	(C)	—	C
New York C.C.	—	—	—	—	—	—	D_1'	(D_1')	—	(DD)	—	—	—	—	—	—	—	—	—	—	—	—	—
Osaka	C	—	—	—	—	C	C	C	—	—	C	—	—	—	—	—	—	—	—	—	—	—	—
Ottawa	C_1'	—	—	—	—	—	C_1' CC	C_1' CC	—	—	—	D_1'	—	eC_1'	—	—	C_1' CC	—	—	C_1'	—	—	C_1'
Palo Alto	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	C		(D)	—
Palomar	—	—	—	—	—	—	—	—	—	—	—	D	D	C	C	—	C	C	—	C	—	C	—
Paris	(D_1')	(D_1')	—	(D_1') (DD)	(D_1')	(C_1') CC	(D_1') CC	C_1' (DD)	(D_1')	(D_1')	D_1'	—	—	—	—	—	—	—	—	—	—	—	—
Pasadena	C	C	C	C	C	—	C	C	C	C		D	D	C	C	C	C DD	C	C	C	(D)	C eC	—
Pavia	C_1'	—	—	(D_1') D_2'	—	D_1'	(D_1')	C_1'	C_1'	C_1'	—	(C_1') eC_1'	C_2'	—	(D_1') (D_2')	C_1'	—	—	—	C_1'	—	eC_1'	—
Perth	—	(C)	—	(C) CC	—	—	(C)	(C)	—	—	—	—	—	—	—	—	—	—	—	—	—	—	D (DD) PcP=C
Philadelphia	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	(CC)	—	—	—	—	DD	—
Pierce Ferry	—	—	—	—	—	—	—	—	—	—	—	(C)	D	(D)	(D)	—	—	—	—	—	—	—	—

Prague	—	C_1'	C_1'	C_1'	—	—	C_1'	C_1'	—	—	—	D_1'	C_1' (D_2')	—	C_1'	D_1' (eC_1')	C_1'	D_1' D_2'	D_2'	C_1'	D_1'	C_1' C_2' DD eC_1' eC_2'	—
Prato	(D_1')	—	—	C_1'	—	—	(D_1')	(D_1')	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Pretoria	—	—	—	—	—	—	—	—	C_1'	—	—	—	—	—	—	—	(D_1')	—	—	—	—	—	—
Quetta	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	C_1'	—	—	—
Rapid City	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	C	C	—	—
Rathfarnham	C_1'	C_1'	—	C_1' CC	C_1'	(C_1')	C_1'	C_1'	—	D_1'	—	—	D_1' (D_2')	D_1'	—	—	C_1'	—	C_1'	C_1' eC_1'	C_1' (DD)	(D_1')	—
Reno	—	—	—	—	—	—	—	—	—	—	—	D	—	—	—	C	C DD	C CC	C eC	C	—	—	—
Resolute Bay	—	—	—	—	—	—	—	—	—	—	—	D CC	(C_1') (CC)	—	C DD eC	D dD	—	—	—	C C_1'	—	(D_1')	C_1'
Reykjavik	—	—	—	—	—	—	—	—	—	—	—	—	D_1'	—	—	—	C_1' CC	—	—	—	—	C_1'	—
Riverside	—	—	—	—	—	—	—	—	—	—	—	D	D	C	C	C	C	C	—	C	C	C	—
Riverview	D (DD)	D CC	D DDD	D DD (dD)	C	C DD	D CC	D CC	D CC dD	C (dD)	C	D CC eC	D (DD) eC	—	C (eC)	C	C DD dD	D (dD)	C (CC) DD	D eC	D (DD) eC	D eC	(D) (eC)
Rome	—	C_1' CC	C_1'	C_1' (DD)	D_1'	D_1' DD	C_1' (DD)	C_1'	C_1'	C_1'	C_1'	—	—	—	C_1'	C_1'	C_1'	—	—	C_1'	—	—	—
Salo	C_1'	C_1'	—	C_1'	C_1'	—	—	—	—	—	—	D_1'	—	—	—	—	—	—	—	—	—	eC_1'	—
Salt Lake City	—	—	—	—	—	—	—	—	—	—	—	—	—	—	C	—	C	—	—	C	C	—	—
San Juan	—	—	DD	—	—	CC	CC	(D_1') DD	—	C_1'	—	—	(C_1')	C_1'	—	—	C_1'	C_1' (CC)	—	C_1'	—	(C_1')	—
Santa Clara	(D)	(C)	—	C CC	—	—	(D)	(D)	—	C	(C)	(C)	(C)	—	—	—	(D)	(D)	C	—	D	—	—
Sapporo	—	—	—	—	—	—	—	—	—	—	—	—	C	(C)	—	—	D	D	D	C CC eC	C PcP=D	C	—
Saskatoon	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	C	—	—	—
Scoresby Sund	—	—	—	—	—	—	—	—	—	—	—	CC	DD	—	—	—	—	—	—	—	—	—	—
Seattle	—	—	—	—	—	—	—	—	—	D	—	D	D	D	—	—	C	—	—	—	—	—	—
Sendai	C	—	—	D	—	—	C	C	—	D	—	D	(D)	—	—	—	(C)	D	—	C	(D)	C	C
Seven Falls	—	—	—	—	—	—	—	—	—	—	—	—	D_1'	—	—	—	—	—	—	C_1'	—	—	—

TABLE III—*Concluded*

Data on which the Solutions are Based

STATION	May 17, 1950	May 19A, 1950	May 19B, 1950	May 26, 1950	May 27, 1950	May 28, 1950	June 21, 1950	June 24, 1950	July 17, 1950	July 21, 1950	July 22, 1950	Feb. 13, 1951	March 23, 1951	August 28, 1951	Feb. 25, 1952	May 9, 1952	July 13, 1952	July 27, 1952	Sept. 11, 1952	July 2, 1953	Sept. 14, 1953	Sept. 29, 1953	Jan. 13, 1954
Shasta	C	C	D	C	C	D	C	C	C	C	—	D	D	D eC	C	—	—	—	—	C CC	D	C	—
Shawinigan Falls	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—		C_1'	—	—	—
Shillong	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	C	—	—	—	C	—	—	—
Sitka	—	—	—	—	—	—	—	C	—	(C)	—	—	—	—	—	D	D	C	—	D	—	—	—
State College	CC	(DD)	—	C_1'	—	—	—	C_1'	—	CC	—	—	—	—	—	—	—	—	—	—	—	—	—
Strasbourg	C_1'	C_1' CC	C_1' C_1'	C_1' C_2' CC	(D_1') CC	D_1'	C_1' CC	C_1'	C_1' CC	(D_1')	D_1'	D_1'	(C_1')	—	C_1'	(D_1')	C_1'	D_1'	C_1'	C_1'	—	C_1'	—
Stuttgart	C_1'	C_1'	C_1' D_2'	C_1'	C_1'	D_1' D_2'	C_1'	C_1'	—	C_1'	C_1'	D_1' eC_1'	D_1' DD	—	C_1'	C_1'	C_1' (eC_1')	D_1'	C_1'	C_1' eC_1'	D_1'	(dD_1')	—
Suva	—	—	—	D	D	—	D	D	(D)	D	D	—	(D)	—	—	—	—	—	—	—	(C)	C	C DD
Tacubaya	DD	—	—	(D)	—	—	DD	—	—	—	—	—	—	—	(D)	—	(D)	—	—	C	—	—	—
Tamanrasset	C_1' D_2' CC	C_1' D_2' CC	—	C_1' D_2'	D_1' D_2'	C_1' C_2' DD	C_1' D_2' (DD)	C_1' D_2' (DD)	C_1' C_2' DD	C_2' DD	C_1' D_2' (DD)	C_1' D_2'	(C_1') (dD_1')	D_1' C_2'	D_1' DD	(D_1') DD	(D_1')	C_1' CC	—	—	—	—	—
Tananarive	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	eC
Tinemaha	—	—	—	—	—	—	—	—	—	—	—	D	(C)	—	C	C	C	C	—	C	(D)	C	—
Tokyo	C	—	—	C DD	—	—	C	C DD	—	D	—	—	—	—	—	—	—	D	—	C DD (dD)	—	—	—
Toledo	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	C_1'	—	—	C_1'	—	—	—
Tortosa	C_1'	C_1'	C_2'	C_1'	—	—	C_1'	C_1'	—	C_1'	C_1'	—	—	—	—	—	—	—	—	—	—	—	—
Trieste	—	—	—	—	—	—	—	—	—	—	—	(C_2')	C_1'	C_1' CC	C_1' C_2'	C_1'	C_1' C_2'	D_1' (C_2')	C_1'	C_1'	(C_1')	C_1' (C_2')	C_1' D_2' (DD)
Tuai	(D)	C	C	—	D	C	C	—	D	C	—	—	(D)	—	(C)	D	D	—	—	C	D	C	D

Tucson	C	C	C	C	C	—	—	C CC	C	C	—	C	D	C dD	C	C	C	C	D	C	C	C	—
Uccle	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	C	cC_1'	—
Ukiah	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	(D)	—	—	(D)	—	—	—
Uppsala	—	—	(CC)	(DD)	—	—	—	CC	—	CC	—	—	C_1'	—	C_1'	C_1'	CC	D_1'	C_1'	(CC)	(DD)	—	(CC)
Victoria	C	—	—	—	—	—	—	C	C	—	—	(C)	D	—	C	—	C	C cC	—	C	—	—	—
Wellington	C	C	C	C	C	C	C	C	D	C	—	D	C	C	C	—	—	—	D	D	D	C	D
Weston	C_1' CC	C_1'	CC	(D_1') CC	(D_1')	(C_1') CC	C_1' CC	C_1' DD	(D_1')	CC	D_1'	—	—	—	D_1'	—	(D_1')	—	—	C_1'	C_1'	(D_1')	—
Witteveen	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	D_1'	(D_1')	—
Zurich	C_1'	C_1'	—	C_1' C_2'	C_1'	(C_1')	C_1' CC	C_1' C_2'	C_1'	C_1'	(D_1')	D_1' cC_1'	(C_1') (CC)	C_1'	C_1'	(D_1')	C_1'	D_1'	—	C_1' cC_1'	D_1'	C_1' (dD_1')	D_2'

ANALYSIS OF THE DATA

In this section solutions will be presented for each of the twenty-three earthquakes for which it has been possible to obtain them. In each case the solution diagram will be given, together with a table showing the number of observations of each sort of phase which were available and the number of these inconsistent with the published solution. The more serious of the inconsistencies will be discussed and, finally, a discussion will be given on any geological implications of the solution which seem pertinent.

The solutions are based on the tables of extended distances already published by this Observatory[6,7,8], as well as on tables not yet published,* giving extended distances for the phase pP′.

Earthquake of 18:13:13, May 17, 1950. $\phi = 21°S$, $\lambda = 169°E$

As shown in Table IV, there are a total of 13 inconsistencies out of 71 observations. Of these the 6 inconsistent observations of P_1' and the 3 of PP are so scattered throughout the diagram that they could not be brought into the solution by any system of circles. Of the 4 inconsistent observations of P, that of Honolulu is described as a "poor" reading. The two inconsistent observations in New Zealand appear more serious. That at Kiamata was described as a questionable dilatation followed by a certain compression, while that at Tuai was described as a certain dilatation followed by a larger compression. There is a temptation to bring at least Kiamata into the solution by adjusting the position of circle *a*, but this, in turn, would make the Japanese stations inconsistent. The present positions of the circles reduce the number of inconsistencies to a minimum and cannot be far from correct.

* Note added in proof. These tables have now been issued. See *Publications of the Dominion Observatory*, 18 83-100, 1956.

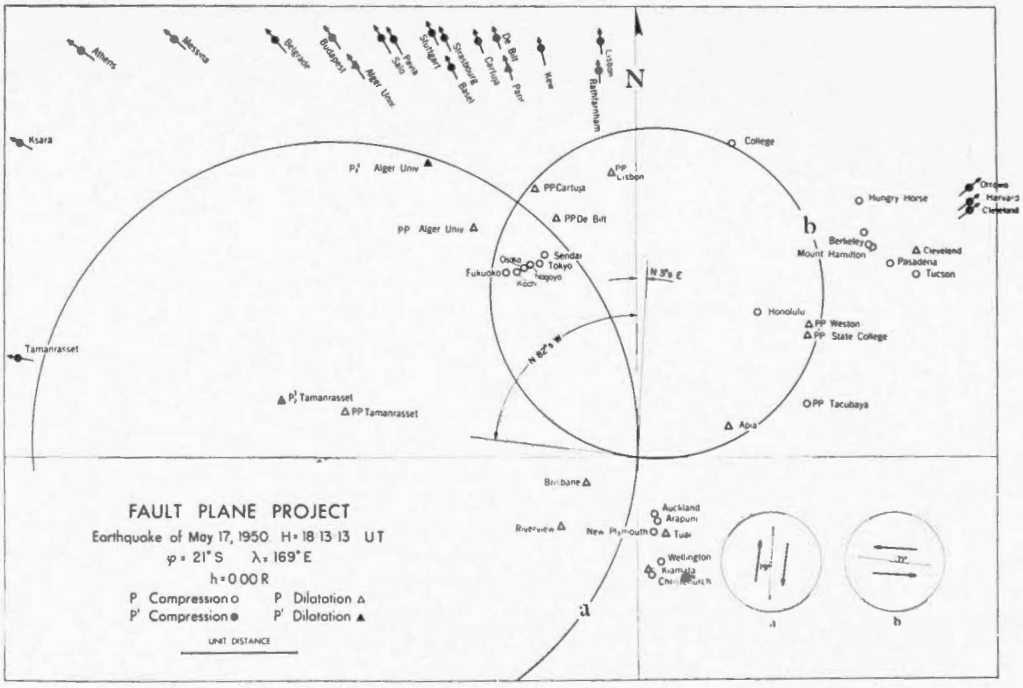


FIGURE 1.

TABLE IV

	P	P_1'	P_2'	PP	Total
Total Number of Observations	28	30	2	11	71
Number of Inconsistent Observations	4	6	0	3	13

The solution, as shown in the insert diagrams, represents two planes, one striking N 3°.5 E and dipping 79° to the west, the other striking N 82°.5W and dipping 71° to the north. Whichever of these planes represents the fault, faulting is strongly transcurrent, with a slight thrust component. There is no appreciable variation permitted in the position of the planes if we accept the points on which the solution is based.

It is worth pointing out that in this case, where the dip component is a thrust, the circles contain dilatations. If the circles contain compressions the dip component is tensional. This is a very helpful rule to follow in interpreting the fault-plane solution diagrams.

Earthquake of 02:38:10, May 19, 1950. $\phi = 20\frac{1}{2}°$S, $\lambda = 169°$E

In this earthquake it was not clear at first whether the field defined by the P′ observations was dilatational or compressional. However, when the P′ observations were plotted on a reduced scale, as shown in the insert diagram, it was found that all but 5 of the 23 observations of this phase could be made consistent by drawing a very large dilatational circle. Of the three inconsistent observations, that of Basel was described as uncertain.

TABLE V

	P	P_1'	P_2'	PP	Total
Total Number of Observations	19	23	2	12	56
Number of Inconsistent Observations	4	5	0	3	12

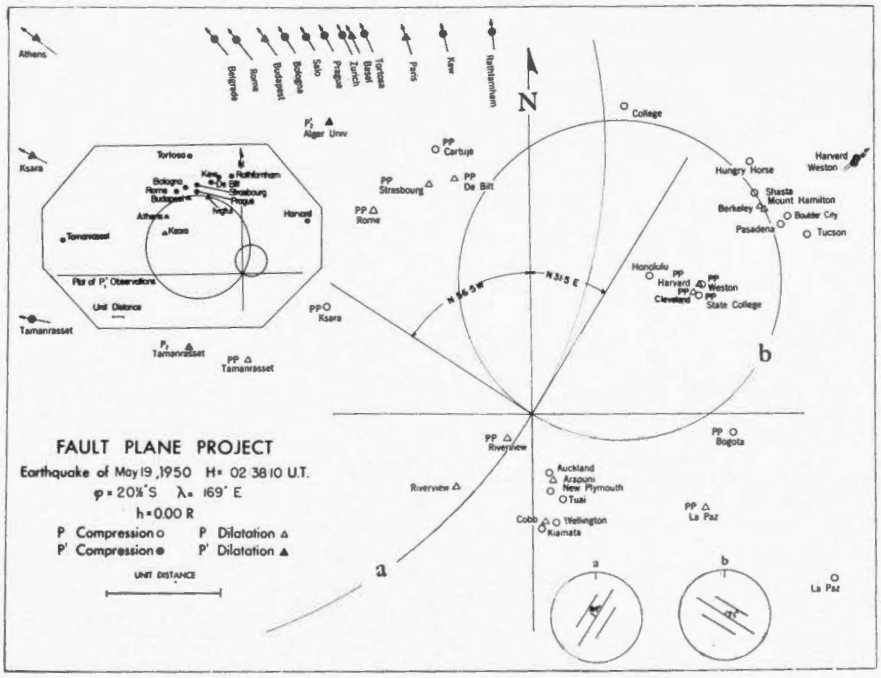


FIGURE 2.

The second circle, drawn in accordance with the orthogonality criterion, separates the dilatations recorded at Berkeley and at Mount Hamilton from the compressions general in the rest of North America. This circle, as drawn, makes Honolulu inconsistent, but the observation at this station is described as "poor". The circle also contains four PP observations, two of them consistent and two inconsistent. The PP dilatations might have been separated from the compressions by a circle smaller than that drawn, but this would have been at the expense of the observations at Berkeley and Mount Hamilton, described as "good" by our collaborators.

A more serious interpretational difficulty arose in New Zealand, where most of the observations were described as doubtful. The preponderance of evidence suggests that all of New Zealand received an initial compression. If this is not true, then the large circle (designated *a* in the figure) would have to be swung around to include the New Zealand stations; this would destroy the separation accomplished in the P′ observations. On the whole, the present solution seems to be the most satisfactory. The observations are summarized in Table V.

The insert diagrams illustrate the geology of the situation. We have to choose between a plane striking N 31°.5 E and dipping 84° to the northwest, and a plane striking N 56°.5 W and dipping 71° to the northeast. In either case the faulting is strongly transcurrent with a very small thrust component.

Earthquake of 07:05:31, May 19, 1950. $\phi = 20\frac{1}{2}°$S, $\lambda = 169°$E

This earthquake is an aftershock of that just discussed, and the solution, shown in Figure 3, is much the same as for the main shock. There are fewer observations of P′ with which to define the position of the larger circle. It has been drawn in a mean position

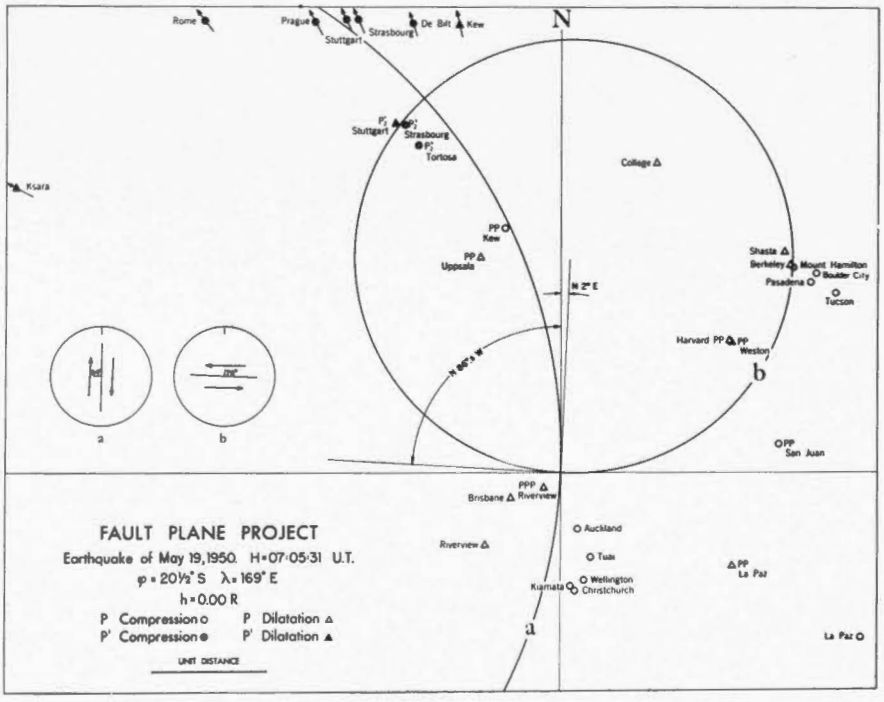


FIGURE 3.

from which a variation of $\pm 1°$ would be permitted by the data. The second circle is very well defined by a separation between Berkeley and Mount Hamilton. It is interesting to note also that this small circle provides a separation between the P_2' observations at Strasbourg and Stuttgart, which have a different direction of movement.

It will be recalled that in the previous example there was some difficulty in deciding whether New Zealand should be plotted as a compressional or dilatational area. In this case there is no ambiguity, all the New Zealand P observations being clearly compressional. This suggests that the correct decision was made in the previous example, where New Zealand was taken to be compressional.

TABLE VI

	P	P_1'	P_2'	PP	PPP	Total
Total Number of Observations.....	15	7	3	8	1	34
Number of Inconsistent Observations.....	0	1	0	3	0	4

The distribution of inconsistent observations among the several phases recorded is shown in Table VI. None of the inconsistencies is serious. The insert diagrams in Figure 3 illustrate the two geological possibilities, which do not differ very much from those in the main shock.

Earthquake of 01:17:25, May 26, 1950. $\phi = 20\frac{1}{4}°S$, $\lambda = 169\frac{1}{4}°E$

As is shown in Table VII, while the number of inconsistencies in the other phase is reasonably small, there are 9 inconsistent observations out of 31 observations of P_1'. This number seems very large. Most of the discrepant observations are not, however, too serious, since they lie surrounded by consistent observations. One exception to this is provided by the group of stations in northeastern United States. Harvard, Weston and

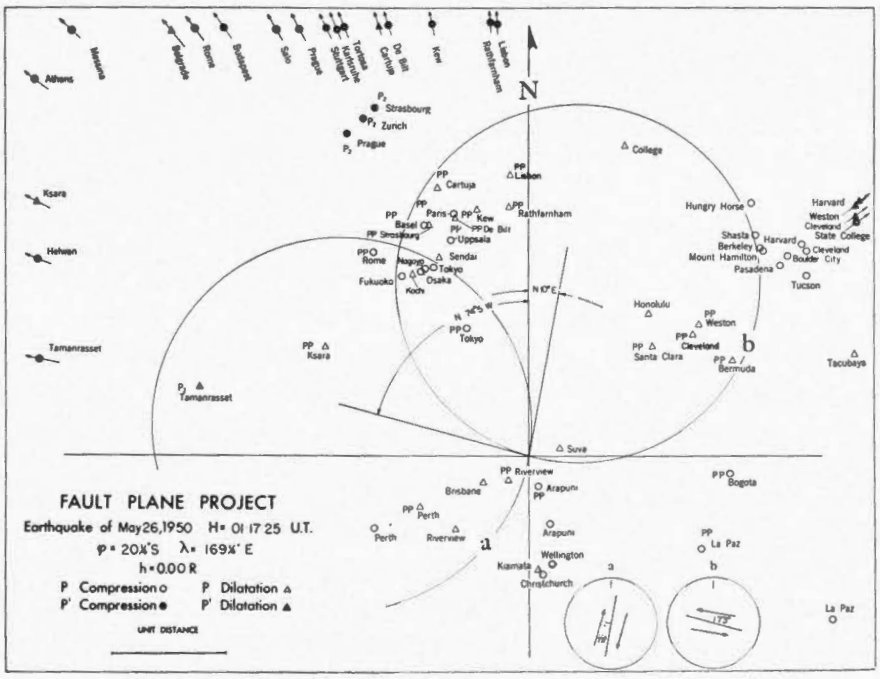


FIGURE 4.

Cleveland all report "clear" dilatations. It has not proved possible to bring these observations into a solution that makes the P compressions, well observed in California, also consistent. It is necessary to conclude that the P′ observations are inconsistent, and these constitute a serious criticism of the solution.

TABLE VII

	P	P_1'	P_2'	PP	pP	Total
Total Number of Observations.....	27	31	4	22	1	85
Number of Inconsistent Observations.....	4	9	0	4	1	18

As shown in the insert diagrams of Figure 4, the solution again shows transcurrent faulting, with a weak thrust component.

Earthquake of 12:39:43, May 27, 1950. $\phi = 20°S$, $\lambda = 168°E$

This earthquake, which had a focal depth of 200 km., was a little too small to provide a satisfactory solution. As shown in Table VIII, there were not as many observations reported as usual, and there is a higher percentage of inconsistencies. Most of these inconsistencies come from P_1' observations at distant stations, and undoubtedly reflect the low magnitude of the earthquake. In spite of the difficulties it seems worthwhile to publish the solution, as shown in Figure 5, since no radically different solution seems possible. Note the reduced scale of the figure as compared with earlier diagrams. This enables the observations of P′ to be plotted on scale. The insert diagrams to the figure indicate that the faulting is almost purely transcurrent.

TABLE VIII

	P	P_1'	P_2'	PP	Total
Total Number of Observations.....	15	16	1	3	35
Number of Inconsistent Observations.....	2	7	0	0	9

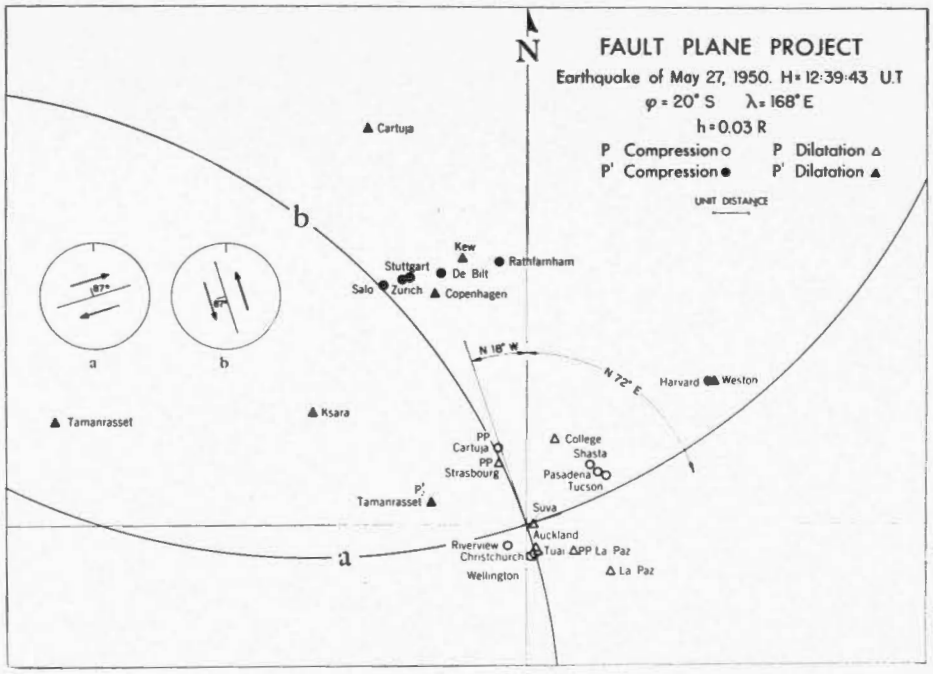


FIGURE 5.

Earthquake of 01:36:44, May 28, 1950. $\phi = 20°S$, $\lambda = 169°E$

The solution for this earthquake, shown in Figure 6, scores 10 failures out of 44 observations. These are enumerated in Table IX. Almost all the inconsistent observations have been described by the readers as doubtful. One exception is that for Berkeley, which is inconsistent with "good" observations at Shasta and Mount Hamilton, but which is itself described as a "fair" observation.

TABLE IX

	P	P_1'	P_2'	PP	Total
Total Number of Observations.....	15	17	2	10	44
Number of Inconsistent Observations.....	3	4	0	3	10

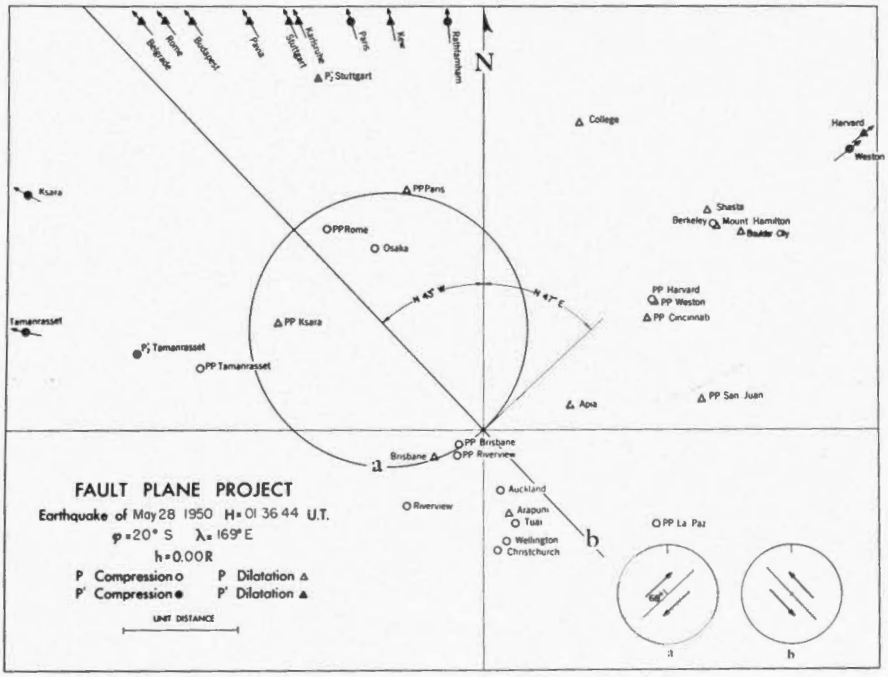


FIGURE 6.

The solution shown in Figure 6, has one plane vertical. In fact the data do not insist on absolute verticality for this plane; a slight curvature in either direction could be tolerated. The solution, as drawn, represents an average position.

Since the one plane has been drawn vertical, the insert diagrams show the faulting to be purely transcurrent.

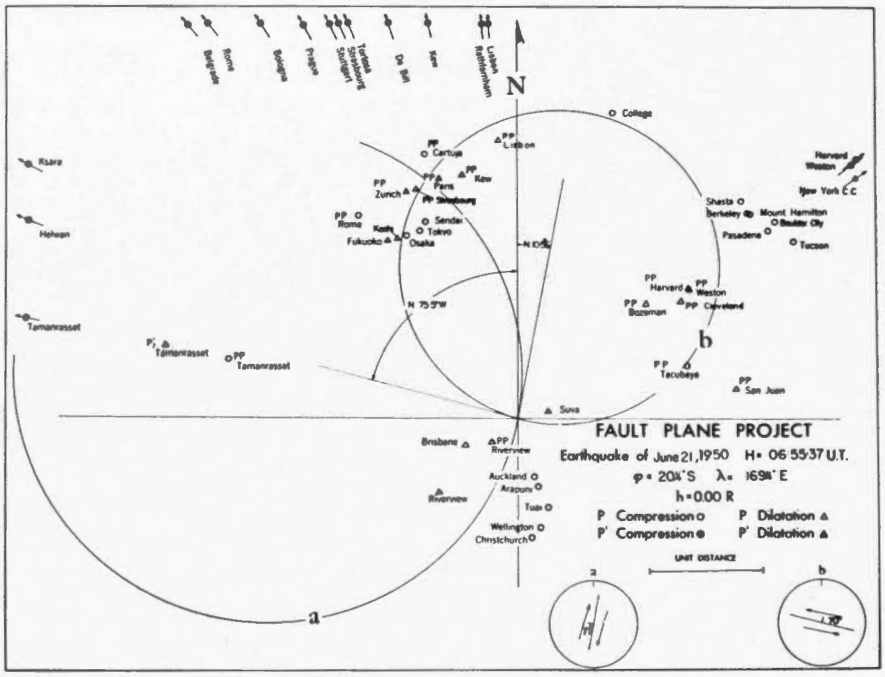
Earthquake of 06:55:37, June 21, 1950. $\phi = 20\frac{1}{4}°S$, $\lambda = 169\frac{1}{4}°E$

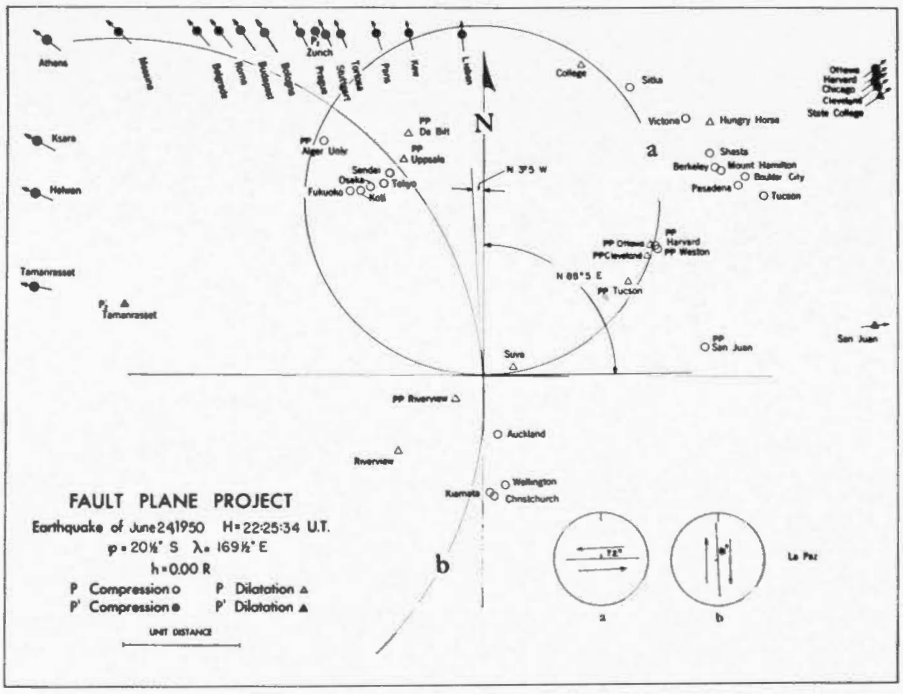
The solution for this earthquake, shown in Figure 7, assumes that the circles are dilatational and that the field should therefore be compressional. As shown in Table X, all but 6 of the 26 observations of P_1' support this, and the inconsistencies are scattered in azimuth. The score on the other phases is reasonably satisfactory.

TABLE X

	P	P_1'	P_2'	PP	Total
Total Number of Observations.....	25	26	1	15	67
Number of Inconsistent Observations.....	5	6	0	4	15

The insert diagrams show that the faulting is largely transcurrent; since the circles contain dilatations, the minor component is a thrust.





FIGURES 7 and 8.

Earthquake of 22:25:34, June 24, 1950. $\phi = 20\frac{1}{2}°S$, $\lambda = 169\frac{1}{2}°E$

The total number of observations, and the number of these inconsistent with the solution here presented, is given in Table XI. The solution itself, which is presented in Figure 8, is quite straightforward and requires no explanation.

TABLE XI

	P	P_1'	P_2'	PP	Total
Total Number of Observations	25	33	2	19	79
Number of Inconsistent Observations	4	7	0	6	17

Earthquake of 20:17:50, July 17, 1950. $\phi = 20\frac{1}{2}°S$, $\lambda = 171°E$

The solution of this earthquake, shown in Figure 9, consists of two planes so steeply dipping that it has been necessary to plot the map on a reduced scale. As itemized in Table XII, the solution accounts for a total of 42 observations with 8 inconsistencies, none of which is serious.

TABLE XII

	P	P_1'	P_2'	PP	pP	Total
Total Number of Observations	20	15	1	5	1	42
Number of Inconsistent Observations	4	3	0	1	0	8

As shown in the insert diagrams, faulting is transcurrent with a slight thrust component.

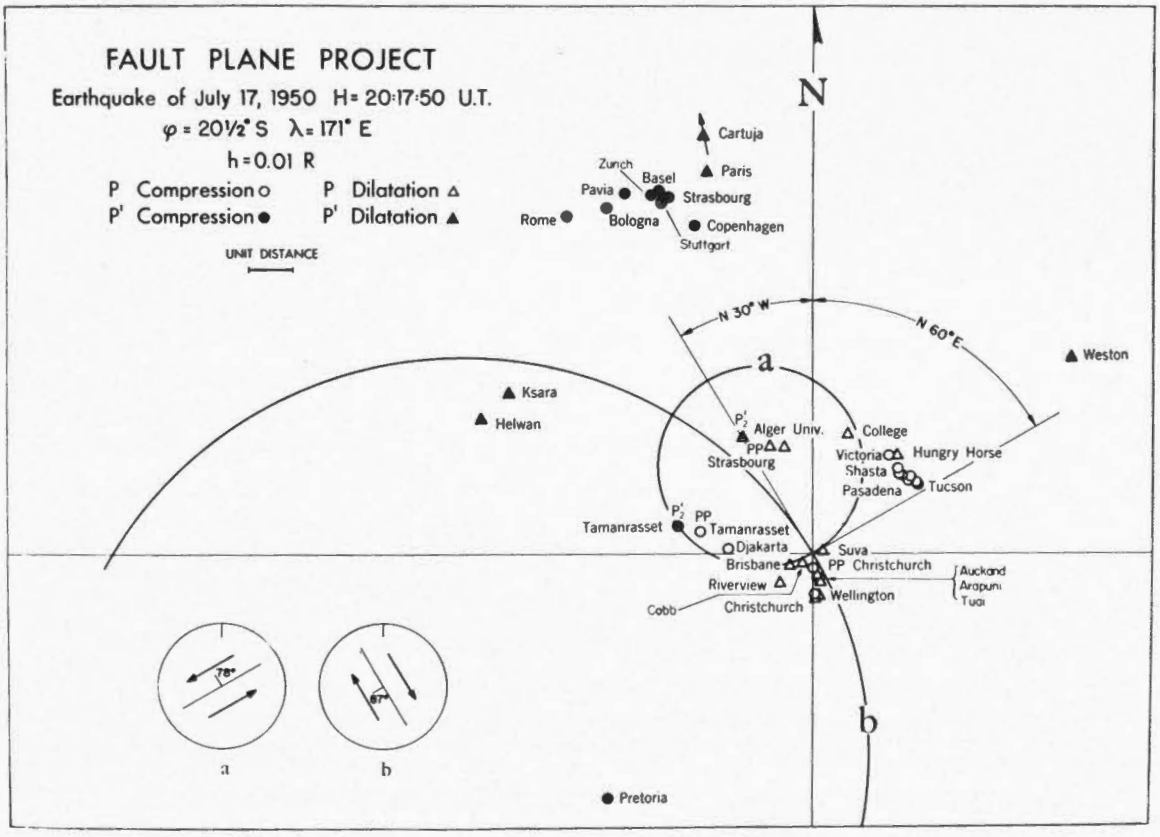


FIGURE 9.

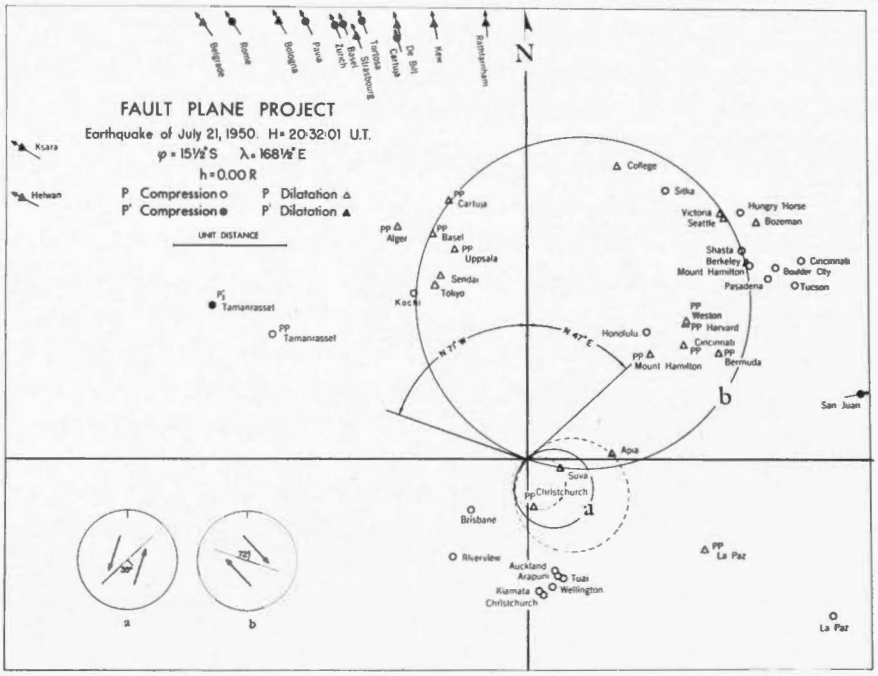


FIGURE 10

Earthquake of 20:32:01, July 21, 1950. $\phi = 15\frac{1}{2}°S$, $\lambda = 168\frac{1}{2}°E$

So many of the earthquakes analysed in the fault-plane project to date have shown nearly pure transcurrent faulting that any evidence in favour of non-transcurrent faulting should be submitted to the reader, even though that evidence is not clear. The solution for this earthquake, shown in Figure 10, is published with this thought in mind; the reader is cautioned to examine it critically.

It will be noted in the figure that a separation is clearly indicated in Japan (Kochi and Tokyo move in opposite senses) and also along the Pacific shore of North America. These separations have been made with circle *b*. A second circle can be drawn to bring in Suva and the PP observation of Christchurch and to satisfy the orthogonality criterion. The extreme and mean positions of this circle *a* have been indicated. The score for this solution is indicated in Table XIII. For the phases other than P_1' the score is not too bad, particularly since many of the inconsistencies are not serious. For example the Berkeley observation is described as "questionable" and in any event Berkeley is very close to the circle as drawn. Observations at Bozeman, Honolulu, Cobb, New Plymouth are also described as questionable.

TABLE XIII

	P	P_1'	P_2'	PP	pP	Total
Total Number of Observations.....	30	18	1	17	1	67
Number of Inconsistent Observations.....	6	8	0	5	1	20

It is when one turns to the observations of P_1' that doubts arise. Here 8 out of 18 observations show dilatations instead of the compressions demanded by the published solution. Repeated attempts have been made to find a system of circles which would

effect a separation of compressions and dilatations in the P_1' and still satisfy the separations in Japan and California. No such system has been found and it has been necessary to conclude that all P_1' observations should be compressional. There is some justification for this in that at least four stations reported a small initial compression followed by a much larger dilatation. Perhaps the inconsistent stations failed to record the small initial compression.

The insert diagrams are based on the mean position of circle *a*. Even in this case the thrust component is very large. Had the smallest value of circle *a* been plotted the thrust nature of the faulting would have been still more pronounced. It will bear repeating that this solution is being published, despite the doubts which attend it, because it does suggest the possibility of a large dip component of motion.

Earthquake of 23:08:00, July 22, 1950. $\phi = 14°S$, $\lambda = 167°E$

This earthquake was rather small, and was not widely recorded, but, as shown in Table XIV, the percentage of inconsistencies is about normal. The solution is shown in Figure 11. It should be noted that this figure is drawn to a reduced scale because of the large size of circle *b*. The insert diagrams demonstrate that the faulting is again transcurrent, with a very small thrust component.

TABLE XIV

	P	P_1'	P_2'	PP	Total
Total Number of Observations	10	11	2	4	27
Number of Inconsistent Observations	2	3	0	2	7

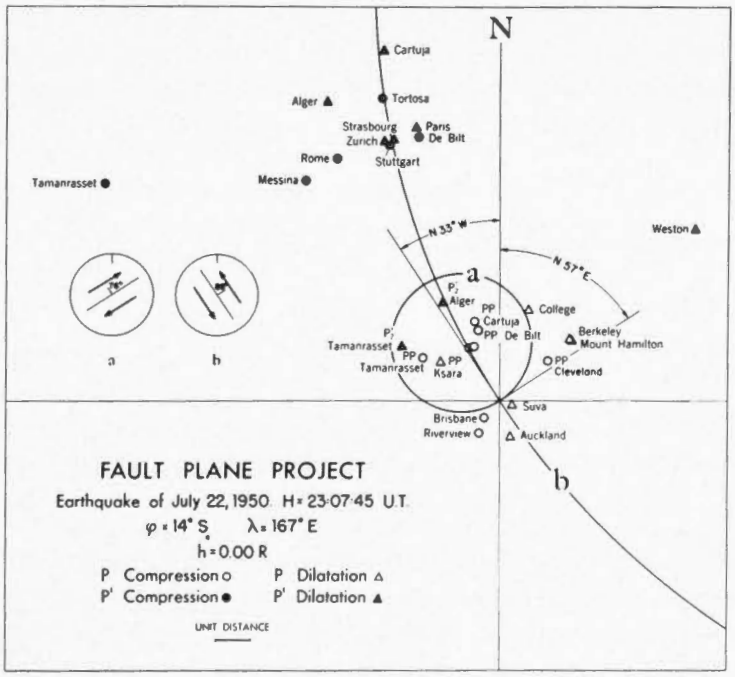


FIGURE 11

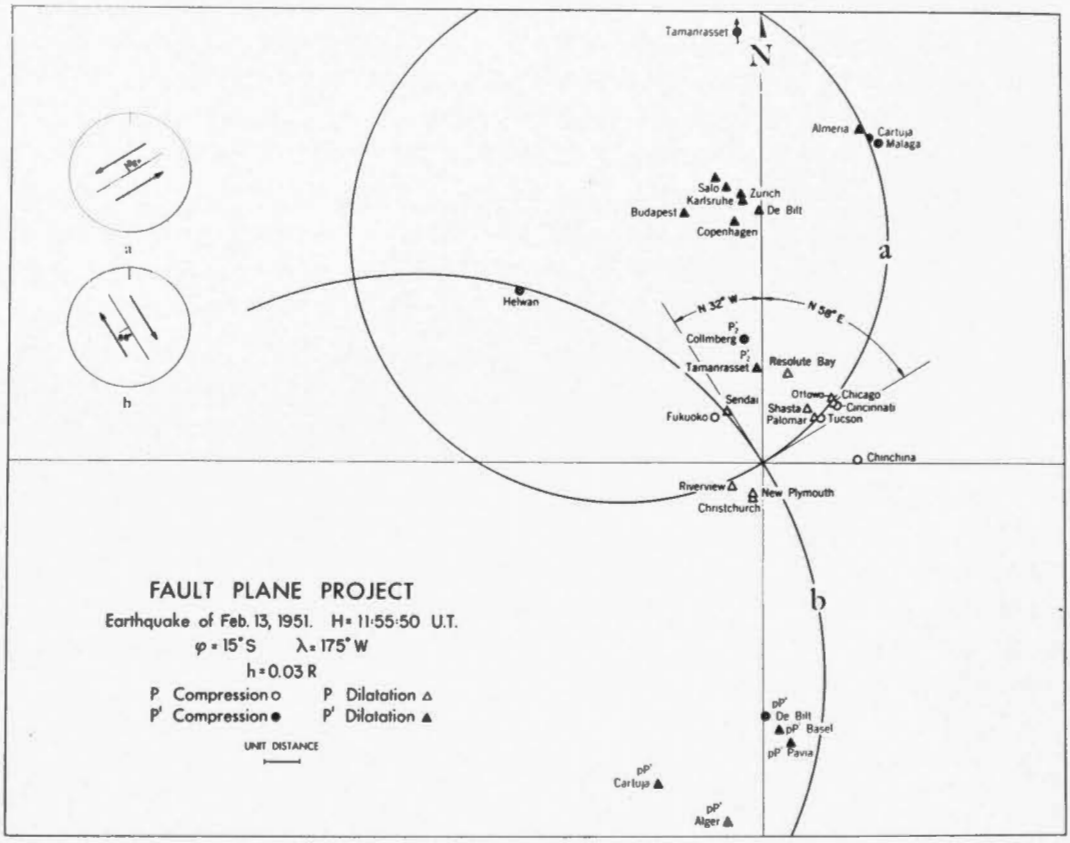


FIGURE 12

Earthquake of 11:55:50, Feb. 13, 1951. $\phi = 15°S$, $\lambda = 175°W$

This earthquake was very widely recorded, a total of 74 observations being available. The solution shown in Figure 12 accounts for all but 16 of these observations.

This solution marks the first time that the phase pP_1' has been used to any large extent in plotting. In order not to confuse the diagram only a few of these observations have been plotted on the figure.

TABLE XV

	P	P_1'	P_2'	PP	pP	pP_1'	Total
Total Number of Observations.....	32	21	3	6	2	10	74
Number of Inconsistent Observations.....	6	1	2	2	1	4	16

The insert diagrams illustrate that the faulting is almost purely transcurrent on almost vertical planes.

Earthquake of 21:38:54, March 23, 1951. $\phi = 31°S$, $\lambda = 180°$

The solution for this earthquake, shown in Figure 13, has 21 inconsistencies among 78 observations. Three of the P inconsistencies are for California stations and lie well surrounded by consistent observations. Two other P inconsistencies are from Suva and Tuai which lie so close to the epicentre that slight error in focal depth, epicentre or in our tables of extended distances could account for the errors.

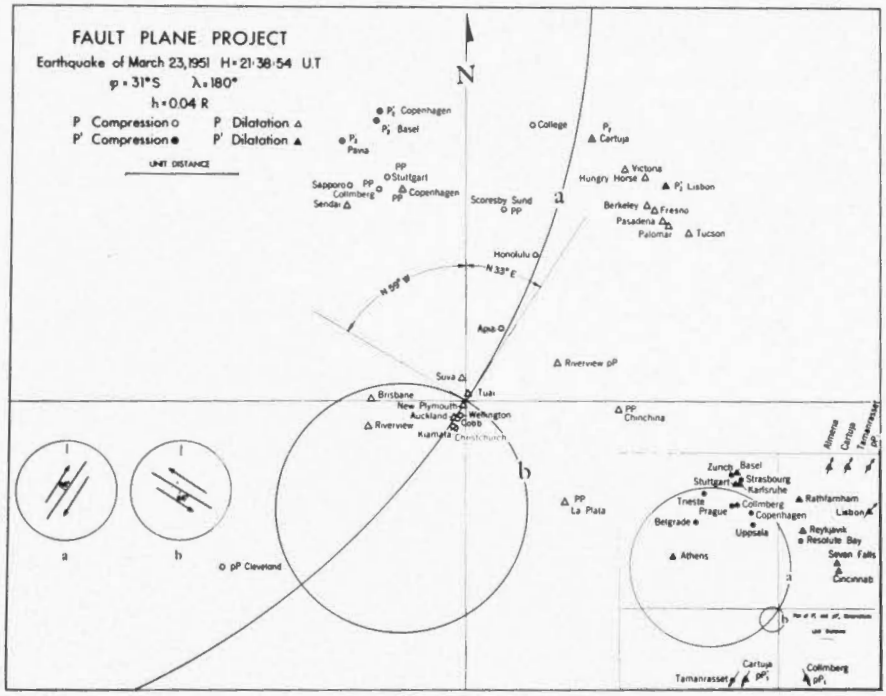


FIGURE 13

TABLE XVI

	P	P_1'	P_2'	PP	pP	pP_1'	Total
Total Number of Observations.....	31	23	8	11	2	3	78
Number of Inconsistent Observations.....	6	6	2	6	0	1	21

None of the inconsistencies in P_1' is particularly serious. The circle *a* might have been drawn larger to include Resolute Bay, Strasbourg and Zurich, but this would have been at the expense of Stuttgart and Karlsruhe. Geologically the difference is slight, an increase of about 1° in the dip of the plane.

The insert diagrams illustrate the two geological possibilities. The uncertainty in the dip of plane *b* is $\pm 5°$, since the circle *b* is not closely limited bv the data.

Earthquake of 16:31:11, August 28, 1951. $\phi = 27°S$, $\lambda = 178°E$

The solution for this earthquake is shown in Figure 14 and the data on which it is based are summarized in Table XVII. Of the four inconsistent observations of P, two are from stations (Auckland and New Plymouth) so near to the epicentre that slight error in epicentre or focal depth could account for them, while a third is for Pierce Ferry, which lies in a cluster of consistent readings. The two inconsistent observations (Butte and College) of pP have been shown in the figure. Both readings are described as doubtful.

TABLE XVII

	P	P_1'	P_2'	PP	pP	pP_1'	Total
Total Number of Observations.....	22	9	4	2	6	2	45
Number of Inconsistent Observations.....	4	2	2	0	2	0	10

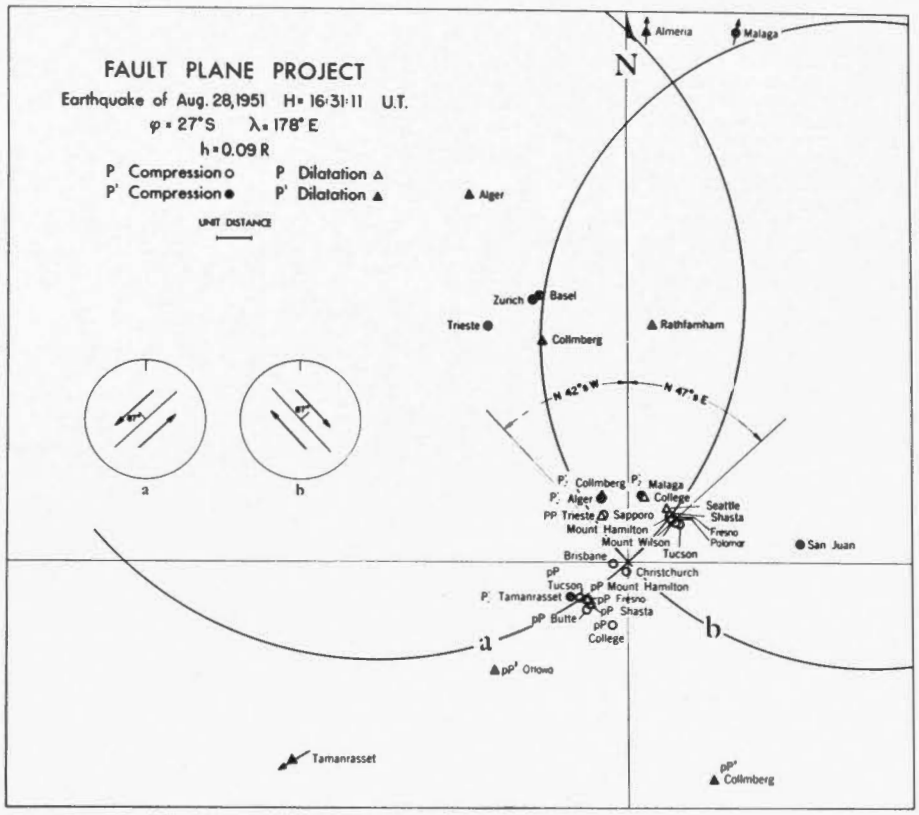


FIGURE 14

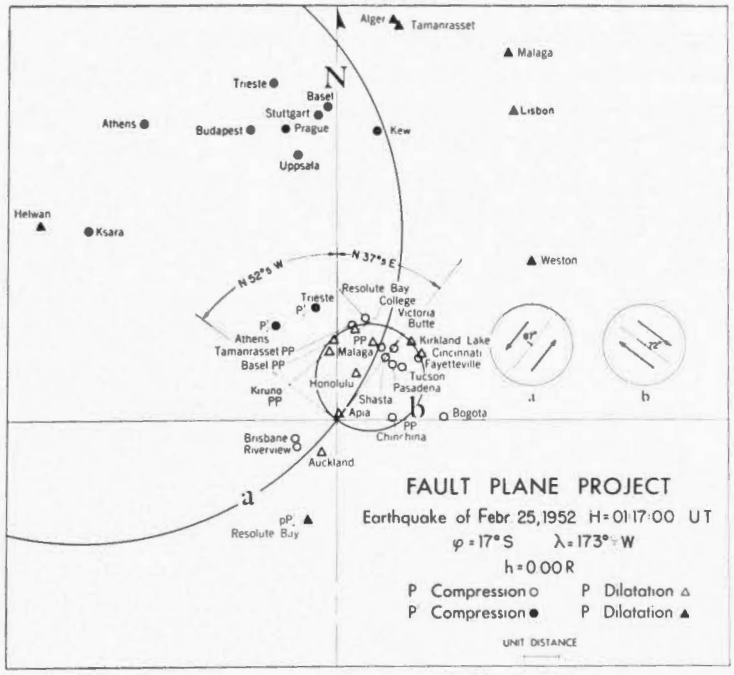
This earthquake had a focal depth of 0·09R, one of the deepest for which a fault-plane solution has been obtained. As shown in the insert diagrams to Figure 14 the faulting is almost purely transcurrent, on almost vertical planes. In an earlier paper[3] a solution for a normal focus earthquake from the same area (the Kermadecs) was given. The two solutions are almost identical except that, whereas the normal-focus earthquake was solved with dilatational circles, the present deep-focus earthquake requires compressional circles.

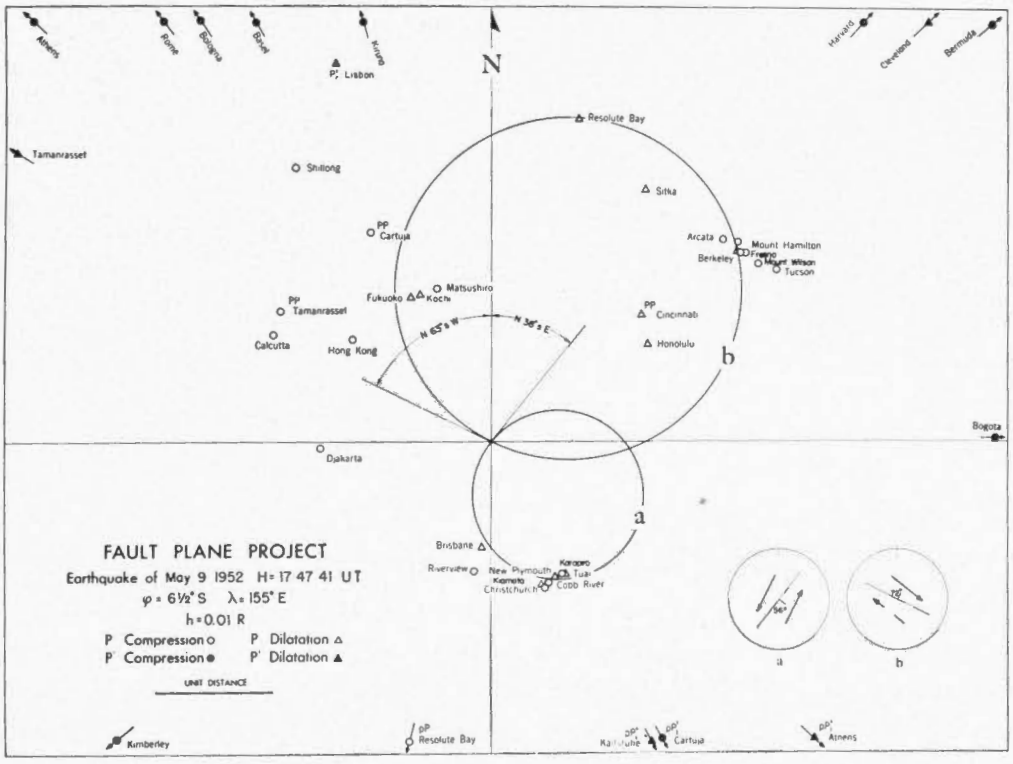
Earthquake of 01:17:00, Feb. 25, 1952. $\phi = 17°S$, $\lambda = 173\frac{1}{2}°W$

The solution of this earthquake is shown in Figure 15, while the data on which it is based are summarized in Table XVIII. One group of inconsistencies is worthy of discussion. Three of the New Zealand stations showed compressions, three dilatations, but the stations were not aligned in such a way that the two groups could be separated. Only one station, Auckland, has been shown on the diagram, and the solution assumes the entire New Zealand area to be dilatational.

TABLE XVIII

	P	P_1'	P_2'	PP	pP_1'	Total
Total Number of Observations.....	32	24	5	11	3	75
Number of Inconsistent Observations.....	5	4	3	3	1	16





FIGURES 15 and 16

Earthquake of 17:47:41, May 9, 1952. $\phi = 6\frac{1}{2}°$S, $\lambda = 155°$E

The solution for this earthquake is shown in Figure 16, while the data on which it is based are summarized in Table XIX. There are some anomalies in the solution which are worthy of discussion. Circle *a*, as drawn, makes Christchurch and Cobb correct, Brisbane

and Kiamata wrong. If the radius had been increased this could have been reversed, Brisbane and Kiamata becoming consistent at the expense of Christchurch and Cobb. By a complete reorientation of the circle all of these stations might have been made consistent, but the orthogonality criterion would then have demanded an inconsistent position for circle *b*. The solution given in the figure is the best compromise, and is probably not very far from the truth.

TABLE XIX

	P	P_1'	P_2'	PP	pP	pP_1'	Total
Total Number of Observations.....	29	29	1	6	1	4	70
Number of Inconsistent Observations.....	5	7	1	1	0	3	17

It should be noted that this is the first solution obtained for an earthquake in the Soloman Islands.

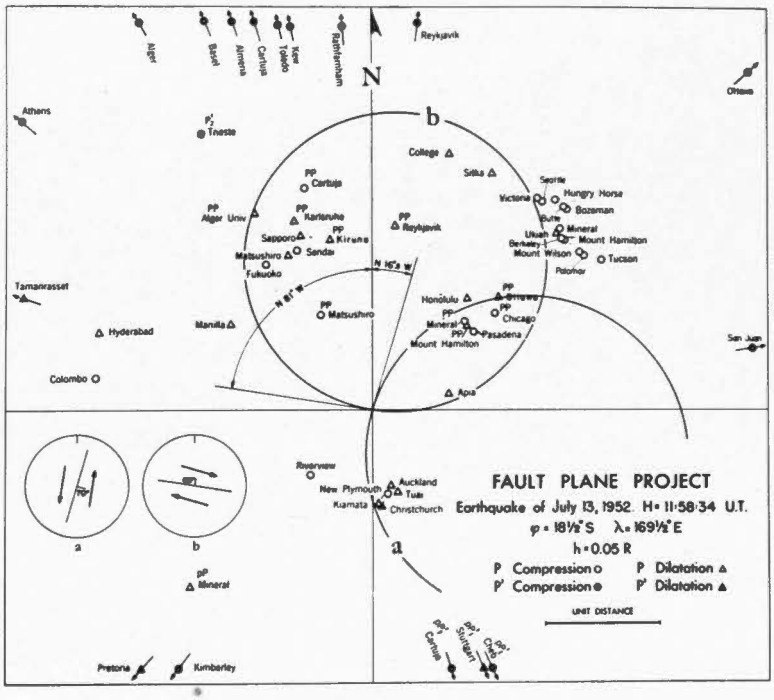


FIGURE 17

Earthquake of 11:58:34, July 13, 1952. $\phi = 18\frac{1}{2}°S$, $\lambda = 169\frac{1}{2}°E$

The solution for this earthquake is shown in Figure 17, while the data on which it is based are shown in Table XX.

TABLE XX

	P	P_1'	P_2'	PP	pP	pP_1'	Total
Total Number of Observations.....	40	28	1	18	2	3	92
Number of Inconsistent Observations.....	8	9	0	4	1	1	23

The positions of the circles as drawn in the figure may not be entirely correct. By shortening up the radius of circle *b*, Apia, Fukuoko and the PP observation at Cartuja could be made consistent, but only at the expense of College and Sitka. On the other

hand, increasing the radius of circle b would make Ukia and Santa Clara consistent, but at the additional expense of Victoria and Seattle. Circle b is therefore drawn in a mean position, and none of the inconsistencies mentioned is too serious.

Earthquake of 08:23:22, July 27, 1952. $\phi = 20\frac{1}{2}°$S, $\lambda = 179°$W

The data on which Figure 18 is based are summarized in Table XXI, which also shows the number of inconsistent observations. Some of these inconsistencies are disturbing. In particular, the inconsistencies in P_2' at Prague, and in P_1' at Prague, Chur, Stuttgart and Alger lie grouped about the same azimuth in such a way as to suggest that they must be brought into the solution. No way has been found to do this without making many other stations inconsistent, but the reader should bear in mind this group of observations in appraising the value of the solution.

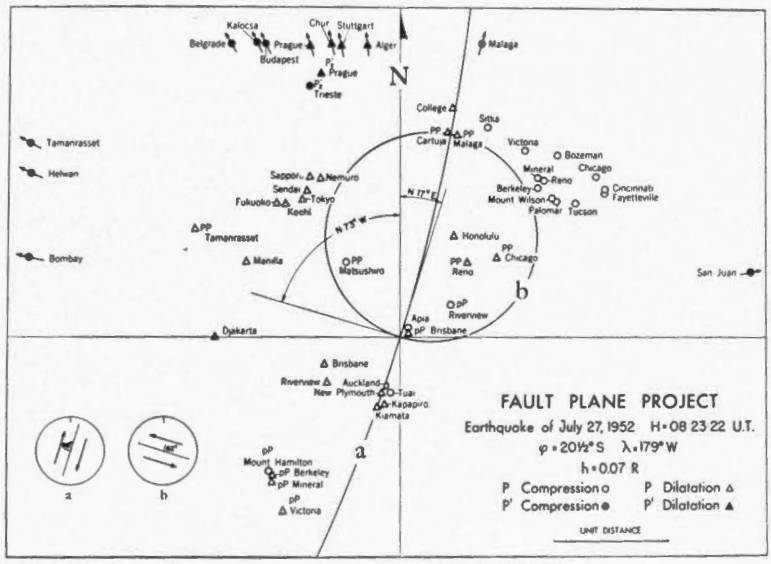


FIGURE 18

TABLE XXI

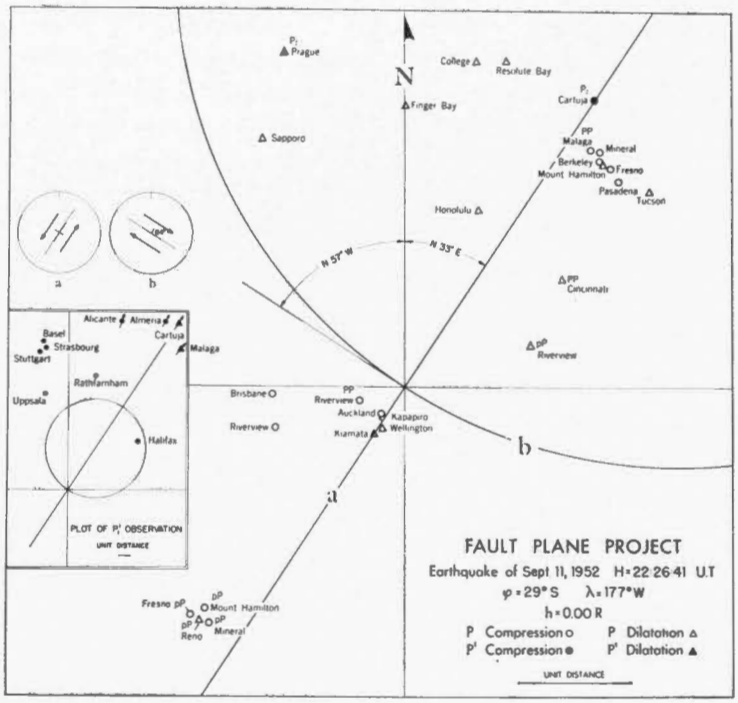
	P	P_1'	P_2'	PP	pP	pP_1'	Total
Total Number of Observations.....	35	20	2	11	5	1	74
Number of Inconsistent Observations.....	4	5	1	4	2	1	17

Earthquake of 22:26:41, Sept. 11, 1952. $\phi = 29°$S, $\lambda = 177°$W

This earthquake provided a smaller body of data than most of the other considered, but the percentage of inconsistencies is about normal. The solution in terms of one vertical plane seems to be demanded both by the distribution in New Zealand and by the fact that the P_1' and the P_2' observations for Cartuja are in opposite senses. The number of inconsistencies, as shown in Table XXII, is about normal.

Table XXII

	P	P_1'	P_2'	PP	pP	Total
Total Number of Observations.....	19	14	3	3	5	44
Number of Inconsistent Observations.....	2	2	1	1	2	8



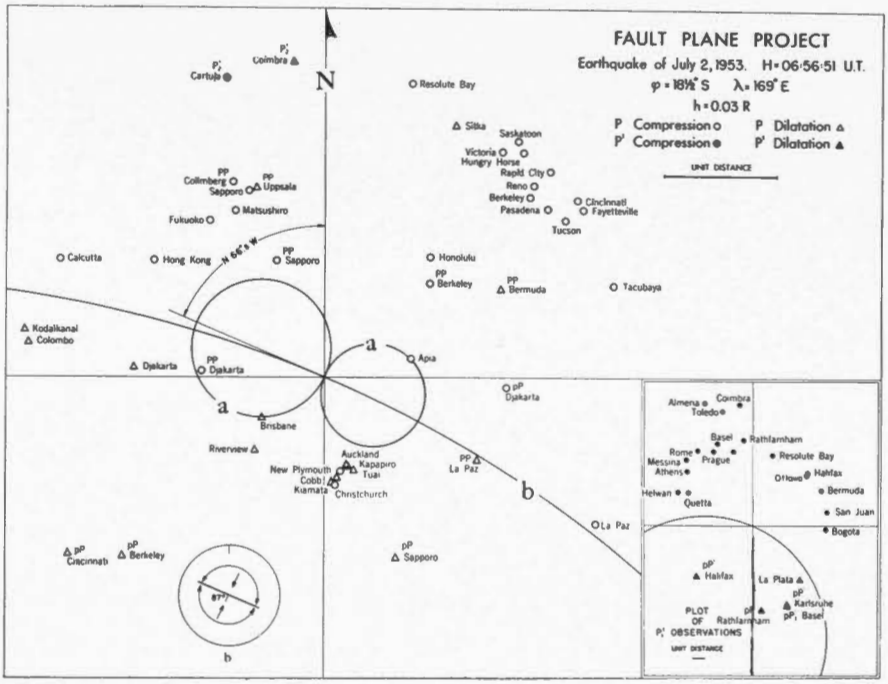


Figure 19 and 20.

Earthquake of 06:56:51, July 2, 1953. $\phi = 18\frac{1}{2}°S$, $\lambda = 169°E$

The solution for this earthquake, shown in Figure 20, is not closely defined, since any circle lying between a' and a'' would satisfy the data satisfactorily. The inconsistencies shown in Table XXIII are based on circle a', but a single observation of PP is not a sufficient basis for insisting on the circle a' and so throwing out the possibility of purely thrust faulting.

TABLE XXIII

	P	P_1'	P_2'	PP	pP	pP_1'	pP_2'	Total
Total Number of Observations.....	54	37	3	15	8	8	1	126
Number of Inconsistent Observations..	5	5	2	3	1	2	0	18

The insert diagram supposes that plane b represents the fault, and indicates that the motion may lie anywhere between transcurrent in either sense to pure thrust.

Earthquake of 00:26:36, Sept. 14, 1953. $\phi = 18\frac{1}{2}°S$, $\lambda = 178\frac{1}{2}°E$

This is the first earthquake which we have considered in the vicinity of the Fiji Islands, and it seems worthwhile to publish the tentative solution shown in Figure 21 even though the number of inconsistencies is higher than normal, for it is clear that the solution must be at least approximately correct.

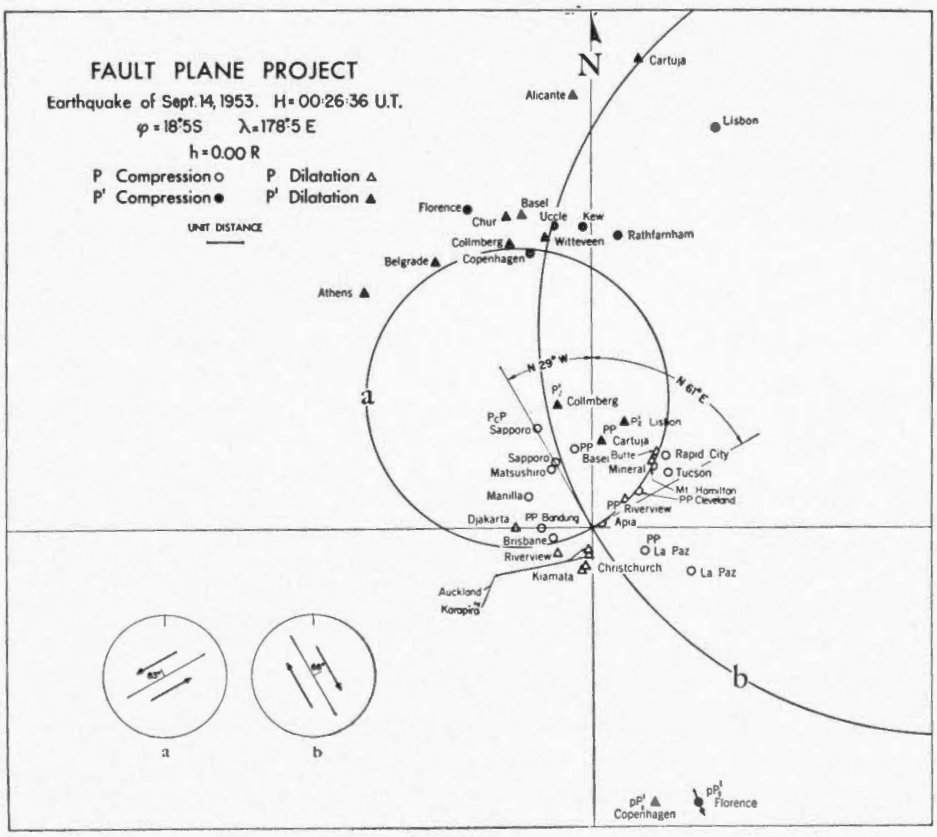


FIGURE 21

Of the inconsistent observations of P, two are in New Zealand and derive from EW seismographs. Since the stations are almost south of the epicentre the error is not surprising. Three other inconsistencies come from California stations lying very close to circle *a*.

TABLE XXIV

	P	P_1'	P_2'	PP	pP	pP_1'	PcP	Total
Total Number of Observations.....	33	21	3	10	1	3	1	72
Number of Inconsistent Observations..	8	4	1	7	0	2	0	22

The most serious group of inconsistencies is provided by the PP phase. Five of the recorded inconsistencies derive from stations lying between Basel and Cartuja in the overlap zone of the two circles. Most of these inconsistent observations are described by the readers as "doubtful", but the solid group does constitute a criticism of the solution.

Earthquake of 01:36:45, Sept. 29, 1953. $\phi = 36\frac{1}{2}°$S, $\lambda = 177°$E

The largest group of inconsistencies in this solution are provided by the phase P_1'. This is not surprising considering the location of the epicentre. Most of the Spanish stations, for example, are almost 180° distant from the epicentre. A more serious series of inconsistencies are provided by the normally consistent group of stations Djakarta, Hong Kong, Hyderabad, Bombay and Athens, a group of compressions all lying along the same azimuth. There does not seem to be any explanation for this group.

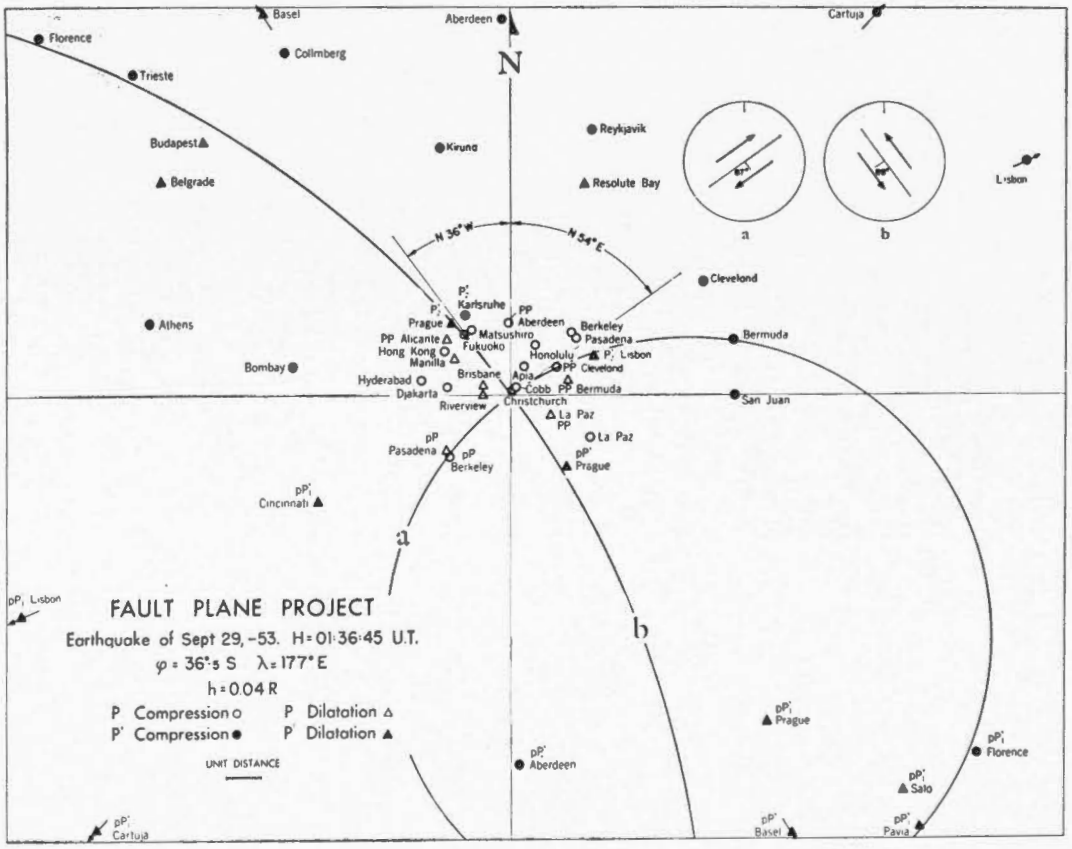


FIGURE 22

TABLE XXV

	P	P_1'	P_2'	PP	pP	pP_1'	pP_2'	Total
Total Number of Observations.....	33	30	6	15	5	13	3	105
Number of Inconsistent Observations..	6	11	3	2	1	2	2	27

Earthquake of 00:13:06, Jan. 13, 1954. $\phi = 49°S$, $\lambda = 165°E$

This, the final earthquake of the present series, is the most southerly epicentre yet considered. It will be seen that, once again, transcurrent faulting along an almost vertical plane is indicated.

TABLE XXVI

	P	P_1'	P_2'	PP	PcP	pP	Total
Total Number of Observations.....	16	12	7	16	2	2	55
Number of Inconsistent Observations.....	1	1	0	4	0	1	7

The score on this earthquake, as shown in Table XXVI, is remarkably good. The only serious discrepancy is for Riverview, both P and pP. It should be noted that a slight shift in the epicentre could have brought both these observations into consistency.

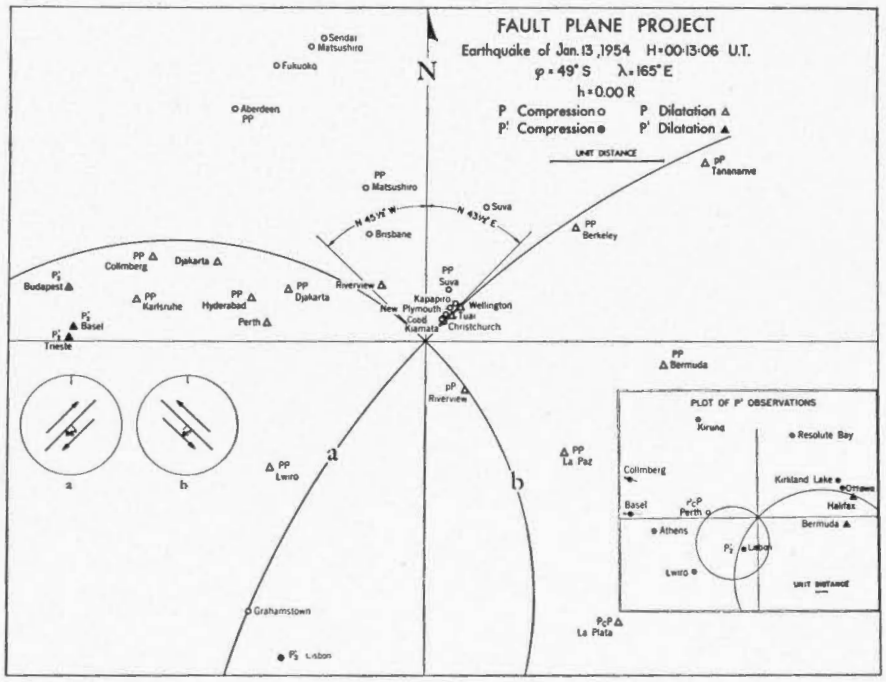


FIGURE 23

SUMMARY AND DISCUSSION

PRESENTATION OF THE DATA

Table XXVII summarizes the results of all fault-plane solutions available for southwest Pacific earthquakes. This includes the data obtained by Webb[10] for five earthquakes and by Hodgson and Storey[3] for two others. The remaining results tabulated are from the present paper.

TABLE XXVII

Summary of Fault-Plane Solutions Available for Southwest Pacific Earthquakes

Earthquake					Plane a					Plane b				
No.	Date	φ	λ	h	Strike Direction	Dip Direction	Dip	Strike Component	Dip Component	Strike Direction	Dip Direction	Dip	Strike Component	Dip Component
	Solomon Islands									—				
1	May 9, 1952	6½°S	155°E	0·01R	N38°5E	S51°5E	56°	0·928	+0·373	N63°5W	N26·5E	72°	0·809	+0·588
	New Hebrides Islands													
2	July 22, 1950	14°S	167°E	0·00R	N57°E	N33°W	76°	1·000	+0·018	N33°W	N57°E	89°	0·970	+0·242
3*	Mar. 10, 1951	15½°S	167½°E	0·02R	N41°E	N49°W	84°	0·988	−0·157	N48°W	N42°E	81°	0·994	−0·105
4	July 21, 1950	15½°S	168½°E	0·00R	N47°E	S43°E	35°	0·842	+0·539	N71°W	N19°E	72°	0·508	+0·861
5*	Dec. 2, 1950	18¼°S	167°E	0·00R	N45°E	S45°E	86°	0·999	+0·034	N44°W	S46°W	88°	0·998	+0·069
6†	July 23, 1949	18½°S	169°E	0·03R	N49°E	S41°E	67°	0·995	+0·095	N40°W	S50°W	85°	0·919	+0·393
7	July 13, 1952	18½°S	169½°E	0·05R	N16°5E	S73°5E	70°	0·924	+0·381	N81°W	N9°E	69°	0·930	+0·367
8	July 2, 1953	18¾°S	169°E	0·03R	—	—	—	+	+	N66°5W	S23°5W	—	—	+
9	May 27, 1950	20°S	168°E	0·03R	N72°E	N18°W	87°	0·999	−0·054	N18°W	S72°W	87°	0·999	−0·051
10	May 28, 1950	20°S	169°E	0·00R	N47°E	N43°W	68°	1·000	0·000	N43W	—	90°	·927	0·375
11	May 26, 1950	20¼°S	169¼°E	0·00R	N10°E	N80°W	73°	0·952	+0·306	N74°5W	N15°5E	73°	0·952	+0·306
12	June 21, 1950	20¼°S	169¼°E	0·00R	N10°5E	N79°5W	77°	0·936	+0·351	N75°5W	N14°5E	70°	0·971	+0·239
13	May 19A, 1950	20½°S	169°E	0·00R	N31°5E	N58°5W	84°	0·944	+0·329	N56°5W	N33°5E	71°	0·994	+0·111
14	May 19B, 1950	20½°S	169°E	0·00R	N2°E	N88°W	84°	0·970	+0·243	N86°5W	N3°5E	76°	0·994	+0·108
15	June 24, 1950	20½°S	169½°E	0·00R	N88°5E	N1°5W	72°	0·950	+0·313	N3°5W	S86°5W	81°	0·986	+0·164
16	July 17, 1950	20½°S	171°E	0·01R	N60°E	N30°W	78°	0·999	+0·053	N30°W	S60°W	87°	0·978	+0·208
17	May 17, 1950	21°S	169°E	0·00R	N3°5E	N86°5W	79°	0·944	+0·331	N82°5W	N7°5E	71°	0·979	+0·202
	Fiji Islands													
18	Sept. 14, 1953	18½°S	178½°E	0·00R	N61°E	N29°W	83°	0·999	−0·035	N29°W	N61°E	88°	0·993	−0·122
	Tonga Islands													
19	Feb. 13, 1951	15°S	175°W	0·03R	N58°E	N32°W	86°	0·999	+0·035	N32°W	S58°W	88°	0·998	+0·070
20*	June 29, 1948	16°S	173°W	0·01R	N47°E	N43W	86°	0·996	+0·087	N42°W	N48°E	85°	0·998	+0·070
21	Feb. 25, 1952	17°S	173½°W	0·00R	N37°5E	N52°5W	87°	0·951	−0·309	N52°5W	N37°5E	72°	0·999	−0·052
22*	Aug. 6, 1949	19¼°S	174¾°W	0·01R	N45°E	N45°W	80°	0·903	+0·429	N52°W	S38°W	65°	0·982	+0·192
23	July 27, 1952	20½°S	179°W	0·07R	N17°E	N73°W	88°	0·883	+0·470	N73°W	N17°E	62°	0·999	+0·040
24*	Sept. 8, 1948	21°S	174¼°W	0·00R	N28°E	S62°E	87°	0·743	+0·670	N59°W	S31°E	48°	0·998	+0·070
	Kermadec Islands													
25	Aug. 28, 1951	27°S	178°E	0·09R	N47°5E	N42°5W	87°	0·999	−0·053	N42°5W	N47°5E	87°	0·999	−0·053
26†	Nov. 22, 1949	29°S	178°W	0·00R	N49°5E	N40°5W	86°	0·999	+0·035	N40°5W	N49°5E	88°	0·999	+0·070
27	Sept. 11, 1952	29°S	177°W	0·00R	N33°E	—	90°	1·000	0·000	N57°W	N33°E	84°	1·000	0·000
28	Mar. 23, 1951	31°S	180°	0·04R	N33°E	N57°W	86°	0·906	−0·423	N59°W	S31°W	66°	0·998	−0·070
	New Zealand													
29	Sept. 29, 1953	36¾°S	177°E	0·04R	N54°E	S36°E	87°	1·000	+0·017	N36°W	S54°W	89°	0·999	+0·052
30	Jan. 13, 1954	49°S	165°E	0·00R	N43°5E	S46°5E	86°	0·988	+0·156	N45°5W	S44°5W	81°	0·998	+0·070

* After Webb, Reference 10. † After Hodgson and Storey, Reference 3.

Table XXVII is divided into three principal columns. The first column gives the time, location and depth of focus of the earthquakes and assigns numbers to them. These numbers will be used in subsequent tables and diagrams. In assigning numbers, the earthquakes have been grouped by geographical areas, and within each area the shocks have been arranged by latitude, from north to south. Within a particular area increasing number therefore indicates increasing southern latitude. Where two earthquakes have the same latitude they are listed in chronological order.

Since there is no way of recognizing which of the two planes obtained in any solution is the fault plane it is necessary to have two principal columns, corresponding to the possibilities *a* and *b* shown in the diagrams. In Table XXVII the plane which strikes into the northeast quadrant has been designated *a*, that which strikes into the northwest quadrant being called *b*. The diagrams of the present paper are consistent with this convention; it has been necessary however to change the published designation in the case of earthquakes 5 and 6.

For each of the possibilities *a* and *b* the strike and dip of the plane, and the direction of dip, have been listed. In each case too a unit vector, drawn in the direction of displacement has been resolved in the direction of strike and in the direction of dip. Where the dip component indicates that the hangingwall moved up the footwall, presumably indicative of a state of compression, a prefix + has been used. Conversely, where the dip component indicates that the hangingwall moved down the footwall, indicating a state of tension, a prefix − has been attached to the dip component.

Nature of the Faulting

By comparing the displacement in the strike direction with that in the dip direction, we find that in all but three cases the faulting is strike-slip, or transcurrent. The three possible exceptions are provided by the non-defined solution of earthquake 8, by the partially defined solution of earthquake 4, and by case *a* of earthquake 24. In the two former cases, which are not closely defined, transcurrent faulting is not ruled out. It must therefore be concluded that in the southwest Pacific the faulting is predominantly transcurrent.

Table XXVIII

Relation of Compressional (+) and Tensional (−) Dip Components To Focal Depth

Focal Depth	Area													
	Solomon Islands		New Hebrides Islands		Fiji		Tonga Islands		Kermadec Islands		New Zealand		Total	
	−	+	−	+	−	+	−	+	−	+	−	+	−	+
·09R									1				1	
·07R								1						1
·05R				1										1
·04R									1			1	1	1
·03R			1	2				1					1	3
·02R			1										1	
·01R		1		1				2						4
·00R				9	1		1	1		1		1	2	12

Admitting that the strike component is the principal one, can we draw any inference from the sign of the dip component? In Table XXVIII the sign of this component, as defined in the paragraph above, has been summarized for each geographical area and for each focal depth. It is clear that there is no simple relationship between the sign of the dip component and the focal depth of the earthquakes, although it may well be that where the dip component is so small its sign is a matter of accident.

We conclude that faulting is transcurrent and that the direction of dip displacement is apparently random.

Direction of Faulting

Direction of Strike

Figures 24, 25 and 26 have been prepared to investigate whether there is any systematic direction of faulting in the various geographic areas. In Figure 24 the strike directions of each of the planes *a* and *b* for the New Hebrides earthquakes have been plotted, the direction of the line indicating the direction of the strike and the length of line indicating the focal depth of the earthquake according to the indicated scale. Recalling that plane *a* is constrained by definition to lie in the northeast quadrant and plane *b* in the northwest one, it is quite clear that there is no systematic arrangement of strike direction. This is true whether we consider the data as a whole or consider specific ranges of focal depth. It will be recalled that numbers were assigned to the earthquakes in the order of their distribution from north to south; the erratic distribution of the numbers in the figure shows that there is no systematic variation of strike direction with epicentre location.

Figures 25 and 26 present similar data for the Tonga and Kermadec earthquakes. While the data in these cases are too few to allow a final conclusion to be drawn, certainly there is no clear indication of any relation between strike direction and either focal depth or geographical location.

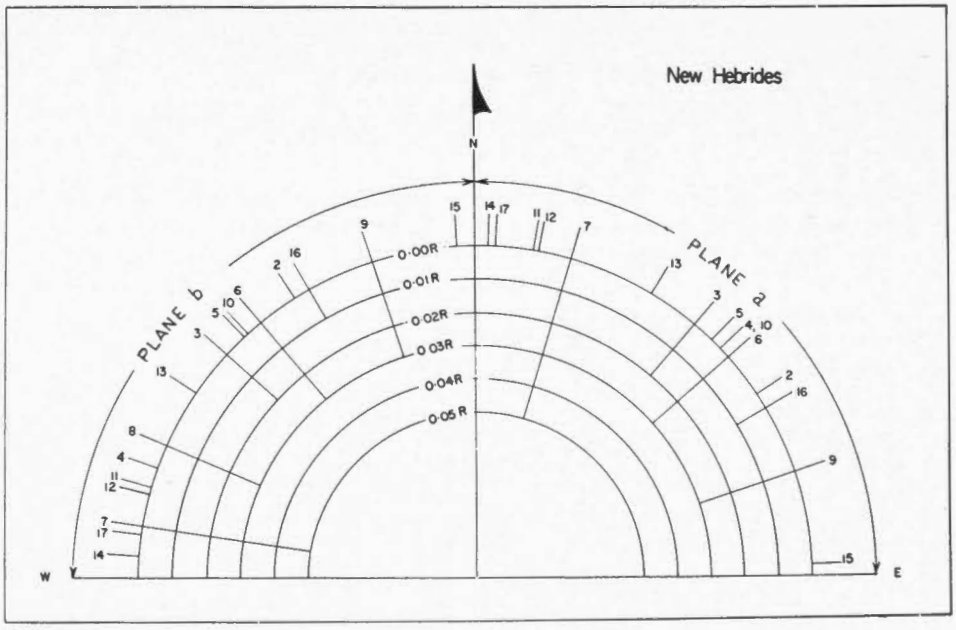


FIGURE 24

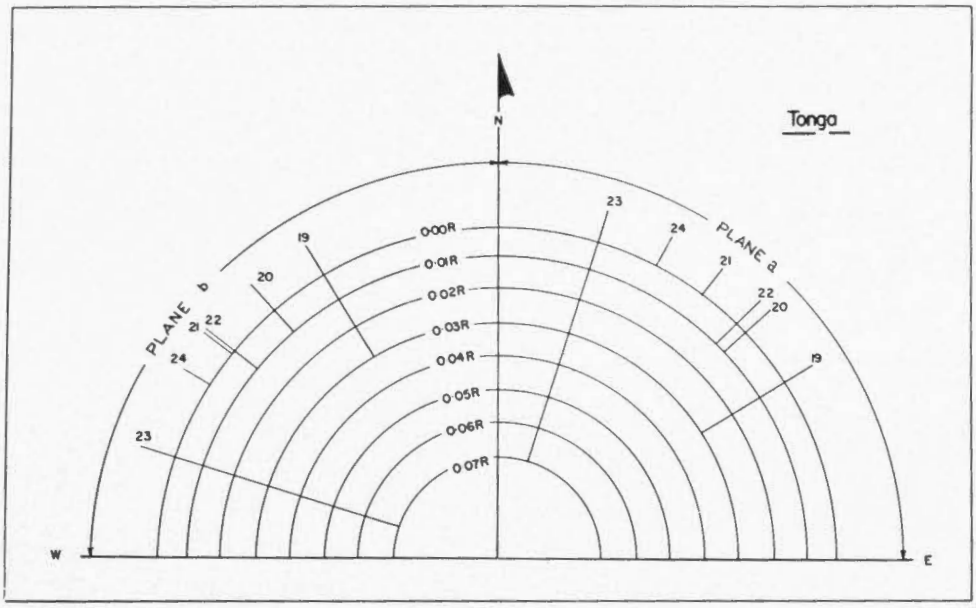


FIGURE 25

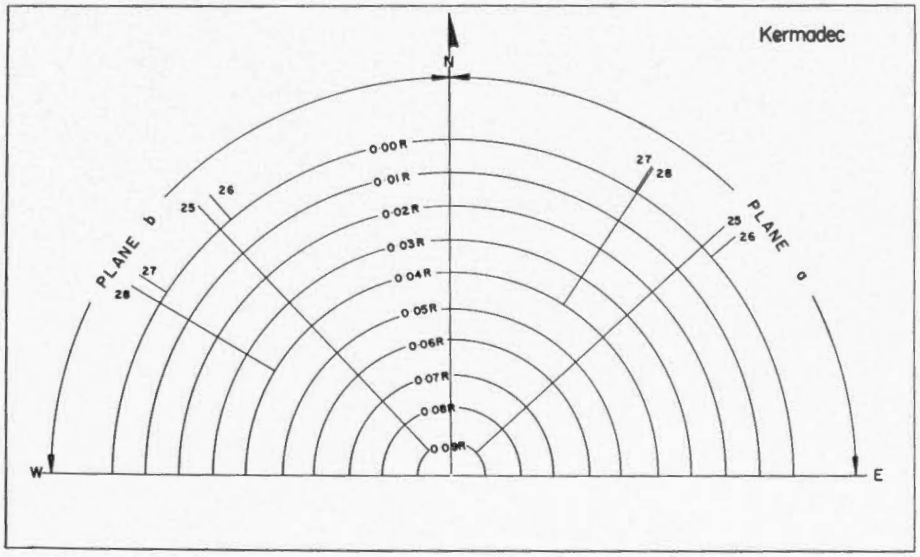


FIGURE 26

Direction of Dip

The dip of a plane is more significant than its strike, for it is a true vector quantity giving both the direction and amount of dip. In order to indicate both these quantities we shall make use of a stereographic projection of the type shown in Figure 27. The upper section of the figure represents the sphere of the earth with an epicentre at E and a line EP, striking the earth at P, representing the dip direction of a plane. Whereas normally in the fault-plane work we have used the anticentre of the earthquake as the pole of projection, we shall here use the epicentre itself as the pole, and project on the equatorial plane. This has the advantage that points near the anticentre of the earthquake, such as P, will plot into a finite region.

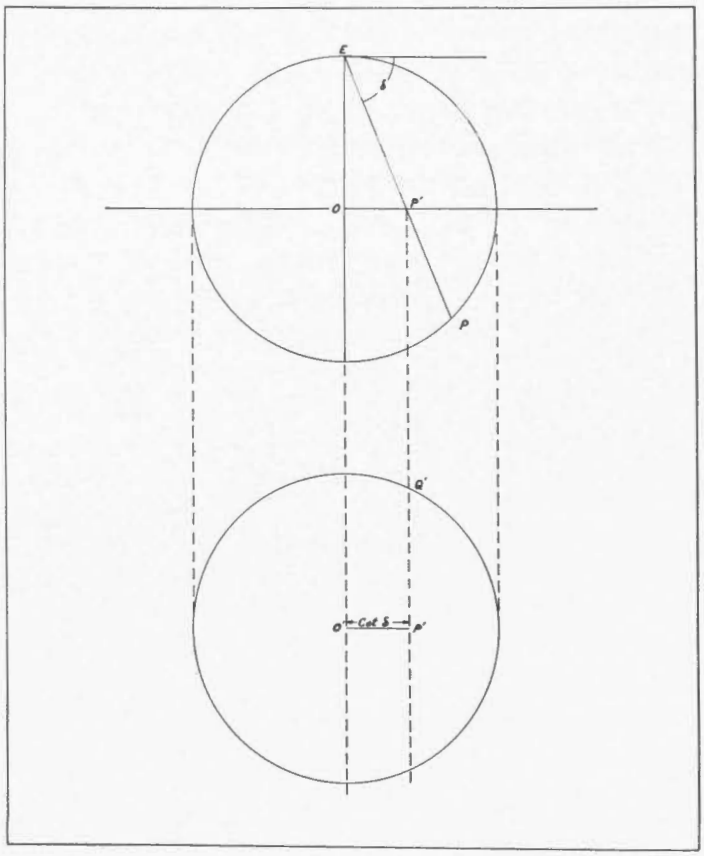


FIGURE 27

The lower section of the diagram indicates the map produced by the projection. The point P projects into a point P′ at the same azimuth as P, and at a distance $= \cot \delta$ from the centre. It will be helpful to make one further observation about the projection. Suppose that, in the upper section of the diagram, a plane be drawn through EP perpendicular to the paper. EP would represent the dip direction of this plane. In the projection the plane would become the straight line P′Q′, at right angles to the line joining P′ to the centre of the map.

Turning now to the data on dip given in Table XXVII, we plot the dip vectors of planes *a* and *b* in the projection just described. The results for the New Hebrides are shown in Figure 28. In plotting all the data on a single figure we are essentially regarding the dip vectors as free vectors, and moving them to a single origin. Dip vectors associated with planes *a* have been indicated by open symbols, those associated with planes *b* by closed ones. It is worth stressing once again that the designation of plane *a* as that one striking into the northeast quadrant was arbitrary, and there is no assurance that the open symbols, for example, do designate a connected system. Nevertheless it is remarkable that except for earthquake 15 the open symbols lie between parallel lines striking N 58° W and representing planes, one dipping SW at an angle of 83° and the other dipping NE at an angle of 84°. Similarly, with the exception again of epicentre 15, the closed symbols are confined between lines striking N 13° E and dipping NW at an angle of 86° and SE at an angle of 83°. If we

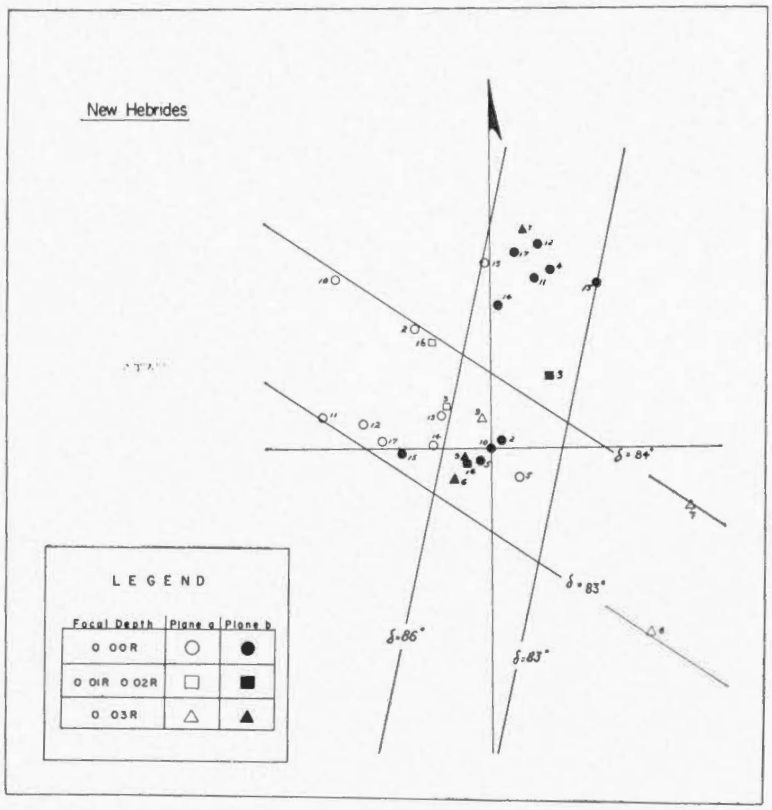


FIGURE 28

were to interchange the designations *a* and *b* for earthquake 15 there would be no inconsistencies in the pattern. This interchange is quite justified since the original designation was arbitrary.

We have then the surprising conclusion that the dip vectors of the New Hebrides earthquakes lie nearly parallel to a pair of vertical planes, one striking N 13° E, the other N 58° W. Is it significant that the mean of these two directions is N 22°.5 E, almost exactly the direction of the geographical feature?

The plot of equivalent data for the Tonga-Kermadec-New Zealand earthquakes is given in Figure 29. In this case the closed symbols lie parallel to a plane striking N 33° E and dipping to the NW at an angle of 87° $\pm$5°. The open symbols lie so closely grouped around the origin that it is not possible to define a plane. In this case in fact the dip vectors might be said to define a single direction.

With only one set of planes defined it is not possible to investigate whether the mean direction of the planes is the same as the direction of the feature, but in this case it seems improbable. The mean direction of the Tonga-Kermadec-New Zealand feature is about N 24° E. The solid symbols in Figure 29 define an angle N 33° E; to give the proper mean the open symbols would have to define a plane striking N 15° E. There is no evidence in support of this direction. However, even without this, the alignments shown in Figures 28 and 29 must be regarded as remarkable.

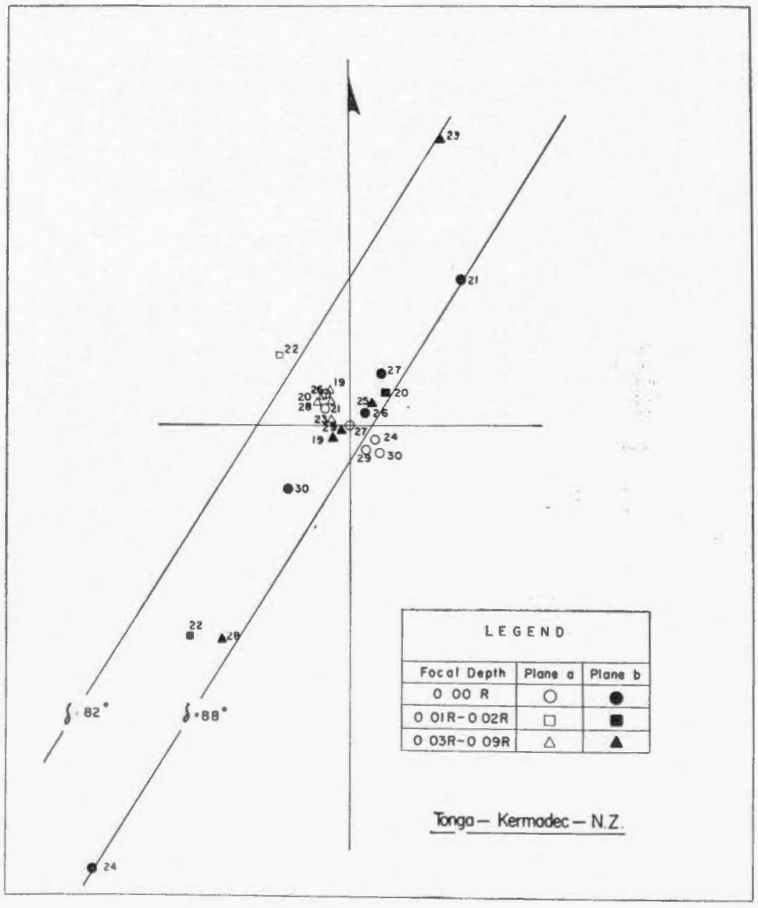


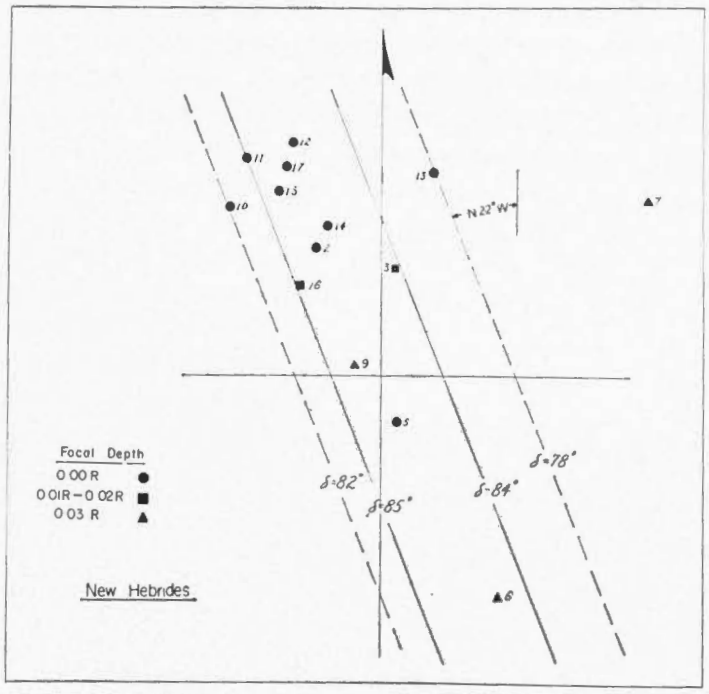
FIGURE 29

Direction of the Null Vector

It may be objected that the patterns shown in Figures 28 and 29 depend on an arbitrary designation of planes *a* and *b* and that this renders the conclusions of no significance. There is one line in each fault-plane solution which avoids this criticism. This is the line joining the two points of intersection of circles *a* and *b*. Provided the solution is closely defined, we can determine in each case the direction and dip of this line. These have been summarized in Table IXXX.

What is the significance of this line? It is a line common to both planes *a* and *b*, and therefore perpendicular to the motion vector, whichever plane represents the fault. It is in fact the axis of the displacement couple, and as such it is the one line in space which certainly undergoes no motion. For that reason we may call it the *null vector*.

In Figure 30 we have plotted on the special projection already described the points of emergence of the null vectors for the New Hebrides earthquakes. Because solutions 4 and 8 were not well defined it has not been possible to define the null vectors in those cases. With the exception of earthquake 7, all the null vectors lie between planes striking N 22° W and dipping respectively 82° to the SW and 78° to the NE. If we were to except



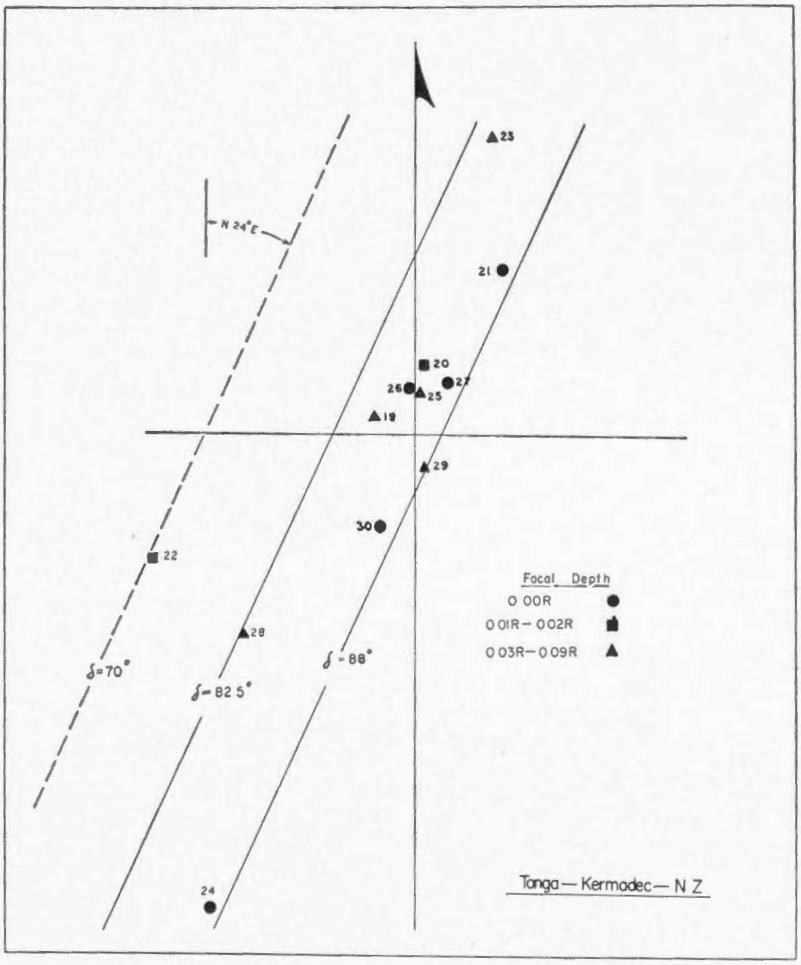


FIGURE 30 and 31.

earthquakes 10 and 13, the dips of these planes could be reduced to 85° and 84° respectively. As already stated the direction N 22° E is a very good value for the strike of the geographical feature.

Figure 31 presents the equivalent diagram for the null vectors of earthquakes of the Tonga-Kermadec-New Zealand area. The vectors clearly define a plane striking N 24° E and dipping to the NW at an angle of 79° ±9°. If earthquake 22 is ignored, this dip is 87° ±5°. As stated earlier, the best average direction for the geographic feature is N 24° E.

We have then the conclusion that the null vectors in southwestern Pacific earthquakes lie parallel, within narrow limits, to planes having the strike of the geographic feature.

It is generally agreed, on the basis of the epicentres and focal depths of earthquakes, (see for example, Gutenberg and Richter[9]), that the foci of New Hebrides earthquakes define a plane having the strike of the feature and dipping to the NE at an angle of some

TABLE XXIX

STRIKE AND DIP OF THE NULL VECTORS

Earthquake Number	Strike	Dip
Solomon Islands		
1	S87°E	50°
New Hebrides Islands		
2	N27°.5W	75°.8
3	N8°E	79°.3
5	S20°E	85°.2
6	S28°.5E	66°.4
7	N56·5E	60°.6
9	N65°W	87°
10	N43°W	68°
11	N32°W	65°.5
12	N21°W	66°.2
13	N14°.5E	69°.7
14	N20°W	74°.3
15	N29°W	69°.5
16	N44°W	77°.8
17	N25°W	67°.9
Fiji Islands		
18	N9°W	82°.9
Tonga Islands		
19	N66°W	85°.5
20	N7°E	82°.9
21	N28°E	71°.8
22	S65°W	62°.8
23	N14°E	61°.5
24	S23°.5W	47°.8
Kermadec Islands		
25	N6°E	86°
26	N6°W	85°.2
27	N33°E	84°
28	S41°W	65°
New Zealand		
29	S19°E	86°.5
30	S21°W	80°.3

70°. Similarly the foci of the Tonga-Kermadec earthquakes appear to define a plane having the strike of the feature and dipping to the NW at an angle of about 45°. It should be remarked that, while the planes defined by the null vectors are approximately vertical they both have a slight preference for the direction of dip defined by the earthquake foci.

One other point is worth making. It will be recalled that increasing number indicates increasing southern latitude within any feature. Examining Figure 30, we find a systematic progression through points 3, 5 and 6, and a close grouping of numbers 10 to 17. This latter group of points derive from earthquakes lying between 20° S and 21° S. The range of latitude involved in Figure 31 is much greater than that for Figure 30, but the steady progression of points 19, 20, and 21 and the close grouping of points 25, 26 and 27 probably has significance. It seems possible that not only do the vectors for an entire feature define a plane, but also that the vectors for a particular part of the feature define a unique direction. Substantiation of this point will have to await the accumulation of much more data.

Is there any relationship between point of emergence of the null vector and focal depth? The focal depths of the earthquakes have been indicated in Figures 30 and 31 by symbols. There does not seem to be any systematic distribution of the deep or intermediate focus symbols.

Two earthquakes, number 1 in the Solomon Islands and number 18 in the Fiji Islands, have been omitted from this discussion. At the point of epicentre 1 the Solomon Islands have a strike of about S 60° E, so that null vector strike of S 87° E does not differ too much from the direction of the feature. It is almost impossible to assign a direction to the Fiji group of islands, against which to check the direction of the null vector. A line connecting the islands would strike slightly west of north, which would be consistent with the null vector direction of N 9° W. At least it may be concluded that there is no obvious inconsistency shown by these two earthquakes to the conclusion that the plane of the null vectors is approximately parallel to the strike.

Discussion

Until analysis similar to that of this section has been applied to earthquakes of other areas the patterns found in the southwest Pacific must be regarded as local ones. So far their physical significance is uncertain, but one conclusion may safely be drawn. The correlation between the strike of the geographical feature and the plane defined by the null vector can scarcely be accidental. Under the circumstances, the techniques of the fault-plane project receive a considerable degree of confirmation, for in the hands of two different operators, and over a period of five years, it has produced results which are not only consistent with themselves but which also indicate relationships with the geographical features of the area.

CONCLUSIONS

Thirty earthquakes, 16 of them associated with the New Hebrides feature and 12 of them with the Tonga-Kermadec-New Zealand feature, and occurring over a period of more than five years have been analysed by the fault-plane techniques by two different investigators. These fault-plane solutions would support the following conclusions:

1. Faulting in the southwest Pacific is predominately transcurrent along steeply dipping planes.

2. There is no consistency in the strike direction of the faults, nor any systematic variation either with latitude, depth of focus or position on the associated arcuate feature.

3. Vectors drawn in the direction of maximum dip of the two planes obtained in any solution tend to lie parallel to two nearly vertical planes; the relationship between the strike of these planes and the strike of the associated feature is not clear.

4. Defining the null vector as that vector common to the two planes, and therefore perpendicular to the displacement couple whichever plane represents the fault, it is found that the null vector has a strong tendency to lie parallel to an almost vertical plane having the strike direction of the associated geographic feature. There is also the suggestion, which the data are too few to establish for certain, that for any closely associated group of epicentres there tends to be a unique direction for the null vector.

5. These relationships, although their physical significance is still obscure, tend to confirm the validity of the techniques of analysis used in these studies of earthquake fault-planes.

ACKNOWLEDGEMENTS

The compilation of data and the original plotting of the 1951 earthquakes was carried out by J. F. J. Allen. Similar work for the more recent earthquakes was done by R. R. Clark. The figures have been drawn by Mrs. I. H. Blüme and P. J. Winter. I am very grateful for all this help. I am also much indebted to my colleague Dr. P. L. Willmore for helpful discussion on the fault-plane results; in particular, it was a suggestion of Dr. Willmore's that led to the plotting of the null vectors.

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DIRECTION OF FAULTING IN SOME OF THE LARGER EARTHQUAKES OF THE NORTH PACIFIC, 1950-1953

BY

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Direction of Faulting in Some of the Larger Earthquakes of the North Pacific, 1950-1953

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ABSTRACT

The direction of faulting is determined for 11 earthquakes occurring in the north Pacific during the years 1950-1953. One of these is the great Kamchatka earthquake of November 4, 1952. It is shown that this earthquake was probably a double one; solutions are presented for each of the postulated shocks.

Combining the present solutions with those published earlier provides 24 solutions for consideration. These indicate that in Alaska, British Columbia and Washington faulting may be normal, thrust or transcurrent with no pattern yet apparent in the direction of strike or dip of the planes. In other areas of the north Pacific transcurrent faulting on steeply dipping planes seems to be the rule. The strike direction of the planes seems to be random, but the dip vectors and the null vectors appear to lie parallel to nearly vertical planes. These planes probably have some tectonic significance, although so far it has not been possible to establish its exact character.

INTRODUCTION

A paper has recently been published[1] giving fault plane solutions for a number of southwest Pacific earthquakes. The present paper gives solutions for 11 earthquakes in the north Pacific; the two are to be regarded as companion papers, the same form of presentation being followed in each. As in the earlier paper, it is assumed that the reader is familiar with the methods of the project.

The solutions here presented derive from questionnaires circulated in May, 1952 and in March, 1954.

PRESENTATION OF THE DATA

Table I lists the earthquakes for which solutions have been attempted, in three groups. In the first of these no pattern was apparent, either because the earthquake was too small or because the beginning was complicated. Whatever the cause, the distribution of compressions and dilatations was random. The second group consisted of five earthquakes, all lying within $\frac{1}{2}°$ of $50\frac{1}{2}°$N, $156\frac{1}{2}°$E, all with a focal depth of 60 km., and all occurring between July and November, 1953. No solution could be obtained for these earthquakes, but for a different reason. Here whole groups of stations would be consistent among themselves, but the several groups could not be brought into a single solution. It seems clear that some mechanism more complicated than failure under a couple is responsible for these earthquakes. In order that others may study these interesting cases all the motion data collected are listed in Table II, together with the distance and azimuths of each of the contributing stations from each of the epicentres.

The third group of earthquakes consists of those for which solutions have been obtained. Table III lists the data on which the solutions are based.

The notation used in Tables II and III has been described in earlier papers.

[1] J. H. Hodgson, "Direction of Faulting in Some of the Larger Earthquakes of the Southwest Pacific, 1950-1954", *Publications of the Dominion Observatory*, 18, No. 9, 1956.

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TABLE I

LIST OF EARTHQUAKES CONSIDERED

Date	H (G.M.T.)	Epicentre		Focal Depth	Magnitude	Remarks
		φ	λ			
Earthquakes for which the data were too few to permit a solution						
April 20, 1950	09:50:44	45°N	150°E	0·00R	6½	Too few data
Aug. 26, 1950.....	04:39:27	65°N	162°W	0·00R	6½	Too few data
Sept. 2, 1950.....	02:47:23	52½°N	169°W	0·01R	6¼	Too few data
Sept. 16, 1950.....	21:58:15	52½°N	178°E	0·01R	6½	Too few data
Jan. 18, 1951.....	21:15:50	52°N	177°W	0·00R	6¼	Too few data
Feb. 13, 1951.....	22:12:58	56°N	155½°W	0·00R	7	Conflict of data
June 25, 1951.....	16:12:32	61°N	150°W	0·01R	6¼	Too few data
July 19, 1951.....	20:41:25	51½°N	177½°W	0·00R	6	Too few data
Aug. 24, 1951.....	14:21:15	47°N	151°E	0·00R	6½	Too few data
Nov. 6, 1951.....	16:40:06	47°N	154°E	0·00R	7	Conflict of data
Nov. 8, 1951.....	13:45:09	54½°N	160°W	0·00R	6¼	Too few data
Nov. 12, 1951.....	08:09:26	47°N	154°E	0·00R	6½	Too few data
Nov. 15, 1951.....	19:42:12	52½°N	160½°E	0·00R	6¼	Too few data
Jan. 5, 1953.....	07:48:17	54°N	170°E	0·00R	6¾	Conflict of data
Earthquakes for which the data were sufficient but inconsistent						
July 1, 1953.....	02:59:35	50½°N	157°E	0·005R	6¾	Conflict of data
July 22, 1953.....	05:11:15	51°N	157°E	0·005R	6¾	Conflict of data
Sept. 4, 1953.....	07:23:05	50°N	156½E	0·005R	6¾	Conflict of data
Sept. 23, 1953.....	02:14:36	50½°N	156°E	0·005R	7	Conflict of data
Nov. 10, 1953.....	23:40:20	50½°N	157°E	0·005R	7	Conflict of data
Earthquakes for which solutions have been obtained						
Feb. 28, 1950.....	10:20:58	46°N	143½°E	0·05R	7¾	
March 27, 1950.....	13:04:40	53½°N	173°E	0·00R	6¾	
June 27, 1950.....	15:41:54	45½°N	140°E	0·00R	6¾	
June 22, 1952.....	21:41:53	46°N	153½°E	0·00R	7	
Nov. 4, 1952.....	16:58:24	52½°N	159°E	0·00R	8½	
Nov. 29A, 1952....	08:22:34	53°N	160°E	0·00R	7	
Nov. 29B, 1952....	23:46:25	56°N	155°W	0·00R	6¾	
Jan. 12, 1953.....	17:23:39	49½°N	156°E	0·00R	6¾	
Feb. 25, 1953.....	21:16:18	56°N	156½°W	0·00R	6¾	
Mar. 5, 1953.....	21:01:23	51°N	158°E	0·005R	6¾	
Oct. 5, 1953.....	04:31:40	53½°N	160½°E	0·00R	6¾	

TABLE II

Distance, Azimuth and First Motion Data for Five Kamchatka Earthquakes for which no Solutions were Obtained

Earthquake	July 1, 1953			July 22, 1953			September 4, 1953			September 23, 1953			November 10, 1953		
Station	Dist.°	Az.°	Motion	Dist.°	Az.°	Motion	Dist.°	Az.°	Motion	Dist.°	Az.°	Motion	Dist.°	Az.°	Motion
Aberdeen				70·6	N11·9W	C CC	71·6	N12·1W	C	71·0	N12·4W	C	71·1	N11·9W	C
Algeria University				89·5	N20·6W	C									
Alicante	89·1	N17·5W	D DD	88·7	N17·5W	C DD	89·5	N17·9W	D DD	89·0	N18·3W	D DD	89·1	N17·5W	D DD
Almeria	91·0	N16·3W	C	90·5	N16·3W	C	91·4	N16·7W	D	90·8	N17·1W	D	91·0	N16·3W	D DD
Athens	82·6	N35·5W	C	82·2	N35·5W	C	82·9	N35·8W	C	82·3	N36·2W	C	82·6	N35·5W	C
Bandung				71·6	N127·5W	C	70·8	N127·6W	C cC	70·8	N128·2W	D			
Basel				78·2	N20·6W	C	79·0	N20·9W	C	78·4	N21·2W	D	78·7	N20·6W	C CC
Belgrade	77·7	N30·1W	D	77·2	N30·1W	C	77·9	N30·3W	C	77·4	N30·7W	C	77·7	N30·1W	C
Berkeley	56·4	N69·6E		56·3	N69·9E	C	56·9	N69E	C	57·0	N69E	C	56·4	N69·6E	C
			cC			cC			cC			cC			
Bermuda–Columbia	89·5	N34·2E	C	89·1	N34·2E	C	90·1	N33·9E	C CC	89·8	N33·5E	C CC	89·5	N34·2E	C
Bogota				109·4	N55·3E	CC							109·7	N55·4E	CC
Bologna				80·2	N24·2W	C	80·9	N24·5W	C						
Bombay				71·9	N82·3W	C	71·7	N82·3W	C	71·3	N82·8W	C			
Bozeman				57·4	N56·3E	C	58·2	N55·5E	C	58·2	N55·5E	C			
Brisbane				78·4	N176·4W	C				77·9	N177·3W	C	77·9	N176·4W	D
Budapest				75·3	N28W	C	76·0	N28·2W	cC						
Butte	56·6	N56·6E	C	56·4	N56·8E	C				57·2	N56·0E	C	56·6	N56·6E	C
Calcutta	59·0	N91·2W	C				59·1	N91·3W	C	58·8	N91·9W	C	59·4	N91·2W	D
Cartuja	90·8	N15·4W	C CC DDD	90·4	N15·4W	D CC PcP=C	91·2	N15·8W	D DD				90·8	N15·4W	D
Chicago-U.S.C.G.S.	72·0	N45·2E	C	71·6	N45·3E	C				72·5	N44·6E	C	72·0	N45·2E	D
Chihuahua													72·5	N66·2E	C
Chinchina	108·6	N56·6E	D				109·1	N56·3E	C	109·1	N55·7E	CC	108·6	N56·6E	C
Chur	78·9	N22·1W	C				79·2	N22·4W	C	78·6	N22·8W	C			
Cincinnati	75·6	N44·9E	C	75·2	N45·E	C	76·1	N44·5E	C dD	76·0	N44·2E	C cC	75·6	N44·9E	C
Cleveland	75·0	N41·6E	D DD cC	74·6	N41·7E	C dD	75·5	N41·2E	C cC	75·4	N40·9E	C cC	75·0	N41·6E	C cC
Coimbra							89·0	N11·5W	D						
College	31·5	N42·2E	D	31·3	N42·7E	D	32·1	N41·6E	D	31·9	N42·2E	D	31·5	N42·2E	D

TABLE II—*Continued*

Distance, Azimuth and First Motion Data for Five Kamchatka Earthquakes for which no Solutions were Obtained

Earthquake	July 1, 1953			July 22, 1953			September 4, 1953			September 23, 1953			November 10, 1953		
Station	Dist.°	Az.°	Motion	Dist.°	Az.°	Motion	Dist.°	Az.°	Motion	Dist.°	Az.°	Motion	Dist.°	Az.°	Motion
Collmberg				73·4	N22·6W	C DD	74·2	N22·8W	C CC				73·9	N22·6W	C
Colombo							76·2	N95·9W	D						
Columbia	81·4	N45·5E	C	81·0	N45·5E	C				81·8	N44·8E	D	81·4	N45·5E	C
Copenhagen				69·5	N20·5W	C	70·3	N20·7W	C	69·8	N21·0W	C			
Debilt	74·8	N17·6W	C dD	74·4	N17·6W	PcP=C C			PcP=C	74·6	N18·2W	C			
Djakarta	71·1	N126·2W	C	71·4	N126·3W	C	70·6	N126·5W	C CC	70·6	N127·1W	C	71·1	N126·2W	C CC cC
Fayetteville	73·2	N53·0E	C	72·9	N53·2E	C	73·8	N52·6E	C CC	73·7	N52·4E	C			
Florence	81·3	N24·4W	C				81·6	N24·7W	C	81·0	N25W	C	81·3	N24·4W	C
Fresno	58·6	N69·0E	C	58·5	N69·3E	C	59·1	N68·4E	C				58·6	N69·0E	C
Fukuoko	25·9	N121·1W	C	26·2	N122·0W	C	25·4	N121·0W	C	25·4	N122·6W	C	25·9	N121·1W	C
Guantanamo Bay							96·7	N47·9E	C						
Halifax	78·7	N28·3E	C	78·3	N28·3E	C	79·3	N27·9E	C	79·0	N27·6E	C	78·7	N28·3E	C
Helwan	86·6	N45·0W	D	86·2	N45·0W	D	86·7	N45·3W	D	86·1	N45·7W	D	86·6	N45·0W	D
Hiroshima	24·2	N123·0W	C				23·7	N122·8W	C				24·2	N123·0W	C
Hong Kong				43·9	N114·8W	C	43·2	N114·3W	C DDD	43·1	N115·3W	C			
Honolulu				46·0	N113·2E	C				46·4	N111·8E	C	45·8	N112·8E	C
Hungry Horse				54·1	N55·4E	C	54·9	N54·6E	C	54·9	N54·6E	D	54·4	N55·1E	C
Hyderabad				69·5	N87·5W	C CC	69·2	N87·5W	C C	68·9	N88·1W	C	69·5	N87·4W	C
Karapiro										89·9	N164·7E	D			
Karlsruhe	77·1	N20·6W	D	76·6	N20·7W	C PcP=D	77·5	N20·9W	C CC	76·9	N21·3W	C	77·1	N20·6E	C CC PcP=C
Kew	76·4	N14·4W	C				76·8	N14·6W	C						
Kirkland Lake	70·0	N36·7E	C	69·6	N36·8E	C CC	70·6	N36·3E	C dD				70·0	N36·7E	C
Kiruna	57·4	N18·0W	C	56·9	N18·1W	C	57·8	N18·1W	C	57·2	N18·4W	C CC PcP=C	57·4	N18·0W	C PcP=d
Kodaikanal							75·2	N91·8W	C				75·5	N91·5W	C
Koti	24·2	N125·9W	C DD	24·5	N126·8W	C DD	23·7	N125·8W	C	23·7	N127·6W	C	24·2	N125·9W	C

La Paz	130·4	N63·3E	C_1' CC	130·2	N62·9E	C_1' CC	130·9	N63·1E	C_1' CC	131·0	N62·2E	C_1' CC	130·4	N63·3E	C_1' CC
La Plata				150·1	N70·7E	C_1'							150·2	N71·5E	C_2'
Lisbon							90·6	N11·2W	C						
Malaga													91·4	N14·8W	C
Manila				46·6	N128·4W	C	45·7	N128·2W	C	45·8	N129·2W	C	46·3	N128·0	C
Matsushiro	19·5	N129·2W	C	19·9	N130·3W	C	19·0	N129·0W	C CC	19·1	N131·1W	C	19·5	N129·2W	C
Messina	85·2	N29·5W	C	84·8	N29·5W	C	85·5	N29·9W	C	84·9	N30·2W	C			
Miami				88·2	N49·3E	C	89·1	N48·9E	D						
Mineral	55·2	N66·9E	C cC				55·1	N66·3E	C	55·8	N66·3E	C	55·2	N66·9E	C
Mount Hamilton	57·2	N69·7E	C cC				57·6	N69·1E	C cC	57·8	N69·1E	C dD			
Mount Wilson	61·4	N70E	C	61·2	N70·3E	C cC	61·9	N69·5E	C	62·0	N69·4E	C			
Neuchâtel				78·9	N20·4W	C	79·7	N20·7W	C				79·3	N20·4W	C
New Delhi				62·1	N78·4W	D	62·0	N78·2W	C	61·6	N78·8W	C			
Osaka							21·9	N127·3W	C						
Ottawa	74·0	N35·7E	C	73·6	N35·8E	C DD DDD	74·6	N35·3E	C DD dD	74·3	N35·1E	C CC	74·0	N35·7E	C
Palisades	78·4	N36·8E	C	78·0	N36·9E	C							78·4	N36·8E	C
Palo Alto										57·4	N69·3E	C			
Palomar				62·6	N70·2E	C cC	63·2	N69·4E	C	63·3	N69·3E	C	62·7	N70·0E	C
Pasadena	61·4	N70·2E	C	61·2	N70·4E	C cC	61·9	N69·6E	C	62·0	N69·5E	C	61·4	N70·2E	C
Pavia				80·0	N22·5W	C									
Philadelphia				78·4	N38·3E	C	79·4	N37·8E	C				78·8	N38·2E	C
Pittsburgh				76·1	N41·2E	C	77·1	N40·7E	C	76·9	N40·5E	C	76·5	N41·1E	C
Prague	74·6	N24·0W	C	74·2	N24·0W	C	75·0	N24·2W	C	74·4	N24·6W	C CC CCC PcP=C	74·6	N24·0W	C
Quetta				67·2	N70W	D	67·2	N69·9W	D	66·7	N70·5W	D			
Rapid City				62·5	N53·2E	C	63·4	N52·5E	C	63·3	N52·4W	C			
Rathfarnham	75·4	N10·3W	C	74·9	N10·3W	C cC	75·8	N10·5W	C	75·3	N10·9W	C dD	75·4	N10·3W	C
Reno	56·8	N66·6E	C	56·6	N66·9E	C cC	57·3	N66E	C cC	57·4	N66·0E	C	56·8	N66·6E	D
Resolute Bay	46·3	N20·5E	C DD	45·8	N20·6E	C PcP=C				46·5	N20·3E	C	46·3	N20·5E	C
Riverside				61·8	N70E	C cC	62·5	N69·2E	C	62·6	N69·1E		62·0	N69·8E	C
Riverview	84·3	N175·1W	C	84·8	N175·1W	C	83·8	N175·5W	C dD	84·3	N176·0W	C CC PcP=D	84·3	N175·1W	C CC
Rome	82·7	N25·9W	C	82·3	N25·9W	C				82·4	N26·6W	C			
Salo				79·3	N23·2W	C				79·5	N23·9W	C			
Salt Lake City	60·5	N60·7E	C				61·0	N60·2E	C	61·1	N60·1E	C	60·5	N60·7E	C

TABLE II—*Concluded*

Distance, Azimuth and First Motion Data for Five Kamchatka Earthquakes for which no Solutions were Obtained

Earthquake	July 1, 1953			July 22, 1953			September 4, 1953			September 23, 1953			November 10, 1953		
Station	Dist.°	Az.°	Motion	Dist.°	Az.°	Motion	Dist.°	Az.°	Motion	Dist.°	Az.°	Motion	Dist.°	Az.°	Motion
San Juan				101·1	N41·4E	C CC							101·5	N41·5E	D
Santa Clara							57·4	N69·3E	D	57·6	N69·2E	D	57·0	N69·9E	D
Sapporo	13·1	N119·5W	C	13·4	N121·3W	D CC	12·6	N118·6W	C CC	12·6	N121·7W	C DD	13·1	N119·5W	D
Sendai	16·9	N131·2W	C	17·2	N132·4W	D	16·3	N131·0W	D	16·4	N133·4W	C	16·9	N131·2W	D
Seven Falls				73·8	N31·8E	C							74·2	N31·7E	C
Shasta	54·5	N67·0E	C							55·1	N66·5E	C DD dD	54·5	N67·0E	C
Shawinigan Falls	74·0	N33·2E	C	73·6	N33·3E	C	74·6	N32·8E	C	74·4	N32·6E	C	74·0	N33·2E	C
Shillong			C						C			C			C
Sitka				38·9	N54·1E	D	39·5	N53·0E	D	39·4	N53·3E	D			
Skalnate	73·8	N27·9W	C				74·1	N28·1W	C						
Strasbourg	77·6	N20·3W	C							77·4	N21·0W	C			
Stuttgart	77·1	N21·2W	C	76·7	N21·2W	C	77·5	N21·5W	C	76·9	N21·8W	C	77·1	N21·2W	C PcP=D
Suva				71·6	N158·5E	DD	70·7	N157·9E	C CC				71·1	N158·4E	C CC
Tamanrasset				102·2	N26·8W	D				102·3	N27·7W	D	102·6	N26·8W	D
Tananarive										116·1	N88·3W	C_1'			
Tinemaha	59·3	N67·8E	C	59·1	N68E	C	59·8	N67·2E	C cC	59·9	N67·1E	C	59·3	N67·8E	C
Tokyo	19·5	N133·7W	C	19·8	N134·7W	C DD	18·9	N133·7W	C	19·0	N135·8W	C	19·5	N133·7W	D CC
Toledo							88·7	N14·9W	C						
Trieste	78·9	N25·3W	D	78·5	N25·4W	C	79·2	N25·6W	D	78·6	N26·0W	C	78·9	N25·3W	C
Tucson	67·1	N66·8E	C	66·9	N67·0E	C	67·6	N66·3E	C	67·7	N66·2E	C	67·1	N66·8E	C
Uccle				75·8	N17·5W	C	76·6	N17·7W	D cC	76·0	N18·1W	D	76·2	N17·5W	C
Uppsala	65·0	N21·3W	C	64·5	N21·3W	C	65·4	N21·4W	C	64·8	N21·8W	C	65·0	N21·3W	D
Victoria	49·2	N59·7E	C dD	49·0	N60·1E	C cC	49·8	N59·1E	C dD				49·2	N59·7E	D dD
Wellington													92·9	N166·7E	C
Weston	78·2	N34·4E	C				78·8	N34·0E	C	78·5	N33·8E	C	78·2	N34·4E	C
Witteveen				73·4	N18·3W	C	74·2	N18·5W	C	73·7	N78·8W	C			
Zurich	78·6	N21·3W	C	78·1	N21·3W	C				78·4	N21·9W	C	78·6	N21·3W	C

TABLE III

Data on Twelve Earthquakes for which Solutions were Obtained

STATION	Feb. 28, 1950	March 27, 1950	June 27, 1950	June 22, 1952	Nov. 4A, 1952	Nov. 4B, 1952	Nov. 29A, 1952	Nov. 29B, 1952	Jan. 12, 1953	Feb. 25, 1953	March 5, 1953	Oct. 5, 1953
Aberdeen				(D) DD		C DD		(D)	DD			C
Algeria University									(D)		C	D
Alicante				C (CC)			C DD	C (CC)	(D) DD	(C) DD	DD	C CC
Almeria	C		D	(D)	(CC)		C	C	C	(C)	(D)	D DD
Apia										C		
Arapuni	D											
Arcata	C	C										
Athens	D cC	(C)		(C)			C			(C)		(C)
Auckland	D					D						D
Bandung						C	D	D DDD			(D)	(C)
Basel	C	D	C CC		C		C	C	C	D	C	C
Belgrade		D	C	C		D	C	D	C	D	C	(C)
Berkeley	C	C	C	D	C	C	(cC)		D dD	D cC	C	C
Bermuda-Columbia							D			D	C	C cC
Besançon								DD				
Bogota	(C_1')					C DD	DD	C		(C)	(CC)	
Bologna			C			D						
Bombay												C
Boulder City		C	C									
Bozeman	C			D	C				D	D	D	C
Brisbane	D	D	D	C	(C)		D	C	C	D DD	(C)	(C)
Budapest	C			(D)	(D)		(D)					C
Butte	(D)				C		C	(C)	D	D	DD C	C
Calcutta	(D)											C
Cartuja	(D)		D	C DD dD	D		D DD	(D) (CC) PcP=C	C (CC)	(C) DD	(D) (CC)	D DD
Chicago—U.S.C.G.S.				D			(D)		(D)	D		(D)
China Lake	C	C										
Chinchina				CC			(CC)			(C)		
Christchurch	D (DD)					D						
Chur	C		C							D	C	C
Cincinnati	C (dD)			C	(D)		C	C	C	D	C cC	C
Cleveland	C cC	C	C	C					C	D	C cC	C
College		D	C	D	D		(D)	C	D	C	D	
Collmberg	(D)							C			C	C
Colombo	(C)											
Columbia	C			C	C		(C)	C		D	C	C
Copenhagen				C				C DD PcP=C		(D) PcP=C	C	(D)
De Bilt	C		C	C				C (CC)	C cC	(C)	C (dD)	C
Djakarta	D						D DD	(C) CC DDD	C (dD)		C (cC)	(C) DD
Fayetteville				(C)			C	D	C	D	C	C
Florence				C	C			C		D	C	C
Fresno	C (dD)	C	D	D cC	C		C dD	(C)	D	D	C	
Fukuoko	C	D		D			(D)		D	C	C	C
Grahamstown										D_1'		
Haiwee	C	C	D									

TABLE III—*Continued*

Data on Twelve Earthquakes for which Solutions were Obtained—*Continued*

STATION	Feb. 28, 1950	March 27, 1950	June 27, 1950	June 22, 1952	Nov. 4A, 1952	Nov. 4B, 1952	Nov. 29A, 1952	Nov. 29B, 1952	Jan. 12, 1953	Feb. 25, 1953	March 5, 1953	Oct. 5, 1953
Halifax					C		D	(D)	C	D	C	C
Harvard	C	C CC	C	C								
Helwan	(C)	D	D	D	D			D			(D)	(D)
Hiroshima				D								C
Hong Kong				(C)		C	C		C		C	C
Honolulu	(C)	C			C				(C)	(D)		(C)
Huancayo	D_1'											
Hungry Horse	C	C	C						(C)	D cC	C	C
Hyderabad	D	D										(D)
Jena				C								
Jersey						C						
Kiamata	(C)					D						
Kalocsa	C			(D)		D	C				(D)	
Karapiro									D			
Karlsruhe	C	(C)	C	C PcP=D			(D)	C	(D)	D PcP=C	C	C
Kew	C	D	C	C	C						C	C
Kirkland Lake				C	D		(D)	C (CC)	C	D dD	(C)	C
Kiruna				C	C		C	C		C dD	C	C PcP=C
Kodaikanal	D											
Koti	C		C	(C)		C	C				C	
Ksara	D	D										
Kumagaya						C						
La Jolla	C											
La Paz	D_1' DD	(CC)	DD	(C_1') CC	(C_1') (CC)		D_1' DD CC	CC	(D_1') CC		(C_1') DD	
La Platta												D_1'
Leipzig	(D) DD											
Lincoln	C	C			(D)				C	D		C
Lisbon	C			(D)	D			C		D		C
Maebashi						C						
Malaga				(D)			D CC	C DD				(D)
Manilla	D				(C)				D		C	C
Matsushiro	C			D		C	dD C	D	(C)	C (DD)	C	C
Merida						(D)						
Messina				D							C	
Mineral	C	C	C	D			C dD		(C)		C	C
Mount Hamilton	C (dD)	C	D	D cC	C	C	C (CC) (cC)	(C) CC	D	D	C PcP=D	C
Mount Wilson	C	C	D*									
Nagoya	C											
Nemuro	D	C	D	(C)		C						
Neuchâtel	(D)										C	C
New Delhi	C	D										
New Plymouth	D											
New York City College	C cC	C	(D)									
Osaka	C					C						
Ottawa	C	C		C	D		C DD CCC	C	C DD		C	C
Palisades	C	(D)		C				C				C
Palo Alto	C (dD)		D									
Palomar	C	C		D		D		D	D	D	C	C

* See note in text *re* Pasadena group of stations.

TABLE III—*Continued*

Data on Twelve Earthquakes for which Solutions were Obtained—*Continued*

STATION	Feb. 28, 1950	March 27, 1950	June 27, 1950	June 22, 1952	Nov. 4A, 1952	Nov. 4B, 1952	Nov. 29A, 1952	Nov. 29B, 1952	Jan. 12, 1953	Feb. 25, 1953	March 5, 1953	Oct. 5, 1953
Pasadena	C	C	D*	D			C	D		D	C	C
Pavia				C			(D)		C		C	
Philadelphia					C		C	C		(C)		C
Pierce Ferry	C	C	C									
Pietermaritzburg	(C_1')									D_1'		
Pittsburgh					D				D			
Poona	D		C									
Prague	C CC cC PcP=C	D	C (DD)	C			C	C	D	C	C	C
Pretoria	D_1'										C_1'	
Pueblo						D						
Quetta										D	(D)	
Rapid City	C						(D)	C	D	D	C	
Rathfarnham			C	(D)	C						C	C
Reno	C	C	C	D			C	D		D	D	D
									(cC)	PcP=C		
Resolute Bay				C	C			C	C	(D)		C DD
Reykjavik											C CC	
Riverside	C	C	D*			C			D	D	C	C
Riverview				D		C			C		D	D
	(cC)						CC		(cC) (PcP=C)		dD	dD
Rome	C	D	C	C	C			C		D	C	
Saint Louis	C	C	C									
Salt Lake City	C		C	D			(D)	D	D	D	C	C
San Juan	(D)				D			C		D		C
											CC	
Santa Clara	(D)	(D)		(C)		C		(C)	D	(C)	C	
Sapporo	C	C	D	(C)		C					C DD	C
Scoresby Sund				C				(D)				
							PcP=C (CCC)					
Seattle	C		(D)		C							
Sendai	C		D	D	(C)		C			C	C	C
Seven Falls										D		C
Shasta	C	C	C							D	C	C
Shawinigan Falls	C								C	D dD	C	C
Shillong											C	C
Sitka	(D)	(D)	(D)	(C)	(C)				(C)		C	
Skalnate Pleso												C
Stara Dala												C
State College				C								
Strasbourg	C		C	C	C			C	C	(C)	C	C
Stuttgart	C		C	C	C			C	C	D	C	C
Suva	D (DD) DDD											
Szeged												C
Tacubaya	C					D	(C)			D		
Tamanrasset				(C)	D							
Tananarive										(C)		
	CC											
Tinemaha	C	C	D*				C	D		D	C	C
Tokyo	C		D	D			(D)				C	C
		dD										
Trieste				C			C	C	(D)	(C)	C	C
Tuai	(C)									(C)		

* See note in text *re* Pasadena group of stations.

TABLE III—*Concluded*

Data on Twelve Earthquakes for which Solutions were Obtained—*Concluded*

STATION	Feb. 28, 1950	March 27, 1950	June 27, 1950	June 22, 1952	Nov. 4A, 1952	Nov. 4B, 1952	Nov. 29A, 1952	Nov. 29B, 1952	Jan. 12, 1953	Feb. 25, 1953	March 5, 1953	Oct. 5, 1953
Tucson	C	C	D	D	C	.....	.....	D	(C)	D (DD)	C	C
Uccle	.....	.....	.....	.....	.....	.....	.....	.....	D	D	C PcP=D	(D)
Ukiah	D	.....	.....	.....	.....	D						
Uppsala	C	.....	C	C (CC) PcP=C	C	.....	C	C	.....	C	C	C
Victoria	C	C	C	D	D	.....	.....	.....	D	D CC	(PcP=C) C	
Wajima	.....	.....	.....	.....	.....	C	.....	.....	cC	cC	.....	C
Wellington	D											
Weston	.....	.....	.....	.....	D	.....	C	.....	.....	D	.....	C
Witteveen	.....	.....	.....	.....	.....	.....	(D)	.....	.....	D	.....	C
Zurich	C	(C)	C	C	.....	.....	C	C	C	D	C	C

Two of the earthquakes listed in Table I occurred on the same day, November 29, 1952. To simplify reference to these earthquakes the dates have been called Nov. 29A and Nov. 29B. The theory will subsequently be advanced that the earthquake of November 4, 1952 was a double one. In Table III the postulated shocks have been referred to as Nov. 4A and Nov. 4B, 1952.

ANALYSIS OF THE DATA

Earthquake of 10:20:58, Feb. 28, 1950. ϕ = 46°N, λ = 143½°E

TABLE IV

	P	P_1'	PP	pP	PPP	PcP	Total
Total Number of Observations	88	5	6	9	1	1	110
Number of Inconsistent Observations	14	2	2	5	0	0	23

The solution for this earthquake is given in Figure 1, the data being summarized in Table IV. The number of inconsistencies is about normal, and the solution cannot be much in error. It might be argued that circle *b* should have been made larger, to separate Helwan and Ksara. This would have made Honolulu correct, but would have made Athens and the PcP observation of Prague incorrect. In any event the two solutions do not differ much geologically.

Earthquake of 13:04:40, March 27, 1950. ϕ = 53½°N, λ = 173°E

The solution for this earthquake is shown in Figure 2. As shown in Table V, there are 7 inconsistencies out of a total of 48 observations. None of the inconsistencies is serious. It might however be noticed that circle *b* is defined by the observation at Brisbane, which observation is described as doubtful. The position of the circle may not be as well defined as it appears to be.

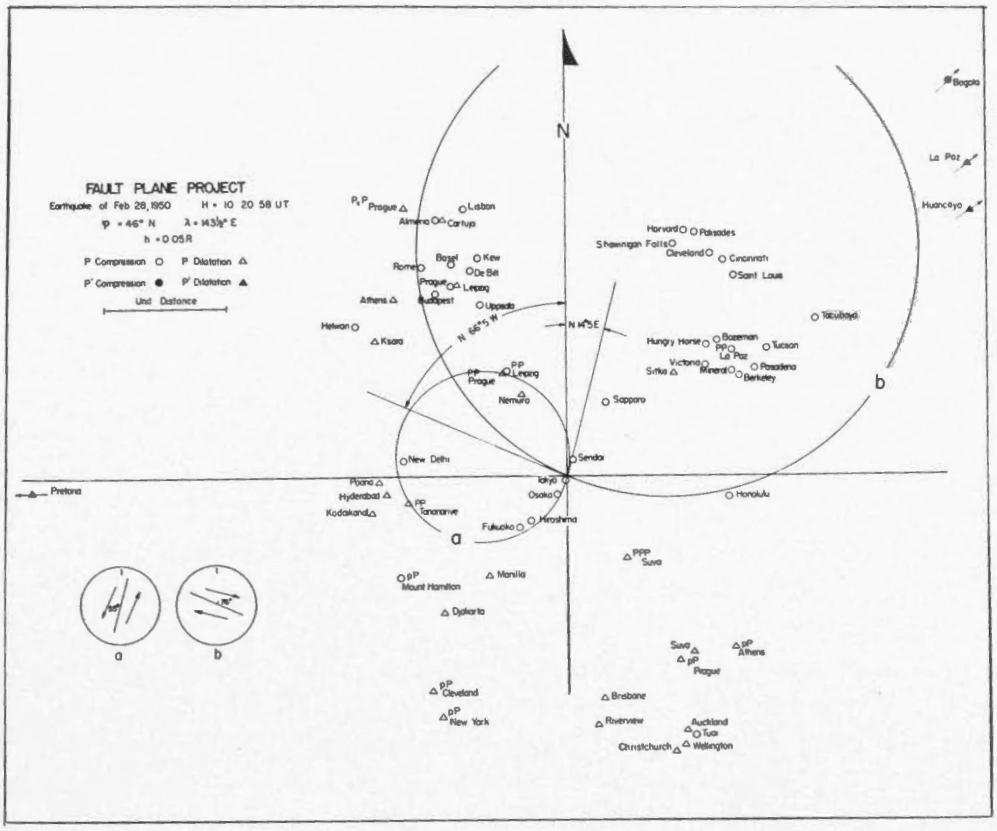


Figure 1

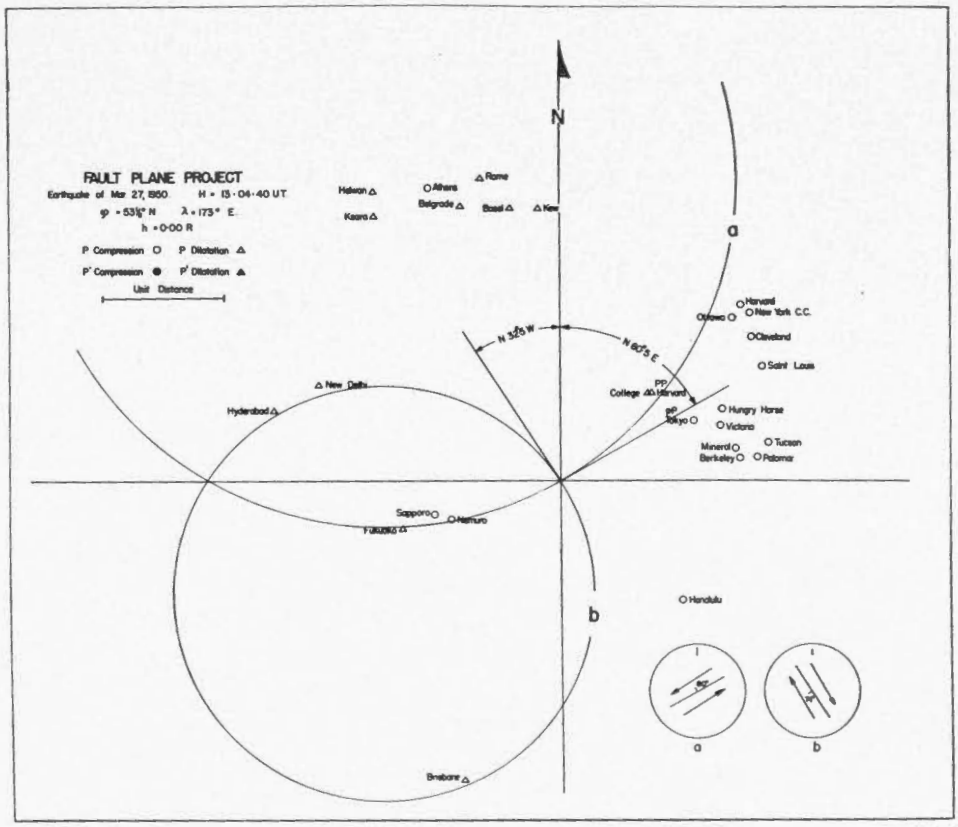


Figure 2

TABLE V

	P	PP	pP	Total
Total number of Observations.....	45	2	1	48
Number of Inconsistent Observations.....	6	1	0	7

Earthquake of 15:41:54, June 27, 1950. ϕ = 45½°N, λ = 140°E

TABLE VI

	P	PP	Total
Total Number of Observations.....	49	3	52
Number of Inconsistent Observations.....	3	1	4

None of the inconsistencies which are listed above is serious, but there are 4 other inconsistencies which have been concealed. These come from four stations of the Pasadena group, indicated by * in Table III, all of which reported a very small initial short-period compression followed by a much larger and longer period dilatation. These four station observations have been interpreted as dilatations. This was done because the separation farther north in California was so sharp that it was concluded that the short-period disturbance was from some preceding disturbance.

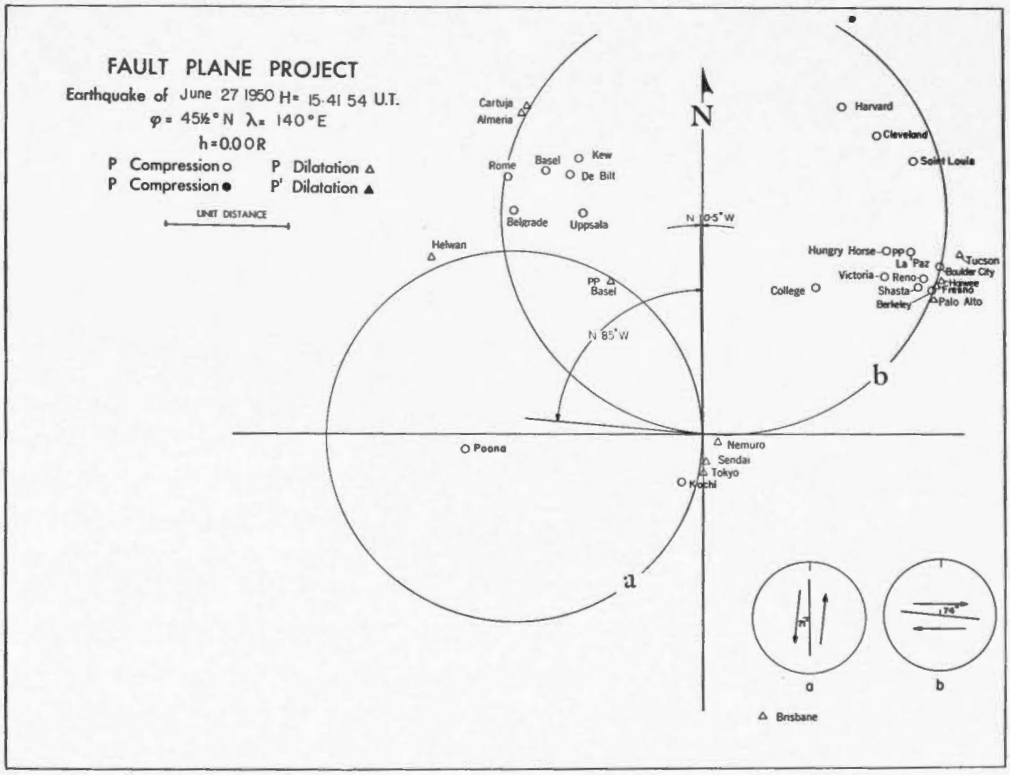


Figure 3

Earthquake of 21:41:53, June 22, 1952. $\phi = 46°N$, $\lambda = 153\frac{1}{2}°E$

The score for this earthquake is shown in Table VII, and the solution is illustrated in Figure 4. Circle *a* accomplishes a very satisfactory separation, both in North America

TABLE VII

	P	PP	pP	PcP	P_1'	Total
Total Number of Observations.....	66	6	3	2	1	78
Number of Inconsistent Observations.....	16	2	0	0	1	19

and in Australia, the only serious inconsistencies being Sitka and Fayetteville. Circle *b* is not so well defined. It might well be drawn with a shorter radius, to make Budapest

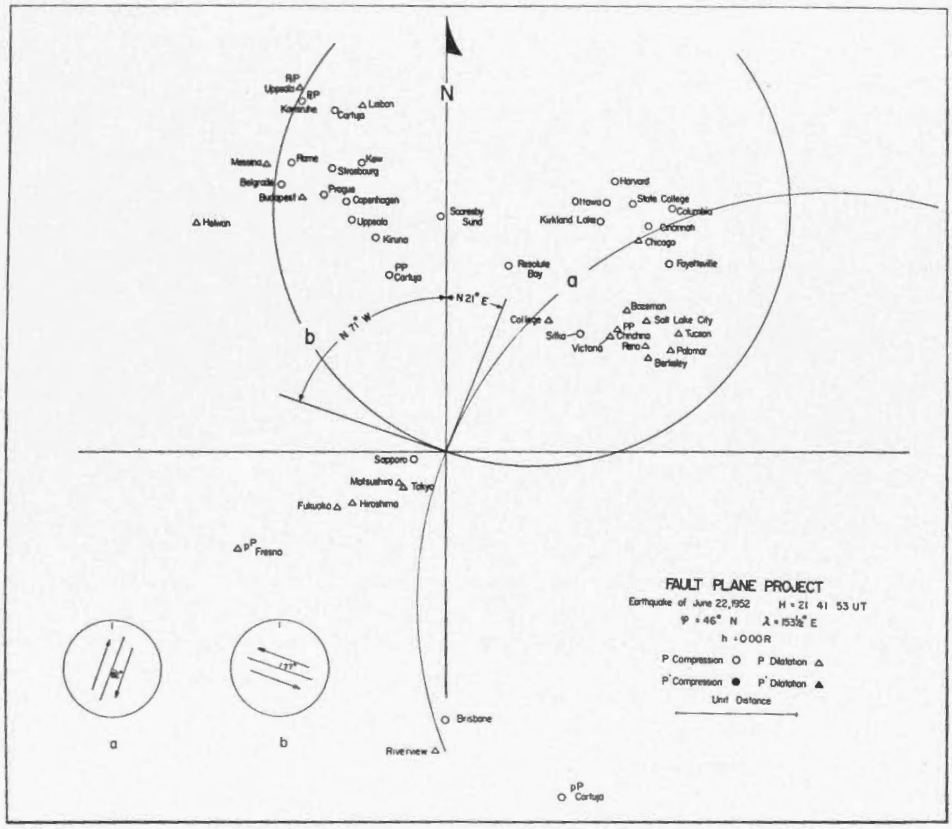


Figure 4

and Lisbon correct and Cartuja, Rome and Belgrade wrong. The position chosen gives the better score; in any event the two solutions would not differ significantly from a geological point of view.

Earthquake of 16:58:24, Nov. 4, 1952. $\phi = 52\frac{1}{2}°N$, $\lambda = 159°E$

In a paper read before the Eastern Section of the Seismological Society of America, Hutchinson[2] discussed the epicentre of this earthquake and of its several aftershocks and advanced the hypothesis that the main shock had a focal depth of about 40 km.

[2] R. O. Hutchinson, "The Kamchatka Earthquakes of November 1952", *Earthquake Notes*, 25, 3-4, 37-41, 1954.

This conclusion was based on the existence of a very large secondary phase which occurred at many stations about 12 seconds after the initial movement. Hutchinson interpreted this phase as pP.

In the discussion which followed the reading of the paper the question was asked whether a first-motion study had been attempted. Hutchinson replied that an attempt had been made, but that there were many conflictions. Someone observed that confused first motion seemed to be characteristic of very large earthquakes and might indicate that in these cases the speed of fault propagation might be comparable with the speed of seismic waves.

First-motion data had already been collected by the author. Examination of these data suggested that the earthquake might in fact be a double one, and that the large second phase, interpreted by Hutchinson as a pP might be the P of a second shock. To test this hypothesis the P – H times of all reported phases were compared with the times calculated from the Jeffreys-Bullen tables. The results of this comparison are shown in Table VIII.

TABLE VIII

Travel-times of Reported Phases for the Kamchatka Earthquake of Nov. 4, 1952, Compared with those Calculated from the Jeffreys-Bullen Tables

Station	Δ°	Calc.-Obs.	I	II
Nemuro	12·9	− 8		C
Sapporo	15·2	− 9		C
Sendai	19·1	− 1	(C)	
Maebashi	21·5	− 9		C
Kumagaya	21·6	− 9		C
Wajima	21·7	− 9		C
Tokyo	21·8	− 5	—	—
Matsushiro	21·8	− 7		C
Osaka	24·6	−12		C
Kochi	26·4	− 9		C
College	29·2	+ 2	D	
Sitka	36·7	− 1	(C)	
Resolute Bay	44·0	+ 2	C	
Honolulu	45·5	+ 4	C	
Hong Kong	45·6	−10		C
Victoria	47·2	+ 1	D	
Seattle	48·3	− 2	C	
Manilla	48·5	− 2	(C)	
Ukiah	53·2	−11		(D)
Butte	54·5	+ 1	C	
Berkeley	54·6	+ 1	C	
		−11		C
Santa Clara	55·1	−14		C
Mt. Hamilton P	55·3	+ 4	C	
		− 6		C
Bozeman	55·5	− 3	C	
Kiruna	55·9	− 1	C	
Fresno	56·1	+ 1	C	
Riverside	60·2	+ 4	—	—
		−10		C
Palomar	60·9	+11		
		− 3		D

TABLE VIII—*Concluded*

Travel-times of Reported Phases for the Kamchatka Earthquake of Nov. 4, 1952, Compared with those Calculated from the Jeffreys-Bullen Tables

Station	Δ°	Calc.-Obs.	I	II
Uppsala	63·6	− 2	C	
Tucson	65·2	− 1	C	
Lincoln	66·3	− 1	(D)	
Kirkland Lake	67·7	+ 1	D	
Aberdeen P	69·4	− 8		C
PP		− 8		DD
Ottawa	71·6	0	D	
Skalnate	72·6	− 5	—	—
Cincinnati	73·3	− 2	(D)	
Prague	73·3	− 6	—	—
Bandung	73·5	− 8		C
Rathfarnham	73·6	− 4	C	
Pittsburgh	74·1	+ 2	D	
Budapest	74·5	− 1	(D)	
Kew	74·8	− 8		C
Weston	75·3	− 1	D	
Kalocsa	75·4	− 7		D
Stuttgart	75·7	− 4	C	
Strasbourg	76·2	− 3	C	
Halifax	76·4	0	C	
Belgrade	76·5	− 7		D
Philadelphia	76·5	+ 2	C	
Basel	77·2	− 4	C	
Jersey	77·2	−16		C
Trieste	77·6	− 5	—	—
Columbia	79·1	− 3	C	
Pavia	79·1	− 6	—	—
Bologne	79·3	− 7		D
Florence	80·0	− 3	C	
Brisbane	80·0	− 4	(C)	
Rome	81·4	− 4	C	
Tacubaya	81·7	−10		D
Pueblo	82·5	−11		D
Merida	85·7	− 9		(D)
Helwan	86·0	− 3	D	
Riverview	86·4	− 7		C
Alicante	87·6	− 8		C
Lisbon	88·4	− 3	D	
Cartuja	89·2	− 4	D	
Almeria P	89·4	− 6	—	—
PP		− 2	(CC)	
Malaga	89·8	− 5	—	—
Auckland	90·2	−13		D
New Plymouth	92·3	−27	—	—
Kiamata	95·4	−18		D
Christ Church	96·6	−15		D
San Juan	99·2	− 3	D	
Tamanrasset	101·4	− 3	D	
Chinchura	106·4	− 5	—	—
Bogota P	107·5	−10		C
PP		−13		D
La Paz P′	128·4	− 1	(C)	
PP		+ 1	(CC)	

Examination of the table shows that the residuals obtained by subtracting observed times from calculated times varies as much as -12 secs. to $+11$ seconds. This certainly suggests some discrepancy in H time. It was decided that phases with a residual of $0^s \pm 4^s$ would be assigned to a first shock with an H time of 16:28:24, while those with a residual of $-11^s \pm 4^s$ would be assigned to a second shock, with an H time of 16:28:34. Phases whose residuals fall outside the indicated limits are not used, since it is not clear to which shock they belong. The table indicates, by entry of the first-motion observation in column I or II, which shock the particular phase has been assigned to. Parentheses enclosing a motion observation indicate that it is inconsistent with the solutions shown in Figures 5 and 6.

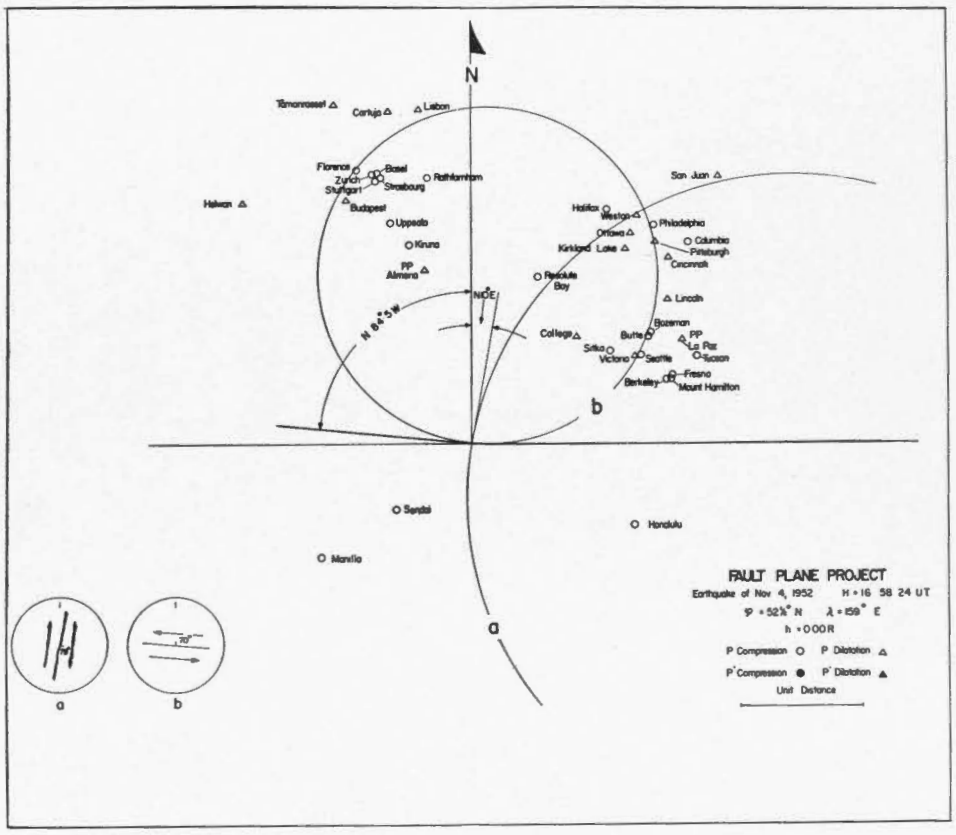


Figure 5

Figure 5 presents the solution for the first shock, Figure 6 for the second. The number of inconsistencies in the first shock as shown in Table IX is large, probably reflecting the small size of this initial shock. On the other hand the solution for the second, and larger, shock has only two inconsistencies as shown in Table X.

TABLE IX

	P	PP	P_1'	Total
Total Number of Observations.....	42	2	1	45
Number of Inconsistent Observations.....	8	2	1	11

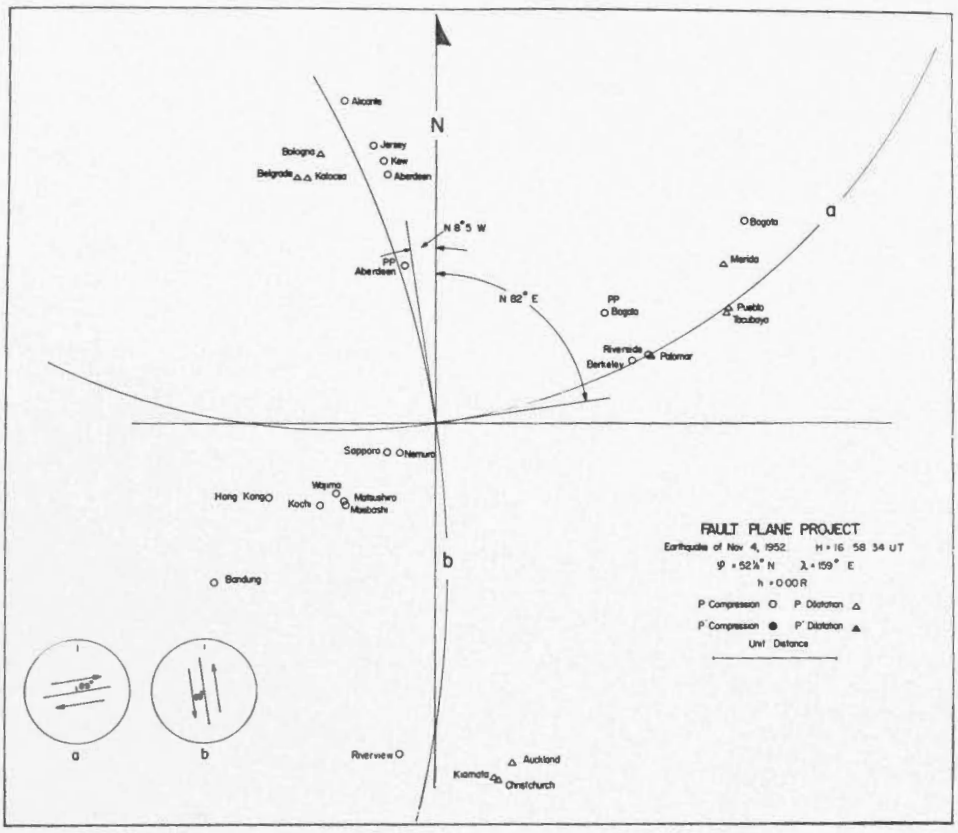


Figure 6

TABLE X

	P	PP	Total
Total Number of Observations.....	29	2	31
Number of Inconsistent Observations.....	2	0	2

If Hutchinson's interpretation is correct, all the observations plotted on Figure 6 as P's should be plotted on Figure 5 as pP's. For a normal focus earthquake pP plots at about the same extended distence as P but at the opposite azimuth, and is plotted with a phase change due to the reflection. Comparing Figures 5 and 6 it is clear that nothing but confusion would result if the transposition were to be carried out. This is an additional argument in favour of the present interpretation.

There is a good deal of similarity between the solutions; in both cases we have steeply dipping planes, one lying approximately north-south, the other east-west. It should be noted however that the motion directions differ in the two cases.

Earthquake of 08:22:34, Nov. 29, 1952. ϕ = 53°N, λ = 160°E

The solution for this earthquake is shown in Figure 7, while the data are summarized in Table XI. The score is rather poor. This reflects some of the uncertainties. For example, circle *a* might come inside Pavia and Witteveen, and circle *b* might be drawn to make Halifax wrong and Columbia correct. In short, there seems to be some doubt

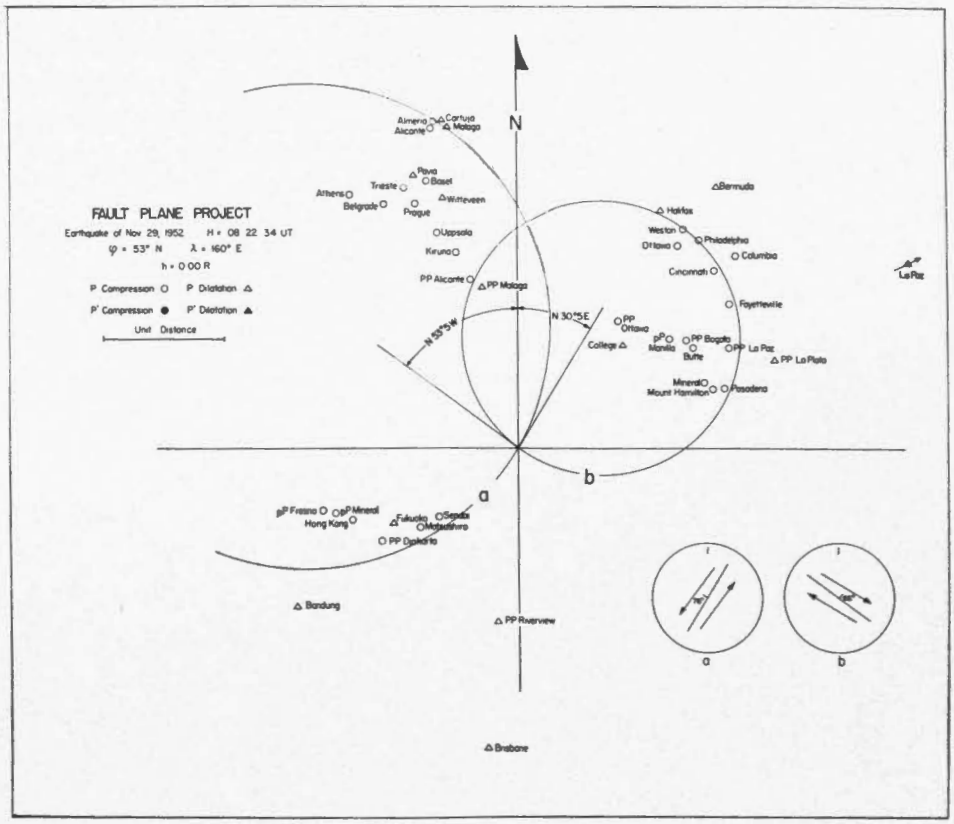


Figure 7

close to the line, and many of the inconsistent observations are called doubtful by our collaborators. In spite of the poor score it seems probable that the solution is very nearly correct.

TABLE XI

	P	P_1'	PP	pP	PPP	PcP	Total
Total Number of Observations.....	47	1	11	5	2	1	67
Number of Inconsistent Observations.....	13	0	2	2	1	0	18

Earthquake of 23:46:25, Nov. 29, 1952. ϕ = 56°N, λ = 155°W

The only serious interpretational difficulty arose in California where Mount Hamilton, Fresno and Santa Clara reported unqualified compressions whereas the rest of California reported weak dilatations, with many stations making no report. A different solution than that shown in Figure 8 might have been drawn to make the separation in California,

TABLE XII

	P	PP	PPP	PcP	Total
Total Number of Observations.....	49	10	2	2	63
Number of Inconsistent Observations.....	9	4	0	0	13

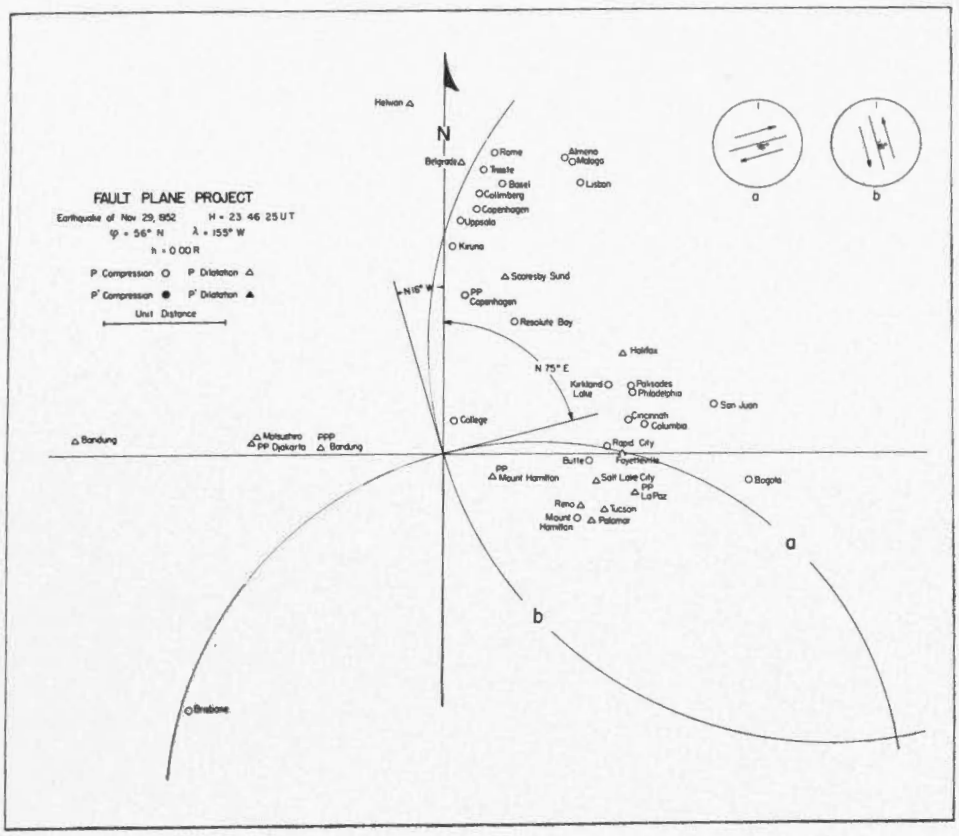


Figure 8

but this would have made a great many other stations inconsistent. The score given in Table XII is reasonably good, and it is probable that the solution is reasonably correct.

Earthquake of 17:23:39, Jan. 12, 1953. ϕ = 49½°N, λ = 156°E

It was mentioned earlier that the second group of earthquakes listed in Table I, having their epicentres in the vicinity of 50½°N, 156½°E, seemed to derive from a more complicated mechanism than that postulated in these studies. The present earthquake lies in about the same area, and exhibits some of the difficulties experienced in the main group. The tentative solution for this earthquake is shown in Figure 9.

Note first of all that the stations in the northwest quadrant of the map, representing Europe and Africa, are fairly evenly divided between compressions and dilatations, but in a random sort of way. Actually, if all the stations were plotted, the results would be numerically in favour of compressions; moreover the dilatation observations are nearly all called questionable, or limited in some way. On the whole there seems to be some justification for taking Europe to be compressional.

Turning now to the North American stations, lying in the northeast quadrant, it seems clear that there is a separation between eastern and western stations, although the exact point of separation is not clear. Circle *a* has been drawn to make College consistent. By shortening up the radius of this circle pP Djakarta might have been

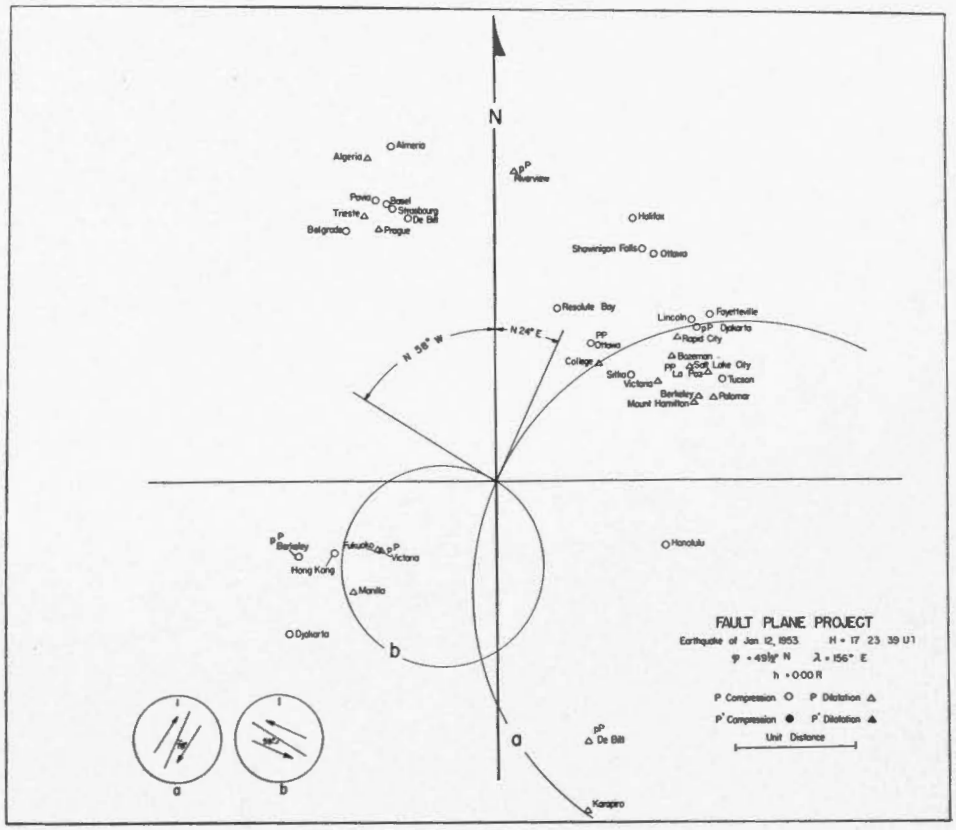


Figure 9

made consistent as well, but this would have been at the expense of pP De Bilt and P Karapiro. The circle is probably not much off its true position, but it should be noted that the unqualified observations at Tucson and Honolulu are made inconsistent. The position of circle *a* being admitted, that for circle *b* is closely limited by the orthogonality criterion and the separation in southeast Asia.

The score for the solution is shown in Table XIII. In appraising the number of inconsistencies it should be noted that many stations mentioned a double beginning, an eP followed in 2 seconds by an iP. This might account for errors at the weaker stations.

TABLE XIII

	P	P_1'	PP	pP	PcP	Total
Total Number of Observations.....	50	1	5	6	1	63
Number of Inconsistent Observations.....	11	1	1	3	1	17

Earthquake of 21:16:18, Feb. 25, 1953. ϕ = 56°N, λ = 156½°W

The solution for this earthquake is shown in Figure 10. As shown in Table XIV, the number of inconsistencies is about normal. Two groups of these are worth discussing. The Spanish stations, Cartuja, Alicant, and Almeria, (only Cartuja is shown) all give compressions, which are inconsistent. Such a solid self-consistent group of stations,

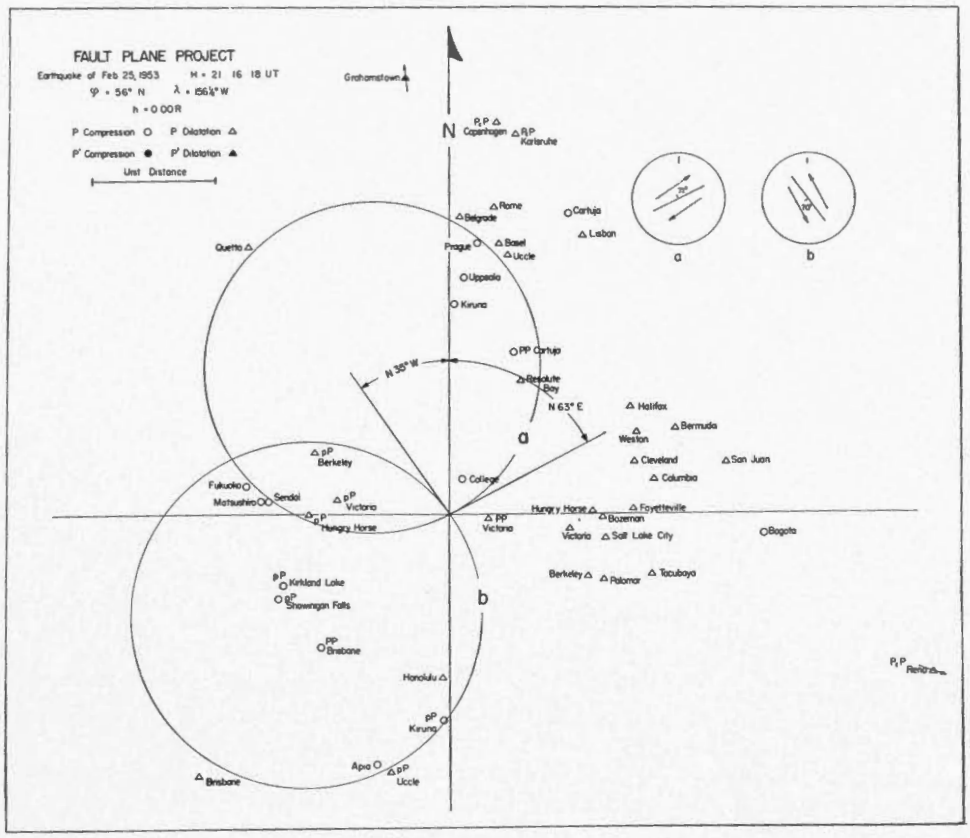


Figure 10

inconsistent with the solution, constitutes a serious criticism of it. A second inconsistent group is presented by Bogota and Chinchina, both of which give unqualified compressions. The reader should bear these two groups in mind in evaluating the solution.

TABLE XIV

	P	P_1'	PP	pP	PcP	Total
Total Number of Observations.....	67	2	6	6	3	84
Number of Inconsistent Observations.....	16	0	2	0	0	18

Earthquake of 21:01:23, March 5, 1953. ϕ = 51°N, λ = 158°E

In arriving at the solution shown in Figure 11, two groups of stations presented serious difficulty. Firstly the dilatations recorded at Almeria, Cartuja, Helwan and Quetta, together with the PcP at Uppsala suggested that a compressional circle should be drawn to leave these stations on the outside. This circle could have been drawn to include College and PP San Juan and Reykjavik in the overlap, but it could not at the same time take account of the compressions recorded generally in Asia.

A second problem was the separation suggested in Australia by the fact that Riverview and Brisbane indicate opposite senses. It has not been possible to accomplish this separation, which is unfortunate since the Brisbane observation is regarded as good by our collaborator.

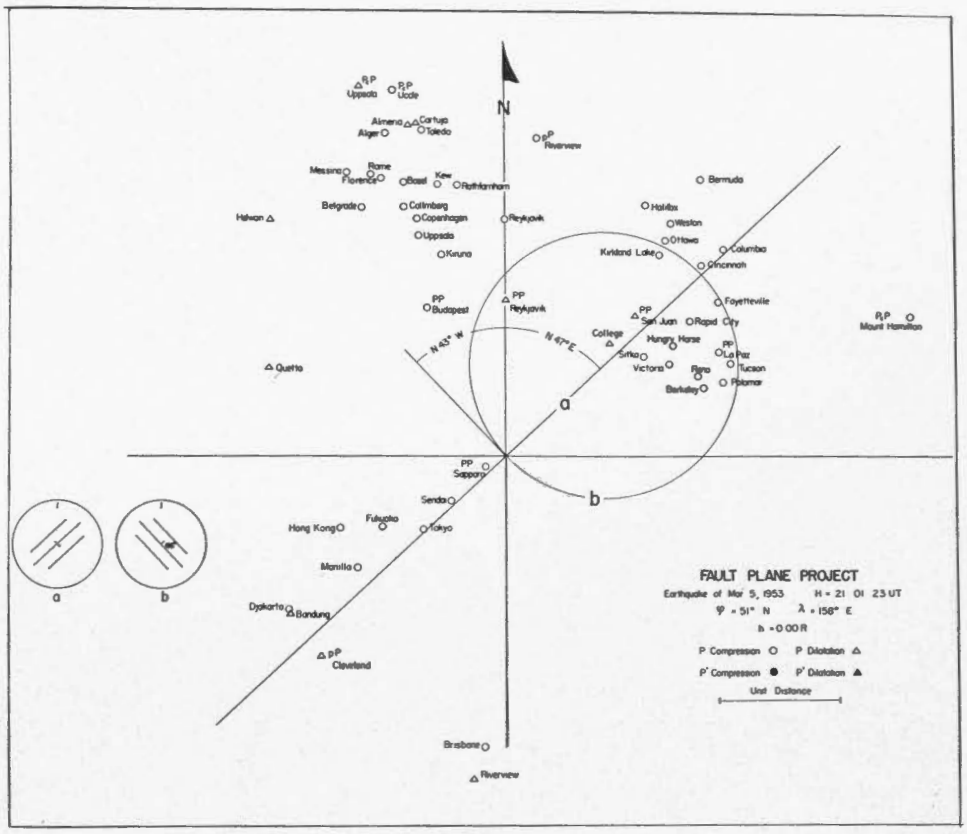


Figure 11

Despite these doubts the score for the solution, as indicated in Table XV, is very satisfactory.

TABLE XV

	P	P_1'	PP	pP	PcP	Total
Total Number of Observations.....	71	2	8	5	3	89
Number of Inconsistent Observations.....	8	1	2	2	2	15

Earthquake of 04:31:40, Oct. 5, 1953. ϕ = 53½°N, λ = 160½°E

The score for this earthquake, as shown in Table XVI, is very good. Despite this there are some doubts as to the exact position of the circles, although the approximate

TABLE XVI

	P	P_1'	PP	pP	PcP	Total
Total Number of Observations.....	84	1	5	2	1	93
Number of Inconsistent Observations.....	12	0	0	0	0	12

position is not in question. For example (see Figure 12) Bandung and Djakarta, both of which recorded compressions, could have been made consistent by an increase in the

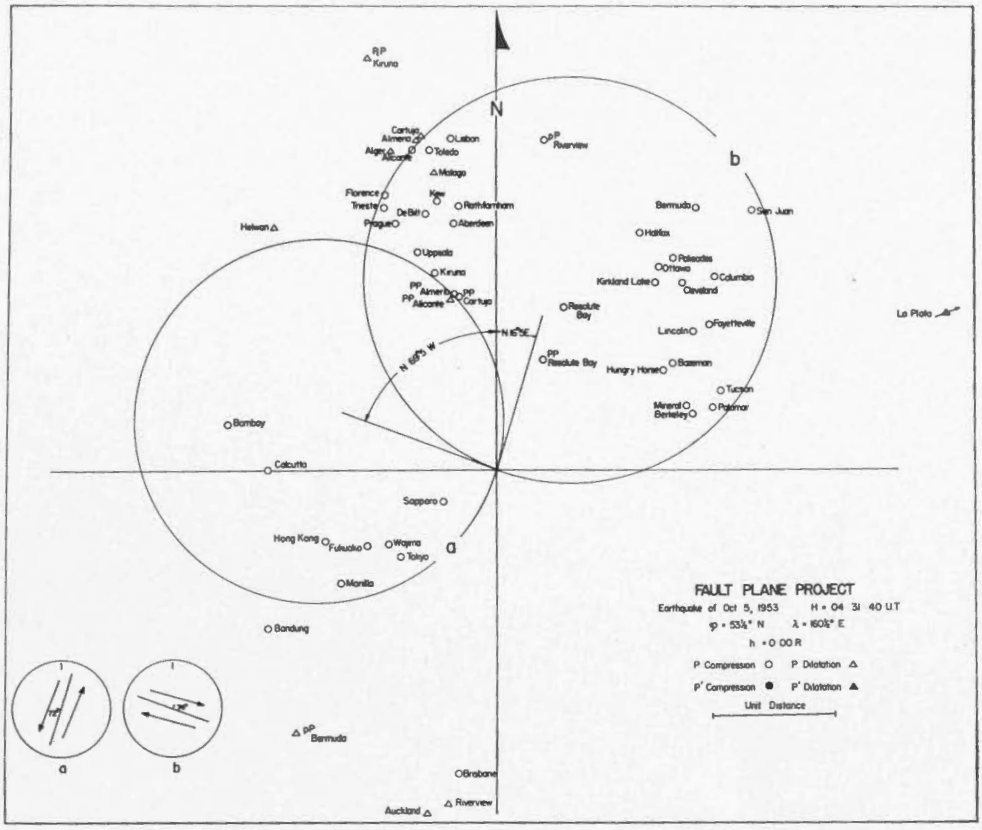


Figure 12

radius of circle *a* but this would have made at least five other stations wrong (Helwan, Uppsala, Kiruna, PP Almeria and PP Cartuja). Despite this problem, it is clear that the solution cannot be much in error.

SUMMARY AND DISCUSSION

In the fault-plane project to date, solutions, or partial solutions have been obtained for 24 north Pacific earthquakes. This number compares favourably with the 30 solutions which were available for discussion[1] in the southwest Pacific. In the present case however the epicentres are spread out over a much wider area, and there are not sufficient data for any one arc to allow an independent discussion such as that given for the New Hebrides arc. Instead we shall be guided by the findings in the southwest Pacific and investigate whether similar patterns may exist in the north Pacific.

Data for the 24 solutions available are summarized in Table XVII; the table includes data taken from three earlier papers [3, 4, 5]. As in the analogous table of the earlier paper there are three principal columns. The first lists the earthquakes, gives the pertinent

[3] J. H. Hodgson and W. G. Milne, "Direction of Faulting in Certain Earthquake of the North Pacific", *Bull. Seism. Soc. Am.*, 41, 221-242, 1951.

[4] J. H. Hodgson and R. S. Storey, "Direction of Faulting In Some of the Larger Earthquakes of 1949", *Bull. Seism. Soc. Am.*, 44, 57-83, 1954.

[5] J. H. Hodgson, "Fault-Plane Solution for the Tango, Japan Earthquake of March 7, 1927", *Bull. Seism. Soc. Am.*, 45, 37-41, 1955.

TABLE XVII

Summary of Fault-Plane Solutions Available for North Pacific Earthquakes

Earthquake					Plane a							Plane b		
No.	Date	φ	λ	h	Strike Direction	Dip Direction	Dip	Strike Component	Dip Component	Strike Direction	Dip Direction	Dip	Strike Component	Dip Component
	Japan													
1[5]	March 7, 1927	35°6N	135°E	Surface	N55°E	S35°E	79°	·931	+ ·365	N29°W	S61°W	64°	·979	+ ·204
	Vladivostock Area													
2[4]	April 5, 1949	43°N	131°E	0·08R	N67°E	N23°W	64°	·831	+ ·556	N6°W	N84°E	60°	·863	+ ·506
	Sakhalin Islands													
3	June 27, 1950	45½°N	140°E	0·00R	N0°5W	S89°5W	71°	·957	− ·291	N85°W	N5°E	74°	·941	− ·339
4	Feb. 28, 1950	46°N	143½°E	0·05R	N14°5E	N75°5W	55°	·955	− ·295	N66°5W	N23°5E	76°	·807	− ·591
	Kurile Islands													
5	June 22, 1952	46°N	153½°E	0·00R	N21°E	S69°E	82°	·974	− ·227	N71°W	N19°E	77°	·990	− ·143
6[4]	Nov. 3, 1949	48°N	154°E	0·03R	N25°E	S65°E	79°	·973	− ·229	N67°W	N23°E	77°	·981	− ·196
7[4]	May 3, 1949	49°N	153°E	0·01R	N89°E	N1°W	71°	·962	+ ·274	N6°W	S84¼°W	75°	·941	+ ·337
8	Jan. 12, 1952	49½°N	156°E	0·00R	N24°E	S66°E	77°5	·850	+ ·528	N58°W	S32°W	59°	·968	+ ·253
	Kamchatka													
9	March 5, 1953	51°N	158°E	0·00R	N47°E	—	90°	·914	·407	N43°W	N47°E	66°	1·000	0·000
10	Nov. 4A, 1952	52½°N	159°E	0·00R	N10°E	S80°E	79°	·937	− ·349	N84°5W	N5°5E	70°	·979	− ·203
11	Nov. 4B, 1952	52½°N	159°E	0·00R	N82°E	N8°W	89°	1·000	− ·017	N8°5W	S81°5W	89°	1·000	− ·017
12	Nov. 29A, 1952	53°N	160°E	0·00R	N30°5E	N59°5W	76°	·908	− ·419	N53°5W	N36°5E	66°	·964	− ·265
13	Oct. 5, 1953	53½°N	160½°E	0·00R	N16°5E	N73°5W	72°	·957	− ·290	N69°5W	N20°5E	74°	·947	− ·322
	Aleutian Islands													
14	March 27, 1950	53½°N	173°E	0·00R	N60°5E	N29°5W	80°	·960	+ ·280	N32°5W	S57°5W	74°	·984	+ ·181
15[4]	August 25, 1949	52½°N	178°W	0·00R	N9°E	N81°W	83°4	← Not Defined →		← Not Defined →				
16[3]	April 1, 1946	53½°N	163°W	0·00R	N22½°E	N67½°W	85°	·906	− ·424	N65°W	N25°E	65°	·995	− ·096
17	Feb. 25, 1953	56°N	156½°W	0·00R	N63°E	N27°W	71°	·932	− ·362	N35°W	S55°W	70°	·938	− ·346
18	Nov. 29B, 1952	56°N	155°W	0·00R	N75°E	S15°E	81°	·987	− ·158	N16°W	N74°E	81°	·987	− ·158
	Alaska													
19[3]	Oct. 16, 1947	64°N	148°W	0·00R	N30°W	N60°E	78°	·000	−1·000	N30°W	S60°W	12°	·000	−1·000
20[4]	Sept. 27, 1949	60°N	149°W	0·00R	← Not Defined →					N70°W	N20°E	72°	← Not Defined →	
	British Columbia and Washington Coast													
21[3]	August 22, 1949	54°1N	132°6W	0·00R	N64°E	S26°E	72°	·972	+ ·237	N29°W	N61°E	77°	·948	+ ·317
22[4]	Dec. 30, 1948	51°N	131°W	0·00R	N56°E	S34°E	67°	·536	− ·844	N65°W	N25°E	39°	·784	+ ·621
23[3]	June 23, 1946	49°9N	124°9N	0·00R	N1°E	N89°W	33°5	·424	− ·906	N23°W	N67°E	60°	·270	− ·963
24[4]	April 13, 1949	47°N	122°6W	0·00R	N49°E	N41°W	83°	·170	+ ·985	N76°W	S14°W	12°	·810	+ ·586

data about them, and attaches numbers to them. These numbers have been assigned in a clockwise direction around the Pacific; on the Asian side they run from south to north, in the Aleutians from west to east, and in North America from north to south.

The second principal column in Table XVII gives the strike and dip of plane *a* and, supposing it to represent the fault, gives the projection, in the direction of strike and in the direction of dip, of a unit vector drawn in the direction of the displacement. Similar information for plane *b* is given in the third principal column. Where possible in Table XVII the designation *a* has been given to that plane striking into the northeast quadrant, the designation *b* to that plane striking into the northwest quadrant. In two cases (earthquakes 3 and 19) neither plane strikes into the northeast quadrant so that the system breaks down.

It should be stressed that the designation of a particular plane as *a* or *b* is quite arbitrary, and there is no reason to believe that the planes listed as *a* are in any way related. The designation is simply a matter of convenience.

Nature of the Faulting

Examination of Table XVII shows that for those earthquakes numbered 1 to 18 inclusive the strike component is much greater than the dip component. This indicates strike-slip, or transcurrent, faulting. Within the limits of these studies then, strike-slip faulting is the rule in Pacific earthquakes from Japan through the Aleutians as it was in the southwest Pacific. It is only when we come to the earthquakes of Alaska and the British Columbia coast that different conditions obtain. In this area only one earthquake, the Queen Charlotte Islands shock of August 22, 1949, resulted from transcurrent faulting. Three others (numbers 19, 22 and 23) were the result of normal faulting while one (number 24) apparently resulted from thrust faulting.

These findings may be summarized as follows: strike-slip faulting is the cause of all north Pacific earthquakes investigated except for those in Alaska and off the coast of British Columbia and Washington. In these latter areas normal, thrust and strike-slip faulting all occur.

TABLE XVIII

Relationship of Compressional (+) and Tensional (−) Dip Components to Focal Depth

Focal Depth	Area																	
	Japan		Vladivostok Area		Sakhalin Islands		Kurile Islands		Kamchatka		Aleutian Islands		Alaska		British Columbia and Washington Coast		Total	
	+	−	+	−	+	−	+	−	+	−	+	−	+	−	+	−	+	−
·08R...	—	—	1	—	—	—	—	—	—	—	—	—	—	—	—	—	1	
·05R...	—	—	—	—	—	1	—	—	—	—	—	—	—	—	—	—	—	1
·03R...	—	—	—	—	—	—	—	1	—	—	—	—	—	—	—	—	—	1
·01R...	—	—	—	—	—	—	1	—	—	—	—	—	—	—	—	—	1	
·00R...	—	—	—	—	—	1	1	1	—	4	2	3	—	1	3	1	6	11
Surface....	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	1	

In Table XVII a sign has been assigned to the dip component of displacement in each case, a negative sign indicating a tension displacement, a positive sign indicating a thrust displacement. These data have been collected in Table XVIII, where they are listed by geographical location and by focal depth. While the data are too few to permit a final conclusion, it does not appear that either tensions or compressions are associated particularly with any arc or with any range of focal depth.

Direction of Faulting

The earlier paper on southwest Pacific earthquakes[1] dealt with shocks principally associated with two features, the New Hebrides arc and the Tonga-Kermadic-New Zealand arc. Each of these arcs has a relatively simple form and can be approximated to by a single direction This simplified the attempt to relate features of the fault solutions to features of the associated arc. In the present case there are a large number of arcs to be considered. Most of these have high curvature so that there is no single direction which can be associated with any arc. Add to this the fact that we have much fewer solutions for each arc and it becomes clear that only a very tentative analysis of the data may be attempted.

For the purpose of this analysis the north Pacific will be divided into three areas, the northwest Pacific, from Japan through Kamchatka, the north Pacific consisting of the Aleutians, and the northeast Pacific, comprising Alaska and the British Columbia coast.

The strike direction of the fault-planes for the northwest Pacific group is investigated in Figure 13. The earthquakes are numbered according to the same system used in Table XVII, the two sets of numbers corresponding to planes *a* and *b*. Recalling that plane *a* by definition was that striking into the northeast quadrant while plane *b* was that striking northwest, it is clear that there is no uniformity of strike direction. In this area numbers were assigned from south to north. If the planes associated with a particular arc were to have a common direction we should expect to find a consecutive group of numbers (as, for example 9 to 13) associated with a single direction. This does not

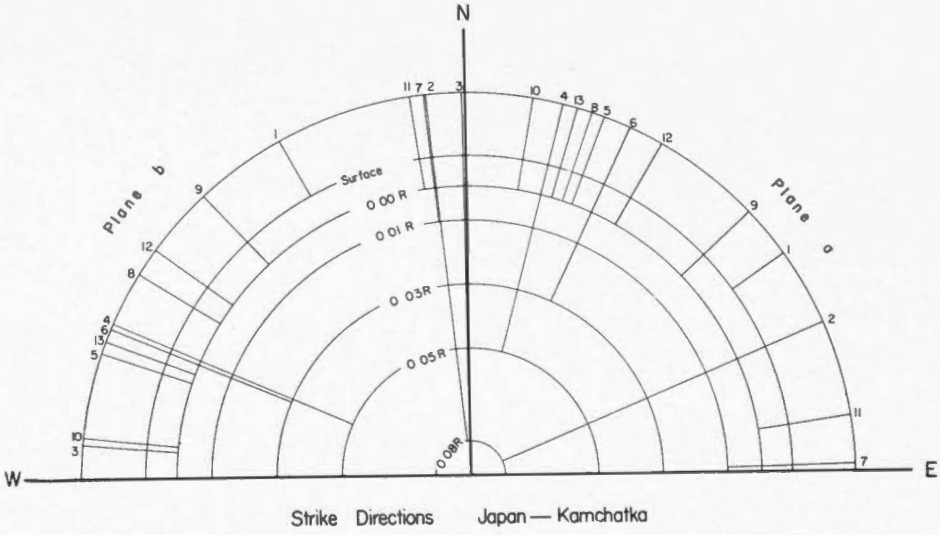
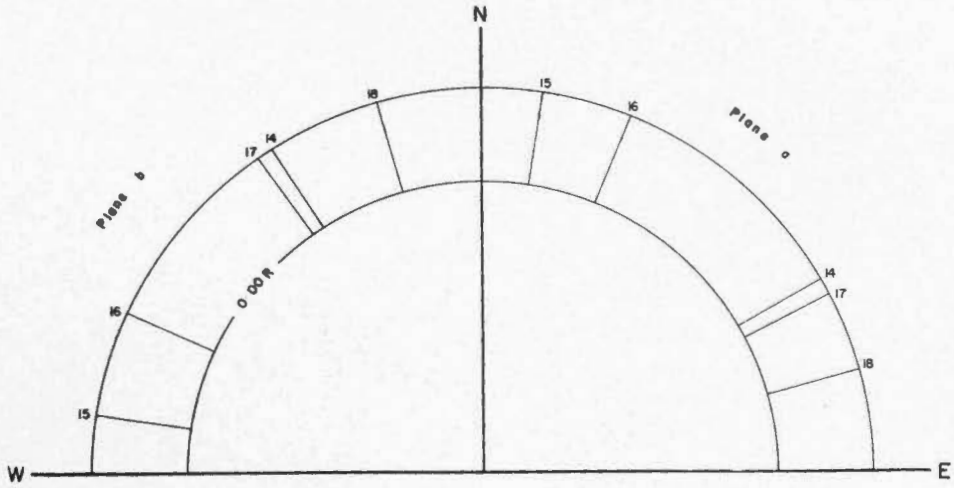


Figure 13

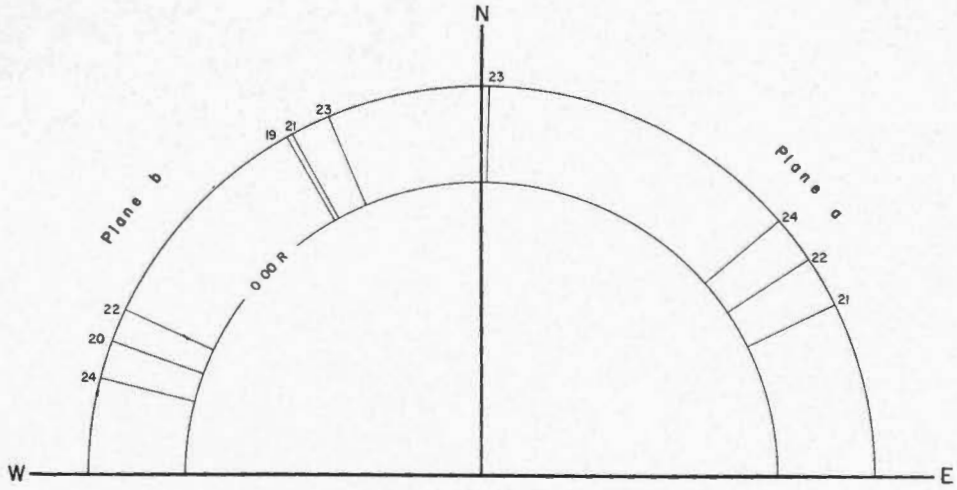
occur. In Figure 13 the focal depth of the earthquakes are indicated by the length of the line. It is obvious from the figure that there is no relationship between the depth of focus and the direction of the planes.

Figures 14 and 15 give the equivalent data for the north and northeast Pacific areas respectively. While the data are scanty, there is certainly no clear indication of a systematic arrangement to the direction of planes *a* and *b*.



Strike Directions —
Aleutians.

Figure 14



Strike Directions

Alaska — Washington.

Figure 15

Direction of Dip

In the earlier paper on southwest Pacific earthquakes[1] it was shown that the dip vectors for the earthquakes associated with a particular arc have a tendency to lie parallel to one or other or a pair of planes, steeply dipping but bearing no obvious relationship to the direction of the associated feature. This was demonstrated by diagrams drawn with

an inverse stereographic projection in which the epicentre of the earthquake rather than its antipodal point is used as the pole of the projection. It is a property of the projection that a plane passing through the origin, having a certain strike direction and a dip δ will project into a line with the same strike direction and at a perpendicular distance = cot δ from the origin.

This projection has been used in Figure 16 to study the dip vectors of the earthquakes lying between Japan and Kamchatka. The open symbols have been used to refer to planes *a*, closed ones to planes *b*. Examination of the figure shows that the open symbols tend to lie in a direction N 70°W, and that the closed ones tend to lie in a direction N 38°E. There are two exceptions to this, earthquakes 2 and 7. By interchanging open and dark symbols for earthquake 7, which is justified since there is no significance to the designations *a* and *b*, this earthquake can be brought into line. This leaves only one shock, number 2, inconsistent.

We conclude that for all but one out of thirteen earthquakes, the dip vectors define a pair of planes. One of these planes strikes N 70°W and dips to the southwest at an angle of 88° ± 6°, the other strikes N 38°E and dips to the northwest at an angle of 86° ± 8°. The uncertainties are not standard deviations but simply the limits necessary to include all observations.

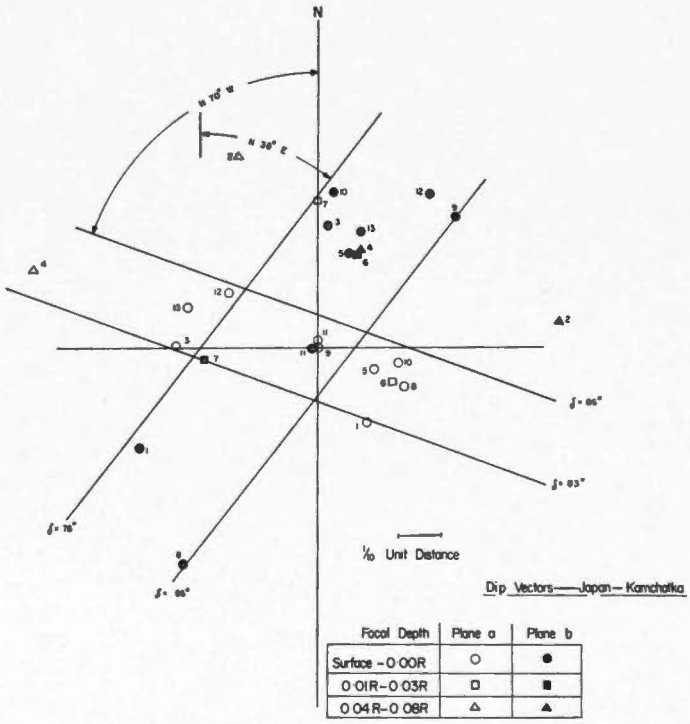


Figure 16

Figure 17 gives similar information for the Aleutians. Admitting that the data are too few to permit any final conclusions to be drawn, two directions seem to be favoured, one striking N 23°W and dipping to the southwest at an angle of 86°.5 ± 2°.5, the other striking N 61°E and dipping to the southeast at an angle of 88°.5 ± 1°.5.

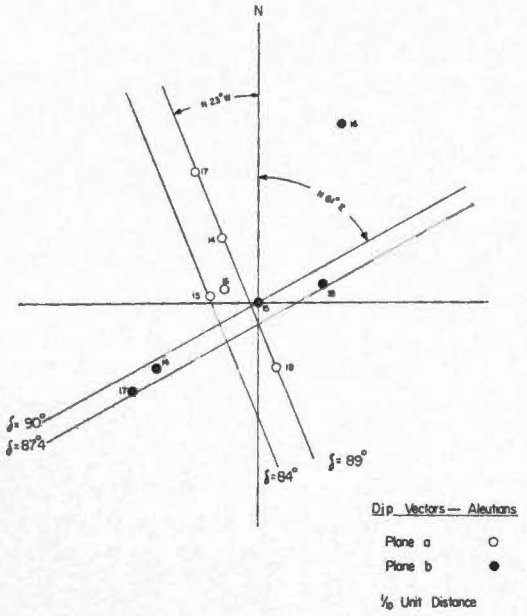


Figure 17

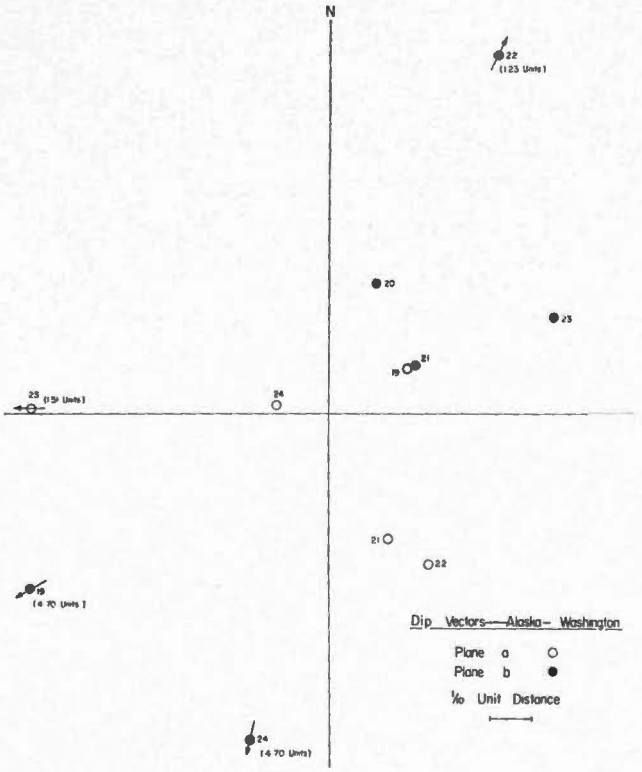


Figure 18

The points of emergence of the dip vectors for the area from Alaska to Washington are shown in Figure 18. Within the limits of the present data it seems clear that the arrangement here is random. It has already been shown that this section of the Pacific is unusual in that transcurrent faulting does not predominate; the random orientation of the dip vectors is another indication that this area differs from other circum-Pacific ones.

Direction of the Null Vectors

The null vector is, as defined in the earlier paper[1], the vector joining the points of intersection of the two circles. It is drawn always in the sense *from* the epicentre *to* the other point of intersection. In the southwest Pacific it was found that the null vectors lay nearly parallel to an almost vertical plane having the strike of the feature with which the earthquake was associated.

The strike and dip of the null vectors for north Pacific earthquakes have been given in Table IXX, and the null vectors for the area from Japan to Kamchatka have been plotted in Figure 19. Here two planes appear to be defined, one striking N 47°W and dipping to the northeast at an angle of 86° ± 4°, the other striking N 34°E and dipping

TABLE XIX

Strike and Dip of the Null Vectors

Earthquake Number	Strike	Dip	Earthquake Number	Strike	Dip
Northwest Pacific			North Pacific		
1	S34°W	61°.6	14	W	71°
2	N34°.5E	46°.1	15	N81°W	90°
3	N47°W	64°.4	16	N17°E	64°.8
4	N48°W	51°.6	17	N75°W	61°.3
5	N53°E	74°.3	18	S57°.5E	77°.2
6	N62.5E	73°.0	Northeast Pacific		
7	N42°W	65°.3			
8	S5°W	55°.9	19	N30°W	0°
9	N47°E	65°.7	20	Not Defined	
10	N36°E	67°.5	21	S63°.5E	67°.8
11	N41°W	83°.6	22	N69°E	29°.6
12	N2°E	62°.2	23	N17°W	11°.9
13	N30°W	65°.0	24	S47°.5W	9°.7

to the southeast at an angle of 86° ± 4°. Two earthquakes lie outside the indicated boundaries, numbers 8 and 12. These might be regarded as defining a north-south striking plane, but until many more earthquakes have been reduced for this area it is better that they be regarded as exceptions.

The equivalent diagram for the Aleutians is given in Figure 20. Here a single direction appears to be defined, striking N 75°W and dipping to the southwest at an angle of 87°.5−2°.5. There is one exception, earthquake number 16. In this case the data are so few that the interpretation must be regarded only as a tentative one.

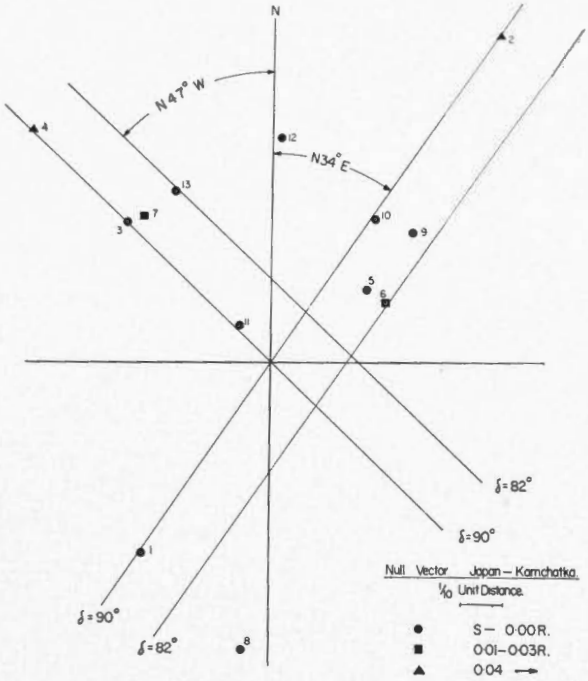


Figure 19

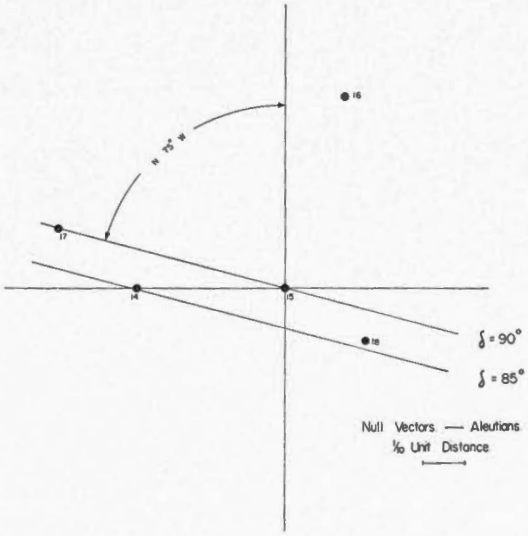


Figure 20

Finally, in Figure 21, are plotted the null vectors for the area from Alaska to Washington. The scale of this diagram is only 1/10 that of earlier diagrams, so that the linear arrangement indicated may be more apparent than real. The fact that point 19 is at an infinite distance dictates one strike direction of N 30°W, and this direction appears to satisfy earthquakes 23 and 21, if we take the dip as northeast at an angle of 65° ± 25°. A second plane, striking N 53°E and dipping to the southeast at an angle of 65°, contains the vectors for earthquakes 22 and 24.

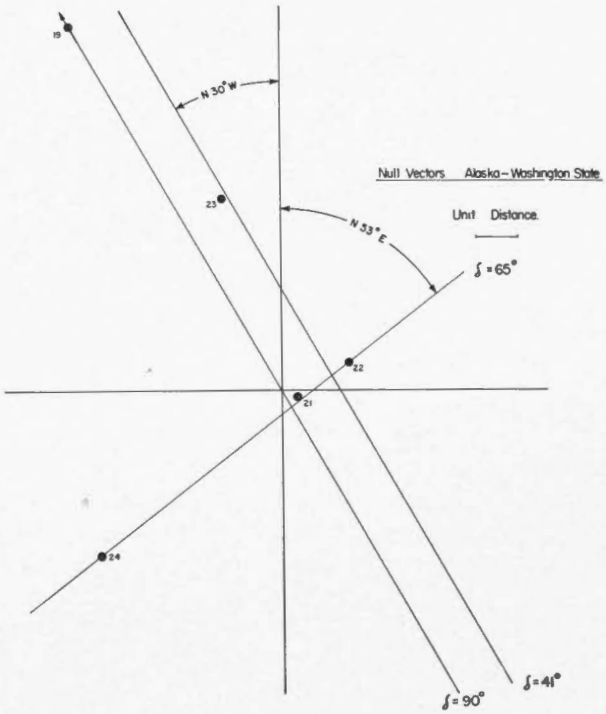


Figure 21

In the earlier paper it was shown that the null vectors of the New Hebrides earthquakes, for example, lie close to a vertical plane having the strike of the New Hebrides arc. Similarly the null vectors of the Tonga-Kermadec-New Zealand earthquakes define a nearly vertical plane having the mean direction of that feature. What interpretation are we to place on the directions defined by Figures 19 to 21?

Earthquake epicentres for the area covered by Figure 19 may best be studied in Figures 17 and 18 of Gutenberg and Richter's[6] "Seismicity of the Earth". Examination of these figures will show that the earthquake epicentres make a very complicated pattern and it is probable that interpreters will differ in determining trends. The following interpretation has much in its favour.

In Figure 17 a line drawn through the point 30°N, 130°E and striking N 38°E is a good approximation to the bands of islands, volcanoes and normal-focus earthquakes stretching through Japan, the Kuriles and Kamchatka. The line is, of course, only an approximation to a number of separate systems, the Japan arc and the Kurile arc, for example, appearing as scallops on the general line. On the continental side of this line the foci become increasingly deep with their distance from the line, as if the line corresponded to an outcrop of a plane, or system of planes, dipping towards the continent.

A second line, drawn through the point 30°N, 140°E, and striking N 30°W appears necessary to account for a number of deep-focus earthquakes. There does not seem to be an accompanying trend of normal focus earthquakes associated with this direction. However another trend does seem to exist for normal focus earthquakes. This would be defined by a north-south line running along the 141st meridian.

[6] B. Gutenberg and C. F. Richter, *Seismicity of the Earth and Related Phenomena*, Princeton University Press, 1949.

In summary, it appears that three directions might be defined by earthquakes in this area, one N 38°E, another N 30°W and a third north-south. The first of these directions corresponds very closely to the direction N 34°E defined in our Figure 19 while the second is in fair agreement with the direction N 47°W. There is even some indication in Figure 19, from earthquakes 8 and 12, of a north-south direction.

Admitting that many more earthquakes must be reduced before the directions defined in our Figure 19 may be accepted, and admitting further that the trend directions in this section of the Pacific are open to question, nevertheless there does appear to be some agreement between the directions of the null vectors and the directions assumed by the earthquake epicentres. It should be pointed out that there is an essential difference between the results found in the southwest Pacific and those suggested here. In the southwest Pacific the null vectors of the New Hebrides earthquakes lie parallel to a plane having the direction of the New Hebrides arc, while the Tonga-Kermadic-New Zealand shocks have null vectors associated with the plane through that feature. In the north Pacific however this close association no longer obtains. Earthquakes 3 and 4, for example, which lie in the Sakhalin Islands and so are associated geographically with the north-south trend have their null vectors associated with the northwest trend. Similarly the Kurile earthquake number 7 and the Kamchatka earthquakes numbers 11 and 13 have null vectors associated with the northwest direction, while the Vladivostock earthquake number 2 has its null vector associated with the northeast system. If these trends should continue when more data are available it will be necessary to conclude that the association of epicentres with particular arcs is more complicated than many authors have supposed.

Gutenberg and Richter's Figure 7 gives the epicentres in the area covered by our Figure 20. Here two directions may be detected. The western Aleutians trend about N 70°W, the eastern Aleutians about N 70°E. As shown in our Figure 20 the limited number of earthquakes so far available appear to define the direction N 75°W, closely parallel to the trend of the western Aleutians, but we should note that epicentres 17 and 18 lie south of the eastern half of the arc, almost as if they were on an easterly extension of the western Aleutians.

Turning now to the area from Alaska through the British Columbia coast to Seattle we find two directions defined in Figure 7 of "Seismicity of the Earth". A line drawn through the length of Vancouver Island passes through several epicentres and, continued to the north, passes along a line of sea mounts. This line has a direction N 55°W. A second line drawn along the length of the Queen Charlotte Islands passes through a line of sea mounts to the south and through a number of earthquake epicentres lying inland from Sitka. This line has a direction N 15°W. There are thus two directions, N 55°W and N 15°W; it is not clear with which of these our direction N 30°W should be associated. There are no obvious tectonic trends corresponding to the second direction, N 53°E.

Discussion

In the earlier paper[1] the correlation between the directions defined by the null vector and the directions of the associated geographic features was regarded as a confirmation of the techniques of the fault plane project, for it seemed very improbable that the correlation could be a matter of accident. In the present examples the correlation has not

been so definite, partly because the number of solutions available for any particular feature is lower, and partly because the tectonic trends in the north Pacific are less clearly defined than they were in the southwest Pacific.

CONCLUSIONS

Twenty-four earthquakes from various parts of the north Pacific have been analysed by the fault-plane techniques. These fault-plane solutions would support the following conclusions.

1. Throughout most of the north Pacific faulting is predominantly transcurrent, on steeply dipping planes. A notable exception is provided by the area from central Alaska through British Columbia to Seattle. In this, normal, thrust, and transcurrent faulting occur.
2. There is no consistency in the strike direction of the faults, nor any systematic variation with latitude, depth of focus or position on the associated geographic feature.
3. Vectors drawn in the direction of maximum dip of the two planes obtained in the solution tend to lie parallel to two nearly vertical planes; the relationship between the strike of these planes and the strike of the associated feature is not clear. In the area from Alaska to Seattle the dip vectors appear to be randomly oriented, another indication of the anomalous nature of this area.
4. The null vectors associated with particular tectonic provinces exhibit a tendency to lie parallel to nearly vertical planes. The direction of these planes appears to be related to the tectonic trends of the areas, insofar as such trends can be established.

ACKNOWLEDGMENTS

The writer is indebted to J. F. J. Allen who compiled the data and did the initial plotting for the 1951 earthquakes, to R. R. Clark who did the same for the more recent earthquakes and to P. J. Winter who has drawn the figures with such care. Particular thanks go to those seismologists all over the world who, by completing the questionnaire forms, have made this research possible.

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A GRAVITY SURVEY OF THE VICINITY OF OTTAWA

BY

SVEND SAXOV

EDMOND CLOUTIER, C.M.G., O.A., D.S.P.
QUEEN'S PRINTER AND CONTROLLER OF STATIONERY
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A Gravity Survey of the Vicinity of Ottawa

By

Svend Saxov

ABSTRACT

A detailed gravity survey of an area of about 400 square miles in the vicinity of Ottawa has been completed. Calibration factors for the various gravimeters employed are assessed and the adopted values of gravity for a short range calibration base line reported.

The gravity measurements are presented in the form of Bouguer anomalies plotted on a geological base map prepared by the Geological Survey of Canada. Correlation of the gravity anomalies with the geology and with the magnetic anomalies are discussed. The results of local traverses over certain major faults are also given, and are compared with results obtained with the torsion balance some years ago.

INTRODUCTION

The geology of the area in the vicinity of Ottawa presents a number of features of interest to the geophysicist, which are capable of investigation by gravimetric methods. Interesting and definite relations were established some 20 years ago between results obtained with the torsion balance[1]—namely, differential curvature, gravity gradients, and deduced gravity anomaly—and the Gloucester and Hazeldean faults, which showed that the structures can be traced by gravity methods and that the throw of the Gloucester fault can be estimated fairly well from the gravity results. Measurements with a magnetometer also showed that the line of maximum vertical intensity corresponded fairly well with the fault plane at Hazeldean (South). Since then a careful study[2] of the geology of the area has been made, and a report which includes a map in two sheets, showing the geology in considerable detail, has been published.

Apart from their usefulness for geodetic purposes, it seems likely that the results of a systematic gravimeter survey of this area might record appreciable effects associated with the surface geology, which would possibly serve as a guide in the interpretation of other gravity surveys where the geology is not so well known. Gravimeter determinations were therefore planned at one-mile intervals over the area, covering it as uniformly as possible. Most of the observations were made in June and August of 1950.

The Ottawa sheet of the National Aeromagnetic Series covering the same area as the geological map was published[3], and a number of detailed gravimeter observations were made along traverses crossing certain prominent magnetic anomalies. In addition, detailed gravimeter traverses were made over the Gloucester and Hazeldean fault zones for comparison with torsion balance results obtained in 1928 and 1929.

[1] Miller, A. H., *Geol. Surv., Canada*, Mem. 165, pp. 197-209, 1931, also *Publications of the Dominion Observatory*, vol. XI, No. 6, 1940.
[2] Wilson, Alice E., *Geol. Surv., Canada*, Mem. 241, 1946.
[3] *Geol. Surv., Canada*, 1950, Sheet 31$\frac{G}{8}$.

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OBSERVATION AND REDUCTION OF DATA

(a) The Regional Gravity Measurements

Although a number of gravity observations had recently been made in Ottawa and vicinity, additional measurements were required to obtain a detailed gravity map of the area. These were completed during the summer of 1950, with observations approximately one mile apart where possible. The stations are all located at easily identifiable places, for example, cross-roads, railway stations, schoolhouses and other permanent points. This should facilitate future measurements.

Several observers, using different gravimeters, contributed to the work. A. H. Miller measured several stations using the Humble gravimeter in 1945, and the Atlas gravimeter in 1948 and 1949. During the first two weeks of June 1950, M. Beer measured almost one-third of the stations with the Atlas gravimeter. G. D. Garland, M. J. S. Innes and M. S. Reford all made measurements during the summer of 1950, using North American Gravimeter No. 85 and Worden Gravity Meters Nos. 42 and 44. Approximately two-thirds of the stations were determined by the writer with the North American Gravimeter No. 85 during the first ten days of August 1950. In September additional stations were laid out to complete the gravity network and at the same time obtain checks on several stations previously measured.

Each field trip was begun and concluded with an observation at the Dominion Observatory gravimeter station. Although no field trip extended beyond one day, some were long enough to render repeat readings at one or more stations desirable for the determination of instrumental drift.

(b) The Performance of the Gravimeters

Five different gravimeters were employed at various times for different portions of the regional gravity measurements in this report. It was therefore important that the performance of the various instruments be examined and their calibrations matched to ensure a homogeneous set of values. This was accomplished by observing concurrently with three of the gravimeters, the North American and the two Worden instruments, at a series of 17 stations extending along the highway through Ottawa from Prescott, Ontario, to Maniwaki, Quebec. These gravity stations lie approximately on a north-south line over which the change in gravity is about 124 mgals., sufficiently large to provide relative calibration factors to an accuracy of about one-tenth of one per cent.

The observations were made in a series of closed loops to permit an accurate estimate of "zero" drift for each instrument. Differences in gravimeter scale readings, corrected for drift, are listed in columns (2), (4) and (6) of Table I, while the corresponding differences in gravity are given in columns (3), (5) and (7).

The gravity differences provided by the North American Gravimeter No. 85 (col. 3), are based upon an adopted[1] calibration factor of 0·2315 mgals. per division. These differences were accepted as standard to provide relative calibrations of 0·10254 mgals. per division and 0·11185 mgals. per division for the Worden gravimeters, No. 42 and No. 44 respectively.

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[1] Innes, M. J. S. and Thompson, L. G. D., *Publications of the Dominion Observatory*, vol. XVI, No. 8, 1953.

TABLE I

Gravimeter Data and Adjusted Values of Gravity for Prescott-Maniwaki Base Line.

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Station	North American Gravimeter No. 85 k=0·2315 mgals/div.		Worden Gravimeter No. 42 k=0·10254 mgals./div.		Worden Gravimeter No. 44 k=0·11185 mgals./div.		P_1 (3) − (5) (mgals.)	P_2 (3) − (7) (mgals.)	P_3 (5) − (7) (mgals.)	Differences in Gravity from Prescott (weighted mean)	Observed Gravity (gals.)
	Reading in scale divisions	Gravity differences	Reading in scale divisions	Gravity differences	Reading in scale divisions	Gravity differences					
		mgals.		mgals.		mgals.					
Prescott, Ont.	0·0	0·00	0·0	0·00	0·0	0·00	—	—	—	0·00	980·56653
Bedell, Ont.	37·6	8·70	85·6	8·78	77·6	8·68	−0·08	0·02	0·10	8·74±0·02	980·57527
Kemptville, Ont.	66·6	15·42	150·8	15·46	137·8	15·41	−0·04	0·01	0·05	15·44±0·01	980·58197
North Gower, Ont.	191·9	44·42	432·9	44·39	397·5	44·46	0·03	−0·04	−0·07	44·41±0·01	980·61094
Manotick, Ont.	233·0	53·94	525·0	53·83	481·5	53·86	0·11	0·08	−0·03	53·86±0·02	980·62039
Black Rapids, Ont.	254·4	58·89	575·4	59·00	527·7	59·02	−0·11	−0·13	−0·02	58·98±0·04	980·62551
Hogs Back, Ont.	257·1	59·52	581·1	59·59	533·1	59·63	−0·07	−0·11	−0·04	59·58±0·02	980·62611
Ottawa (steps) Ont.	239·3	55·40	540·2	55·39	495·9	55·47	0·01	−0·07	−0·08	55·41±0·02	980·62194
Chelsea, P.Q.	230·0	53·25	519·4	53·26	476·4	53·29	−0·01	−0·04	−0·03	53·26±0·01	980·61979
Cascades, P.Q.	262·8	60·84	593·8	60·89	544·7	60·92	−0·05	−0·08	−0·03	60·89±0·01	980·62742
Wakefield, P.Q.	295·4	68·39	666·8	68·37	611·9	68·44	0·02	−0·05	−0·07	68·39±0·01	980·63492
Farrelton, P.Q.	359·3	83·18	811·0	83·16	743·6	83·17	0·02	0·01	−0·01	83·17±0·01	980·64970
Low, P.Q.	369·6	85·56	834·6	85·58	765·0	85·57	−0·02	−0·01	0·01	85·57±0·01	980·65210
Gracefield, P.Q.	454·9	105·31	1026·6	105·27	940·3	105·17	0·04	0·14	0·10	105·26±0·02	980·67179
Bouchette, P.Q.	501·6	116·16	1131·6	116·03	1037·0	115·99	0·13	0·17	0·04	116·05±0·03	980·68258
Messines, P.Q.	495·2	114·64	1118·4	114·68	1025·0	114·65	−0·04	−0·01	0·03	114·66±0·01	980·68119
Maniwaki, P.Q.	536·1	124·11	1210·1	124·08	1109·7	124·12	0·03	−0·01	−0·04	124·10±0·01	980·69063
Mean square of the Differences						0·0039	0·0064	0·0030			
Root mean square of the Differences						±0·06	±0·08	±0·05			

The differences between the various sets of measurements, columns (8), (9) and (10), are quite small and vary from 0·01 to 0·13 mgals. The root mean square difference between successive pairs are ±0·06, ±0·08 and ± 0·05 mgals. The probable error of each instrument therefore, in measuring the same gravity difference, is somewhat smaller than these amounts, and it seems safe to conclude that the relative calibrations have been well determined and that all instruments are capable of providing values of gravity, consistent with each other.

As no similar looping program was carried out with the Humble and Atlas gravimeters, the consistency of the gravity results with these instruments was determined by repeating some of the observations with the North American gravimeter. Comparisons were made at both Humble and Atlas gravimeter sites over the full gravity range of the survey. No systematic differences for either instrument were observed and the maximum difference was found not to exceed 0·3 mgals.

(c) The Prescott-Maniwaki Base Line

Column (11) in Table I gives the mean difference in gravity from Prescott, Ontario, for each of the 17 stations. These differences have been weighted inversely as the standard deviations of the three instruments. The weights assigned are 2, 2 and 5 for the North American No. 85, Worden No. 44 and Worden No. 42, respectively. The final values of gravity are given in column (12) and are based upon an adopted value of 980·622 cm./sec^2. for the national reference pier in the Dominion Observatory.

As has been shown, this group of stations is well connected and will provide a useful baseline for checking the behaviour and calibration factors of gravimeters in the future. Its usefulness as such will increase as measurements are repeated and more refined values of gravity obtained. To facilitate the re-location of the stations at a later date, sketches are given in the Appendix indicating their positions relative to features which may be easily identified.

(d) The Elevations

Known elevations such as bench marks and points along railway lines, as well as those from the topographic map were used for most of the gravity stations. However, it was not possible to locate all gravity stations at points of known elevations and it was therefore necessary to employ one or two aneroid altimeters. By repeating measurements it was possible to obtain an elevation correct to within 5 feet or less. Comparison of deduced barometric elevations, with either elevations given on the map or those estimated from the elevation contours, shows that the adopted elevations are usually correct within 5 feet and that the maximum error for any of the stations is not likely to exceed 15 feet. Five feet in elevation corresponds to a difference of approximately one-third of a milligal in the Bouguer anomaly and to one-half a milligal in the Free Air anomaly.

(e) Principal Facts for Gravity Stations

The principal facts concerning the gravity stations are collected in the table given in Appendix B. The stations are listed according to increasing latitude. The longitudes and latitudes were scaled from topographic maps on a scale of one mile to an inch. The

value of observed gravity for each station given in column (6) is quoted to four decimal places, and as has been shown in the previous sections, most values are likely to have that accuracy.

The Free Air and Bouguer anomalies are listed in the last two columns of the table. They have been computed in the usual manner and are based upon the International Gravity Formula for gravity[1] at sea level and an assumed mean density of 2·67 gms./cc. for the surface rocks.

No systematic correction for the terrain effects has been made but these effects have been calculated for 3 stations. Inspection of the topographic contours on the Ottawa one-mile sheet shows generally that the topography is fairly level and uniform, and the terrain correction for these areas is not likely to exceed 0·2 mgals. Large differences in elevation, however, occur only for a small portion of the surveyed area northwest of Hull, where the Precambrian Shield enters in a southeasterly direction. For this reason terrain corrections were evaluated for stations No. 278, 280 and 286, and found to be 2·6, 1·9 and 0·3 mgals. respectively. The corrections, if applied to the gravity values for the stations concerned, reduce by about one-half the anomaly difference between these stations.

SUMMARY OF GEOLOGICAL STRUCTURAL RELATIONSHIPS

The area under consideration is an interesting one as it occupies the border zone between two of the chief physiographic divisions of eastern Canada, the Ottawa-St. Lawrence Lowland underlain by flat-lying Palæozoic formations, and the more rugged Laurentian Highlands of the Precambrian Shield. The geology and structural

[1] Swick, C. H., *U.S. Coast and Geod. Surv.*, Special Publication No. 232, 1942.

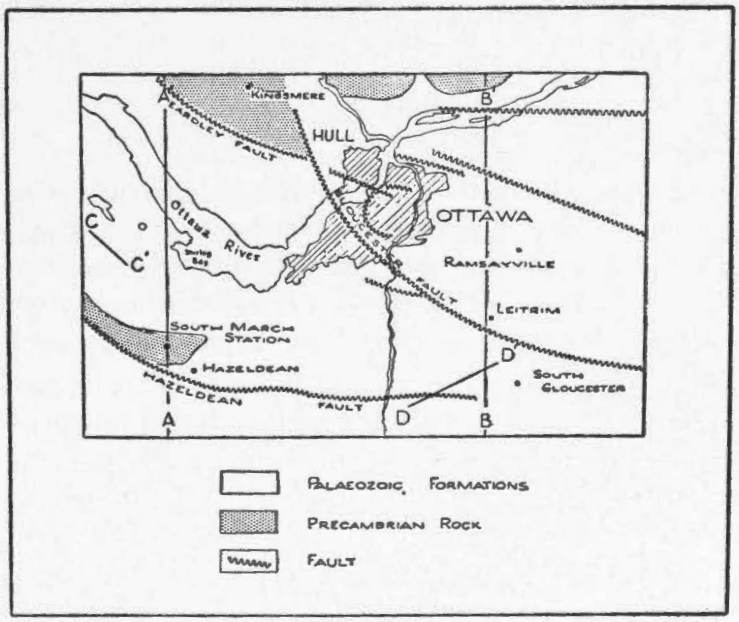

FIGURE 1. Map of Ottawa area showing main structural elements and location of gravity profiles.

relationships have been well examined and described by A. E. Wilson[1] of the Geological Survey of Canada, and these are illustrated on the geological map[2] (in pocket) on which the gravity results have also been plotted.

The most important structural elements of the area whose gravitational effects are examined in a later section, are a number of large fault-blocks of Palæozoic rocks which occupy the greater part of the area, and two small wedge-shaped or triangular exposures of Precambrian rocks. The latter, which according to A. E. Wilson, have been brought to their present position by faulting and are, therefore, in fault contact with and partially bounded by the Palæozoic formations, lie the one to the northwest from the city of Hull and the other to the west in March and Nepean townships.

Two major faults or fault zones, the Gloucester and the Hazeldean (*see* also Figure 1) cut across the Palæozoic rocks in broad arcs throughout the central part of the area. The former trends to the southeast while the latter trends in an easterly direction. The northwestern extensions of these, together with the Eardley fault which intersects the Gloucester fault west of Hull, form the contacts between the Palæozoic formations and the Precambrian rocks mentioned in the previous paragraph. Movements along these faults have been such that the rocks within the central area between the Hazeldean fault to the southwest and the Gloucester and Eardley faults to the north can best be described as a large fault block varying from about 5 miles in width near Gloucester station to a maximum of about 12 miles over most of the region to the west. The block is tilted to the northeast, thus exposing rocks which are progressively younger in that direction.

A large block, bounded on three of its sides by faults, lies directly east of the city of Ottawa. It forms the down-thrown side of the Gloucester fault and is so tilted to the southeast that the throw of the fault varies from about zero near Hull to nearly 1,200 feet 2 miles northeast of South Gloucester where the oldest and youngest Ordovician strata have been brought into juxtaposition. These relationships may be more clearly understood from an examination of the geological sections shown in Figures 2 and 3.

RESULTS

(a) Density Measurements

To interpret the variations in the Bouguer gravity anomalies the densities of the underlying rocks in the vicinity of the gravity stations must be known. The densities of about 80 specimens collected from the various geological formations in the Ottawa district are summarized in Table II. The mean densities, standard deviations of mean values and the number of specimens sampled from each formation are given.

It is difficult, if not impossible, to know how representative these results may be of the actual formation densities. Although the standard deviations provide some measure of their uncertainty, lacking sufficient data for more precise computation, the means have been calculated without regard to the volumes of different rock types in each of the formations. Nevertheless, the results appear sufficiently precise to permit certain generalities to be noted. The Ordovician rocks appear to have the most consistent

[1] Geology of the Ottawa-St. Lawrence Lowland, Ontario and Quebec, *Geol. Surv., Canada*, Mem. 241, 1946.
[2] Prepared by the Geological Survey of Canada.

TABLE II.

Densities of Rocks — Ottawa and District.

Era	Period	Sub-Epoch	Formation	Subdivisions	Number of Samples	Mean Density	Standard Deviation	Remarks
Palæozoic	Ordovician	Lorraine	Carlsbad	Gray shale and sandy rusty shale	12	2·62	± 0·07	
		Gloucester	Billings	Black shale with a few feet of brown shale at base	8	2·62	± 0·01	
		Trenton and Black River	Ottawa	Limestone	10	2·69	± 0·03	
		Chazy	Rockcliffe	Shale and sandstone lenses	10	2·49	± 0·12	All samples
					7	2·43	± 0·06	Sandstones
					3	2·63	± 0·02	Shale
		Beekmantown	Oxford	Dolomite	13	2·72	± 0·05	
			March	Interbedded sandstone and dolomite	4	2·58	± 0·07	
	Ordovician or Cambrian		Nepean	Sandstone	4	2·52	± 0·03	
Precambrian			Syenite Buckingham	Syenite, limestone, quartzites and metamorphic rocks; associated granite and granite gneiss	27	2·66	± 0·10	from all samples
					5	2·66	± 0·11	from Ste. Rose de Lima, Que.
			Grenville		16	2·64	± 0·10	from King Mountain, Que.
					3	2·71	± 0·01	from Hazeldean, Ont.

densities with deviations ranging from 0·01 to 0·07 gms./cm³. The Oxford dolomites and Ottawa limestone are the heaviest, having mean densities of 2·72 gms./cm³. and 2·69 gms./cm³. respectively. The lightest rocks are the sandstones which have mean densities of 2·43 gms./cm³. for the Rockcliffe formation, 2·58 gms./cm³. for March formation and 2·52 gms./cm³. for Nepean sandstone. Intermediate to these density groups are the shales which have densities of about 2·62 gms./cm³. regardless of age.

The mean density for all Precambrian rocks tested is 2·66 gms./cm³. It will be shown in a later section that the densities of the underlying Precambrian rocks in this area are most likely more variable than suggested by the table.

(b) General Features of the Gravity Field

The gravity stations, their numbers and corresponding Bouguer anomalies in units of tenths of milligals (1 x 10^{-4}c.g.s. units) are drawn on the enclosed map. Contours of equal anomaly are shown at one-milligal intervals. The anomalies have a range of 30 mgals., increasing from a minimum of −39 near Kingsmere, northwest from Hull, to a maximum of nearly −9 mgals. near South Gloucester. These two areas of contrasting anomaly are probably the most outstanding features of the gravity map. The coincidence of the more negative anomalies over the Precambrian granitic rocks to the northwest, together with the fact that low densities were found for these rocks (*see* Table II) strongly suggest that the granite itself is at least partly responsible for the gravity minimum. The Precambrian rocks near South March station are granite gneisses with considerably higher densities and correspondingly larger gravity anomalies.

Because of this large control by the Precambrian rocks, correlations between the Palæozoic formations and the anomalies are not too obvious. At first it might appear, for instance, that the gravity high near South Gloucester is largely controlled by the dolomites and limestones of the Oxford (Beekmantown) formation which were found to have densities (2·72 gms./cm³.) considerably higher than most of the rock specimens measured. However, if it can be assumed that the mean density of this formation is about 0·1 gms./cm³. greater than the mean density of the surrounding rocks, and that its thickness does not exceed[1] 300 feet, then its maximum gravitational effect is estimated[2] not to increase the total anomaly by more than four tenths of a milligal. Since the lower Palæozoic formations (March and Nepean) have considerably lower densities, it is necessary to conclude that the Gloucester high is largely controlled by the underlying Precambrian rocks.

There is, however, some correlation between the anomalies and the Palæozoic rocks where the latter are thick enough. This is particularly noticeable northeast of the Gloucester fault where the anomalies are generally more negative than they are to the south. The variation in the vertical displacement of the Gloucester fault is also evident from the gravity data. Where its throw is greatest to the southeast, the contours tend to parallel the fault. Near Ottawa, however, where the throw is considerably less, the gravity contours cut directly across the fault zone and are nearly normal to it.

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[1] Well records on file with the Geological Survey of Canada, show thicknesses as great as 260 feet for the Oxford formation in the Ottawa district. Near South Gloucester, the Oxford is likely to be considerably less thick. *(See Geol. Surv., Canada,* Mem. 241, 1946, p. 34.)

[2] On the basis of the simple Bouguer formula for an extensive plateau.

In addition to the gravity features discussed above, less pronounced minima and maxima occur at several places within the map area. For example, a gravity minimum with an amplitude of about 2 mgals. occurs about a mile south of Eagleson Corners. An unusually thick mantle of overburden or drift might account for much of this anomaly, since 100 feet of drift suitably distributed is capable of producing an anomaly of about one mgal. Although no direct evidence is available, it is noticed that the gravity stations supporting this anomaly are situated in a low-lying area south of the escarpment of the Hazeldean fault zone, where depths to the bedrock surfaces are probably much greater than usual. Other gravity maxima and minima of similar amplitudes occur along the Ottawa River.

(c) Gravity and Magnetic Profiles

Other features of the gravity field will be studied from the profiles, whose positions are shown on the location map (*see* Figure 1). Geological sections for the profiles have been taken from the Geological Survey of Canada Maps 413A, and 414B. Variations in the intensity of the total magnetic field also shown in profile have been obtained from the aeromagnetic map[1] for the Ottawa area.

(i) Profile A – A′

This profile, which shows the data for a north-south line through South March station is illustrated in Figure 2. The anomalies rise from comparatively low and uniform values over the block of Palæozoic sediments lying south of the Hazeldean fault to a maximum over the Precambrian ridge in March township. On the basis of the thicknesses shown and the densities given in Table II, the mean density of the Palæozoic section is 2·65 gms./cm^3., or 0·06 gms./cm^3. lower than the densities obtained for the Precambrian rocks. The trend of the gravity anomalies is therefore consistent with the measurements of density, but it is interesting to note that the increase in the anomaly is quite small[2] over the fault zone with the steepest gradient about half a mile further north. Although other causes may contribute, the low gradient over the fault is thought to be due to the local effect of low density sandstone (Nepean) which lies immediately north of the fault and in contact with the more dense limestone (Black River) to the south. This is the interpretation given by A. H. Miller[3] to explain the gravity gradients he observed with a torsion balance in 1929. His profile which is about 3 miles to the east is shown in Figure 3. For comparison, the results of detailed gravimeter measurements made by the writer in 1950 along the same line are plotted. The indications of the two types of instruments are in remarkably good agreement as the peaks of the gradient profile occur at the places where the gravity curve is the steepest. Miller showed that the unusual form of the gradient curve, including the minimum directly over the fault, agreed with the calculated profile and the assumed geological section.

It is also interesting to note that, with the exception of the Precambrian rocks, the mean densities used by Miller agree to within 2 per cent of those in Table II. To make the calculated gradient curve coincide with the observed values he found it was necessary

[1] *Geol. Surv., Canada*, Geophysics Paper No. 8, 1950.
[2] Theoretically the gravity anomaly due to a vertical fault reaches half its peak value directly over the fault.
[3] Miller, A. H., *Geol. Surv., Canada*, Mem. 165, 1931.

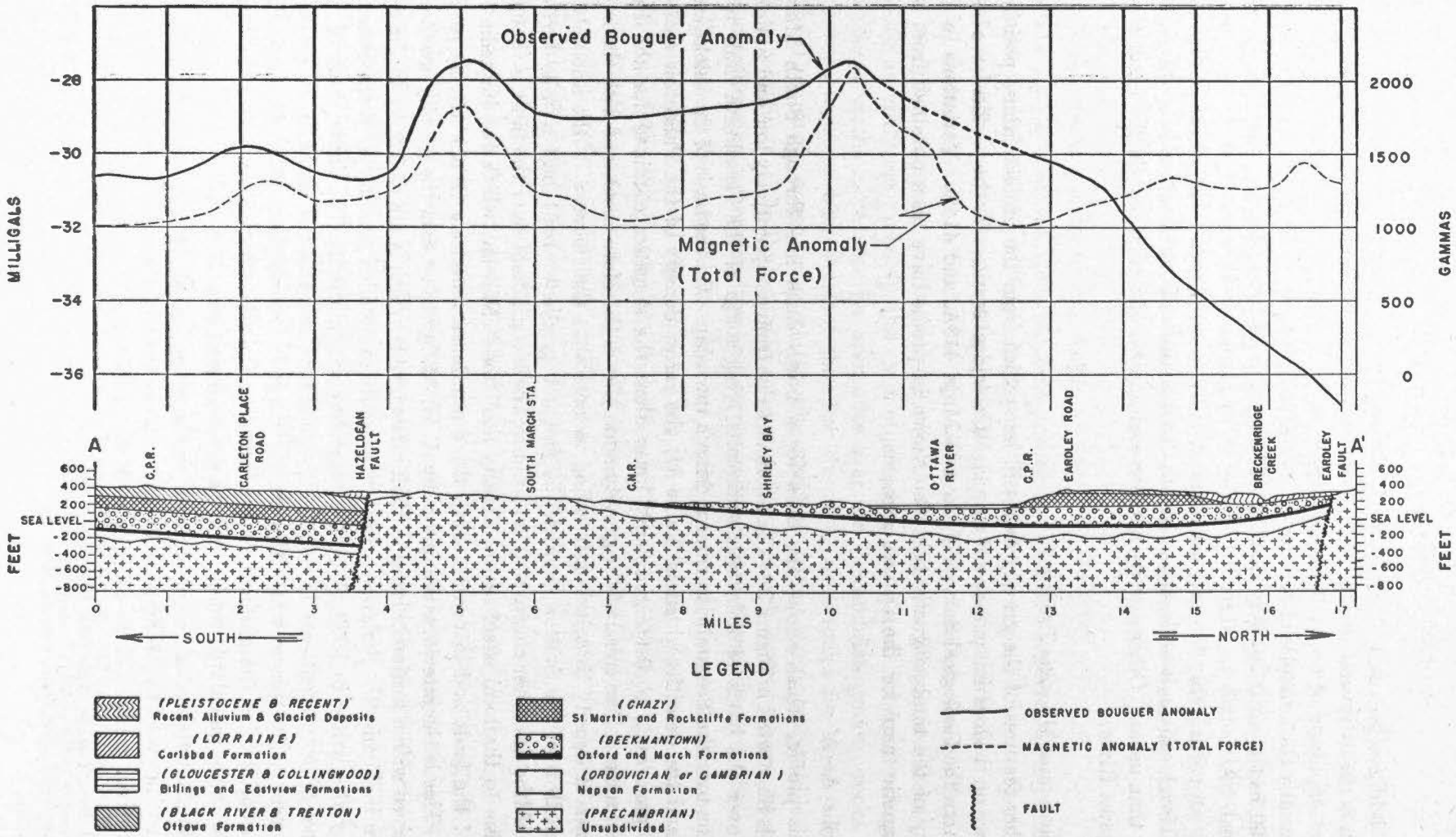


FIGURE 2. Gravity and magnetic profile and structure section (after A. E. Wilson) for the line A – A'.

to assume a mean density of 3·0 gms./cm³. for the Precambrian rocks. On the basis of a vertical displacement of 600 feet for the Hazeldean fault and the mean densities from Table II, the calculated anomalous effect of the fault is only about 0·5 mgals. On the other hand, if a density of 3·0 gms./cm³. is assumed for the Precambrian rocks, the calculated effect becomes about 2·6 mgals., which is in much closer agreement with the observed values.

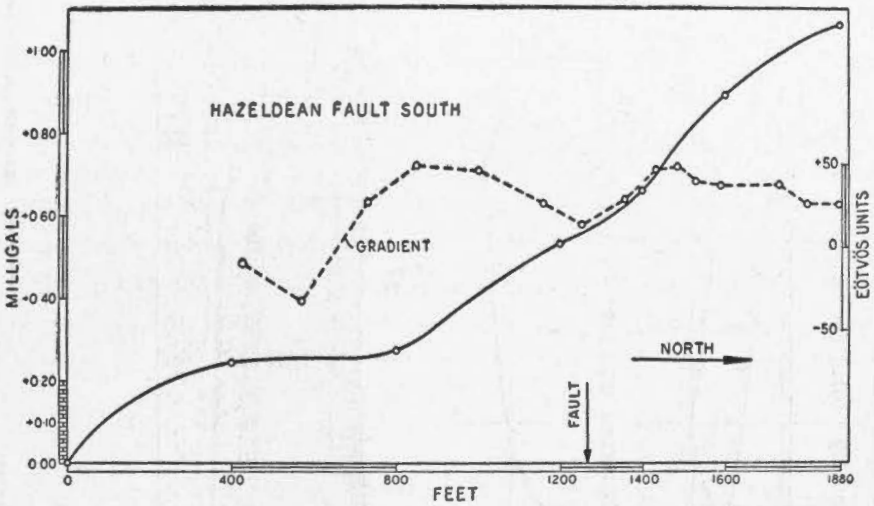


Figure 3. Relative Bouguer gravity anomalies and gravity gradients along a profile over the Hazeldean fault at Hazeldean South, Ontario.

Along the remainder of profile A – A′, there is little or no correspondence between the magnitude of the anomalies and the geological section, and it must be concluded that the cause is due to topographical or lithological variations, or both, within the Precambrian. North of Shirley Bay, on the Ottawa River, the gravity curve reaches a second peak having about the same amplitude as the high near South March station. From the Ottawa River, gravity decreases at a uniform rate of more than 2 mgals./mile, and this gradient is maintained to the northern limit of the profile.

It might be considered that the steep gradient reflects a general thickening of the Palæozoic formations toward the Eardley escarpment where they are down-faulted against the Precambrian rocks, and to an accumulation of unconsolidated sediments south of the fault. However, calculations based upon thicknesses illustrated show that the maximum deficiency from these sources is less than 2 mgals. Another factor that may decrease the Bouguer anomaly in this area is an unusually great thickness of sandstone at the base of the Ordovician. According to A. E. Wilson the thicknesses of the basal sandstones are quite variable depending upon the irregularities in the Precambrian floor upon which they were laid down. Their greatest recorded thickness is about 500 feet. An equal thickness for the Nepean sandstones south of the Eardley escarpment would account for another milligal of the gravity low, so that the maximum deficiency we can assign to possible variations in the Palæozoic column (from that shown in the section) is less than 3 mgals. The greatest part of the negative anomaly, therefore, must arise from a rather rapid decrease in density within the Precambrian rock masses.

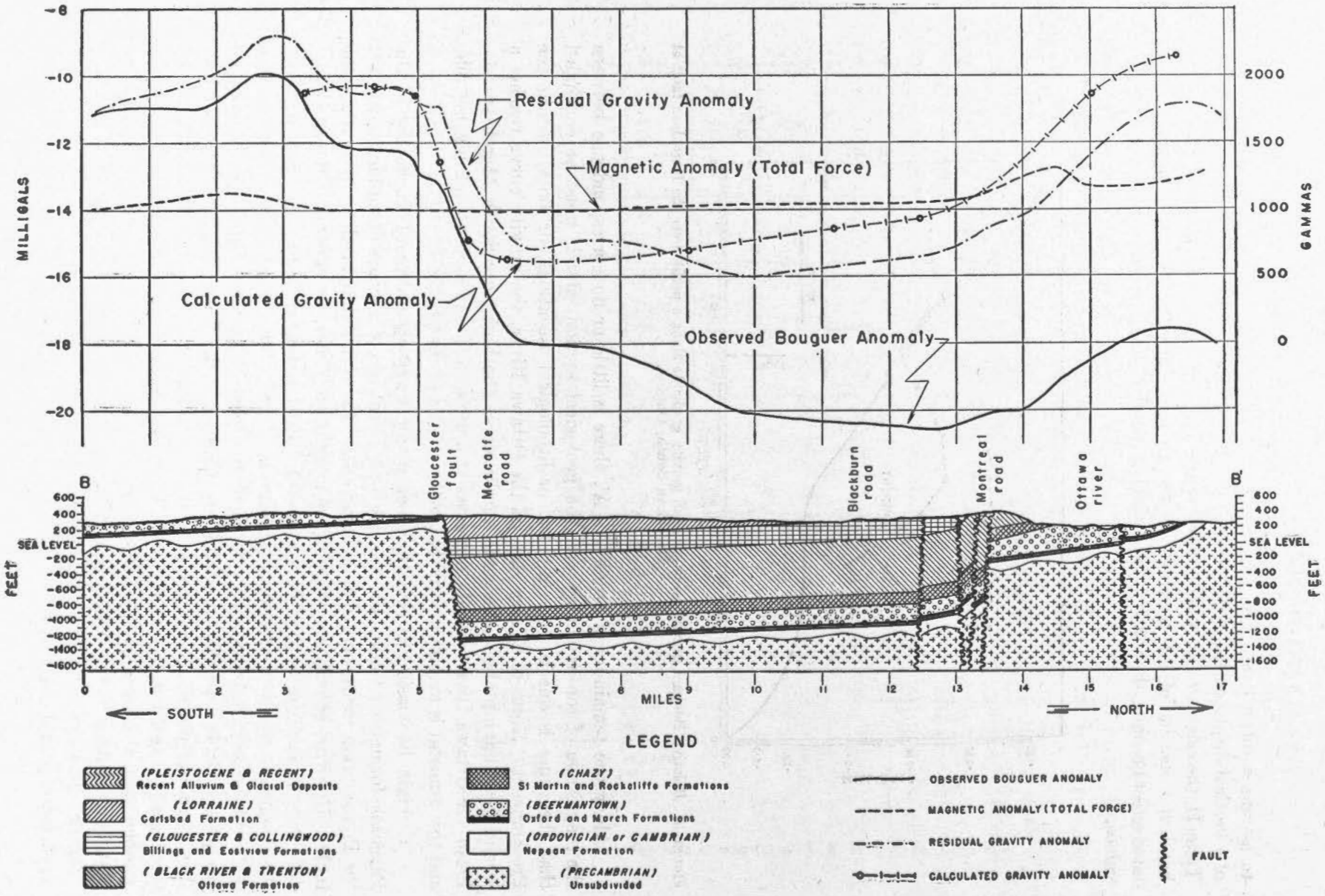


FIGURE 4. Gravity and magnetic profile and structure section (after A. E. Wilson) for the line B – B'.

(ii) Profile B – B′

The gravitational low over the large down-faulted block extending eastward from Ottawa (Figure 4) is apparently due to the density contrast between the block of sedimentary rocks and the denser rocks (Precambrian rocks with a thin veneer of lower Ordovician sediments) which lie south of the fault. The effect of the fault-block appears as a local anomaly superimposed upon a broader regional trend decreasing to the north. Assuming a uniform regional gradient of 0·4 mgals./mile, this local effect has been estimated and is illustrated as the residual profile in Figure 4.

The theoretical gravitational effect of an extensive body having the same cross-section as the fault-block is shown for comparison. The calculations are based upon the densities given in Table II with the exception of those listed for the Precambrian rocks. For the latter a density of 2·9 gms./cm³. was assumed to bring the residual and calculated profiles into near coincidence over the Gloucester fault zone. While this may seem large for the Precambrian rocks, higher densities than these are obtained for basic granite gneisses in other parts of the Canadian Shield. The fit between the two curves is reasonable and shows that the greater part of the variation in gravity may be explained by a deficiency caused by the Palæozoic rocks and uniform anomaly gradient decreasing to the north.

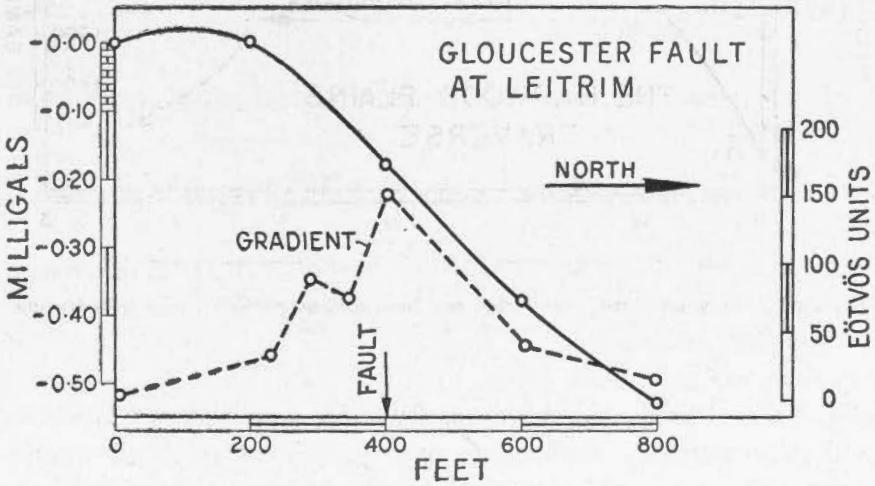


FIGURE 5. Relative Bouguer gravity anomalies and gravity gradients along a profile over the Gloucester fault near Leitrim, Ontario.

Figure 5 shows the gravimeter and torsion balance[2] results for a detailed north-south traverse over the Gloucester fault zone at Leitrim, about a mile to the east of profile B – B′. The vertical displacement (or throw) of the fault here is estimated to be about 1,500 feet. In contrast to the Hazeldean fault, the distribution of density is such that a gradient maximum is produced over the fault. This was observed with the torsion balance and confirmed by the form of the gravity profile.

[1] Miller, A. H. and Innes, M. J. S., *Publications of the Dominion Observatory*, vol. XVIII, No. 2, 1955.
[2] Miller, A. H., loc. cit.

(iii) Comparison of Gravity and Magnetic Data

Total magnetic field intensities have been plotted in Figures 2 and 4 for comparison with the gravity anomalies. The profiles in Figure 2 are strikingly similar largely because the two maxima occur at the same points. The general tendency is for both gravity and magnetic anomalies to be more positive over the exposed Precambrian rocks on the upthrow side of the Hazeldean fault, or where the Palæozoic mantle is less deep. The rather sharp maximum north of Shirley Bay may be the expression of rapid variations in the magnetic properties within the Precambrian floor or to a buried ridge of heavy Precambrian rocks. In contrast, variations in magnetic intensity along the line B – B′ (*see* Figure 4) are quite small, as might be expected considering the greater thicknesses of sedimentary cover along this line. It is noted, however, that small magnetic maxima coincide in position with points of higher gravity anomaly. Generally then, the magnetic data would appear to reflect structures within the Precambrian rocks in much the same way as the gravity results.

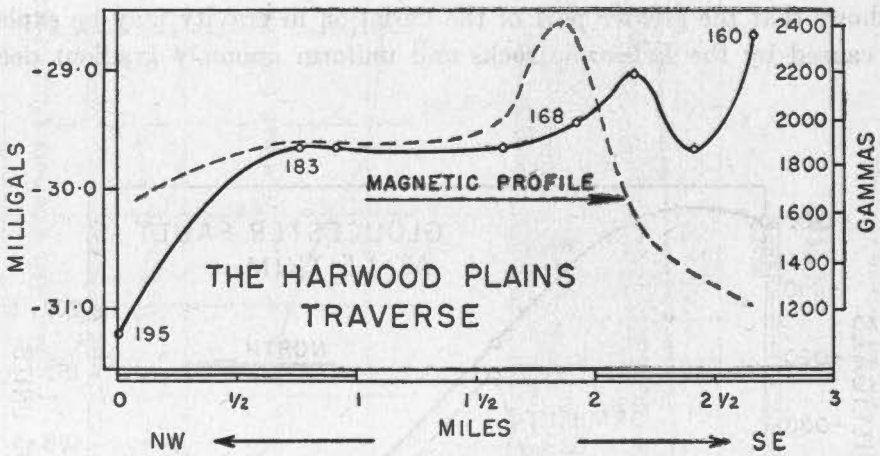


FIGURE 6. Bouguer gravity anomalies and total field magnetic anomalies for the line C – C′ near Harwood Plains.

To examine more closely the correspondence between the two types of anomalies, detailed gravimeter traverses were made over prominent magnetic anomalies shown within the Ottawa map area. The location of the traverses are shown in Figure 1 and also on the gravity map. The Harwood Plains traverse (C – C′) crosses a narrow east-west trending magnetic high with a relief of about 1,200 gammas (*see* Figure 6). This high extends from an area of exposed Precambrian rocks to the west, and is therefore probably related to a more magnetic phase of the gneissic basement rocks. The Bouguer gravity anomaly profile for this traverse is shown, together with the total field magnetic anomaly, as recorded at a height of 1,000 feet. It must be pointed out that the exact position of the peak of the magnetic profile is uncertain, as a spacing of flight lines for the aeromagnetic survey was rather wide (about a mile). However, there is a small gravity maximum of about 0·7 mgal. relief approximately corresponding to the peak of the magnetic curve. This would appear to indicate that both effects are due to a more basic band of the Precambrian gneisses, which is denser and more magnetic than its surroundings.

A similar traverse (D – D′) was made along the road extending southwesterly from Johnston Corners, across a roughly circular magnetic high of about 1,000 gammas relief. The Bouguer anomalies and also the magnetic profile are given in Figure 7. Although the regional gravity increase to the northeast has not been removed, the local maximum of about 1 milligal near mile 1·5 is evident. The peak of the magnetic curve is indicated to be somewhat to the northeast of this point, but as before, its position is uncertain because of the spacing of flight lines. It is probable that both maxima are related to a phase of the basement rocks. The profile does cross a possible extension of the Hazeldean fault, at the point indicated on Figure 7 but no definite indication of the fault can be seen on the gravity profile.

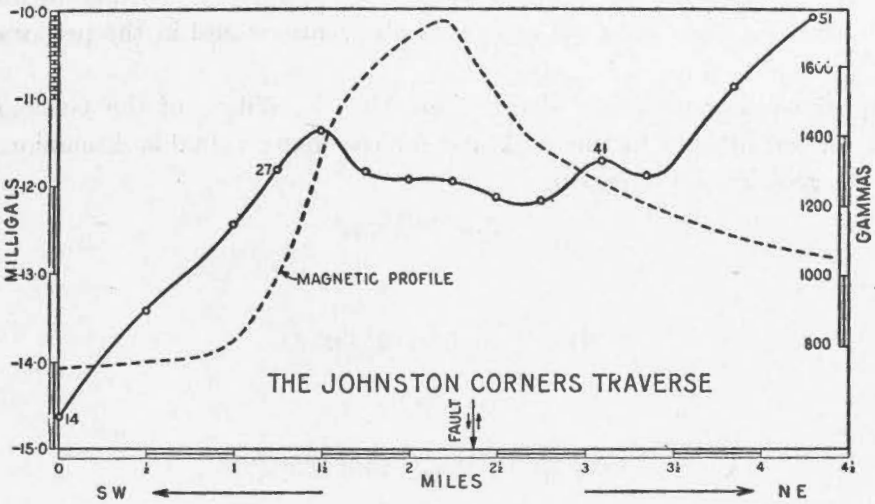


FIGURE 7. Bouguer gravity anomalies and total field magnetic anomalies for the line D – D′ near Johnston Corners.

In conclusion, therefore, it may be noted that relatively minor gravity anomalies are to be found in association with the strongest magnetic highs of the area; and although the correlation between the two is only of a very general character, it is probable that both are due to more basic phases of the Precambrian gneisses underlying the sedimentary rocks.

SUMMARY

It has been shown that the major features of the Bouguer anomaly field as observed throughout the Ottawa district are made up of 2 parts: (1) large scale regional effects due to density changes within the underlying Precambrian rocks, (2) the effect of variations in the thickness of the Palæozoic rocks, regarded as local effects with amplitudes no greater than 6 mgals. Prominent local effects were found in the case of certain major normal faults which cross the area, and which had been previously investigated with the torsion balance.

Gravity observations over areas of positive magnetic anomaly showed a correlation, suggestive of the presence of denser, more magnetic phases in the Precambrian basement.

The gravity values for a base line between Prescott, Ontario, and Maniwaki, Quebec, suitable for the calibration of gravimeters to one part in a thousand, are given.

ACKNOWLEDGMENTS

A six months' fellowship from the Canadian Council for Reconstruction through UNESCO enabled the writer to obtain a closer knowledge of Canadian geophysical research. The Dominion Observatory at Ottawa kindly invited the writer to take part in its work and made it possible for him to see gravity investigations being carried out in various regions of Canada. Two and a half months were spent participating in field work in the middle west and in the Maritimes, and the rest of the time was spent on the work reported upon here.

The writer wishes to thank Dr. C. S. Beals, Dominion Astronomer, and Mr. A. H. Miller, former chief of the Gravity Division, for many helpful suggestions during the investigation. Thanks are also due to Dr. M. J. S. Innes and other members of the Gravity Division for their help with the field observations and in the preparation of the report.

Finally, the writer wishes to thank Miss Alice E. Wilson of the Geological Survey of Canada, for her interest in the work and for the many valuable discussions held with her about the geology of the region.

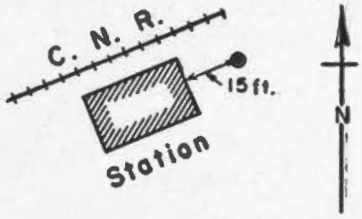
APPENDIX A

Description of Sites

of

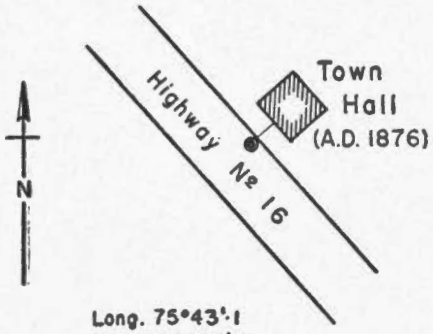
Gravimeter Base Stations

PRESCOTT, ONT.



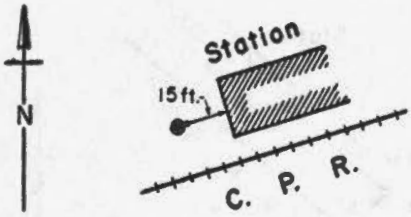
Long. 75°31'5
Lat. 44°42'·8
Elev. 311 ft.
g 980 56653 gals

NORTH GOWER, ONT.



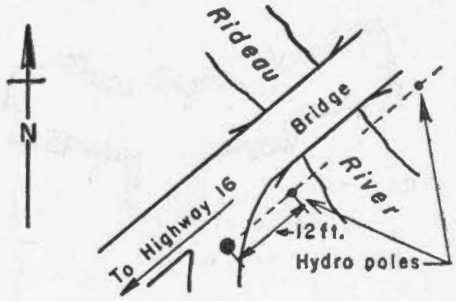
Long. 75°43'·1
Lat. 45°07'·9
Elev. 300 ft.
g 980 61094 gals

BEDELL, ONT.



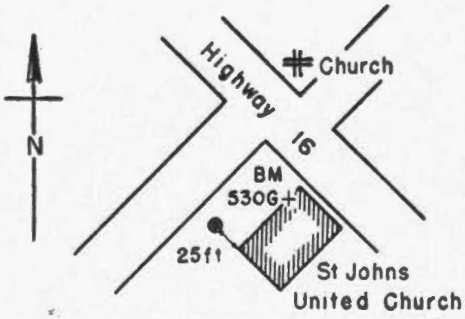
Long 75°37'·9
Lat 44°59'·8
Elev 334 ft.
g 980 57527 gals.

MANOTICK, ONT.



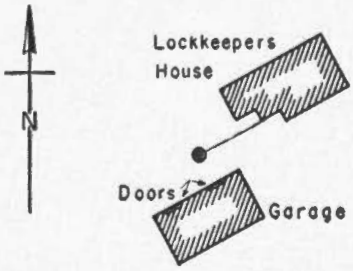
Long. 75°41'·1
Lat. 45°13'·6
Elev. 275 ft.
g 980 62039 gals

KEMPTVILLE, ONT.



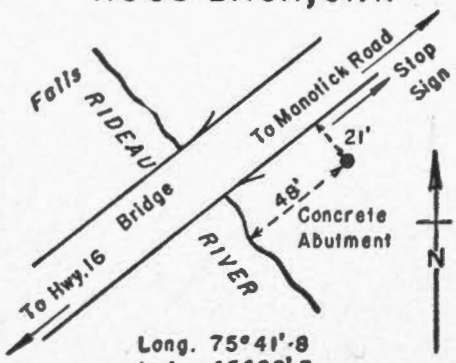
Long 75°38'·6
Lat. 45°00'·8
Elev 319 ft
g 980·58197 gals

BLACK RAPIDS, ONT.



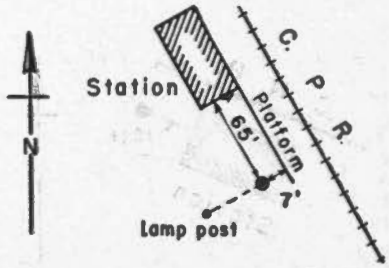
Long. 75°42'·0
Lat. 45°19'·3
Elev. 255 ft.
g 980·62551 gals

HOGS BACK, ONT.



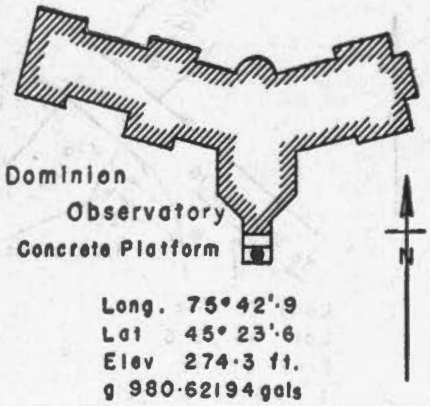
Long. 75°41'·8
Lat. 45°22'·3
Elev. 250 ft.
g 980·62611 gals

CASCADES, QUE.



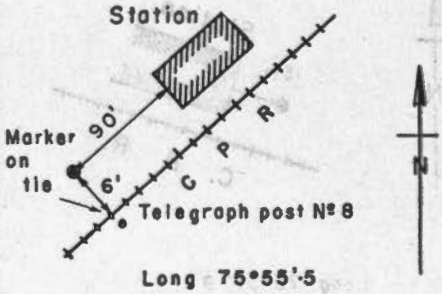
Long 75°52'·6
Lat 45°35'·5
Elev 330 ft.
g 980 62742 gals

OTTAWA, ONT.



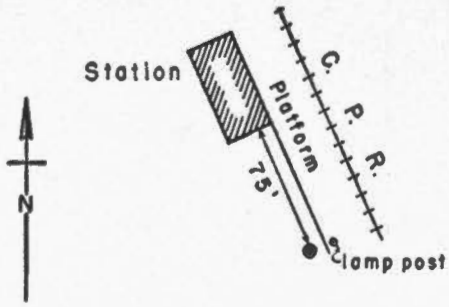
Long. 75°42'·9
Lat 45°23'·6
Elev 274·3 ft.
g 980·62194 gals

WAKEFIELD, QUE.



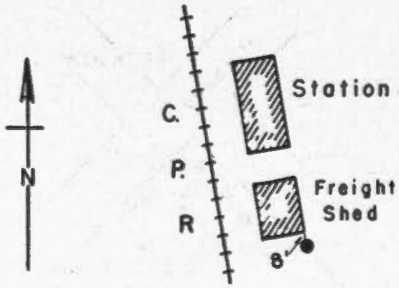
Long 75°55'·5
Lat 45°38'·5
Elev 330 ft
g 980·63492 gals

CHELSEA, QUE.



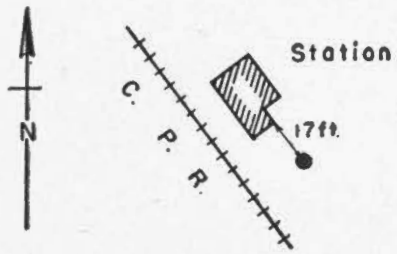
Long. 75°47'·1
Lat. 45°30'·3
Elev 369 ft.
g 980·61979 gals

FARRELTON, QUE.



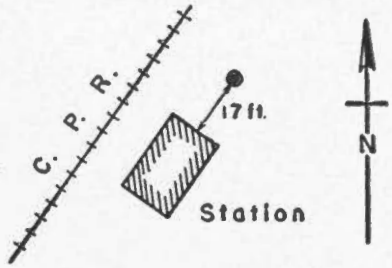
Long 75°54'·9
Lat 45°44'·9
Elev 345 ft
g 980·64970 gals

LOW, QUE.



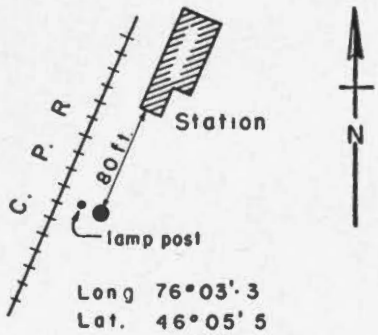
Long. 75°57'·3
Lat. 45°48'·6
Elev. 411 ft.
g 980·65210 gals

MESSINES, QUE.



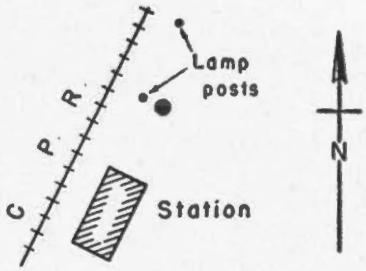
Long. 76°01'·4
Lat. 46°14'·4
Elev. 571 ft.
g 980·68119 gals

GRACEFIELD, QUE.



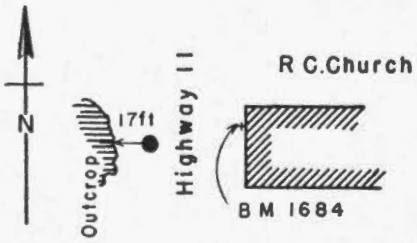
Long 76°03'·3
Lat. 46°05' 5
Elev. 508 ft.
g 980 67179 gals

MANIWAKI, OUE.



Long 75°58' 6
Lat. 46°22' 4
Elev. 569 ft.
g 980·69063 gals

BOUCHETTE, QUE



Long 75°57'·6
Lat. 46°12' 1
Elev. 531 ft
g 980·68258 gals

APPENDIX B

Principal Facts

for

Gravity Stations near Ottawa, Ontario

PRINCIPAL FACTS FOR GRAVITY STATIONS NEAR OTTAWA, ONTARIO

Station		Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name							Free Air	Bouguer
		°	′	°	′	Ft.			
1	Dominion Observatory	75	42·9	45	23·6	274·3	980·6220	−0·0171	−0·0265
2		75	43·6	45	14·1	308	·6135	− ·0082	− ·0187
3		75	40·2	45	14·2	286	·6218	− ·0021	− ·0118
4	Little Island	75	42·5	45	14·6	256	·6185	− ·0088	− ·0175
5		75	38·9	45	14·7	313	·6208	− ·0013	− ·0120
6		75	53·2	45	14·8	330	·6029	− ·0178	− ·0290
7		75	50·9	45	15·0	319	·6055	− ·0165	− ·0274
8		75	35·5	45	15·0	353	·6199	− ·0011	− ·0109
9		75	54·7	45	15·1	390	·5983	− ·0171	− ·0304
10		75	47·7	45	15·1	305	·6104	− ·0130	− ·0234
11		75	41·8	45	15·1	276	980·6187	−0·0075	−0·0169
12		75	44·2	45	15·2	296	·6142	− ·0102	− ·0203
13		75	52·7	45	15·3	338	·6033	− ·0173	− ·0288
14		75	40·9	45	15·3	301	·6197	− ·0044	− ·0146
15	Manotick Station	75	37·3	45	15·3	327	·6213	− ·0004	− ·0115
16		75	32·4	45	15·3	292	·6215	− ·0035	− ·0134
17		75	58·4	45	15·4	450	·5937	− ·0166	− ·0319
18		75	53·8	45	15·4	352	·6014	− ·0181	− ·0301
19		75	57·1	45	15·5	414	·5976	− ·0162	− ·0303
20	Stittsville Station	75	55·2	45	15·5	398	·5981	− ·0772	− ·0308
21		75	36·9	45	15·6	327	980·6220	−0·0001	−0·0112
22		75	49·6	45	15·6	310	·6072	− ·0165	− ·0271
23		75	51·2	45	15·7	318	·6051	− ·0180	− ·0288
24	Fallowfield Station	75	46·2	45	15·7	305	·6138	− ·0106	− ·0210
25		75	42·6	45	15·7	284	·6182	− ·0082	− ·0178
26	Greeley	75	33·6	45	15·8	311	·6229	− ·0010	− ·0116
27		75	39·5	45	15·8	330	·6215	− ·0006	− ·0118
28	Greeley	75	33·8	45	15·9	307	·6233	− ·0011	− ·0116
29		75	31·0	45	15·9	299	·6222	− ·0030	− ·0132
30	Old Stittsville	75	56·2	45	16·0	413	·5980	− ·0167	− ·0307
31		75	42·8	45	16·0	298	980·6172	−0·0083	−0·0184
32		75	42·1	45	16·0	291	·6195	− ·0067	− ·0166
33		75	51·5	45	16·1	315	·6045	− ·0195	− ·0302
34		75	48·2	45	16·2	390	·6058	− ·0113	− ·0246
35		75	44·7	45	16·2	327	·6145	− ·0085	− ·0196
36		75	35·7	45	16·2	347	·6226	− ·0015	− ·0103
37		75	56·9	45	16·3	413	·5973	− ·0178	− ·0318
38		75	45·6	45	16·3	320	·6131	− ·0107	− ·0216
39		75	52·1	45	16·5	322	·6038	− ·0202	− ·0311
40		75	59·9	45	16·6	428	·5965	− ·0176	− ·0322
41		75	37·7	45	16·6	350	980·6217	+0·0002	−0·0117
42		75	46·9	45	16·7	338	·6113	− ·0114	− ·0229
43		75	31·6	45	16·7	274	·6258	− ·0029	− ·0123
44		75	55·0	45	16·8	343	·6042	− ·0182	− ·0299
45		75	45·1	45	16·8	312	·6154	− ·0100	− ·0206
46		75	40·1	45	16·8	301	·6234	− ·0030	− ·0132
47	South Gloucester	75	34·2	45	16·8	336	·6231	− ·0000	− ·0114
48		75	50·3	45	16·9	382	·6038	− ·0151	− ·0281
49		75	43·3	45	16·9	300	·6187	− ·0079	− ·0181
50		75	52·9	45	17·0	318	·6049	− ·0201	− ·0310

PRINCIPAL FACTS FOR GRAVITY STATIONS NEAR OTTAWA, ONTARIO—*Continued*

Station		Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name							Free Air	Bouguer
		°	′	°	′	Ft.			
51	Johnston Corners	75	36·2	45	17·1	387	980·6218	+0·0031	−0·0101
52		75	45·5	45	17·2	308	·6168	− ·0095	− ·0200
53		75	30·1	45	17·2	286	·6258	− ·0026	− ·0123
54		75	55·3	45	17·3	328	·6056	− ·0190	− ·0302
55		75	33·0	45	17·3	291	·6269	− ·0011	− ·0110
56		75	52·2	45	17·5	358	·6052	− ·0169	− ·0291
57		75	41·7	45	17·5	268	·6243	− ·0062	− ·0153
58		75	57·3	45	17·6	376	·6011	− ·0194	− ·0322
59		75	38·2	45	17·6	329	·6235	− ·0015	− ·0127
60	Hazeldean	75	53·6	45	17·7	340	·6063	− ·0177	− ·0293
61		75	44·4	45	17·7	302	980·6189	−0·0087	−0·0190
62		75	47·4	45	17·8	313	·6148	− ·0127	− ·0237
63		75	40·7	45	17·8	295	·6237	− ·0047	− ·0148
64		75	36·7	45	17·8	398	·6222	+ ·0034	− ·0102
65		75	34·8	45	17·8	387	·6233	+ ·0035	− ·0097
66		75	31·6	45	17·9	266	·6282	− ·0031	− ·0122
67	Gloucester Station	75	38·4	45	18·0	356	·6224	− ·0006	− ·0127
68		75	50·0	45	18·1	368	·6095	− ·0125	− ·0251
69	Merivale Station	75	44·1	45	18·1	298	·6204	− ·0082	− ·0184
70	Eagleson Corners	75	52·8	45	18·2	364	·6076	− ·0149	− ·0273
71		75	46·1	45	18·3	303	980·6161	−0·0124	−0·0227
72		75	33·6	45	18·3	322	·6269	+ ·0002	− ·0108
73		75	30·7	45	18·3	264	·6265	− ·0056	− ·0146
74		75	30·4	45	18·4	265	·6254	− ·0068	− ·0158
75		75	56·8	45	18·5	322	·6071	− ·0199	− ·0309
76		75	55·0	45	18·5	306	·6085	− ·0200	− ·0304
77		75	42·6	45	18·5	297	·6229	− ·0064	− ·0165
78		75	38·8	45	18·5	370	·6224	− ·0001	− ·0127
79		75	51·5	45	18·7	354	·6086	− ·0157	− ·0277
80		75	59·9	45	18·9	389	·6018	− ·0194	− ·0327
81		75	48·1	45	18·9	312	980·6151	−0·0134	−0·0241
82		75	41·2	45	18·9	302	·6240	− ·0055	− ·0157
83		75	35·5	45	18·9	297	·6279	− ·0020	− ·0121
84		75	44·5	45	19·0	314	·6185	− ·0100	− ·0207
85		75	38·0	45	19·0	328	·6249	− ·0022	− ·0128
86		75	32·2	45	19·0	274	·6261	− ·0061	− ·0154
87		75	55·7	45	19·2	356	·6096	− ·0152	− ·0273
88		75	37·5	45	19·2	324	·6267	− ·0011	− ·0122
89		75	59·1	45	19·3	342	·6051	− ·0212	− ·0328
90		75	53·1	45	19·3	295	·6118	− ·0189	− ·0290
91		75	46·7	45	19·4	316	980·6134	−0·0155	−0·0263
92	Merivale	75	43·1	45	19·4	302	·6226	− ·0075	− ·0178
93		75	37·1	45	19·4	315	·6270	− ·0020	− ·0127
94		75	34·2	45	19·4	278	·6276	− ·0048	− ·0143
95	Bells Corners	75	49·7	45	19·5	301	·6130	− ·0175	− ·0277
96		75	50·2	45	19·6	294	·6132	− ·0180	− ·0280
97		75	36·5	45	19·6	322	·6264	− ·0022	− ·0132
98		75	30·9	45	19·6	267	·6252	− ·0086	− ·0177
99		75	58·2	45	19·7	304	·6102	− ·0203	− ·0307
100		75	39·4	45	19·7	380	·6211	− ·0022	− ·0152

PRINCIPAL FACTS FOR GRAVITY STATIONS NEAR OTTAWA, ONTARIO—*Continued*

Station		Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name							Free Air	Bouguer
		°	′	°	′	Ft.			
101	.....	75	42·2	45	19·8	279	980·6234	−0·0095	−0·0190
102	Leitrim.....	75	36·1	45	19·8	337	·6241	− ·0034	− ·0148
103	Bells Corners Station.....	75	48·7	45	19·9	284	·6158	− ·0168	− ·0265
104	.....	75	56·0	45	20·0	318	·6132	− ·0164	− ·0273
105	.....	75	51·4	45	20·0	280	·6146	− ·0186	− ·0281
106	.....	75	45·1	45	20·0	287	·6179	− ·0146	− ·0244
107	.....	75	33·2	45	20·0	276	·6252	− ·0084	− ·0178
108	South March Station.....	75	54·9	45	20·2	283	·6139	− ·0193	− ·0289
109	.....	75	36·3	45	20·2	319	·6249	− ·0049	− ·0158
110	.....	75	53·7	45	20·3	226	·6158	− ·0228	− ·0305
111	.....	75	41·1	45	20·3	336	980·6228	−0·0056	−0·0170
112	.....	75	38·0	45	20·3	326	·6246	− ·0047	− ·0158
113	.....	75	59·1	45	20·4	410	·6045	− ·0170	− ·0310
114	.....	75	50·4	45	20·4	219	·6196	− ·0199	− ·0274
115	.....	75	43·6	45	20·4	287	·6209	− ·0122	− ·0220
116	.....	75	36·9	45	20·4	313	·6243	− ·0064	− ·0170
117	.....	75	34·7	45	20·4	289	·6260	− ·0069	− ·0168
118	.....	75	47·2	45	20·5	254	·6179	− ·0185	− ·0271
119	.....	75	41·3	45	20·6	317	·6225	− ·0080	− ·0188
120	.....	75	37·2	45	20·6	305	·6248	− ·0069	− ·0173
121	.....	75	31·5	45	20·6	264	980·6262	−0·0094	−0·0184
122	.....	75	43·9	45	20·7	288	·6206	− ·0128	− ·0227
123	.....	75	42·0	45	20·7	272	·6248	− ·0102	− ·0195
124	.....	75	40·0	45	20·7	321	·6256	− ·0048	− ·0157
125	Graham Bay Station.....	75	48·4	45	20·8	222	·6200	− ·0198	− ·0274
126	.....	75	41·7	45	20·9	297	·6237	− ·0092	− ·0193
127	.....	75	36·6	45	20·9	295	·6252	− ·0079	− ·0180
128	.....	75	59·9	45	21·0	390	·6083	− ·0160	− ·0293
129	.....	75	57·1	45	21·0	337	·6118	− ·0175	− ·0290
130	.....	75	54·4	45	21·0	246	·6166	− ·0212	− ·0296
131	.....	75	52·6	45	21·0	222	980·6188	−0·0213	−0·0289
132	Graham Bay.....	75	49·1	45	21·0	232	·6191	− ·0200	− ·0279
133	.....	75	45·9	45	21·1	274	·6175	− ·0179	− ·0272
134	.....	75	33·5	45	21·1	270	·6261	− ·0096	− ·0188
135	.....	75	30·1	45	21·1	253	·6279	− ·0094	− ·0180
136	.....	75	51·0	45	21·2	211	·6205	− ·0210	− ·0282
137	.....	75	42·4	55	21·2	286	·6227	− ·0117	− ·0215
138	.....	75	38·8	45	21·2	309	·6243	− ·0080	− ·0185
139	.....	75	38·6	45	21·2	310	·6239	− ·0082	− ·0188
140	South March.....	75	56·0	45	21·3	256	·6174	− ·0200	− ·0287
141	.....	75	31·8	45	21·4	261	980·6267	−0·0103	−0·0192
142	.....	75	59·1	45	21·5	334	·6110	− ·0193	− ·0307
143	.....	75	44·3	45	21·5	311	·6187	− ·0138	− ·0244
144	.....	75	35·1	45	21·5	277	·6273	− ·0084	− ·0178
145	Strathearn Station.....	75	55·3	45	21·6	226	·6196	− ·0211	− ·0288
146	.....	75	47·5	45	21·6	256	·6199	− ·0179	− ·0266
147	.....	75	32·2	45	21·6	261	·6268	− ·0105	− ·0194
148	.....	75	40·9	45	21·8	267	·6267	− ·0104	− ·0195
149	.....	75	53·0	45	21·9	196	·6208	− ·0232	− ·0298
150	City View.....	75	44·0	45	21·9	322	·6192	− ·0128	− ·0238

PRINCIPAL FACTS FOR GRAVITY STATIONS NEAR OTTAWA, ONTARIO—*Continued*

Station		Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name							Free Air	Bouguer
		°	′	°	′	Ft.			
151	.....	75	37·1	45	21·9	282	980·6271	−0·0087	−0·0183
152	.....	75	58·4	45	22·0	332	·6131	− ·0182	− ·0295
153	.....	75	34·0	45	22·0	262	·6281	− ·0098	− ·0187
154	.....	78	46·3	45	22·1	264	·6210	− ·0169	− ·0259
155	Ellwood.....	75	39·9	45	22·1	288	·6250	− ·0105	− ·0203
156	.....	75	30·7	45	22·1	259	·6284	− ·0099	− ·0187
157	Britannia Bay.....	75	48·0	45	22·4	219	·6234	− ·0191	− ·0266
158	.....	75	39·2	45	22·4	304	·6250	− ·0095	− ·0199
159	.....	75	35·9	45	22·4	276	·6285	− ·0087	− ·0181
160	.....	75	57·5	45	22·6	310	·6161	− ·0182	− ·0287
161	Ramsayville Station.....	75	34·0	45	22·6	242	980·6301	−0·0106	−0·0188
162	.....	75	32·6	45	22·6	237	·6294	− ·0117	− ·0198
163	.....	75	45·2	45	22·7	260	·6213	− ·0178	− ·0267
164	.....	75	40·0	45	22·7	289	·6250	− ·0114	− ·0212
165	.....	75	42·4	45	22·8	251	·6252	− ·0149	− ·0234
166	Wychwood.....	75	50·4	45	22·9	205	·6237	− ·0208	− ·0278
167	Woodroffe.....	75	46·5	45	22·9	223	·6248	− ·0181	− ·0257
168	Harwoods Plains.....	75	58·2	45	23·0	282	·6177	− ·0198	− ·0294
169	.....	75	56·8	45	23·0	222	·6218	− ·0213	− ·0289
170	.....	75	49·4	45	23·0	207	·6240	− ·0205	− ·0276
171	.....	75	37·7	45	23·0	280	980·6270	−0·0107	− ·0202
172	.....	75	31·1	45	23·0	243	·6299	− ·0112	− ·0195
173	Deschênes Mills.....	75	48·3	45	23·2	203	·6260	− ·0192	− ·0260
174	Billings Bridge.....	75	40·6	45	23·2	208	·6296	− ·0151	− ·0222
175	Laurentian View.....	75	44·0	45	23·4	240	·6247	− ·0174	− ·0255
176	Hawthorne Station.....	75	35·7	45	23·5	221	·6239	− ·0111	− ·0186
177	.....	75	47·5	45	23·6	201	·6272	− ·0188	− ·0256
178	Westboro Station.....	75	45·6	45	23·6	219	·6244	− ·0200	− ·0274
179	Ottawa.....	75	41·9	45	23·6	218	·6273	− ·0171	− ·0245
180	.....	75	36·6	45	23·6	248	·6300	− ·0115	− ·0200
181	.....	75	33·1	45	23·6	247	980·6300	−0·0116	−0·0201
182	.....	75	30·9	45	23·7	253	·6312	− ·0101	− ·0187
183	.....	75	59·0	45	23·8	246	·6208	− ·0213	− ·0297
184	Aylmer.....	75	50·9	45	23·8	276	·6194	− ·0199	− ·0293
185	Gatineau Country Club.....	75	49·8	45	23·8	280	·6202	− ·0186	− ·0282
186	Ottawa.....	75	41·1	45	23·8	205	·6285	− ·0174	− ·0244
187	.....	75	34·9	45	23·8	252	·6314	− ·0101	− ·0187
188	.....	75	40·1	45	23·9	213	·6298	− ·0155	− ·0228
189	.....	75	55·2	45	24·0	249	·6230	− ·0191	− ·0276
190	Aylmer.....	75	51·8	45	24·0	197	·6252	− ·0217	− ·0284
191	.....	75	48·4	45	24·0	297	980·6207	−0·0169	−0·0270
192	Ottawa.....	75	44·8	45	24·0	201	·6253	− ·0213	− ·0281
193	.....	75	38·9	45	24·0	268	·6275	− ·0128	− ·0219
194	.....	75	37·4	45	24·1	256	·6293	− ·0123	− ·0210
195	Malwood Station.....	75	59·9	45	24·2	223	·6212	− ·0236	− ·0312
196	.....	75	47·6	45	24·3	288	·6219	− ·0169	− ·0268
197	Ottawa.....	75	41·4	45	24·4	224	·6271	− ·0179	− ·0256
198	.....	75	31·0	45	24·4	242	·6336	− ·0098	− ·0180
199	Bate Island.....	75	45·4	45	24·5	197	·6260	− ·0218	− ·0285
200	Ottawa West Station.....	75	43·5	45	24·5	185	·6265	− ·0224	− ·0287

PRINCIPAL FACTS FOR GRAVITY STATIONS NEAR OTTAWA, ONTARIO—*Continued*

Station		Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name							Free Air	Bouguer
		°	′	°	′	Ft.			
201	.....	75	33·7	45	24·5	256	980·6313	−0·0109	−0·0196
202	.....	75	51·0	45	24·6	347	·6167	− ·0171	− ·0289
203	.....	75	57·6	45	24·7	282	·6195	− ·0205	− ·0301
204	.....	75	49·8	45	24·7	356	·6169	− ·0162	− ·0284
205	.....	75	48·5	45	24·8	334	·6177	− ·0176	− ·0290
206	.....	75	45·8	45	24·8	193	·6269	− ·0217	− ·0282
207	.....	75	52·6	45	24·9	360	·6176	− ·0154	− ·0277
208	Ottawa.....	75	43·9	45	25·0	179	·6262	− ·0240	− ·0301
209	Ottawa.....	75	43·0	45	25·0	174	·6276	− ·0231	− ·0290
210	Ottawa.....	75	40·0	45	25·0	193	·6307	− ·0182	− ·0247
211	Blackburn Station.....	75	33·9	45	25·0	229	980·6340	−0·0115	−0·0193
212	Val Tetreau.....	75	44·6	45	25·1	188	·6264	− ·0231	− ·0295
213	.....	75	56·8	45	25·2	378	·6147	− ·0170	− ·0299
214	Cyrville.....	75	38·0	45	25·2	222	·6316	− ·0148	− ·0224
215	.....	75	35·7	45	25·2	219	·6346	− ·0122	− ·0196
216	.....	75	53·9	45	25·3	218	·6248	− ·0221	− ·0296
217	.....	75	32·0	45	25·3	230	·6358	− ·0101	− ·0179
218	.....	75	52·7	45	25·4	405	·6147	− ·0149	− ·0286
219	Ottawa.....	75	42·0	45	25·4	238	·6248	− ·0204	− ·0285
220	.....	75	51·1	45	25·5	453	·6123	− ·0128	− ·0283
221	Hull.....	75	43·2	45	25·5	179	980·6294	−0·0216	−0·0277
222	.....	75	49·0	45	25·6	358	·6171	− ·0172	− ·0294
223	.....	75	31·0	45	25·8	265	·6350	− ·0082	− ·0173
224	.....	75	57·9	45	25·9	330	·6184	− ·0189	− ·0301
225	Hull.....	75	42·6	45	26·0	160	·6294	− ·0241	− ·0295
226	Ottawa.....	75	40·6	45	26·0	235	·6279	− ·0185	− ·0265
227	.....	75	36·6	45	26·1	263	·6323	− ·0116	− ·0206
228	.....	75	54·1	45	26·2	400	·6144	− ·0168	− ·0304
229	.....	75	52·9	45	26·2	453	·6125	− ·0137	− ·0291
230	Blackburn.....	75	33·0	45	26·2	273	·6347	− ·0085	− ·0178
231	.....	75	59·7	45	26·3	254	980·6240	−0·0211	−0·0297
232	Ottawa, Nat. Res. Council.....	75	41·8	45	26·3	182	·6296	− ·0222	− ·0284
233	.....	75	51·9	45	26·4	439	·6129	− ·0149	− ·0298
234	.....	75	45·8	45	26·4	311	·6198	− ·0201	− ·0307
235	Simmons.....	75	49·2	45	26·5	365	·6169	− ·0181	− ·0305
236	Hull.....	75	44·0	45	26·5	224	·6254	− ·0228	− ·0304
237	Eastview.....	75	38·9	45	26·5	226	·6316	− ·0165	− ·0242
238	.....	75	58·9	45	26·8	330	·6209	− ·0178	− ·0291
239	.....	75	55·2	45	26·8	378	·6163	− ·0179	− ·0307
240	.....	75	36·9	45	26·8	317	·6305	− ·0094	− ·0202
241	.....	75	32·0	45	26·8	302	980·6389	−0·0024	−0·0127
242	.....	75	42·7	45	26·9	156	·6316	− ·0236	− ·0289
243	.....	75	54·2	45	27·0	363	·6165	− ·0194	− ·0318
244	.....	75	35·2	45	27·0	210	·6393	− ·0109	− ·0181
245	.....	75	53·0	45	27·1	388	·6147	− ·0189	− ·0322
246	Rockcliffe.....	75	40·7	45	27·2	246	·6320	− ·0152	− ·0236
247	.....	75	51·3	45	27·3	391	·6147	− ·0190	− ·0323
248	.....	75	39·4	45	27·3	198	·6353	− ·0160	− ·0233
249	.....	75	30·2	45	27·3	291	·6407	− ·0024	− ·0123
250	.....	75	48·3	45	27·5	376	·6176	− ·0179	− ·0307

PRINCIPAL FACTS FOR GRAVITY STATIONS NEAR OTTAWA, ONTARIO—*Concluded*

Station		Longitude		Latitude		Elevation	Observed Gravity	Gravity Anomalies	
No.	Name							Free Air	Bouguer
		°	′	°	′	Ft.			
251	.....	75	33·9	45	27·5	245	980·6418	−0·0059	−0·0143
252	.....	75	56·0	45	27·6	333	·6175	− ·0221	− ·0335
253	.....	75	46·0	45	27·6	335	·6214	− ·0180	− ·0294
254	.....	75	54·3	45	27·7	348	·6172	− ·0212	− ·0330
255	.....	75	44·5	45	27·7	179	·6309	− ·0234	− ·0295
256	Gatineau Point.....	75	41·9	45	27·7	160	·6348	− ·0212	− ·0267
257	.....	75	37·4	45	27·7	161	·6404	− ·0156	− ·0210
258	.....	75	49·4	45	27·8	410	·6146	− ·0181	− ·0321
259	.....	75	35·6	45	27·8	159	·6443	− ·0120	− ·0174
260	C.P.R. Bridge.....	75	43·5	45	27·9	148	·6341	− ·0233	− ·0284
261	.....	75	32·2	45	27·9	200	980·6452	−0·0074	−0·0142
262	.....	75	52·7	45	28·0	356	·6152	− ·0228	− 0·349
263	.....	75	51·5	45	28·1	354	·6149	− ·0253	− ·0355
264	(Orleans).....	75	32·0	45	28·1	220	·6446	− ·0063	− ·0138
265	Ironside Station.....	75	44·7	45	28·4	185	·6322	− ·0226	− ·0289
266	.....	75	40·2	45	28·4	157	·6379	− ·0195	− ·0248
267	.....	75	47·0	45	28·5	345	·6201	− ·0197	− ·0315
268	.....	75	43·8	45	28·6	167	·6326	− ·0244	− ·0301
269	Orleans.....	75	31·0	45	28·6	205	·6480	− ·0052	− ·0122
270	Breckenridge Station.....	75	57·2	45	28·7	219	·6284	− ·0236	− ·0310
271	Talon Station.....	75	42·0	45	28·7	179	980·6352	−0·0206	−0·0267
272	Gatineau.....	75	38·4	45	28·9	148	·6448	− ·0142	− ·0192
273	East Templeton.....	75	37·3	45	28·9	152	·6462	− ·0124	− ·0176
274	.....	75	53·2	45	29·0	347	·6162	− ·0242	− ·0360
275	.....	75	45·1	45	29·0	195	·6310	− ·0237	− ·0303
276	.....	75	40·5	45	29·0	180	·6382	− ·0179	− ·0241
277	.....	75	33·0	45	29·0	146	·6495	− ·0098	− ·0148
278	.....	75	51·9	45	29·1	390	·6118	− ·0247	− ·0380
279	.....	75	57·8	45	29·2	223	·6288	− ·0236	− ·0312
280	.....	75	48·8	45	29·3	343	·6146	− ·0266	− ·0383
281	.....	75	44·9	45	29·3	145	980·6354	−0·0244	−0·0294
282	Gatineau Station.....	75	39·0	45	29·3	181	·6420	− ·0145	− ·0206
283	.....	75	55·9	45	29·4	331	·6182	− ·0243	− ·0356
284	.....	75	42·1	45	29·4	180	·6361	− ·0206	− ·0267
285	.....	75	54·5	45	29·5	331	·6168	− ·0259	− ·0371
286	Kingsmere.....	75	50·6	45	29·5	810	·5920	− ·0056	− ·0332
287	.....	75	40·6	45	29·5	180	·6390	− ·0179	− ·0240
288	.....	75	56·9	45	29·6	210	·6300	− ·0242	− ·0314
289	.....	75	38·0	45	29·6	199	·6441	− ·0111	− ·0179
290	.....	75	34·8	45	29·6	177	·6457	− ·0116	− ·0176
291	East Templeton Station.....	75	36·4	45	29·7	159	980·6466	−0·0125	−0·0180
292	.....	75	48·9	45	30·0	337	·6154	− ·0274	− ·0389
293	.....	75	45·8	45	30·0	357	·6195	− ·0214	− ·0336
294	.....	75	56·0	45	17·9	312	·6053	− ·0217	− ·0323
295	.....	75	54·0	45	18·1	364	·6069	− ·0155	− ·0279
296	.....	75	53·0	45	18·8	330	·6096	− ·0171	− ·0283
297	Ottawa, Victoria Museum.....	75	41·3	45	24·8	228	·6253	− ·0200	− ·0278
298	Hull.....	75	44·1	45	25·9	225	·6252	− ·0220	− ·0297
299	Eastview.....	75	39·7	45	26·2	206	·6318	− ·0176	− ·0246
300	.....	75	46·7	45	26·7	332	·6191	− ·0193	− ·0306
301	Rockcliffe.....	75	40·7	45	26·8	231	980·6311	−0·0169	−0·0248
302	.....	75	40·3	45	27·2	197	·6364	− ·0154	− ·0221

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CHARACTERISTICS OF MAGNETIC DISTURBANCE AT THE CANADIAN ARCTIC OBSERVATORIES

Part I: Cyclic Field Changes on Quiet and Disturbed Days
Part II: Transient Field Changes

BY

K. WHITHAM AND E. I. LOOMER

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Characteristics of Magnetic Disturbance at the Canadian Arctic Observatories

BY

K. WHITHAM AND E. I. LOOMER

PART I: CYCLIC FIELD CHANGES ON QUIET AND DISTURBED DAYS

ABSTRACT

A selection has been made of three classes of days at Resolute Bay* (geomagnetic latitude = 83°N) and Baker Lake (geomagnetic latitude = 73.7°N) corresponding to "local disturbed", "local quiet", and "local very quiet" conditions at a time of sunspot minimum. The disturbance daily variation has been harmonically analysed, and the statistical properties of the cyclic disturbance waves examined.

Well inside the polar cap, it has been demonstrated that the form of the disturbance field remains substantially constant independent of the intensity of disturbance and the season, and can be well represented by 24-hour waves only. The 12-hour waves are only very partially persistent and higher harmonic waves are random. The results from Resolute Bay are in excellent agreement with a simple atmospheric dynamo model, but modifications of the theory lead to contradictions, and the plausibility of the model is thus in doubt.

In the transitional region to the north of the auroral zone, diurnal disturbance is much more complex and variable, changing form as the disturbance increases. The persistent properties of the waves are discussed in connection with a number of theories of auroral zone magnetic disturbance, and it is shown that none of these theories satisfactorily explain the observations.

INTRODUCTION

The quiet day solar daily variation and the disturbance daily variation in moderate and low latitudes have been widely analysed and the findings discussed in detail by Chapman and Bartels (1940, Chs. 6, 7, 9, 23). Until recently the observational material available from polar regions has been very limited and it has been only partially discussed. The Dominion Observatory has operated two magnetic observatories in the Canadian Arctic since 1948. One of these is situated at Resolute Bay, Cornwallis Island (latitude 74.7° N, longitude 265.1° E) and the other at Baker Lake, Northwest Territories (latitude 64.3° N, longitude 264.0° E). The geomagnetic coordinates of these observatories are $\Phi = 83.0°$ N, $\Lambda = 289.0°$ E and $\Phi = 73.7°$ N, $\Lambda = 315.3°$ E respectively, assuming 78.5° N, 291° E for the position of the north geomagnetic pole. Resolute Bay observatory is thus well situated for the study of magnetic phenomena found within the geomagnetic polar cap, and so far as is known to the authors, it is the only permanent observatory besides Thule in continuous operation well inside the auroral zone. Magnetic disturbance at Baker Lake is representative of disturbance found in the transitional region to the north of the auroral zone. Again permanent observatories in these latitudes are few in number: Calm Bay (Tikhaya) magnetic observatory located in Franz Joseph Land at geomagnetic latitude 71.5° N should be comparable.

An analysis of the outstanding features of magnetic disturbance at Resolute Bay and Baker Lake observatories is described in this paper. Part I refers to cyclic field changes on quiet and disturbed days whereas in Part II the transient storm disturbances are discussed. The statistical techniques used have been largely those tried for low and

*A recent decision by the Canadian Board on Geographical Names has assigned the single name 'Resolute' to this location.

moderate latitude stations with certain modifications and additions. Wherever possible the results obtained have been compared with the predictions of different theories: however, with two stations only this is often an ambiguous process. A similar analysis for a denser network of Arctic observatories would be more valuable and such a treatment may become possible after the IGY. However, the results discussed in these two papers are of great value to any comprehensive discussions of magnetic disturbance because of the position of the observatories.

THE SELECTION OF DAYS

Continuous photographic registration of three magnetic elements has been carried out at Baker Lake since 1950 but at Resolute Bay since mid-October 1953 only. In order to use records in three components for the same period of time at both observatories, days were selected from the period November 1953 to March 1955. At the time these investigations began, data were not available beyond March 1955. The number of months in each of the solstitial and equinoctial periods is different, but this is thought to be unimportant since the period is almost centred about the sunspot minimum of April 1954. The results obtained should be representative of sunspot minimum: the amplitudes of the cyclic changes found are probably only about 70 per cent of the mean for a complete sunspot cycle.

The method in current use for the selection of the international magnetically quiet and disturbed days in each month has been described by Bartels and Veldkamp (1955). Although the incidence of disturbance is world wide the relative intensity is not uniformly distributed. Consequently it seemed more reasonable to use the measured K indices for the two stations to select local quiet and local disturbed days, rather than the internationally selected days based on twelve observatories between geographic latitudes 47° and 63°. The working criterion adopted was the sum of K, and limits were set so that on the average throughout the interval approximately five days per month were disturbed and five quiet. However, in order to examine the data seasonally it was necessary to change the limits for the winter months at Resolute Bay corresponding to the decrease in the average K sum during the winter months.

Table I shows the relative number of days selected in each season for the observatories: at Resolute Bay the criterion of a disturbed day is approximately $\Sigma K \geq \overline{\Sigma K}_{AV} + 5$ and for a quiet day is $\Sigma K \leq \overline{\Sigma K}_{AV} - 5$. At Baker Lake the same K limits were chosen as for Resolute Bay, although the seasonal change of disturbance intensity is different at the two stations. As measured by the average sum of K in the three seasons, the summer is most disturbed in the polar cap whereas equinoctial peaks are found at Baker Lake as at middle and low latitudes. Winter is always least disturbed. The data in Table I also indicate that in the most disturbed season the average level of disturbance increases at the two stations, rather than the intensity of disturbance during the greatly disturbed days.

Some tests were made using the sum of K squared criterion for selecting days: during the winter 1953-54 fewer than one in eight days would be changed had this been adopted. This criterion modifies the selection of quiet days a little more than the selection of disturbed days. For the purpose of selection, it seems sufficient therefore to employ the sum of K test.

LLOYD'S SEASON	N° of MONTHS	$\overline{\Sigma K}$ ALL DAYS	N° of DISTURBED DAYS	$\overline{\Sigma K}$	N° of QUIET DAYS	$\overline{\Sigma K}$	N° of VERY QUIET DAYS	$\overline{\Sigma K}$
RESOLUTE BAY								
SUMMER	4	20.3	15 $\Sigma K \geq 25$	26.5	12 $\Sigma K \leq 15$	13.5	0 (No K>1)	
EQUINOX	5	19.7	21 $\Sigma K \geq 25$	26.8	25 $\Sigma K < 15$	11.0	3	
WINTER	8	14.3	43 $\Sigma K > 20$	24.9	68 $\Sigma K \leq 10$	7.2	12	
TOTAL	17	17.3	79	25.7	105	8.8	15	3.1
BAKER LAKE								
SUMMER	4	19.2	21 $\Sigma K > 25$	26.8	26 $\Sigma K \leq 15$	12.3	0 (Not more than 2 K's >2)	
EQUINOX	5	22.4	61 $\Sigma K > 25$	28.4	21 $\Sigma K < 15$	11.4	3	
WINTER	8	18.5	93 $\Sigma K \geq 20$	26.2	21 $\Sigma K \leq 10$	5.6	14	
TOTAL	17	19.8	175	27.0	68	10.0	17	4.3

TABLE I. Table of selected days at Resolute Bay and Baker Lake from November 1953 to March 1955.

A further selection of very quiet days was made from the selected quiet days: at Resolute Bay the criterion was that no K>1 during a very quiet day. Fifteen such days were found at Resolute Bay, twelve of which occurred during the least disturbed winter months and three during equinoctial periods. At Baker Lake only three days satisfying this criterion were found, and to increase the number of days, the criterion was relaxed to allow days with two K values equal to 2: seventeen days were found.

	Nº IN OUR SELECTION	MAX Nº WHICH COULD OCCUR IN 5 INT'L DAYS	Nº WHICH DO OCCUR	AGREEMENT RATIO	MAX Nº WHICH COULD OCCUR IN 10 INT'L DAYS	Nº WHICH DO OCCUR	AGREEMENT RATIO
	RESOLUTE BAY						
QUIET	71	34	29	0.85	52	47	0.90
DISTURBED	58	40	32	0.80			
TOTAL	129	74	61	0.82	92	79	0.86
	BAKER LAKE						
QUIET	49	35	25	0.72	47	38	0.81
DISTURBED	121	53	48	0.91			
TOTAL	170	88	73	0.83	100	86	0.86

TABLE II. Comparison of selected days at Resolute Bay and Baker Lake with international quiet and disturbed days, 1954.

It is informative to compare this selection of days with the internationally selected days, although a simple comparison is not possible. Table II shows the results. At both stations more than 80 per cent of the days selected which could be international days were in fact so. At Resolute Bay not one of the disturbed days selected is listed as an international quiet day (5 or 10 per month) and vice versa. At Baker Lake one of the quiet days is listed as an international disturbed day, and four of the disturbed days are listed as quiet days (10 per month). This suggests that in future comprehensive programs, it may be sufficient in the analysis of Arctic data to examine the days recommended internationally. This conclusion is supported from a comparison of the very quiet days with the very quiet intervals given by Bartels and Veldkamp (1955). One day only at Resolute Bay was selected at a time not common to lower latitude observatories; this day was not selected at Baker Lake.

HARMONIC ANALYSIS OF SELECTED DAYS

Methods

The material for the analysis of daily variation consisted of 24-h mean values in three components, X, Y, Z at Resolute Bay and H, D, Z at Baker Lake. These mean values were plotted on graph paper with suitable abscissa (400 mm. ≡24 hrs) and ordinate scales (1 mm. ≡1 gamma on quiet days, and 1 mm. ≡2 gammas on disturbed days). The hourly means are centred on the hour; twenty-five points are shown for each Greenwich day, the first being the mean of the first hourly value for the day and the last hourly value of the previous day, and similarly at the end of the day. The curves were analysed on a Coradi Harmonic Analyser, and in general 4 sets of harmonic coefficients (a_1, b_1, ... a_4, b_4) determined for each day.

Scaling, drawing, tracking and instrumental errors influence the coefficients. Drawing errors do not exceed about $\frac{1}{2}$ mm. with the scales adopted and experiments with the analyser showed that results were reproducible using average care to an accuracy of about $1\frac{1}{2}$ mm. in 100 mm. amplitudes, and the absolute scale error of the machine was less than 0.5 per cent. It was concluded that errors in the coefficients determined by the machine, i.e. in a_1, b_1, $2a_2$, ... $4b_4$ do not exceed 2 per cent of large amplitudes or 2 mm., whichever is larger. Scaling errors are difficult to estimate, but are unlikely to produce systematic errors, unless e.g. the scale constants of the magnetograms are in error. It seems reasonable to assume from the observatory records that this source of error cannot exceed 5 per cent, and probably doesn't exceed 3 per cent. In practice this means that the uncertainties in the determination of na_n, nb_n do not exceed 5 per cent, or 2 gammas, whichever is larger. The accidental errors in any means are of course much smaller.

Non-cyclic corrections were applied; this procedure seemed best on quiet days in view of the existence of the post-perturbation effect which can be approximated by a linear function. It is however, arguable whether a non-cyclic correction is best applied to the results on disturbed days, since there seems little doubt that the disturbance daily variation (S_D) at times of definite storm commencement is best described as a disturbance local time inequality (D_S) and changes amplitude regularly during the development and decay of the storm (Chapman, 1952). However, the analysis on disturbed days generally corresponds to the determination of the solar daily variation during weak magnetic

disturbance where no storm-time can be assigned, and the average cyclic conception has meaning. Consequently non-cyclic corrections were applied to all the results, after the machine analysis using the form

$$n \Delta b_n = \frac{d_{24} - d_0}{\pi}$$

where d_{24} = value in magnetic element of 25th point on graph;

d_0 = value in magnetic element of 1st point on graph;

and nb_n (corrected) = nb_n (measured) + $n\Delta b_n$.

RESOLUTE BAY

HARMONIC		1							2							3							4						
DISTURBED DAYS		N	C γ	ε L.T. hrs	S_a^2 γ²	S_b^2 γ²	r	θ	R	C γ	ε L.T. hrs.	S_a^2 γ²	S_b^2 γ²	r	θ	R	C γ	ε L.T. hrs.	S_a^2 γ²	S_b^2 γ²	r	θ	R	C γ	ε L.T. hrs.	S_a^2 γ²	S_b^2 γ²	r	θ	R
SUMMER	-X	15	52·8	14·2	436	360	0·22	19·9	1·3	10·9	1·7	136	227	0·10	8·3	1·3														
	-Y	15	77·0	19·7	225	325	0·00	23·7	1·1	2·1	7·2	296	419	0·17	7·9	1·3	3·2	5·7	175	141	0·17	2·1	1·2	4·6	2·7	92	150	0·07	1·1	1·3
	Z	15	27·8	3·7	144	420	-0·39	0·2	3·6	3·4	2·8	208	264	0·74	7·4	1·6														
EQUINOX	-X	21	83·0	13·9	192	560	0·07	23·4	1·7	5·4	2·7	115	117	-0·35	10·2	1·4	4·4	5·0	100	156	-0·27	4·3	1·4	3·3	5·9	125	93	-0·03	2·6	1·2
	-Y	21	73·5	20·0	300	450	0·27	21·9	1·4	9·0	6·4	150	119	-0·05	11·3	1·1	3·0	6·7	161	144	0·30	2·6	1·4	3·8	2·2	77	84	-0·08	0·2	1·0
	Z	21	18·3	6·0	112	588	-0·37	0·4	2·7	10·6	1·1	77	138	0·00	8·7	1·3	2·7	4·2	72	120	0·05	3·5	1·1	2·6	2·6	42	63	-0·17	1·5	1·3
WINTER	-X	42	50·4	13·5	100	292	0·01	23·7	1·3	4·8	10·5	111	150	-0·14	9·4	1·2														
	-Y	43	61·5	19·7	400	525	0·38	21·4	1·5	8·0	1·2	250	212	0·30	6·9	1·3	2·3	6·0	119	175	0·33	4·4	2·7	0·1	1·9	144	56	0·04	5·7	1·6
	Z	42	24·0	5·3	256	264	0·12	21·0	1·1	1·3	8·6	96	104	0·12	7·5	1·1														
QUIET DAYS																														
SUMMER	-X	12	39·9	14·2	91	159	-0·30	1·3	1·6	6·8	0·9	31	78	0·72	7·8	2·8														
	-Y	12	41·6	19·8	34	152	-0·35	0·2	2·3	7·2	3·7	89	75	0·39	6·0	1·5	4·3	6·2	32	44	-0·52	2·5	1·2	2·8	1·2	14	40	0·65	2·3	2·5
	Z	12	6·9	2·7	179	328	-0·33	1·2	1·6	4·4	4·0	139	65	0·14	6·0	2·0														
EQUINOX	-X	25	30·3	13·8	132	246	0·48	1·6	1·8	2·6	9·7	74	54	0·22	10·8	1·3	4·2	5·8	55	30	0·10	5·5	1·4	2·7	5·8	15	19	0·06	1·0	1·1
	-Y	24	30·8	19·2	180	101	0·46	19·6	1·8	2·4	1·7	30	71	-0·07	8·8	1·6	0·9	7·8	28	29	0·00	5·6	1·0	2·5	1·2	26	13	-0·05	2·3	1·4
	Z	25	14·2	2·6	153	99	-0·22	4·2	1·4	3·7	4·7	39	45	0·06	8·0	1·1	0·5	3·1	14	26	0·14	3·4	1·4	0·9	2·4	11	11	0·18	0·6	1·2
WINTER	-X	67	17·5	13·3	26	93	-0·37	0·6	2·4	2·8	10·1	22	30	0·24	7·7	2·4														
	-Y	68	15·8	19·2	63	39	0·38	19·6	1·4	3·8	1·5	24	18	-0·24	7·7	1·3	0·6	6·8	8	10	0·18	3·0	1·2	0·3	3·2	7	9	0·22	0·6	1·3
	Z	67	5·8	6·2	19	37	-0·15	0·5	1·4	0·2	11·7	13	15	0·12	8·1	1·2														
ALL DISTURBED DAYS	-X	78	59·4	13·8	283	499	-0·20	0·8	1·4	2·7	0·6	119	173	-0·16	9·4	1·3														
	-Y	79	67·8	19·9	354	509	0·35	21·6	1·5	1·9	2·3	269	242	0·29	7·0	1·3	2·5	6·2	141	161	-0·13	4·4	1·2	2·1	2·4	119	82	0·01	5·8	1·2
	Z	78	21·3	5·0	203	601	-0·14	0·2	1·4	2·8	1·1	125	156	0·36	7·5	1·5														
ALL QUIET DAYS	-X	104	23·2	13·6	95	167	-0·57	1·8	1·8	2·6	10·6	37	45	0·17	7·7	1·2														
	-Y	104	22·2	19·3	149	93	0·52	19·9	1·9	3·6	2·0	36	39	-0·06	9·6	1·1	1·0	6·7	17	19	-0·04	4·6	1·1	0·7	1·5	13	16	0·18	0·7	1·2
	Z	104	7·2	4·3	74	107	-0·29	1·6	1·4	1·3	4·4	36	29	0·04	6·1	1·1														
ALL VERY QUIET DAYS	-X	14	9·1	12·7	3	26	-0·45	0·4	12·2	2·1	9·9	13	52	0·38	8·1	5·3														
	-Y	15	8·5	19·1	11	22	0·06	23·4	1·4	2·7	1·8	37	17	0·00	0·0	1·5	0·6	5·7	32	33	-0·18	4·7	1·3	0·0	5·4	20	29	0·04	1·1	1·2
	Z	15	2·6	6·4	10	21	-0·21	0·6	1·6	1·3	3·3	18	28	-0·09	9·1	1·2														

BAKER LAKE

HARMONIC		1							2							3							4						
DISTURBED DAYS	H, Z D	N	C γ mins	ε L.T. hrs.	S_a^2 γ² mins²	S_b^2 γ² mins²	r	θ	R	C γ mins	ε L.T. hrs	S_a^2 γ² mins²	S_b^2 γ² mins²	r	θ	R	C γ mins	ε L.T. hrs	S_a^2 γ² mins²	S_b^2 γ² mins²	r	θ	R	C γ mins	ε L.T. hrs	S_a^2 γ² mins²	S_b^2 γ² mins²	r	θ	R
SUMMER	D	21	51·0	9·4	36	188	0·02	23·6	2·3	22·0	4·4	174	159	0·13	6·8	1·1	11·8	0·4	90	128	0·54	2·8	1·9	4·0	1·9	113	99	-0·36	1·9	1·5
	H	21	15·6	20·4	224	424	-0·16	0·5	1·4	40·9	3·5	237	129	0·46	6·5	1·8	16·0	6·4	161	234	0·24	3·0	1·4	4·0	0·4	90	165	-0·43	1·6	1·7
	Z	21	85·4	4·8	576	672	0·42	21·0	1·6	14·7	10·6	740	540	0·10	6·1	1·2	20·6	6·7	394	358	-0·07	4·6	1·1	9·3	0·4	137	442	0·24	0·8	1·9
EQUINOX	D	61	59·6	9·3	532	328	0·24	19·1	1·4	9·8	4·4	253	165	0·15	6·2	1·3	2·8	3·0	104	117	-0·08	4·2	1·1	4·9	2·4	88	118	-0·02	1·2	1·2
	H	59	20·5	21·1	456	1316	0·06	23·4	1·7	28·5	3·3	485	544	-0·14	9·7	1·2	7·0	5·6	206	361	0·09	3·4	1·3	3·6	1·0	288	307	-0·18	1·8	1·2
	Z	61	10·2	4·2	688	752	0·06	21·8	1·1	21·3	10·0	715	527	-0·03	10·8	1·3	12·0	0·2	433	420	0·04	2·4	1·0	2·9	0·8	189	176	-0·02	2·4	1·1
WINTER	D	89	33·6	9·4	164	280	0·60	21·4	2·1	11·9	5·8	105	129	0·18	7·6	1·2	2·4	4·5	84	76	0·00	3·6	1·1	3·2	2·6	68	42	-0·18	2·3	1·4
	H	91	21·8	19·2	432	720	0·24	22·2	1·4	32·4	3·0	325	419	0·16	7·8	1·2	6·7	5·0	305	360	0·24	2·9	1·3	4·5	0·9	165	258	-0·03	1·2	1·3
	Z	91	75·6	4·6	1036	772	-0·13	4·2	1·2	12·0	8·9	359	623	-0·05	8·8	1·3	6·1	0·0	285	337	0·17	2·9	1·2	4·0	0·7	188	240	0·10	0·8	1·2
QUIET DAYS																														
SUMMER	D	25	24·2	8·5	47	72	-0·14	0·7	1·3	9·5	5·3	41	51	0·05	7·9	1·2	5·7	0·2	45	29	-0·09	5·1	1·3	2·3	1·7	12	23	-0·14	1·3	1·4
	H	21	27·8	20·3	61	97	0·38	21·7	1·6	23·9	3·3	81	80	-0·54	10·1	1·8	2·8	6·2	51	26	-0·05	5·5	1·4	3·8	4·9	20	29	-0·15	1·4	1·3
	Z	25	37·3	5·2	173	246	0·07	22·9	1·2	8·4	1·9	173	124	0·53	6·8	1·4	14·2	6·4	115	45	0·24	1·9	1·7	3·2	0·6	39	68	-0·03	1·2	1·3
EQUINOX	D	21	16·1	8·9	20	60	0·29	22·7	1·9	6·0	4·9	24	21	-0·04	10·9	1·1	1·8	0·0	21	15	0·24	2·3	1·3	5·1	2·7	12	18	0·06	1·0	1·2
	H	21	18·0	20·1	102	223	0·71	21·6	2·7	24·3	3·3	106	142	-0·65	9·6	2·2	8·6	6·3	116	48	0·06	2·1	1·9	4·6	1·2	19	50	-0·09	1·2	1·6
	Z	21	37·0	4·8	351	143	0·26	18·6	1·7	5·3	11·6	85	323	0·03	8·5	2·0	3·2	5·4	81	84	-0·15	4·5	1·2	5·5	1·6	68	55	0·19	0·1	1·3
WINTER	D	21	3·4	7·7	8	11	0·64	21·1	2·2	5·5	6·1	5	9	-0·39	9·5	1·7	1·4	1·7	1	3	-0·23	3·9	1·7	1·5	2·8	1	2	0·01	1·1	1·4
	H	21	13·2	18·3	23	33	0·25	21·8	1·3	10·4	3·3	8	37	-0·17	8·8	2·1	1·9	6·3	6	13	0·15	3·4	1·5	1·0	4·3	8	5	-0·28	2·2	1·5
	Z	21	14·3	4·1	51	44	-0·21	5·1	1·3	4·3	2·4	14	19	0·35	7·5	1·7	3·5	6·8	9	7	0·33	2·3	1·1	1·8	1·8	9	8	-0·23	1·9	1·3
ALL DISTURBED DAYS	D	171	45·0	9·3	335	378	0·49	20·8	1·7	11·7	5·1	175	168	0·11	6·9	1·1	0·8	4·4	100	112	-0·04	2·0	1·1	3·8	2·5	82	77	0·13	0·2	1·2
	H	171	20·2	20·0	428	903	0·12	23·0	1·1	32·0	3·2	382	436	0·03	8·2	1·1	7·1	5·5	258	361	0·22	3·0	1·3	4·0	0·8	199	264	-0·13	0·0	1·2
	Z	173	85·6	4·4	975	822	-0·11	21·9	1·2	14·6	9·6	563	586	-0·09	6·9	1·1	8·8	7·8	388	380	0·11	2·5	1·1	4·1	0·6	211	217	0·09	0·4	1·1
ALL QUIET DAYS	D	67	15·2	8·6	64	87	0·51	21·2	1·8	6·9	5·4	28	31	-0·01	5·9	1·1	2·9	0·4	25	23	-0·12	2·8	1·1	2·6	2·5	12	16	0·05	1·0	1·2
	H	63	19·4	19·9	73	167	0·63	21·7	2·4	19·9	3·2	68	131	-0·56	6·6	2·1	5·2	6·3	64	31	0·30	2·0	1·6	1·3	1·9	19	37	0·03	1·1	1·4
	Z	67	29·3	4·9	307	152	0·12	18·2	1·4	5·1	1·4	99	165	0·23	7·9	1·4	7·2	6·4	89	57	0·24	2·1	1·4	3·0	1·3	42	47	0·03	0·9	1·1
ALL VERY QUIET DAYS	D	17	3·4	7·0	7	6	0·10	19·3	1·1	5·5	6·6	4	3	-0·32	10·5	1·4	1·4	1·7	1	2	0·20	3·2	1·4	1·8	3·2	1	1	-0·46	2·2	1·9
	H	17	13·5	18·7	22	21	0·35	8·4	1·4	9·3	10·7	6	4	-0·92	10·2	5·2	1·6	6·1	6	8	0·14	2·0	1·3	1·0	5·6	4	3	-0·08	2·3	1·2
	Z	17	10·4	4·3	24	17	-0·31	1·5	1·4	3·9	2·9	11	13	0·21	7·5	1·3	3·1	6·6	10	14	-0·09	4·0	1·2	1·7	1·7	4	5	0·09	0·8	1·2

TABLE III. Geometrical properties of the clouds of points for four harmonics and three selected classes of days at Resolute Bay and Baker Lake observatories.

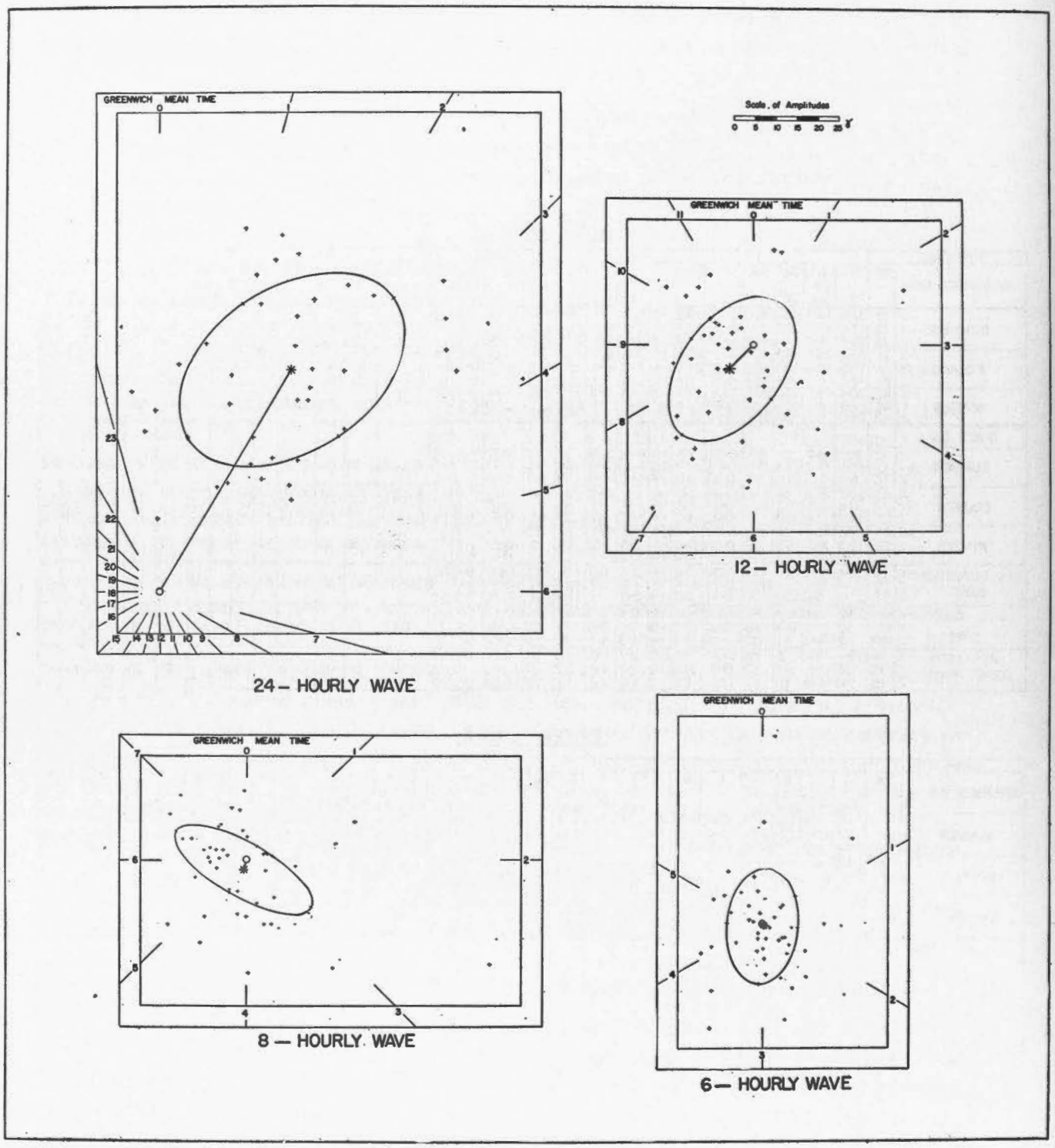


FIGURE 1. Harmonic dials for the 24-h, 12-h, 8-h, and 6-h waves in the diurnal variation of —Y at Resolute Bay, N.W.T. The 43 points refer to 43 disturbed days in the winters 1953-1955. The vector from the origin to the star on the dial indicates the amplitude and G.M.T. of the maximum of the sine wave. The average vectors and probable error ellipses are drawn.

The smoothing corrections were not applied since in the first and second harmonics they do not sensibly affect the results; in the fourth harmonic the correction is still less than 5 per cent.

Results for Resolute Bay and Baker Lake

Following Bartels (1935), harmonic dials for 24-h, 12-h, 8-h, and 6-h periods were constructed in which each point may be conceived as the end point of a clock hand which indicates the time of wave maximum and whose length indicates the amplitude of the wave. Analysis of the variability of the harmonics becomes an analysis of the geometrical properties of the clouds of points. Dials were constructed for each magnetic component in each season for quiet and disturbed days, and for all quiet, disturbed and very quiet days. Figure 1 is typical of the results for Resolute Bay showing the mean amplitudes and the probable error ellipses, and Table III is a summary of the results for both stations. Defining the variance as the quotient of the sum of the squares of the deviations from the average divided by the number in the sample, Table III shows the mean amplitude C, mean phase ϵ, the variance S_a^2, S_b^2 of the Fourier cosine and sine coefficients a and b, the coefficient of correlation r between a and b for the sample of N and the axis ratio R. The major and minor axes of the ellipse are equal to 0.83 S_1 and 0.83 S_2 respectively where S_1^2, S_2^2 are the variances found when the first coordinate axis lies along the major axis of the probable error ellipse, and the second coordinate axis along the minor.

Table IV shows the amplitude, phase and standard deviation of any sample. The expected amplitude for the average of N vectors having the same N amplitudes as the observed vectors but with phases random is equal to $\frac{1}{\sqrt{N}}$ times the expectancy $\sqrt{\left\{\frac{\Sigma_N(a^2 + b^2)}{N}\right\}}$ i.e. to $\sqrt{\left\{\frac{C^2 + M^2}{N}\right\}}$ where M is the standard deviation in the amplitude ($M^2 = S_a^2 + S_b^2$). The probability that the average vector C is K times as large as this expected amplitude is e^{-K^2} where $C = K\sqrt{\left\{\frac{C^2 + M^2}{N}\right\}}$ i.e. $K^2 = \frac{NC^2}{C^2 + M^2}$.
Thus assuming that the points for the selected days are independent, the probability that the mean amplitude C is accidental is e^{-K^2}. A small value for this probability shows that the directions of the N individual vectors are not random, but does not prove the presence of a purely periodic persistent wave in the data because quasi-persistent effects on successive days are known to exist in the solar variation, and this results in a serious reduction of the effective number of independent points in any dial. To examine the influence of quasi-persistence the data for Y west (—Y) at Resolute Bay in the winter solstice were examined, and the expectancies $E_h = \sqrt{\frac{C^2 + M^2}{N}}$ computed for the averages of h = 1, 2, 4, 8, 16, 32 and 64 successive vectors. The results are shown in curves of Figure 2. Quasi-persistence would be indicated by the ordinate increasing linearly with h for small h and becoming constant at large h; random waves by a constant ordinate value of unity and complete persistence by a slope of 45°. The curves obtained show that the third and fourth harmonic waves are random, whereas the first harmonic is noticeably persistent and the second harmonic semi-persistent. No striking evidence for quasi-persistence is obtained, and so the effective expectancy to be used in calculating probabilities in a dial should be $\frac{N}{\alpha}$ where α is a small number. The test described above together with the fact

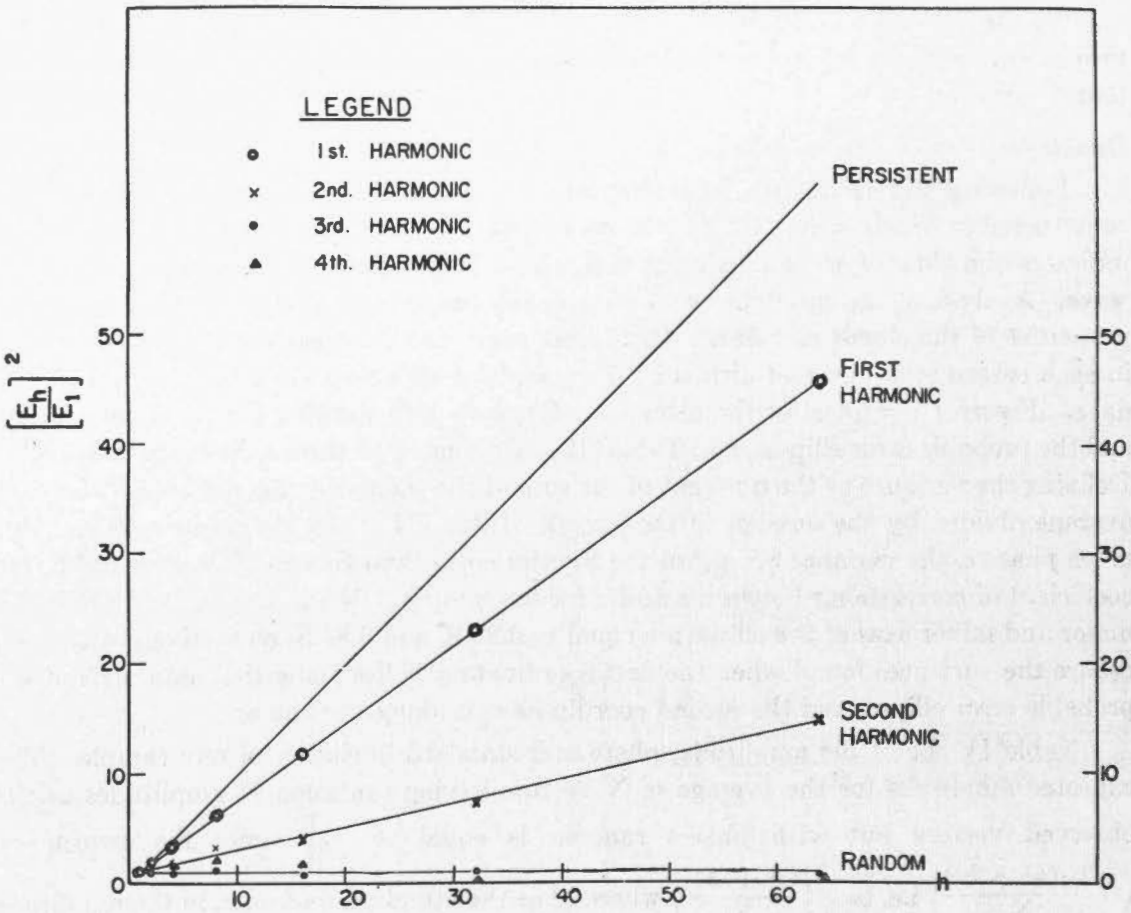


FIGURE 2. Persistence curves for —Y at Resolute Bay, N.W.T. on quiet days in the winters 1953-1955.

that quasi-persistence must be less important for the data where the number of selected days in any season is small suggests that if $\alpha = 2$ is adopted, no serious errors should arise. The column in Table IV showing $P_1 = e^{\frac{-C^2N}{(2C^2+M^2)}}$ should then be an over estimate, if anything, of the probability that the mean amplitude found was produced by accidental superposition of random waves. Table IV also shows the standard deviation in the mean amplitude calculated on the basis of N/2 independent points. This is $\pm\ \delta S = \pm \frac{M}{\sqrt{N/2}}$ where $M^2 = S_1^2 + S_2^2 = S_a^2 + S_b^2$. The standard deviation in the mean phase δ_ϵ is calculated using the concept of phase variance of the points of the cloud; the phase variance s^2 is defined $s^2 = \frac{1}{C^4}\left\{\bar{a}^2 S_b^2 + \bar{b}^2 S_a^2\right\}$ which result can be obtained by differentiation. Then by analogy $\delta\epsilon = s \Big/ \sqrt{\frac{N}{2}}$.

In Table IV a probability P_2 computed from the ellipticity statistic L_e, discussed by Mauchly (1940), is given. L_e is defined as $\frac{2R}{1+R^2}$ where R is the axis ratio of the probable error ellipse. The parameter L_e is used to discuss whether the cloud is significantly elliptical or not. $P_2(L_e)$ is the probability that an ellipticity statistic as small or smaller

RESOLUTE BAY

HARMONIC		1							2							3							4						
DISTURBED DAYS		C γ	±δC γ	M γ	P_1	ε LT. hrs.	±δε hrs.	P_2	C γ	±δC γ	M γ	P_1	ε LT. hrs.	±δε hrs.	P_2	C γ	±δC γ	M γ	P_1	ε LT. hrs.	±δε hrs.	P_2	C γ	±δC γ	M γ	P_1	ε LT. hrs.	±δε hrs.	P_2
SUMMER	-X	52·8	10·3	28·2	3×10^{-5}	14·2	0·6	0·85	10·9	7·0	19·0	0·16	1·7		0·97														
	-Y	7·0	8·6	23·5	1×10^{-5}	19·7	0·3	0·99	2·1	9·8	26·7	0·96	7·2		0·97	3·2	6·6	17 9	0·80	5·7		0·90	4·6	5·7	15·5	0·55	2·7		0·65
	Z	27·8	14 5	39·6	0·08	3·7	1·7	0·03	3·4	8·0	21·7	0·83	2·8		0·56														
EQUINOX	-X	83·0	8·5	27·4	1×10^{-4}	13·9	0·3	0·33	5·4	4·7	15·2	0·30	2·7		0·59	4·4	5·0	16·1	0·78	5·0		0·59	3·3	4·6	14·8	0·61	5·9		0·64
	-Y	73·5	8·5	27·5	1×10^{-4}	20·0	0·3	0·61	9·0	5·1	16·5	0·09	6·4		0·98	3·0	5·4	17 5	0·74	6·7		0·59	3·8	4·0	12·8	0·44	2·2		0·98
	Z	18·3	8·2	26·6	0·03	6·0	1·6	0·02	10·6	4·6	14·7	0·03	1·1	0·6	0·78	2·7	4·2	13·7	0·68	4·2		0·98	2·6	3·2	10·3	0·52	2·6		0·78
WINTER	-X	50·4	4·3	19·8	2×10^{-4}	13·5	0·1	0·57	4·8	3·7	16·2	0·18	10·5	1·0	0·68														
	-Y	61·5	6·6	30·5	3×10^{-6}	19·7	0·3	0·23	8·0	4·9	21·5	0·07	1·2	0·7	0·56	2·3	3·9	17·2	0·70	6·0		2×10^{-4}	0·1	3·2	14·1	1·00	1·9		0·13
	Z	24·0	5·0	22·8	2×10^{-3}	5·3	0·6	0·95	1·3	3·2	14·1	0·84	8·6		0·94														
QUIET DAYS																													
SUMMER	-X	39·9	6·4	15·8	5×10^{-5}	14·2	0·4	0·66	6·8	4·3	10·5	0·17	0·9		0·16														
	-Y	41·6	6·8	16·6	5×10^{-5}	19·8	0·4	0·28	7·2	5·2	12·8	0·25	3·7		0·75	4·3	3·6	8.7	0·33	6·2		0·92	2·8	4·8	11·8	0·41	1·2		0·23
	Z	6·9	9·1	22·3	0·59	2·7	3·7	0·66	4·4	5·8	14·2	0·59	4·0		0·41														
EQUINOX	-X	30·3	5·5	19·4	1×10^{-4}	13·8	0·4	0·19	2·6	3·2	11·3	0·53	9·7		0·73	4·2	3·6	9·2	0·11	5·8		0·52	2·7	1·6	5·8	0·12	5·8		0·97
	-Y	30·8	4·7	16·8	1×10^{-4}	19·2	0·4	0·19	2·4	2·8	10·0	0·51	1·7		0·33	0·9	2·2	7·6	0·82	7·8		1·00	2·5	1·8	6·2	0·20	1·2		0·52
	Z	14·2	4·6	15·9	3×10^{-3}	2·6	0·8	0·56	3·7	2·6	9·2	0·17	4 7	1·0	0·97	0·5	1·8	6·3	0·93	3·1		0·52	0·9	1·3	4·7	0·61	2·4		0·81
WINTER	-X	17·5	1·9	10·9	3×10^{-11}	13·3	0·3	2×10^{-5}	2·8	1·2	7,2	0·01	10·1	0·6	2×10^{-5}														
	-Y	15·8	1·7	10·1	3×10^{-11}	19 2	0·3	0·16	3·8	1·1	6·5	2×10^{-6}	1·5	0·4	0·38	0·6	0·7	4·3	0·51	6·8		0·53	0·3	0·6	3·7	0·80	3·2		0·38
	Z	5·8	1·3	7·5	3×10^{-6}	6·2	0·7	0·16	0·2	0·9	5·1	0·95	11·7		0·53														
ALL DISTURBED DAYS	-X	59·4	4,5	28·0	1×10^{-14}	13·8	0·2	0·12	2·7	2·7	17·1	0·40	0·6	1·5	0·31														
	-Y	67·8	4·7	29·5	1×10^{-14}	19·9	0·2	0·06	1·9	3·6	22·6	0·75	2·3	2·5	0·20	2·5	2·8	17,4	0·46	6·2	1·0	0·64	2·1	2·3	14·2	0·42	2·4	0·7	0·55
	Z	21·3	4·5	28·4	1×10^{-6}	5·0	0·7	0·12	2·8	2·3	16·5	0·35	1·1	1·4	0·06														
ALL QUIET DAYS	-X	23·2	2·2	16·0	1×10^{-15}	13·6	0·2	2×10^{-5}	2·6	1·3	9·1	0·02	10·6	0·7	0·39														
	-Y	22·2	2·2	15·9	1×10^{-15}	19·3	0·2	8×10^{-5}	3·6	1·2	8·6	5×10^{-5}	2·0	0·4	0·82	1·0	0·8	6·0	0·25	6·7	0·8	0·82	0·7	0·8	5·1	0·37	1·5	0·7	0·39
	Z	7·2	1·9	13·4	1×10^{-15}	4·3	0·8	6×10^{-2}	1·3	1·1	8·0	0·28	4·4	1·2	0·55														
ALL VERY QUIET DAYS	-X	9·1	2·0	5·4	5×10^{-3}	12·7	0·3	1×10^{-4}	2·1	1·5	4·0	0·22	9·9	0·9	7×10^{-3}														
	-Y	8·5	2·1	5·7	5×10^{-3}	19·1	0·7	0·71	2·7	1·4	3·7	0·07	1·8	0·7	0·63	0·6	1·0	2·7	0,70	5·7	1·6	0·89	0·0	0·7	1·8	1·00	5·4	1·6	0·89
	Z	2·6	2·0	5·6	0·27	6·4	2·3	0·17	1·3	1·2	3·4	0·38	3·3	1·2	0·89														

BAKER LAKE

HARMONIC		1							2							3							4						
DISTURBED DAYS. H,Z	D	C γ mins	±δC γ mins	M γ mins	P_1	ε LT. hrs.	±δε hrs.	P_2	C γ mins	±δC γ mins	M γ mins	P_1	ε LT. hrs.	±δε hrs.	P_2	C γ mins	±δC γ mins	M γ mins	P_1	ε LT. hrs.	±δε hrs.	P_2	C γ mins	±δC γ mins	M γ mins	P_1	ε LT. hrs.	±δε hrs.	P_2
SUMMER	D	51·0	4·6	15·0	8×10^{-5}	9·4	0·2	0·07	22·0	5·6	18·2	2×10^{-3}	4·4	0·3	0·97	11·8	4·5	14·7	0·02	0·4	0·3	0·20	4·0	4·5	14·6	0·48	1·9	0·8	0·51
	H	15·6	7·8	25·4	0·06	20·4	1·4	0·62	40·9	5·9	19·1	2×10^{-4}	3·5	0·2	0·25	16·0	6·1	19·9	0·02	6·4	0·4	0·62	4·0	4·9	16·0	0·55	0·1	0·9	0·32
	Z	85·4	11	35·4	1×10^{-4}	4·8	0·4	0·41	14·7	11·	35·8	0·22	10·6	1·1	0·87	20·6	8·6	27·8	0·02	6·7	0·3	0·97	9·3	7·4	24·1	0·25	0·4	0·6	0·20
EQUINOX	D	59·6	5·3	29·4	1×10^{-6}	9·3	0·3	0·21	9·8	3·7	20·4	3×10^{-3}	4·4	0·5	0·38	2·8	2·7	14·9	0·35	3·0	0·9	0·90	4·9	2·6	14·4	0·04	2·4	0·4	0·63
	H	20·5	7·7	42·0	3×10^{-3}	21·1	0·9	0·03	28·5	5·9	32·1	2×10^{-6}	3·3	0·3	0·64	7·0	4·4	23·8	0·09	5 6	0·7	0·40	3·6	4·5	24·4	0·55	1·0	0·3	0·64
	Z	102	6·9	38·0	1×10^{-12}	4·2	0·2	0·90	21·3	6·4	35·2	3×10^{-4}	10·0	0·4	0·38	12·0	5·3	29·2	0·01	0·2	0·4	0·97	2·9	3·5	19·1	0·52	0·8	0·8	0·90
WINTER	D	33·6	3·1	21·0	1×10^{-10}	9·4	0·2	2×10^{-3}	11,9	2·3	15·3	3×10^{-6}	5·8	0·3	0·50	2·4	1·9	12·7	0·20	4·5	0·7	0·85	3·2	1·6	10·5	0·02	2·6	0·3	0·10
	H	21·8	5·0	34·0	1×10^{-6}	19·2	0·7	0·09	32·4	4·0	27·3	1×10^{-12}	3·0	0·2	0·50	6·7	3·9	26·2	0·06	5·0	0·5	0·23	4·5	3·0	20·5	0·12	0·9	0·4	0·23
	Z	75,6	6·3	42·6	1×10^{-15}	4·6	0·2	0·60	12·0	4·6	31·4	3×10^{-3}	8·9	0·5	0·23	6·1	3·7	24·9	0·07	0·0	0·6	0·50	4·0	3·1	20·7	0·20	0·7	0·5	0·50
QUIET DAYS																													
SUMMER	D	24·2	3·1	10·9	3×10^{-5}	8·5	0·3	0·70	9·5	2·7	9·6	2×10^{-3}	5·3	0·4	0·88	5·7	2·4	8·6	0·02	0·2	0·4	0.76	2·3	1·7	5·9	0·20	1·7	0·5	0·52
	H	27·8	3·9	12·6	3×10^{-5}	20·3	0·4	0·42	23·9	3·9	12·7	5×10^{-5}	3·3	0·2	0·22	2·8	2·7	8·8	0·30	6,2	0·5	0.63	3·8	2·2	7·1	0·07	4·9	0·3	0·79
	Z	37·3	5·8	20·5	7×10^{-5}	5·2	0·4	0·81	8·4	4·9	17·2	0·09	1·9	0·8	0·60	14·2	3·6	12·6	9×10^{-4}	6·4	0·2	0·25	3·2	2·9	10·4	0·33	0·6	0·6	0·68
EQUINOX	D	16·1	2·7	8·9	5×10^{-4}	8·9	0·4	0·18	6·0	2·1	6·7	0·01	4·9	0·5	0·98	1·8	1·9	6·0	0·44	0·0	1·0	0·71	5·1	1·7	5·5	7×10^{-3}	2·7	0·2	0·84
	H	18·0	5·6	18·0	5×10^{-3}	20·1	0·9	0·03	24·3	4·9	15·8	6×10^{-4}	3·3	0·3	0·09	8·6	4·0	12·8	0·04	6·3	0·4	0·20	4·6	2·6	8·3	0·08	1·2	0·3	0·37
	Z	37·0	6·8	22·2	5×10^{-4}	4·8	0·4	0·33	5·3	6·2	20·2	0·51	11·6	2·1	0·17	3·2	4·0	12·9	0·55	5·4	1·1	0·93	5·5	3·4	11·1	0·13	1·6	0·4	0·83
WINTER	D	3·4	1·4	4·4	0·02	7·7	1·1	0·10	5·5	1·1	3·7	1×10^{-3}	6·1	0·3	0·34	1·4	0·7	2·1	0·03	1·7	0·5	0·34	1·5	0·6	1·8	0·02	2·8	0·3	0·61
	H	13·2	2·3	7·5	5×10^{-4}	18·3	0·5	0·70	10·4	2·1	6·7	6×10^{-4}	3·3	0·2	0·11	1·9	1·4	4·4	0·18	6·3	1·0	0·54	1·0	1·1	3·5	0·45	4·3	0·7	0·50
	Z	14·3	3·0	9·8	1×10^{-3}	4·1	0·6	0·80	4·3	1·8	5·8	0·03	2·4	0·5	0·32	3·5	1·2	4·0	0·01	6·8	0·3	0·93	1·8	1·3	4·1	0·20	1·8	0·5	0·77
ALL DISTURBED DAYS	D	45·0	2·9	26·7	3×10^{-20}	9·3	0·2	1×10^{-5}	11·7	2·0	18·5	2×10^{-11}	5·1	0·2	0·72	0·8	1·6	14·5	0·67	4·4	1·8	0·78	3·8	1·4	12·6	1×10^{-3}	2·5	0·2	0·56
	H	20·2	3·9	36·5	2×10^{-19}	20·0	0·5	0·78	32·0	3·1	28·6	2×10^{-21}	3·2	0·4	0·78	7·1	2·7	25·1	2×10^{-3}	5·5	0·4	0·05	4·0	2·3	21·5	0·06	0·8	0·4	0·24
	Z	85·6	4·6	42·5	7×10^{-31}	4·4	0·1	0·56	14·6	3·7	33·9	1×10^{-6}	9·6	0·3	0·72	8·8	3·0	27·7	4×10^{-4}	7·8	0·3	0·72	4·1	2·2	20·7	0·04	0·6	0·4	0·72
ALL QUIET DAYS	D	15·2	2·1	12·2	1×10^{-19}	8·6	0·4	4×10^{-3}	6·9	1·3	7·7	3×10^{-7}	5·4	1·5	0·94	2·9	1·2	6·8	6×10^{-3}	0·4	0·4	0·88	2·6	0·9	5·3	2×10^{-3}	2·5	0·3	0·58
	H	19·4	2·5	13·9	4×10^{-10}	19·9	0·4	5×10^{-3}	19·9	2·5	14·1	8×10^{-10}	3·2	0·2	9×10^{-4}	5·2	1·4	9·7	9×10^{-4}	6·3	0·3	0·04	1·3	1·3	7·5	0·15	1·9	0·4	0·20
	Z	29·3	3·7	21·7	4×10^{-10}	4·9	0·3	0·13	5·1	2·8	16·3	0·05	1·4	0·7	0·15	7·2	2·1	12·1	2×10^{-4}	6.4	0·3	0·18	3·0	1·6	9·4	0·05	1·3	0·4	0·91
ALL VERY QUIET DAYS	D	3·4	1·3	3·7	4×10^{-4}	7·0	0·6	0·98	5·5	0·8	2·6	1×10^{-3}	6,6	0·2	0·67	1·4	0·6	1·5	0·02	1·7	0·3	0·71	1·8	0·4	1·3	4×10^{-3}	3·2	0·1	0·27
	H	13·5	2·3	6·5	1×10^{-3}	18·7	0·3	0·67	9·3	1·1	3·3	5×10^{-3}	10·7	0·1	2×10^{-3}	1·6	1·3	3·7	0·26	6·1	0·5	0·84	1·0	1·0	2·7	0·36	5·6	0·4	0·93
	Z	10·4	2·3	6·4	2×10^{-3}	4·3	0·4	0·66	3·9	1·7	5·0	0·04	2·9	0·4	0·86	3·1	1·7	4 8	0·08	6·6	0·3	0·90	1·7	1·0	3·0	0·13	1·7	0·3	0·90

TABLE IV. Statistical properties of the harmonic waves for four harmonics and three selected classes of days at Resolute Bay and Baker Lake observatories.

than the value found for the cloud might be obtained in a random sample of N/2 points drawn from a circular population. $P_2 = L_e^{(N/2-2)}$ after Mauchly (1940).

Discussion of Seasonal Results for Resolute Bay

Using the probabilities P_1 it is apparent that whereas the 24-h waves in the horizontal components are very persistent, the Z wave is much more variable and in the summer on quiet days cannot be well described as a persistent wave. This is not a result of the number of quiet days in the summer season being small. The 12-h waves are very ill

defined by comparison with the 24-h waves, and the higher harmonics completely random. For this reason it was considered worthwhile completing the analysis in 4 harmonics for the Y component only at Resolute Bay. In Figure 1 probable error ellipses are shown, but the values P_2 in Table IV show that with the exception of the winter quiet day data in the X component only, the clouds are not significantly elliptical. This trend is true for both the 24- and 12-h waves, and so in general the direction θ shown for the major axis is not significant: there is also little evidence for real correlation between a and b in the sets.

Table V summarises the seasonal trends at Resolute Bay: no statistically significant differences appear in the phases of the waves for the quiet and disturbed days in all seasons, and no very significant shifts occur seasonally in phase. There is a suggestion that the average phase of the horizontal component waves is advanced from summer to winter by one half hour. The greater variability in Z and the correspondingly larger uncertainties mask any real seasonal shift. These suggest that quiet day effects at Resolute Bay represent a residual disturbance daily variation, and that the development of additional disturbance field in polar regions remains approximately constant independent of the intensity of disturbance. The quiet day mean horizontal amplitudes vary seasonally as would be expected, with amplitudes in summer, equinox and winter in the ratios 1 : 0.75: 0.41 respectively. (The average K sum from Table I goes as 13.4 : 11.0 : 7.2 or 1 : 0.82: 0.54.) The disturbed day means are less systematic but the equinoctial and summer amplitudes exceed those in the winter as would be expected. The mean Z amplitude data is too uncertain to be of much use.

RESOLUTE BAY		PERSISTENT 24 hr. WAVES			
		DISTURBED DAYS		QUIET DAYS	
		AMPLITUDE γ	L.T. of MAX. hrs.	AMPLITUDE γ	L.T. of MAX. hrs.
−X	SUMMER	52.8 ± 10.3	14.2 ± 0.6	39.9 ± 6.4	14.2 ± 0.4
	EQUINOX	83.0 ± 8.5	13.9 ± 0.3	30.3 ± 5.5	13.8 ± 0.4
	WINTER	50.4 ± 4.3	13.5 ± 0.1	17.5 ± 1.9	13.3 ± 0.3
−Y	SUMMER	77.0 ± 8.6	19.7 ± 0.3	41.6 ± 6.8	19.8 ± 0.4
	EQUINOX	73.5 ± 8.5	20.0 ± 0.3	30.8 ± 4.7	19.2 ± 0.4
	WINTER	61.5 ± 6.6	19.7 ± 0.3	15.8 ± 1.7	19.2 ± 0.3
Z	SUMMER	27.8 ± 14.5	3.7 ± 1.7	6.9 ± 9.1	2.7 ± 3.7
	EQUINOX	18.3 ± 8.2	6.0 ± 1.6	14.2 ± 4.6	2.6 ± 0.8
	WINTER	24.0 ± 5.0	5.3 ± 0.6	5.8 ± 1.3	6.2 ± 0.7
		PARTIALLY PERSISTENT 12 hr. WAVES			
−X	WINTER	4.8 ± 3.7	10.5 ± 1.0	2.8 ± 1.2	10.1 ± 0.6
−Y	WINTER	8.0 ± 4.9	1.2 ± 0.7	3.8 ± 1.1	1.5 ± 0.4
Z	EQUINOX	10.6 ± 4.6	1.1 ± 0.6	3.7 ± 2.6	4.7 ± 1.0

TABLE V. Summary of persistent seasonal waves at Resolute Bay.

It thus appears that disturbance at Resolute Bay merely enhances the quiet day daily variation, or alternatively the latter can be regarded as representing the residual effect of disturbance daily variation. The exact amplitude relationships depend on the criterion used in selecting the days, but the conclusion does not. Figure 3 illustrates this conclusion graphically showing the seasonal variation in the mean amplitude and phase and the probable error ellipse (circles might have been drawn) for the two classes of days.

The results for any 12-h waves which show partial persistence (one $P_1 < 0.05$) are shown in Table V, and no real differences are apparent. Once again the almost random Z wave shows poorest agreement.

Very Quiet Day Results at Resolute Bay

The question naturally arises whether there is a real quiet day field distinctly different in form from the disturbance variation and which can be detected at a polar cap station. To answer this question the selection described earlier of very quiet days was made. The last third of both Tables III and IV summarises the features found for the three classes of days over the period of 17 months investigated around sunspot minimum. The notation is that discussed earlier.

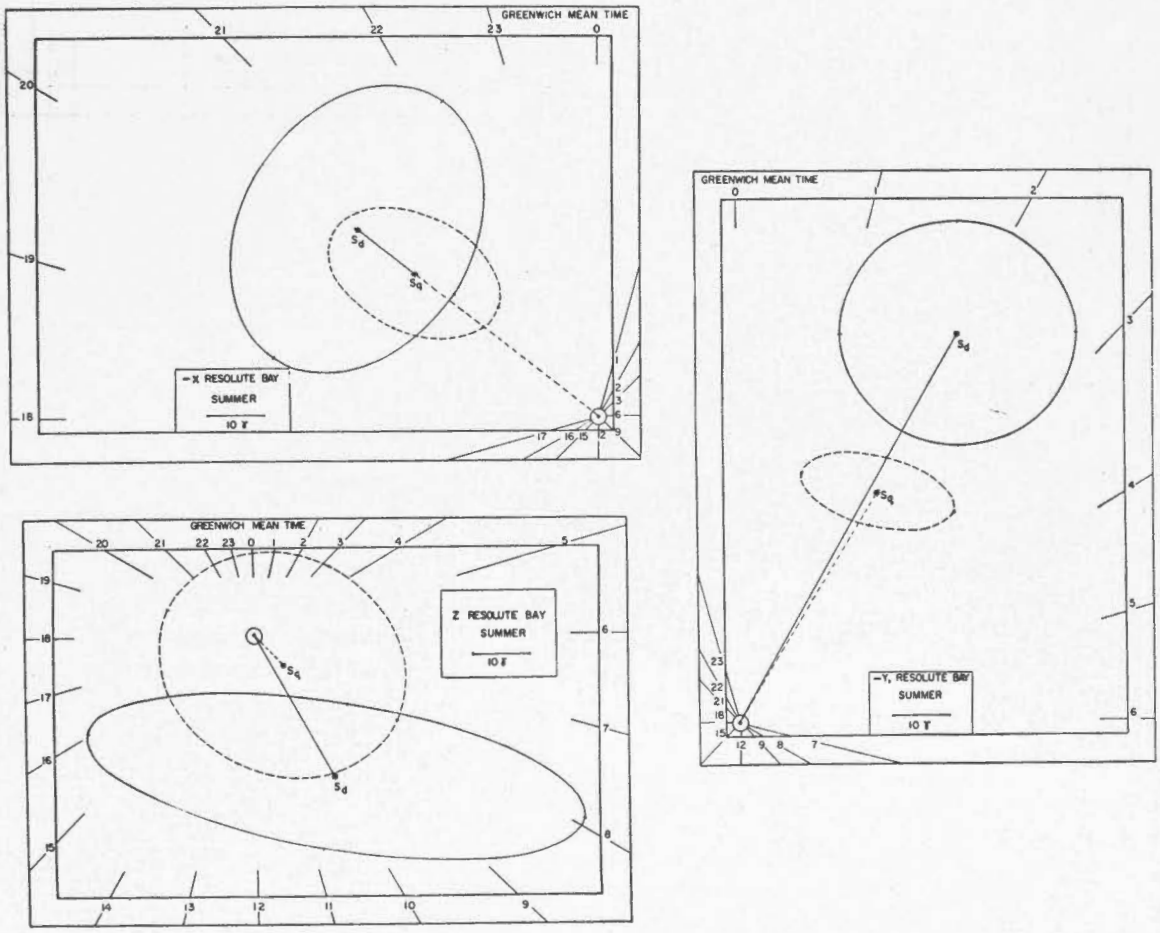
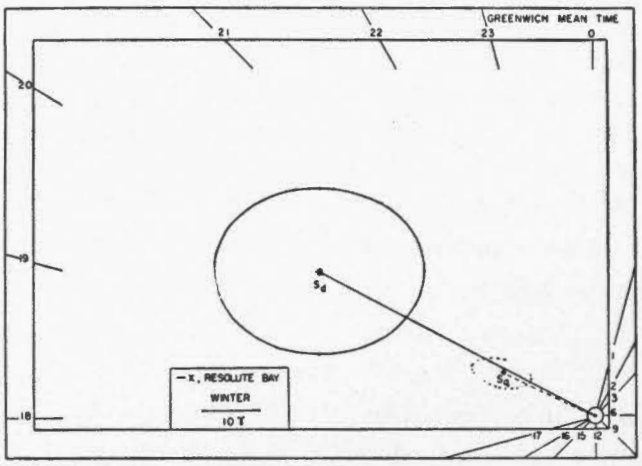
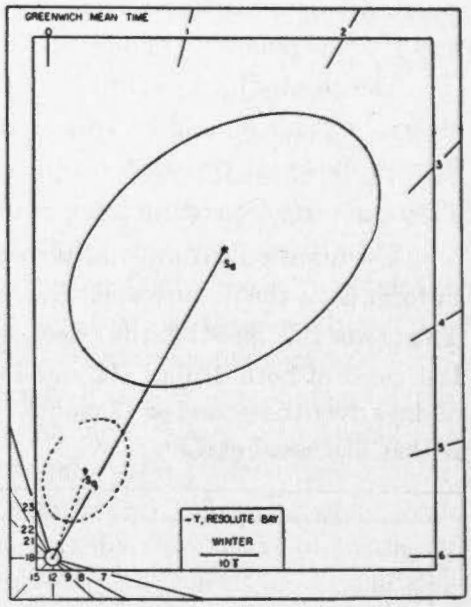


Figure 3a.

FIGURES 3a, (*and overleaf*) b, and c. Harmonic dials for the 24-h waves in —X, —Y, Z at Resolute Bay, N.W.T. for quiet and disturbed days in the summer and winter solstices and the equinoxes respectively.


GREENWICH MEAN TIME
-X, RESOLUTE BAY
WINTER
10 γ


GREENWICH MEAN TIME
-Y, RESOLUTE BAY
WINTER
10 γ

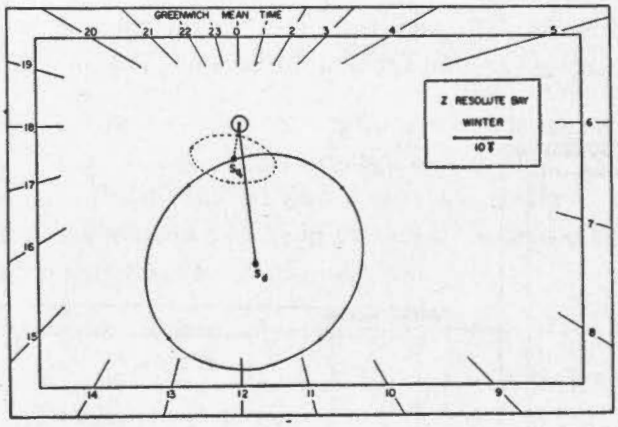
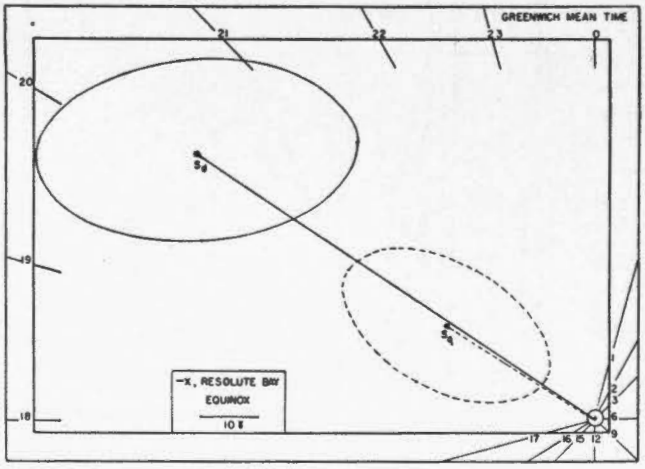
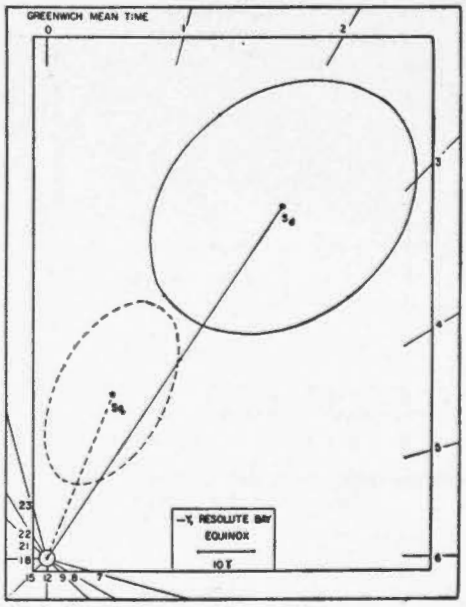
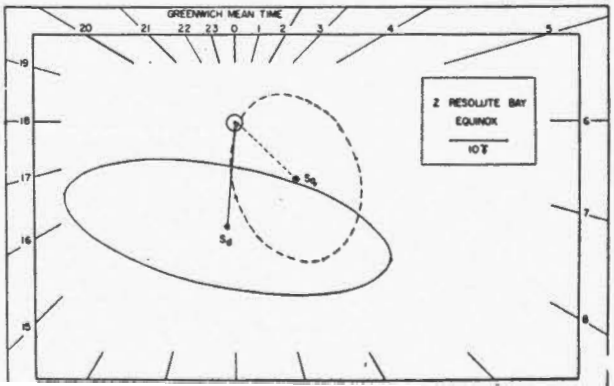

GREENWICH MEAN TIME
Z RESOLUTE BAY
WINTER
10 γ

Figure 3b


GREENWICH MEAN TIME
-X, RESOLUTE BAY
EQUINOX
10 γ


GREENWICH MEAN TIME
-Y, RESOLUTE BAY
EQUINOX
10 γ


GREENWICH MEAN TIME
Z RESOLUTE BAY
EQUINOX
10 γ

The probabilities P_1 indicate that the 24-h waves are not random, although once again the Z variability on very quiet days is pronounced. The clouds appear significantly elliptical except for very quiet days. The correlation coefficient r is real and pronounced for the quiet days only in the horizontal components; however, it is significant that the signs in r and the directions found for the major axes agree in the three classes very well. The harmonic dials of Figure 4 illustrate the three classes of days, and show there are no real differences in the form of the field.

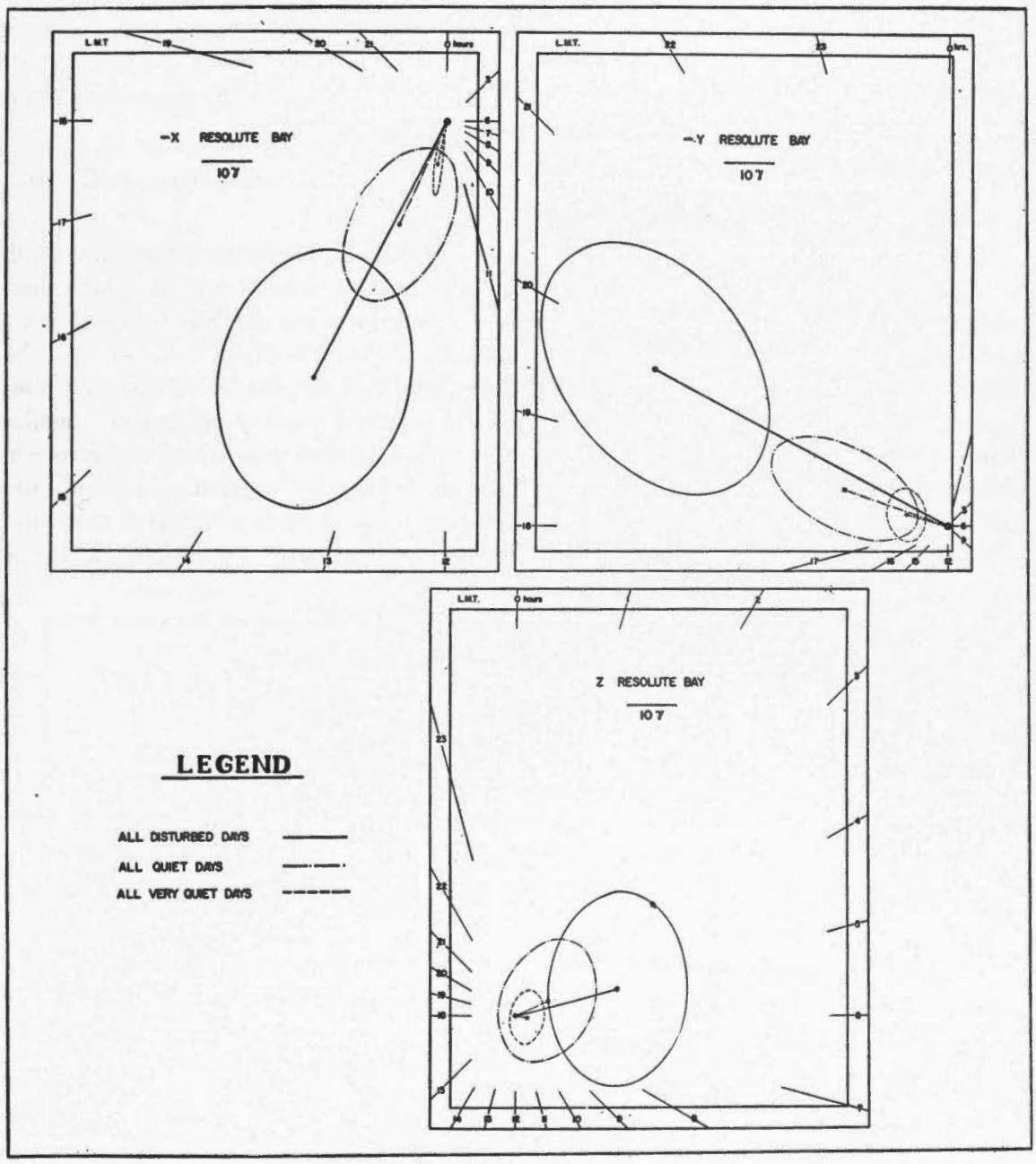


FIGURE 4. Harmonic dials for the 24-h waves in —X, —Y, Z at Resolute Bay, N.W.T., for very quiet, quiet and disturbed days during November 1953 to March 1955.

The tabular data indicate that the third and fourth harmonics are random, and partial persistence can be seen only in the horizontal components on quiet days. It should be noted that the 24-h wave amplitudes form much the largest part of the range observed in practice, and a theoretical explanation of these terms only would account for more than 90 per cent of the disturbance field on disturbed days, more than 80 per cent on quiet days and 60 per cent on very quiet days.

The ratio of amplitudes weighted according to their uncertainties in the usual manner on quiet and disturbed days is 0.35 ± 0.07 with no significant differences in this ratio for the three components. The ratio of very quiet day amplitudes to disturbed day amplitudes is 0.14 ± 0.04 for all components. It is of interest to note that the average K sums on the days adopted, shown in Table I, have corresponding ratios of 0.34 and 0.12. Consequently it follows that the K sum is a very good linear predictor of the diurnal variation amplitude, or smoothed range.

Day to Day Changes at Resolute Bay in the Amplitudes of the Disturbance Waves in Different Components

The analysis so far does not indicate how the relationship between the amplitudes in X, Y and Z varies from day to day. The 24-h wave amplitude in each of the three components was obtained for each day of the winter months using the Fourier coefficients a_1, b_1, and the day to day correlations computed. Table VI shows the results. The correlations are significantly high, even for the small diurnal amplitudes on the very quiet days: the correlations are highest for the class of quiet days, possibly because of irregular disturbance and bays influencing the results somewhat on disturbed days, and errors in determination of the Fourier coefficients being proportionately larger on the very quiet days. In all cases the correlation between the horizontal components is higher than that between a horizontal component and the vertical component. This agrees with the

	CORRELATION COEFFICIENTS	
	$r_{x,y}$	$r_{x,z}$
DISTURBED DAYS	0.45 ± 0.08	0.35 ± 0.09
QUIET DAYS	0.70 ± 0.04	0.48 ± 0.06
VERY QUIET DAYS	0.54 ± 0.14	0.30 ± 0.18

TABLE VI. Correlation coefficients between the first harmonic wave amplitudes at Resolute Bay for very quiet, quiet and disturbed days in the winters 1953-1955.

experience of Chapman and Stagg (1931), but it is not certain that at Resolute Bay the result is not a consequence of the small Z amplitudes found and the larger uncertainties in the determination of any one. In any case the systematic nature of the cyclic field changes at Resolute Bay is clear.

Discussion of Seasonal Results for Baker Lake

Table VII summarises the seasonal characteristics for the persistent waves at Baker Lake. Because of the greater complexity of disturbance at Baker Lake, it was considered best to complete the analysis in all seasons for quiet and disturbed days in four harmonics. Most of the 24-h and 12-h waves, though highly variable, do show persistence in each season, whereas the 8-h and 6-h waves are almost random. Without a fuller examination of the influence of quasi-persistence at Baker Lake it is doubtful if the probabilities P_1 in Table IV really demonstrate the existence of persistent 8-h and 6-h waves. The 12-h wave in Z and the 24-h wave in D are only developed on disturbed days.

BAKER LAKE		24 hr. WAVES			
		DISTURBED DAYS		QUIET DAYS	
	H, Z / D	AMPLITUDE γ mins.	L.T. of MAX hrs. "	AMPLITUDE γ mins.	L.T. of MAX. hrs. "
H	SUMMER	15.6 ± 7.8	20.4 ± 1.4	27.8 ± 3.9	20.3 ± 0.4
	EQUINOX	20.5 ± 7.7	21.1 ± 0.9	18.0 ± 5.6	20.1 ± 0.9
	WINTER	21.8 ± 5.0	19.2 ± 0.7	13.2 ± 2.3	18.3 ± 0.5
D	SUMMER	51.0 ± 4.6	9.4 ± 0.2	24.2 ± 3.1	8.5 ± 0.3
	EQUINOX	59.6 ± 5.3	9.3 ± 0.3	16.1 ± 2.7	8.9 ± 0.4
	WINTER	33.6 ± 3.1	9.4 ± 0.4	3.4 ± 1.4	7.7 ± 1.1
Z	SUMMER	85.4 ± 11.	4.8 ± 0.4	37.3 ± 5.8	5.2 ± 0.4
	EQUINOX	102. ± 6.9	4.2 ± 0.2	37.0 ± 6.8	4.8 ± 0.4
	WINTER	75.6 ± 6.3	4.6 ± 0.2	14.3 ± 3.0	4.1 ± 0.6
		12 hr. WAVES			
H	SUMMER	40.9 ± 5.9	3.5 ± 0.2	23.9 ± 3.9	3.3 ± 0.2
	EQUINOX	28.5 ± 5.9	3.3 ± 0.3	24.3 ± 4.9	3.3 ± 0.3
	WINTER	32.4 ± 4.0	3.0 ± 0.2	10.4 ± 2.1	3.3 ± 0.2
D	SUMMER	22.0 ± 5.6	4.4 ± 0.3	9.5 ± 2.7	5.3 ± 0.4
	EQUINOX	9.8 ± 3.7	4.4 ± 0.5	6.0 ± 2.1	4.9 ± 0.5
	WINTER	11.9 ± 2.3	5.8 ± 0.3	5.5 ± 1.1	6.1 ± 0.3
Z	SUMMER	14.7 ± 11.	10.6 ± 1.1	8.4 ± 4.9	1.9 ± 0.8
	EQUINOX	21.3 ± 6.4	10.0 ± 0.4	5.3 ± 6.2	11.6 ± 2.1
	WINTER	12.0 ± 4.6	8.9 ± 0.5	4.3 ± 1.8	2.4 ± 0.5

TABLE VII. Summary of persistent seasonal waves at Baker Lake.

The distribution of the cloud of points is usually not significantly elliptical, although the necessary parameters required to define the probable error ellipse are given in every case. The exceptions usually occur on quiet days.

Table VII summarises the seasonal changes for the significant first and second harmonics. Any significant vertical differences in L.T. of maximum in the eighteen rows occurs for the 12-h Z wave where the phase is advanced by more than 90° on disturbed days. The physical consequences of this are discussed later. The amplitudes of the first harmonics show a seasonal variation compatible with the average sum of K for the selected classes (*see* Table I) at different seasons. The 12-h disturbed day amplitude in H is somewhat smaller in the equinoctial months than might be expected; the interpretation advanced later requires that the concentrated currents of the auroral zone be further from the station on these equinoctial days.

Very Quiet Day Results at Baker Lake

If the above results are interpreted in terms of a considerable change of type in the disturbance daily variation as the intensity of disturbances changes (the change of type being formally represented in terms of the different relative magnitudes of the first and second harmonic waves with less important phase changes), it is of interest to examine the results for the very quiet days, the selection of which was described earlier. The features for the three classes of days, disturbed, quiet and very quiet days, are shown in Tables III and IV.

The very quiet day disturbance shows persistent first and second harmonic waves only; the populations are circular and the other harmonics random. Reasons are advanced later for estimating that approximately 50 per cent of the disturbance amplitudes on very quiet days is produced by residual disturbance: thus no pure solar daily variation on quiet days, such as can be derived at low latitude observatories, can be isolated from the Baker Lake data.

However, if corrections for the solar daily variation on quiet days are to be made to Baker Lake results, the formal representation of the very quiet day results in terms of the first and second harmonic waves is the best approximation.

Day to Day Changes at Baker Lake in the Amplitudes of the Disturbance Waves in Different Field Components

The procedure used was similar to that described on page 304. The correlations between the 24-h waves and 12-h waves in H and Z were computed for the winter months on disturbed days for comparison with the systematic results shown in Table VI. The coefficients found were $+ 0.23 \pm 0.07$ and $+ 0.21 \pm 0.07$ respectively for the first and second harmonics indicating very poor correlation, in contrast with the results obtained at Resolute Bay. Hence the field changes from day to day in different components do not change proportionally, although they do increase together. This is considered further later.

DYNAMO THEORIES

Dynamo Theory Applied to Polar Cap Disturbance

The harmonic analysis of Resolute Bay cyclic field changes has demonstrated the existence of a unitary phenomenon, expanding from very quiet to quiet to disturbed days

with no significant change of form. It is suggested therefore that an atmospheric dynamo might have this property, and the conductivity, or the amplitude of the driving motion, or both, must change for different levels of disturbance.

Chapman and Bartels (1940, Ch. 23) and Fukushima (1953) have discussed dynamo theories and derived the dynamo equation: the derivation given below is added only to clarify the concept of conductivity in high magnetic latitudes. Using Martyn's (1948) expression for the conductivity in the ionosphere in a region where the magnetic dip can be considered 90°, and letting Ox be an axis to the south, Oy to the west and Oz vertically downwards, then the current density j has components along the axes

$$j_x = \sigma_1 E_x - \sigma_2 E_y,\ j_y = \sigma_2 E_x + \sigma_1 E_y,\ j_z = \sigma_0 E_z$$

$$\text{where } \sigma_0 = e^2 \left\{ \frac{n_e}{m_e \nu_e} + \frac{n_-}{m_- \nu_-} + \frac{n_+}{m_+ \nu_+} \right\}$$

$$\sigma_1 = e^2 \left\{ \frac{n_e}{m_e} \frac{\nu_e}{\nu_e^2 + \omega_e^2} + \frac{n_-}{m_-} \frac{\nu_-}{\nu_-^2 + \omega_-^2} + \frac{n_+}{m_+} \frac{\nu_+}{\nu_+^2 + \omega_+^2} \right\}$$

$$\sigma_2 = \frac{e}{F} \left\{ \frac{n_e \omega_e^2}{\nu_e^2 + \omega_e^2} + \frac{n_- \omega_-^2}{\nu_-^2 + \omega_-^2} - \frac{n_+ \omega_+^2}{\nu_+^2 + \omega_+^2} \right\}$$

$$\text{with } \omega_e = \frac{eF}{m_e},\ \omega_- = \frac{eF}{m_-},\ \omega_+ = \frac{eF}{m_+},$$

and suffices refer to electrons, negative ions and positive ions respectively. Then $\sigma_3 E_x = j_x + (\sigma_2/\sigma_1)\, j_y$, $\sigma_3 E_y = -(\sigma_2/\sigma_1)\, j_x + j_y$ where $\sigma_3 = \sigma_1 + \sigma_2^2/\sigma_1$. Denoting the height integrated conductivity by Σ and current density by I

$$\Sigma_3 E_x = I_x + \Sigma_2 I_y/\Sigma_1,\ \Sigma_3 E_y = -\Sigma_2 I_x/\Sigma_1 + I_y$$

If the motion of the layer is considered horizontal and irrotational, it is associated with a velocity potential ψ such that if u, v, are velocity components along axes Ox, Oy respectively $u = \frac{-\partial\psi}{\partial x}$, $v = \frac{-\partial\psi}{\partial y}$. If θ is the colatitude, ϕ the east longitude measured from the Greenwich meridian and a the radius of the shell $u = \frac{-\partial\psi}{a\partial\theta}$, $v = \frac{\partial\psi}{a \sin\theta \partial\phi}$.

With the usual notation the vertical magnetic field

$$Z = \frac{2\,M \cos\theta}{a^3} = 2\,G \cos\theta. \quad \text{Then } E_x = vZ = \frac{2G}{a}\left(\cot\theta \frac{\partial\psi}{\partial\phi}\right)$$

$$\text{and } E_y = -uZ = \frac{2G}{a}\left(\cos\theta \frac{\partial\psi}{\partial\theta}\right)$$

The existence of a steady current system implies that I_x, I_y, are derivable from a current function J such that

$$I_x = \frac{1}{a \sin\theta} \frac{\partial J}{\partial\phi},\ I_y = \frac{1}{a} \frac{\partial J}{\partial\theta}.$$

$$\text{Therefore } 2\,G\,\Sigma_3 \left(\cot\theta \frac{\partial\psi}{\partial\phi}\right) = \frac{1}{\sin\theta} \frac{\partial J}{\partial\phi} + \frac{\Sigma_2}{\Sigma_1} \frac{\partial J}{\partial\theta}$$

$$\text{and } 2\,G\,\Sigma_3 \left(\cos\theta \frac{\partial\psi}{\partial\theta}\right) = \frac{-\Sigma_2}{\Sigma_1} \frac{1}{\sin\theta} \frac{\partial J}{\partial\phi} + \frac{\partial J}{\partial\theta}$$

From these equations it is simple to derive the well known dynamo equation assuming uniform conductivity in the region of interest

$$2\,G\,\Sigma_3 \left\{ \cot\theta \frac{\partial^2\psi}{\partial\phi^2} + \frac{\partial}{\partial\theta}(\sin\theta\cos\theta\frac{\partial\psi}{\partial\theta}) \right\} = \frac{1}{\sin\theta}\frac{\partial^2 J}{\partial\phi^2} + \frac{\partial}{\partial\theta}(\sin\theta\frac{\partial J}{\partial\theta})$$

showing the enhanced conductivity Σ_3 is applicable to the polar cap.

Assuming no obliquity of the earth's axis, if $\psi = k_1^1 P_1^1 \sin(t + \alpha_1^1)$ where t = L.T. in degrees i.e. $t = \phi + t^1$, t^1 being the time of the Greenwich meridian, and P_1^1 is the normalized Schmidt spherical harmonic function, then the solution of the dynamo equation is

$$J = 2\,G\,\Sigma_3 \frac{\sqrt{3}}{2.3} k_1^1 P_2^1 \sin(t + \alpha_1^1)$$

The magnetic potential

$$= -4\pi\frac{3}{5}\left(\frac{r}{a}\right)^2 2\,G\,\Sigma_3 \frac{\sqrt{3}}{2.3} k_1^1 P_2^1 \sin(t + \alpha_1^1)$$

where r is the radius of the earth and it is simple to derive the field components ΔX^1 southerly, ΔY^1 westerly and ΔZ^1 downwards. For small θ,

$$\Delta X^1 = C\cos(t + \alpha_1^1 - 90°),\ \Delta Y^1 = C\cos(t + \alpha_1^1 - 180°),$$
$$\Delta Z^1 = C.\,2\,\theta\cos(t + \alpha_1^1 + 90°) \text{ where } C = 4\pi.\frac{3}{5}\frac{r}{a^2}G\,\Sigma_3 k_1^1.$$

If the angle between the geographic meridian and a great circle through Resolute Bay and the effective pole of the dynamo is β, then

$$\Delta X_s = C\cos(t + \alpha_1^1 - 90° + \beta)$$
$$\Delta Y_w = C\cos(t + \alpha_1^1 - 180° + \beta)$$
$$\Delta Z = C.\,2\,\theta\cos(t + \alpha_1^1 + 90°).$$

It would appear best to compare these predictions with the results for the quiet class of days: the disturbed class then requires an expansion of 2.9 times and the very quiet days a contraction of 2.5 times.

Using the ratio of vertical to horizontal component amplitudes, $\theta = 9 \pm 3$ degrees.

Using the phase of the Z wave, $\alpha_1^1 = 206 \pm 12°$, and then the phase of $-X$ wave requires $\beta = 40 \pm 12°$, and the phase of $-Y$ wave requires $\beta = 44 \pm 12°$.

Assuming the pole of the dynamo coincides with the geomagnetic pole at 78.5°N, 291°E, the geomagnetic colatitude of Resolute Bay is 7° and the angle $\beta = 45.6°$, in remarkably good agreement with the predictions above. It should be noted that in a more rigorous treatment with a transformation of the effective pole of the system, geomagnetic rather than local time should be used: geomagnetic local noon is 3.0 hrs. behind local noon at Resolute Bay at the equinoxes and varies by about one-half hour from the winter to summer solstices.

The partially persistent 12-h waves at Resolute Bay are consistent with a P_2^2 term in the velocity potential, but the uncertainties in the mean data are such as to make the determination of θ and β not possible: however it can be shown that $\frac{k_1^1}{k_2^2} = 2.0 \pm 1.0$ so the amplitude ratio of the first harmonic to the second harmonic motions is 19:1. The phase of the semi-diurnal wind referred to these axes is $139 \pm 36°$.

We note that if $2G \approx 0.6$ e.m.u., we require

$$3.5 \times 10^{-9}\,\Sigma_3 k_1^1 = 8.8 \pm 2.0 \times 10^{-5} \text{ on very quiet days}$$
$$= 23 \pm 2 \times 10^{-5} \text{ on quiet days}$$
$$= 64 \pm 5 \times 10^{-5} \text{ on disturbed days.}$$

Comparison with Earlier Analyses

The phase angle $\alpha_1^1 = 206 \pm 12°$ deduced at Resolute Bay corresponds to a current sheet across the polar cap directed towards the 10.3 hrs. local time meridian. This is in approximate agreement with the idealised current system for the disturbance field of Chapman (1935), and in close agreement with the results of Hasegawa (1940). However this phase angle does not agree with that deduced by Chapman (1919) in his analysis of the S_q field for sunspot minimum: referred to the same axes his result was 305°, with a change to 294° at sunspot maximum. This discrepancy is not explained by assuming that the very quiet day amplitudes at Resolute Bay correspond to a masking of the true quiet day effect by residual disturbance. Using Chapman's velocity potential it was estimated that C = 13 gammas, whereas the amplitudes of the 24-h waves in horizontal components at the sunspot minimum 1954 were 9 ± 2 gammas. The phase of the driving motion is thus about 90° different from that predicted by the lower latitude Chapman analyses in the dynamo theory of solar daily variation on quiet days.

Fukushima (1953) has considered the complementary functions

$$J = C_1^1 \tan \frac{\theta}{2} \sin (t + \alpha_1^1)$$

and considered this current system responsible for the disturbance field. Inside the polar cap $\tan\frac{\theta}{2}$ is very nearly equal to $\frac{1}{2}P_1^1(\theta)$ (error less than 3 per cent at $\theta = 20°$) so the expected vertical to horizontal component ratio should be θ instead of the 2θ found above. We note that

$$\frac{\text{Z amplitude}}{\text{X or Y amplitude}} = 0.30 \pm 0.30 \text{ on very quiet days,}$$
$$= 0.32 \pm 0.11 \text{ on quiet days,}$$
$$= 0.33 \pm 0.09 \text{ on disturbed days,}$$
$$\text{and } = 0.34 \pm 0.12 \text{ for (disturbed-very quiet) days.}$$

There is no obvious change by a factor of 2 in this ratio between the disturbance field and the quiet or very quiet day field, although the uncertainties are such that definite rejection of Fukushima's solution is not possible. There is also the possibility that internal field contributions might modify these ratios in different ways.

The Polar Cap Conductivity and the Velocity Amplitude

In the absence of appreciable ionisation by incoming charged particles it seems reasonable to assume $\Sigma_1 = 1.2 \times 10^{-10}$ e.m.u. and $\Sigma_2 = 1.8 \times 10^{-9}$ e.m.u. for a 20 km. thick layer at 100 km. height. These correspond to 3.4×10^4 electrons and ions/cc. at 100 km. as a yearly average around sunspot minimum. Then $\Sigma_3 = 2.7 \times 10^{-8}$ e.m.u., and since on very quiet days $\Sigma_3 k_1^1 \times 10^{-4} = 8.8/3.5$,

$$k_1^1 = 9 \text{ m/sec.} = 34 \text{ km./hr.}$$

The phase corresponds to an air flow from the p.m. hemisphere to the a.m. hemisphere (to the N at 16.3 hrs.). The way in which these very quiet day currents complete their circuit is obscure.

Since there are no important seasonal shifts in phase, which in itself does not suggest a heat driven air circulation, but rather a tidal motion, it is possible that the different

amplitudes on different days reflect changes in conductivity rather than changes in the amplitude of the circulation. This is supported by the relationship suggested earlier between the average amplitude and the average K sum, which can be roughly regarded as an index of solar particle precipitation.

The class of disturbed days would require a conductivity of about 2×10^{-7} e.m.u., which could be produced by (say) a positive ion and electron density of 2×10^5/cc. in a twenty km. thick layer. It has been shown by Fukushima (1953) that a proton stream of 1/cc. moving with an initial velocity of 10^9 cms./sec. (500 keV.) produces about 2×10^7 ion pairs/c.c. near the bottom of its penetration range, a little above 100 km. from the ground. It seems likely therefore that the direct entry of weak corpuscular streams into the polar cap during disturbed conditions could easily produce the conductivity required. Then statistical variations in the wind and in the distribution of ionization produce the large uncertainties described analytically earlier in the day to day features of disturbance. The large scale circulation of air from the p.m. to the a.m. hemispheres approximately is the only statistically persistent feature in the problem.

Extension of Dynamo Theory

In view of the successful numerical aspects of the elementary dynamo outlined above, it seemed worthwhile to consider the implications of more refined models, and in particular to consider the effects produced by the difference between the positions of the geomagnetic pole and the geographic pole and the effects produced by a diurnally varying conductivity on very quiet days. Both these problems have been considered before at different latitudes.

(1) Using geographic axes, if the geomagnetic pole has coordinates (θ_0, ϕ_0), then $Z = 2\,G\,\{\cos\theta + \tan\theta_0 \sin\theta \cos(\phi - \phi_0)\}$. Assuming $\psi = k_1^1 P_1^1 \sin(t + \alpha_1^1)$ an exact solution of the dyanmo equation is of the form

$$\begin{aligned} J = {} & 2\,G\,\Sigma_3 \frac{\sqrt{3}}{2\cdot 3} k_1^1 P_2^1 \sin(t + \alpha_1^1) \\ & - 2\,G\,\Sigma_3 \tan\theta_0 \frac{1}{6} k_1^1 P_2^\circ \sin(\alpha_1^1 + \theta_0) \\ & + R(\theta) \sin(2t + \alpha_1^1 - \phi_0) \end{aligned}$$

where R satisfies the equation $\dfrac{-4R}{\sin\theta} + \dfrac{\partial}{\partial\theta}\left(\sin\theta \dfrac{\partial R}{\partial\theta}\right) = -2\sin\theta\tan\theta_0$.

This suggests that the X and Z first harmonic waves should be in phase which is not true. The zonal terms are largest in Z, and are $2\frac{1}{2}$ times larger in Z than in X. Their magnitude is too small to relate to the phenomena discussed in Part II of this paper. In practice the second harmonic amplitudes are known to be unimportant.

(2) In view of the complexity of the actual field distribution over the polar cap region, which corresponds to a complex Z distribution in the lower part of the ionosphere, it is of interest to examine the simple case when $Z = 2\,G$ is assumed. In northern Canada this is not at all a bad approximation particularly near the auroral zone. Then the solution leads to a magnetic potential

$$= -4\pi \frac{2}{3}\left(\frac{r}{a}\right)^2 2\,G\,\Sigma_3 k_1^1 \sin\theta \sin(t + \alpha_1^1)$$

and the situation is the same as before except that $\frac{Z}{X \text{ or } Y} \approx \theta$ instead of $2\,\theta$. Once again an effective centre for the motion not at the north geographic pole is required to explain the observed phases.

(3) It has been found that the horizontal movements in the ionosphere in moderate northern latitudes show a pronounced 12-h period with a mean velocity of about 30 m/sec. (Briggs and Spencer, 1954). This suggests that the 24-h periods found in magnetic variation may be produced by the semi-diurnal wind movements when allowance is made for the diurnally varying conductivity of the layer. Chapman (1913) has examined this question using a certain conductivity expression, and recently his work has been extended by Chakrabarty and Pratap (1954) who give reasons for using a diurnally varying conductivity of the form $\Sigma \propto 1 + 2.45 \cos \chi + 2.25 \cos^2 \chi$ where χ is the zenith distance of the sun. Using this expression the field produced by a semi-diurnal motion has been calculated with the aid of the current function coefficients found by Chakrabarty and Pratap (1954): at the summer and winter solstices the semi-diurnal component amplitudes predicted are 70 per cent of the diurnal ones, and a phase change occurs unless $\alpha_2 = 0$. At the equinoxes a negligible (2 per cent) semi-diurnal amplitude is predicted. Furthermore the predicted phase relationships between the components, and the measured amplitude relationships between the diurnal terms do not agree with experience. It is therefore considered doubtful whether a semi-diurnal oscillation could be responsible for the fields found inside the polar cap, and with the present state of knowledge of atmospheric motions, it is considered that detailed calculations are not justified.

Furthermore using the selected quiet days, the equinox: summer amplitude ratio is 0.75 whereas examination of vertical incidence ionospheric records for Resolute Bay for the year 1954 gives a $n_{max.}$ ratio of 0.22; the seasonal average of the radio data gives 0.50. Thus $n_{max.}$ of the E layer above the station is an unsatisfactory parameter for the determination of the conductivity in the dynamo layer; this might be expected since the field variations are influenced by the integrated effect of conductivity over a wide area and height. During the summer months, the average value of $n_{max.}$ is not appreciably different on the selected disturbed and quiet days.

At Resolute Bay the expression $1 + 2.45 \cos \chi + 2.25 \cos^2 \chi$ represents the seasonal variation in $n_{max.}$ of the E layer no better than Chapman's expression $(1 + 1.5 \cos \chi)^2$. At the summer solstice when the sun is above the horizon for 24 hrs., then $\frac{n_{min}}{n_{max}}$ in 1954 = 0.43. Chapman's expression predicts 0.39 and the former 0.40.

Corrections for Internal Contributions Inside the Polar Cap

The internal contributions to the observed daily variation have been neglected; it would however appear reasonable for very quiet day phenomena to reduce the observed horizontal components by multiplication by 0.71 and increase the observed vertical components by multiplication by 2.5 to obtain the external contribution only. These figures correspond to an external: internal amplitude ratio of 2.5, $n = 2$, $m = 1$ and neglecting the small phase difference in the internal and external contributions. The effective pole of the dynamo becomes east of Greenland and agreement with the geomagnetic pole disappears.

This suggests that inside the polar cap, internal contributions to very quiet day variations are not so large as the analysis of quiet day variations at low and moderate latitudes suggests. When the results from a greater number of stations are published this point should be pursued further. Other authors (Vestine *et al.* 1947) have used corrections of 10 per cent inside the polar cap for the disturbance field; since all three classes above reflect the same phenomenon this figure might also be applicable to the very quiet day variation.

Application of Dynamo Theory to Very Quiet Day Results at Baker Lake

Since the very quiet days selected at Baker Lake and Resolute Bay are much the same, it is important to compare the Baker Lake data with predictions based on the velocity potential described above which fits the Resolute Bay data. We then find that

(i) the predicted 24-h wave in D is more than four times the observed amplitude,

(ii) the predicted ratio of $\frac{Z}{H}$ corresponds to an angle of 16.3°, and the observed ratio corresponds to an angle of 22 ± 9°,

(iii) the angle α_1^1 required at Baker Lake referred to axes as before is 206 ± 6°,

(iv) the difference in phase between the two horizontal components is 177 ± 10° instead of 90°,

(v) the angle β required at Baker Lake = 144°, whilst the actual angle between the magnetic meridian and the geomagnetic meridian is 17°, and

(vi) similarly unsatisfactory conclusions can be drawn from the second harmonic.

Generally the results are not compatible with functions of the form$P_n^{1,2}$ unless n is not small. Presumably this means that there is an appreciable residual disturbance field (n known to be large) on very quiet days at Baker Lake. Assuming on these days equal Σ K products at the two stations, the horizontal components expected at Baker Lake should be ~ 9 and 6 gammas respectively in 24-h and 12-h components and ~ 6 and 3 gammas respectively in the vertical components. These estimates suggest that approximately 50 per cent of the disturbance on very quiet days is produced by residual disturbance (n large), and hence predictions based on the elementary model described above are worthless.

THE DISTURBANCE FIELD AT BAKER LAKE

We have shown that the application of dynamo theory to Baker Lake observations fails for very quiet day phenomena and that the disturbance field present on quiet days is different in intensity and form from that present on disturbed days. The implications of the formal results presented earlier are best seen in the form of vector diagrams.

The Magnetic Auroral Zone near Longitude 60°W Geomagnetic

Harang (1946) has given a graphical representation of the disturbance field determined as a function of geomagnetic latitude and local time using observatories situated near geomagnetic longitude 120°E. No corresponding line of observatories is in operation in the western hemisphere, but if the results from Resolute Bay and Baker Lake are combined with those from Second Polar Year and other stations (note that both 1954 and

1932-33 were years of minimum solar activity) approximate polar plots are possible which can be continued beyond geomagnetic latitude 75°. The stations used at different times include Thule, Resolute Bay, Baker Lake, Chesterfield Inlet, Fort Rae, Meanook, Agincourt and Tucson. Although geomagnetic position coordinates are used it is simpler to consider the plots as local time plots: the refinements in correcting to geomagnetic local time are probably not important for the purpose of the diagrams shown. At Baker Lake, at the equinoxes the difference between local noon and local geomagnetic noon is 1.2 hrs. Figure 5 is typical of many plots, and shows the diurnal variation for all days in June of the disturbance field in Z across the geomagnetic meridian $\Lambda = 60°W$. The heavy line indicates the horizontal position of any assumed line current system. The similarity with Harang's (1944) results is striking, but the latitude range covered is much larger. Figure 6 shows approximate estimates of the positions of the lines of zero ΔZ and the maximum ΔH, and a mean between these. This mean line is regarded as the best approximation to the auroral zone. The dotted lines at lower latitudes in the afternoon and evening hours

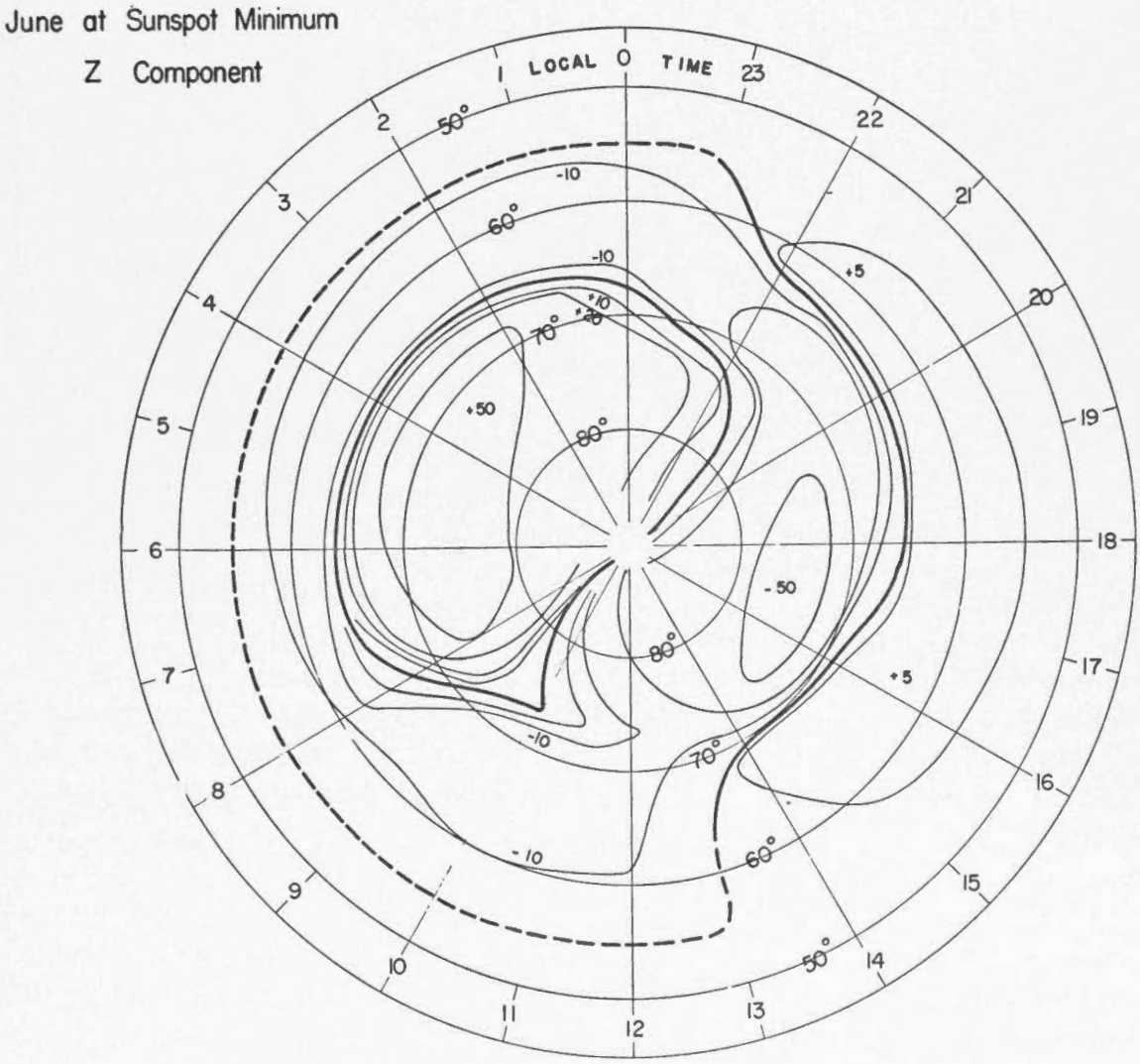


FIGURE 5. Diurnal variation of the disturbance field in Z (all days) across geomagnetic meridian $\Lambda = 300°$. The heavy line indicates the horizontal position of any assumed line current.

correspond to a minor maximum in Δ H and an ill defined line Δ Z = 0. The auroral zone is much more clearly defined on the morning side. In Figure 6 the maximum Δ H and zero Δ Z curves intersect at about 16-h and 24-h L.T. in approximate agreement with Harang (1946) and suggesting that the systematic change in phase of the amplitude of the disturbance field with longitude, which can approach 4 hours, is not obvious on two lines 180° apart. The material is not yet sufficient for a closer examination of the pattern.

Vector Diagrams at Baker Lake

The analysis of Baker Lake disturbance field characteristics can contribute to the study of the morphology of auroral zone disturbance. Figure 7 shows mean horizontal vector diagrams for the three classes, correcting the quiet and disturbed days using the

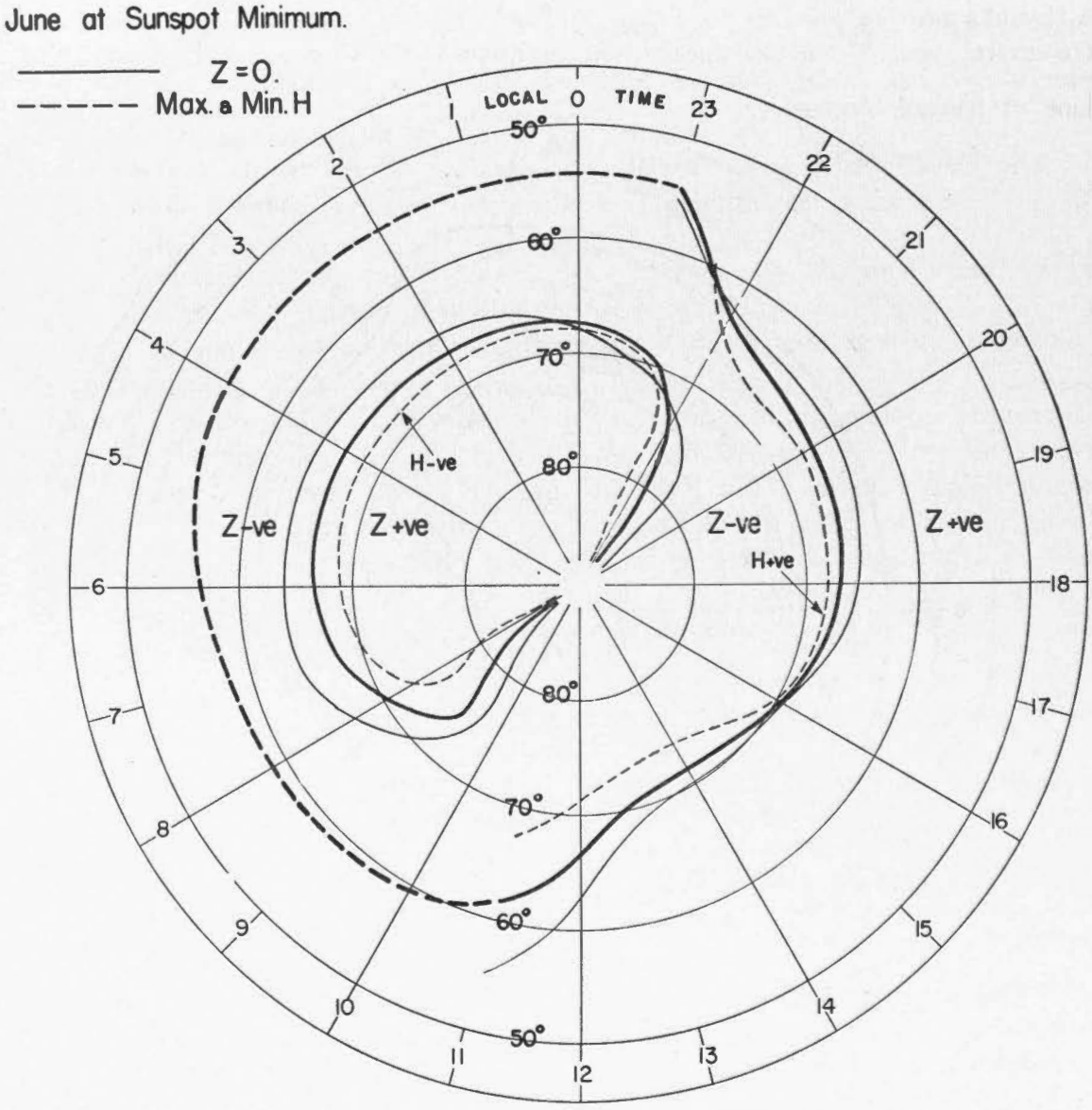


FIGURE 6. Polar plot of the position of the lines of zero Δ Z, maximum | Δ H | and the auroral zone, deduced from the diurnal variations of the disturbance field in H and Z across geomagnetic meridian Λ = 300°.

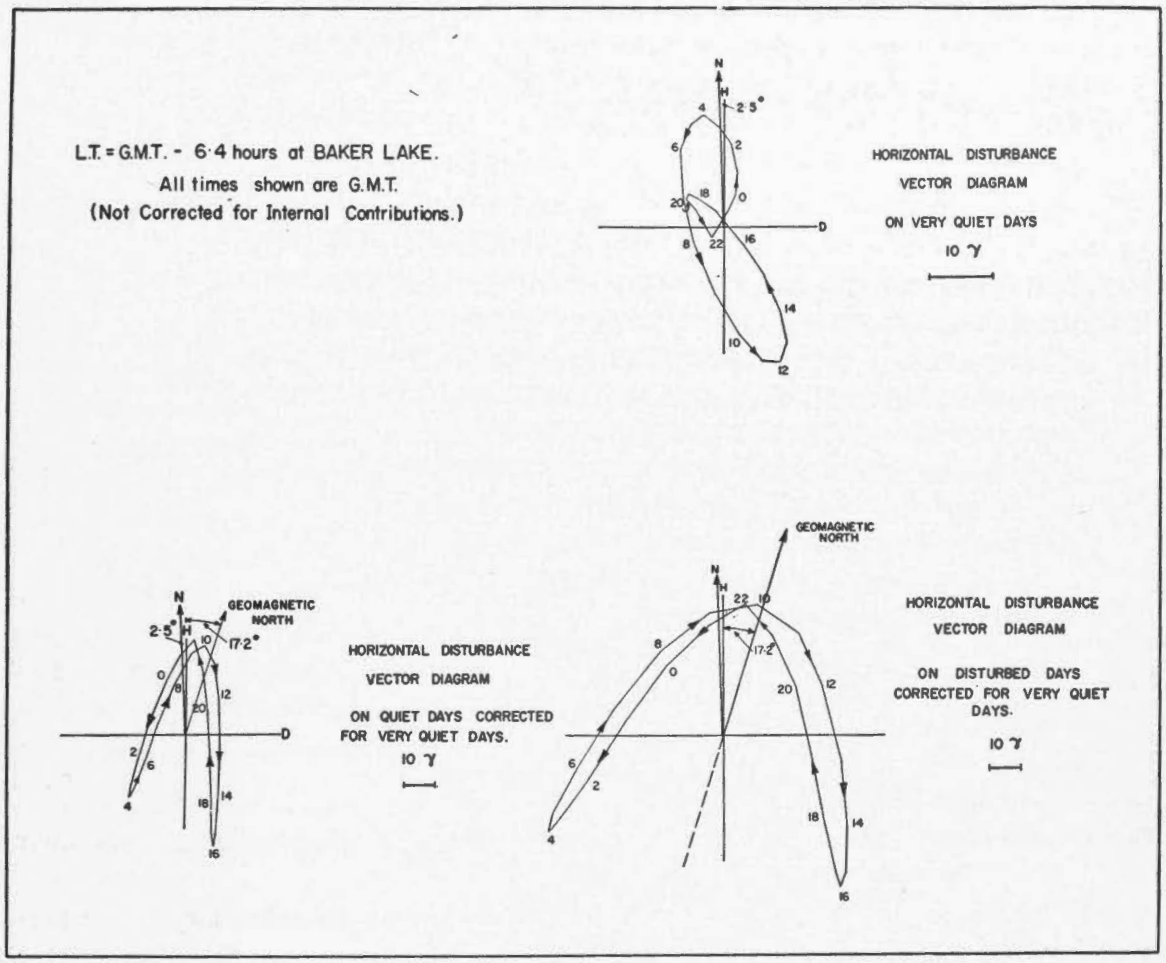


FIGURE 7. Horizontal vector diagrams for the three classes of selected days at Baker Lake, N.W.T.

very quiet day disturbance as an approximation to the true unperturbed solar daily variation. The similarity between the quiet and disturbed classes is striking, and the distinction from very quiet day phenomena clear. In Figure 7 the persistent features of disturbance only are shown: the inclusion of the higher harmonic terms, however, changes nothing significantly. Figure 8 shows the diurnal variation for the three classes in Z. No attempt has been made to combine Figures 7 and 8 in the form of total perturbing vector diagrams, vertical plane vector diagrams and so on, because it is not clear what corrections are required for internal contributions to the observed cyclic field variations.

However, it does seem likely that the average night-time perturbing vector is larger than the average daytime perturbing vector on very quiet days, but smaller by 10 to 20 per cent (depending on the corrections adopted) for the quiet and disturbed days: this again suggests a difference. The perturbations are stronger over the p.m. than over the a.m. hemisphere, a result in agreement with those found in the belt between zones.

Table VIII summarises certain numerical results deduced from Figures 7 and 8. The horizontal vector diagrams suggest symmetry about an axis between true and geomagnetic north, and tending towards the latter with increasing disturbance. At local times 04 hrs.

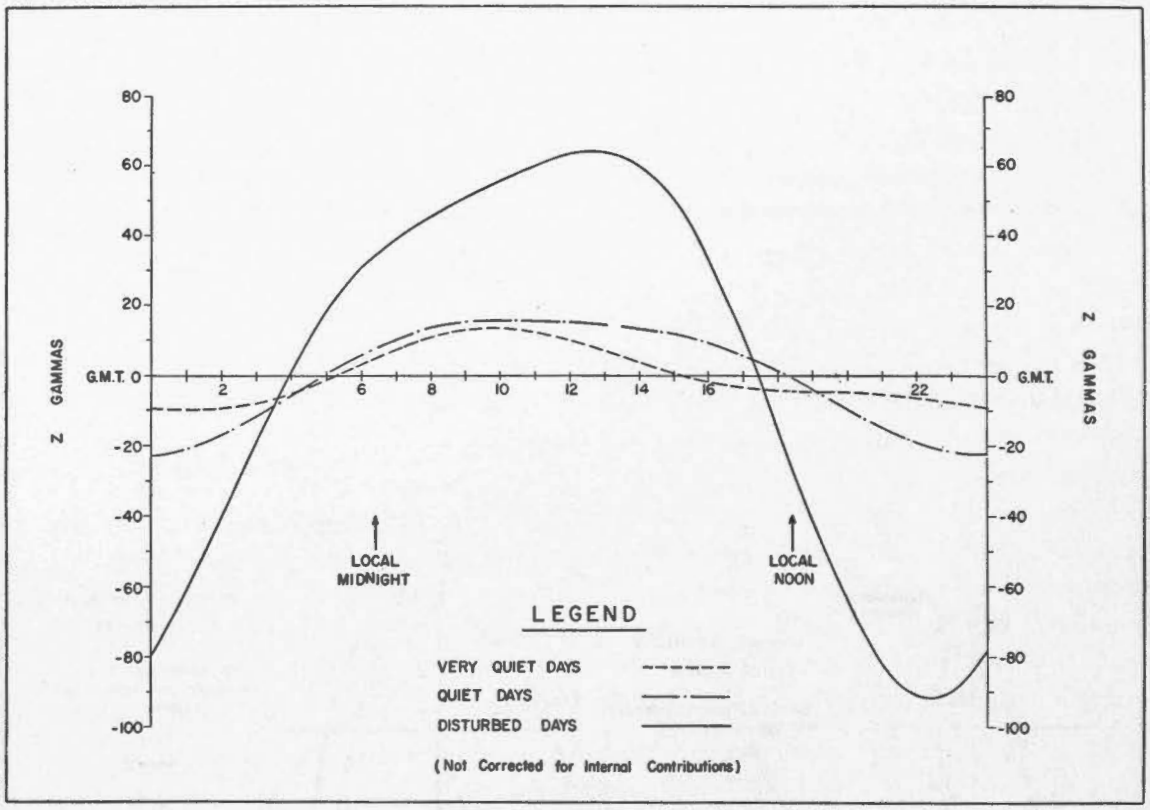


FIGURE 8. The diurnal variation of the disturbance field in Z for three classes of selected days at Baker Lake, N.W.T.

and 15 hrs. approximately, corresponding closely to the second subsidiary set of horizontal vector maximum, the auroral zone currents are along geomagnetic parallels of latitude. The afternoon maximum corresponds to easterly flowing current in the auroral zone to the south of Baker Lake, and in Table VIII the current in this branch is calculated assuming a line current (or sheet of small lateral extent), and its position south of the station estimated assuming a height of 100 km. The estimates are made using a number of different corrections: it appears that corrections of 30 per cent to 40 per cent are necessary to obtain general agreement with the synoptic plots and place the concentrated current at geomagnetic latitude 69°. This agrees well with Vestine's (1947) estimate but not with that of Harang (1946).

The morning flow is more surprising. The equivalent line current is flowing easterly N of the station. Either this implies that Baker Lake is so far north of the main westerly auroral zone currents in the morning that the direction of the resultant horizontal force is influenced more by the return path currents north of the station, which seems unlikely, or the westward flowing currents south of Baker Lake in the morning branch are more diffuse laterally than the eastward currents to the north of Baker Lake. In any case, because of the effective Z enhancement in the centre of even a diffuse ring, calculations of current or position based on one station assuming a line current north of the station are not very reliable, though corresponding estimates are shown in Table VIII. A more dense network of observations in this transitional region might therefore show a maximum

in Δ H corresponding to Δ Z = 0 at geomagnetic latitudes around 76° at the time of the minimum in Δ H corresponding to Δ Z = 0 known to exist around this local time about geomagnetic latitude 68° (*see* Figure 6).

Table VIII demonstrates that the effect of increasing disturbance is to increase the latitude separation of the branches considered above by about 4-5°: as might be expected the movement to the south of the stronger p.m. branch is the larger.

It is of interest to consider the closure paths of the auroral zone currents. Much of the p.m. branch is closed in the form of a sheet flowing parallel to the 10-h meridian in the centre of the cap. However, the Baker Lake results show that by geomagnetic latitude 74° this sheet is so distorted that Δ Z = 0 about one hour later in the morning: this distortion can also be seen in that the second set of horizontal vector maxima near 10-h and 22-h L.T. for the two classes do not coincide exactly with the times when Δ Z = 0. Furthermore it can be seen from the magnitude of the horizontal vector when Δ Z = 0 that closure must correspond to some sheet and cannot be well represented by a concentrated current on the average. Chapman and Bartels (1940, Ch. 9) suggested that more than 80 per cent of the current in the auroral zone returns over the polar cap, whereas Harang (1946) considered that the available material was insufficient to support the view that the perturbing currents as a whole are closed over the polar cap. Combining the data in Table VIII with the horizontal amplitudes at Resolute Bay found on quiet and disturbed

	NO CORRECTIONS	10% CORRECTIONS	30% CORRECTIONS	40% CORRECTIONS
i_{pm}				
DISTURBED DAYS	0.6×10^5 a	1.6×10^5 a	3.1×10^5 a	4.7×10^5 a
QUIET DAYS	0.2×10^5 a	0.2×10^5 a	0.3×10^5 a	0.4×10^5 a
i_{am}				
DISTURBED DAYS	0.6×10^5 a	0.7×10^5 a	1.2×10^5 a	1.8×10^5 a
QUIET DAYS	0.2×10^5 a	0.2×10^5 a	0.2×10^5 a	0.3×10^5 a
d_s°				
DISTURBED DAYS	2.0	2.4	4.1	5.4
QUIET DAYS	0.6	0.7	1.2	1.6
d_N°				
DISTURBED DAYS	1.2	1.4	2.5	3.3
QUIET DAYS	0.5	0.6	1.0	1.4
i_{pm}/i_{am}				
DISTURBED DAYS	2.1	2.3	2.6	2.6
QUIET DAYS	1.1	1.1	1.2	1.3

ASSUMED HEIGHT = 100 km

TABLE VIII. Summary of strength of perturbing currents, with and without corrections for internal contributions, assuming auroral zone characteristics at Baker Lake, N.W.T.

days, it was estimated that about 40 per cent of the auroral zone currents return over the polar cap on disturbed days, and all the current returns over the polar cap on quiet days. This estimate suggests therefore that a rückstrom for lower latitudes is only significantly developed on the selected disturbed days, and on the quiet days (or days of moderate disturbance) this rückstrom is not appreciable.

The correlation between the 24-h wave amplitudes in Z at Baker Lake and Z and X at Resolute Bay were computed for the common disturbed days in the winter months. The results were $r_{Z,Z} = 0.75 \pm 0.05$ and $r_{Z,X} = 0.45 \pm 0.08$. These coefficients are higher than the internal ones found in the polar cap (*see* page 304) and contrast strikingly with the results for Baker Lake (*see* page 306). The coefficients found suggest partial or complete closure on disturbed days: however it is not clear why the correlation between the Z amplitudes exceeds that between Z Baker Lake and a horizontal component at Resolute Bay. Whitham and Loomer (1956) have found that disturbance generally is as highly correlated between the two stations as the 24-h wave amplitudes in Z.

Comparison of Observations with Auroral Zone Theories

Meek (1955) has re-examined the Polar Year data 1932-33 in a discussion of the location and shape of the auroral zone, and gives reasons for doubting the existence of an equatorial ring current. The stream of particles from the sun is supposed to separate under the influence of the earth's magnetic field, and the charged particles of opposite sign are precipitated into the atmosphere in the form of Størmer-like spirals: the spiral produced by positive particle precipitation expands in an anticlockwise direction and that due to negative particle precipitation in a clockwise direction. The positions of these spirals are deduced from the local geomagnetic time of the diurnal increase and decrease in H respectively, and the cross over points are near 10 a.m. and 10 p.m. L.G.M.T. Since the basic data used was much the same as that used in deriving Figures 5 and 6, it is obvious that the existence of spirals is open to considerable doubt. Furthermore it is not clear how spiral precipitation could account for the observed minimum in geomagnetic north component at about 22 hrs. L.T., and maximum at about 16 hrs. L.T., or the results at Resolute Bay. However, the large declination changes observed during disturbance at Baker Lake do not support the idealised concept of concentrated current flow westwards on the a.m. side and eastwards on the p.m. side advanced by Chapman (1935) or the drift currents advanced by Martyn (1951).

At the present time it would appear that the proposals of charge leaking down the lines of force of the earth's magnetic field advanced by Chapman-Ferraro-Martyn (1951) and Alfven (1950) form a satisfactory basis for the explanation of auroral zone magnetic disturbance. However, idealized concepts of concentrated current flow are not very valid even in the average data discussed above. The authors consider it premature to discuss the detailed form of precipitation unless the morphology of the disturbance field is much more carefully determined from observatory records. However, a number of the magnetic field changes discussed in Part II of this paper suggest that none of the theories presently advanced is fully satisfactory.

Nikolski (1947) has discussed in detail magnetic disturbance at Calm Bay (Tikhaya) ($\Phi = 71.5°$N, $\Lambda = 153.3°$E) in an important paper. He concludes that "the changes of

magnetic disturbance during the night and morning hours depend on different laws and that the mean regular variations S_D and D_{st} in the disturbed field do not correspond to any real prolonged phenomena in the field of magnetic storms and are fictitious i.e. merely statistical results". Since Baker Lake and Calm Bay are both north of the auroral zone and show similar diurnal variation in K index when plotted against L.G.M.T., it is important to consider how applicable Nikolski's conclusions are to the analysis described in this paper. The similarities of the horizontal vector diagrams shown in Figure 7 suggest that there is correlation between the two disturbance maxima (the wing tips in Figure 7), and that there is no shift in the times of the maximum disturbance on the more disturbed days. Moreover in Part II of this paper clear evidence is presented for the existence of regular non-cyclic field changes at times of disturbance at both Baker Lake and Resolute Bay. Hence since the harmonic analysis has given a formal representation of persistent features of the disturbance field, it is difficult to agree with Nikolski's conclusions that "the mean regular peculiarities in the field of disturbance of magnetic storms in high latitudes . . . represent fictitious, quite statistical results, and have nothing to do with any real long-period physical phenomena".

Fukushima (1953) and Vestine (1954) have discussed dynamo theories of auroral zone disturbance, assuming that the conductivity in the auroral zone is much greater than in other atmospheric regions, and have pointed out the difficulties. The current systems calculated on certain two-layer conductivity models show features similar to those of Chapman's (1935) idealized system but often more diffuse and to this extent may be thought to be in agreement with observation. It should, however, be noted that the low correlation coefficients described on page 306 do not in themselves support very strongly a dynamo model.

Variations in the Position of the Auroral Zone

The averaged persistent waves described earlier strongly suggest that the afternoon maximum at Baker Lake is the most pronounced auroral zone feature at Baker Lake. Table VIII discusses the average features associated with this maximum, but cannot indicate how stable its properties are from day to day. To consider this the correlation between the 12-h wave amplitude in H and the sum of the 24-h and 12-h wave amplitudes in Z was computed. These parameters can be seen to largely define the amplitudes of the field disturbance at the time of the afternoon maximum. The result was $+ 0.11 \pm 0.07$ for all disturbed days in the winter months. A similar calculation for the morning maximum gave $- 0.19 \pm 0.07$. Thus we conclude that though the waves show formal persistence properties their interdependence is random, and the mean position of the auroral zone deduced above is a statistical average: the position for any day can vary widely.

ACKNOWLEDGEMENTS

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PART II: TRANSIENT FIELD CHANGES

ABSTRACT

The analysis of magnetic disturbance at Resolute Bay and Baker Lake has been extended to include sudden commencements, sudden commencement storms, non-sudden commencement storms, and bay phenomena. The physical meaning of the mean disturbance field and non-cyclic changes is also discussed.

A number of new results are suggested by these analyses. There seems little doubt that Arctic sudden commencements are atmospheric in origin. They occur equally frequently throughout the day but appear to show systematic diurnal properties in preliminary impulse only.

The distinctions found at lower latitudes in the properties of sudden commencement and non-sudden commencement storms are not so evident. In particular both classes of storm evidence storm time effects in one of two regular patterns which are discussed. The expected differences in recurrence properties are not found. The equivalent current systems of different types of storm are discussed.

The frequency, amplitude and sign of bays occurring on the selected days have been analysed. It was found that Martyn's explanation of bays is not satisfactory, and that the idealized form of the elementary polar disturbance field shows properties systematically different from that of the idealized S_D field. The relation of bays to aurora and polar blackouts is discussed.

Inside the polar cap certain features of the bay field appear which may be related to the second class of storms found. The suggestion emerges of an inner pattern of zonal current and bay disturbance which predominates in the polar cap in the summer months, and shows certain features the reverse of those found in the auroral zone. It appears to develop instead of, rather than with, the usual pattern.

The mean disturbance field is shown to represent very largely the effect of the bay field, but unexplained terms remain.

INTRODUCTION

The analysis of Resolute Bay and Baker Lake magnetograms described in the previous paper has been extended to include a number of non-cyclic magnetic phenomena: these include storm sudden commencements, moderate magnetic storms of the sudden and non-sudden commencement type, bay phenomena, the mean disturbance field and non-cyclic changes. The records used cover the period from 1949 to 1955 with special attention being given the previously selected days. In each case an attempt has been made to relate the findings to recent ideas in the field and show what contribution, if any, it is possible for observatories in high latitudes to make. A number of properties of disturbance have been found which are very different from those generally accepted; these suggest that at the best, present day theory is inadequate.

It is the hope of the authors that some of the features of high latitude disturbance outlined below will be investigated at other observatories before or after the forthcoming International Geophysical Year, and that the unexplained differences in disturbance characteristics from those at lower latitudes will help in the development of more satisfactory theories, and act as a guide in deciding between them. The terminology used here follows Chapman (1951, 1952).

INVESTIGATIONS OF SUDDEN COMMENCEMENTS

Comparison with Occurrence at Lower Latitudes

Resolute Bay magnetograms from September 1949 to November 1955 and Baker Lake magnetograms from February 1951 to November 1955 were searched for sudden commencements. The S C listed in the I.U.G.G. (earlier in the I.A.T.M.E.) bulletins were used as a guide, but the magnetograms for each day were examined. During the

interval September 1949 to December 1954, 167 S S C and S C were listed (in 1949, the bulletin included S C only: in 1950 S S C and S C were listed and in the following years only S S C), whereas 70 only were definitely identified at Resolute Bay. From February 1951 to December 1954, 71 S S C were listed in the bulletins and 20 only were clearly identified at Baker Lake. In each case a number of those found were not included in the bulletins. It therefore appears that inside the polar cap, sudden commencements can be identified half as frequently as in low and moderate latitudes, and nearer the auroral zone less than one third as frequently. S C is however definitely not a localized equatorial phenomenon, as has been suggested by certain authors. A comparison with the selected planetary S C listed in the I.U.G.G. (earlier I.A.T.M.E.) bulletins of Bartels and Veldkamp (1949 to 1954) showed that 41 per cent of the planetary S C (53 out of a possible 128) were identified at Resolute Bay and 26 per cent (15 out of a possible 58) at Baker Lake. Approximately one in four of the identified S C at both stations during these intervals were not listed.

Comparison with Lower Latitude Times

Except for seven cases all times agree within 1 minute with the times found at lower latitudes: in one case the time difference was 4 minutes and in the remaining cases less than 2 minutes. It is doubtful if these differences are significant since it is not now possible to check the accuracy of the time marks. It seems likely that polar S C occur simultaneously (to within 1 minute) with those at lower latitudes.

Classification of Sudden Commencements

The S C were classified according to a scheme suggested by Jacobs and Obayishi (1956). S C with a preliminary reverse impulse, sometimes very quick and sometimes lasting for a few minutes, were most common, forming 78 per cent of the S C at Resolute Bay and 89 per cent at Baker Lake. The amplitudes of both the initial and main phases were measured, wherever possible. Sudden impulses (S I) were not recorded: in northern stations S I occur very frequently, and occasionally almost continuously, and it did not seem reasonable to discuss their statistics with the well marked events preceding clear and well defined disturbance. The data below does not include the sudden commencements corresponding to the leading edge of a clear bay-like disturbance: these are often pulsational and well marked in the horizontal force components at Baker Lake, where they occur frequently.

The Diurnal Frequency Distribution

Figure 1 shows the diurnal frequency distribution of all identified S C in three-hour intervals for the two observatories, for the cases where a reverse impulse does and does not occur; the total number in the latter case is however very small. Chi-squared tests for homogeneity indicate that the hypothesis of equal frequency of total S C in each interval is a satisfactory fit, and it is considered therefore that the deviations shown from a straight line are random. A Poisson distribution would then be expected and the numbers found at both stations are satisfactory on this hypothesis. For example, at Resolute Bay the maximum number in any interval is 15 and the chance of this appearing in any interval is nearly 30 per cent assuming a Poisson distribution, and a mean of 9. Thus there appears

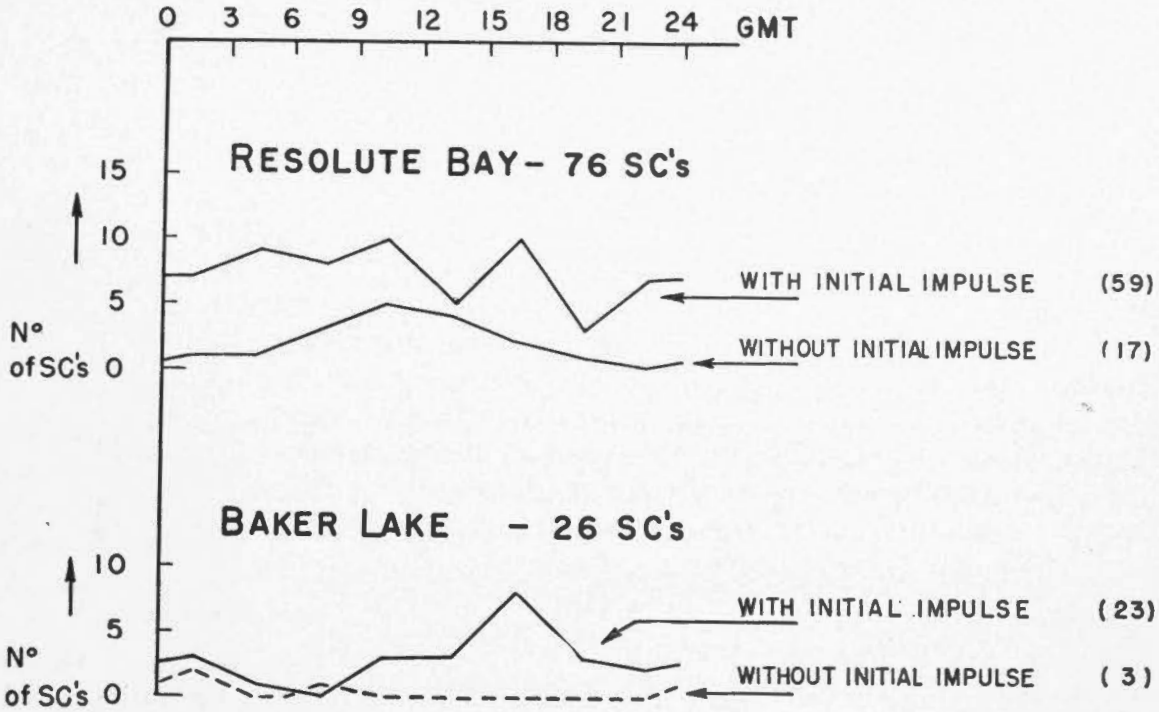


FIGURE 1. The diurnal frequency distribution of S C at Resolute Bay 1949-1955 and Baker Lake 1951-1955.

to be no evidence for a significant diurnal variation (D V) in the frequency of occurrence. Since most of the S C are of the type with a reverse preliminary impulse, this result does not confirm the suggestions of Ferraro *et al.* (1951) of a local time effect with an afternoon maximum. It is in agreement with the analysis of Forbush and Vestine (1955) of S C occurrence at Watheroo and Huancayo observatories. It may be that a significant diurnal variation (D V) in the frequency of occurrence can only be found when the form of the S C can change appreciably: since the above results largely refer to one type of S C, homogeneity may not be surprising. Many more years of records would be necessary to test this suggestion in polar regions.

The Diurnal Variation in Amplitude of the Initial Movement

At Resolute Bay three component records are available only after October 1953, and the determination of the mean azimuth and inclination of the perturbing vector is only possible for the morning hours. Although substantially constant values are found, it is believed that a real D V exists. Figure 2 shows the mean results for the nine cases where measurements are possible at Resolute Bay: Δ Z is always negative and the azimuth is never in the north quadrants. An examination of the longer sequence of La Cour declination records for the entire period of operation of the observatory showed that 14 out of 17 S C with no reverse impulse show northerly motions, whereas 41 out of 59 S C with an initial impulse show initial southerly motions: thus over 70 per cent of the main motions are to the north. It should be noted that this is the same direction as that generally accepted for a normal S C at low and moderate latitudes. Both the D and the three component records suggest that sudden commencements near noon are larger than ones occurring near midnight.

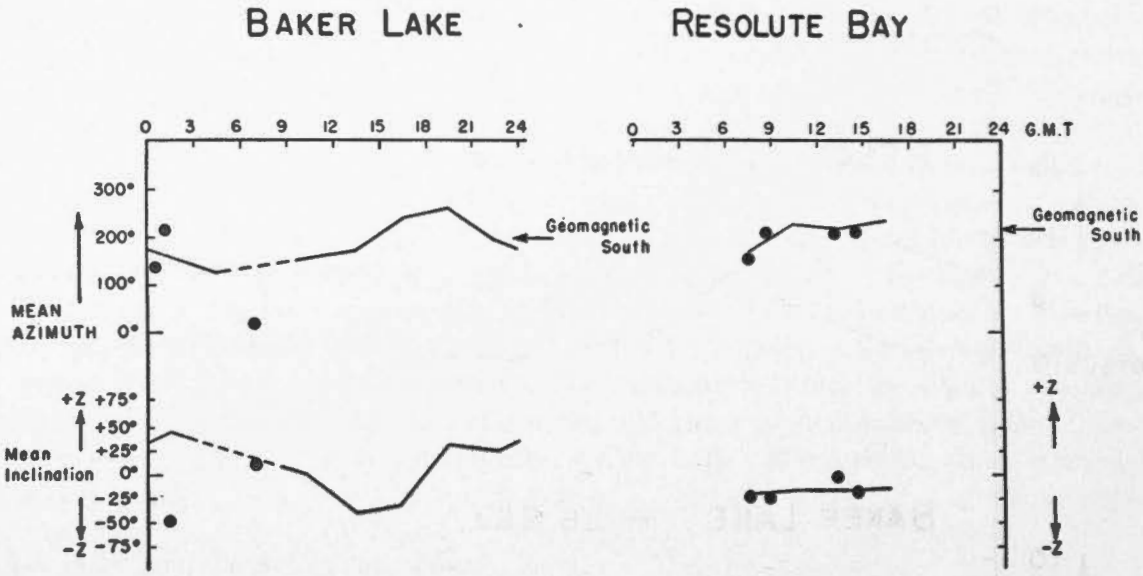


FIGURE 2. The diurnal variation in the azimuth and inclination of the perturbing vector producing the initial impulse of S C at Resolute Bay and Baker Lake.

At Baker Lake three component records are available covering the entire period searched, and Figure 2 shows the estimated D V in azimuth and inclination for the initial motion based on twenty-one cases. In 79 per cent of the cases the motion is southerly, whether a reverse impulse or the main phase of S C without reverse impulse. If an atmospheric current source is assumed, Figure 2 shows that during the initial impulse, the burst of current is westerly and north of both stations in the morning hours whereas in the afternoon hours the Baker Lake results indicate an equivalent current flow south of the station. The direction of the Z motion during the afternoon at Resolute Bay cannot yet be determined.

Analysis of the Main Impulse in Sudden Commencements

Measurement on the D records at Resolute Bay suggest that the main impulse is not appreciably different in size whether it appears with or without a preliminary impulse: an average of 35 gammas in Δ X was obtained for both classes. The main impulse movements do not appear to be at all systematic, and it was concluded that no persistent D V could be found. However, in Figure 2, the individual points shown refer to the main impulse for those few cases where records in three components are available and no initial impulse occurs. At Resolute Bay the points lie close to the partial curve derived for the systematic initial impulses, but this is not the case at Baker Lake. It is concluded that the initial impulse in S C is a physically distinct phenomenon.

The only systematic feature found in the main impulses of four S C which were identified at both observatories and for which three component records exist is that the main perturbing vector is about twice as intense at Baker Lake as at Resolute Bay, whereas the initial impulse perturbation is twice as intense at Resolute Bay as at Baker Lake. In the preliminary impulse these four S C have azimuths close to geomagnetic south at both observatories (all in 06-12 hr. L.T.), and an elementary calculation shows that the position

of an equivalent westerly line current source is about 3.5° of latitude N of Resolute Bay at a height of 1100 km.: the internal corrections are then about 10 per cent. It is of interest to note that this corresponds to the calculated latitude of the dip pole at this height, 5° north of its epochal position (Jacobs and Sachs, 1956). There are certain longitude uncertainties but there is a possibility that the two facts may be related. In any case, if charged particle precipitation north of Resolute Bay is assumed, within minutes of time the pattern of disturbance becomes much more complex and diffuse, and its maximum certainly moves south. Although the mean azimuths for the initial phase are often close to geomagnetic south, the initial phase data from Resolute Bay suggests that deviations from this occur, particularly around noon and midnight. This suggests the possibility of a dynamo-like generation of the initial impulse in S C, and it would be of interest to discover the world-wide pattern and its relations to auroral zone precipitation. Forbush and Vestine (1955) have shown that there is a major and immediate atmospheric source of field in S C and the initial phase of storms at low latitude stations, and suggested that electric currents in or near the E layer near the magnetic equator are driven by electrojets of polar regions.

The Size of Sudden Commencements at High Latitude Stations

Chree (1912) found that S C in the Antarctic average about 4.5 times the amplitudes found at Greenwich. Combining all the S C for which the total perturbing vector could be measured, the preliminary impulses were found to have equal amplitude (54 gammas) at both stations, whereas the main impulse amplitude was nearly twice as large at Baker Lake as at Resolute Bay (101 gammas compared with 54 gammas). Since the data is not homogeneous, and no internal contribution corrections are applied, the figures are not too reliable, but they confirm the trend discussed above for the few common S C. A comparison with the median size for Hucancayo determined by Forbush and Vestine (1955) shows the average Baker Lake amplitude to be only slightly larger, but a direct comparison using homogeneous data would be preferable.

A seasonal effect is suggested in that the average perturbing vector found in the summer at Baker Lake is larger than that in the equinoxes and about twice that found in the winter. Furthermore there is the suggestion of a daylight hours enhancement since the initial phases at Baker Lake are 80 per cent larger and the main phases 60 per cent larger during daylight hours than during night hours. The Resolute Bay results, with one main phase exception show a similar daylight enhancement. These results support an atmospheric origin.

It is suggested that the relations between polar and equatorial S C require further examination preferably with fast magnetographs and accurate timing.

Internal Corrections

The approximate calculation considered above suggested that perhaps about 10 per cent of an average observed movement is produced by field sources internal to the earth. It is the purpose of this paragraph to note that initial impulses followed by a main impulse can often be approximated by a sine wave with a period of a few minutes, and it is not

unreasonable that corrections of this order could occur. The neglect, for example, of the influence of the oceans on the size of the S C observed at certain observatories may be serious: it should be noted that the integrated conductivity of 10,000 ft. of sea water is $\sim 10^{-5}$ e.m.u. or one hundred to one thousand times that of the ionosphere. There might well be systematic differences in the amplitude of the S C field determined from island and coastal observatories and from those in the centres of land masses.

THE ANALYSIS OF SUDDEN COMMENCEMENT STORMS

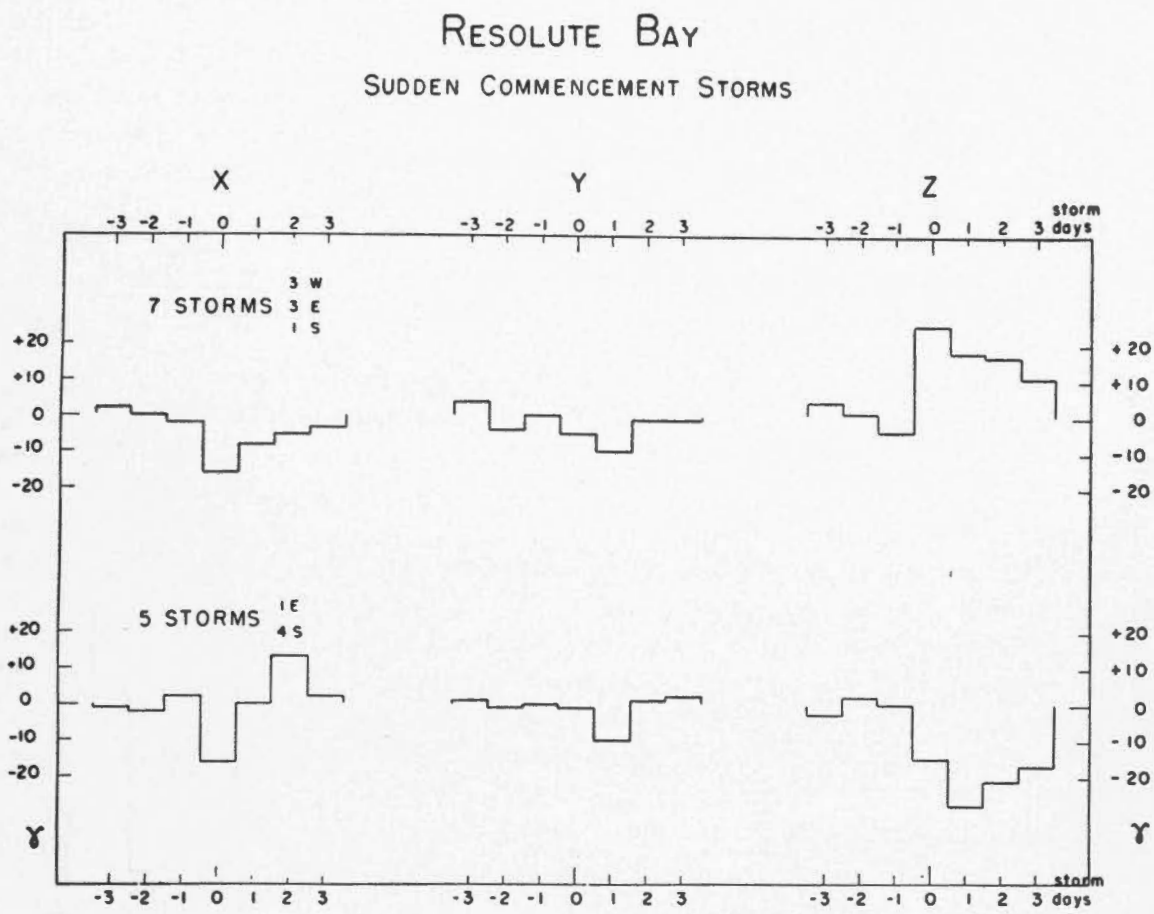
The Selection of Storms

A total of 12 storms at Resolute Bay and 23 storms at Baker Lake were examined in three components. The intervals searched and the storms selected correspond to the S C described above.

The Storm-Time Variation, D_{st}

In order to obtain the character of the storm-time variation in these high magnetic latitudes a number of procedures are possible. Derivations of storm-time variations have been described for lower latitude stations by Chapman (1927) using 40 storms, and for a wider range of latitude by Vestine (1947) using 11 storms of the Polar Year. The results of Vestine (1947) showed incomplete removal of the local time disturbance field S_d, or the disturbance local time inequality D_s as it appears at the time of moderate disturbance (Chapman, 1952).

An attempt to derive D_{st} for the first 48 hours of a storm was made, but the incomplete removal of D_s and irregular disturbance, and the small number of storms made the development in time of the storms at these high latitudes very difficult to follow. Local time corrections based on monthly means, or on the idealized S_d field, described in Part I of this paper, all failed to remove the disturbance local time inequality satisfactorily. Consequently the superposed epoch method was used to derive the storm-time effects averaged over daily intervals. This method of course, tells nothing about initial phases of storms. The daily means for the day of the storm (commencing at the time of the S C) and for the three 24-h periods previous to and after the first day of the storm were derived and averaged. Figure 3 shows the results at Resolute Bay and Figure 4 the results at Baker Lake, collecting the storms into two classes at Resolute Bay and three classes, at Baker Lake. The zero line for each plot is the average of days -3, -2, and -1. The figures also indicate the seasonal distribution among the classes and the mean storm changes. The latter in any component is arbitrarily defined by the mean change in the first seventy-two hours of the storm from the value in the seventy-two hours previous to the commencement of the storm. This definition seems a reasonable one since whenever storm-time changes are clearly defined in any component, the time constant of recovery seems to be about one day, so that the mean storm changes are effectively zero after about four days. In any case it seems a more reliable measure of magnitude than the change in amplitude on the first day of a storm, particularly for field components in which real storm-time effects are small. It should be noted that all the storms are moderate to small in intensity, and it is not certain if the time constant of recovery changes with more intense storms. No weighting procedures were used in deriving Figures 3 and 4.



Mean Storm Changes	X γ	Y γ	Z γ
7 + ΔZ storms	−10	−5	+20
5 − ΔZ storms	−1	−3	−21

FIGURE 3. Mean storm changes for sudden commencement storms at Resolute Bay, 1953-1955.

The two classes of storms at Resolute Bay, + Δ Z and − Δ Z storms, might well be called winter-type and summer-type storms respectively. The horizontal components for the summer-type storms are very small and southerly, and from Figure 3 obviously ill defined. Those for the winter type storms appear well defined in X only and are negative. The winter type storms therefore correspond to zonal current flow westwards south of the station.

At Baker Lake, 16 out of 23 of the storms correspond to westerly current flow south of the station. The azimuth of the mean perturbing vector is 190°, which agrees more closely with geomagnetic south, 197°, than geographic south, and is in very good agreement with the direction of the axis suggested in Part I of this paper, Figure 7, for the S_D field variation. However, in 7 storms real positive changes in Δ H occur, corresponding to a current reversal. Four were associated with large negative Δ Z values and 3 with large positive Δ Z values; i.e. concentrated current flow south and north of Baker

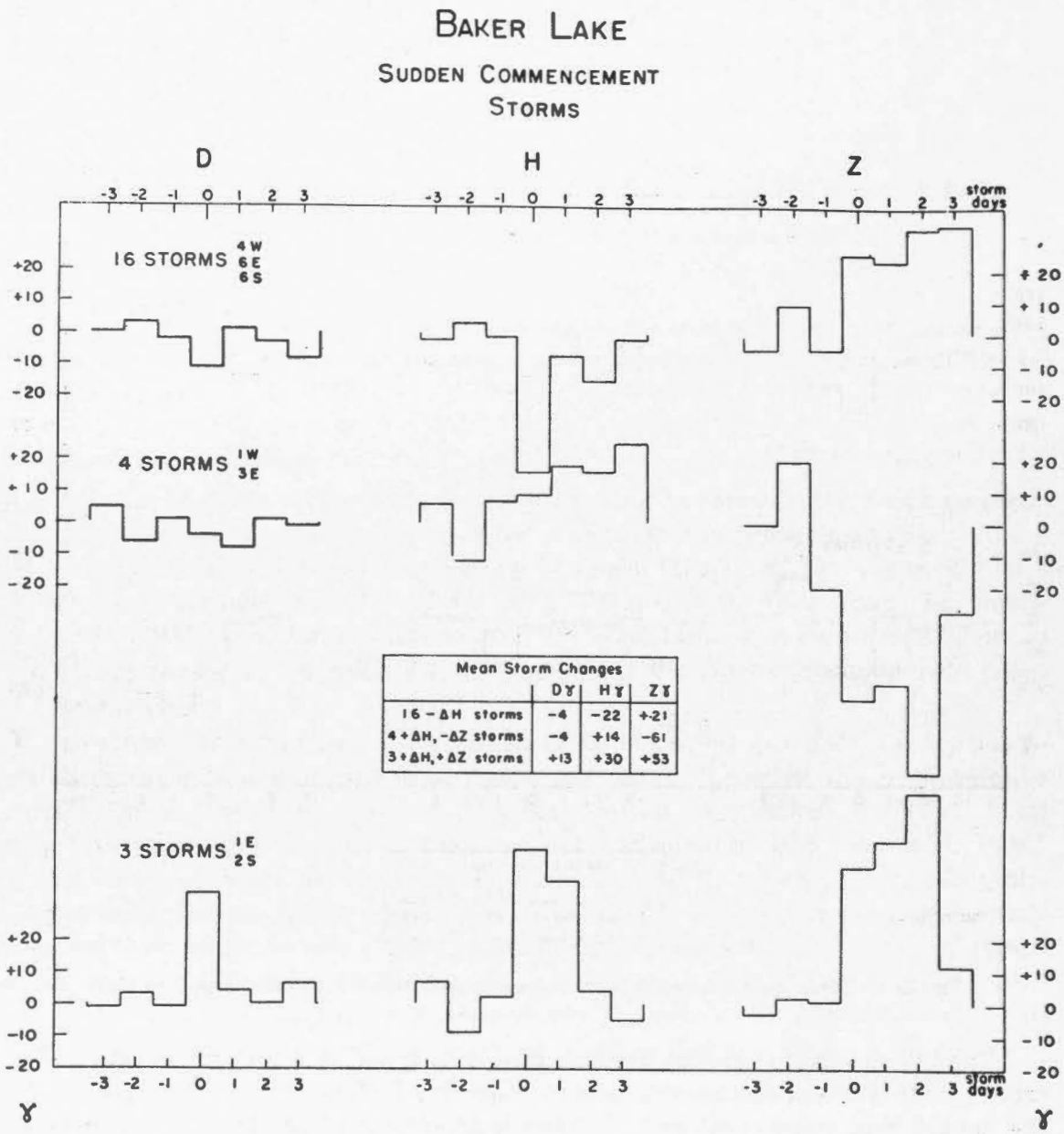


FIGURE 4. Mean storm changes for sudden commencement storms at Baker Lake, 1951-1955.

Lake, respectively. This type of storm occurs most frequently in the summer and equinoctial months. Neglecting the small and ill-defined horizontal components found at Resolute Bay for the summer type storms, it appears that these correspond to the + Δ H classes at Baker Lake. Two opposite systems of zonal current flow are required therefore to explain the character of averaged storm-time.

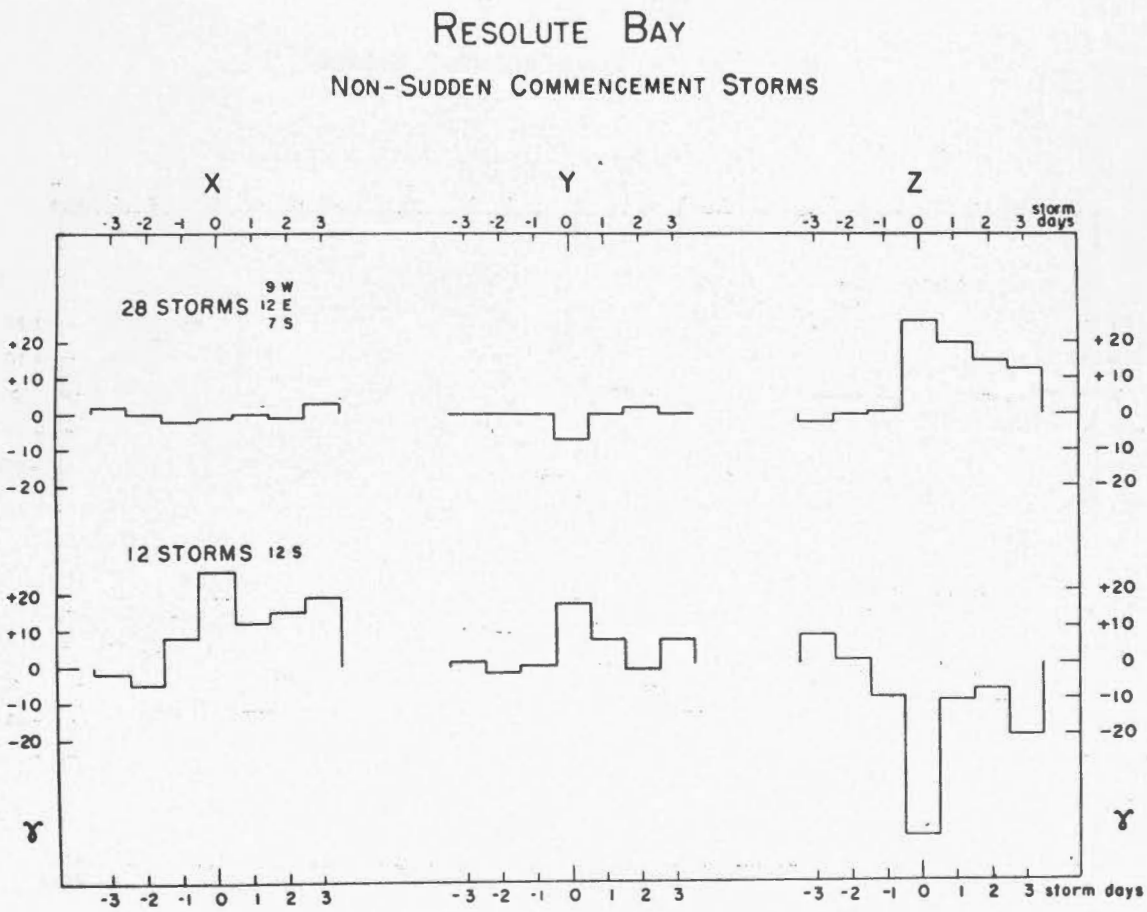
Since the number of S C storms measured which are common to both stations is only 4 and these belong to the different classes, it does not seem worthwhile examining their numerical implications. These are presumably the same as those discussed below in an account of the non-sudden commencement storms.

THE ANALYSIS OF NON-SUDDEN COMMENCEMENT STORMS

A total of 40 such storms were selected at Resolute Bay and 47 at Baker Lake in the intervals discussed. Many of these corresponded to stormy periods reported by the observers in the Journal of Geophysical Research, but in any case the magnetograms were searched individually. One only of the storms selected was reported elsewhere as a sudden commencement storm. In each case the onset was indefinite to the extent of about one hour as would be expected. It appears likely that the storms correspond to the polar equatorial storms of Birkeland (1908).

The Storm-Time Variation D_{st}

Newton and Milsom (1954) have discussed the characteristics of small storms of the non-S C type found in the Greenwich records, and compared them with S C type storms. Characteristic differences were noted, and it was suggested that the origin of these small



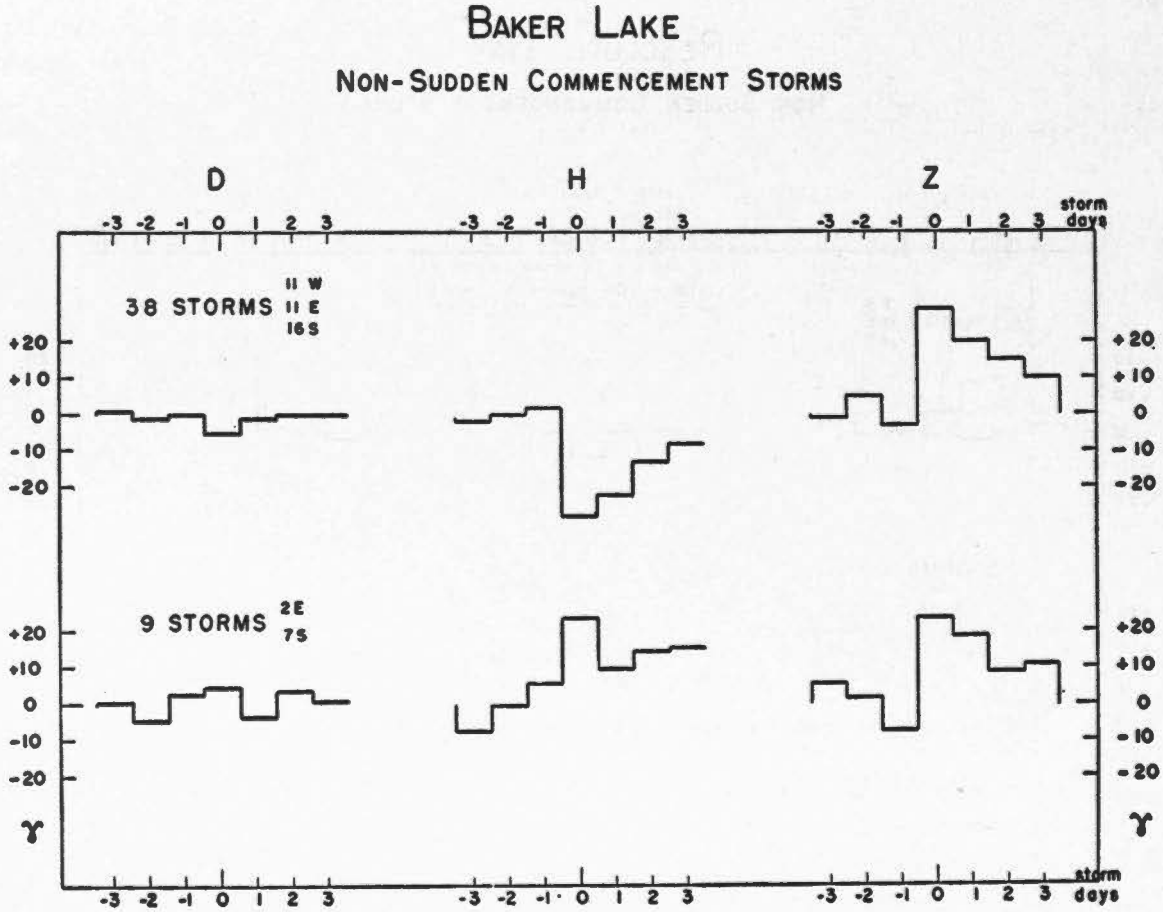
Mean Storm Changes	XT	YT	ZT
28 +ΔZ storms	-1	-2	+20
12 -ΔZ storms	+18	+8	-22

FIGURE 5. Mean storm changes for non-sudden commencement storms at Resolute Bay, 1953-1955.

storms might be in the corona. Non-S C storms at Greenwich also show 27 day recurrence characteristics, particularly near sunspot minimum, not shown by the S C storms, but do not show a storm-time variation.

The storms selected above were tested for storm-time effects using the superposed epoch method described above, and estimating the time of beginning of the storm day to the nearest hour. Such effects are very clear, and again two classes of winter type (+ Δ Z at Resolute Bay, − Δ H at Baker Lake) and summer type (− Δ Z at Resolute Bay, + Δ H at Baker Lake) storms are found. Figure 5 for Resolute Bay and Figure 6 for Baker Lake show the results, with the seasonal distribution and the mean storm changes defined as before, since no striking differences in the time constant of decay of the mean storm changes is apparent.

The mean azimuths determined from Baker Lake results are again between geographic and geomagnetic south for the − Δ H storms and north for the + Δ H storms.



Mean Storm Changes	Dγ	Hγ	Zγ
38 − ΔH storms	−2	−21	+21
9 + ΔH storms	+2	+16	+17

FIGURE 6. Mean storm changes for non-sudden commencement storms at Baker Lake, 1951-1955.

27-Day Recurrence Characteristics

The superposed epoch method has given results which suggest that there are no fundamental differences in storm-time between the S C and non-S C types of storm, although there do appear to be systematic differences in the ratio of horizontal to vertical field components and hence in the latitude of the effective atmospheric ring. The K-indices available from the two stations were used therefore to examine the recurrence characteristics of the two classes at both observatories. Since the K-indices are available until the end of March 1955 only, the results in Figures 7 and 8 do not apply to all the storms examined. The sum of K was subjected to a recurrence examination: it is considered that recurrence (a broad peak about 28 days after the onset of the storm) is shown for both classes of storms at Resolute Bay whereas the Baker Lake results are rather ambiguous. However irregular disturbance, bay-like events, pulsations, etc., which largely influence the K measure, persist several days longer for the S C storms than for the non-S C storms. It is concluded that residual disturbance does persist for a longer time in the case of S C storms, and this effect is believed to be real although it is the opposite to that previously accepted for moderate latitude stations (Newton and Milsom, 1954).

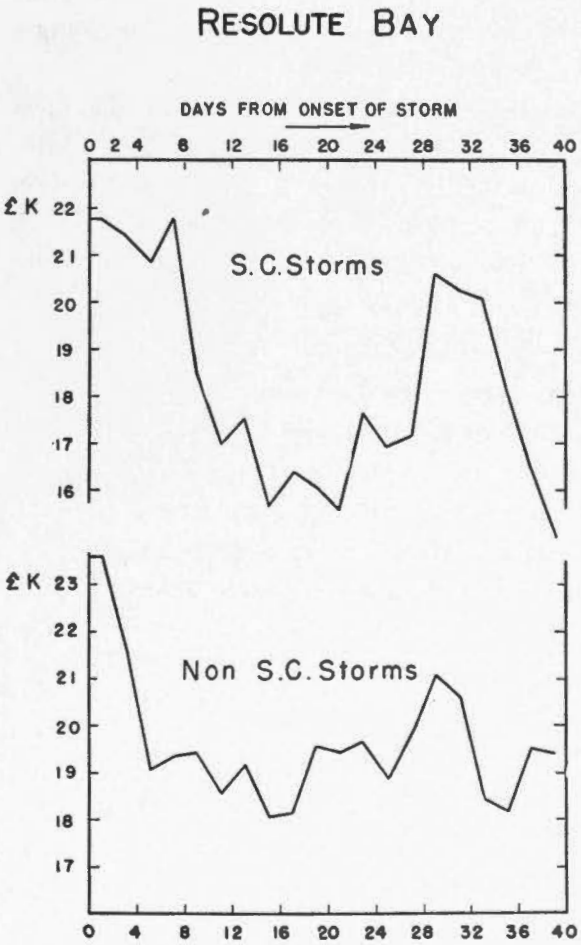


FIGURE 7. Recurrence of Σ K for non-sudden and sudden commencement storms at Resolute Bay.

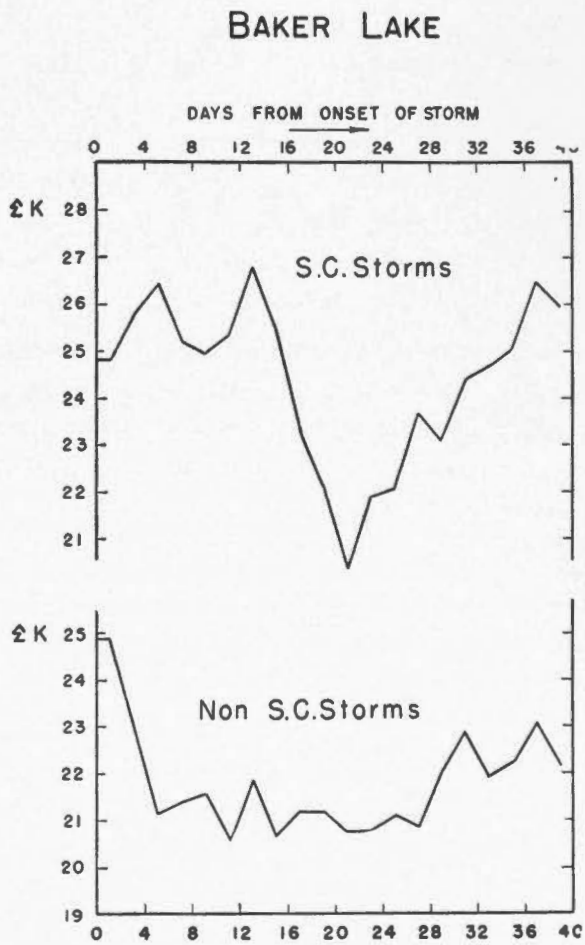


FIGURE 8. Recurrence of Σ K for non-sudden and sudden commencement storms at Baker Lake.

Since atmospheric current flow in high latitudes seems to provide the only reasonable explanation of highly differentiated storm-time patterns at high latitudes, and since such a current flow is commonly associated with an equatorial ring current, the suggestion follows that both S C and non-S C storms require the formation of an equatorial ring, but that the instabilities associated with the ring, producing bay-like and irregular disturbance, persist much longer than the zonal current flow, and possibly the ring itself in the case of the S C storms.

Alternatively if a completely atmospheric source is assumed for storms, and elementary polar disturbances are generated by wind action in the atmosphere (Vestine, 1954), the length of time that residual disturbance persists apparently requires entry of charged particles from the sun into the atmosphere at these latitudes for a longer period of time for S C type storms.

Non-Sudden Commencement Storms Common to Resolute Bay and Baker Lake

Eighteen storms were examined common to both observatories; 13 of these were of the winter type and the remaining 5, in the summer months, were of the opposite type. Table I shows the mean storm changes defined as before. The azimuths at both stations correspond closely to current flow along geomagnetic parallels of latitude. The changes were examined with the following results for the winter-type storms:

(1) if corrections for internal induction at both stations are made of the form $H_{obs.} = H_{ext.}(1 + \alpha)$ and $Z_{obs.} = Z_{ext.}(1 - \alpha)$ corresponding to a highly differentiated storm-time field at these latitudes and n in a P_n harmonic description assumed large, then a westerly current flow near geomagnetic latitude 71° is required at a height of 500 km. to obtain these results, and $\alpha = -0.5$ approximately. This sign would not be expected from the results at low latitude stations (Chapman and Price, 1930);

(2) alternatively, if a current at 100 km. in latitude 67° is assumed, then different corrections are required at the two stations: $\alpha = +0.68$ at Baker Lake and $\alpha = +0.87$ at Resolute Bay. However, an observed horizontal amplitude of more than twenty gammas would be expected at Resolute Bay and this is not observed. This model is therefore not very convincing.

STORM TYPE	Nº OF STORMS	RESOLUTE BAY			BAKER LAKE		
		X γ	Y γ	Z γ	D γ	H γ	Z γ
WINTER	13	-3	- 2	+26	- 1	-20	+28
SUMMER	5	+20	+19	-10	+ 5	+14	+26

TABLE I. Mean storm-time changes at Resolute Bay and Baker Lake for eighteen non-sudden commencement storms.

For the summer type storms the storm-time changes indicate an easterly current flow near latitude 81°N geomagnetic at a height of about 900 kms. with $\alpha = -0.3$ approximately.

It should be emphasized that there were no cases when a storm did not clearly fit into one of these two classes corresponding to westerly or reversed current flow, but occasionally storms do occur where the westerly flow at Baker Lake can move north of the station as the storm progresses.

Although it is obvious that the field of an equatorial ring current could not produce the $-\Delta Z$ changes found at Resolute Bay in the summer unless the ring is reversed, which is not reported at lower latitudes, it is instructive to compare the horizontal components found with those to be expected in the field of such a current ring for the winter type storms. The potential of a strictly linear circular current of radius R expressed in terms of spherical polar coordinates with respect to the earth's centre and axis is

$$2\pi i \sum_{n=0}^{n=\infty} (-1)^n \frac{1.3 \ldots\ldots (2n-1)}{2.4 \ldots\ldots 2n} \left(\frac{r}{R}\right)^{2n+1} P_{2n+1} (\cos \theta)$$

The principal term at low latitudes is that for $n = 0$, and the horizontal to vertical components ratio is $\frac{1+\beta}{1-2\beta} \cdot \tan \theta$, where the fraction β has its origin in sources internal to the earth and θ is the colatitude. We can immediately deduce that at Resolute Bay it is required that $\beta = 0.04$ and at Baker Lake $\beta = 0.24$, and the corrected perturbing vectors at the two stations are 24 gammas at Resolute Bay and 29 gammas at Baker Lake instead of being equal. Since Chapman and Price (1930) have shown that at low latitudes $\beta = 0.42$ effectively for $n = 0$ in the above expression, it is not very convincing evidence for an explanation of storm-time changes produced entirely by extra-atmospheric current flow, and more complex atmospheric zonal currents than those discussed above seem a more likely explanation.

Relation to Theories of Magnetic Storms

The relation of these findings to theories of magnetic storms is obscure. It appears at any rate that the incomplete corpuscular theory of Chapman and Ferraro (1931) and Martyn (1951) does not anticipate the summer-type storms. The possibility of a dynamo origin of magnetic disturbance generally, including the main phase and the D_{st} components of storms has been discussed in great detail by Vestine (1954) and Fukushima (1953). Vestine (1954) has discussed the difficulties regarding conductivity and the driving force of the wind systems. It seems worthwhile pointing out that in the summer months over the polar cap, appreciable changes in heat driven air circulation of the upper atmosphere might reasonably be expected though whether they would correspond to a reversal of the zonal and meridional flows deduced by Vestine (1954) for the main phase of what we would call a winter-type storm is not clear. Data from southern polar cap stations might provide an important check.

CHARACTERISTICS OF BAY DISTURBANCE

Bay occurrence is a very characteristic feature in the magnetograms from Resolute Bay and Baker Lake, being particularly evident nearer the auroral zone at Baker Lake.

It may be regarded as the elementary polar disturbances of Birkeland (1908) and shows a variety of pattern and form. Meek (1954) has examined the relationship between bays, visible aurora and ionospheric phenomena at Saskatoon and elsewhere, and other authors (Fukushima, 1953) have examined the form of the bay field during certain well defined bays using polar year data. A systematic study of the properties of bays north of the auroral zone has apparently not yet been made.

Selection and Measurement of Bays

The magnetograms on each of the days whose selection is described in the first part of this study were examined, and bay occurrence, duration and average amplitude noted. Since the change in time of particular appearances of the bay field has been previously studied (*see* for example, Fukushima 1953), this interesting aspect was not considered further. Instead the amplitude measured was an estimated mean for the entire duration of the bay.

Because of the complexity of the magnetic disturbance on the selected disturbed days and the high level of irregular disturbances at both observatories, it was found necessary to arbitrarily measure only those events with a duration exceeding one half hour and persisting less than two hours. Only those bay-like events were measured where the beginning and end of the disturbance could be determined: at times of irregular disturbance this condition becomes virtually the same as that of being definite in at least two components. Many bays are obviously double, but this complexity was ignored in the succeeding analysis. It is also possible to recognize certain differences in type of bays (e.g. those with a sharp and often pulsational beginning are common at Baker Lake) and seasonal differences in definition seem to be present, but a more complete classification must be deferred until a later publication. Occasionally bay-like events were noted in which rapid sign changes occur in the horizontal perturbing vector. These were particularly noticeable in certain polar cap records, and should be studied synoptically.

Characteristics of the Bays at Baker Lake

Since bays are much more evident nearer the auroral zone, it seems reasonable to discuss first the findings at Baker Lake. Figure 9 shows the diurnal distribution of bays for three seasons on the selected disturbed days and the diurnal variation during the year 1954 for all selected disturbed and quiet days in the year. The quiet day data represents the pattern expected from residual disturbance, and can therefore be neglected in this treatment. A pronounced peak at about 23:00 hrs. L.T. or 22:00 hrs. local geomagnetic time is apparent in all three seasons. This peak is not at all sharply defined, and has a half-width of between 4-h and 5-h in all seasons. Figure 9 also indicates the average number of bays per selected disturbed day, and a small equinoctial maximum is found. This requires that the total number of bays also reaches a maximum in the equinoxes. It is not clear if the minor peaks evident in Figure 9 are real.

Figure 10 shows the diurnal variation of the average bay amplitude in different seasons and in 1954 at Baker Lake, obtained by finding the average amplitude in each field component in three hourly intervals of the day. The curves are dashed where the

points are based on a total of fewer than five bays. From these curves it is simple to derive an equivalent line current which would produce such a D V in bay amplitude. This is discussed later.

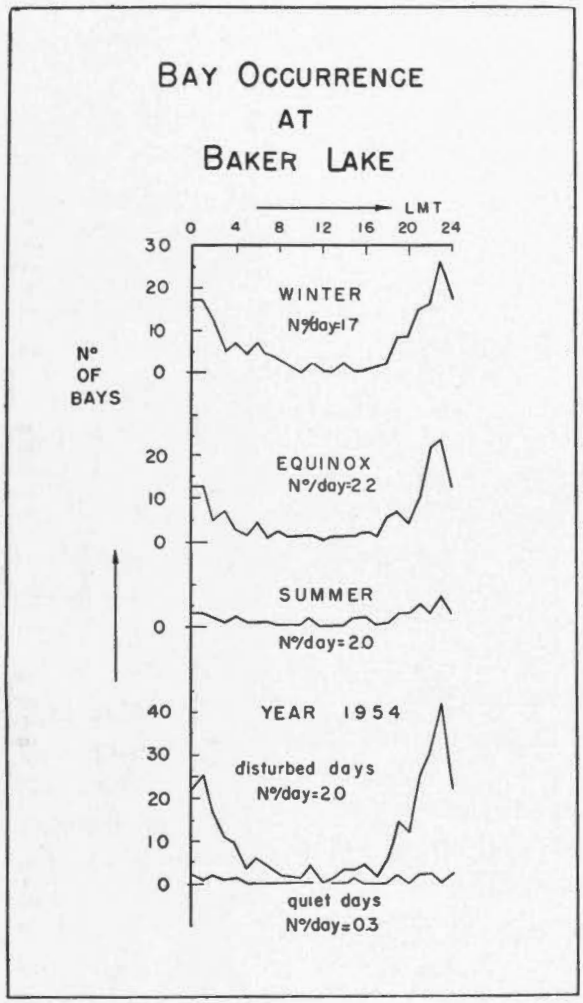


FIGURE 9. The diurnal frequency distribution of bays on local disturbed days at Baker Lake during three seasons.

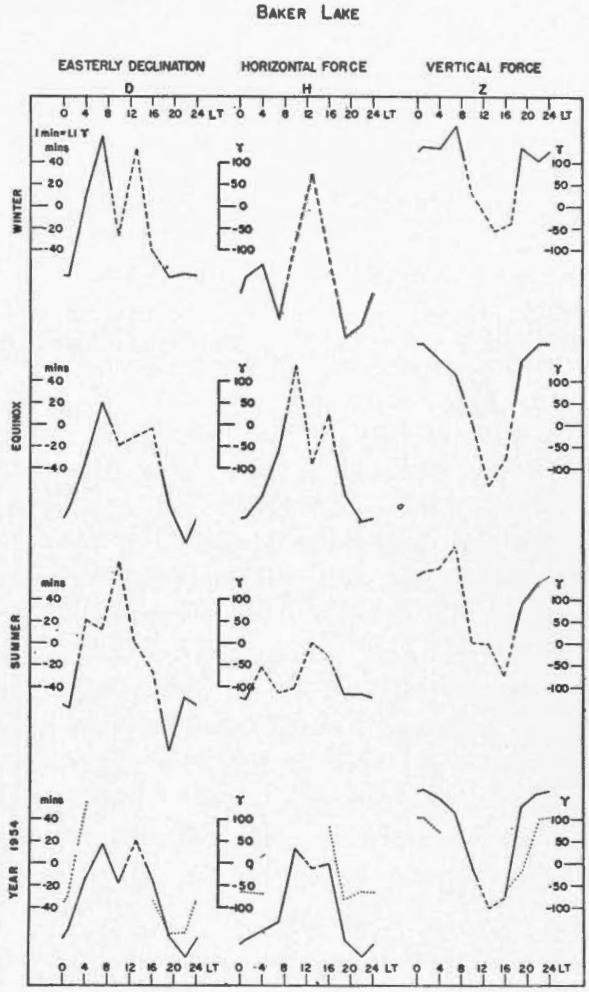


FIGURE 10. The diurnal variation in three force components of the average bay amplitude on the selected disturbed days during three seasons at Baker Lake. The dotted lines indicate the partially derived diurnal variation of the average bay amplitude on the selected quiet days during 1954.

Characteristics of the Bays at Resolute Bay

Figure 11 shows the D V in frequency of occurrence and Figure 12 the D V in the average bay amplitude at Resolute Bay. The data refers to the selected days at Resolute Bay described in Part I. The frequency of occurrence of well-defined bays on any day at Resolute Bay is almost one half that found at Baker Lake: this is true for all seasons, and on both the selected quiet and selected disturbed days. This suggests that half the bays identifiable to the north of the auroral zone can be seen over the polar cap. There are two peaks of occurrence, near 22:00 hrs. and 13:00 hrs. L.T. respectively; the night peak is predominant in the winter months and the midday one in the summer months, whilst they are about equal in the equinoxes. Both peaks are very broad

On the very quiet days discussed in Part I of this paper, only one very small bay at Baker Lake was found.

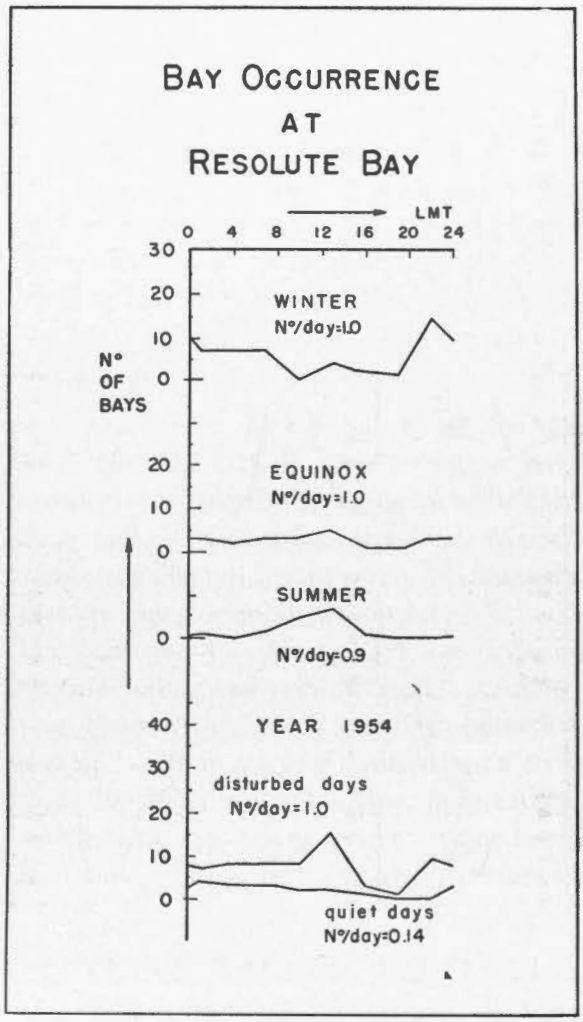


FIGURE 11. The diurnal frequency distribution of bays on local disturbed days at Resolute Bay during three seasons.

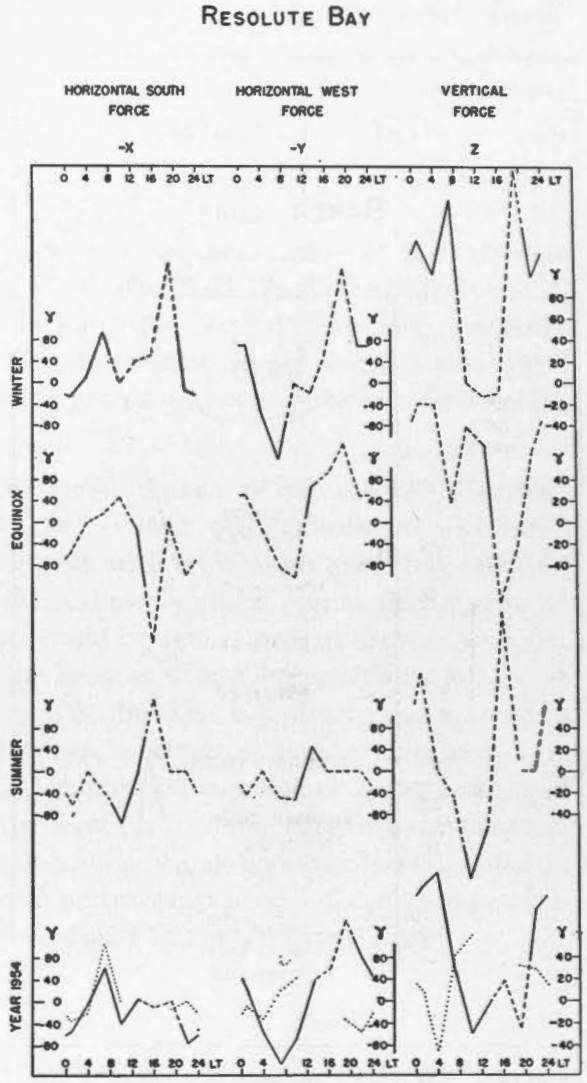


FIGURE 12. The diurnal variation in three force components of the average bay amplitude on the selected disturbed days during three seasons at Resolute Bay. The dotted lines indicate the partially derived diurnal variation of the average bay amplitude on the selected quiet days during 1954.

Duration of the Bays

At Resolute Bay the average duration of all bays on the selected disturbed days was 1.3 hours with insignificant seasonal differences: on the selected quiet days the average duration was 1.1 hours. It is not clear whether this difference is real and what its implication is in such a case, since the infrequent bays on quiet days have amplitudes comparable to the average amplitudes found on disturbed days for bays appearing at the same period of the day.

In deriving the bay field the approximation was made that all bays last equally long—about one and a quarter hours: this seems reasonable since no systematic DV in duration is apparent from the inspection of many magnetograms.

Relation to Irregular Disturbance

It is clear that a number of bays are not considered because of practical limitations and the background of low frequency magnetic noise on the magnetograms. At Baker Lake the very large amplitude pulsational noise frequently found on the magnetograms always appears in the interval local noon $\pm$ 6 hours, i.e. around the bay occurrence minimum. Because of the masking effect of this noise, it is possible that the evening peak in bay occurrence has been unintentionally emphasized. This is not, however, very likely since on days when no such masking noise is present, an evening peak in bay frequency is still pronounced. It seems possible that the noise bursts and bay activity are closely related, and can both be regarded as produced from peculiar instabilities in an equatorial ring. The relationship between them should be studied further. Irregular oscillations and noise bursts often begin abruptly and less frequently end abruptly. Relationship with daylight aurora is a possibility.

At Resolute Bay, well inside the polar cap, irregular oscillations occur less frequently and with smaller amplitudes: however they too appear in the interval local noon $\pm$ 6 hours. It should be emphasized that this aspect of disturbance is not a daylight zone phenomena. It occurs frequently in winter when both observatories are in darkness.

Large pulsations, usually very clear in vertical force, with amplitudes of a few tens of gammas and periods from 5 to 10 minutes were noted on occasion at both observatories. The regularity of these pulsations is pronounced in contrast to pulsational noise. It was noted that the abrupt start to well-defined pulsations can often be seen to take the form of a higher frequency pulsational burst, suggesting a possible local atmospheric resonant phenomenon. At Resolute Bay, during a great part of the total period under investigation the sensitivity of the Y variometer was several times larger than that of the X and Z variometers. It was then apparent that irregular pulsations of low amplitude are very commonly present. All periods from the shortest resolvable, 1 to 2 mins., up to a half hour or so are recorded at different times.

The 24-h Recurrence of Bays

This property of bays is very easily seen at even a casual inspection of Baker Lake magnetograms. At Resolute Bay it is less pronounced. Further detailed studies are required but a number of preliminary conclusions are possible:

(1) the recurrence interval can commonly vary by up to 2 hrs. from 24 hrs.,
(2) the average recurrence time of the bays is apparently nearer 23 hrs. than 24 hrs.,
(3) there is the suggestion at Baker Lake that bays occurring before local midnight have an average recurrence interval less than 24 hrs., whereas often, but not always, bays developing after local midnight recur later than 24 hrs.

This should be investigated further but suggests that if bay particles are ejected from equatorial ring instabilities, then an analysis of recurrence may throw some light on the drift motions of the instabilities. It should be emphasized that because of changes in form it is not always possible to measure the recurrence interval very exactly. At Resolute Bay where bay forms usually have less clear commencements, it is only possible to say that deviations from 24 hrs. occur and that the mean value is somewhat less than one day.

The Amplitude of Bays on the Selected Quiet Days

Although bays occur on the selected disturbed days about seven times more frequently than on the quiet days, it appears that the rather inaccurately determined D V in bay amplitude at Baker Lake is much the same on both types of days, see the dotted lines in Figure 10. At Resolute Bay (*see* Figure 12) the results are much more ambiguous, but so are the bays. It is suggested therefore that at least near the auroral zone, the average amplitude of a bay appearing at a given local time is much the same on local quiet and disturbed days. This result would perhaps not be expected, since most theories require a close relationship between bay amplitude and the disturbance daily variation. However, it is hoped to investigate this further at some later date.

The Relationship between Bays and Auroral Activity

Davies (1950) has discussed the diurnal occurrence of aurora across the auroral zone in Canada and concluded that auroral activity reaches a maximum about one hour before local midnight at the centre of the auroral zone, and appears to become progressively later with respect to local midnight south and north from the centre of the auroral zone. Towards the northern limit of the effective auroral zone, a diurnal maximum appears in both morning and evening hours: thus winter observations at Clyde (Φ = 81.5°N) showed maxima about 19:00 and 06:00 L.T. This morning maximum at 06:00 L.T. was observed at Chesterfield Inlet during the polar year 1932-33. The frequency of occurrence of radiation 3578 Å of the second positive system of nitrogen corresponds to that of bright and active auroral bands and rays and was found to have a maximum at about 23:00 L.T at Chesterfield Inlet. No secondary morning maximum of occurrence of this line was found by Currie and Edwards (1936). This maximum close to local midnight corresponds closely to the peak in bay occurrence shown in Figure 9. Visual observations at Baker Lake also confirm the presence of bright active aurora often covering a great part of the sky during bay occurrence, and so it seems quite possible that magnetic disturbance during bays is produced by the moving charged particles in the auroral forms.

The relationships of the changes observed in Figure 11 to auroral frequency at Resolute Bay is unknown. Daytime measurements on aurora by radio means during the summer months to discover the significance of the midday peak should be undertaken, if possible.

Positive and Negative Bay Occurrence at Baker Lake

The averaged data show that positive bays in Δ H are infrequent at Baker Lake. The diurnal frequency of occurrence of negative bays is therefore much the same as that shown in Figure 9, but positive bays occur throughout the day with a diffuse maximum near 16:00 L.T. which may not be significant. It should be noted that these results are different from those reported by Meek (1954) at Saskatoon. Figure 13 summarises the findings for more than 300 positive and negative bays examined in this analysis.

Comparison with Martyn's Theory of the Auroral Zone

Martyn's (1951) theory of aurora predicts an auroral zone of $\sim$5° latitude in width with auroral effects produced by precipitation, along magnetic lines of force, of positively and negatively charged particles from an equatorial ring about five earth's radii away.

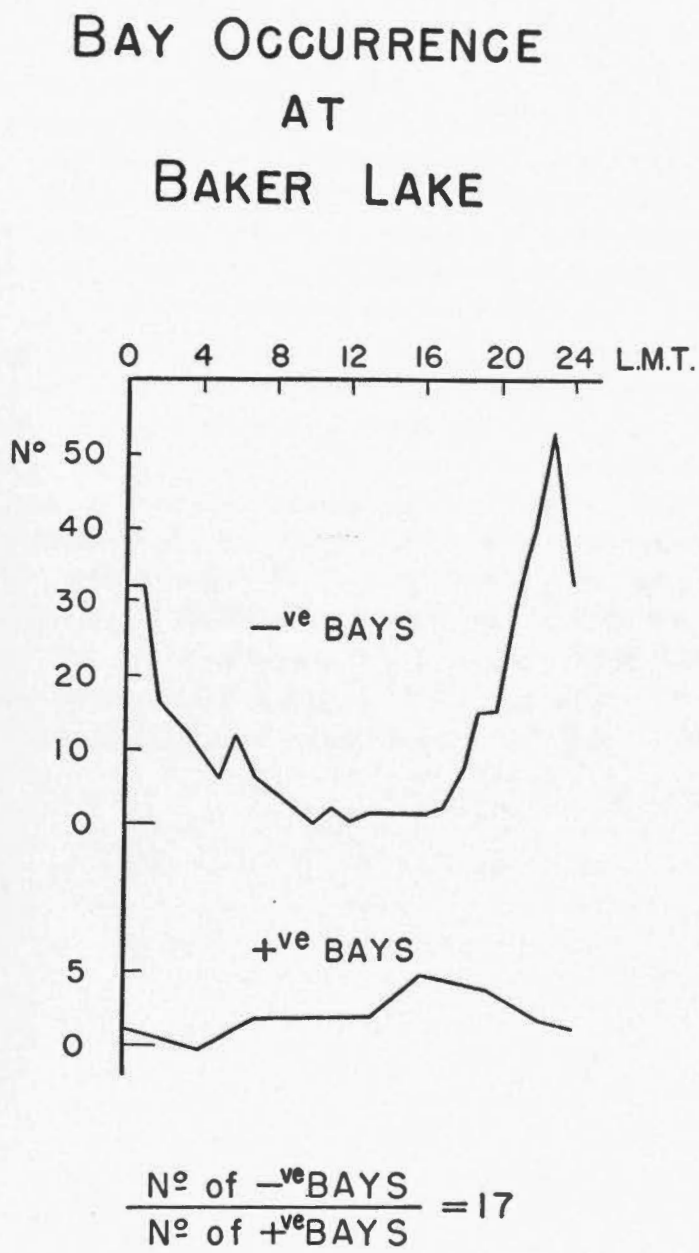


FIGURE 13. The diurnal frequency distribution of all positive and negative bays measured at Baker Lake.

In the early stages of disturbance during the afternoon and early evening, precipitation of positively charged particles occurs at the northern edge of the auroral zone and negatively charged particles at the southern. After midnight this situation is reversed, and in the final stages of disturbance the latter condition is thought to exist in both the morning and evening. Drift currents in which the positive ions drift faster than the negative are set up, and are thought to explain certain ionospheric and magnetic phenomena. The current system of bay disturbances is regarded as similar to that for the diurnal disturbance variation but advanced in phase 6 hours.

Thus it would be expected that during the early phase of a storm at a station like Baker Lake, negative bays ($-\Delta H$, $+\Delta Z$) would occur in the period from 6 p.m. to 6 a.m. and the positive bays ($+\Delta H$, $-\Delta Z$) in the period from 6 a.m. to 6 p.m. In the later main stages of a storm, negative bays should occur over 24 hrs. Figure 13 shows that during disturbed days no clear cross-over times are found, although positive bays are found mainly in the hours around noon and negative bays in the hours around midnight. The presence of negative bays at all hours, since they occur throughout the day in the main phase of disturbance, might be expected. It should also be noted that the total number of positive bays found at times not predicted above is small.

It is difficult to determine at a station like Baker Lake if positive bays develop during the early phase of a disturbance since disturbance is more or less continuous. Thus examination of the magnetograms at the times of positive bay occurrence suggests that such is not the case, but an examination of the international character figures for the days of positive bay occurrence show that most of them correspond to a local maximum in the C_i figure. Bay occurrence on quiet days, which it might be thought could be regarded as definitely referring to the very early stage of disturbance, revealed 21 negative bays (between 19:00 and 05:00 L.T.) and 1 positive bay (15:00 L.T.): these do not contradict the expectations of theory.

It was noted that the tendency of the small number of positive bays to appear in the equinoxes is striking, during the 17 months data used around sunspot minimum.

At the northern edge of the zone, negative changes in ΔZ should occur in the period 6 a.m. to 6 p.m. in the early phase of disturbance and should be associated with $+\Delta H$ changes. 29 cases only out of more than 300 bays have $-\Delta Z$ movements at Baker Lake; 17 of these occur in the predicted time interval but only 12 are associated with $+\Delta H$ changes. It is concluded that bay phenomena at Baker Lake are not very perfectly explained in terms of Martyn's theory.

At Resolute Bay the situation is more complex and the summer midday peak is associated with $-\Delta Z$ changes whilst before noon ΔX and ΔY are positive and after noon largely negative. This corresponds to current flowing easterly on the a.m. side and westerly on the p.m. side which is the reverse of idealized concepts of current flow producing the disturbance daily variation near the auroral zone. Furthermore the current system of the bay disturbances is effectively south of the station before noon and north in the afternoon hours. The data from the winter months which show a peak in frequency of occurrence before midnight correspond largely to $+\Delta Z$ changes and changes in the geomagnetic horizontal component to the south. This is what would be expected in the main phase of disturbance. The Resolute Bay bays occurring near noon in the summer months appear different in character from, and more diffuse than, the evening bays in the Baker Lake magnetograms, suggesting again that a different origin and explanation is required.

The suggestion of occurrence of a bay current system of limited size appearing inside the polar cap during the summer seasons is an important one. Its morphology appears in certain respects to be the opposite of that associated with the auroral zone, which suggests a relation with the reversed summer type of storm discussed above. The relation to the

inner zone of high magnetic disturbance suggested by Russian Arctic research is not clear (Anon., 1954), and it may be a reflection of an outer equatorial ring with reversed properties from the Martyn (1951) ring. Alfvén (1955) in a recent discussion of his electric field theory of magnetic storms and aurora has shown that if the inertia of the storm-producing beam is considered, a second ring current is produced which flows anticlockwise at about 30 earth radii and he assumes this to be an extra-atmospheric source of the initial phase (I P) of storms, associated with an inner auroral zone with a polar distance of 5°-10°. The theoretical duration of this I P is a few minutes only. Whitham and Loomer (1956) have shown that disturbance at Resolute Bay and Baker Lake is highly correlated in general and the results in Part I of this paper make it clear that there are no cyclic field changes at Resolute Bay analogous to those found at Baker Lake; these results suggest little support for the existence of an inner auroral zone magnetically. However, the anti-clockwise ring in Alfvén's theory exists together with the usual clockwise ring in the main phase of storms, and it is interesting to wonder if its properties are associated with the probably atmospheric zonal currents discussed above for summer-type storms. If this is the case, it should be possible to show that at lower latitudes the usual pattern is present and there might be interesting time differences apparent in the development of the two, and interesting relations between the magnitude of the two systems. It is hoped to pursue this point in a later publication. The seasonal nature of the reversed ring is difficult to understand on this hypothesis. Considering all the results in these papers it seems difficult to support the contention that observational data require the existence of an inner auroral zone, but obviously much more work is required.

Another possibility is that a real change occurs in the heat driven air circulation of the upper atmosphere as discussed earlier. This is required if a dynamo origin for the main phase of storms and bays is accepted. It is then reasonable that partial appearance in the equinoxes is possible, but not at all clear why two apparently reversed modes of zonal and meridional air circulation can exist with different frequency in different seasons.

The unusual features at Resolute Bay may be a consequence of the pronounced non-dipole properties of the earth's magnetic field in Canada. Thus the vertical force map of Canada suggests the presence of a large regional pole over the barren lands, and Resolute Bay is only about 100 miles from the dip pole of the earth's field. It seems likely that theories involving the interaction of the field with single incoming charged particles, or leakage down lines of force to the lower atmosphere, would produce unique observational aspects at the Canadian Arctic observatories. Against this viewpoint is the experimental result of surprisingly good geomagnetic control in much of the data discussed. One obvious need is a similar discussion for the Antarctic.

Relation of the Bay Field to the Disturbance Daily Variation

Figures 10 and 12 show the diurnal variation in bay amplitude, independent of the probability of appearance of a bay in any interval. These curves show striking similarities with the disturbance daily variation curves discussed in the previous paper: however, agreement in form is not very good for the horizontal component at Baker Lake and the vertical component at Resolute Bay. Fukushima (1953) in an examination of the equivalent current systems of the field of elementary polar disturbances has arrived at two

groups, one of which corresponds to the equivalent current system of the average disturbance daily variation field, or of the average bay field, and one in which marked differences occur because of a predominant westward auroral zone flow. The simplest pattern is thought to be similar to the electric current system on a conducting spherical surface caused by an electric doublet situated on the auroral zone and directed westward. Bays are thus considered to be a temporary appearance of a polar magnetic storm within a short duration of time.

The analysis considered here supports the idea that the bay field represents a temporary appearance of a systematic disturbance field, similar to, but not identical with, that of the disturbance daily variation. It would also suggest that the presence of a current ring is a necessary condition for the appearance of bays. To search for the presence of D_{st} in the field for a few hours before a bay occurs is very difficult at Baker Lake since the reference value for the month in any component is so uncertain. It is thought that at the present time such a determination is not possible. However, at Resolute Bay where the magnetic conditions are less disturbed, a test of this sort using the Z component was attempted with inconclusive results. Once again the correct reference values to use are difficult to determine.

Relation to Polar Blackouts

Wells (1947) has discussed the relation between individual bays and radio blackouts at College, Alaska, and explained the latter by the development of intense ionization in the ionosphere below the normal E layer, produced directly or indirectly by the incoming charged particles. Cox and Davies (1954) have published statistical studies on blackouts recorded at ionosphere stations in Canada, including Baker Lake and Resolute Bay, over the period 1949-1952. The DV in frequency shows a well-defined maximum near 11:00 L.T. at Baker Lake and two maxima near 06:00 hrs. and 13:00 hrs. L.T. at Resolute Bay. More blackouts are observed at Resolute Bay (500/year) than at Baker Lake (250/year). Considering their evidence with the bay analysis presented above, it is by no means clear that the direct relationship reported by Wells (1947) can be said to be evident, and a direct examination of the radio data might be of help in considering the classification of bays.

It should be noted that the times of maximum K index at the two stations are 09-12 hrs. 90°W meridian time at Baker Lake and 12-15 hrs. at Resolute Bay in agreement with the times of maxima found by Cox and Davies (1954). However by the geomagnetic latitude of Meanook ($\Phi = 61.8°$) even this agreement disappears.

THE GEOMAGNETIC POST-PERTURBATION

The monthly mean values of the geomagnetic field undergo changes due to the variation of average disturbance with season and the effect of disturbance on the daily means. One convenient measure of this effect is provided by the average D_m field defined by the mean daily values for disturbed days minus those for quiet days. Second order errors produced by secular change and base-line errors are unimportant. The annual variation can then be regarded as produced by this averaged field appearing in different months

with different frequency and intensity. The seasonal variation in disturbance at Baker Lake and Resolute Bay is discussed in Part I of this paper.

The annual variation in 1954 is shown in Figure 14 together with estimates of the secular change rate in that year. Figure 14 also shows the monthly variation in the D_m field derived for each month using the selected quiet days and disturbed days discussed in Part I. It is clear that partial appearance of this field in different months can explain the main features observed in the annual variation. The Z component shows the largest annual variation and also the greatest variation from month to month in the D_m field.

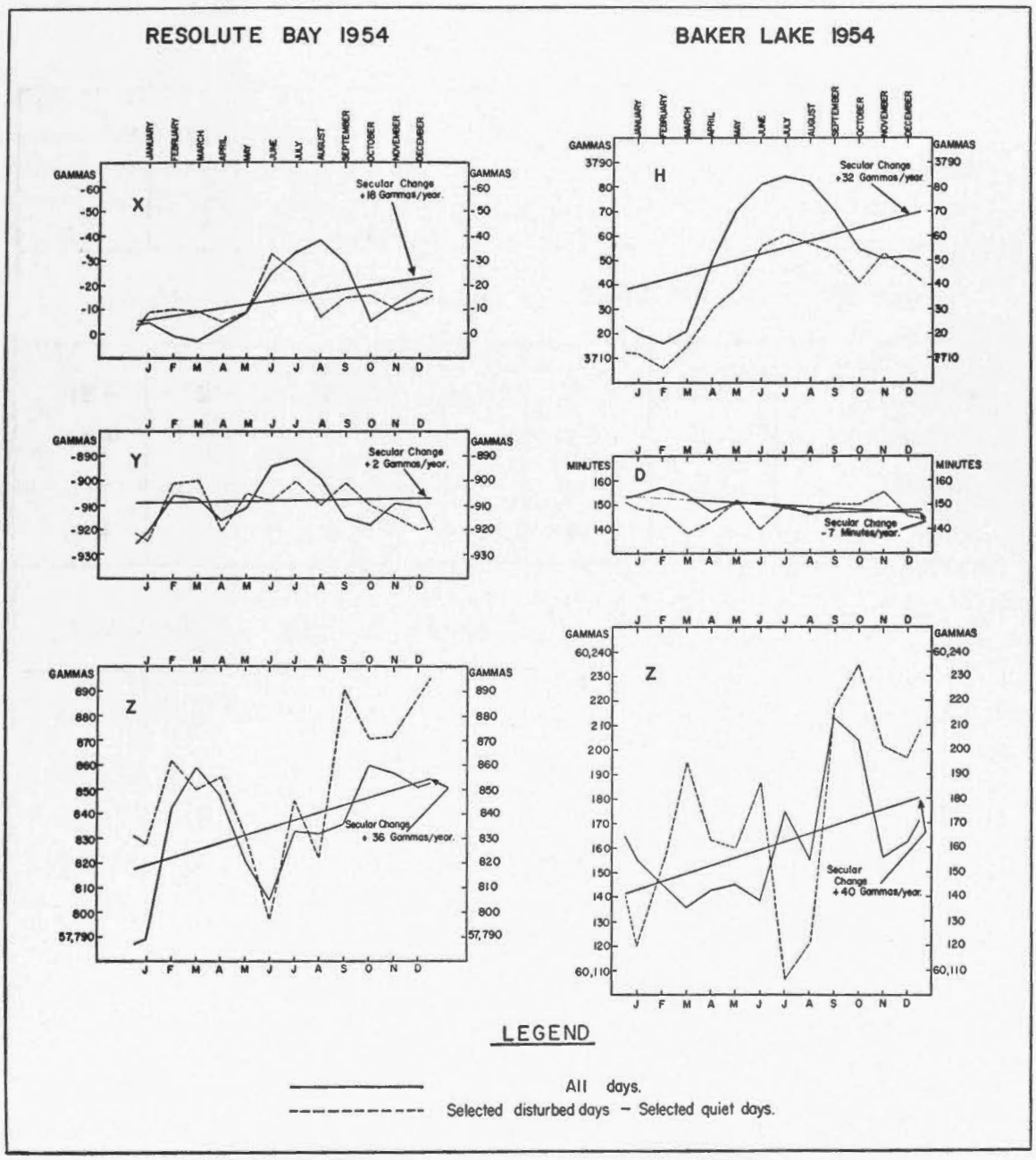


FIGURE 14. The annual variation in 1954 at Resolute Bay and Baker Lake: all day means and selected disturbed minus selected quiet means are shown. The ordinates of X Resolute Bay are shown reversed in the figure in error.

In view of the studies which have been made using the relatively easily computed D_m field values, it is of interest to consider the contributions of the different phenomena described previously to the measured D_m values. Table II shows the seasonal value of the D_m field to the nearest gamma, over 17 months in 1953-55, and the value for the year 1954; since the number of disturbed days/month varies in the selection made in Part I the monthly values were weighted according to the number of selected days/month in this determination of field components. This is thought to give the purest form of D_m variation but the results were not substantially different with each month assigned equal weight. Also shown is an estimate of the influence of the bays measured and defined as described earlier.

SEASON	BAKER LAKE			RESOLUTE BAY		
	D γ	H γ	Z γ	X γ	Y γ	Z γ
D_m = SELECTED DISTURBED − SELECTED QUIET DAY MEANS						
WINTER	−2	−28	+18	−6	−2	+31
EQUINOX	−5	−23	+46	−3	+3	+31
SUMMER	−3	+1	−40	+2	+3	−1
YEAR 1954	−3	−18	+14	0	0	+21
ESTIMATED CONTRIBUTION OF SELECTED BAY DISTURBANCE						
WINTER	−4	−20	+11	−1	0	+5
EQUINOX	−10	−21	+18	+1	−1	+3
SUMMER	−5	−11	+12	+2	0	−2
YEAR 1954	−7	−18	+14	+1	0	+2

TABLE II. Seasonal values of D_m field and estimated contributions from the bay field at Resolute Bay and Baker Lake.

At both observatories it is clear from Table II that this measure represents largely the average effect of bays; the residual part of the D_m components must correspond to the averaged effect of storm-time and irregular variations. The only serious discrepancy occurs in Z Baker Lake where the influence of bays is of opposite sign to the D_m field recorded; when zonal terms corresponding to the average pattern of summer-type storms (*see* Figure 6) are added, the discrepancy is increased. This may mean that the residual

effects of the summer-type storms on average disturbed days correspond to easterly flow south of Baker Lake (whereas the concentration is usually to the north during the first few days of a storm). This seems unlikely both numerically and in view of the time constant of decay of the order of one day discussed earlier. Alternatively it appears that the average effect of irregular disturbance during the summer months is largely to depress the Z field component, a surprising result. At Resolute Bay, the influence of measurable bays is much smaller and we conclude that the D_m field is effectively a description of the averaged zonal terms described earlier.

In any case the magnitude of the difficulties in reducing field observations to a satisfactory epochal value is clear, and the authors suggest that the only reliable secular variation data is that obtained from observatories operating continuously, and programs of repeat observations at infrequent intervals over short durations are of doubtful use. The magnitude of the seasonal changes is such that the determination of 11-year cycles in secular variation near the auroral zone should be quite feasible. There are certain suggestions of this (Barta, 1956).

NON-CYCLIC CHANGES

In the harmonic analysis of the selected groups of days described in Part I, the non-cyclic changes were removed mathematically, assuming a linear variation with time to be a good physical approximation. Because of irregular disturbance, not completely removed in the use of hourly mean values, it is not certain how regular such changes are. For the three classes of selected days at Baker Lake, Table III shows the results of an analysis of non-cyclic changes in the Z component for three seasons. The storm-time analysis showed that the main phase of storms usually results in a Z enhancement at Baker Lake: therefore on disturbed days on the average one might expect a positive or zero non-cyclic variation and on quiet days a negative variation on the average. Such simple results are not found in the selection made, except in so far as the non-cyclic change on disturbed days is always smaller than on quiet days, and the equinoctial results do show the predicted pattern.

SEASON	DISTURBED DAYS	QUIET DAYS	VERY QUIET DAYS
WINTER	−0.2 γ	+6.8 γ	+5.6 γ
EQUINOX	+2.7 γ	−5.6 γ	−8.0 γ
SUMMER	−1.9 γ	+5.6 γ	(NO DAYS)

TABLE III. Non-Cyclic changes in Z, Baker Lake 1954, for three selected classes of days.

There is a suggestion therefore that because of the influence of bays and irregular variation, the corrections introduced in Part I are not always physically plausible. However, it is apparent from Table III that the corrections introduced to the sine components do not exceed 2 to 3 gammas on the average in even the first harmonic, and the final statistical uncertainties exceed this. This investigation suggests that the practice of publishing calculated non-cyclic changes may be worthless for high latitude stations.

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A SEISMIC INVESTIGATION OF MINE "BUMPS" IN THE CROWSNEST PASS COAL FIELD

BY

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A Seismic Investigation of Mine "Bumps" in the Crowsnest Pass Coal Field

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ABSTRACT

In September, 1953, seismographs were installed in the Crowsnest Pass area of Alberta and British Columbia to study the 'bumps' which were occurring in the coal mines at Fernie and Coleman, and to investigate the possibility that they might be related to minor earthquakes in the area. During the initial phase of the work, three seismographs were operated at widely separated stations, two in the region of coal mines at Coal Creek and Coleman and one at Turner Valley, distant from any mining operations. Some earthquakes were recorded at all three stations and, in addition, many small disturbances were recorded by the seismographs located near the mines, especially by the instrument at Coal Creek. A closer network of radio-linked seismographs was then installed near Fernie, the records of which definitely established that the small disturbances were occurring in the mine workings, both active and inactive. No relationship was established between bumps and local earthquakes in the area.

This work was initiated as a co-operative effort with the Fuels Division of the Mines Branch, Department of Mines and Technical Surveys, which has undertaken a study into the phenomena of ground stress relief in underground mine workings.

* * *

Introduction

DEVELOPMENT of coal fields near the southern border of Alberta and British Columbia began around 1900, and there is evidence, as early as 1906, that the mines in the Fernie area of British Columbia were troubled by 'bumps'. This is a term used to describe underground disturbances in coal mines analagous to the 'rockbursts' associated with hard-rock mining in northern Ontario. The bumps are characterized by violent explosive activity of the walls, floors, or roofs of mine roadways, and project great quantities of broken rock and coal into such passageways. Another form of violent stress relief, called an 'outburst of gas and coal', expels large quantities of coal from the solid seam and is usually accompanied by the liberation of huge volumes of gas. In these latter disturbances the roof and floor rocks are seldom damaged. In this report the term 'bump' will be used to describe a disturbance known, either from seismic evidence or from direct observation, to have occurred in a mine. The term 'earthquake' will be used to describe a disturbance known to have originated at some distance from a mine, and until they are classified all disturbances will be called 'events'.

As part of their general study into the phenomena of ground stress relief, the Fuels Division of the Mines Branch, Department of Mines and Technical Surveys, has devoted considerable attention to the problem of mine bumps.

Obviously it would be desirable to know whether the bumps are the direct result of mining operations and always occur within the mine tunnels, or whether, as a result of large-scale regional geological activity in the past, there are residual stresses in the rock, the energy of which is released by the mining operations. The Fuels Division was also interested in the possibility that currently active geological activity is a contributing factor. It appeared probable that, if such stresses were present, there should be minor earthquakes occurring throughout the area; otherwise disturbances might be expected to be confined to the mine workings and their immediately adjacent areas. In order to investigate the problem, the Seismological Division of the Dominion Observatory was asked to set up seismographic stations in the area.

A network of three seismograph stations was installed in September, 1953, two located over active mine workings at Coal Creek and Coleman, and one at Turner Valley, some distance from the mountains and from mining operations. While the results of this initial investigation were not as informative as had been anticipated, nevertheless they did indicate that a few earthquakes occurred in the area of the stations, that there was little local activity recorded at the Turner Valley station, but that there was a great deal of local activity recorded at both the Coal Creek and Coleman stations. Since the local disturbances recorded at Coal Creek and at Coleman did not in any case register at both stations at the same time they were interpreted as being due to bumps related directly to the mining operations going on at one particular station. Unfortunately, since each disturbance was recorded at only one station, its precise location could not be determined, and further not one of the recorded disturbances was noticed by the miners. This lack of positive results led to the termination of the initial project in June, 1955, and the setting up of a more detailed investigation.

The second project, carried out during the summer of 1955, made use of a set of radio-linked seismographs, arranged to form a triangle in the immediate vicinity of the mine workings. These were installed at the Coal Creek mines near Fernie and, for a short period, in the Coleman area, and while the results indicated that no precise location could be determined for the source of recorded disturbances, it was

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reasonably certain that some of them originated within the mine workings. At the same time, the seismograph at Turner Valley was moved to Banff, a location free of background noise, thus permitting the instrument to be operated at full sensitivity. The recordings at the Banff station have confirmed that there are some earthquakes having their origins in this general area.

It should be noted that this project does not represent the first use of a seismograph to study mine disturbances. In the early 1930's, F. Napier Denison, of the Victoria Meteorological Observatory, operated a Milne seismograph at the Fernie mines. No report is available concerning this work, but considering the low magnification and the long period of the Milne seismograph, it is probable that few, if any, bumps were recorded.

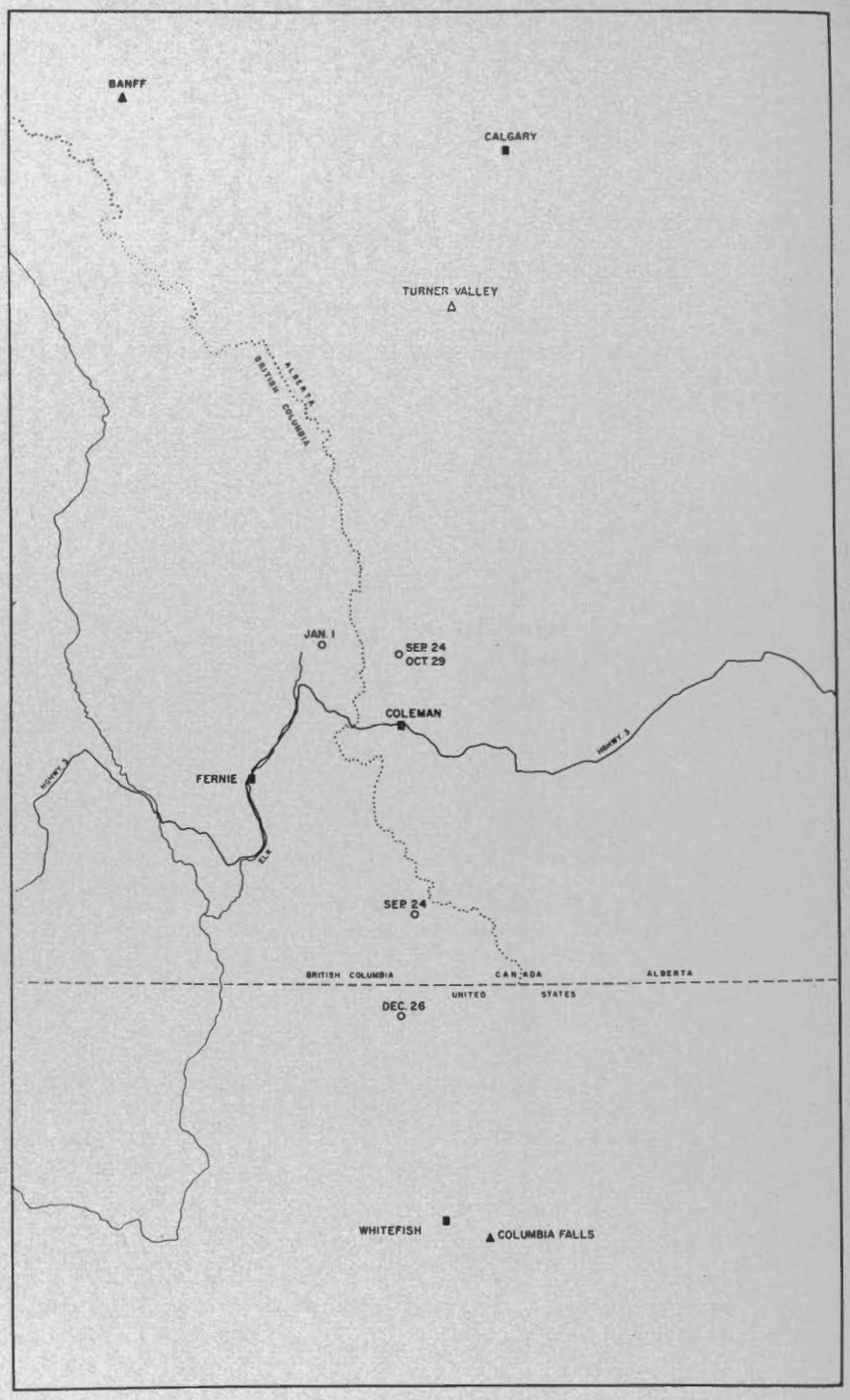

Figure 1.—Seismograph stations, and earthquakes located during initial programme.

Seismological Methods

This section will explain some of the terms of seismology used within this report. The record of a disturbance registered on a seismogram is much the same, whether the source of the disturbance in the earth is an earthquake, a blast, or a bump. At the time the event occurs, a compression wave and a shear wave are set up in the adjacent rock, and each is transmitted outward from the source in all directions. The former travels with about twice the speed of the latter and is called the *P* or compression wave. The slower wave is called the *S* or shear wave. Normally, both are recorded clearly and the difference in their arrival times can be read from the seismogram. If the speed of each type of wave is known, it is then possible to calculate the distance of the recording seismic station from the source. This method of obtaining distance from one record alone is called the *S minus P* method, or more simply, *S-P*. If one has an *S-P* distance of each of three seismograph stations from the centre of a common disturbance, it is possible to determine the location of the centre graphically on a map.

The *P*-wave arrives first at the station and hence usually appears as a sharp beginning on a quiet record, whereas the *S*-wave arrives at a time when the record is disturbed by the train of *P*-waves. Thus the time of beginning of the *P*-wave can be read more accurately. For this reason the *S-P* method of obtaining an origin is not used as much as are methods using the *P*-wave only, but in each case where an origin is determined from the *P*-wave arrival times at several seismographic stations, it is customary to compute *S-P* distances as well, to assure that no gross error has been made. The exact centre of a seismic disturbance within the earth is known as the 'focus'. Focal depth is the distance of the focus beneath the surface — in this investigation the focal depth has been assumed to be very small or zero. The 'epicentre' is the position on the earth's surface directly above the focus. The epicentral distance of a seismograph station is the distance from the epicentre to that station.

Initial Study of the General Area

Seismograph stations at Coal Creek and at Coleman, in the mining area, and at Turner Valley, east of the Rocky Mountain range, made up the initial network. Figure 1 shows a map of the area. Each station was equipped with a Willmore seismograph, made up of a Willmore vertical seismometer ($T_s = 1$ sec.) recording through a galvanometer with a period of 0.25 seconds. This equipment, shown in Figures 2 and 3, has the great advantage that it does not require a vault for its operation.

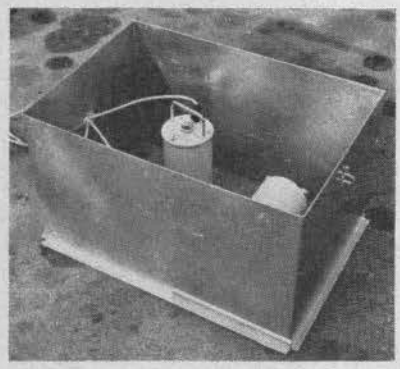

Figure 2.—Willmore-Watt seimometers in metal case.

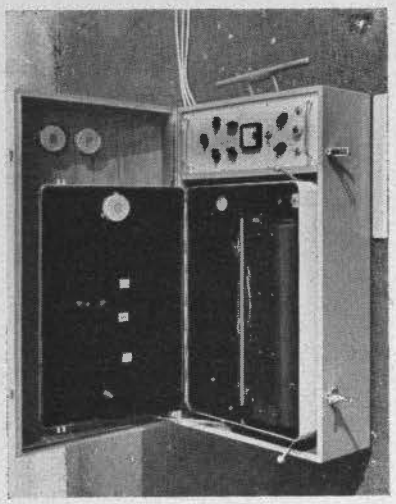

Figure 3.—Willmore-Watt 3-component recorder

The recorder can be installed in an ordinary room which need not be darkened. The seismometer can be buried in the ground in a waterproof metal container. For the three stations of this network, however, the instrument was set on bedrock and no special precautions were considered necessary.

At Coleman the seismometer was set on bed-rock a few hundred feet from the entrance to the McGillivray mine. About 700 feet of cable was used to carry the seismic signal to the basement of the mine office, where the recorder was installed. The recorder was operated with the paper speed set at 53.4 mm. per minute, and the records were changed daily. A chronometer was used to insert minute-marks on the record. At the beginning, no radio time-signals were available at Coleman but later radio station *CJOC* in Lethbridge agreed to broadcast the daily *CBC* time-signal at 18 hours *GMT* and these were recorded. In 1954 the *CBC* installed a booster station at Blairmore, only a few miles from the seismograph site, and from then on their signals were used. Noise from mining operations at Coleman necessitated operation of the instruments at approximately one-third full sensitivity.

At Coal Creek, the seismometer was placed on bed-rock about 900 feet from the recorder, located in the lamp-house at the mine office. The recorder was operated at a paper speed of 13.5 mm. per minute, and records were changed every four days. Time-signals were received here only about 25 per cent of the time, due to the high level of local static on the radio. Again, the sensitivity control was set at one-tenth or one-third maximum due to mine noise. Unfortunately, a conveyor belt, operating during two of the three shifts the mine worked, ran past the seismometer and disturbed the records greatly.

The processing of photographic records for both Coleman and Fernie was carried out in an office maintained by the Mines Branch at Coleman.

Seismic records were obtained for about a year at Turner Valley under fairly quiet background conditions. The recorder was installed in the basement of the operator's house and the seismometer was set on a nearby outcrop of rock. Later, the house was moved, necessitating the transfer of the recorder to another basement nearby. Unfortunately, chronometer troubles combined with lack of radio time-signals interfered with the accuracy of time-control for much of the time. However, a fairly continuous record of ground movement was obtained over the period of a year, and it appears that no local earthquakes occurred in the Turner Valley area during that time.

Events recorded on the network seem to fall into two groups. The first group have a fairly large *S-P* interval, and are thus events that occurred a considerable distance from the recording station. The second group have an *S-P* interval so small that the events must have occurred very near to the seismograph stations. Disturbances of the first group are regarded as earthquakes, although there is no report of any of them having been felt.

Table I.—Earthquakes Recorded at Coleman Fernie, Sept. 1953 to June 1955

Date	Time (G.M.T.) h.	m.	Remarks
1953 November 28	23	57	Coleman distance 125 miles, Fernie distance 116 miles.
December 10	09	14	Coleman distance 159 miles.
December 25	17	15	Approximately 44 miles (probably south) from Coleman
December 26	15	18	Coleman distance 54 miles, Fernie distance 49 miles, Hungry Horse distance 44 miles. Epicentre is 114°.5 W, 48°.9 N; about 10 miles south of the Canada-United States border.
1954 January 1	06	11	A small tremor (or bump) within 5 miles of Coleman.
September 9	18	07	Distance about 136 miles from Coleman. This was not recorded at Hungry Horse, hence the epicentre must be west or north of Coleman.
September 10	20	50	Approximately 25 miles from Coleman.
September 24	07	30	Hungry Horse and Coleman data indicate an origin 20 miles north of Coleman.
September 24	23	02	Hungry Horse and Coleman data indicate an origin south of Coleman near the border.
September 26	19	16	Probably close to Fernie. Recorded at Hungry Horse and Coleman.
1954 October 29	05	22	Epicentre about 19 miles north of Coleman, from Hungry Horse data.
November 4	21	38	Fernie and Coleman readings indicate an origin north of Coleman.
November 20	22	19	Distance 12 miles north of Coleman.
November 29	23	33	Approximately 10 miles from Coleman.
1955 January 1	21	19	Epicentre northwest of Coleman 20-30 miles.

From September 1953 to June 1955, a total of sixteen events were recorded at Fernie and Coleman which are, by the above definition, earthquakes. Table I lists these disturbances, and their epicentral distances, computed by the *S-P* method. The travel-time curves used to obtain the distances are those computed by J. H. Hodgson (1) in his study of the Canadian Shield. In those cases where readings from the United States Coast and Geodetic Survey station at Hungry Horse were available, epicentres were determined and are shown in Figure 1.

Events belonging to the second group were much more numerous, although they were confined entirely to the Fernie and Coleman stations. There is no case of an event local to one station being recorded at another, indicating that these disturbances must have been very small. No attempt is made here to list all such small shocks for the whole period, but Table II contains the list for a typical interval. The mine offices attempted to keep a record of bumps felt underground and these lists were compared with the list of recorded events. As indicated in Table I, local events recorded by the seismograph were not felt, and those felt and reported were not normally recorded by the seismograph.

A severe outburst of gas and coal occurred at the Elk River mines, Fernie, on March 9th, 1955, causing the collapse of the walls of a tunnel where miners were working, and resulting in casualties. During the four-day period covering the time of the bump, the Fernie seismograms recorded a total of seventeen very sharp events. In addition, two very weak disturbances were recorded at the time the bump was reported to be felt. Coleman seismograms show no trace of any of these events. This incident strengthened the previous conviction that the events the miners feel are usually not recorded, and that the numerous very sharp events the seismograms record are usually not felt in the workings.

Since the spacing of the stations made the determination of the centre of small disturbances impossible, it was decided to move the stations so as to form a small triangle over one mine, and thus to concentrate on finding the source of such events. In June 1955, the initial programme was terminated in favour of a detailed two-month investigation. One conclusion drawn from the initial programme is that there are a few, but not many, small local earthquakes in the area of the Rocky Mountain range. It is not possible to state definitely whether they are sufficient in number and size to indicate the existence of stresses that may be an indirect cause of bumps.

TABLE II.—TYPICAL SERIES OF EVENTS RECORDED BY FERNIE AND COLEMAN SEISMOGRAPHS, WITH MINING COMPANY RECORDS OF BUMPS REPORTED TO BE FELT DURING THE SAME INTERVAL

Date	Location	Time	M.S.T.	Remarks
1954		h.	m.	
September 17	Coleman	20	14	Small bump recorded
20	Coleman	15	25	Medium bump recorded
21	Coleman	12	00	Sharp bump felt. Not recorded.
23	Coleman	12:00	13:00	Small bump felt. Not recorded.
24	Coleman	01	11	Small bump recorded
24	Coleman	13	24	Medium bump recorded
25	Fernie	05	50	Small bump recorded
26	Fernie	07	30	Small bump recorded
26	Fernie	19	06	Small bump recorded
26	Fernie	19	28	Small bump recorded
27	Coleman	00	48	Small bump recorded
28	Fernie	13	20	Small bump recorded
28	Fernie	13	40	Small bump recorded
28	Fernie	15	05	Small bump recorded
28	Fernie	18	01	Small bump recorded
28	Fernie	19	15	Small bump recorded
28	Fernie	21	35	Small bump recorded
28	Fernie	23	30	Small bump recorded
29	Coleman	05	52	Medium bump recorded
October 1	Fernie	00	08	Small bump recorded
1	Fernie	01	26	Small bump recorded
1	Fernie	05	42	Small bump recorded
1	Coleman	15	35	Small bump recorded
2	Fernie	01	31	Small bump recorded
2	Fernie	05	35	Small bump recorded
2	Coleman	18	30	Small bump felt. Not recorded
3	Coleman	19	15	Small bump recorded
6	Coleman	14	12	Small bump recorded
7	Coleman	22	00	Sharp bump felt. Not recorded
8	Coleman	08	36	Sharp bump felt. Not recorded
8	Coleman	09	43	Sharp bump felt. Not recorded
8	Coleman	12	45	Sharp bump felt. Not recorded
8	Coleman	15	13	Sharp bump felt. Not recorded
10	Coleman	20	02	Small bump recorded
11	Coleman	01	00	Small bump recorded
12	Coleman	16	15	Small bump recorded
14	Coleman	17	00	Sharp bump felt. Not recorded

DETAILED STUDY OF TWO SPECIFIC MINING AREAS

In order to be able to locate the small events within useful limits, it is necessary that the records yield the time to better the 0.1 second. Radio time-signal reception in the Fernie area was so erratic that the required accuracy could not be obtained from three seismograph stations, each recording time independently of the other. For this reason use was made of radio-linked seismographs built for the project by Dr. P. L. Willmore. Three seismograph stations were provided; two of these transmitted their output by shortwave radio to a central point where their signals were recorded, together with the output of a third seismograph recording directly on a single drum. With this system, time control would be limited only by the accuracy of reading records, because the necessity of obtaining corrections for three stations to a standard of time had been eliminated.

Table III is a list of the seismograph instruments used, together with their known constants. At the master station a direct-recording seismograph arrangement was used. The output of the Willmore-Watt seismometer was recorded through a 0.25-second galvanometer on a Willmore recorder. At the transmitting stations the output from the seismometers was amplified, and then used to frequency-modulate an audio-tone, which in turn amplitude-modulated a 148-megacycle carrier. A two-channel receiver was used at the master station to receive the signals from the two transmitting sites. The output of each channel of the receiver was fed into a 30 c.p.s. galvanometer in the Willmore recorder, and the seismic information from all three stations was recorded on a single sheet of photographic paper. The driving mechanism in the recorder was set to rotate the drum at a paper speed of 53.4 mm. per minute. Use of the three galvanometers necessitated changing the records three times daily. This was done at 08:00, 15:00, and 23:00 hours P.S.T. The direct recording seismograph was operated at full sensitivity, equivalent to a magnification of about 100,000 at the period of the waves being recorded.

TABLE III.—SEISMOGRAPH INSTRUMENTS USED

STATION	SEISMOMETER	GALVANOMETER	RECORDER
Master Station	Willmore-Watt. Period 1 sec.	Turner Period 0.25 sec.	Willmore
Transmitting Stations	Willmore-Watt. Period 1 sec.	Turner Period 0.03 sec.	Willmore

(1) HODGSON, J. H., *A Seismic Survey in the Canadian Shield;* Publications of the Dominion Observatory, Vol. 16, No. 5, 1953.

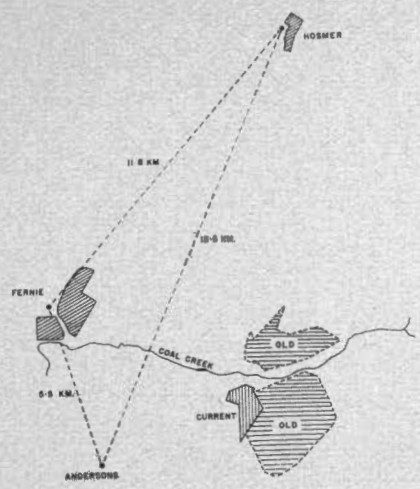

Figure 4.—Sketch-map of Fernie area, showing location of seismic stations.

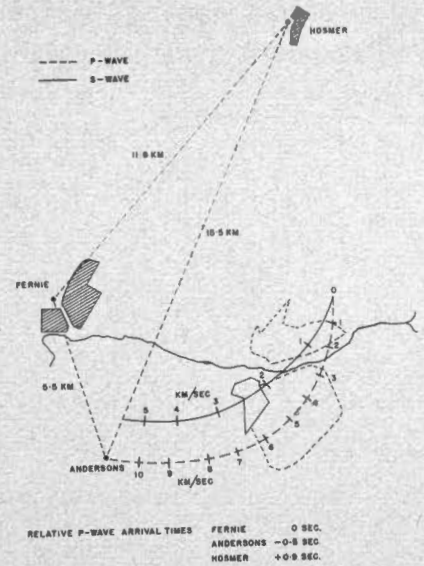

Figure 5.—Series of bumps located at Fernie.

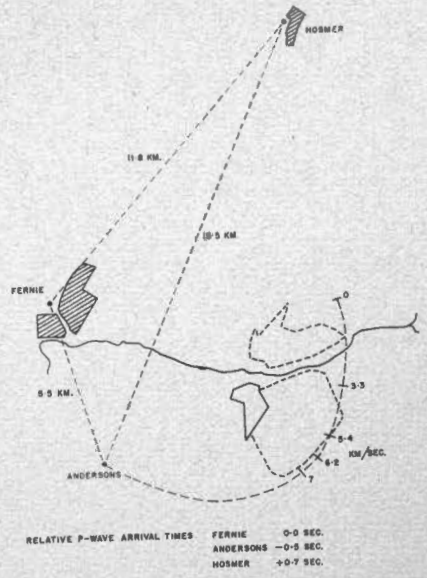

Figure 6.—Series of bumps located at Fernie.

The first triangle of stations was placed to study seismic activity near the Elk River colliery. In choosing sites for the stations the requirements included access to power, line of sight from the two transmitting stations to the master station, and, if possible, an outcrop of bedrock on which to place the seismometers. An advantage of the Willmore seismograph is that, where bedrock is not available, it is considered to be satisfactory to bury the seismometer in solidly packed earth. Such proved to be necessary in the case of this triangle. Due to the topography of the area the triangle took the form shown in Figure 4, the master station being placed at the apex of the elbow in the Elk River valley, just outside Fernie. The transmitting stations were placed in opposite directions along the valley, at Hosmer and Anderson's farm.

The geographical co-ordinates of the stations were obtained by plotting the positions on a large-scale map (scale 1 in. = 0.4 mile). These are shown in Table IV. The sides of the triangle have lengths 5.5 km., 11.8 km., and 15.5 km.

The radio seismograph network was in operation at Fernie from July 12th, 1955, to August 12th, 1955. On August 12th the network was moved to the Coleman area, where the master station was located near the Chinook Cabins (Sentinel), and the transmitting stations near the Greenhill mine, north of Blairmore, and at the Ironstone Fire Range station, south of Coleman.

TABLE IV.—CO-ORDINATES OF FERNIE NETWORK OF SEISMOGRAPH STATIONS

	LATITUDE	LONGITUDE	ELEVATION
Fernie.....	49° 30. 4'N.	115° 04. 4'W.	3,250 feet
Hosmer.....	49° 35. 3'N.	114° 58. 1'W.	3,500 feet
Anderson's Farm..	49° 27. 6'N.	115° 03. 1'W.	3,250 feet

TABLE V.—CO-ORDINATES OF COLEMAN NETWORK OF SEISMOGRAPH STATIONS

	LATITUDE	LONGITUDE	ELEVATION
Sentinel.....	49° 38. 0'N.	114° 34. 8'W.	4,500 feet
Ironstone.....	49° 34. 2'N.	114° 30. 0'W.	6,800 feet
Blarimore.....	49° 37. 7'N.	114° 26. 6'W.	5,000 feet

The co-ordinates for the Coleman sites are given in Table V, and the Fernie-Coleman network is shown on the maps of Figures 7 and 8. Records were obtained at Coleman from August 15th to August 29th.

From the records obtained for the thirty-one days during which the radio seismographs were operated at Fernie, a total of thirty events were analyzed. A few other events are omitted from the discussion because of their doubtful appearance on the records. Of the thirty events discussed, the relative times of the arrival of their *P*-waves at the three stations suggest that fifteen had their origin in the same area. These fifteen are listed in Table VI. Relative *P*-wave arrival times are given, the arrival time at the master station being taken as zero. In addition, the corresponding arrival times of the *S*-wave are shown. The values of *S-P* for each station agree well for this series of events. The fifteen events recorded by the direct-coupled seismograph are similar in appearance, except for amplitudes.

The determination of an epicentre for any event is, of course, dependent upon the seismic-wave velocities in the area. Such velocities have not been determined in southwestern Alberta (with the possible exception of work done by oil-prospecting groups). It has been established, however, that crustal *P*-wave velocities fall between 5.6 and 6.2 km./-sec. The method used in the investigation to locate the centres of recorded events as lying within the area of the mine camp did not require that the *P*-wave velocity be specified more accurately than that it falls within the above range.

Stations on the network were assumed to have equal elevations and,

TABLE VI.—BUMPS RECORDED AT FERNIE (SUMMER 1955)

No.	Date	Approx. Time MST h.m.	Phase	Arrival Times Fernie secs.	Hosmer secs.	(Relative) Andersons secs.	Fernie Double Trace Amplitude (mms)
5	July 22	21:00	P	0	0.8	-	10
			S	1.5	-	-	
6	July 24	02:30	P	0	0.9	-	4
			S	1.5			
7	July 24	03:30	P	0	0.9		3
			S	1.6			
9	July 24	23:00	P	0	1.0		7
			S	1.5			
11	July 26	07:00	P	0	0.9	-0.5	1
			S	1.5	3.7	+0.7	
13	July 26	24:00	P	0	0.7	-0.5	3
			S	1.5	3.6	+0.6	
14	July 27	03:00	P	0	0.5	-0.5	2
18	July 28	15:00	P	0		-0.8	4
			S	1.5			
19	July 29	09:30	P	0		-0.5	3
			S	1.5			
20	July 30	02:00	P	0		-0.5	1
			S	1.5			
21	July 30	03:00	P	0		-0.5	
			S	1.5			
22	July 30	06:00	S-P	1.5			1
27	Aug. 9	00:10	P	0	0.9	-0.5	2
			S	1.5	3.6	+0.5	
29	Aug.11	01:30	P	0	1.1		2
			S	1.5			
30	Aug. 12	04:00	P	0		-0.4	1
			S	1.5			

TABLE VII.—EVENTS RECORDED AT FERNIE (SUMMER 1955)

Map No.	Date	Approx. Time MST	Phase	Arrival Times Fernie	Hosmer	(seconds after nearest minute mark) Andersons
1	July 17	13:30	P		11.1	10.8
			S	12.7	13.0	12.5
2	July 17	13:35	P		45.7	45.6
3	July 17	13.44	P		14.0	13.6
4	July 17	13:45	P			15.9
			S		19.6	19.3
8	July 24	14:00	P	43.0	41.3	
			S	49.3		
10	July 25	16:00	S-P	4.1		
12	July 26	12:00	S-P	5.7		
15	July 27	14:30	P	57.3	58.0	
			S	58.0		
16	July 28	11:30	P	13.8	11.7	14.4
			S	17.3		
17	July 28	13:00	P	38.4	37.7	40.0
23	July 30	11:00	P	30.4	29.9	31.6
24	July 31	08:00	S-P	5.0	-	
25	Aug. 3	16:30	P	31.5	31.4	31.7
			S	35.0		
26	Aug. 8	13:15	P	49.9	50.5	47.8
28	Aug. 9	11:30	P	09.7	08.3	10.0
			S	15.4	12.7	16.0

TABLE VIII.—EVENTS RECORDED AT COLEMAN (SUMMER 1955)

Event No.	Date	Approx. Time MST h.m.	Phase	Arrival Times (Secs. after nearest min.) Sentinel	Blairmore	Ironside	Sentinel Double Trace Amplitude
1	Aug. 22	14:30	P	34.7	-	35.8	1.0 mm.
			S	37.4			
2	Aug. 24	16:30	S-P	2.7s.	-	-	1.0 mm.
3.	Aug. 24	18:15	P	24.4	-	25.1	0.5 mm.
			S	29.1			
4	Aug. 25	14:45	P	25.4	27.2	26.7	1.0 mm.
			S	28.1			
5	Aug. 26	15:30	P	23.9	-	-	1.0 mm.
			S	26.6			

in the absence of any evidence to the contrary, all events were assumed to have a surface focus. Differences in arrival times between pairs of stations were calculated for the fifteen events listed in Table VI. The locus of all possible locations for each event was then determined, assuming values of *P*-wave velocities from 0 to 10 km./-sec. (see Figures 5 and 6).

Diagrams showing the locus for each event were forwarded to the Mines Branch in Ottawa, where the approximate area covered by the mine workings was indicated. In each case, when a reasonable value for the velocity of the *P*-wave is used, the epicentre of the event falls within the area of the mine camp. Only if the velocity is assumed to be greater than 6.5 km./sec. or less than 4 km./sec. does the epicentre lie outside the area of the mine camp. It thus appears reasonable to regard all fifteen recorded events as bumps, associated with the mining operations. It should be pointed out, however, that not one of the fifteen events was reported to be felt. It is probable that the small events recorded during the initial programme can be grouped with the fifteen events here identified as bumps.

It was pointed out earlier that the *S*-waves are normally used to check the computed epicentre location. When this was done for the fifteen events noted above, and the results were plotted in the same manner as for the *P*-wave data, it was found that the two loci, the *S*-wave and the *P*-wave curves, did not coincide. The explanation for the disagreement may be that the *P*-waves and the *S*-waves did not travel similar paths to the seismograph, due to the variable content of the surface layers in the area. The *P*-wave data are considered the more reliable, since, as already pointed out, the *P*-wave arrives first at the seismograph station and, falling on an undisturbed record, can be read more accurately.

Table VII contains a list of events recorded at Fernie whose centres did not lie within the mine area, and which thus, by definition, represent earthquakes. The epicentres of these events were computed by the *S-P* method, using the travel-time curves of Hodgson (1).

(1) *Op. cit.*

Caution should be exercised in relating these epicentres with known faults until such time as the velocities used can be checked by experimental means.

One of these earthquakes was of sufficient size to record at the Banff and Hungry Horse stations as well. Its epicentre, shown as number 16 on the map of Figure 7, probably represents the most accurate determination in the group of earthquakes listed in Table VII and plotted in Figure 7. In some cases the locations are in doubt because only two stations have recorded the events. As was the case for the bumps recorded, none of the recorded earthquakes was felt.

At Coleman there were fewer events; those that occurred are listed in Table VIII. Four of them appear to have a common origin.

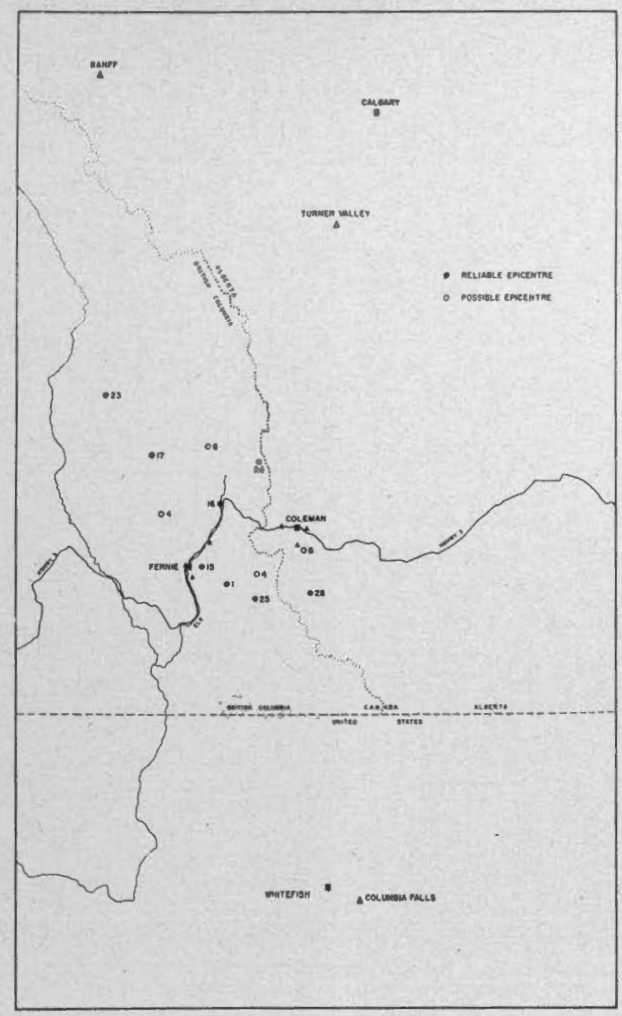

Figure 7.—Earthquakes located from Fernie network.

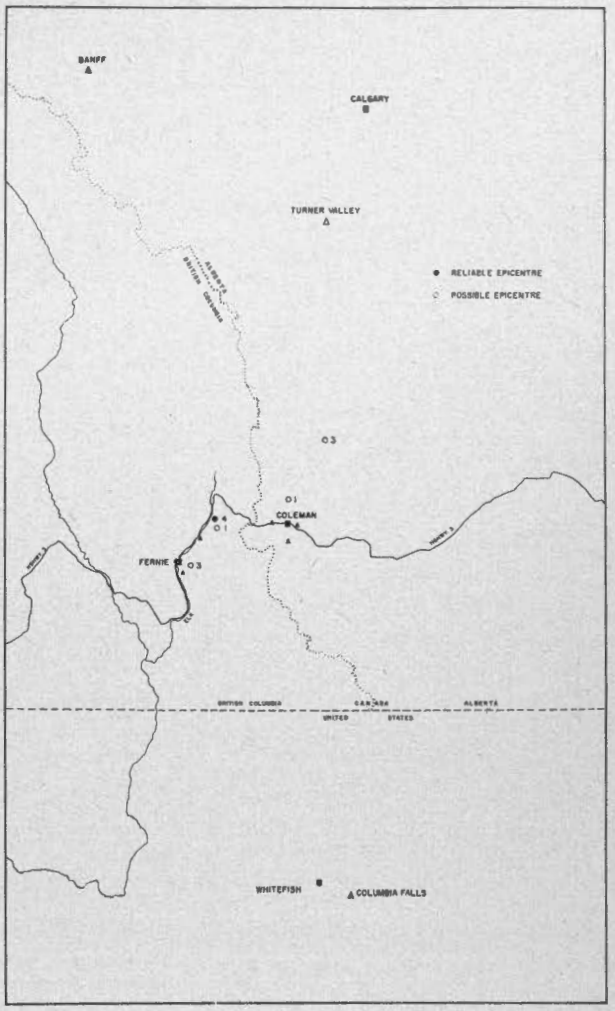

Figure 8.—Earthquakes located from Coleman network.

Their epicentres are plotted on the map of Figure 8. Portions of the seismograms for some of the events are shown in Figure 9.

Banff Station

In July 1955 the Turner Valley seismograph was moved to Banff where it could be operated at maximum sensitivity. Since this location is in the general area under study, and since there have been to date almost two years of continuous seismic recording, the list of earthquakes recorded are of interest in this study. While there is a possibility that some of the minor disturbances are outbursts from the mines at nearby Canmore, the majority of them are at considerably greater distances, and are thus considered to be earthquakes. Table IX is a list of such tremors for 18 months beginning July 1955. The computed distances of the epicentres from Banff are shown, but the locations can seldom be determined.

Conclusion

There are small earthquakes occurring in the area extending from the United States border to at least as far north as Banff, and from the foothills across the Rocky Mountain range. The records obtained at the stations in the Crowsnest area and at Banff indicate that the distribution of epicentres is random. During the three-year period covered by our investigation, none of the local earthquakes recorded had a magnitude greater than 3, and none was felt.

During the initial programme it was apparent that bumps or local events were being recorded at Fernie and Coleman, and not at Turner Valley. On the Fernie records, these bumps were more frequent and stronger than on the Coleman records. Few correlations are possible between events recorded by the seismographs and bumps reported to be felt in the mines. However, during the investigation at Coleman, work in the mines was continually decreasing; so was the number of recorded bumps. At Fernie there were four to five bumps recorded on an average day.

During one of the weeks that the radio seismograph network was in operation at Fernie, the miners were on annual holiday and mining operations had ceased. During this time no small local events were recorded, but when the mine reopened, the disturbances resumed. This appears to be the most definite correlation obtained between mining activities and the recording of bumps. It is evident that most of the bumps do occur in the active mine workings or in older worked-out areas. The latter source may partly explain the fact that most recorded bumps are not reported to be felt. The instruments, in particular the lack of sufficiently precise time control, prevented the bumps being located more definitely.

There seems to be no correlation between earthquakes and bumps. Following a tremor, the number of

TABLE IX.—EVENTS RECORDED AT BANFF, 1955-1956

Date 1955	Time GMT h.m.	Banff S-P (secs.)	Banff Distance (miles)	Distance from Hungry Horse
July 28	18:45	23.0	133	121
Aug. 15	01.57	23.4	135	103
16	18:49	4.1	20	
31	20:31	22.0	127	
Oct. 5	19:16		close	
7	12:57	14.1	69	19
14	15.37		close	
22	21:19		close	
Nov. 21	21:38		close	
Dec. 1	14:34	4.3	21	
6	21:29	4.0	19	
8	17:54	5.4	25	
9	16:18	4.7	23	
21	03:50	22.3	130	121
1956				
Jan. 12	22:22	1.9	14	
Mar. 2	19:00	5.8	28	
17	22:15		close	
Apr. 11	22:24	3.5	16	
14	11:17	23.0	215	
16	21:52	5.5	26	
18	18:47	6.3	31	
21	17:37		close	
Sept. 14	21:27	7.5	36	
22	15:17		close	
Oct. 4	00:13	1.0	9	
7	16:56	1.0	9	
7	22:58	1.0	9	
9	21.39	0.9	8	
9	23.42	4.3	20	
12	01:08	0.8	7	
14	22:48	1.3	11	
Oct. 17	01:28	0.9	7	
18	00:38	1.0	9	
18	01:09	1.1	10	
Nov. 2	21:33	1.0	9	
2	22:30	4.0	18	
5	22:42	3.8	17	
10	20:24	1.7	13	
15	23:22	3.8	17	
16	22:38	3.8	17	
17	20:12	3.2	15	
22	22:56	11.4	54	
24	22:58	0.9	7	
27	23:02	0.9	7	
Dec. 4	18:55	3.3	15	
4	20:32	3.3	15	
21	19:41	2.0	14	
24	23:27	1.6	12	

bumps did not increase, but this was not expected since the earthquakes were weak, and none was felt. Data now being accumulated at the Banff station will help in the future to locate more precisely the earthquakes that occur in the area.

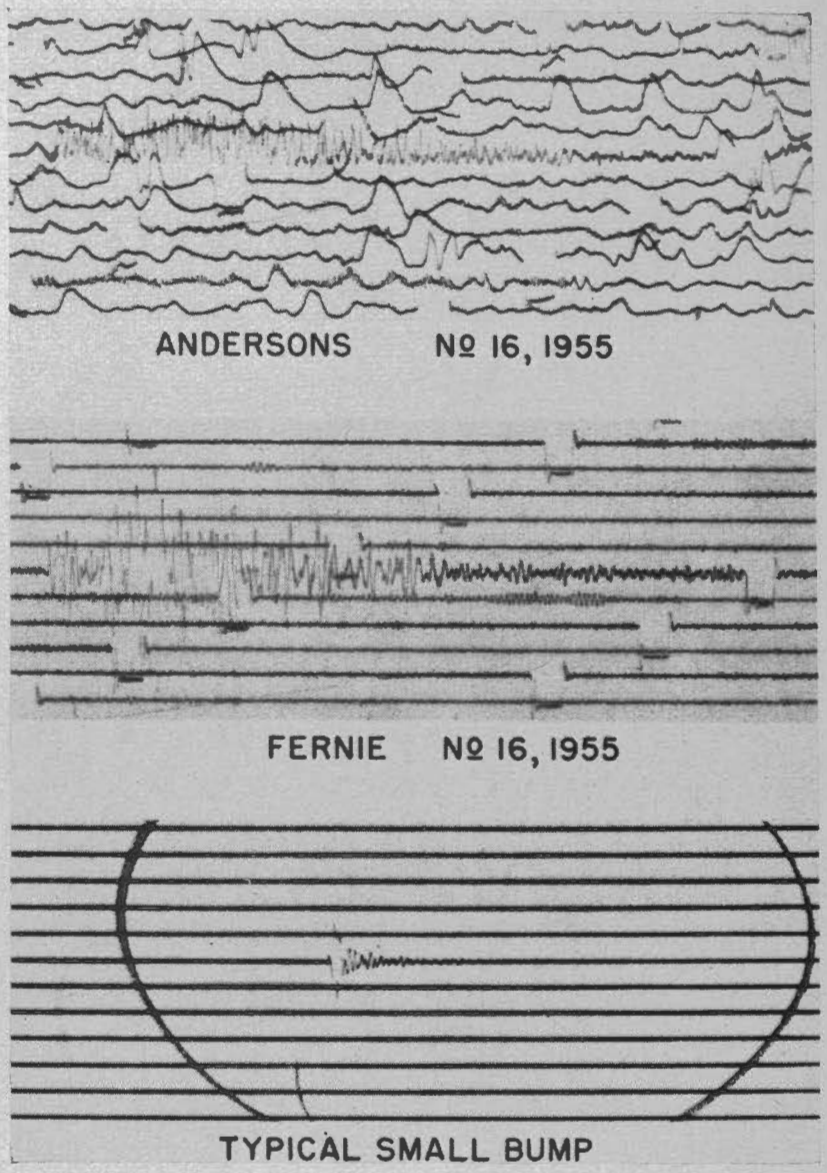

Figure 9.—Typical records of bumps.

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During the period of installing and operating the seismic stations, assistance was received from several members of different branches of the Department of Mines and Technical Surveys. Dr. D. K. Norris and his field party of the Geological Survey assisted in setting up the original network at Fernie, Coleman, and Turner Valley; T. S. Cochrane and F. Grant of the Mines Branch at Blairmore operated the seismographs during the programme. In particular, L. C. Richards was of great assistance many times. The assistance of Jack Merner and Alan Goodacre in our summer field work is acknowledged. We are grateful to the members of the Division of Seismology who designed and supplied the instruments and who gave training in the operation of the radio seismographs.