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Empirical Investigation of Surface-Waves Generated by Distant Earthquakes

BY

L. DON LEET

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PREFACE

I wish to acknowledge a particular indebtedness to Mr. Ernest A. Hodgson, Chief of the Seismological Division of the Observatory, and to Mr. R. Meldrum Stewart, the Director, without whose interest, co-operation, and advice, the prosecution of the investigation here reported would have been impossible. I wish, further, to express my thanks to Dr. James B. Macelwane, S.J., whose papers on surface-waves, at Washington and New York in April, 1929, and subsequent specific suggestions, led to the selection of those waves as a subject for study; to Dr. Frank Wenner for his ready assistance in clearing up certain problems concerning instrumental registration theory; and to Dr. Beno Gutenberg for his valuable suggestions during a series of personal conferences made possible in the course of the investigation by his visit to Ottawa.

DOMINION OBSERVATORY,
OTTAWA, CANADA.

L. DON LEET.

December 1, 1929.

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EMPIRICAL INVESTIGATION OF SURFACE-WAVES GENERATED BY DISTANT EARTHQUAKES

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The data for this investigation were taken, with five exceptions, from records of the Seismological Division of the Dominion Observatory, Ottawa, Canada. Four records supplementing these were obtained at the Harvard seismograph station, Cambridge, Massachusetts, U.S.A., and one at Rio de Janeiro, on Milne-Shaw seismographs adjusted to the same constants as the instruments of that make in service at Ottawa.

There were several important reasons for concentrating on Ottawa records. In the first place, it was felt that valuable information about surface-waves could be deduced from the records of a single station, obtained over a period of years. These offer for study earthquakes from all parts of the globe registered under identical conditions by the same instruments *with constants well determined*, as opposed to the material represented by the records of a single quake at many stations. It is of course recognized that an additional unknown is thus introduced, in the form of differing epicentral conditions. It is felt, however, that this is more than compensated by the elimination of uncertainties regarding timing and instrumental constants, which inevitably accompany the use of records from many stations.

Another consideration in practically limiting the study to Ottawa records is the time service. Timing uniform to within a few hundredths of a second on all the records used is a consequence of the station's direct connection with the Observatory's time service. It is difficult to over-emphasize the importance of this exact timing.

A further factor, which made it possible to widen the scope of the investigation by confining it to Ottawa records, is the system of filing and record-keeping which has been in use at Ottawa for some six years ([36]). This makes it possible to secure, in a couple of hours, certain types of information which could be obtained otherwise only by the examination of several thousand record sheets.

Earthquakes Studied

Records for the period between 1922 and 1929 were examined and 127 of the quakes best recorded selected for study. The locations of these are shown in fig. 5. Distances and azimuths from Ottawa are indicated. Numbers underlined are the Ottawa serial numbers of the quakes for which earth amplitude graphs were made.

Epicentre locations up to and including the year 1927 were determined at Ottawa ([13]) For the purpose of securing uniformity, this series of locations has been based on the Klotz Tables ([41]). The positions of the epicentres were determined by the stereographic projection method.

As the location work of the Observatory has been discontinued from the close of 1927, the epicentres for the few quakes used from 1928 and 1929 records were taken from the preliminary determinations of the United States Coast and Geodetic Survey and of the Central Station of the Jesuit Seismological Association at St. Louis.

Table I presents a reference list of the 127 quakes the records of which were used in obtaining the final results of the investigation. The Ottawa quake records have been given serial numbers since April 1, 1908. These numbers are used throughout this report to identify quakes under discussion.

TABLE I.—QUAKES WHOSE RECORDS WERE USED IN THIS INVESTIGATION

Ottawa Number	Date	O (GMT) h. m. s.	Distance in km.	Latitude	Longitude
1274	1922, April 8	20-42-15	4,450	72·0 N.	8·5 W.
1351	1922, November 7	23-00-23	8,060	27·0 S.	73·0 W.
1353	1922, November 11	04-32-48	8,230	28·7 S.	72·0 W.
1354	1922, November 11	18-09-34	8,080	27·0 S.	71·0 W.
1356	1922, November 17	11-03-03	8,020	27·0 S.	77·3 W.
1386	1923, February 2	05-07-45	7,260	52·0 N.	164·0 E.
1387	1923, February 3	16-01-40	7,620	52·5 N.	162·0 E.
1417	1923, February 24	07-34-36	7,390	54·0 N.	166·7 E.
1446	1923, April 13	15-30-56	7,380	56·0 N.	163·0 E.
1462	1923, May 4	16-26-42	5,520	55·0 N.	156·5 W.
1531	1923, July 13	11-13-43	9,520	31·3 N.	131·0 E.
1536	1923, July 18	01-05-55	3,600	43·6 N.	29·5 W.
1537	1923, July 18	06-02-11	3,600	43·6 N.	29·5 W.
1571	1923, August 28	23-15-06	3,470	24·4 N.	106·0 W.
1573	1923, September 1	02-58-36	9,780	35·1 N.	140·2 E.
1639	1923, November 5	21-57-55	11,300	28·5 N.	132·5 E.
1663	1923, December 5	20-56-43	7,640	40·5 N.	24·8 E.
1682	1924, January 14	20-50-30	9,300	36·5 N.	139·2 E.
1706	1924, March 4	10-07-49	3,900	10·5 N.	84·0 W.
1707	1924, March 4	11-44-02	3,780	10·0 N.	84·5 W.
1715	1924, March 11	10-41-18	3,900	10·0 N.	84·0 W.
1747	1924, April 14	16-20-32	14,000	6·8 N.	122·5 E.
1753	1924, April 21	20-01-04	3,440	20·0 N.	100·0 W.
1763	1924, May 1	19-54-27	3,690	12·5 N.	88·0 W.
1805	1924, June 26	01-37-20	16,100	57·0 S.	159·0 E.
1812	1924, June 30	15-44-30	8,780	47·5 N.	149·0 E.
1815	1924, July 3	04-40-10	10,620	36·0 N.	86·0 E.
1856	1924, August 14	18-02-37	10,140	37·0 N.	141·5 E.
1866	1924, August 25	23-07-04	7,600	55·0 N.	164·0 E.
1870	1924, August 30	03-05-15	13,300	12·0 N.	125·5 E.
1885	1924, September 13	14-34-08	8,740	40·0 N.	43·0 E.
1887	1924, September 13	13-13-07	7,200	50·5 N.	177·5 E.
1910	1924, October 14	05-00-12	3,530	22·5 N.	44·5 W.
1917	1924, October 20	19-52-46	7,320	56·0 N.	166·0 E.
1957	1925, January 18	12-06-02	8,400	49·0 N.	154·0 E.
1961	1925, January 26	19-02·2	4,140	8·5 N.	79·5 W.
1963	1925, January 28	10-58·4	4,140	8·5 N.	79·5 W.
1969	1925, February 1	05-23-58	8,860	45·0 N.	150·0 E.
1974	1925, February 2	19-46-50	9,230	44·0 N.	149·0 E.
1996	1925, February 23	23-53-43	4,700	60·8 N.	146·7 W.
1999	1925, March 1	02-19-20	480	47·6 N.	70·1 W.
2028	1925, March 22	08-41-53	13,300	17·0 S.	168·0 E.
2039	1925, March 29	21-12-27	3,980	9·0 N.	79·5 W.
2045	1925, April 11	10-42-08	16,000	34·0 S.	59·0 E.
2125	1925, June 28	01-21-06	2,690	45·0 N.	110·8 W.
2131	1925, June 29	14-42-16	3,900	33·5 N.	118·5 W.
2149	1925, July 7	14-12-20	4,080	20·0 N.	107·0 W.
2151	1925, July 7	17-43-34	3,200	18·0 N.	61·5 W.

TABLE I.—QUAKES WHOSE RECORDS WERE USED IN THIS INVESTIGATION—*Continued*

Ottawa Number	Date	O (GMT)	Distance in km.	Latitude	Longitude
		h. m. s.			
2178	1925, August 7	07-47-50	3,600	19·5 N.	100·5 W.
2194	1925, August 19	12-07-31	7,390	55·0 N.	166·0 E.
2202	1925, August 29	22-36-35	3,560	25·0 N.	109·0 W.
2244	1925, October 5	04-09-07	3,540	14·0 N.	84·5 W.
2245	1925, October 5	04-11-08	3,050	18·0 N.	81·0 W.
2250	1925, October 13	17-40-31	4,900	10·5 N.	43·0 W.
2297	1925, December 10	14-14-40	3,680	14·0 N.	93·0 W.
2307	1925, December 19	16-09-32	9,400	31·7 S.	112·0 W.
2336	1926, January 25	00-36-14	13,200	10·0 S.	162·0 E.
2350	1926, February 8	15-17-38	3,900	12·0 N.	88·5 W.
2356	1926, February 15	02-59-50	3,700	13·0 N.	86·5 W.
2381	1926, March 17	11-53-37	3,530	12·0 N.	82·0 W.
2413	1926, April 12	08-32-20	13,050	10·0 S.	165·0 E.
2471	1926, June 26	19-46-31	7,900	35·5 N.	27·5 E.
2567	1926, August 30	11-38-05	7,480	37·0 N.	24·5 E.
2570	1926, September 2	01-21-55	16,100	33·0 S.	59·0 E.
2580	1926, September 10	10-34-23	16,000	9·0 S.	113·0 E.
2585	1926, September 16	17-59-15	13,600	10·0 S.	158·0 E.
2616	1926, October 13	06-02-21	7,020	51·5 N.	178·0 W.
2617	1926, October 13	14-17-47	6,920	51·0 N.	178·4 W.
2618	1926, October 13	19-08-08	6,780	50·4 N.	174·0 W.
2619	1926, October 14	02-11-09	6,800	51·0 N.	175·8 W.
2623	1926, October 22	12-35-20	4,160	37·0 N.	125·0 W.
2624	1926, October 22	13-35-15	4,160	37·0 N.	125·0 W.
2630	1926, October 26	03-44-43	14·000	1·0 S.	140·0 E.
2639	1926, October 30	19-41-53	3,700	49·0 N.	128·5 W.
2646	1926, November 5	07-55-39	3,520	14·2 N.	85·5 W.
2697	1927, January 24	01-05·6	13,600	17·0 S.	167·0 E.
2738	1927, March 7	09-27-41	10,230	35·5 N.	135·4 E.
2779	1927, April 14	06-23-35	8,320	31·0 S.	70·3 W.
2799	1927, May 9	20-05-36	4,020	14·0 N.	93·0 W.
2811	1927, May 22	22-32-40	10,800	37·0 N.	102·5 E.
2818	1927, June 3	07-12-02	15,200	8·0 S.	131·0 E.
2889	1927, August 5	21-13-02	9,750	38·6 N.	142·0 E.
2890	1927, August 6	00-14-00	5,500	54·8 N.	157·0 W.
2898	1927, August 10	01-35-30	4·200	7·0 N.	81·6 W.
2900	1927, August 10	11-36-11	14,600	2·0 S.	130·0 E.
2905	1927, August 18	19-27-50	10,000	36·0 N.	144·0 E.
2909	1927, August 20	23-54-28	4,370	6·3 N.	83·0 W.
2921	1927, September 3	19-47-40	4,880	10·7 N.	43·3 W.
2931	1927, September 11	22-15-42	7,950	44·5 N.	34·5 E.
2949	1927, October 2	04-47-45	3,530	12·0 N.	92·0 W.
2973	1927, October 24	15-59-50	4,260	57·0 N.	136·0 W.
2980	1927, November 4	13-51-00	3,910	34·4 N.	120·8 W.
2992	1927, November 14	00-12-04	7,020	70·0 N.	126·7 E.
3024	1927, December 28	18-20-20	7,720	53·0 N.	163·0 E.
3083	1928, March 16	05-01-01	13,400	23·0 S.	170·4 E.
3092	1928, March 22	04-16-57	3,590	14·0 N.	95·0 W.
3115	1928, April 17	03-25-16	3,380	16·0 N.	95·5 W.
3117	1928, April 18	19-22-50	7,620	42·3 N.	24·8 E.
3139	1928, May 14	22-14-33	5,680	8·0 S.	80·5 W.
3161	1928, May 27	09-50-33	9·580	39·0 N.	149·0 E.
3185	1928, June 17	03-19-20	3,700	14·0 N.	96·0 W.
3192	1928, June 21	16-26-52	4,650	61·8 N.	148·7 W.

TABLE I.—QUAKES WHOSE RECORDS WERE USED IN THIS INVESTIGATION—*Concluded*

Ottawa Number	Date	O (GMT)	Distance in km.	Latitude	Longitude
		h. m. s.			
3223	1928, August 4	18-26-01	4,000	14·0 N.	98·0 W.
3263	1928, October 9	03-01-02	3,700	15·0 N.	97·0 W.
3284	1928, October 25	12-32-57	3,720	12·0 N.	86·0 W.
3292	1928, November 1	04-12-43	3,250	26·0 N.	106·0 W.
3303	1928, November 20	20-35-09	7,550	23·0 S.	73·0 W.
3314	1928, December 1	04-06-06	8,980	35·0 S.	74·0 W.
3317	1928, December 2	04-20-26	8,920	35·0 S.	74·0 W.
3334	1928, December 19	11-37-ca	13,900	7·0 N.	128·0 E.
3341	1929, January 13	00-03-17	8,050	54·0 N.	154·0 E.
3343	1929, January 21	10-30-40	4,950	64·0 N.	152·0 W.
3344	1929, January 24	20-36-31	3,740	12·0 N.	90·0 W.
3352	1929, February 2	00-00-28	7,350	2·0 S.	23·0 W.
3361	1929, February 10	15-38-30	3,580	11·7 N.	90·8 W.
3368	1929, February 22	20-41-47	4,900	17·0 N.	35·3 W.
3370	1929, February 26	09-00-44	5,900	54·0 N.	163·0 W.
3372	1929, March 1	07-30-54	4,000	53·0 N.	132·0 W.
3381	1929, March 7	01-34-37	6,480	51·0 N.	170·0 W.
3395	1929, March 21	02-36-56	3,660	12·0 N.	90·0 W.
3437	1929, May 1	15-37-37	9,620	37·0 N.	58·0 E.
		(Harvard)	9,620		
3540	1929, July 5	14-19-00	7,000	50·0 N.	177·0 W.
		(Harvard)	7,500		
3542	1929, July 5	22-36-13	6,950	50·0 N.	177·0 W.
		(Harvard)	7,450		
3543	1929, July 6	02-03-46	6,950	50·0 N.	177·0 W.
		(Harvard)	7,450		
3544	1929, July 6	09-46-04	4,300	15·6 N.	43·4 W.
		(Harvard)	3,900		
3551	1929, July 7	21-23-07	6,980	50·0 N.	177·0 W.
		(Harvard)	7,450		
3654	1929, September 17	19-17-27	3,930	52·0 N.	133·0 W.

INSTRUMENTS

During the period covered by this investigation, there were in service at Ottawa one vertical component and four horizontal component seismographs: a Spindler-Höyer vertical, following the design of Wiechert; Milne-Shaw seismographs 17 and 23; two Bosch photographic instruments.

All constants of the instruments had been determined at regular intervals. This is of the greatest importance because of the direct and fundamental influence of the constants of an instrument on the character of the records which it yields. The manufacturers of the better modern instruments, such as the Milne-Shaw, Wilip-Galitzin, Wenner, and others, are increasing the recording value of stations tremendously by making it advisable for all the instruments of a given kind to be adjusted to the same constants and making it an easy matter to check those constants frequently.

Table II records the constants of the Ottawa and Harvard stations, and of the instruments as determined at intervals throughout the period for which records were studied.

TABLE II.—STATION AND INSTRUMENTAL CONSTANTS

OTTAWA SEISMOLOGIC STATION—DOMINION OBSERVATORY

Latitude =45° 23′ 38″ North
Longitude =75° 42′ 57″ West
Elevation =83 meters

Foundation: Boulder clay over Ordovician limestone
Time: Mean Greenwich, midnight to midnight
Time correction: Within ·25 sec.

INSTRUMENTS—FIXED CONSTANTS

Instrument	Symbol	Registration	Damping	Paper Speed	Mass
Bosch	I	Photographic	Air	15 mm/minute	200 grams
Bosch	II	Photographic	Magnetic	15 mm/minute	200 grams
Milne-Shaw	17	Photographic	Magnetic	8 mm/minute	1 pound
Milne-Shaw	23	Photographic	Magnetic	8 mm/minute	1 pound
Spindler-Hoyer	W	Smoked Sheet	Air	15 mm/minute	80 kg.

INSTRUMENTS—DETERMINED CONSTANTS

Instrument	T_o	r	R	V	Damping ratio	Com-ponent	Deflection per second of arc tilt	Date determined
	sec.	cm.	dynes				mm.	
W	6·0	0·06	0·27	160	5 : 1	Z		1922, July 26.
I	5·5			120	2 : 1	NS		1922, December.
II	6·5			120	20 : 1	EW		1922, December.
17	12·0			250	20 : 1	EW	44·0	1922, December.
23	12·0			250	20 : 1	NS	44·0	1922, December.

These are normal operating constants. They were effective except as noted below, where only those which were changed are listed.

II	7·8				18 : 1			1923, February 7.

During March and April, 1923, No. 23 was run to record the EW component, with various values for the damping ratio (35). It was kept at:—20 : 1 until 1923, March 9
15 : 1 until 1923, March 17
10 : 1 until 1923, May 3
5 : 1 until 1923, May 30

II	5·8							1923, April 4.
II	5·3							1923, May 3.
17							44·5	1923, May 3.
23					5 : 1	EW	42·0	1923, May 3
W	5·9	0·06						1923, May 30.
23	Out of operation from 1923, July 20, to 1924, January 9, at Ottawa, the instrument being used for experimental purposes at Shirley Bay and Kemptville, Ont.							

TABLE II—STATION AND INSTRUMENTAL CONSTANTS—*Continued*

OTTAWA SEISMOLOGIC STATION—DOMINION OBSERVATORY—*Concluded*

INSTRUMENTS—DETERMINED CONSTANTS—*Concluded*

Instrument	T_0	r	R	V	Damping ratio	Component	Deflection per second of arc tilt	Date determined
	sec.	cm.	dynes				mm.	
W	5·5				4 : 1			1923, August 22.
II	5·4				15 : 1			1923, August 21.
23	12·0				20 : 1	NS	44·0	1924, January 9.
I	5·5				9 : 5			1924, March 5.
II	5·8				13 : 4			1924, March 5.
I	5·3				2 : 1			1924, May 7.
II	6·0				15 : 1			1924, May 7.
17							51·0	1924, May 7.
23							44·6	1924, May 5.
17							44·0	1924, November 28.
23							44·0	1924, November 28.
II	5·5				10 : 1			1926, February 16.
17							43·0	1926, February 12.
23							42·0	1926, February 12.
W	5·2							1926, February 15.
I	5·2							1927, January 31.
II	5·9							1927, January 31.
W	5·1							1927, January 31.
17							42·5	1927, February 8.
23							43·0	1927, February 13.
II	6·2							1928, January 10.
17							44·0	1927, December 30.
23							44·0	1928, January 11.
W	5·2							1928, January 18.
II	6·9				14 : 1			1929, February 2.
23							43·0	1929, January 31.
W	5·0				6 : 1			1929, February 25.
W	Out of operation from June 15 to July 4, while it was being moved to a recording pier in a constant temperature vault.							
W	7·0	0·053	0·13		11 : 1			1929, July 5.

TABLE II—STATION AND INSTRUMENTAL CONSTANTS—*Concluded*

HARVARD UNIVERSITY
SEISMOGRAPH STATION, DEPARTMENT OF GEOLOGY AND GEOGRAPHY,
CAMBRIDGE, MASSACHUSETTS, U.S.A.

Latitude =42° 22′ 36″ North
Longitude =71° 06′ 59′ West
Elevation =5·367 meters

Foundation: Glacial sand over clay
Time: Mean Greenwich, midnight to midnight
Time correction: Within 0·5 second.

INSTRUMENTS—FIXED CONSTANTS

Instrument	Symbol	Registration	Damping	Paper Speed	Mass
Milne-Shaw...............	43	Photographic	Magnetic	8 mm/minute	1 pound
Milne-Shaw...............	44	Photographic	Magnetic	8 mm/minute	1 pound

INSTRUMENTS—DETERMINED CONSTANTS

Instrument	T_o	V	Damping ratio	Component	Deflection per second of arc tilt	Date determined
	sec.				mm.	
43..................	12·0	250	20 : 1	EW	44·0	1928, November 28.
44..................	12·0	250	20 : 1	NS	44·0	1928, November 28.

Particular attention should be paid to the constants of the mechanically recording vertical seismograph. A. Mohorovičić (61), Reid (74), and others have stressed the importance of accurate determinations of constants, and indicated procedures to follow. Mohorovičić, in particular, commented on the fatal carelessness of most seismograph stations in such matters.

It is essential to determine the sensitivity of a seismograph with the damping removed. Optically registering instruments have, in general, an exceptionally small friction. It is also far less variable than that of mechanically recording instruments. This problem, therefore, concerns the vertical much more vitally than any of the other instruments at Ottawa.

The friction, R, in dynes is given by Mohorovičić as

$$R = \frac{r\,4\pi^2\,M}{T_o^2\,V^2} \qquad (1)$$

where r is the half width in centimeters of the zone within which friction will completely arrest the recording pen; T_o the undamped period of the seismograph in seconds; M the mass of the pendulum in grams; and V the static magnification, that is, the ratio of the amplitude of the writing point to the corresponding amplitude of the displacement of the centre of gravity of the mass.

According to Mohorovičić, the best instruments, properly handled, should have a friction of less than one-half of a dyne. One of the most critical places at which friction must be as low as possible if this value is to be obtained, is the contact of the writing point with the smoked sheet. It should press so lightly upon the paper that the slightest reduction of the pressure would prevent its recording. The line written in the soot should become virtually a series of dots. An effective means of accomplishing this was first proposed by Marvin in 1906 ([55]) and further mentioned by Reid ([71]) and Hodgson ([34]). It consists of a small electric buzzer attached rigidly to the small post supporting the stylus bearings. The writing arm is, of course, carefully counterbalanced also.

The vertical seismograph at Ottawa, equipped with a sensitizing buzzer, and kept under rigorous temperature control ([34]), was brought to a high degree of operating efficiency. In July, 1922, R was found to be ·27 dynes. In July, 1929, after the instrument's removal to a different recording position, a period of 7 seconds, instead of the 6 seconds used for some time, was found to be practicable. With that set-up, from a decay curve whose maximum amplitude was 4·5 cm., R was found to be only ·13 dynes, a remarkably low value for such an instrument, r in this case being ·053 cm.

These facts are stressed because of the important rôle of the vertical seismograph in certain phases of the investigation. The nature of earth movements during the passage of the Rayleigh-wave has been carefully studied, and here the ratio of vertical to horizontal components of true earth amplitudes is important. Where investigators have found vertical components less than horizontal, rather than of the order of 1·5 times as great, there has been a tendency to discount the reliability of the vertical record. Accordingly, every effort has been made in the present study to base findings only on the records of instruments which were known to be in optimum adjustment.

Earth Amplitude Graphs of Surface-waves—Theory

A thorough analysis of the surface-waves from distant earthquakes can be made only in terms of the actual movement of the earth particle. If that is determined, an understanding of the nature of the waves themselves is possible on the principle that any undulatory process may be described by considering a given point in the path of the wave as executing a vibration.

As a preliminary to certain parts of the present investigation, portions of the surface-wave groups of several earthquakes weie ieduced to actual earth amplitudes and plotted on a uniform time scale. The accuracy of such work must be examined on three main counts: (1) the exactness with which trace amplitudes can be translated into true amplitudes, (2) the relationship in phase between the earth particle and the record trace, and (3) the reliability of trace amplitudes where there are sudden changes of earth amplitude or period.

A. Mohorovičić ([61]) gives as his finding after detailed examination that the mean error in the determination of true earth movements amounts to about ten per cent. This is under the assumption that all measurements of instrumental constants are made with the greatest of care. If they are only moderately well determined, the error may become as much as double that amount.

With regard to phase relationships, in general a properly damped pendulum leads in phase a sustained harmonic motion of longer period that is impressed upon it. The amount depends on the ratio between the period of the forced motion and that of the undamped pendulum as well as upon the amount of damping. Thus, pendulums of different periods will lead the same earth vibration in phase by different amounts. At the same time, any given pendulum's phase angle changes as the earth period changes.

The first of these effects can be taken into account readily by the application of a correction to the phase of one pendulum to render it comparable to that of another of different period, when both are recording the same earth vibration.

The second, however, leads to disastrous complications in all but certain special cases. The horizontal seismographs of most recording stations are oriented in NS and EW planes. Accordingly, if waves arrive whose planes of propagation do not intersect the surface at the station in either of these pairs of cardinal directions, the resulting motion will in general have a component on each instrument. At such times as mixed waves are arriving (some with dominantly transverse, others with longitudinal, horizontal vibrations, and each type with a different period), a resolution of the resulting records in terms of absolute earth amplitudes, and of phases of each wave type becomes a problem difficult, if not impossible, to solve.

As an example of the simultaneous arrival of transverse surface-waves and Rayleigh-waves with their longitudinal and vertical displacements, each with a different period, let us examine the records from an epicentre directly south of Ottawa. Such records show the component movements resolved on the appropriate seismograms (fig. 18c). Between 5h 12 m and 5h 14 m there is a distinct vibration of the EW component with an apparent period of 26 seconds. At the same time the NS and vertical display a 30-second vibration period. Figs. 18a and 18b show the same thing in the graphs of computed true earth amplitudes.

Reid (71), following Wiechert, has shown the difference of phase for varying ratios of earth period to instrument period. His diagram assumes a phase difference of about 180° for periods of ground movement very short relative to the instrument's period. Wenner (126) treats the same problem on the assumption of zero phase difference for short earth periods. Whether a momentary displacement of the ground and the resulting displacement shown on the record are considered to have the same or opposite sign is a matter of convention. The choice of assumptions does not affect the computation of phase difference between two instruments of different periods as they record the same earth vibration.

Fig. 8 of Wenner's valuable paper (126) is plotted from the equation:—

$$\tan \alpha = \frac{\omega D}{\omega^2 K - U} \text{ (127)} \qquad \text{(2)}$$

where α is the phase angle; ω is the frequency of earth displacement, or 2π divided by the period; D is the damping constant of the seismograph; K the moment of inertia of the moving system of the seismograph; and U the restoring constant of the seismograph D is taken equal to $2\sqrt{KU}$, the condition giving critical damping; K is taken equal to

$4U$, giving a period of 4π or 12·6 seconds for the seismograph; and, as indicated above, the phase displacement is assumed to be zero when ω is very large, that is, when the period of the ground movement is very short.

These constants appear in the equation of motion of the steady mass of a seismograph with respect to its support,

$$K\frac{d^2\varphi}{dt^2} + D\frac{d\varphi}{dt} + U\varphi = LM\frac{d^2X}{dt^2} \qquad (3)$$

where φ is the angular displacement; t is the time; X is the displacement of the support; L is the distance from the centre of mass of the moving system of the seismograph to the axis of rotation; and M is the mass of the moving system of the seismograph.

In the present investigation, we shall not be concerned with the absolute amount by which our instruments lead the ground movement. We need to know, rather, the difference between the phase lead of a 12-second pendulum and that of a 6-second, since the Milne-Shaw seismographs have the former period and the vertical has the latter. Where Bosch and vertical records are compared, the problem does not exist, for the Bosch period is practically the same as that of the vertical. Differences in damping ratios also affect phase, theoretically. The magnitude of this effect in the present study, however, was within the limits of observational error.

The periods of earth displacements whose records on 6- and 12-second instruments were compared were all over 20 seconds, within a range where available graphs indicate expectable phase differences of about 3 seconds and less. As the earth period increases, the phase difference between the instruments decreases.

Accordingly, wherever the Milne-Shaw records were compared with the vertical, determinations of phase differences were made. The equipment at Ottawa fortunately made it possible to do this instrumentally, since 6-second Bosch and 12-second Milne-Shaw records of the same horizontal components of given quakes were available for comparison. This is illustrated by fig. 11a, where earth amplitudes computed from Bosch II, EW, are plotted on the same time scale as those computed from Milne-Shaw 17, EW. The short-period Bosch registers the maxima consistently earlier than the longer-period Milne-Shaw, as theory indicates it should. It is immaterial whether the Bosch be regarded as leading the earth displacement by more than the Milne-Shaw, or lagging behind it less.

Berlage (5) investigated the behaviour of the Milne-Shaw seismograph at the onset of impulses. This should indicate, qualitatively at least, its reaction to marked changes of amplitude as well. His results suggest that the instrument does not respond accurately to such changes, in its representation of apparent period or in amplitudes computed from its trace.

Unfortunately, any significance that these results might have had so far as Milne-Shaw recording is concerned, seems to have been vitiated by the use of a 5 : 1 damping ratio. Computations and experiments were made "dans le cas où le rapport d'amortissement est le rapport habituel, 5 : 1." Instructions (95) for the operation of these instruments, however, state quite clearly that 20 : 1 is the ratio to be used.

The effect which the damping ratio would have on Milne-Shaw registration was well demonstrated by a series of experiments conducted by Hodgson at Ottawa ([35]). Two instruments were operated to record the same component of motion, with all constants the same; then the damping ratio of one was reduced successively to 15 : 1, 10 : 1, and 5 : 1. There were no measurable differences in the seismograms for damping ratios of 10 : 1 and greater. There were distinct differences, however, between 5 : 1 and 20 : 1 recording. Fig. 1 shows records of quake No. 1462 obtained during the course of these experiments. In particular, the impulse at the left of the figure is similar to the type used by Berlage. The record of the instrument with 5 : 1 damping differs from that of the one with 20 : 1 by an amount which seems to be comparable to the discrepancies reported by Berlage between theory and observation, both in apparent period and in amplitude.

So far as can be found, there has been no determination made as yet of the effect of sudden amplitude changes on the recording of, say, a Milne-Shaw seismograph in the surface phase. If the negative evidence adduced by comparing the Berlage and Hodgson experiments is accepted as an indication, a properly damped Milne-Shaw seismograph gives a record of such changes which is accurate within the present limits of measurement.

The reaction of the Milne-Shaw to sudden changes of period, when the amplitude of motion is constant, was investigated by Rothé ([82]). He found that the inscription immediately indicated a variation of magnification proportional to the variation of period, as indicated in the Milne-Shaw magnification curve ([95]).

Earth Amplitude Graphs of Surface-waves—Procedure

Earth amplitudes were computed from Milne-Shaw seismograms by using the magnification curve supplied with these instruments ([95]). This is based on the Wiechert formula given below.

Bosch and vertical trace amplitudes were reduced by the aid of curves drawn from Wiechert's formula ([128]):—

$$V_d = \frac{V}{\sqrt{\left[1 - \left({}^{T_e}/_{T_o}\right)^2\right]^2 + 4\left(\frac{T_o}{2\pi\tau}\right)^2\left({}^{T_e}/_{T_o}\right)^2}} \quad \ldots\ldots\ldots\ldots (4)$$

where V_d is the dynamic magnification, V is the static magnification, T_e and T_o, respectively, the periods of the earth particle and of the undamped pendulum, and τ the relaxation time. V is constant; V_d is not. These curves can be found in the Klotz Tables ([41]).

Tables III, IV, and V were constructed as computation aids.

The first step was to establish the zero line through the portion of the seismogram to be measured. Then the exact time to the nearest second of each turning point in the trace was measured, with the trace amplitude, or distance from the zero line, of the point. The effective period, which determines V_d, was assumed to be the time between successive turning points on the same side of the zero line. Then, with the effective earth period and the trace amplitude at a given point known, the computed true earth amplitude was read directly from the tables indicated.

A sample computation form indicates the method of tabulating these data:—

Quake 3544 MS 23 NS Up trace = South movement of ground 1929, Aug. 13.

Time	T.	Trace Amp in ½ mm.	Microns per ½ mm.	Microns
10-05-21	(26)	3 N	12	36
13				
34	29	4 S	12	48
16				
50	30	3 N	12	36
14				
06-04	24	5 S	8	40
10				
14	24	4 N	8	32
14				
28	27	5 S	10	50
13				
41	21	4 N	6	24
8				
49	16	7 S	4	28
8				
57	19	5 N	5	25
11				
07-08	22	5 S	7	35

The graphs for this quake are shown in fig. 6.

Earth amplitudes were computed only for the turning points. Intermediate positions were obtained by graphical interpolation.

Measurements of trace amplitudes were made to the nearest ⅛ mm. Accordingly, the limits of accuracy at each point are represented by a fourth of the figure in the column headed "microns per ½ mm." making no allowance for the limits within which the period was determined—approximately ± 1 second.

Earth amplitude graphs were made for 56 components, representing 18 quakes. Each begins at the earliest surface phase which can be identified. They vary in length from 15 to 25 minutes. They are reproduced in figs. 6 to 23. The accuracy of these graphs, it must be kept in mind, is subject to the conditions discussed on page 274.

TABLE III.—SECONDS PER HALF MILLIMETER

For normal minute interval of 15 mm.

(Bosch and Vertical)

½ mm.	Minute Interval in ½ mm.							
	25	26	27	28	29	30	31	32
1	2·4	2·31	2·22	2·14	2·07	2	1·94	1·88
2	4·8	4·62	4·44	4·29	4·14	4	3·87	3·75
3	7·2	6·92	6·67	6·43	6·21	6	5·81	5·63
4	9·6	9·23	8·89	8·57	8·28	8	7·74	7·50
5	12·0	11·54	11·11	10·71	10·35	10	9·68	9·38
6	14·4	13·85	13·33	12·86	12·41	12	11·61	11·25
7	16·8	16·15	15·56	15·00	14·48	14	13·55	13·23
8	19·2	18·46	17·78	17·14	16·55	16	15·48	15·00
9	21·6	20·77	20·00	19·29	18·62	18	17·42	16·88
10	24·0	23·08	22·22	21·43	20·69	20	19·36	18·75
11	26·4	25·39	24·44	23·57	22·76	22	21·29	20·63
12	28·8	27·69	26·67	25·71	24·83	24	23·23	22·50
13	31·2	30·00	28·89	27·86	26·90	26	25·16	24·38
14	33·6	32·31	31·11	30·00	28·97	28	27·09	26·25
15	36·0	34·62	33·33	32·14	31·04	30	29·03	28·12
16	38·4	36·92	35·56	34·29	33·10	32	30·97	30·00
17	40·8	39·23	37·78	36·43	35·17	34	32·90	31·88
18	43·2	41·54	40·00	38·57	37·24	36	34·84	33·75
19	45·6	43·85	42·22	40·71	39·31	38	26·77	35·63
20	48·0	46·15	44·44	42·86	41·38	40	38·71	37·50
21	50·4	48·46	46·67	45·00	43·45	42	40·65	39·38
22	52·8	50·77	48·89	47·14	45·52	44	42·58	41·25
23	55·2	53·08	51·11	49·29	47·59	46	44·52	43·13
24	57·6	55·39	53·33	51·43	49·66	48	46·45	45·00
25	60·0	57·69	55·56	53·57	51·73	50	48·39	46·88
26	....	60·00	57·78	55·71	53·79	52	50·32	48·75
27	....	....	60·00	57·86	55·86	54	52·26	50·63
28	....	....	....	60·00	57·93	56	54·19	52·50
29	....	....	....	....	60·00	58	56·13	54·38
30	....	....	....	....	....	60	58·07	56·25
31	....	....	....	....	....	....	60·00	58·13
32	....	....	....	....	....	....	....	60·00

TABLE IV.—SECONDS PER HALF MILLIMETER

For normal minute interval of 8 mm.

(Milne-Shaw)

½ mm.	Minute Interval in ½ mm.					
	14·5	15	15·5	16	16·5	17
0·5	2·07	2	1·94	1·88	1·82	1·77
1·0	4·14	4	3·87	3·75	3·64	3·53
1·5	6·21	6	5·81	5·63	5·45	5·29
2·0	8·28	8	7·74	7·50	7·27	7·06
2·5	10·35	10	9·68	9·38	9·09	8·82
3·0	12·41	12	11·61	11·25	10·91	10·59
3·5	14·48	14	13·55	13·13	12·73	12·36
4·0	16·55	16	15·48	15·00	14·54	14·12
4·5	18·62	18	17·42	16·88	16·36	15·89
5·0	20·69	20	19·36	18·75	18·18	17·65
5·5	22·76	22	21·29	20·63	20·00	19·41
6·0	24·83	24	23·23	22·50	21·82	21·18
6·5	26·90	26	25·16	24·38	23·64	22·94
7·0	28·97	28	27·09	26·25	25·45	24·71
7·5	31·03	30	29·03	28·12	27·27	26·48
8·0	33·09	32	30·97	30·00	29·09	28·24
8·5	35·16	34	32·90	31·88	30·91	30·00
9·0	37·23	36	34·84	33·75	32·73	31·77
9·5	39·30	38	36·77	35·62	34·54	33·53
10·0	41·37	40	38·71	37·50	36·36	35·29
10·5	43·44	42	40·65	39·38	38·18	37·06
11·0	45·51	44	42·58	41·25	40·00	38·82
11·5	47·58	46	44·52	43·12	41·82	40·59
12·0	49·65	48	46·45	45·00	43·64	42·36
12·5	51·72	50	48·39	46·88	45·45	44·12
13·0	53·78	52	50·32	48·75	47·27	45·89
13·5	55·85	54	52·26	50·62	49·09	47·65
14·0	57·92	56	54·19	52·50	50·91	49·41
14·5	60·00	58	56·13	54·38	52·73	51·18
15·0		60	58·07	56·25	54·54	52·94
15·5			60·00	58·12	56·36	54·71
16·0				60·00	58·18	56·48
16·5					60·00	58·24
17·0						60·00

TABLE V.—MAGNIFICATION AND EARTH DISPLACEMENT

For Milne-Shaw Seismograph of 12s Period, Static Magnification 250, Damping Ratio 20 : 1

$$\frac{\text{Trace Amplitude in mm.}}{F} \times 1000 = \text{Earth Displacement in microns.}$$

$$\frac{\text{Trace Amplitude in } \tfrac{1}{2} \text{ mm.}}{2F} \times 1000 = \text{Earth Displacement in microns where } F \text{ is the Magnification Factor.}$$

T_e	F	$2F$	Microns per ½ mm. trace
4	250·0	500	2·00
5	248·0	496	2·02
6	245·0	490	2·04
7	240·0	480	2·08
8	232·5	465	2·15
9	222·0	444	2·25
10	210·0	420	2·38
11	196·0	392	2·55
12	182·0	364	2·75
13	167·5	335	2·99
14	152·5	305	3·28
15	140·0	280	3·57
16	126·0	252	3·97
17	115·0	230	4·35
18	105·0	210	4·76
19	95·0	190	5·26
20	87·0	174	5·75
21	79·0	158	6·33
22	73·0	146	6·85
23	67·0	134	7·46
24	61·5	123	8·13
25	57·5	115	8·77
26	53·0	106	9·43
27	49·0	98	10·20
28	46·0	92	10·87
29	43·0	86	11·63
30	40·5	81	12·35
31	38·0	76	13·16
32	35·5	71	14·08
33	33·0	66	15·15
34	31·0	62	16·13
35	29·0	58	17·24
36	27·5	55	18·18
37	26·0	52	19·23
38	24·5	49	20·41
39	23·5	47	21·28
40	22·5	45	22·22
Greater than 40	20·0	40	25·00

The measurement of time on the vertical records required special attention. The writing arm has a short radius—approximately 15·3 cm.—and introduces a decided curvature into the trace for amplitudes of more than a few millimeters. When this occurs, the exact time of a turning point cannot be determined by the foot of a perpendicular to the zero line. It is represented, rather, by the point on the zero line intersected by the arc of writing passing through the turning point. Accordingly, a transparent template was designed with an arc of 15·3 cm. radius and a zero line for reference inscribed on it. When the template's reference line coincides with the seismogram's zero line and its arc passes through a turning point, the time of the turning point is read at the point where the template's arc crosses the zero line.

The greatest inaccuracies in the earth amplitude graphs are to be expected in the early portions of the first surface-waves—normally the transverse type. The long periods of these waves are subject to a minimum magnification by the instruments. Furthermore, they are commonly combined with shorter period body waves. The reduction of the resulting trace is irregular and to a certain extent indefinite. The underlying long periods can be identified with reasonable accuracy, but the trace amplitude due to the long periods as distinguished from that introduced by the short must be estimated. These uncertainties, however, are present usually in only the first few minutes of the surface-wave group of a seismogram.

The quakes for which earth amplitude graphs were made, arranged by distance from Ottawa, are:—

Figure	Number	Distance in km.	Azimuth
6	3544	4,300	SE
4 and 7	1996	4,700	NW
8	3542	6,950	NW
9	3543	6,950	NW
10	3551	6,980	NW
11	3540	7,000	NW
12	3352	7,350	SE
13	2194	7,390	NW
14	3303	7,550	S
15	3117	7,620	NE
16	1387	7,620	NW
17	3024	7,720	NW
18	1353	8,230	S
19	3314	8,980	S
20	3161	9,580	NW
21	3437	9,620	NE
22	1815	10,620	N
23	2028	13,500	W

Earth Particle Path in the Rayleigh-wave

It has been known for some time that there are at least two distinct types of surface-waves, the transverse with no vertical component, and one whose vibrations are essentially longitudinal and vertical. The terms transverse and longitudinal are, of course, used with reference to the direction of propagation, or, more exactly, to the plane determined by the epicentre, recording station, and earth's centre.

The longitudinal-vertical waves have been most commonly referred to as "*M*," or maximum waves, owing to the fact that the maximum trace amplitude usually occurs during their passage, and as Rayleigh-waves, following Lord Rayleigh's theoretical results presented in 1885 ([69]), when he investigated waves propagated along the surface of a semi-infinite isotropic elastic solid, and described a wave type which is composed of longitudinal and vertical elements.

Though these waves often cause the maximum trace amplitude on a seismogram, the transverse surface waves frequently have the maximum true earth amplitude. Differential magnification of the long-period transverse and the shorter-period longitudinal-vertical waves by recording instruments accounts for the misleading appearance of the seismogram.

Throughout this report, reference will be made to the longitudinal-vertical surface waves as *R*-waves, or Rayleigh-waves, following the usage of Gutenberg ([29]). The transverse surface waves, again following Gutenberg, will be designated as Q-waves, or "querwellen" rather than Love-waves, as is often done. Their classification as Love-waves carries a genetic implication which at present seems to be unwarranted, since the theory of Love requires a layering of the outer crust, while transverse surface-waves have been shown by E. Meissner ([60]) to be possible where the velocity of bodily transverse waves increases with depth.

No satisfactory evidence has been found, in the present investigation, of the existence of other types at a recording station distant from the epicentre, though specific search was made for induced surface-wave forms described by Uller.

It is proposed at this point to investigate the path of the earth particle during the passage of Rayleigh-waves.

The first problem is the identification of the *R*-waves. The vertical component is, of course, the main criterion, since it distinguishes *R* from *Q*. The ideal situation is encountered in the recording of a quake which originated in an azimuth from the station which corresponds to the orientation of one of its horizontal instruments, an "end-on" quake, so to speak. In such a case, one horizontal component instrument records only *Q*, while the other horizontal and the vertical record *R* simultaneously.

Such a situation arose at the Ottawa station in the recording of the violent Atacama quake of 1922, November 11. This was number 1353, practically due south of Ottawa, at a distance of 8,230 km. Copies of tracings from the original seismograms are reproduced in fig. 18c. Earth amplitude graphs for this quake are shown in figs. 18a and 18b, in the first of which the vertical and NS are combined to show the recording of the *R*-waves.

The horizontal components of this quake were computed from Bosch records. No phase difference need be considered when comparing the NS with the vertical.

The nature of the earth particle movement can be readily ascertained. Starting at any given instant of time during the recording of the *R*-waves, the sequence of positions will be seen to be Up-South-Down-North, etc. In other words, *the rotation was retrograde with regard to the direction of propagation of the disturbance.*

A series of graphs of the earth particle path as shown by these records from 5h 10m 35s to 5h 20m 10s appears in fig. 24.

The path is elliptical. At the beginning of the first train of R-waves, the ellipse is oriented with its major axis horizontal. During the passage of the train, this orientation gradually changes, until at one point just after 13 minutes the major axis is vertical. In the more regular second train of R, the rotation ellipse is in a practically constant orientation, with the major axis horizontal and roughly in a ratio of 4 : 3 with the vertical minor axis. The reality of the apparent change in orientation of the ellipse in the first train may be open to question. As can be seen on the reproductions of the original seismograms in fig. 18c, the irregularities make it quite possible that errors in the determination of apparent turning points were sufficient to seem to alter the ellipse's orientation. In general, the rotation ellipses were found to have their major axes practically horizontal, or only slightly inclined.

The vertical seismograph during the recording of 1,353 was working with optimum sensitivity, and there seems to be no valid reason for doubting the reliability of the earth amplitudes computed from it. Any doubt which may be justifiable as to the reliability of the amplitude graphs would be connected rather with the Bosch instruments, and any corrections, if made, would be such as to increase the excess of horizontal over vertical motion. At another point of the investigation, several direct comparisons were made between earth amplitudes for the same quake computed from Bosch and Milne-Shaw records. The Bosch reductions were consistently smaller than the Milne-Shaw. Fig. 11a shows an interval from the surface phases of 3540 in which the EW component of true earth movement, as computed from Bosch II, is compared with the same as computed from Milne-Shaw 17.

Fig. 25 is an earth particle path graph for quake No. 2028, from 13,300 km. practically due west of Ottawa. It will be noted that here the sense of rotation is also retrograde as regards the propagation direction of the disturbance. The ellipse is flatter, the ratio of horizontal to vertical being nearer 3 : 1.

Like determinations were made for quakes 1274, 1815, 1910, 1961, 2045, 2307, 2336, 2413, 3117, and 3544, a total of twelve, including 1353 and 2028 above. These represent every cardinal azimuth from Ottawa, and three intermediate ones, where the combined horizontal components indicated a practically pure longitudinal vibration which could be combined with the vertical. Of the twelve, one originated in the vicinity of Jan Mayen, two in the southern mid-Atlantic, one on the isthmus of Panama, one southeast of Madagascar, one north of Easter island, one in Turkey, one in the interior of China, three in the south Pacific near the New Hebrides, and one in Chili. Without exception, the particle was found to be rotating in a retrograde sense as regards the propagation direction of the disturbance.

It remained, however, for quake 2413 to give the outstanding illustration of the phenomenon. It originated at a distance of 13,500 km. practically due west of Ottawa. The direct R-waves exhibit the retrograde rotation of the earth particle as usual. A little over an hour after the first R arrivals, the W_2-waves, which travelled from the origin via the antipodes and the major arc, reaching the station from the east, are among the most clearly marked of any that have been identified on Ottawa records. Where the first R-waves, coming from the *west*, exhibit a vibration direction of ***east-up-west-down***, that is, retrograde the W_2-waves, coming from the *east*, quite distinctly show a vibration sequence of ***west-up-east-down***.

Photographic facsimiles of the original records of the EW Bosch and the vertical component in the R and W_2 portions of 2413 are shown in fig. 2. Examine the top of the two lines of surface waves at, say, 46 minutes. On the exact minute, the horizontal component shows the earth particle at its maximum excursion to the east. The vertical component at that instant is approaching its maximum excursion up, which it reaches shortly after the minute. (The minute breaks are 2 seconds in length, from 58 to 60 seconds.) The sequence, then, is *east-up-west-down.* Now examine the 46th minute in the next line. (The arrival of W_2 is not shown in the figure.) Just before the minute, the horizontal component registers a maximum displacement to the west, followed on the minute by a maximum up on the vertical. The sequence here is *west-up-east-down.*

EARTH PARTICLE PATH IN THE R-WAVE—DISCUSSION AND THEORY

Only one reference, and that implicit, has been found in the literature on this subject, which touches on the fact that the earth particle traverses its elliptical path in a retrograde sense during the passage of R-waves. Mlle. Y. Dammann ([12]), in fig. 3 of her treatise on long-waves, reproduces records obtained at Strasbourg of the earthquake of 1924, March 4 (Ottawa No. 1706). The azimuth from Strasbourg was practically due west, so the EW and vertical components inscribed the R-waves. These two components are found to be directly comparable in amplitude and apparent period, but slightly out of phase, with the horizontal component in the lead. This gives a rotation sense of *east-up-west-down,* the retrograde motion established in the present investigation. Mlle. Dammann states, in discussing the records, "Le sens de parcours de l'ellipse est conforme à celui que prevoit la théorie de Lord Rayleigh."

There are not sufficient instrumental data given to show whether an apparent slight excess of vertical over horizontal trace amplitudes would be maintained, or increased, when the motion is reduced to true earth amplitudes.

In Lord Rayleigh's classic paper ([69]), page 447, equations ([39]), he gives as the equations determining motion at the surface, when $\sigma = \cdot 25$,

$$\alpha = \cdot 4227 \sin (pt + fx)$$
$$\gamma = - \cdot 6204 \cos (pt + fx) \qquad (5)$$

where α denotes displacement along the x-axis, and γ along the z-axis; p/f being the velocity of propagation of the progressive wave.

The motion of an earth particle, as defined by these equations, is determined by considering t to increase while x remains constant. Taking the positive direction of the x-axis toward the right and of the z-axis (as Rayleigh does) downward, and assigning successive values to t, it is obvious that the earth particle traces out an elliptical path in the clockwise direction.

The direction of propagation of the disturbance is given by holding the argument $(pt + fx)$ constant while t and x vary; hence x decreases as t increases, and the direction of propagation is from right to left.

The motion of the earth particle at the highest point of its path is thus opposite to the direction of propagation of the wave-front, and its path is therefore designated as *retrograde.*

It should be noted that the ratio $Z : H$ of the vertical to horizontal displacements defined above results from the assumption that the medium on the surface of which the waves are propagated is a homogeneous isotropic one, and that for this medium Poisson's ratio (σ) has the value $\frac{1}{4}$.

This ratio is a number expressing the ratio of lateral contraction to longitudinal extension when a bar of the material is strained by forces applied to its ends, and is frequently used as a convenient means of expressing the relation between the elastic constants of a material. The elastic constants λ and μ, usually called Lamé's constants, are generally used in stating the equations of motion in an elastic solid, from which equations (5) and (6) are derived. μ has a direct physical meaning. It is the rigidity, or resistance to change of shape. λ, however, does not have a direct physical significance. It enters a definition of Poisson's ratio, σ,

$$\sigma = \frac{\lambda}{2\,(\lambda+\mu)}$$

and that of another physical constant determinable by experiment, the modulus of compression, or incompressibility, κ,

$$\kappa = \lambda + \tfrac{2}{3}\mu$$

which is a quantity obtained by dividing the measure of a uniform pressure by the measure of the cubical compression which it produces.

Experiments have led to the widespread acceptance of $\frac{1}{4}$ as a close approximation to the value of σ for materials in the earth's outer crust. As a result, it has been assumed that the constants determining Rayleigh-waves are essentially those deduced from the acceptance of $\frac{1}{4}$ as Poisson's ratio. It is obvious, however, that this may not be the case. On the other hand, it is to be noted that no possible value of Poisson's ratio will lead to values of the $Z : H$ ratio less than unity in the case of an isotropic medium.

In the present investigation, the ratio $Z : H$ of the vertical to the horizontal component of motion in the R-waves was found in all cases examined to be less than unity.

Theory shows that for an isotropic medium for which Poisson's ratio is $\frac{1}{4}$, the $Z : H$ ratio in R should be approximately 1·5. We are, however, dealing with a medium which is not isotropic. Quite possibly the modulus of rigidity (μ) is different in the vertical and horizontal directions, and we may expect the modulus of incompressibility (K) to vary with the depth. It may be pertinent to investigate the extent to which the $Z : H$ ratio would be affected by such conditions.

Other investigators have reported somewhat similar results. Mainka, in particular, ([53]), ([54]), has made a large number of observations in this connection. From 280 seismograms, with 534 values for $Z : H$, he found that for about 31 per cent the $Z : H$ ratio lay between ·91 and 1·00, while for 28 per cent it lay between 1·21 and 1·50, with most of the values around 1·3 and 1·4.

Galitzin ([15]) found the $Z : H$ ratio ranged from ·46 to 1·28 with the greatest number of observations between ·7 and 1·0.

Where the quakes used in such measurements are not "end-on" to the recording instruments, however, there may be some doubt as to the accuracy of horizontal component records, as will be discussed later.*

The status of the matter as this investigation appears to leave it may be summarized briefly. The earth particle during the passage of Rayleigh-waves was found, without exception in the present instance, to rotate in a retrograde sense as regards the propagation direction of the waves. This is required by the theory of Rayleigh, but does not seem, so far as the writer can find, to have been previously established explicitly by observational data.

The observed $Z : H$ ratio of displacements is, in all the cases examined, less than unity, and thus disagrees with the theoretical ratio for a homogeneous isotropic medium. It is regarded as possible that this arises from the non-isotropic character of the earth's surface layers.

The relation of rotation sense to propagation direction is suggested as a means of identifying the various *W*-waves which are registered after arrival by the major arc, or after one or more circuits of the globe. It might also be used in trying to establish a propagation direction for microseisms.

There has been no attempt to include this last within the scope of the present study, but a casual application of the test to a few trains of microseisms at Ottawa has indicated distinct possibilities.

R-wave Velocities

As indicated in the study of earth particle paths, the vertical component is the vital criterion in the identification of *R*-waves. In collecting data for the present investigation, the only velocities used were those computed from quakes for which the vertical record at Ottawa permitted a reliable identification of *R*.

The observations of this investigation have been tabulated in six groups, according to the nature of the surface path from epicentre to station. The first group includes continental paths northwest of Ottawa; the second, continental paths south and southwest of Ottawa; the third, Atlantic Ocean paths; the fourth, Pacific Ocean-North America paths; the fifth, Europe-Atlantic paths; and the sixth, isolated exceptions, such as an Africa-Atlantic and an Asia-Arctic-Greenland path. Table VI lists the data. For each velocity, the periods found to exhibit that velocity are shown under the indicated path columns. The quake numbers and distances are used to identify the entries. Only the velocities of centres of energy at the head of well-defined groups were measured. The first period shown is that for which the velocity was computed. The maximum and

*Love made the following suggestion, from the theoretical standpoint: (47, page 178)

"All the general features of the large waves of earthquakes are represented in the theory suggested by the analogous theory of waves on deep water, except the observed comparative smallness of the vertical motion. Now, if the oscillatory waves which appear to be transmitted over the surface were physically existing simple harmonic wave-trains, this difficulty could only be met by the supposition that adequate instruments for separating the vertical motion from the horizontal, and recording it faithfully, have not so far been devised. But the suggestion which has been made already that these observed oscillations are the result of superposing an infinite number of standing simple harmonic waves, may perhaps furnish a different explanation. Such waves can combine to form progressive oscillatory waves, but we have seen that there is no reason why the ratio of amplitude of the vertical and horizontal component displacements which is characteristic of the constituent standing waves should be maintained in the maxima of the aggregates. The difficulty may, therefore, perhaps be regarded as less serious than it has been thought to be."

This suggestion, however, may lead to greater difficulties than those from which it extricates us. The principle of super-position of simple harmonic waves allows for a combined amplitude greater than that of the constituent waves, as well as one which is less than that of the individual waves. Yet the reported observations of Z : H greater than 1·5 are so few as to be outstanding. If the superposition of simple waves gives the recorded surface motion, it would seem to be entirely likely that the true vertical motion of individual waves is considerably less than that of the recorded group, or centre of energy.

TABLE VI.—R-WAVE VELOCITIES

Velocity	1. Continental Path			2. Continental Path			3. Oceanic Path			4. Oceanic-Continental			5. Oceanic-Continental			6. Oceanic-Continental		
	Northwest			South and Southwest			Atlantic			Pacific-N. America			Atlantic-Europe			Miscellaneous		
	T_e	Quake No.	Distance	T_e	Quake No.	Distance	T_e	Quake No.	Distance	T_e	Quake No.	Distance	T_e	Quake No.	Distance	T_e	Quake No.	Distance
km./sec.			km.			km.			km.			km.			km.			km.
2·50																		
2·51	17−16	1387	7,620															
2·52	−14																	
2·53																		
2·54																		
2·55																		
2·56																		
2·57																		
2·58																		
2·59																		
2·60																		
2·61				17	1353	8,230												
2·62	18	1387	7,620															
2·63																		
2·64	17	1812	8,780															
2·65																		
2·66																		
2·67	18	1974	9,230	19	3,092	3,590												
2·68																		
2·69																		
2·70																		
2·71																		
2·72																		
2·73																		
2·74																		
2·75																		
2·76																		
2·77	? > 15	1969	8,860															
2·78																		
2·79																		
2·80	20−17	3551	6,980															
	18−15	2194	7,390															
2·81																		
2·82	17	3341	8,050															

2·83																	
2·84																	
2·85																	
2·86																	
2·87																	
2·88																	
2·89																	
2·90																	
2·91																	
2·92	20	1974	9,230														
2·93	20	1446	7,380														
2·94																	
2·95																	
2·96	20–19	3161	9,580										(Greenland)				
2·97													13	1274	4,450		
2·98																	
2·99																	
3·00	24–22 –17	2194	7,390														
3·01																	
3·02	24	2194	7,390														
3·03	19–14	1812	8,780														
3·04																	
3·05																	
3·06	18–15	3540	7,000														
	18–15	3551	6,980														
3·07																	
3·08	18	1887	7,200										25–20	3117	7,620		
3·09	20–18	3542	6,950														
3·10																	
3·11																	
3·12	24	2616	7,020														
3·13	24–22	3161	9,580	26–20	3317	8,920											
	30–24	1387	7,620														
3·14																	
3·15																	
3·16																	
3·17				25–20	3314	8,980											
3·18	20	1462	5,520														
				22–13	1715	3,900											
3·19				20–17	1353	8,230											
				25–20 –17	3303	7,550											

TABLE VI.—R-WAVE VELOCITIES—*Continued*

Velocity	1. Continental Path			2. Continental Path			3. Oceanic Path			4. Oceanic-Continental			5. Oceanic-Continental			6. Oceanic-Continental		
	Northwest			South and Southwest			Atlantic			Pacific-N. America			Atlantic-Europe			Miscellaneous		
	T_0	Quake No.	Distance	T_0	Quake No.	Distance	T_0	Quake No.	Distance	T_0	Quake No.	Distance	T_0	Quake No.	Distance	T_0	Quake No.	Distance
km./sec.			km.			km.			km.			km.			km.			km.
3·20	25	3542	6,950	20−18	1351	8,060										24−15	(Lena R.) 2992	7,020
	24−15	2992	7,020	20−18	1354	8,080												
				22	3139	5,680												
3·21																		
3·22				24−16	1706	3,900												
3·23	22−20	3540	7,000										Harv. 23−18	3437	9,620			
	25−22	3551	6,980										Ott. 23−18	3437	9,620			
3·24																		
3·25																		
3·26	30	1974	9,230															
3·27	27−25	3543	6,950															
3·28													22	2931	7,950			
3·29																		
3·30				24−10 −13	2039	3,980												
3·31													27−19	1885	8,740			
3·32																		
3·33																		
3·34																		
3·35																		
3·36																		
3·37																		
3·38	(20+)	2194	7,390	24	3317	8,920												
	30	2616	7,020															
	(21−17)	1417	7,390															
3·40	30−24	1387	7,620															
3·41																		
3·42	24−20	1917	7,320										25 Harv.	3437	9,620			
3·43	20	1887	7,200										25 Ott.	3437	9,620			
	26	1462	5,520															
3·44																		

3·45				30–22	1351	8,060												
3·46																		
3·47																		
3·48													25–19	1274	4,450			
3·49																		
3·50										23	2413	13·050						
3·51				$W_2$28	1353	31·770				*M*								
3·52																		
3·53														Asia				
3·54													32–27	1815	10,620			
3·55																		
3·56																		
3·57	30–20	3542	6,950															
3·58	40–29	3161	9,580	48–24	3185	3,700												
				32	2356	3,700												
3·59																		
3·60				38–20	3303	7,550												
3·61																		
	Harv. Ott. (Atl.) 500																	
3·62	38–33	3544	(4,400)	34–26	1353	8,230												
3·63	35–27	3551	6,980															
3·64				35–22	3314	8,980												
3·65				44–24	3092	3,590												
3·66							23–18	3352	7,350									
3·67	40	3161	9,580	37–21	1961	4,140												
	40–12	3341	8,050															
3·68	37–26	3540	7,000															
	34	3543	6,950										30	1885	8,740			
3·69				44–20	3263	3,700												
3·70				44–24	1763	3,690												
3·71				–16														
3·72																Africa-Atl. N. A.		
3·73																22–16	2570	16,100
																M16		
3·74																		
3·75	50–41	1812	8,780															
	–27																	
3·76																		
3·77																		
3·78										$W_2$21	2413	26,950						
3·79																		
3·80				50–20	3344	3,740				(43)	2413	13,050						

TABLE VI.—R-WAVE VELOCITIES—*Concluded*

Velocity	1. Continental Path			2. Continental Path			3. Oceanic Path			4. Oceanic-Continental			5. Oceanic-Continental			6. Oceanic-Continental		
	Northwest			South and Southwest			Atlantic			Pacific-N. America			Atlantic-Europe			Miscellaneous		
	T_o	Quake No.	Distance	T_o	Quake No.	Distance	T_o	Quake No.	Distance	T_o	Quake No.	Distance	T_o	Quake No.	Distance	T_d	Quake No.	Distance
km./sec.			km.			km.			km.			km.			km.			km.
3·81										NW						Africa-Atl. N. A.		
										36–24	2630	14,000				21	2045	16,000
										M						M		
3·82										$W_2$24	2630	26,000						
3·83													35	1885	8,740			
3·84										34–25 –19 M M	2307	9,400						
										W_5	2630	94,000						
3·85							34–19	1910	3,530	35–20	2028	13,300						
										34–22	3083	13,400						
3·86							33–17	3544	4,400									
3·87																		
3·88	50	3551	6,980							40–33 –27–20	2336	13,200						
														Asia				
								(Harv.)										
3·89							28–17	3544	3,900	W_4	2630	66,000	41–38	1815	10,620			
							28–16	3368	4,900									
3·90	60–30	1387	7,620				37–15	1536	3,600									
							37–15	1537	3,600	38–20 –17	2697	13,600						
3·91							26–19	2250	4,900									
							30	3352	7,350									
3·92																		
3·93																		
3·94																		
3·95										(W_2)								
										23–19	3083	26,600						
3·96																		
3·97																		
3·98																		
3·99																		

4·00						
4·01						
4·02						
4·03						
4·04						
4·05						
4·06						
4·07	....	50–20 2350 3,900				
4·08						
4·09						
4·10	....	....	....	....	37–30 2931 7,950	
4·11						
4·12						
4·13						
4·14						
4·15						
4·16						
4·17						
4·18						
4·19						
4·20						
Quakes used	2639, 3372, 2973, 1996, 3192, 1462, 2890, 3370, 3381, 1887, 2616, 2617, 2618, 2619, 3540, 3542, 3543, 3551, 1387, 1386, 3024, 1417, 2194, 1866, 1917, 1446, 3341, 3161, 1969, 1812, 1974. Total..........31	1351, 1353, 1354, 1356, 1706, 2245, 2291, 2779, 3139, 3092, 3303, 3314, 3317, 1961, 1715, 3690, 2350, 2356, 3185, 3263, 3292, 3344. Total..........22	1556, 1537, 1910, 2151, 2250, 2921, 3352, 3368, 3544. Total.......... 9	2028, 2307, 2697, 2336, 2413, 3083, 2630, 2900. Total.......... 8	2931, 1815, 1885, 3437, 1274, 3117. Total.......... 6	2045, 2570, 2992. Total.......... 3
Maxima at T_e =	15, 17, 18, 20, 23, 30, 35.	20, 22, 23, 25, 30, 34, 35.	Maxima in general not defined — uniformly lessening peaks. (Absence of strong enough Q to cause interference?)	17, 19, 25, 20, 24	....	16, 21.
No clearly marked surface phases on	....	2779, Distance 8,320 km.	2151, Distance 3,200 km.			
No R identified on	....	1356, Distance 8,020 km. 2245, Distance 3,050 km.				
No Q identified on	....	1354, Distance 8,080 km. 2350, Distance 3,900 km. 3185, Distance 3,700 km.	3544, Distance 4,400 km. 1910, Distance 3,530 km.	....	....	2045, Distance 16,000 km. 2570, Distance 16,100 km.

minimum apparent periods in some of the wave groups are also shown. They were recorded on the possibility that the range of periods might be found to influence the velocity of the head of the train. No such correlation seems to be established.

The velocities observed are, in all probability, group velocities. No attempt has been made to determine statistical or graphical averages. Apparent periods in the early portions of wave trains cannot be determined with an accuracy which warrants the arbitrary statement that a given period exhibits a definite velocity and no other. Accordingly, it is felt that the point has not yet been reached where it is safe to attempt to determine exact velocity laws from the data available. Another important reason for listing the data exactly as observed, without combining to obtain averages, is that it is felt that only by some such method will local effects of path on velocity be discovered.

Within given path groups, notably 1 and 2, for which there are more observations, *there is a distinct tendency for velocity to increase with period.* There is strong evidence for the reality of this phenomenon in spite of overlapping of values and general haziness of transition zones, which are possibly introduced in part by uncertainties of observation, by local path differences, or by errors in the computations of distance and time of origin.

There is, further, a marked correlation between the values obtained for NW and S continental paths, indicating a similarity which might be expected, but should not be assumed simply because both paths are continental.

The values for the Atlantic, while not numerous, are well enough determined to clearly indicate a markedly higher velocity for those paths than for the continental ones. They are, in fact, of the same order of magnitude as for the Pacific-North America paths.

Number 3544 was well recorded at both Harvard and Ottawa on the same great circle from the epicentre, and merits special attention. The apparent velocity of *R* from the epicentre to Harvard was 3·89 km./sec. The first waves at Harvard had an apparent period of 28 seconds. The beginning of the same train at Ottawa showed an apparent period of 33 seconds, but a velocity from Harvard to Ottawa, using the epicentre-Harvard value and Harvard-Ottawa value weighted according to the respective distances, was computed to be 3·86 km./sec., the exact value observed for the epicentre to Ottawa path. It will be noted that the velocity of 3·62 km./sec. from Harvard to Ottawa is in line with others for the same periods over total continental paths (columns 1 and 2 of Table VI). This gives direct evidence of the difference between Atlantic and continental velocities.

At the bottom of each column in Table VI are listed the periods at which concentrations of energy appeared on the seismograms. It may be noted that in the two continental groups there is an absence of periods between 25 and 30 seconds. Whether or not this has a real physical significance could not be estimated from the data of the present study.

Wrinch and Jeffreys ([132]) suggested the possibility that *R*-wave velocities might yield information concerning the thickness of a postulated surface layer of the crust, that is, the so-called granitic layer. It was suggested that, if the lower layers transmitted vibrations with greater velocities than the outer, *R*-waves of increasing wave length would derive increasing velocities from the underlying higher-speed layers as their effects outweighed those of the surface layers.

If the change in velocity in a lower layer were sudden, the *R*-wave velocities might be expected to show a discontinuity of velocity in the vicinity of the periods which first penetrated the high-speed layer sufficiently to have their velocity controlled by it. No such discontinuity in the velocities appears in Table VI. Actually, as can be clearly seen, the data are too variable to permit clean-cut quantitative inferences.

Considerations of *R*-wave velocities must include possibilities of changing wave form in the course of propagation, as discussed by Sezawa ([91]).

Macelwane ([48]) in a study of records of the California Earthquake of 1922, January 31, reported a progressive lengthening of period and wave length in "*M*" waves with distance, while the velocity remained approximately the same. This finding, however, cannot be compared directly with the results of the present investigation. It applies to "*M*" which, as shown in a later section of this report, is not in general identifiable as *R*.

Gutenberg ([23 24 29b]) appears to be the only previous investigator to have published observations of Rayleigh-wave velocities in terms of period and path, resulting in evidence that they are subject to dispersion. His results were obtained, in the main, from studies of a few individual quakes as recorded at many stations, such as the quakes of 1927, June 26, in the Tonga Deep, 1923, September 1 and 2, in Japan, and others. The paths on which he reports are not directly comparable with the ones studied here. He finds, however, over all paths, an increase of velocity with greater periods. His tables, also, show a distinctly higher velocity for Atlantic Ocean-Europe paths than, for example, for Eurasian paths. Pacific paths show the highest velocities, but they are only slightly in excess of the Atlantic values which in this case, it must be remembered, include a portion of continental path.

In calculating the apparent velocities from a computed epicentre, there is, of course, uncertainty as to the exact point at which the *R*-waves can be regarded as having started. Investigations of Nakano ([64]) indicate that for an assumed depth of focus of 30 km., Rayleigh-waves may be expected to originate from 20 to 70 km. from the epicentre. Since the limits within which the epicentres are determined are no closer than this, *R* may be considered, for purposes of velocity computations at a distance, as having originated practically at the epicentre.

The effect of focal depth has been studied by Banerji ([4]), who demonstrates that the amplitudes of *R* decrease as the depth of focus increases. Several records were found in the present study which at Ottawa showed practically no clearly-defined *R*-waves. It is likely that the absence of *R* in those cases offers a qualitative indication of abnormal depth of focus.

Finally, consider Table VI, column 4, velocities 3·78 and 3·80. It will be noted that while the *R*-waves of 2413 with periods of the order of 43 seconds display a velocity of 3·80 km./sec., the W_2-waves from the same quake, with periods of 21 seconds, show a velocity of 3·78 km./sec. (*W*-waves, in fact, are generally notable for their uniformity of period and velocity. An explanation of this was suggested by Gutenberg in a paper, "The Process of Formation of Seismic Surface-waves," translation by Ernest A. Hodgson, which was presented before the New York 1929 meeting of the Eastern Section of the Seismological Society of America, and is to be published in the bulletin of the society.) Fig. 2 illustrates a possible explanation of this apparent anomaly. The $Z : H$ ratio in the *R*-wave section is of the order of ·5, whereas it is practically 1·0 in the Rayleigh-wave groups of W_2. There might seem, then, to be a possibility that a relationship exists between the $Z : H$ ratio and the ratio of depth of penetration to wave length. It might be found that, though the same velocity is shown by different periods, a given period does not at all times represent the same depth of penetration, hence its velocity is not always controlled by the same materials.

Group Velocity

Group velocity undoubtedly plays an important rôle in determining the character of *R*-wave oscillations as recorded at seismograph stations. The seismogram, in all probability, registers the apparent motion of centres of energy which have been propagated with the appropriate group velocity. The effect on the $Z : H$ ratio of amplitudes, as discussed by Love, has already received mention (page 287). A discussion of what is meant by group velocity can be found in such texts as those of Gutenberg ([29]), Haas ([31]), Lorentz ([46]), and others.

Rayleigh-waves—Horizontal Component Records

Most of the reduced earth amplitude graphs were made for the specific purpose of attempting to determine the reality of certain apparent phases or groups in the *R*-waves. The study resulted in some rather definite indications concerning the significance of horizontal component records of the so-called maximum portions of seismograms, which are generally indicated by reporting stations as "*M*."

When a quake is "end-on" relative to the orientation of the horizontal component instruments, there is a definite correlation between the onset of *R* as indicated by the vertical, and the beginning of the longitudinal motion on the proper horizontal component instrument. Figs. 18a and 23 illustrate this. When it is not "end-on," however, the horizontal records do not in general indicate the beginning of *R*. Figs. 8, 9, 10, 11, 13, and 21 are examples. In such cases, moreover, the horizontal records (reduced to true earth amplitudes) do not show maxima with any consistent relation to the actual *R*-wave maxima as indicated by the vertical.

No identity was established between apparent surface phases at varying distances, other than similar groupings where periods were comparable. 3540 and 3551 (7,000 km. NW.), and 1353 (8,230 km. S.) illustrate similar groups of this kind. (Figs. 10, 11, 18.)

Fig. 8 offers a comparison of the Harvard and Ottawa records of 3542—the stations lying on the same great circle with the epicentre. Even reduced to true earth amplitudes they display discordance of wave form. The original seismograms show still greater apparent discrepancies. In contrast to this, fig. 6 shows the reduced amplitudes for 3544, in which transverse surface-waves seemed to be almost entirely absent. Here *R*-waves were being recorded essentially without the interference of other types of motion, and the horizontal records were reliable. In this connection, number 1910, recorded five years earlier, from a neighbouring epicentre, distance 3,530 km., is practically a facsimile copy of the Harvard record of 3544, for which the Harvard distance was 3,800 km.

The findings apply to the records of horizontal component instruments which are not oriented in line with or normal to the direction of propagation of an earthquake disturbance. The evidence seems to indicate that the so-called "maxima" in such cases owe their character in general to fortuitous fluctuations in the phase, period, and amplitude of the transverse and longitudinal motions which combine to cause them. As a result, unless a station is equipped with a vertical seismograph, its records do not give a reliable indication of the onset, duration, or character of R, for quakes which are not "end-on" with respect to the instruments' orientation.

This would suggest that *the reading of "M" for the bulletins of seismograph stations is meaningless.* Only when the azimuth of the quake is "end-on" can an accurate determination of true amplitude maxima be made, and those amplitudes be resolved in terms of transverse and longitudinal motions. It is, of course, well known that *trace* maxima, in any case, are a definite function of the recording instrument's period and consequent magnification of different earth periods. When a quake is not "end-on" interference between longitudinal and transverse motions of the ground, if these are of different periods, gives a trace pattern that cannot be untangled in terms of true longitudinal and transverse motions.

From this, it will be clear that no part of the horizontal record of a quake whose azimuth was not one of the cardinal instrument directions can be selected with assurance as representative R-wave registration—there is at practically all times a transverse element of unknown magnitude present.

Complication arises from the problem of phase as discussed previously. When the periods of Q and R are comparable in magnitude, as appears to be the case frequently, if not invariably, in the later parts of seismograms, the problem of phase is unimportant. If, however, in earlier portions of Q and R, their periods differ to any marked extent, and a single instrument is registering a component of each, the instrument will have one phase lead for Q and another for R. It would, accordingly, be practically impossible to accurately resolve the trace in terms of components of Q and R. This point is further amplified in the discussion of record character, below.

Record Character in Connection With Place of Origin

In the course of the present study, a few opportunities were presented to compare records from the same and neighbouring epicentres, in the light of the opinion held by some station seismologists that certain epicentral regions yield quakes of characteristic types.

Fig. 10a shows the EW record of 3540 superposed on the same component of 3551. The practically point-for-point identity of the two records in period and relative amplitude is remarkable, though the energy of 3540, as evidenced by maximum amplitudes, is very much less than that of 3551.

A second case, not illustrated, was mentioned above in connection with quakes 1910 and 3544. 1910, distance 3,530 km., was recorded at Ottawa 1924, October 14. 3544 was registered at Ottawa and Harvard on Milne-Shaw seismographs adjusted to the same constants, on 1929, July 6. The distance from Ottawa was 4,300 km., from Harvard, 3,800 km. The epicentres were in the same general region in the Atlantic Ocean. Both Ottawa and Harvard records of 3544 are identical in character with that of 1910.

Numbers 2623 and 2624 presented an interesting case of two shocks almost exactly an hour apart, from approximately the same origin. Their records, one immediately below the other on the seismograms for that day, are almost perfect twins. Fig. 3 illustrates this.

On the other hand, 1763 and 2350, computed to have practically the same epicentre, are totally different in character.

Two series from the same region in the Aleutians provided an interesting comparison. 2616, 2617, 2618, and 2619 followed each other in close succession, 1926, October 13 and 14. 3540, 3542, 3543, and 3551 occurred in the same region, 1929, July 6 and 7. The records are similar, though not identical, in character.

Number 2039, 1925, March 29, was recorded at Ottawa and Rio de Janeiro at distances of 3,980 and 4,400 km. respectively. (See fig. 4.) The epicentre was about S.10°W. from Ottawa, and NW. from Rio de Janeiro. The EW Milne-Shaw component records at the two stations present a striking contrast. The instruments were operating with the same constants. The record of the surface-waves at Ottawa is quite regular, with a maximum period of 21 seconds well marked. At Rio de Janeiro, it is much less regular, with a period of the order of 9 seconds. *The Rio de Janeiro record, in fact, might serve as a fair type representative of Ottawa records of quakes from the NW. or SW. at comparable distances.* In fig. 4, the Ottawa record of No. 1996, from the NW., is shown for comparison.

This instance of No. 2039 suggests that either there are marked differences between the epicentre-Rio de Janeiro path and the epicentre-Ottawa path which merit investigation, or the orientation of instruments has a much more fundamental influence on the utility of horizontal component seismograms than has been recognized. It is proposed at Ottawa to re-orient the Milne-Shaw horizontal instruments at an early date to place them in line with and normal to the many quakes which originate along the great circles northwest and southwest of the station, with a view to comparing records thus obtained with those registered on NS and EW instruments at present.

Without multiplying examples further, the indications observed may be summarized briefly. It seems clear that quakes from exactly the same epicentre (as nearly as it can be determined) do, on occasion, give practically identical records at Ottawa. It cannot be said, however, from the observations made in this investigation, that there is any notable inherent identity between the surface phases of quakes from a given region, or difference between those of comparable distances from different epicentral regions. It is believed that many apparently unique characteristics are for the most part functions of the azimuth of the quake from Ottawa, coupled with the orientation of the instruments.

Summary

A study of earthquake surface-waves at a distance from the epicentre was made from the records of a single station. It was found desirable to concentrate chiefly on Rayleigh-waves, concerning which there seem to be fewer empirical data than for most of the other wave types recorded by seismographs.

The data for the investigation were taken, with five exceptions, from records of the Ottawa seismograph station. Four records supplementing these were obtained at the Harvard seismograph station, and one at Rio de Janeiro, on Milne-Shaw seismographs adjusted to the same constants as the instruments of that make in service at Ottawa. The records from Ottawa, obtained over a period of years, offer for study earthquakes from all parts of the globe, registered under identical conditions by the same instruments, with constants well determined, and with accurate time registration.

Records for the period between 1922 and 1929 were examined, and 127 of the quakes best recorded were selected for study.

In the discussion of the recording instruments, a special attention was accorded the constants of, and reliability of records from, the vertical component instrument.

Portions from the surface phases of fifty-six components, representing eighteen quakes, were reduced to true earth amplitudes, for purposes of rigorous comparison. The accuracy of this work is discussed.

It has been known for some time that there are at least two distinct types of surface waves: the Q, "querwellen," or transverse wave, with no vertical component; and a type with dominantly longitudinal and vertical displacements. No satisfactory evidence was found, in the present investigation, of the existence of other types at a recording station distant from the epicentre. The longitudinal-vertical type has generally been assumed to represent a motion first described mathematically by Lord Rayleigh, in 1885. So far as could be found, however, no explicit confirmation of this identity between observation and theory has been presented in connection with the fundamental relationship between the rotation sense of the earth particle and the propagation direction of the disturbance. Accordingly, such confirmation was sought in the present study.

The earth particle during the passage of Rayleigh-waves was found, without exception in the cases studied, to rotate in an elliptical path in a retrograde sense as regards the propagation direction of the disturbance. The same was found to be true for W_2-waves which, arriving from the opposite direction, exhibit a rotation sense which is the reverse of that in R. It is shown that this is required by the theory of Rayleigh.

The $Z : H$ ratio of vertical to horizontal displacements differs from the ratio predicted by theory for an isotropic medium. This result is in part confirmed by other investigations. It is regarded as possible that the disagreement arises from the non-isotropic character of the medium.

The relation of rotation sense to propagation direction is suggested as a means of identifying the various W-waves which are registered after arrival by the major arc, or after one or more circuits of the globe. It might also be used in trying to establish a propagation direction for microseisms.

There was no attempt to include this last within the scope of the present study, but a casual application of the test to a few trains of microseisms at Ottawa indicated distinct possibilities.

Rayleigh-wave velocities were studied in terms of period and path, using only those computed from quakes for which the vertical record at Ottawa permitted a reliable identification of R. These in all probability represent group velocities. No attempt was made to determine statistical or graphical averages, since it is felt that the point has not yet been reached where it is safe to attempt to determine exact velocity laws from the data available.

It was found that there is a distinct tendency for longer periods to exhibit greater velocities, that is, for the waves to be subject to dispersion.

There was, further, a definite correlation between the values obtained for northwest and south continental paths, while the values for the Atlantic indicated a markedly higher velocity than for continental paths.

Most of the reduced earth amplitude graphs were made for the specific purpose of attempting to determine the reality of certain apparent phases or groups in the surface-waves. The findings applied to the records of horizontal component instruments which are not oriented in line with or normal to the direction of propagation of an earthquake disturbance. The evidence indicated that the so-called "maxima" in such cases owed their character, in general, to fortuitous fluctuatious in the phase, period, and amplitude of the transverse and longitudinal motions which combined to cause them. As a result, unless a station is equipped with a vertical seismograph, its records do not give reliable indications of the onset, duration, or character of *R*, for quakes which are not "end-on" with respect to the instruments' orientation.

This would suggest that, except in certain special cases, the reading of "*M*" for the bulletins of seismograph stations is meaningless.

It seems clear that no part of the horizontal record of a quake whose azimuth was not one of the cardinal instrument directions can be selected with assurance as representative *R*-wave registration—there is at practically all times a transverse element of unknown magnitude present.

In the course of this study, a few opportuuities were presented to compare records from the same and neighbouring epicentres, in the light of the opinion held by some station seismologists that certain epicentral regions yield quakes of characteristic types. It was found that quakes from exactly the same epicentre (as nearly as it can be determined) do on occasion give practically identical records at Ottawa. It cannot be said, however, from the observations made in this investigation, that there is any notable inherent identity between the surface phases of quakes from a given region, or difference between those of comparable distances from different epicentral regions. It is believed that many apparently unique characteristics are for the most part functions of the distance, the azimuth of the quake, and the orientation of the instruments.

Lastly, the problem of instrumental orientation seems to assume important proportions. Horizontal component seismographs do not appear to give satisfactory records of all the earth vibrations reaching them from a given quake unless they are in line with and normal to the epicentre-station great circle. This is particularly true for surface waves, but it should not be surprising to find it true to a greater or less extent for other phases.

For this reason, it is suggested that recording stations, to render optimum service, should orient at least some of their instruments with reference to one or more epicentral regions from which most of their records are obtained, rather than in the traditional NS-EW planes.

TABLE VII.—SEISMOLOGICAL NOTATION EMPLOYED

ORIGIN OF THE DISTURBANCE

Focus	The exact place at which the disturbance originated. Generally beneath the surface of the earth. Theoretically regarded as practically a point.
Epicentre	A theoretical point (?) on the earth's surface, vertically above the focus.

WAVE GROUPS OR PHASES

P	Primæ; first preliminary tremors; longitudinal body waves that have penetrated below the outermost surface layer, following the shortest-time path from focus to station.
S	Secundæ; second preliminary tremors; transverse body waves that have penetrated below the outermost surface layers, following the shortest-time path from focus to station.
SS	S reflected once at the earth's surface between the focus and recording station.
SSS	S reflected twice at the earth's surface between the focus and recording station.
SSSS	S reflected three times at the earth's surface between the focus and recording station.
Q	Querwellen, or transverse surface-waves, with no vertical component of motion.
R	Rayleigh-waves; surface-waves with a vertical component and a horizontal longitudinal component; first discussed mathematically by Lord Rayleigh (69).
L	Long-waves; an indeterminate designation for waves, presumably of the surface groups, whose exact character is uncertain.
W_2	Surface-waves recorded after travelling by the major arc from the epicentre to the station.
W_3	Surface-waves recorded after travelling by the minor arc, epicentre to station, and one complete circuit of the earth.
W_4	W_2-waves after another complete circuit of the earth.
W_5	W_3-waves after another complete circuit of the earth.

NATURE OF THE MOTION

A	Amplitude: either *(a)* amplitude of the earth motion measured from the position of equilibrium in microns, + toward the north, east, or zenith; − toward the south, west, or nadir; or *(b) when so marked*, the *trace* amplitude or half range of movement on the record, measured from the median line, in millimeters.
μ	Micron; 1/1000 of a millimeter.
T_e	Period of earth motion.

DEDUCED DATA

h, m, s	Hour, minutes, seconds; Greenwich Mean Time (GMT), midnight to nidnight, 00h to 23h.
O	Time of the earthquake at the focus.
V	Arcual distance from the epicentre to the station.

CONSTANTS OF THE SEISMOGRAPH

T_o	Period of the seismograph.
V	Static magnification.
V_d	Dynamic magnification.
ϵ	Damping ratio; ratio of successive damped amplitudes.
r	Half width of zone within which friction will completely arrest the recording system. Expressed in centimeters.
R	Friction of a recording system, in dynes. (This is rarely used, and where it does occur would, by reason of the context, scarcely be confused with the symbol for Rayleigh-waves.)

BIBLIOGRAPHY

1. AICHI, K., "Transversal Seismic Waves on the Surface of Heterogeneous Material." (In English), *Proceedings of the Physico-Mathematical Society of Japan*, **4**, 137-142, Tokyo, 1922, July.

2. ANGENHEISTER, G., "Beobachtungen an pazifischen Beben," *Nachrichten von der Königlichen Gesellschaft der Wissenschaften zu Göttingen*, Mathematisch-physikalische Klasse, Heft 2, 113-146, 1921.

3. ANGENHEISTER, G., "A Study of Pacific Earthquakes," *New Zealand Journal of Science and Technology*, **4**, No. 5, 209-231, 1921.

4. BANERJI, S. K., "On the Depth of Earthquake Focus," *Philosophical Magazine*, Sixth Series, **49**, No. 289, 65-80, London, 1925, January.

   A review of this paper, in considerable detail, is given by P. Byerly in the *Bulletin of the Seismological Society of America*, **15**, No. 2, 148-152, June, 1925.

5. BERLAGE, H. P., "Recherches sur le début d'une phase d'un tremblement de terre," *Publications du Bureau central sismologique international*, Série A. Travaux scientifiques, Fascicule 1, 73-81, Strasbourg, 1924.

6. BYERLY, Perry, "Dispersion of Energy Without Dispersion of Frequencies in Transverse Elastic Waves in the Earth," *Bulletin of the Seismological Society of America*, **14**, No. 2, 90-135, Stanford, 1924, June.

7. BYERLY, Perry, "The Measurement of Time on Seismograms," *Bulletin of the Seismological Society of America*, **16**, No. 3, 194-195, Stanford, 1926, September.

8. BYERLY, Perry, "The Montana Earthquake of June 28, 1925," *Bulletin of the Seismological Society of America*, **16**, No. 4, 209-265, Stanford, 1926, December.

9. BYERLY, Perry, "The Nature of the First Motion in the Chilean Earthquake of November 11, 1922," *American Journal of Science*, Fifth Series, **16**, No. 93, 232-236, New Haven, 1928, September.

10. CAVASINO, Alfonso, "Sulla registrazione e velocità della onde W_2, W_3, W_4," *Bolletino della Società sismologica italiana*, **23**, 39 pages, 1 figure, Rome, 1920-21, 1922.

    Reviewed by J. B. Macelwane in the *Bulletin of the Seismological Society of America*, **13**, No. 2, 75, Stanford, 1923, June.

11. CONRAD, V., "Zur Frage des Schemas zur Auswertung von Seismogrammen," *Zeitschrift für Geophysik*, **2**, Heft 5, 168-169, Göttingen, 1926.

12. DAMMANN, (Mlle.) Y., "Contribution à l'étude des longues ondes. Tremblement de terre de Kan-Sou (16 décembre 1920)," *Publications du Bureau central sismologique international*, Série A, Travaux scientifiques, Fascicule 5, 59-91, Strasbourg, 1927.

13. (1) DOXSEE, W. W., "The Location of Epicentres, 1922," *Publications of the Dominion Observatory, Ottawa*, **7**, No. 3, 83-102, 1926.

13. (2) Doxsee, W. W., "The Location of Epicentres, 1923-4-5," *Publications of the Dominion Observatory, Ottawa*, 7, No. 4, 105-188, 1929.

13. (3) Doxsee, W. W., "The Location of Epicentres, 1926-7," *Publications of the Dominion Observatory, Ottawa*, 7, No. 5, 189-259, 1930.

14. Galitzin, B., "Étude comparative du mouvement du sol dans la phase principale d'un tremblement de terre," *Saint Pétersbourg, Comptes rendus, Commission sismique permanente*, 7, Book 1.

15. Galitzin, B., "Beobachtungen über die Vertikalkomponente der Bodenbewegung," *Bulletin de l'Académie Impériale des Sciences de Saint Pétersbourg*, Sixth Series, 983-1006, 1911.

A review by Elmar Rosenthal appears in *Gerlands Beiträge zur Geophysik*, **12**, Heft 2, (Besprechungen) 118, Leipzig, 1913.

16. Galitzin, B., "Über die Dispersion und Dämpfung der seismischen Oberflächenwellen," *Bulletin de l'Académie Impériale des Sciences de Saint Pétersbourg*, Sixth Series, **6**, (first half), 219-236, 1912.

A review by Elmar Rosenthal appears in *Gerlands Beitrage zur Geophysik*, **12**, Heft 2, (Besprechungen) 119-120, Leipzig, 1913.

17. Galitzin, B., "Zur Frage der Analyse zusammengezetzer harmonischer Schwingunen," *Bulletin de l'Académie Impériale des Sciences de Saint Pétersbourg*, 449-474, 1913.

18. Galitzin, B., "Vorlesungen über Seismometrie," B. G. Teubner, 538 pages, 162 illustrations, Berlin, 1914.

"Die Theorie der Oberflächenwellen," pages 64-93.

This is a German translation from the Russian, made with the assistance of Clara Reinfeldt, and edited by O. Hecker. It is an outstanding book dealing with the fundamental theory of the science of seismology. A bibliography of sixty-five numbers is appended.

19. Geiger, Ludwig, "Seismische Registrierungen in Göttingen im Jahre 1907 mit einem Vorwort über die Bearbeitung der Erdbebendiagramme," *Nachrichten der Königlichen Gesellschaft der Wissenschaften zu Göttingen*, Mathematisch-physikalische Klasse, 45 pages, 2 plates, Göttingen, 1909.

20. Gherzi, E., S.J., "Le tremblement de terre du 23 mai 1927, près de Liangchow, Kansu occidental," *Observatoire de Zi-Ka-Wei, Notes de Séismologie*, No. 9, 1-9, 1927.

21. Gutenberg, Beno, "Absorption und Fortpflanzungsgeschwindigkeit von seismischen Oberflächenwellen," *Physikalische Zeitschrift*, **24**, No. 21-22, 458-459, Leipzig, 1923, November 1-15.

Deals in particular with the Atacama quake of Chili, 1922, November 11. (Ottawa, No. 1353.)

22. Gutenberg, Beno, "Bearbeitung der instrumentellen Aufzeichnungen des Atacamabebens am 10. November, 1922," *Veroffentlichungen der Reichanstalt für Erdbebenforschung in Jena*, Nachtrag zu Heft 3, 1924. (Ottawa No. 1353.)

23. Gutenberg, Beno, "Der Aufbau der Erde," Gebrüder Borntraeger, 168 pages, 23 figures. Price 11 RM 10 pfg (bound). Berlin, 1925.

For an extended review of this book by V. Conrad, see *Physikalische Berichte*, **7**, (first half), No. 1, 16-17, 1926.

24. Gutenberg, Beno, "Bearbeitung von Aufzeichnungen einiger Weltbeben," *Abhandlungen der Senckenbergischen Naturforschenden* Gesellschaft, **40**, Heft 1, 57-88, 1925.

On page 77 are given R-velocities for particular periods, from the Japan quake of 1923, September 2. A lengthy bibliography of similar publications accompanies the article.

25. Gutenberg, Beno, "Die Geschwindigkeit der Erdbebenwellen und die elastischen Konstanten in den obersten Erdschichten," *Naturwissenschaften*, **13**, No. 17, 360-362, 1925.

A bibliography of twenty-seven numbers accompanies the paper.

26. Gutenberg, Beno, "Die Geschwindigkeit der Erdbebenwellen in der obersten Erdschichten und ihr Einfluss auf die Ergebnisse einiger Probleme der Seismometrie," *Gerlands Beiträge zur Geophysik*, **15**, Heft 1, 51-63, Leipzig, 1926.

27. Gutenberg, Beno, "Über Gruppengeschwindigkeit bei Erdbebenwellen," *Physikalische Zeitschrift*, **27**, 111-114, Leipzig, 1926.

28. Gutenberg, Beno, "Grundlagen der Erdbebenkunde," Gebrüder Borntraeger, 6 by 9 inches, 189 pages, 84 illustrations. Price 6.6 RM. Berlin, 1927.

This is number twelve of a series of scientific handbooks issued by the same publishers. It is designed to present, in a general but authoritative way, the basic ideas of geologists and seismologists on the causes and various manifestations of earthquakes, and to outline as completely as possible the methods of research, the interpretations of typical seismogram *et cetera*. A bibliography of 134 items, listing current literature bearing on the subject, is appended.

"Die Oberflächenwellen" are treated in Chapter 39, pages 158-168. Fig. 76, page 165, is a diagram of the earth's crust derived from surface-wave velocities as proposed by Gutenberg.

29. Gutenberg, Beno, "Theorie der Erdbebenwellen," Gebrüder Borntraeger (Handbuch der Geophysik, 4, Lieferung 1), 298 pages, 146 text-figures, 85 tabulations. Price 30 RM. Berlin, 1929.

The Handbuch der Geophysik, published by Borntraeger, is to be edited by Dr. Gutenberg. Lieferung 1 of Band 4 is the first section to appear. It is proposed to complete this Band and to begin the issue of Band 6 at an early date. The above presentation, written by Gutenberg, is a most important contribution to seismological literature. His discussion of the theory of seismic waves is brought up to date, including the contributions of Uller and Sezawa. The Lieferung is divided into three sections:—

(*a*) Theorie der Erdbebenwellen, pages 1-150.
(*b*) Beobachtungen von Erdbebenwellen, pages 151-263.
(*c*) Die seismische Bodenunruhe, pages 264-298.

— GUTENBERG, Beno, "Die Langenwellen bei Fernbeben," In Sieberg's "Erdbebenkunde," Chapter 32, 321-333. See No. 96 of this list.

30. GUTENBERG, Beno and SIEBERG, A., "Das Erdbeben in der chilenischen Provinz Atacama am 10. November 1922," *Veröffentlichungen der Reichsanstalt für Erdbebenforschung in Jena*, Heft 3, 1924.

31. HAAS, Arthur, "Materiewellen und Quantenmechanik," translated by CODD, L. W., as "Wave Mechanics and the New Quantum Theory," Constable and Company, Limited, 119 pages. Price 7 shillings 6 pence. London, 1928.

Chapters I and II, pages 1-18, treat Fermat's Principle, and the concept of Group Velocity, in fundamental demonstrations which should be of value to students of seismology.

32. HILLER, Wilhelm, "Über die Geschwindigkeit der seismischen Oberflächenwellen bei Weltbeben, insbesondere ihre Abhängigkeit von der geophysikalischen Beschaffenheit des durchlaufenden Weges," *Gerlands Beiträge zur Geophysik*, **17**, Heft 3, 279-310, Leipzig, 1927, August 29.

The author finds the following maximum velocities for the surface-waves of the nature of Rayleigh-waves (without reference to periods); in Eurasia, 2·87 kilometers per second; in the Pacific, 3·69 kilometers per second; in the Atlantic, 3·58 kilometers per second; in all ocean deeps greater than four kilometers, 3·66 kilometers per second; and in Antarctica, 2·78 kilometers per second. No change in velocity after more than one complete passage about the earth was found to occur.

33. HODGSON, Ernest A., "Variable Velocity of L-Waves," *Bulletin of the Seismological Society of America*, **11**, No. 1, 58-62, 1921, March.

34. HODGSON, Ernest A., "Temperature Control of the Vertical Seismograph at the Dominion Observatory, Ottawa," *Bulletin of the Seismological Society of America*, **11**, No. 2, 134-135, Stanford, 1921, June.

35. HODGSON, Ernest A., "Experiments on the Effect of Changing Milne-Shaw Damping Ratios." Published in abstract only, on page 371 of the Report of the British Association for the Advancement of Science (Toronto Meeting, 1924), London, 1925.

36. HODGSON, Ernest A., "The Recording of Seismological Data at the Dominion Observatory, Ottawa, Canada, "*Publications du Bureau central séismologique international*, Travaux scientifiques, Série A, Fascicule 2, 89-120, Strasbourg, 1925.

The first two pages of this article were omitted in Fascicule 2. The missing pages are given as 132 and 133 of Fascicule 4 of the same series.

The same article appears in the *Bulletin of the Seismological Society of America*, **14**, No. 4, 265-273, Stanford, 1924, December.

37. JEANS, J. H., "The Propagation of Earthquake Waves," *Proceedings of the Royal Society of London*, Series A, **102**, 554, 1923.

The results of this paper are discussed by Gutenberg in 29 (*a*) of this list, page 106, paragraph 44.

38. Jeffreys, Harold, "On the Surface-waves of Earthquakes," *Monthly Notices of the Royal Astronomical Society, Geophysical Supplement*, **1**, No. 6, 282-292, London, 1925, December.

39. Jeffreys, Harold, "The Effect on Love-waves of Heterogeneity in the Lower Layer," *Monthly Notices of the Royal Astronomical Society, Geophysical Supplement*, **2**, No. 2, 101-111, London, 1928, October.

40. Jeffreys, Harold, "The Earth. Its Origin, History, and Physical Constitution" (Second Edition), Cambridge University Press, x + 346 pages, 13 figures. Price $5.50. London, 1929.

Chapter VI—"Seismology: General Considerations and the Structure of the Upper Layers," pages 81-116.

Chapter VII—"Seismology: The Earth's Interior," pages 117-137.

— Jeffreys, Harold and Wrinch, Dorothy, "On the Seismic Waves from the Oppau Explosion of September 21, 1921." See No. 132 of this list.

41. Klotz, Otto, "Seismological Tables," *Publications of the Dominion Observatory, Ottawa*, **3**, No. 2, 19-61, 1916.

42. Koveslīgethy, R. V., "Über den Inflexionspunkt der Laufkurve und das Bertrandsche Problem," *Gerlands Beiträge zur Geophysik*, **12**, Heft 1, 164-185, Leipzig, 1913.

43. Kunitomi, Sin'iti, "Propagation of the Seismic Wave in Japan," *Gerlands Beiträge zur Geophysik*, **17**, Heft 1, 36-39, Leipzig, 1927.

44. Labrouste, H., "Analyse des courbes resultant de la superposition de sinusoïdes," *Comptes rendus de l'Académie des Sciences*, **184**, 259, Paris, 1927.

— Lacoste, J. and Rothé, E., "Essaies de sismographes à la plate-forme." See No. 82 of this list.

45. Lambe, Horace, "The Propagation of Tremors over the Surface of an Elastic Solid," *Philosophical Transactions of the Royal Society of London*, Series A, **203**, 1-42, 1904.

46. Lorentz, "Problems of Modern Physics," Ginn and Company, 1927. Includes a treatment of group velocity.

47. Love, A. E. H., "Some Problems of Geodynamics," Cambridge University Press, 178 pages, royal octavo. Price $6.75. London, 1911. Second Edition, 1928.

An essay to which the Adams Prize in the University of Cambridge was adjudged in 1911. Chapter XI of this book, comprising pages 144-178, deals with the "Theory of the Propagation of Seismic Waves," and forms the classic presentation of a theory of the transverse surface-waves, since designated by some writers as "Love-waves."

48. Macelwane, James B., S.J., "A Study of the Relation Between the Periods of Elastic Waves and the Distance Travelled by Them, Based upon the Seismographic Records of the California Earthquake of January 31, 1922," *Bulletin of the Seismological Society of America*, **13**, No. 2, 13-69, Stanford, 1923, June.

A review of this report, by G. Dejardin, appears in Le Journal de Physique et le Radium, **6**, 655, Paris, 1925.

49. Mack, K., "Über die bei Weltbeben die Erde umkreisenden Oberflächenwellen," *Festschrift zur Feier des hundertjährigen Bestehens der Königlichen württembergisch landwirtschaftlichen Hochschule, Hohenheim*, 102-111, 1918, November 20.

50. Mack, K., "Über Weltbeben und Langewellen," *Physikalische Zeitschrift*, **21**, No. 1, 7-11, Leipzig, 1920, January 1.

Defines Weltbeben as those from which W_2 and W_3 are recorded and identified; suggests the use of these W-waves as a check of arcual distance.

51. Mack, K., "Die Ermittelung der Herdentfernung eines Erdbebens mittels Oberflächenwellen," *Zeitschrift für angewandte Geophysik*, **1**, Heft 2, 39-42, Berlin, 1922, December.

52. Mack, K., "Einige Bemerkungen über Weltbeben und die sogenannten Wiederkehrwellen," *Zeitschrift für Geophysik*, **2**, Heft 7, 266-269 Göttingen, 1926.

A review by Gutenberg appears in *Physikalische Berichte*, Heft 4, 326, Braunschweig, 1927.

53. Mainka, Carl, "Über das Amplitudenverhältnis bei Rayleighschen Oberflächenwellen," *Physikalische Zeitschrift*, **16**, 117-121, Leipzig, 1915.

54. Mainka, Carl, "Physik der Erdbebenwellen," Gebrüder Borntraeger, 156 pages, 35 figures, 20 tables, Berlin, 1923.

"Oberflächenwellen," Chapters III and IV, pages 21-45.

This is the first of a series of geophysical publications edited by Mainka. A review may be found in *Physikalische Zeitschrift*, **26**, 422-423, Leipzig, 1925, June 1.

55. Marvin, C. F., "Improvements in Seismographs with Mechanical Registration," *United States Monthly Weather Review*, **34**, 212-217, Washington, 1906.

56. Matuzawa, Takeo, "Relative Magnitude of the Preliminary and the Principal Portions of Earthquake Motions," *Japanese Journal of Astronomy and Geophysics*, **4**, 1-33, National Research Council, Tokyo, 1926.

An abstract of this paper appeared in *Proceedings of the Imperial Academy*, **2**, No. 1, 17-19, Tokyo, 1926, January.

57. Matuzawa, Takeo, "Propagation of Love-waves along a Doubly Stratified Layer," *Proceedings of the Physico-Mathematical Society of Japan*, Series 3, **10**, 25-33, Tokyo, 1928, March 10.

An abstract appears in *Science Abstracts*, **31**, Part 10, No. 370, 754, 1928, October 25.

58. Matuzawa, Takeo, "Observations of Some Recent Earthquakes and Their Time-distance Curves" (Parts II, III, IV), *Bulletin of the Earthquake Research Institute, Tokyo Imperial University*, **6**, 177-229, 1929, March.

59. Meissner, E., "Elastische Oberflächenwellen mit Dispersion in einem inhomogenen Medium," *Zurich Naturforschung Gesellschaft Vierteljahrschrift*, **66**, 181-195, 1921.

60. Meissner, E., "Elastische Oberflächenquerwellen," *Verhandlungen international Kongress für technische Mechanik, Zurich*, 1926, **2**, 3-11, 1927.

Reported by *Zeitschrift fur Geophysik*, **3**, XL, Göttingen, 1927-28; and by *Gerlands Beiträge zur Geophysik*, **18**, Heft 3, 360, Leipzig, 1927.

61. Mohorovičić, A., "A Critical Review of the Seismic Instruments Used Today and of the Organization of Seismic Service," *Bulletin of the Seismological Society of America*, **14**, No. 1, 38-59, 1924, March.

(Though not credited in the publication, this is a translation by Ernest A. Hodgson.)

62. Mohorovičić, Stjepan, "Über Nahbeben und über Konstitution des Erd– und Mondinnern," *Gerlands Beiträge zur Geophysik*, **17**, Heft 2, 180-231, Leipzig, 1927.

A review, in German, by W. Schneider, appears in *Physikalische Berichte*, **8**, 2115, 1927, October 1.

63. Nagaoka, H., "Stationary Surface Tremors," *Publications of the Earthquake Investigation Committee*, No. 22, Section B, Article 2, 17-25, Tokyo, 1906.

64. Nakano, H., "On Rayleigh-wave," *Japanese Journal of Astronomy and Geophysics*, **2**; No. 5, 233-326, Tokyo, 1925.

65. Nakano, H., "Rayleigh-waves in Cylindrical Co-ordinates," *The Geophysical Magazine*, **1**, No. 6, 255-303, Tokyo, 1928, September.

66. Neumann, Frank, "The Velocity of Seismic Surface-waves over Pacific Paths," *Bulletin of the Seismological Society of America*, **19**, No. 2, 63-76, Stanford, 1929, June.

67. Pechau, W., "Über die bei Erdbeben auftretenden Oberflächenwellen", Jena Dissertation, Thomas und Hubert, 1913.

68. Pechau, W., "Absorption und Fortpflanzungsgeschwindigkeit der Hauptbebenwellen," *Gerlands Beiträge zur Geophysik*, **13**, Heft 3, 205-216, Leipzig, 1914; concluded in the same journal, **13**, Heft 4, 261-282, 1914.

69. Rayleigh, Lord (Strutt, John William, Baron Rayleigh), "On Waves Propagated along the Plane Surface of an Elastic Solid," *Proceedings of the London Mathematical Society*, **17**, 4-11, 1885. Published also in "Scientific Papers," **2**, 1881-1887, Cambridge University Press, xiv + 598 pages, London, 1900, as pages 441-447.

This paper forms the classic presentation of the theory of the so-called "Rayleigh-waves" of seismology.

70. REICH, H., "Über die Intensität der Hauptphase eines Bebens in ihrer Beziehung zur Tektonik," *Nachrichten der Königlichen Gesellschaft zu Göttingen*, Mathematisch-physikalische Klasse, 93-98, 1921.

71. REID, Harry Fielding, "The Mechanics of the Earthquake," The California Earthquake of April 18, 1906, **2**, The Carnegie Institution of Washington, Publication No. 87. Price (of volume 2) $2. Washington, 1910.

"Surface-waves," pages 125-132.

"Phase angles," page 173.

72. REID, Harry Fielding, "Starting Points of Earthquake Vibrations," *Bulletin of the Seismological Society of America*, **8**, Nos. 2-3, 79-82, 1918, June-September.

73. REID, Harry Fielding, "Note on the Record of Surface-waves," *Bulletin of the Seismological Society of America*, **13**, No. 3, 107-108, Stanford, 1923, September.

74. REID, Harry Fielding, "The Influence of Friction on Seismographs," *Bulletin of the Seismological Society of America*, **15**, No. 3, 222-241, Stanford, 1925, September.

75. REID, Harry Fielding, "Note on Surface Earthquake Waves," *Proceedings of the Third Pan-Pacific Science Congress*, Tokyo, **2**, Section E, Article 16, 1531-1533, 1926.

76. REPETTI, William C., S.J., "A Fast Surface-wave in the South Pacific Earthquake of June 26, 1924," *Bulletin of the Seismological Society of America*, **17**, No. 4, 207-212, Stanford, 1927, December.

77. ROESENER, Friedrich, "Vergleichende Untersuchungen über die Perioden der Erdbebenwellen mit besonderer Berücksichtigung der Nachläuferwellen," *Gerlands Beiträge zur Geophysik*, **12**, Heft 2, 207-276, 4 figures, Leipzig, 1913.

78. ROSENTHAL, Elmar, "Über die Fortpflanzung der langen Erdbebenwellen," *Physikalische Zeitschrift*, **8**, No. 15, 510-512, Leipzig, 1907, August 1.

79. ROSENTHAL, Elmar, "Remarques sur la propagation des sismiques longues," *Comptes rendus de l'Association internationale de Sismologie*, 258-260, La Hague, 1907.

A discussion of velocities of propagation and a plastic substratum theory.

80. ROTHÉ, E., "Sur la nature des maximums inscrits dans les séismogrammes," *Comptes rendus de l'Académie des Sciences*, **183**, No. 2, 136-139, 1926, July 12.

81. ROTHÉ, E., "Summary of the Note Presented to the Pan-Pacific Congress of October, 1926," *Proceedings of the Third Pan-Pacific Science Congress, Tokyo*, **2**, Section E, Article 8, 1926.

82. ROTHÉ, E. and LACOSTE, J., "Essaies de sismographes à la plate-forme, "*Publications du Bureau central sismologique*, Travaux scientifiques, Série A, Fascicule 1, 60-72, Strasbourg, 1924.

83. RUDSKI, M. P., "Über die Bewegung des horizontals Pendels," *Gerlands Beiträge zur Geophysik*, **6**, 138-155, Leipzig, 1904.

84. RUDSKI, M. P., "Sur la propagation d'une onde élastique superficielle dans un milieu transversalement isotrope," *Bulletin de l'Académie des Sciences de Cracovie*, Classe des Sciences, Mathématiques, et Naturelle, Série A, 47-58, 1912.

A review by Pockels appears in *Gerlands Beiträge zur Geophysik*, **12**, (Besprechungen, 75-79, Leipzig, 1913.

85. SCHUSTER, Arthur, "Über die durch seismische Wellen hervergerufene Oberflächenbewegung," *Physikalische Zeitschrift*, **8**, No. 2, 51-53, Leipzig, 1907, January 15.

86. SEZAWA, Katsutada, "Propagation of Rayleigh-waves on a Spherical Surface," *Proceedings of the Physico-Mathematical Society of Japan*, Series 3, **8**, 379-382, Tokyo, 1926.

87. SEZAWA, Katsutada, "Propagation of Rayleigh-waves in Two Dimensions," *Proceedings of the Imperial Academy of Japan*, **2**, No. 7, 314-317, Tokyo, 1926, July.

88. SEZAWA, Katsutada, "On the Propagation of Rayleigh-waves on Plane and Spherical Surfaces" (in English), *Bulletin of the Earthquake Research Institute, Tokyo Imperial University*, **2**, 21-28, 1927, March.

89. SEZAWA, Katsutada, "Dispersion of Elastic Waves Propagated on the Surface of Stratified Bodies and on Curved Surfaces," *Bulletin of the Earthquake Research Institute of Japan*, **3**, 1-18, Tokyo, 1927, September.

90. SEZAWA, Katsutada, "Scattering of Elastic Waves and Some Allied Problems," *Bulletin of the Earthquake Research Institute of Japan*, **3**, 19-42, 1927, September.

This paper, which contains two figures, is in English with an abstract in Japanese.

91. SEZAWA, Katsutada, "On the Propagation of the Leading and Trailing Parts of a Train of Elastic Waves," *Bulletin of the Earthquake Research Institute, Tokyo Imperial University*, **4**, 107-122, 1928, March.

92. SEZAWA, Katsutada, "Propagation of Rayleigh-waves Having a Certain Azimuthal Distribution of Displacements," *Proceedings of the Imperial Academy of Japan*, **4**, No. 6, 267-270, 1928, June.

93. SEZAWA, Katsutada, "Further Studies on Rayleigh-waves Having Some Azimuthal Distribution," *Bulletin of the Earthquake Research Institute, Tokyo Imperial University*, **6**, 1-18, 1929, March.

94. SEZAWA, Katsutada, "Periodic Rayleigh-waves Caused by an Arbitrary Disturbance" (in English), *Bulletin of the Earthquake Research Institute, Tokyo Imperial University*, **7**, Part 2, 193-206, 1929, September.

95. (1) SHAW, J. J., "Milne-Shaw Handbook," J. J. Shaw, West Bromwich, England. (The book of instructions issued with the Milne-Shaw seismographs.)

95. (2) SHAW, J. J., "The Milne-Shaw Seismograph," *Publications du Bureau central sismologique, Travaux scientifique*, Série A, Fascicule 4, 3-18, Strasbourg, 1927.

96. SIEBERG, A., "Erdbebenkunde," Gustav Fischer, 572 pages, 178 illustrations, 17 tables, Jena, 1923.

With chapters by Dr. Gutenberg; a textbook.

— SIEBERG, A. and GUTENBERG, Beno, "Das Erdbeben in der chilenischen Provinz Atacama am 10. November 1922." See No. 30 of this list.

97. STONELEY, R., "Dispersion of Seismic Waves," *Monthly Notices of the Royal Astronomical Society, Geophysical Supplement*, **1**, No. 6, 280-282, London, 1925, December.

98. STONELEY, R., "Effect of a Compressible Ocean on Rayleigh-waves," *Monthly Notices of the Royal Astronomical Society, Geophysical Supplement*, **1**, No. 7 349-355, 1926, June.

An abstract appears in *Science Abstracts*, **29**, 694, 1926, October.

99. STONELEY, R., "The Dispersion of Waves in a Double Superficial Layer," *Monthly Notices of the Royal Astronomical Society, Geophysical Supplement.* **1**, No. 10, 527-532, London, 1928, March.

The author stresses the importance of obtaining accurate values for the velocities of waves of different periods, and suggests that, ". . . . well-determined values from single earthquakes, with particulars of the path traversed would probably be better than statistical averages."

100. STONELEY, R., "A Rayleigh-wave Problem," *Proceedings of the Leeds Philosophical and Literary Society*, **1**, Part VI, 217-225, 1928, April.

An abstract by the author appears in *Science Abstracts*, **31**, Part 10, No. 370, 742-743, 1928, October 25.

101. STONELEY, R. and TILLOTSON, E., "The Effect of a Double Surface Layer on Love-waves," *Monthly Notices of the Royal Astronomical Society, Geophysical Supplement*, **1**, No. 10, 521-527, London, 1928, March.

102. STÜCKER, Norbert, "Ausführliche nomographische Tafel zur Auswertung von Bebendiagrammen," *Gerlands Beiträge zur Geophysik*, **19**, Heft 2-3, 318-320, Leipzig, 1928.

Graphical diagrams to permit the evaluation of the earth-particle displacement from the seismogram.

103. SUDA, K., "On the Energy Distribution of the Main Wave of a Near Earthquake," *Memoirs of the Imperial Marine Observatory, Kobe, Japan*, **1**, 52-65, 1923.

104. SUDA, K., "On the Great Japanese Earthquake of September 1, 1923," *Memoirs of the Imperial Marine Observatory, Kobe, Japan*, **1**, No. 4, 152 pages, 31 plates, 1924, August.

This paper was briefly reviewed by Perry Byerly in the *Bulletin of the Seismological Society of America*, **16**, 66, 1926, March.

105. SUYEHIRO, Kyoji, "On the Nature of the Earthquake Motions Examined by a Seismic Vibration Analyser, "*Proceedings of the Imperial Academy of Japan*, **2**, 268-270, 1926, June.

106. Suyehiro, Kyoji, "A Seismic Vibration Analyser and the Records Obtained Therewith," *Bulletin of the Earthquake Research Institute of Japan*, **1**, 59-64, 1926, August.

In Japanese with an abstract in English. Two pages of plates bear captions in English.

107. Tams, E., "Die Fortschritte in der Dynamik der festen Erdrinde 1922-26," *Geographisches Jahrbuch*, **42**, 229-293, Gotha, 1928.

This review of the progress of the study of the dynamics of the earth for the period 1922-26 is remarkable for the amount of detail given. More than 700 publications, which have contributed to this progress, are mentioned one after another. The general contribution of each is pointed out, the more important papers being briefly abstracted. Part IV deals with earthquakes.

108. Tams, E., "Die Seismizität der Ozeane und Kontinente," *Zeitschrift für Geophysik*, **4**, Heft 7-8, 321-348, Göttingen, 1928.

An abstract appears in *Zeitschrift für Geophysik*, **4**, Heft 5, 245-246, Braunschweig, 1928. The complete paper includes a list of Hamburg determinations of epicentres from 1922 to 1927.

— Tillotson, E. and Stoneley, R., "The Effect of a Double Surface Layer on Love-waves." See No. 101 of this list.

109. Tsubi, Chuji, "On the Velocity of an Elastic Wave along the Surface of a Stratified Layer," *Proceedings of the Physico-Mathematical Society of Japan*, Third Series, **9**, 93, Tokyo, 1927, May.

An abstract appears in *Science Abstracts*, **31**, Part I, 4, 1928, January.

110. Turner, H. H., "The International Seismological Summary" (Quarterly through April, May, June, 1926) British Association for the Advancement of Science, London.

The latest issue, 1926—April, May, June, was published 1929, July 9.

111. Uller, Karl, "Zurückwerfung und Brechung elastischer Wellen," *Verhandelungen der Deutschen physikalischen Gesellschaft*, **16**, 835, 1914.

112. Uller, Karl, "Eine Wellenstudie," Arbeiten aus den Gebieten der Physik, Mathematik, Chemie. Julius Elster und Hans Geital gewidmet Friedrich Vieweg und Sohn, Braunschweig, 1915.

113. Uller, Karl, "Grundlegung der Kinematik einer physikalischen Welle von elementarer Schwingungsform, I," *Physikalische Zeitschrift*, **17**, 168-172, 1916.

114. Uller, Karl, "Elastische Oberflächen-Planwellen," *Annalen der Physik*, Vierte Folge, **56**, No. 14, 463-496, Leipzig, 1918.

115. Uller, Karl, "Die gebundenen Verzerrungswellen," *Zeitschrift für Physik*, **6**, Heft 4, 298-302, 1921.

116. Uller, Karl, "Wellen-Induktion," *Gerlands Beiträge zur Geophysik*, **19**, 134, Leipzig, 1928.

117. ULLER, Karl, "Die elastischen Wellen von elementarer Schwankungsform in schweren, festen, und isotropen Mitteln," *Gerlands Beiträge zur Geophysik*, **20**, Heft 3-4, 397-409, Leipzig, 1928.

118. ULLER, Karl, "Die geführten elastischen Zweimittel-Planwellen in ruhenden, festen isotropen, und schwerelosen Mitteln," *Gerlands Beiträge zur Geophysik*, **20**, Heft 3-4, 410-423, Leipzig, 1928.

119. ULLER, Karl, "Die geführten elastischen Zweimittel-Wellen," *Zeitschrift für Geophysik*, **4**, Heft 5, 259-260, Leipzig, 1928.

120. ULLER, Karl, "Die mehrfach geführten Wellen in mehrerer fliessenden Mitteln," *Zeitschrift für angewandte Mathematik und Mechanik*, **8**, Heft 4, 282-293, 1928, August.

121. VISSER, S. W., "Some Researches into the Propagation of Seismic Long Waves," *Koninklijk Magnetisch en Meteorologisch Observatorium te Batavia Verhandelingen*, No. 16, 1-24, 1925.

Reviewed by Perry Byerly in the *Bulletin of the Seismological Society of America*, **16**, No. 1, 66, 1926, March.

122. WADATI, K., "Shallow and Deep Earthquakes," *The Geophysical Magazine*, **1**, No. 4, 161-202, Tokyo, 1928, March.

123. WAETZMANN, E., "Zur Ausbreitung elastischer Wellen in der Erdoberfläche," *Naturwissenschaften*, **15**, No. 18, 401-403, 1927.

Reviewed by Mainka in *Physikalische Berichte*, **9**, Heft 7, 614, 1928, April 1.

124. WALKER, George W., "Surface Reflexion of Earthquake Waves," *Philosophical Transactions of the Royal Society of London*, Series A, 218, 373-393, 1919.

125. WELLMANN, Hermann, "Untersuchungen über die Perioden der Nachläufer in Fernbebenregistrierungen," *Zeitschrift für angewandte Geophysik*, **1**, Heft 7, 214-217, 1923, December.

126. WENNER, Frank, "A New Seismometer Equipped for Electromagnetic Damping and Electromagnetic and Optical Magnification (Theory, General Design, and Preliminary Results)," *Bureau of Standards Journal of Research*, **2**, Research Paper No. 66, 963-999, Washington, 1929.

This paper is also issued as a reprint in separate cover, and may be obtained from the Superintendent of Documents, Government Printing Office, Washington, D.C., at the nominal price of fifteen cents.

127. WENNER, Frank, A personal communication to the author regarding phase angles and the equation for fig. 8 of No. 126 of this list.

128. WIECHERT, E., "Theorie der automatischen Seismographen," *Abhandlungen der Königlichen Gesellschaft der Wissenschaften zu Göttingen*, Mathematisch-physikalische Klasse, Neue Folge, **2**, No. 1, 128 pages, Berlin, 1903.

This book presents a classic outline of the theory of the seismograph.

129. WIECHERT, E., "Oberflächenwellen und Bemerkungen über den Einfluss der Schichtung der Erdoberfläche," *Nachrichtungen der Gesellschaft der Wissenschaften zu Göttingen*, Mathematisch-physikalische Klasse, 47-59, 1907.

130. WIECHERT, E. and ZOEPPRITZ, K., "Über Erdbebenwellen, II, Laufzeiten," *Nachrichten der Königlichen Gesellschaft der Wissenschaften zu Göttingen*, Mathematisch-physikalische Klasse, 1907.

131. WILLIS, Bailey (and others), "Earthquake Conditions in Chile," Carnegie Institution of Washington (Studies in Comparative Seismology), Publication No. 382, 178 pages, numerous illustrations, tables, etc. Price $5.50. Washington, 1929.

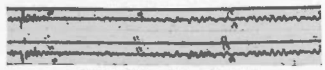
Includes appendices by James B. Macelwane, S.J., and Perry Byerly; describes a detailed field investigation of the Atacama quake of 1922, November 11. (Ottawa No. 1353.)

132. WRINCH, Dorothy and JEFFREYS, Harold, "On the Seismic Waves from the Oppau Explosion of September 21, 1921," *Monthly Notices of the Royal Astronomical Society, Geophysical Supplement*, 1, No. 2, 17-22, London, 1923, January.

133. ZOEPPRITZ, K., "Über Erdbebenwellen, VII," *Nachrichten der Königlichen Gesellschaft zu Göttingen*, Mathematisch-physikalische Klasse, 57-65, 1919.

— ZOEPPRITZ, K. and WIECHERT, E., "Über Erdbebenwellen, II, Laufzeiten." See No. 130 of this list.

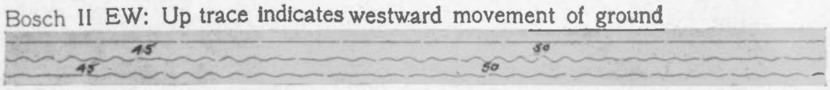
Milne-Shaw No. 17 E-W
Damping ratio 20:1



Milne-Shaw No. 23 E-W
Damping ratio 5:1
S and L phases of small quake
May 4, 1923
Constants otherwise the same

FIGURE 1
Number 1462

Bosch II EW: Up trace indicates westward movement of ground



Vertical: Up trace indicates downward movement of ground

40 45

45 50 55

FIGURE 2
Number 2413

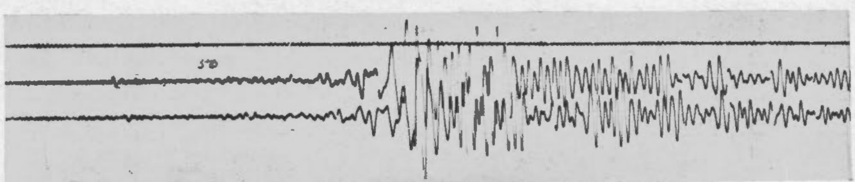


FIGURE 3
Numbers 2623 and 2624

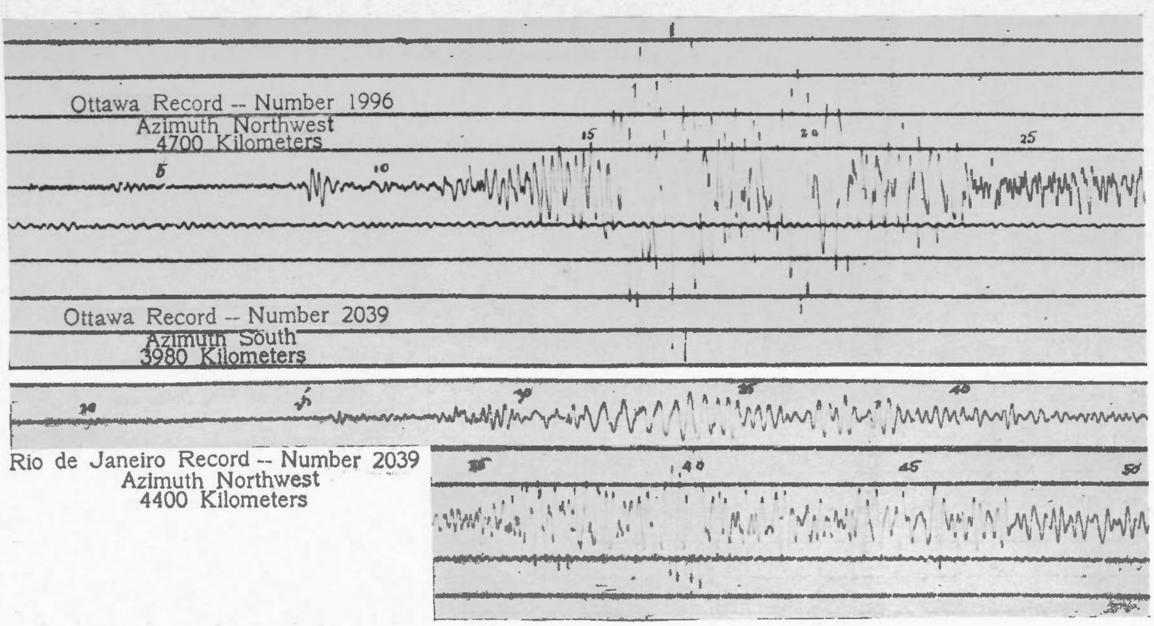


FIGURE 4

14653—6

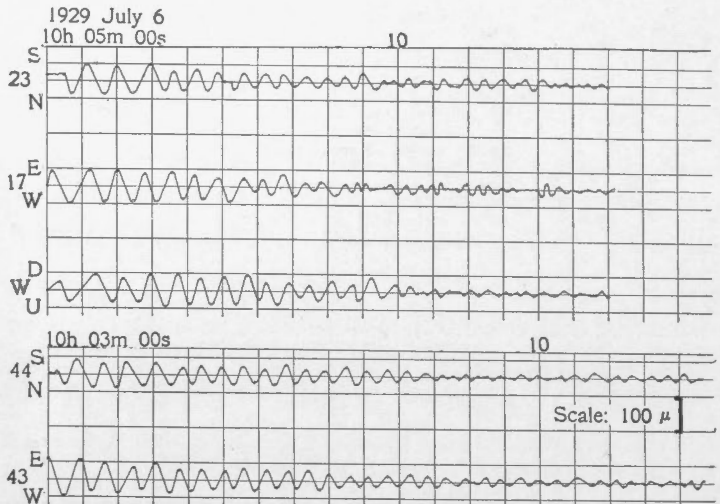


FIGURE 6
Earth Amplitude Graph
Number 3544

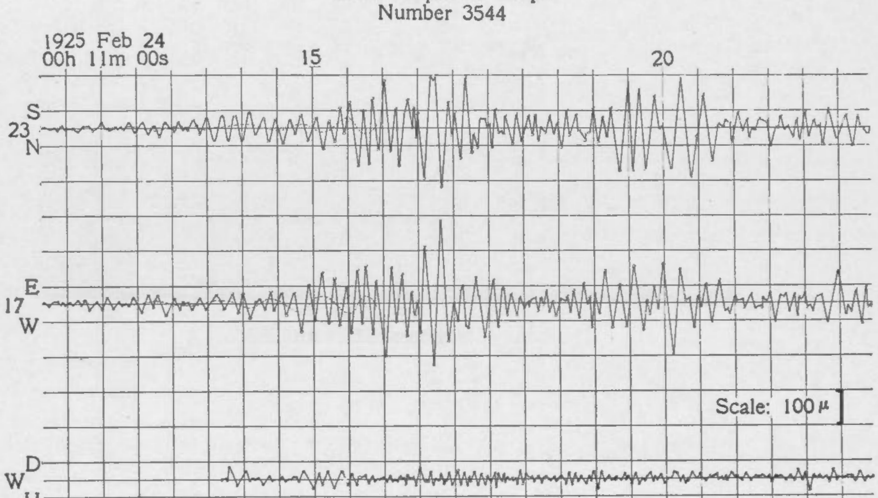


FIGURE 7
Earth Amplitude Graph
Number 1996

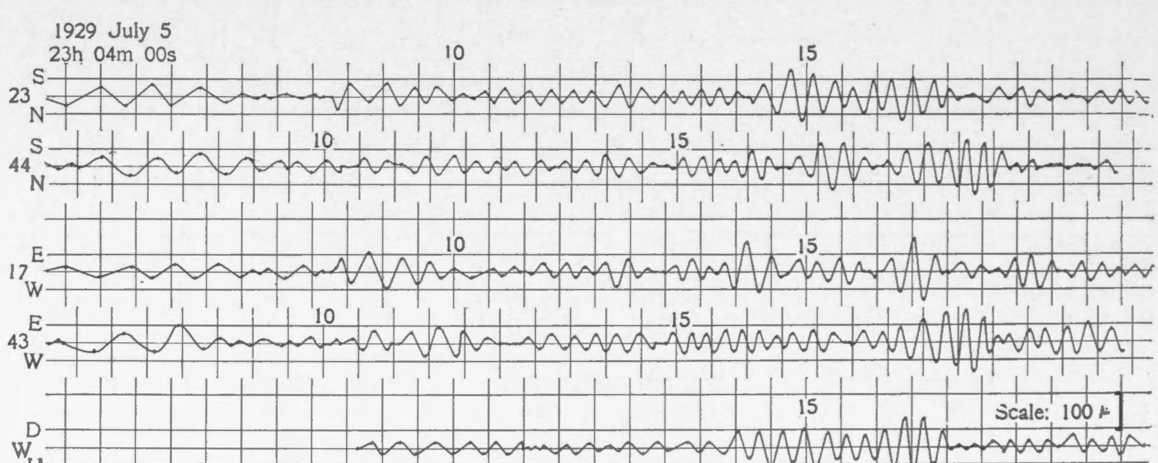


FIGURE 8
Earth Amplitude Graph
Number 3542

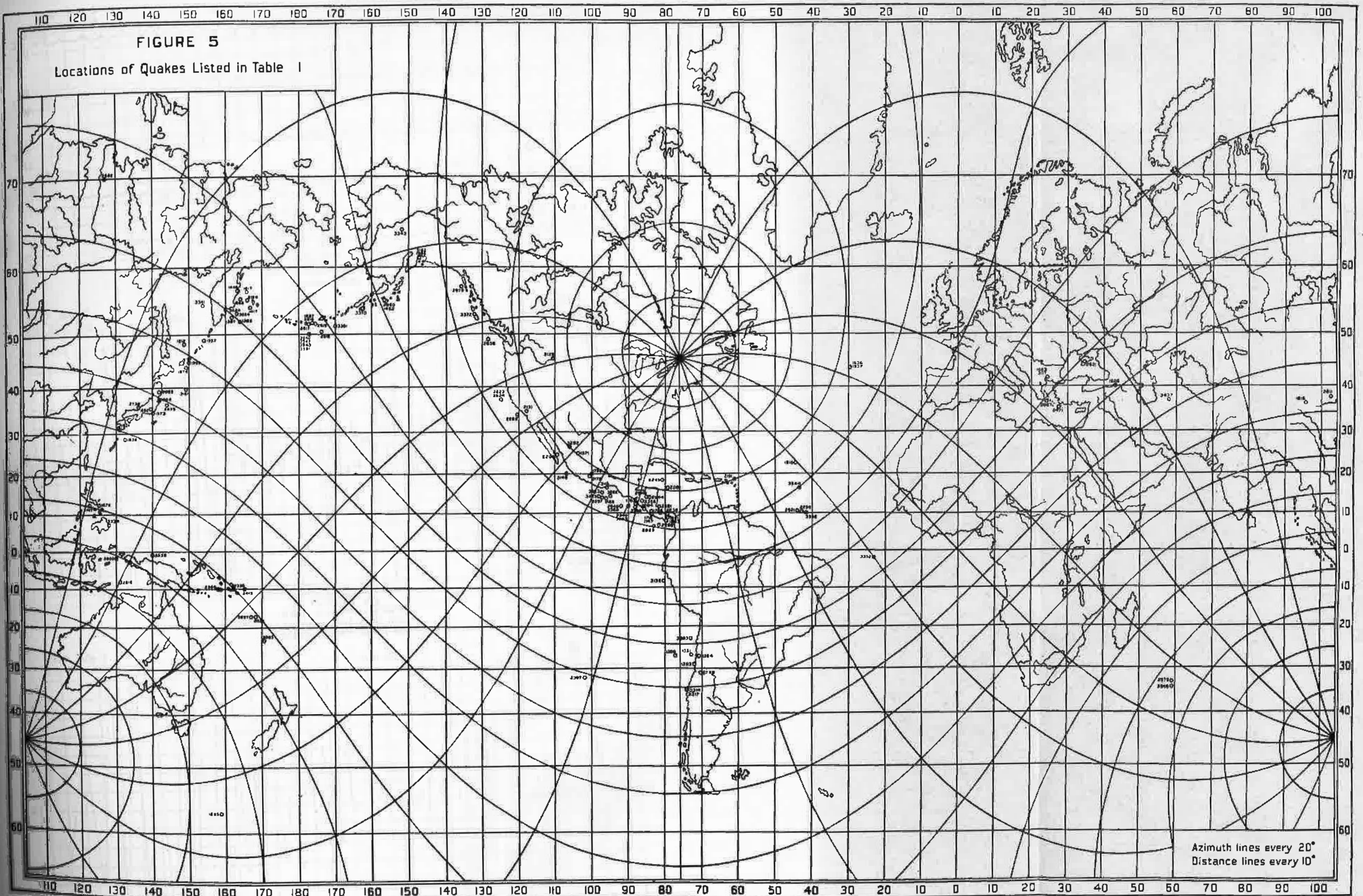


FIGURE 5
Locations of Quakes Listed in Table I
Azimuth lines every 20°
Distance lines every 10°

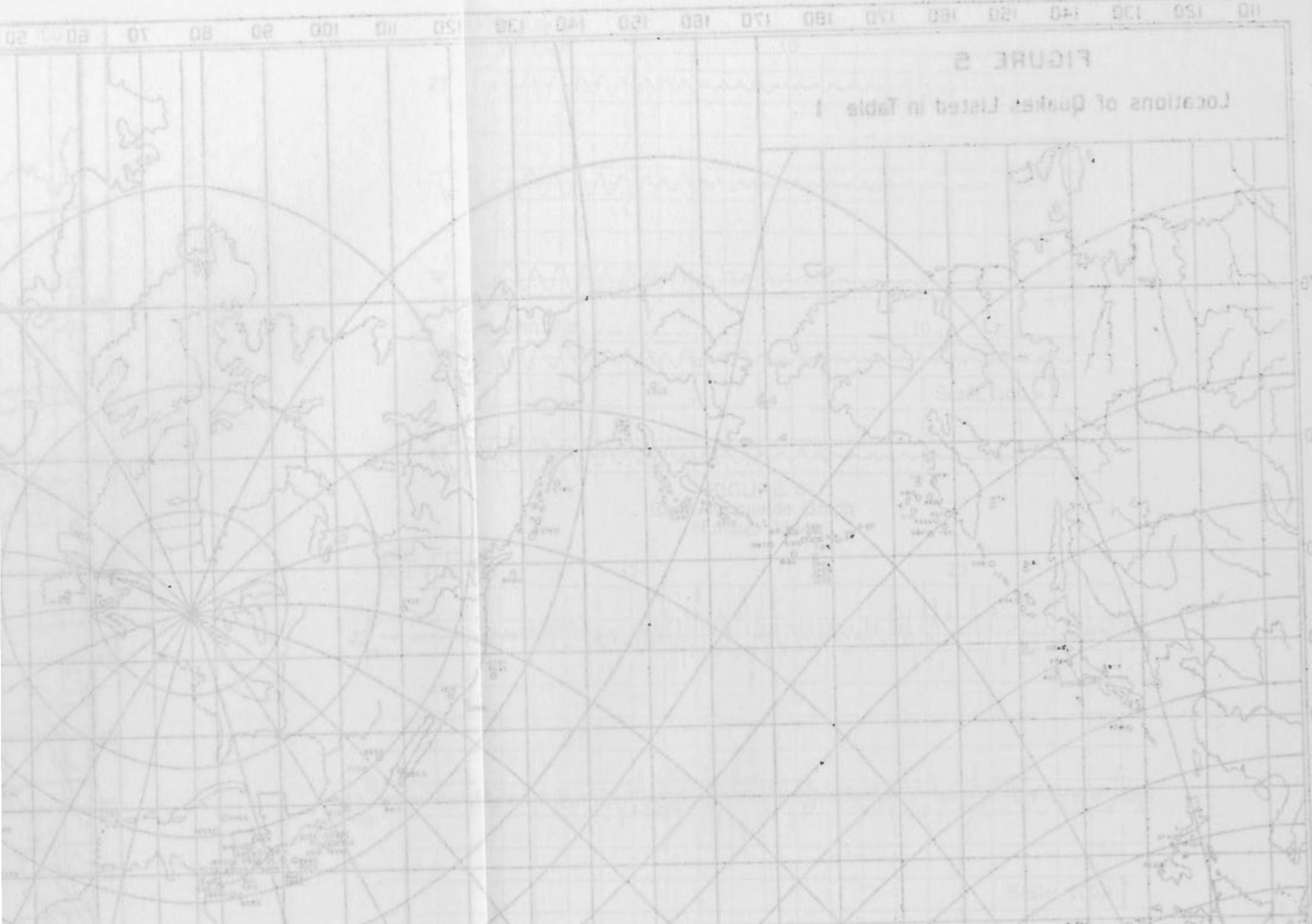


FIGURE 5

Locations of Quakes Listed in Table 1

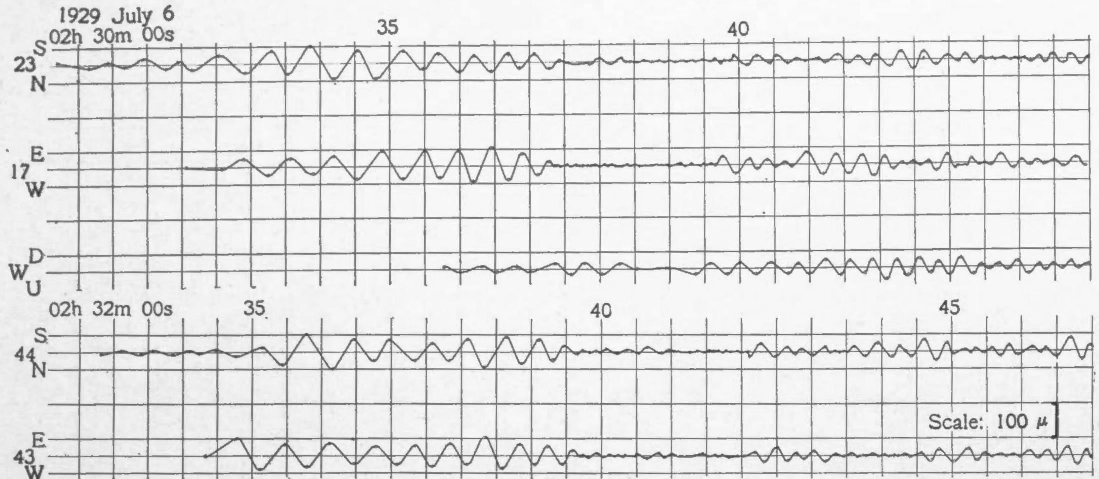


FIGURE 9
Earth Amplitude Graph
Number 3543

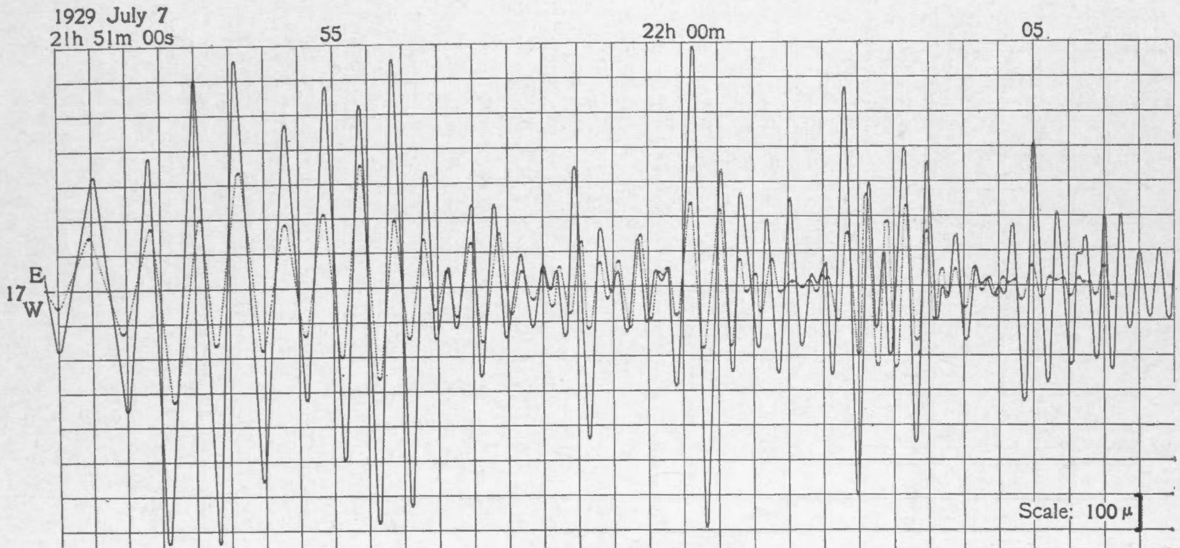


FIGURE 10a
Earth Amplitude Graphs
Number 3551 solid line
Number 3540 dotted line

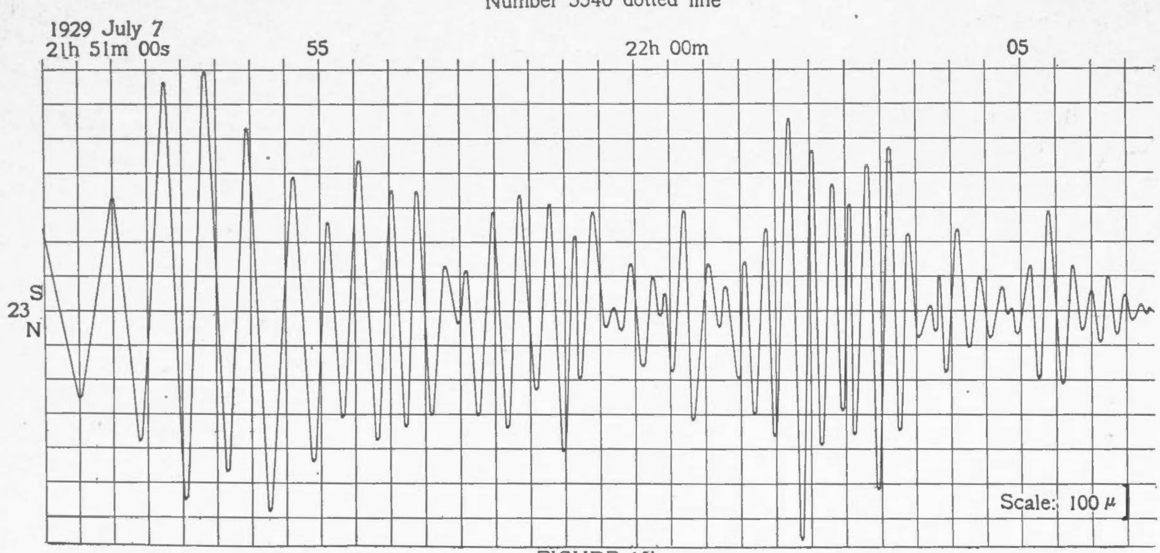


FIGURE 10b
Earth Amplitude Graph
Number 3551

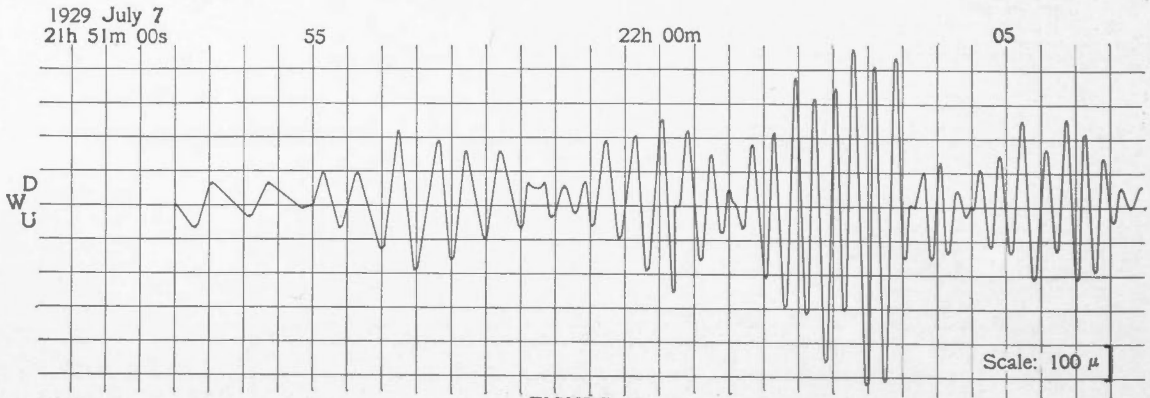


FIGURE 10c
Earth Amplitude Graph
Number 3551

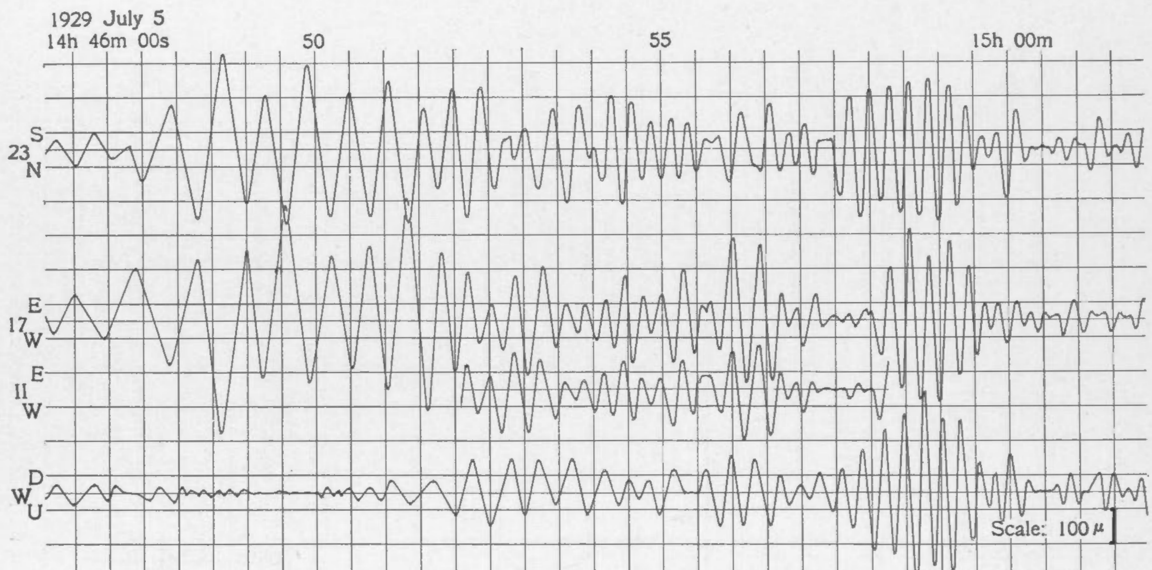


FIGURE 11a
Earth Amplitude Graph
Number 3540

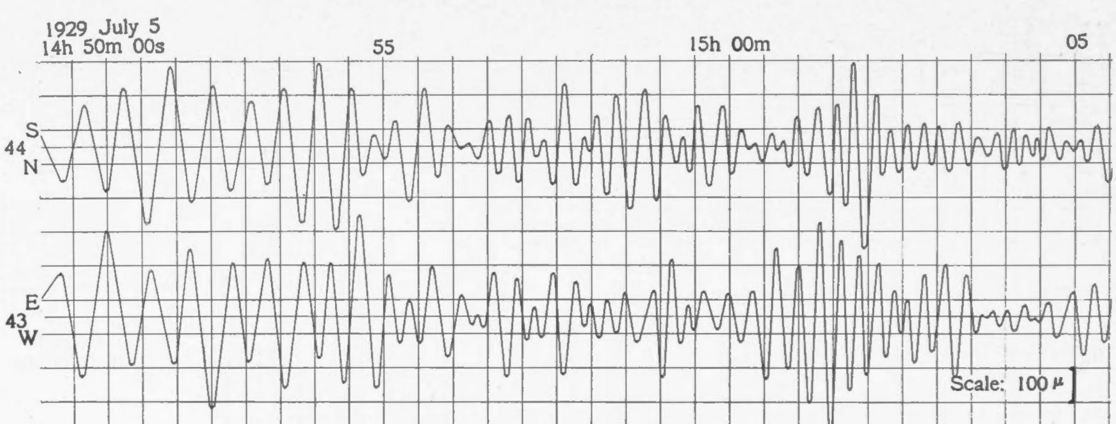


FIGURE 11b
Earth Amplitude Graph
Number 3540

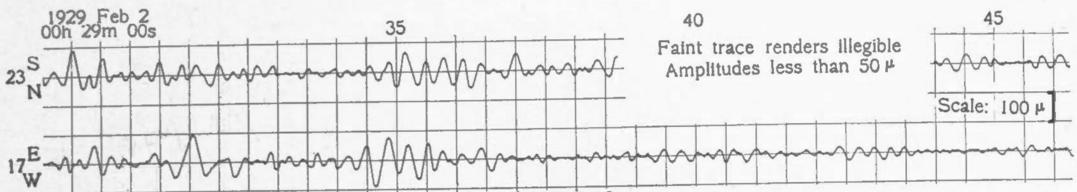


FIGURE 12
Earth Amplitude Graph
Number 3352

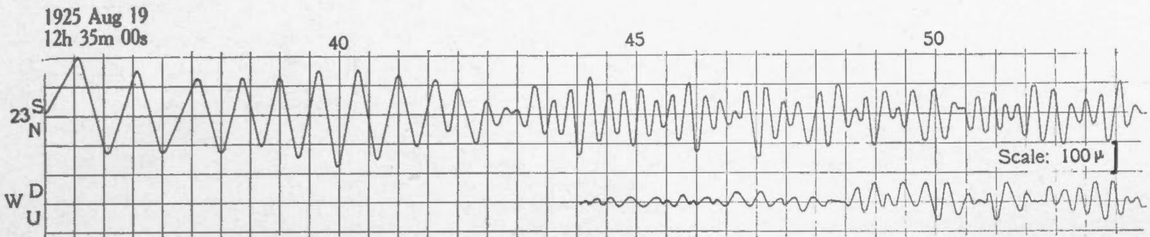


FIGURE 13
Earth Amplitude Graph
Number 2194

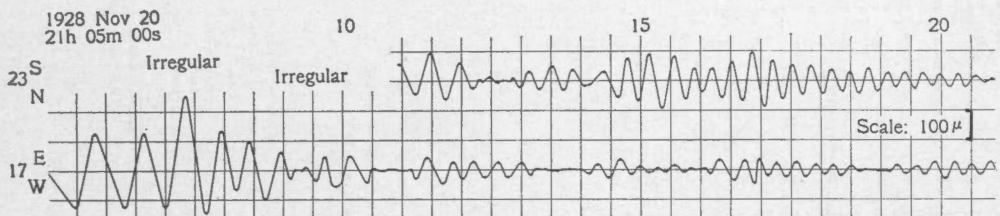


FIGURE 14
Earth Amplitude Graph
Number 3303

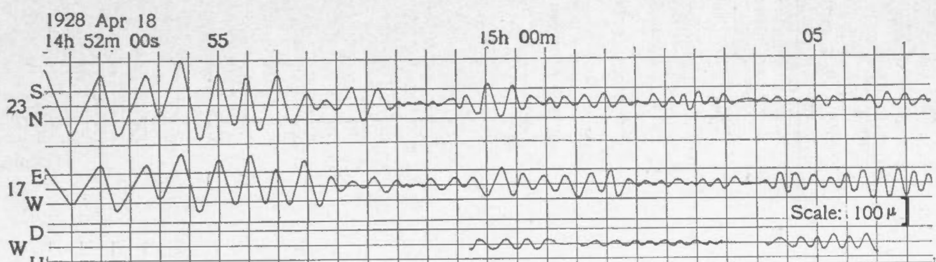


FIGURE 15
Earth Amplitude Graph
Number 3117

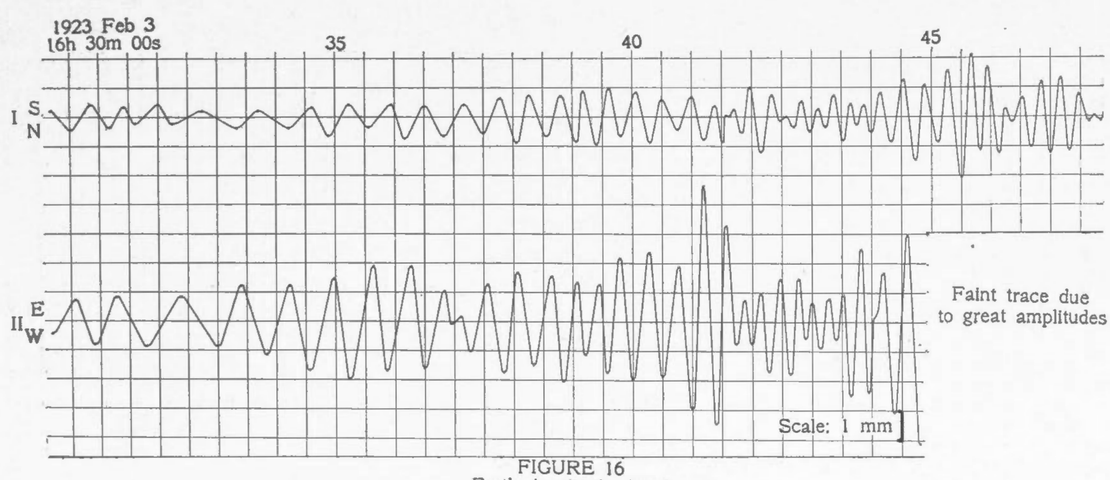


FIGURE 16
Earth Amplitude Graph
GREAT QUAKE
Number 1387

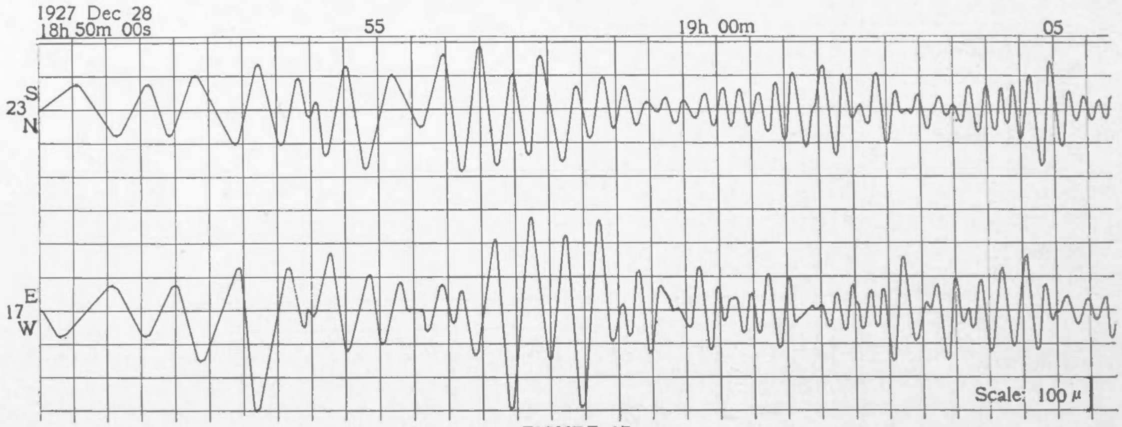


FIGURE 17
Earth Amplitude Graph
Number 3024

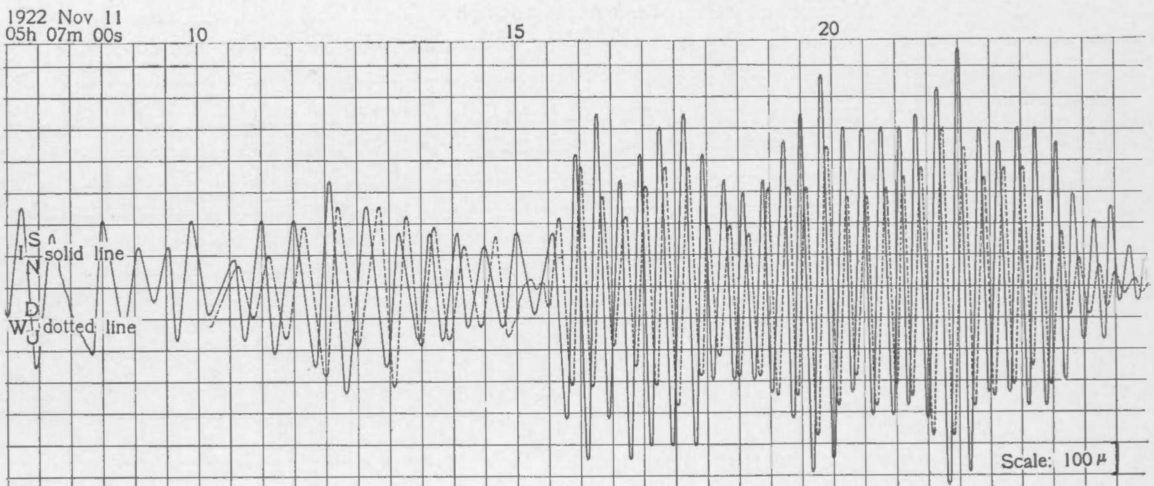


FIGURE 18a
Earth Amplitude Graph
Number 1353

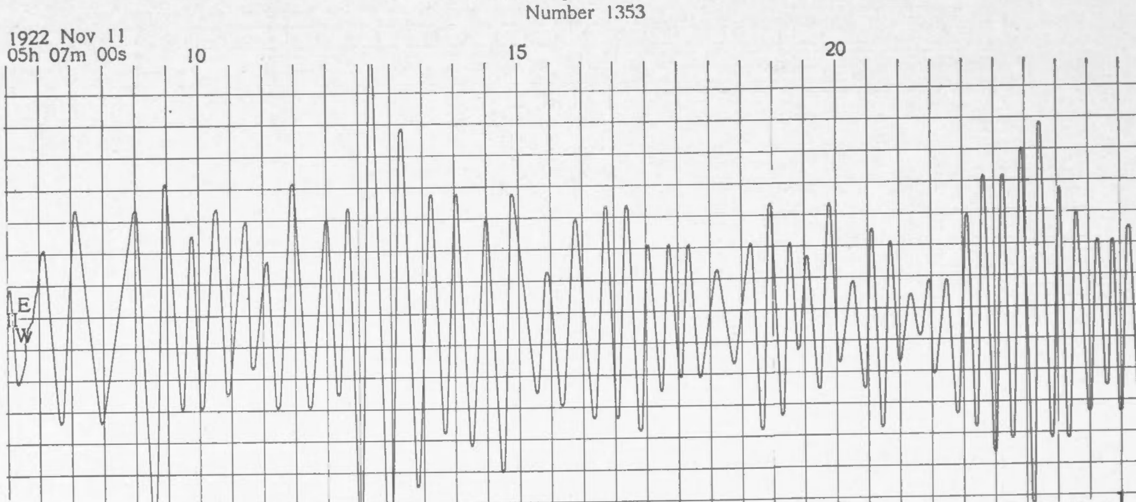


FIGURE 18b
Earth Amplitude Graph
Number 1353

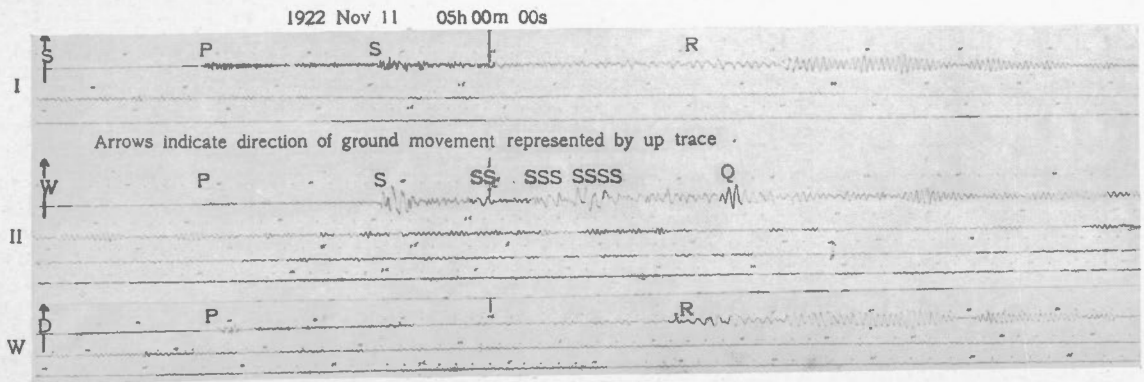


FIGURE 18c
Tracings of Original Seismograms
Number 1353

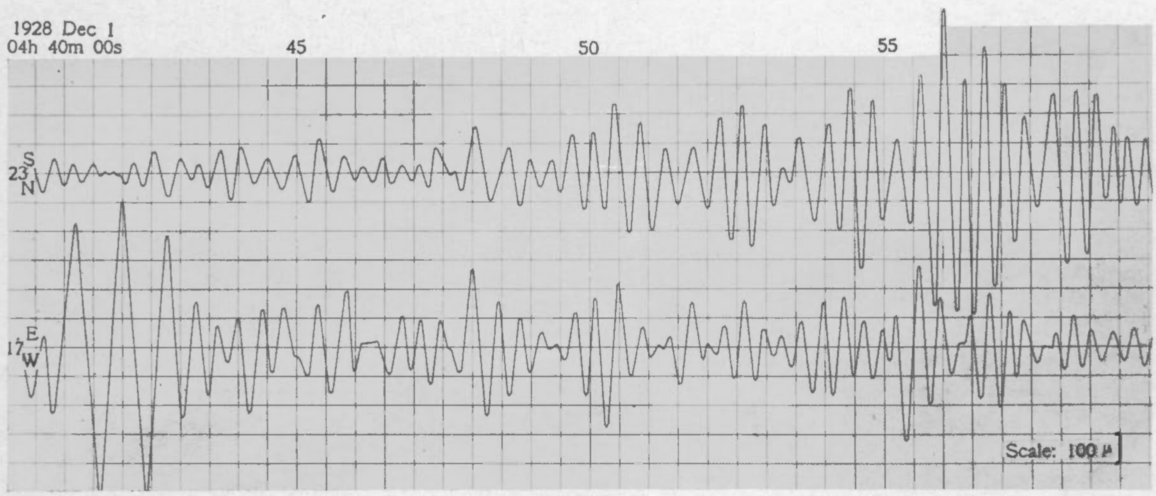


FIGURE 19
Earth Amplitude Graph
Number 3314

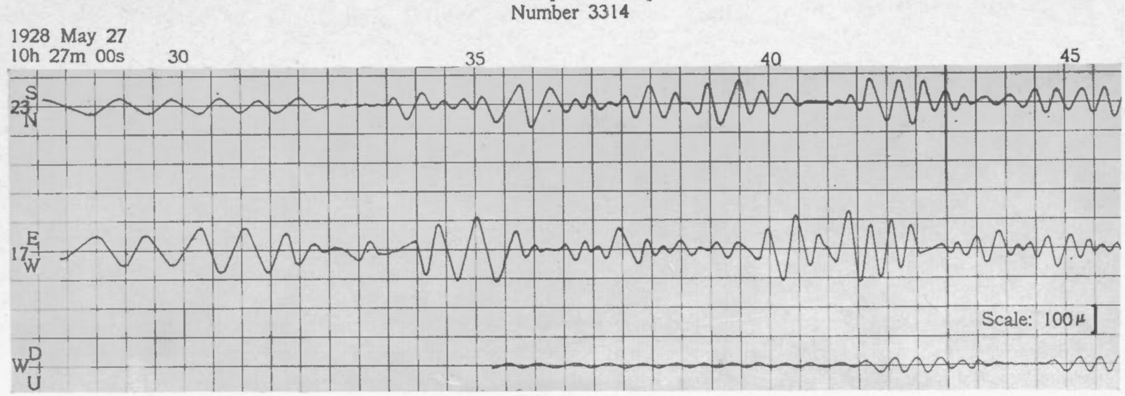


FIGURE 20
Earth Amplitude Graph
Number 3161

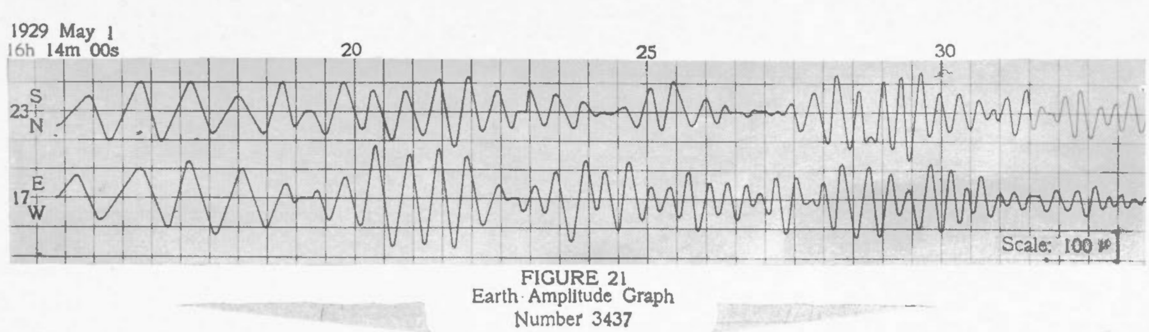


FIGURE 21
Earth Amplitude Graph
Number 3437

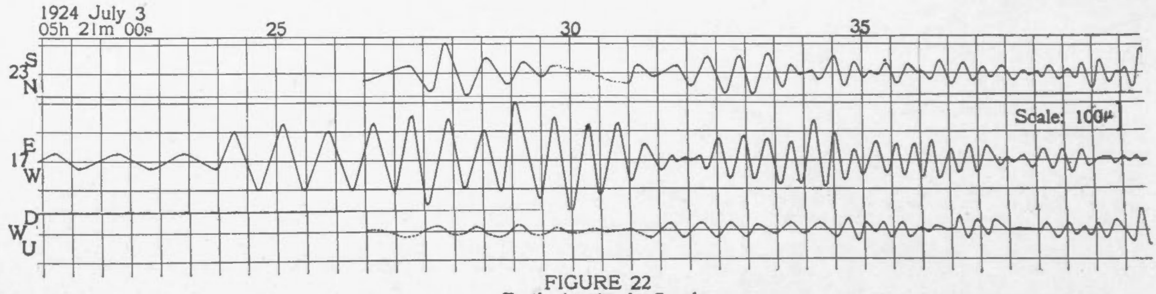


FIGURE 22
Earth Amplitude Graph
Number 1815

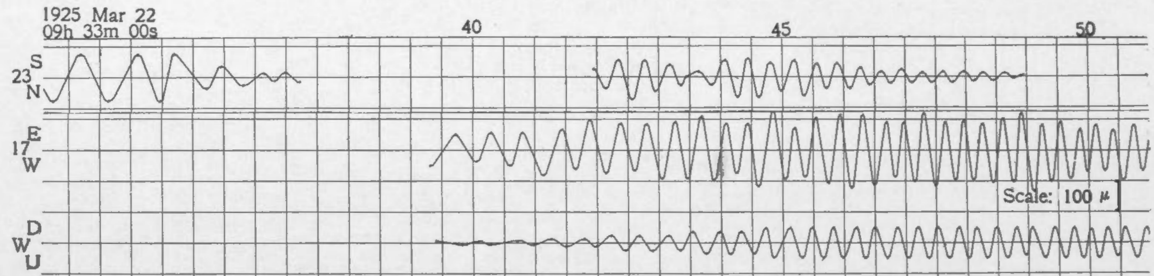


FIGURE 23
Earth Amplitude Graph
Number 2028

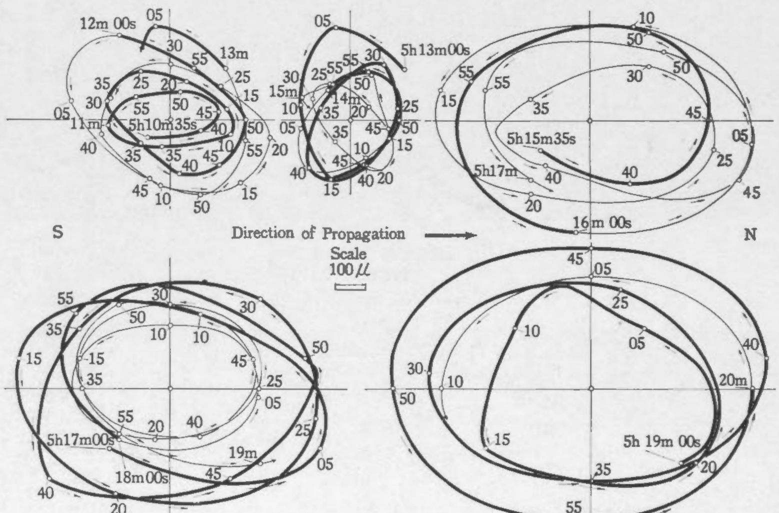


FIGURE 24
Earth Particle Paths
Number 1353

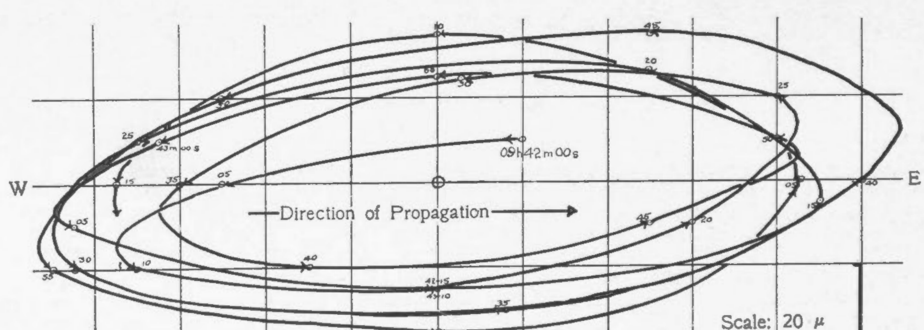


FIGURE 25
Earth Particle Path
Number 2028