Seismological Investigations.—Fifth Report of the Committee, consisting of Professor J. W. JUDD (*Chairman*), Mr. JOHN MILNE (*Secretary*), Lord KELVIN, Professor W. G. ADAMS, Professor T. G. BONNEY, Sir F. J. BRAMWELL, Mr. C. V. BOYS, Professor G. H. DARWIN, Mr. HORACE DARWIN, Major L. DARWIN, Professor J. H. EWING, Professor C. G. KNOTT, Professor R. MELDOLA, Mr. R. D. OLDHAM, Professor J. PERRY, Mr. W. E. PLUMMER, Professor J. H. POYNTING, Mr. CLEMENT REID, Mr. NELSON RICHARDSON, the late Mr. G. J. SYMONS, *and* Professor H. H. TURNER.

[PLATES II. AND III.]

CONTENTS.

I. *On Seismological Stations abroad and in Great Britain.*

IN addition to the twenty-three stations referred to in the Report for 1899 instruments have been ordered for the Observatory, Melbourne, the Observatory, Sydney, N.S.W., for Ceylon, for the Johns Hopkins University, Baltimore, the Liverpool Observatory, Bidston, and the Royal Observatory, Edinburgh. The total number of similar installations which may be expected to be in working order before the end of the current year will therefore be twenty-nine. The positions of these are shown on the map (Plate II.).

Registers ending December 31, 1899, referring to Shide, Kew, Calcutta, Madras, Bombay, San Fernando (Spain), Cairo, Mauritius, Batavia, Cape of Good Hope, and Tokio, have been printed and issued as a circular to all co-operating stations, to those who have assisted this committee in their work, and to persons expressing a wish to possess the same. With the object of finding permanent quarters at which a central observing station might be established in England, at the suggestion of this Committee its Secretary, in company with Mr. Horace Darwin, visited the Office of Works, the Treasury, and the Admiralty, and, with Major Leonard Darwin, the Horse Guards. Many sites were discussed, and through the kindness of Colonel Hildebrand, R.E., and commanding officers of the Royal Engineers facilities were given to visit forts and other buildings at Chatham, Folkestone, Porchester, and in the Isle of Wight.

A report on these visits and on those to other places, together with a reference to steps generally which have been taken to find the required site, has been drawn up for the Council of the British Association.

In consequence of the generosity of Mr. M. H. Gray, an instrument room is now being built at Shide.

II. *Analyses of Large Earthquakes recorded in* 1899. *By* JOHN MILNE.

1. *Nature and Object of these Analyses.*

In 1897 the Seismological Investigation Committee of the British Association issued to the directors of observatories and other persons in various parts of the world a circular in which they called attention to the desirability of observing earthquake waves which had travelled great distances. It was pointed out that similar instruments should be used at all stations, and the type recommended as being simple to work, and one that yielded results sufficiently accurate for the main objects in view, was described by the Committee in a report (see Reports of the British Association, 1897, p. 137 *et seq.*).

The result of this appeal is that instruments have been forwarded to the following twenty-six stations :—Shide, Kew, Toronto, Victoria, B.C., San Fernando (Spain), Madras, Bombay, Calcutta, Mauritius, Cairo, Cape of Good Hope, Tokio, Batavia, Arequipa, Swarthmore College (Philadelphia), Cordova (Argentina), New Zealand (two instruments), Paisley, Mexico, Beyrut, Honolulu, Trinidad, Melbourne, Sydney, Johns Hopkins University (Baltimore).

For the year 1899 registers were received from the first thirteen of these stations. With the exception of those relating to Toronto and Victoria, these have been communicated to observers by the Committee as a circular. This circular is independent of the present report, but continuous with registers contained in corresponding reports subsequent to 1895.

A glance at these registers, or tables based upon them (see pp. 80-87), shows that while certain earthquakes have evidently shaken the whole surface of our globe, and have probably disturbed the same throughout its mass, there are others of less intensity which have only affected certain parts of the same. For example, one set of earthquakes were only recorded at stations in Western Europe, whilst another set were apparently confined to the Indian Ocean. In the following paper the earthquakes referred to are only those which were recorded in England, from which it follows that although the largest earthquakes of the year 1899 are discussed many earthquakes which are comparatively smaller have been omitted.

The object of the discussion is to indicate by examples some of the directions in which this extensive system of earthquake observation is increasing our knowledge of dynamical phenomena inherent to the world on which we live.

The plan of the discussion is as follows:—First, those earthquakes which have been recorded at the greatest number of stations, and which have *known* origins, have been selected from the others and analysed separately. To confirm the results towards which these analyses point, references have been made to the more trustworthy records obtained by similar instruments in previous years. The principal objects in view have been as follows. The determination of the velocities with which various types of earth vibrations are propagated and the duration of preliminary tremors at varying distances from origins; to show that earthquake repetition and echoes are fairly frequent and to point out the existence of phenomena for which satisfactory explanations are as yet wanting. In connection with these investigations references are made to hypotheses relating to the physical condition of the interior of our earth.

Second, the results obtained by the above analyses are used as a means to determine the foci of disturbances not included in the first section of this paper. These foci, which for the most part are sub-oceanic, in some instances indicate localities where it would be unwise to lay cables, and where we may expect to find configurations differing from those shown upon our physical maps.

Remembering that very many of the earthquakes discussed represent initial disturbances which were followed by many after-shocks, the map depicting these foci shows the regions on the surface of the earth where in the year 1899 seismic activity was most pronounced.

2. *Velocities of Earthquake Waves.*

The knowledge hitherto at our disposal respecting the velocity of transmission of earthquake motion over long paths has been based on records obtained from instruments differing in type and sensibility, all of which were installed in Europe. The result of this has been that, although the registers led to the determination of average velocities along paths of varying lengths, they never gave actual velocity from point to point. It was seen that along paths from 10° to 90° the velocity of transmission of the preliminary tremors increased rapidly with the lengths of these paths, whilst the average velocity for large waves increased but slightly. With regard to the former my own analyses of heterogeneous materials led to the conclusion that, if the preliminary tremors travelled along paths approximating to chords through the earth, then the average velocity of transmission to a distant station was practically dependent on the square root of the average depth of the chord connecting that station and the earthquake centre. This furnished Dr. C. G. Knott with the hypothesis that the square of the velocity of these particular vibrations, which were in all probability compressional, was a linear function of the depth. With this assumption, and with a given initial velocity, the rate of transmission at any point within the earth could be determined and wave fronts drawn; and by accepting a law respecting the increase of density within our earth the elasticity governing the transmission of condensational waves could be determined. The following notes show that, although the first conclusion and the consequent hypothesis do not require modification, constants necessary in farther calculations require to be modified.

With regard to the large waves my own assumption was that their apparent increase in velocity with distance might be due to the fact that it was only large waves which, travelling faster than small waves, reached great distances.

The observations brought together in this paper show that this idea has to be abandoned, and in its place we are to accept either the hypothesis of a surface wave which increases its velocity in regions 90° from the focus, or of a distortional wave passing through the earth the outcrop of which gives rise to similar surface undulations.

3. *Sources of Error.*

The phases of earthquake motion here considered are the first preliminary tremors and the first group of large waves, which latter in a seismogram representing an earthquake which has originated at a great distance usually correspond to the maximum movement.

Although near to the origin of an earthquake there is a varying interval of several seconds between the first movements and the shock or shocks, it is the time of occurrence of this latter phase which is taken as the datum to which observations made at great distances from origins are referred. The initial time for all large earthquakes has been a matter of inference. It may be deduced from the times at which clocks have been stopped, or which have been noted with varying degrees of accuracy by survivors in an epifocal district, but more generally it has been deduced from automatic time determinations outside such an area, and subtracting from the same an interval which the shock is assumed to have taken to travel from its origin to the point or points where these chronographic records have been made. The determination of this interval is based upon repeated observations of earthquake velocities made between stations well removed from an epicentre and well outside a meizoseismal area. These figures are important, not only for this particular purpose, but also for completing velocity curves which may represent transmission over the surface and through the material of the whole globe. They have been arrived at by many observers, the last being those given by Dr. F. Omori, who for paths commencing 100 kms. from an origin and extending to distances of 1,000 kms. gives the velocities of 2·2 km. for preliminary tremors and 1·7 km. for large waves, and within these limits the former outrace the latter at the constant rate of 15 seconds per 100 kms.

When we remember that large earthquakes may sometimes originate as practically simultaneous displacements over very large areas, it is seen that the application of the method here considered might easily result in determinations of initial times from a few to some sixty seconds earlier than had really been the case. Errors of this nature would result in a general lowering of the determinations for true velocity of transmission of earthquake motion to distant stations, the deviation from the truth being most marked for the preliminary tremors, and in records referring to transmission to stations comparatively near to an origin.

Another serious error affecting the determination of initial time arises from the difficulty in accurately locating the position of a focus, especially when this is sub-oceanic.

The assumption that for large earthquakes, at least, the origin has been at an epicentre rather than in a region at a certain depth below the surface, is, so far as velocity determinations are concerned, of but small importance. Although all stations have similar instruments, the records from one or two of them indicate that their adjustment has not been similar to that adopted at the remaining stations. Not only should each instrument have a period of 15 seconds, but when its boom is deflected 7 or 8 mm. from its normal position, and then set free, it should take 7 or 8 minutes before returning to rest. If this latter condition has not been observed, an instrument may not respond to the first preliminary tremors, with the result that the time recorded for the commencement of a given earthquake may be registered as one or two minutes after the true time.

Although errors of this order may affect the results deduced from observations within 20° of an earthquake origin, when we deal with paths of greater length, and especially with large waves, the errors in the final results are practically inappreciable.

Another assumption made in connection with velocity determinations is that the group of vibrations and waves as recorded at a distant station extending between the first preliminary tremor and the first maximum—which may extend over any interval up to 100 minutes—were all the result of the principal movement or movements at the origin ; or, in other words, they have the same initial times. To this assumption I do not know of any serious objection. The fact that pronounced phases of movement near to an origin are not only extended in time as they radiate, but are also more or less equalised in their amplitude, frequently renders the determination of corresponding points in seismograms obtained at different stations more or less uncertain. This source of error is sometimes serious.

4. *Preliminary Tremors.*

In the compilation of the following table the only seismograms used are those which show a distinct commencement. Each earthquake is indicated by its British Association Register number, and the locality from which it originated. Following this are the initial letters (see p. 88) of the station or stations at which it was observed. The figures following these initial letters give the number of minutes taken by the preliminary tremors to reach these stations, and the number of degrees between the stations and the earthquake origins. These figures are respectively placed in positions corresponding to the numerators and denominators of fractions. If an initial letter is followed by a zero for a numerator, this indicates that all other time intervals are measured relatively to the observation made at the station represented by the initial letter.

The fewness of these records chiefly arises from these facts : first, they only refer to earthquakes with a known origin ; secondly, the seismograms of small earthquakes recorded at distant stations do not show the preliminary tremors corresponding to those given by large earthquakes ; and lastly, in consequence of air tremors and other causes, the earlier vibrations have in many instances been eclipsed or lost. Their chief merit is that they give for several earthquakes records from point to point, and that we have for the first time records relating to paths which practically extend from an origin to its antipodes.

36 Japan .	S. $\frac{16}{87}$	—	—	—	—	—	—	—	—	—	—
119 „ .	S. $\frac{13}{87}$	—	—	—	—	—	—	—	—	—	—
133 Borneo .	S. $\frac{20}{103}$	—	—	—	—	—	—	—	—	—	—
157 Hayti .	S. $\frac{8}{60}$	—	T. $\frac{0}{24}$	...	...	—	—	—	—	—	—
193 Japan .	S. $\frac{25}{87}$	—	T. $\frac{26}{89}$	—	S.F. $\frac{26}{100}$	—	—	—	—	—	—
250 Mexico .	—	K. $\frac{13}{86}$	T. $\frac{7}{35}$	V. $\frac{7·5}{33}$	—	—	—	—	—	—	—
263 Japan .	—	K. $\frac{24}{87}$	T. $\frac{26}{89}$	V. $\frac{22}{63}$	—	—	—		—	—	—
333 Alaska .	--	K. $\frac{7}{70}$	T. $\frac{4}{40}$	V. $\frac{0}{16}$	S.F. $\frac{7}{77}$	B. $\frac{19}{105}$	—	—	—	C.G.H. $\frac{20}{165}$	To. $\frac{5}{50}$
337 „ .	--	K. $\frac{4}{70}$	T. $\frac{0}{40}$	...	—	--	Ba. $\frac{19}{108}$	Ma. $\frac{17}{105}$	—	C.G.H. $\frac{25}{165}$	—
338 „ .	—	K. $\frac{14}{70}$	T. $\frac{0}{40}$	--	S.F. $\frac{17}{77}$	—	Ba. $\frac{23}{108}$	--	—	C.G.H. $\frac{24}{165}$	—
343 Smyrna	S. $\frac{0}{25}$	K. $\frac{0}{25}$	--	—	S.F. $\frac{1}{27}$	B. $\frac{7}{43}$	—	--	—	C.G.H. $\frac{18}{74}$	To. $\frac{15}{85}$
347 Ceram .	S. $\frac{16}{121}$	K. $\frac{16}{121}$	—	V. $\frac{11}{105}$	S.F. $\frac{19}{129}$	B. $\frac{6}{61}$	Ba. $\frac{0}{22}$	--	C. $\frac{4}{50}$	C.G.H. $\frac{21}{105}$	To. $\frac{4}{47}$
381 Mexico .	—	K. $\frac{15}{86}$	T. $\frac{9}{35}$	V. $\frac{8}{33}$	--	—	Ba. $\frac{86}{148}$	--	—	—	—

The numbers given in the preceding table have been plotted on squared paper, degrees being measured horizontally and minutes vertically. From the curves thus obtained the average times for preliminary tremors to travel distances of 20°, 30°, 40°, &c. have been determined, and are shown diagrammatically in fig. 1. The initial velocity is taken at 2·2 km. per second. A glance at the table on which this curve is founded indicates that the same can for the present only be regarded as provisional. The incurvation between 50 and 80 degrees is evidently due to errors in observation.

5. *Large Waves.*

The construction of the following table is similar to that given for the preliminary tremors. Following the initial letter of each station, in the position of a numerator, the number of minutes is given which large waves occupied in travelling to that station from the origin or from the isoseist of the locality, the initial letter of which is followed by a zero. The figures corresponding to denominators are the distances of the localities beneath which they appear from the origins of the different earthquakes.

250[1] Mexico	S. $\frac{31}{80}$	T. $\frac{2}{34}$	V. $\frac{0}{30}$	—	—	—	M. $\frac{92}{160}$	—	—	—	—	—
381[1] „	S. $\frac{32}{83}$	T. $\frac{2}{36}$	V. $\frac{0}{32}$	—	—	Ba. $\frac{86}{150}$	—	—		—	—	—
333 Alaska	S. $\frac{30}{70}$	T. $\frac{13}{40}$	V. $\frac{0}{20}$	S.F. $\frac{36}{77}$	B. $\frac{47}{105}$	—	M. $\frac{81}{145}$	—	C.G.H. 100 89 $\frac{79}{165}$	To. $\frac{17}{50}$	—	—
337 „	S. $\frac{20}{70}$	T. $\frac{0}{40}$	—	S.F. $\frac{22}{77}$	B. $\frac{34}{105}$	Ba. $\frac{50}{108}$	—	Me. $\frac{7}{49}$	C.G.H. $\frac{69}{165}$	—	Ma. $\frac{39}{165}$	—
338 „	S. $\frac{19}{70}$	T. $\frac{0}{40}$	—	S.F. $\frac{22}{77}$	B. $\frac{35}{105}$	Ba. $\frac{53}{108}$	M. $\frac{64}{145}$	Me. $\frac{6}{49}$	C.G.H. $\frac{61}{165}$	—	—	—
347 Ceram	S. $\frac{70}{121}$	—	V. $\frac{73}{105}$	S.F. $\frac{30}{132}$	B. $\frac{28}{62}$	Ba. $\frac{16}{22}$	M. $\frac{40}{73}$	—	C.G.H. $\frac{60}{105}$	To. $\frac{18}{47}$	—	C. $\frac{18}{50}$
343 Smyrna	S. $\frac{0}{25}$	—	—	S.F. $\frac{10}{27}$	B. $\frac{14}{43}$	—	M. $\frac{34}{65}$	—	C.G.H. $\frac{29}{74}$	To. $\frac{30}{85}$	—	—

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[1] The times at the origin for these two earthquakes were 21 and 22 min. before Victoria.

When these observations are plotted on squared paper it is found that they practically lie on the straight line referring to large waves in fig. 1, indicating that this form of movement passes from its origin to its antipodes with a constant arcual velocity of 3 km. per second. If, however, the direction of propagation has been along a diameter, the average velocity becomes 1·9 km. per second. The time taken for an earthquake to travel from its origin to its antipodes, whether it does so as a surface wave or as a mass wave, is about 110 minutes.

One modification to this general statement respecting a constant velocity rests on the fact that repeated observations made within ten degrees of an earthquake origin have shown that the large wave velocity within that region is about 1·8 km. per second. Whatever the conditions may be which give rise to this increase in velocity in a wave as it radiates from its origin, it seems probable that the converse would take place as it approached its antipodes, while the maximum velocity should be sought for in the equatorial or quadrantal[1] region of the earthquake's transit. Inasmuch as curves drawn for the Alaskan and Ceram earthquakes show that between 70° and 110° from their respective origins velocities may reach 4 km. per second, and that many earthquakes indicate an increased average velocity as their paths increase up to 110° in their lengths, there are strong reasons for suspecting that the suggested phenomena may exist. The comparatively small initial velocity and the slightly increased quadrantal velocity above the average arcual velocity are indicated in fig. 1 by dotted lines; but whether this modification can be retained remains to be determined by further observations. That the average arcual velocity between 0° and 90° is practically 3 km. per second finds confirmation in the records for earthquakes Nos. 36, 83, 100, 119, and 193, originating in Japan, 133 and 134, originating near Borneo, and 105, from N.E. India, all of which were recorded by the same instrument in the Isle of Wight.

6. *Interval between the First Tremor and the Maximum Motion.*

In the British Association Reports for 1898, pp. 221–224, I discussed a table showing the duration of preliminary tremors or the interval in time between the first tremor and the *commencement* of the large wave phase of motion at different distances from a number of known origins. One object of the discussion was to establish a working rule enabling an observer to determine from the inspection of a single seismogram the distance of an origin from the station at which such a record had been obtained. Inasmuch as the table was to a great extent based upon descriptions of records obtained from different types of instruments which had different degrees of sensibility, the results obtained could not be expected to be more than approximately correct. The following table, which gives the time in minutes by which the first tremor has outraced the maximum movement over paths of varying lengths, is based on measurements made on seismograms obtained from similar instruments. These intervals not only enable us to correct the working rule indicated above, but, as it will be shown, they enable us to check the accuracy of the curves relating to the arcual velocity of preliminary tremors and large waves.

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[1] This word means the district 90° distant from the earthquake origin.

Intervals between the First Tremor and the Maximum Motion.

No.	Date	Origin	Observing Stations indicated by initial letters and time intervals and distances, as $\frac{\text{Minutes}}{\text{Degrees}}$
36	August 30, 1896	Japan	S., $\frac{40}{84}$.
56	October 31, 1896	Tashkent	S., $\frac{13}{45}$.
83	February 6, 1897	Japan	S., $\frac{34}{86}$. Record not clear.
119	August 4, 1897	"	S., $\frac{46}{86}$.
131	September 17, 1897	Tashkent	S., $\frac{15}{45}$.
132	September 17, 1897	"	S., $\frac{15}{45}$.
133	September 20, 1897	Borneo	S., $\frac{52}{103}$.
134	September 20, 1897	"	S., $\frac{60}{103}$.
157	December 29, 1897	Hayti	S., $\frac{29}{62}$. T., $\frac{3}{24}$.
163	January 29, 1898	Asia Minor	S., $\frac{12}{25}$.
189	April 15, 1898	California	T., $\frac{5}{35}$?
193	April 22, 1898	Japan	S., $\frac{35}{86}$ (not clear). T., $\frac{35}{89}$.
249	January 22, 1899	Greece	S., $\frac{10}{21}$. K., $\frac{7}{21}$.
250	January 24, 1899	Mexico	K., $\frac{40}{80}$. T., $\frac{15}{34}$. V., $\frac{14}{30}$. P., $\frac{15}{30}$.
333	September 3, 1899	Alaska	K., $\frac{30}{70}$. T., $\frac{18}{40}$. V., $\frac{5}{20}$. S.F., $\frac{34}{77}$. B., $\frac{33}{105}$? To., $\frac{13}{50}$. C.G.H., $\frac{65}{105}$.
337	September 10, 1899	"	K., $\frac{35}{70}$. T., $\frac{13}{34}$. C.G.H., $\frac{43}{165}$? B., $\frac{41}{105}$. S.F., $\frac{31}{77}$. Me., $\frac{28}{49}$.
338	September 10, 1899	"	K., $\frac{30}{70}$. T., $\frac{27}{34}$? Me., $\frac{20}{49}$. Ba., $\frac{55}{108}$.
343	September 20, 1899	Aidin	S., $\frac{9}{25}$. C.G.H., $\frac{13}{74}$? B., $\frac{15}{43}$. K., $\frac{6}{25}$. To., $\frac{32}{85}$.
347	September 29, 1899	Ceram	S., $\frac{60}{121}$. C.G.H., $\frac{41}{105}$. Ba., $\frac{4}{22}$. B., $\frac{10}{62}$? V., $\frac{70}{105}$?
381	January 20, 1900	Mexico	K., $\frac{39}{83}$. T., $\frac{14}{36}$. V., $\frac{13}{32}$.

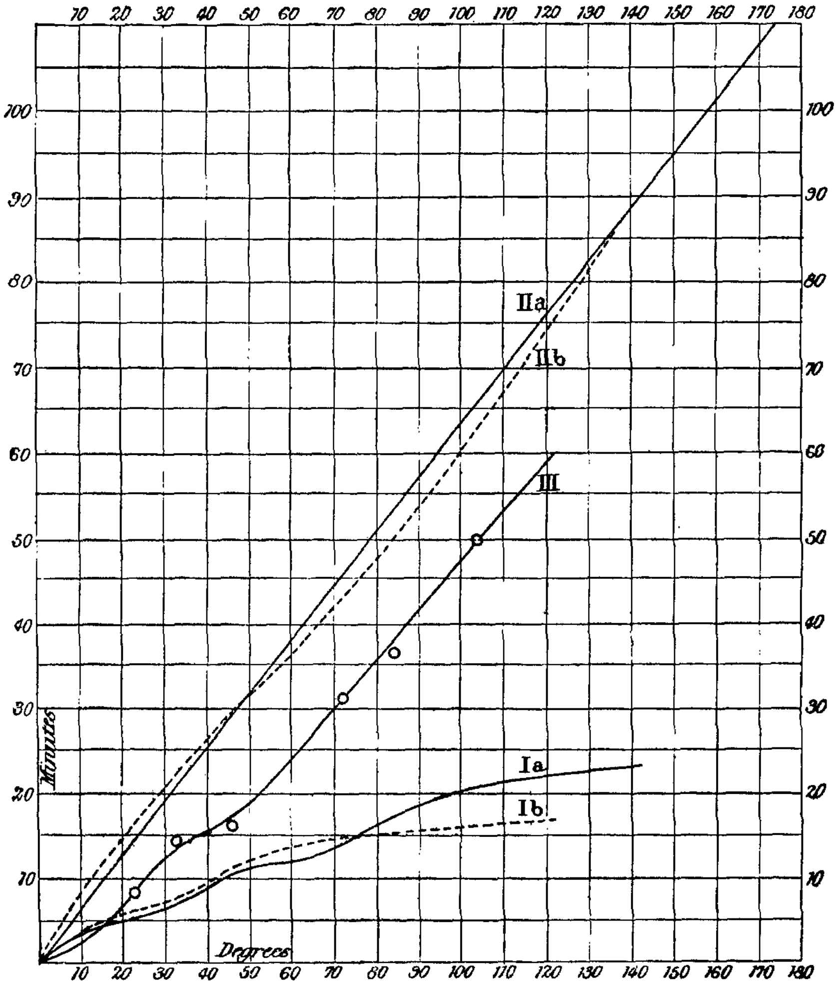
These observations have been plotted upon squared paper, and their mean position determined. This is shown in fig. 1 as Curve No. III.

On Curves I, II, and III, fig. 1.—Although in fig. 1 we have three curves which have been obtained from partly independent data, it will be observed that any one of them might have been obtained from the other remaining two. Although errors exist in all our data, these are probably least in the figures relating to the arcual velocity of large waves and the duration of preliminary tremors. By subtracting the ordinates for the latter curve, marked III, from those of the first curve, marked II, the curve I *b* is obtained. This should coincide with I *a*. It hardly does so; but if the second incurvature of I *a*, lying between 50 and 80 degrees, be effaced as probably doubtful the agreement between these two curves becomes closer.

7. *Earthquake Recurrence.*

It would be naturally expected that if the large waves of earthquakes were simply surface disturbances, we should find in the seismograms obtained at stations far distant from origins not only records of the waves which had travelled over the shortest paths, but also a record of those which had travelled in an exactly opposite direction. The supposition that these latter records were without existence has been used as evidence in support of the hypothesis that all the movements of a large earthquake passed through the earth. Mr. R. D. Oldham, in his account of the Indian earthquake of 1897, however, shows that in the seismograms obtained in Edinburgh, Shide, Leghorn, Rocca di Papa, and Catania there are excrescences succeeding the maxima movements at

FIG. 1.



Arcual Velocities.—Ia. Preliminary Tremors by direct observation ; Ib. Preliminary Tremors deduced from IIa and III ; IIa. Large Waves if the Velocity is constant ; IIb. Large Waves if the Velocity varies ; III. Intervals by which Preliminary Tremors outrace Large Waves.

times we should expect them to occur on the supposition that they had travelled round the world from their origins on the longest paths.

Without discussing the merits of the particular seismograms here referred to, we must bear in mind that it is possible for body waves to give rise to repetitions by reflection just as easily as two trains of waves coming round the surface of the world in opposite directions. Further, the repetition at a given station as a reflection of a disturbance at the antipodal point of its origin might occur at an interval of time after the first movement not very different from that separating the two surface trains.

Such a possibility indicates that seismic repetitions cannot be exclusively used to support the hypothesis of surface radiation. Examples of earthquake recurrences are given in the following table. The first column gives the numbers of the earthquakes in the British Association registers and their origins. Where the position of an origin is not known from observations made in its vicinity its latitude and longitude are determined by one of the methods described in the succeeding sections of this report (see pp. 79–80). Such determinations must only be regarded as approximations. The second column gives the arcual degree-distances of the origins from the observing stations referred to in the third column by their initial letters. In this third column there is also noted the number of minutes' interval between the maximum motion and its apparent repetition. The fourth column gives the calculated distance of the observing station from the origin, and the nearness to which it approximates to the corresponding figures in the second column is evidently an indication of the value of these observations in determining seismic foci. The basis for these calculations is that a surface-wave travels 180 degrees in 105 minutes. In the last column the letters G, I, and B (good, indifferent, and bad) indicate that the determinations in the fourth column lie within 10°, 20°, or more than 20° from those in the second column, which latter figures, however, it must be remembered, are themselves but approximations.

No. of Earthquake and its Origin	Distance to Origin in Degrees	Repetition Interval in minutes at a given Station	Distance to Origin determined from Repetition Interval	Character of the Determination
	°	m.	°	
119. Japan . .	87	85 S.	96	G
140. . . .	110	105 S.	82	B
278. 30° N. 70° W.	60	122 S.	68	G
309. 60° N. 180° W.	70	132 S.	62	G
	70	121 K.	70	G
	160	144 C.G.H.	52	B
333. W. of Alaska .	16?	212 V.	0	G
	40	159 T.	40	G
	70	127 to 145 K.	66 to 52	G
337. W. of Alaska .	40	129 T.	62	B
	165	75 C.G.H.	108	B
	77	185 S.F.	18	B
338. W. of Alaska .	40	163 T.	38	G
	165	123 C.G.H.	70	B
	77	128 S.F.	66	I
343. Smyrna . .	25	73 S.	108	B
347. Ceram . .	121	59 S.	120	G
	121	78 K.	106	I
	105	80 V.	102	G
354. 5 S. 130 E. or 20 S. 100 E.	120	70 S.	110	G
	100	63 C.G.H.	116	I
	110	95 V.	90	I
355. Like 354. .	120?	60 S.	118	G
364. 20° N. 170 E.?	106	73 M.	108	G

We have here twenty-four determinations, out of which thirteen are considered as being good, four as indifferent, and seven as bad. The three bad determinations for earthquake No. 337 may be explained by the assumption that we have here been dealing with markings due to secondary shocks which simulated seismic repetitions, a view that is strengthened when we refer to the seismograms of this earthquake. It must also be noted that No. 337 was less than Nos. 333 or 338, from which it may be inferred that the original impulse was not sufficiently great to give rise to duplications. The fact that the Cape of Good Hope records for 309 and 338 are bad may arise from the circumstance that this station was within a comparatively short distance of the antipodes of these shocks, and therefore any wave coming from that point would be eclipsed in the records of the main disturbance. The remaining two bad determinations may be explained in the same manner that those for No. 337 have been explained.

The Victorian record for No. 333 is of particular interest as indicating that the time taken for an earthquake to travel round the world or to traverse two diameters slightly exceeds 210 minutes.

When considering whether these repetitions are to be regarded as surface waves or as mass waves reflected from an antipodes, a feature not to be overlooked is their smallness. To illustrate this I here give a table for the thirteen good observations showing the amplitudes in millimetres of the primary disturbances and those of their repetitions, together with the arcual distance each may be supposed to have travelled.

B. A. No.	Primary		Repetition	
	Distance	Amp.	Distance	Amp.
	°	mm.	°	mm.
119	87 S.	>16	273	1·5
278	60 S.	2·5	300	·5
309	70 S.	3	290	·5
	70 K.	2·5	290	·5 ?
333	20 V.	>16	340	·75
	40 T.	>17	320	·5
	70 K.	10	290	·5 ?
338	40 T.	>17	320	·75
347	121 S.	3·5	239	1·5
	105 V.	2	255	·5
354	120 S.	2	240	·5
355	120 S.	1·5	240	·5
364	106 M.	3	254	1

It is satisfactory to note that the magnitude of these repetition amplitudes fairly accords with what might be anticipated (see p. 70).

8. *Amplitude in relation to Distance from an Origin.*

In the following table amplitudes are expressed in millimetres and occupy a position corresponding to the numerator of a fraction, whilst in the position of a denominator distances from origins are expressed in degrees. Observing stations are indicated by their initial letter or letters.

Inasmuch as there are reasons for believing that the instruments giving the subjoined records have not in all cases been adjusted to have the same frictional resistances and as these records are few, the result to which they point must be received with caution. When they are plotted as curves it is seen that each has the same general character. The rate at which amplitude at first decreases is about ·2 mm. per degree of travel. Earthquakes like Nos. 343 and 347 from whatever may have been their amplitude in the epifocal district, are reduced to an amplitude of 4 mm. after about 50° of travel. Larger earthquakes, like Nos. 337, 344, and 345, travelled 80° or 90° before their amplitude sank to this quantity; whilst the largest of all, Nos. 333 and 338, show an amplitude of more than 4 mm. after travelling nearly halfway round the world. From an amplitude of 4 or 5 mm. the rate of decrease becomes less and less. For example, the amplitude of No. 337 between 77° and 105° falls from 5 mm. to 3 mm., or at the rate of ·07 mm. per degree; whilst from 105° to 165° the rate at which amplitude decreases has been ·01 mm. per degree at travel.

250. Mexico .	S. 6/80	K 4·5/80	T. 8/34	V. >17/30	—	—	—	—	—	—	—	P. 6/34
344. Alaska .	S. 5/70	—	T.>17/20	—	—	B. 0·5/105	—	M. ·75/145	—	—	To. 2·5/50	—
345. „ .	S. 5/70	—	T.>17/20	—	—	B. 0·5/105	—		—	—	—	—
333. „ .	S.>17/70	—	T.>17/40	V. >17/20	S.F. 20/77	B.>17/105	—	M.>17/145	—	C.G.H. 10/165	To. 1/50	—
337. „ .	— —	—	T. 20/40	—	S.F. 5/77	B. 3/105	—	—	M. 4/49	C.G.H. 2/165	—	—
338. „ .	— —	K. >17/70	T.>17/40	—	S.F. 20/77	B. 9/105	—	M. 4/145	—	C.G.H. 10/165	—	—
347. Ceram .	S. 2·5/121	—	—	V. 2/105	—	B. 1/62	Ba. 10/22	M. 1·5/73	—	C.G.H. 0·5/105	To. 5/47	—
343. Smyrna	S. 9/25	—	—	—	—	B. 4/43	—	M. 1/65	—	C.G.H. 6/74	To. 4/85	—

These slow rates of decrease indicate that it is reasonable to suppose that the large waves of earthquakes may reach distant stations by travelling in opposite directions round the world.

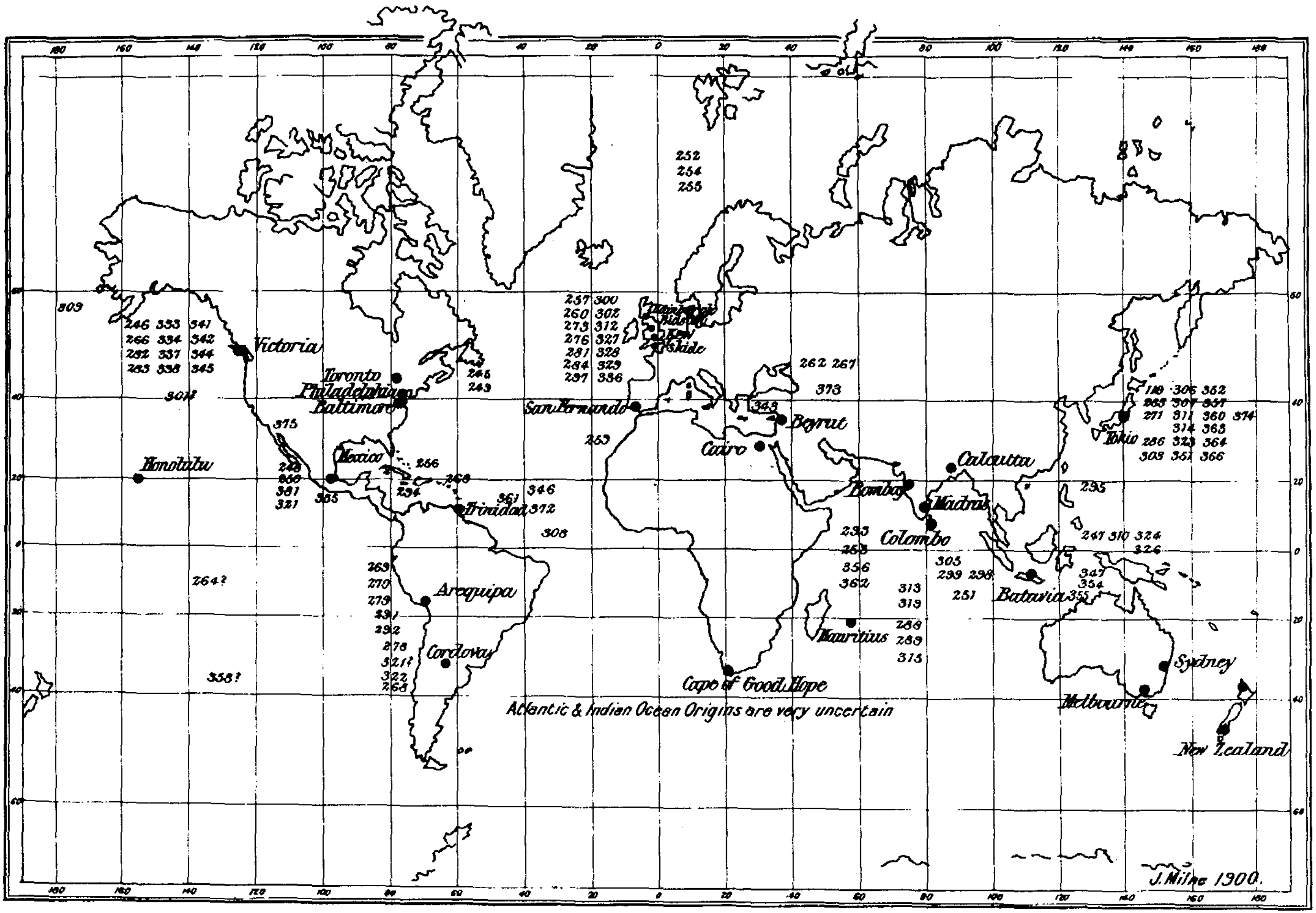
If the large waves of earthquakes are merely surface waves, it would be expected that oceans would exert a marked damping effect upon their amplitude. Indications of this apparently exist in the records for earthquakes Nos. 337, 338, and 347 (also see earthquake 263, p. 81). In the first the amplitude for Toronto is greater than that observed in Mexico, the path to the former being across North America, and the latter being suboceanic. In No. 338 the record for Mauritius is less than that for the Cape of Good Hope. In No. 333 this condition is, however, reversed. Lastly, in No. 347 the Shide record, which refers to a comparatively long continental path, is greater than the records for Victoria, the Cape of Good Hope, Bombay, or Mauritius, the shorter paths to which are beneath oceans. Although, for reasons already stated, stress cannot be laid upon these observations, the latter at least suggests that we are dealing with surface waves rather than with mass waves.

9. *Arcual Velocity in relation to Surface Configuration of the Earth.*

With the object of determining whether large waves are propagated more quickly over continents than over ocean beds, whether the rate of transmission along mountain axes is greater than in directions transverse to the same, and generally to determine whether there are directions over or through our globe in which motion is transmitted more rapidly than in others, the following table has been prepared. The apparent surface

The Large Earthquakes of 1899.

Origins are indicated by their B.A. Register numbers. **Stations with similar horizontal pendulums (Milne type) are named.**



Illustrating the Report on Seismological Investigation.

velocities indicated in kilometres per second are from the isoseist of the place indicated by its initial letter to the place beneath which it is written. These latter places in the top line are also indicated by their initial letters The letter O refers to a velocity measured between an origin and the place named in the upper line.

	S.	T.	V.	SF.	B.	Ba.	M.	Me.	CGH.	To.	C.
250. Mexico .	T. 3·1	Me. 2·7	Me. 2·6	—	—	O. 3·2	O. 3·2	—	—	—	—
381. „ .	T. 3·2	Me. 2·6	Me. 2·6	—	—	—	—	—	—	—	—
333. Alaska .	T. 3·2	V. 3·4	—	T. 3·1	T. 3·6	T. 2·9	B. 2·1	—	T. 3·4	V. 3·7	—
337. „ .	T. 2·7	—	—	T. 3·1	T. 3·6	T. 2·3	—	T. 2·3	T. 3·5	—	—
338. „ .	T. 2·9	—	—	T. 3·1	T. 3·4	—	B. 2·5	T. 2·7	T. 3·7	—	—
347. Ceram .	Ba. 2·3	—	Ba. 2·1	—	Ba. 2·6	—	Ba. 2·1	—	Ba. 2·5	Ba. 2·6	Ba. 2·3
343. Smyrna .	—	—	—	S. 6·3	S. 2·3	—	S. 2·1	—	S. 3·1	S. 3·7	—
193. Japan .	O. 2·6	O. 2·8	—	—	—	—	—	—	—	—	—

As it is difficult to picture the directions of great circle paths outside equatorial regions, these are shown with the above velocities and the earthquakes to which they refer in the accompanying map (Plate II.). A line not referred to in the above table is that for earthquakes numbered 36, 83, 100, and 119, which originated in Japan and travelled to the Isle of Wight with an average velocity of 2·9 kms. per second.

An inspection of the map (Plate I.) shows that the apparent velocities over long paths are greater than those over short paths. Velocities across the Pacific are apparently lower than those across the Atlantic, and those across Northern Asia to Shide are lower than those across North America to Shide. Between Mexico and Victoria along the strike of the chief North American anticline the velocity of transmission is the same as that between Mexico and Toronto. Along paths terminating at the Cape of Good Hope the rate of transmission has been high, whilst on those terminating at Mauritius, excepting that referring to the long path for earthquake 250, the velocity of propagation appears to be low.

There does not appear to be any indication that direction of propagation is related to speed, and although earthquake 381 was larger than 250, and 333 and 338 were larger than 337, we do not seem to have any definite evidence that velocity of propagation is connected with the intensity of the initial disturbance.

Taking the results of this investigation generally, we are hardly in a position as yet to draw definite conclusions, and must wait for further observations.

10. *Earthquake Echoes.*

In the British Association Report for 1899, p. 227, I drew attention to the fact that in seismograms where a group of large vibrations corresponding to a shock or shocks at an origin is pronounced, this is frequently succeeded by a set of fairly similar movements. These latter impulses, which may be repeated, but with decreasing intensity, many times, I provisionally called earthquake echoes. Although earthquake repetitions (see pp. 66–69) which succeed their primaries at very irregular intervals may possibly be antipodean reflections of mass waves, they must not be confounded with the so-called echoes which succeed the maxima movements at fairly regular intervals.

The following table gives time intervals in minutes between a number of shocks and their first echoes, together with their respective amplitudes expressed in millimetres. These records are from similar instruments.

B.A. No.	Origin and its Distance		Amplitudes		Interval	Observing Station
			Primary	Echo		
		°	mm.	mm.	Mins.	
36	Japan	84	5	5	9	Shide
56	Tashkent	46	6	4	3	„
83	Japan	87	>7	>7	8	„
119	„	87	17	10	7	„
157	Hayti	62	2·5	2·5	7	„
„	„	24	6	3	3	Toronto
163	Asia Minor	25	3	4	5	Shide. Record not clear
189	California	75	2	3	2	„
„	„	or	2	1	7	„
193	Japan „	86	5	3	3	„
250	Mexico	80	5	5	3	„
„	„	80	6	7	7	Kew. Doubtful
„	„	34	7	8	5	Toronto
„	„	30	17	9	5	Victoria
322	Concepcion		2·5	1·5	6	Toronto
333	Alaska	20	>17	17	22	Victoria
„	„	40	17	12	22	Toronto
„	„	70	10	7	5	Kew
„	„	105	17	15	4	Bombay
„	„	165	7	7	9 or 20	Cape of Good Hope
„	„	77	17	10	5	San Fernando
337	„	40	18	7	25	Toronto
„	„	105	3	2	3	Bombay
338	„	40	>17	15	25	Toronto
„	„	70	17	7	5	Kew
„	„	145	4	4	8	Mauritius
„	„	165	11	10	17	Cape of Good Hope
„	„	105	8	7	4	Bombay
„	„	49	17	7	3	Mexico
343	Smyrna	25	7	8	5	Shide
„	„	85	3	3	3	Tokio
„	„	74	7	5	5	Cape of Good Hope
„	„	43	4	4	3	Bombay
„	„	25	5	5	4	Kew
344	Alaska	70	4	3	4	Shide
„	„	20	17	7	4	Victoria
345	„	70	5	4	5	Shide
„	„	20	>17	7	4	Victoria. Larger than 344
381	Mexico. At Victoria and Toronto the chief motion is followed by three reinforcements at intervals of 3 minutes. At Kew there are two at intervals of about 3 minutes.					

The second group of waves, giving the large interval for the Cape of Good Hope in 333 and 338, may possibly refer to the motion which reached that station by the longest path round the earth.

If so regarded, these entries do not refer to echoes, but to repetitions. The large entries for Victoria and Toronto on account of the comparative nearness of these places to the origins of earthquakes 333, 337, and 338, cannot, however, be so regarded. Between these extremely large reinforcements it must not be overlooked that there are others of less magnitude separated by intervals of from two to four minutes.

All that we can conclude from an inspection of the above table is that after all sensible motion of a large earthquake has ceased horizontal pendulums, whether they are situated near to its origin or at a great distance from the same, indicate that the earth waves at intervals of from two to six minutes show marked increments in amplitude. The earthquake does not die out gradually, but by surgings. In its latter stages, for intervals of one or two minutes, the ground may be entirely at rest, after which movement recommences. This alternation of rest and movement may be repeated many times.

If it can be admitted that large earthquakes result from the collapse of ill-supported portions of the earth's crust upon a more or less plastic layer beneath, it may be imagined that rest is attained by a series of more or less regular surgings, which are propagated to distant places to disturb horizontal pendulums in the way observed.

11. *The Nature of Large Waves.*

To explain the existence of the large waves of earthquakes we are at present left to choose between two hypotheses. One is that the large waves of earthquakes are disturbances travelling partly under the influence of gravity over the surface of our earth, and the latter that they represent the outcrop of distortional waves passing through its mass.

Near to the origin of a large earthquake earth waves are visible ; some distance away their existence has been inferred from the wave-like motion seen on the tops of forests, at a distance of 300 miles, and even at very much greater distances the feeling occasioned by the moving ground is similar to that which is felt upon a raft moved by an ocean swell. Bracket seismographs, hanging pictures and lamps, water in vessels, ponds, and even in lakes, do not move with their natural periods, but are clearly influenced by a forced tilting. Finally, even as far as the antipodes of an origin, the character of motion assumed by horizontal and other pendulums shows that this is due to slow but repeated changes in the inclination of their supporting foundations.

If we except the movements observed within the epifocal area, all the other movements are as explicable by the assumption of the outcrop of mass waves as they are by the assumption of surface radiation.

The explanation that these waves have an increased velocity in their quadrantal region (assuming such to be the case) may perhaps rest on the fact that we are not dealing with radiation in uniformly widening rings, as would be the case over a plane surface. The condition in this region is such that energy is transferred from ring to ring, the diameters of which are but little different from each other. Radiation from a pole to its antipodes over a spherical surface may be likened to that of a wave which runs along a channel, which expands for half its length and then contracts.

The phenomena which give the greatest support to the idea of surface radiation are, first, the existence of earthquake recurrences or waves which have travelled from an origin to a distant station in opposite directions round the world, the one arriving last having its amplitude reduced to expected dimensions ; and second, the observations which show that waves travelling over a continental surface are not so rapidly reduced in magnitude as those which have been propagated over the beds of deep oceans. Were the large waves of earthquakes mass waves, it is assumed that the damping effect of oceanic waters would be insignificant.

When considering the large waves to be distortional mass waves, an observation of importance is that they travel from their origin to their antipodes in about 110 minutes (see fig. 1). If the path was along a diameter, the average velocity of propagation must therefore have been 1·9 km. per second, which is practically the so-called initial velocity. The close correspondence of these two velocities suggests the idea that there has not been any symmetrical change in the velocity of propagation of waves through the earth with regard to its centre, or, in other words, the large waves have had a diametral velocity which is practically constant. This idea of a constant velocity for all depths indicates that arcual and diametral velocities should be equal, which is not the case. An escape from the dilemma is to suppose that the large waves do not pass through the earth, but round its surface.

12. *Criticisms and Analyses by Dr. C. G. Knott.*

In reference to the conclusion implied in the last paragraph, Dr. Knott remarks that it does not necessarily follow from the premises, the initial speed referred to being an arcual speed, or a speed for short distances from an origin through the surface layers. When a disturbance travels straight down it very soon gets probably into more homogeneous materials beneath the crust. It may therefore be a mere coincidence that the average speed along a diameter may come out almost exactly the same as the arcual speed in the crust.

The evidence seems to show that once you get into the nucleus proper, the speed of the large waves decreases with depth. But this does not prevent the speed suffering a distinct increase when the disturbance passes from the lower layers of the crust into the higher layers of the nucleus. That the arcual speed should be 1·9 for small arcs, and then become on the average three when the arc is half a circumference, seems to be an immeasurably more difficult thing to understand than that the speed downwards should first increase and then decrease as the depth increases. A not improbable change in the nature of the material could easily account for the latter variation; but it is difficult to see how a surface wave of the size of the large waves could gain in speed as it ran round the earth.

Writing more generally respecting the propagation of large waves, Dr. Knott says :—

I have looked pretty carefully into your numbers and curves, and now I shall indicate some of my conclusions. As you have pointed out, the one doubtful point is the precise instant at which the disturbance began, also to some extent the exact position of the origin. I take your determinations as being as accurate as they can be obtained, and proceed to consider the speeds indicated. The accompanying tables will show you what I have tried to do. Take the Alaskan group, the most complete of all you have. It is gratifying to find how similar the results are for the three different earthquakes. The greatest discrepancy is in the two numbers for the Batavian records. It is curious that these time records do not fit well into the general scheme. Can there be any mistake? The arcual speed indicated is distinctly smaller than we find in all the other cases, except the case of Mauritius. If there is no mistake in calculating the times, then the disturbance travels comparatively slowly along the Alaskan Batavian route. This route, *if it lies near the surface*, is almost wholly beneath the deeps of the North Pacific. But then, on the other hand, the Alaskan Mauritius route is also a comparatively slow route, and it lies further to the west, under Siberia, India, and the Indian Ocean. Still, these two routes are in the same quarter of the globe, so that a similar value for the speed is not unlikely. It may be not merely a question as to whether sea or land is overhead, but may depend on the general character of the rocky material. These two routes left out of account, there is a very striking constancy in the value of the arcual speed calculated for these various routes. In the four routes to Shide, San Fernando, Bombay, and Cape of Good Hope, the great circles pass all very near the poles. It is beautiful to see how well these four polar routes agree. With the somewhat scanty material you have to hand, I doubt if you would be at all warranted in making any deductions as to variations of speed. The Alaskan results suggest a constant value for the arcual speed. The same constancy is indicated in the Mexican earthquakes, but the value comes out distinctly smaller than in the Alaskan quakes. Why is this ? Still thinking of great-circle routes, we see that there cannot be much difference between the Mexican Batavian and the polar routes from Alaska, unless, of course, the former goes preferably by way of the South Pole. But that possibility is not considered in calculating the speeds. If we took it that way the speed would come out larger in the ratio of 210 to 150 or 7·5, giving 1·9 instead of 1·4, a remarkable coincidence truly. The Mauritius number will also be increased in much the same ratio. But what are we to make of the others ? No, I think we must get at an explanation of the much smaller speeds associated with the Mexican earthquakes in some other way. Is it possible that the depth of the seismic focus might have something to do with it ? Have you any facts to guide you to an estimate of the probable depth ?

And now pass on to the Ceram quake. Here the constancy, so marked a feature in the other cases, no longer holds. There is an undoubted increase in the arcual speed over the longer arcs. The most striking feature is the smallness of the Mauritius route speed as compared with that associated with the Cape of Good Hope route ; for there cannot be much difference in the routes for the greater part of the way. But did not Mauritius give a too small value in the Alaskan earthquake also ? Again, I ask, is there no possibility of an error in the time estimate ? Ceram Victoria and Mexico Batavia give approximately the same value for the arcual speed—a point which tells in favour of the accuracy of the time estimates, for the routes are very different in the two cases. Leaving out of account all but the broad features, we may conclude that the speeds (arcual) associated with the Alaskan are distinctly greater than those associated with the Mexican and Ceram earthquakes. But I confess I can give no satisfactory explanation of this, nor can I see why Batavia and Mauritius should give smaller values than the others in the Alaskan group, and why Cape of Good Hope and Shide should give comparatively large values in the Ceram group.

And now let us see what comes of taking the chord as the approximate path of shortest time. Interpreted in this way the results indicate that the waves must go diametrically through the earth at a much slower average rate than along a course near the surface. Thus, from the Alaskan group we should infer an average diametrial speed of about 2·2 km. per sec.; from the Mexican group about 1·8; and from the Ceram group about 2·5. This suggests that the speed of propagation along a diameter depends upon the particular diameter considered—a very curious result surely, unless, of course, the depth of the focus below the surface be very different in the different cases.

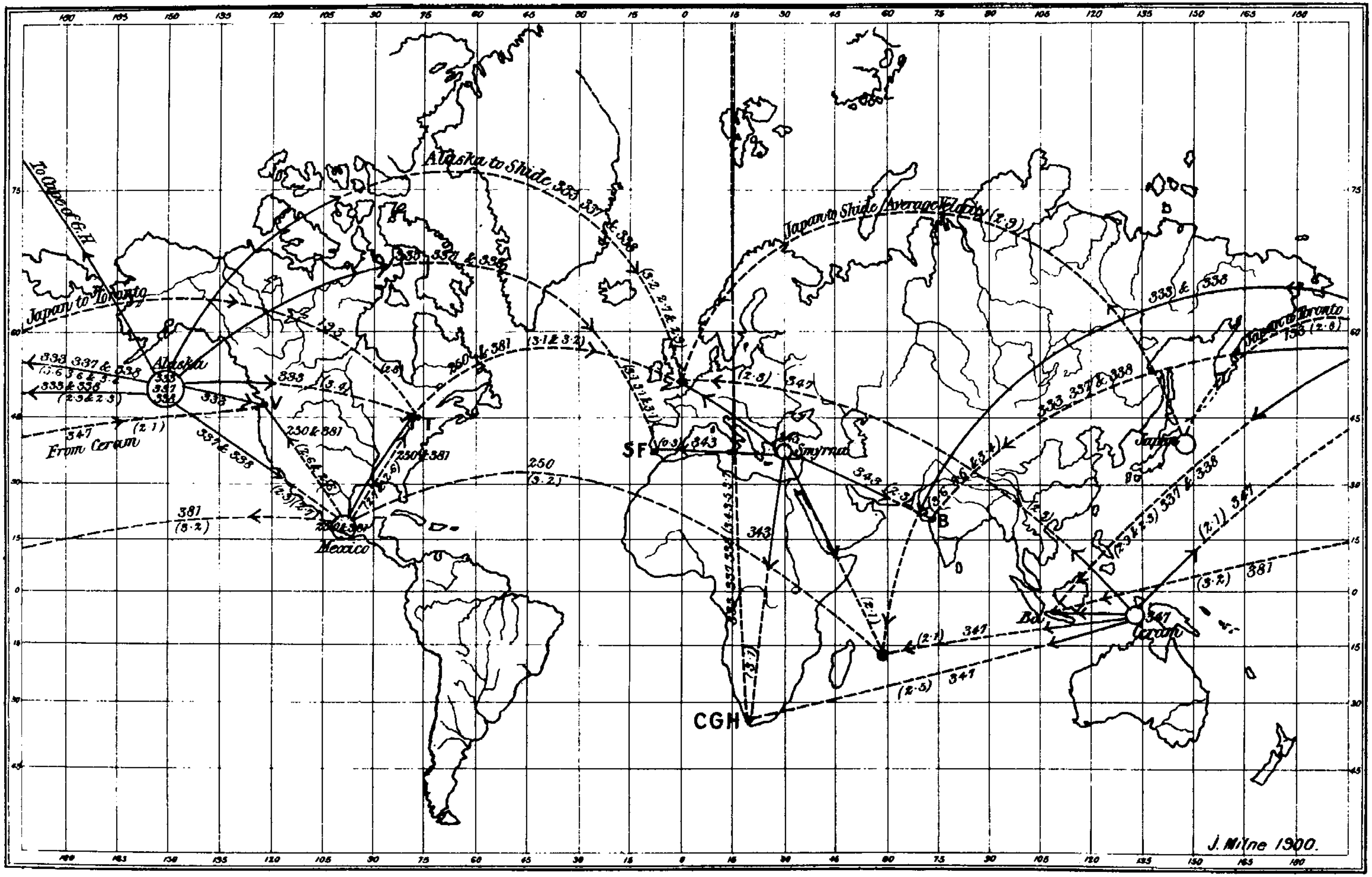
As regards the general question of the diminution of speed at greater depths, all we can say is that it is not impossible. True, the result is unexpected, seeing that there can be little doubt that the preliminary tremors travel quicker at the greater depths. But then it is also certain that the elastic constants involved in the transmission of the two types of waves must be essentially different, and there is no necessity for them to obey similar laws of variation with depth. In my 'Scottish Geographical Magazine' article I pointed out that the bulk modulus might increase at a much quicker rate than the density, whereas the rigidity might increase at much the same rate. To meet the new need we have merely to assume that the rigidity does not increase so quickly as the density. We know that the density increases with the depth, and we know nothing whatever about the elastic constants except what we learn from seismic phenomena. It was, in fact, with feelings of surprise that we first recognised the high speeds of earthquake disturbances through the body of the earth. That another type of wave should travel more slowly at the greater depths should not therefore be matter of any surprise, although certainly remarkable.

The hypothesis that the large waves really pass along brachistochronic paths seems to require that the speed diminishes with distance from the centre. This means that the paths are convex outwards, concave towards the centre. Hence the paths to points within 90° of the origin will tend to follow more or less closely the arc of the outer crust. When the arcual distance exceeds the quadrant, then the paths begin to pass through deeper parts of the earth, and the fall off in the value of the average speed becomes more apparent. This is precisely what is indicated in the values deduced from the Alaskan group, since it is not till the arc exceeds 105° that the value of the calculated average speed shows marked diminution. The Mexican group shows the same feature, but not so the Ceram earthquake. Still it is only one against five, and we shall be safer in following the five.

Comparing the two hypotheses, the surface wave and the brachistochronic path, we see that up to distances of a quadrant or so they give much the same result, because the brachistochronic path is largely confined to the surface layers. As regards greater distances the evidence in hand is not very clear. Increased 'arcual speed' is hinted at, and this, if it exist, is a serious stumbling-block in the way of accepting the surface wave theory. But at best the increase is small, and, except in the case of the Ceram quake, really too small to build any conclusions upon. I should rather be inclined to say that the evidence so far is in favour of a practically constant 'arcual speed' over all distances. But I still entertain strong suspicion of the possibility of surface waves of the magnitude required being transmitted over the earth's surface. If we take the values of the arcual speeds in the Ceram earthquake as being accurate, we meet what seems to me to be an insurmountable difficulty in the surface wave theory. On the other hand, we have no insurmountable difficulties if we

Apparent Paths of the Large Waves of Earthquakes from five origins (indicated by circles) to various observing stations.

The Alaskan origin for earthquakes Nos. 333, 337, and 338 might possibly be moved 10° to the east. The velocities, given in kms. per sec. and placed in brackets, refer to paths or portion of paths, indicated by dotted lines. The earthquakes are indicated by numbers (see B.A. Reports).



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take the other theory, although there are difficulties of detail that are somewhat troublesome. I do not think we are in a position as yet to make any serious calculations. We must get more data and look all round them before engaging in complicated calculations.

Character of path in three cases on the assumption that the path is not along the chord, but more approximately along the arc.

Alaskan.

Victoria	Under sea.
Toronto	Half sea, half land.
Mexico	Half sea, half land.
Shide	Mostly sea, polar archipelago, Greenland ?
San Fernando	Half sea and land, largely polar.
Bombay	Mostly land, Siberia, Tibet.
Batavia	Deep sea, east of Asia.
Mauritius	Siberia, India, Indian Ocean.
Cape of Good Hope	Polar sea, Europe, Africa.

Mexico.

Victoria	Under N. America.
Toronto	” ”
Shide	Skirting E. of N. America and then under Atlantic.
Batavia	N. America, Pole, Asia.
Mauritius	N. America, Pole, Russia, Persia, Indian Ocean, or by way of S. Pole.

Ceram.

Batavia	East India Archipelago.
Mauritius	Indian Ocean.
Victoria	Pacific Ocean.
Cape of Good Hope	Indian Ocean.
Shide	India, Persia, Europe.

Alaskan Earthquakes (333, 327, 338).

Assuming constant speed for small distances, we find 9 min. as the time from the origin to Victoria. Hence the following table :—

Arc		Chord	Time of Passage in Min.			Speed		
						Arc Degrees / Min.	Chord / Min.	Arc Radians / Min.
Victoria	16°	·28	9	—	—	1·8	·031	·031
Toronto	40	·68	22	22	22	1·8	·31	·31
Mexico	49	·83	—	29	28	1·7	·29	·30
Shide	70	1·15	39	42	41	1·8	·29	·31
San Fernando	77	1·25	44	44	44	1·75	·28	·305
Bombay	105	1·59	55	55	57	1·9	·28	·33
Batavia	108	1·62	—	65	75	1·66 1·44	·23	—
Mauritius	145	1·91	90	—	88	1·63	·215	·284
Cape of Good Hope	165	1·98	88	89	83	1·9	·226	·33

Mexico (250, 381).

Assuming 21, 22 mins. as times from origins to Victoria :

Arc		Chord	Time in Min.	$\frac{\text{Arc Degrees}}{\text{Min.}}$	$\frac{\text{Chord}}{\text{Min.}}$
Victoria . .	30–32	·52–·55	21–22	1·4	·025
Toronto . .	34–36	·58–·62	23–27	1·4	·25
Shide . . .	80–83	1·29–1·33	52–54	1·52	·25
Batavia . .	150	1·93	108	1·39	·18
Mauritius . .	160	1·97	113	1·41	·175

Ceram (347).

Time calculated as in Alaskan earthquake.

Arc		Chord	Time	$\frac{\text{Arc Degrees}}{\text{Min.}}$	$\frac{\text{Chord}}{\text{Min.}}$
	°		Min.		
Batavia . . .	22	·38	14	1·57	·027
Mauritius . .	73	1·19	47	1·55	·25
Victoria . . .	105	1·59	74	1·42	·22
Cape of Good Hope.	105	1·59	61	1·72	·26
Shide . . .	121	1·74	71	1·71	·246

$\frac{\text{chord}}{\text{min.}}$ and $\frac{\text{arc radians}}{\text{min.}}$ may be reduced to $\frac{\text{kilom.}}{\text{sec.}}$ by multiplying by 1·06

$\frac{\text{arc degrees}}{\text{min.}}$ „ „ „ „ „ „ „ „ 1·84

It will be noted that there are certain slight differences between the figures used in this last table and those in the table on p. 81. These, however, do not produce any appreciable effect upon the general character of the investigations which have been made.

13. *The Origin of Large Earthquakes which were recorded in the Isle of Wight in the Year* 1899.

In 1899, at Shide, in the Isle of Wight, 130 earthquakes were recorded. One hundred and five of these were also recorded at one or more of the following places: Kew, Toronto, Victoria (B.C.), San Fernando, Bombay, Madras, Calcutta, Mauritius, Batavia, Cape of Good Hope, Tokio, Cairo, and Mexico. There is no doubt that many of these were also recorded at other observatories, but from these registers have not yet been received.

The localities at which a certain number of these earthquakes originated have been determined with a fair amount of accuracy. Other determinations are somewhat indefinite, whilst a large residuum of comparatively small disturbances have been grouped as having originated somewhere in the vicinity of the one or two stations at which they were recorded.

The results exhibited in map (Plate III.) are therefore of varying values, and although they give a general idea as to the distribution of seismic activity for 1899, they are chiefly of interest as illustrating the character of the more definite information which we may expect to derive from the extension of the present system of observation.

The methods and considerations which have led to these determinations have been as follows :

(1). *Determination of Origins by Comparisons between Time Intervals.*

Earthquakes from the same district will arrive at distant observing stations at times the differences between which will be constant. If, for example, we have once determined the difference in time at which an earthquake originating off the coast of Japan arrives at Batavia, Bombay, Cape of Good Hope, Shide, &c., whenever these differences are repeated at four or more stations, without knowing anything about observations in Japan, we can at once say where such an earthquake has originated. It will be noted that our knowledge respecting the speed with which earthquake motion is transmitted enables us to give approximate values for the time differences here considered.

(2). *By the Difference in the Times at which the Maximum Motion has been recorded at different Stations.*

In the present state of our knowledge all determinations of the position of origins from time intervals require the assumption that the velocity of propagation of earthquake movement is constant. This condition is most nearly fulfilled by the large waves of earthquakes. The methods by which an earthquake origin may be determined from the differences between the times at which it was recorded at distant stations are several. The method of circles which is here employed has been selected chiefly on account of its comparative simplicity in application. It is briefly as follows : If the large waves of an earthquake reach stations B, C, D, &c., four, ten, twenty, &c., minutes after reaching station A, then the centre of a circle which passes through A and touches circles drawn round B, C, D, &c., the radii of which are respectively $4 \times 1^\circ{\cdot}6$, $10 \times 1^\circ{\cdot}6$, $20 \times 1^\circ{\cdot}6$, &c., will be the centre of the origin required. The constant $1^\circ{\cdot}6$ means that the arcual velocity for large waves is taken at $1^\circ{\cdot}6$ per minute, or approximately 3 km. per second. In the British Association Report for 1899, p. 193, the speed there given was 2·5 km. per second, which appears to be too low. The operation of drawing these circles is carried out on a 'slate' globe. For a complete solution observations are required from at least four stations. With only three observations we are left to choose between two possible centres, but as these may be widely separated there is usually but little difficulty in selecting the one required.

(3). *By the Time Intervals between the Arrival of Preliminary Tremors and Maximum Movement.*

From what has been said respecting preliminary tremors and large waves it may be inferred that the interval in time between the appearance of these two phases of earthquake motion at a given station has a relation to the distance of that station from the origin. This relationship is shown in fig. 1. An observer with this curve before him, although his timekeeper may have failed, or although he may be so situated that it is impossible to obtain accurate time, is immediately able to determine from a well-defined seismogram the distance at which the motion it represents originated. With this fact, the magnitude of his record, and a knowledge of the physical configuration of districts from which earthquakes originate, he is frequently able to locate an origin. With time records from several stations the distances corresponding to each of them from an origin are read from the curve, and by the intersection of these on a globe seismic foci are determined with greater certainty.

(4). *By the Intervals represented by Seismic Recurrences.*

Whenever a seismogram shows the interval of time between a maximum movement and a distinct reinforcement of vibrations which cannot be accounted for as forming part of the gradually decreasing surgings following the principal disturbance, this interval enables us to state the distance of the origin from the station at which the seismogram was obtained. Opportunities to apply this method are not frequent (see p. 68).

14. *The Application of the above Methods to the Records for* 1899.

To carry into effect the method of determining origins by comparisons of time differences, the following eleven tables have been prepared. In these the 105 Shide records are referred to by their British Association register number and their date. For each of these the time intervals between the arrival of maximum motion at the station beneath which a zero is placed and its arrival at other stations are given in minutes. In those instances where the time at which an earthquake originated is approximately known, as in Table I., the zero is placed beneath the word 'origin.' So far as possible the various earthquakes have been analysed according to the localities from which they originated. When the time intervals in a series are less than three in number, the location of an origin is sometimes doubtful. A dash beneath a station indicates that an earthquake was observed, but for reasons which are various the time of its maximum could not be determined. A query indicates that an observation is uncertain.

TABLE I. *West Pacific. Japan.*

—	Shide	Kew	Toronto	Victoria, B.C.	San Fernando	Bombay	Batavia	Mauritius	Madras	Calcutta	Cape of Good Hope	Cairo	Origin
Distance in degrees	87	87	90	62	100	65	57	102	62	52	136	87	0
Expected time to travel in mins.	57	57	59	38	65	43	35	66	38	35	85	57	0
366. Nov. 24 .	57	58	—	32	68	37	14	51	37	—	68	60	Japan
364. Nov. 23 .	—	20?	58	32	64	40	31	54	54	—	54 or 85	—	”
360. Nov. 18 .	46	—	—	—	—	—	—	—	—	—	—	—	”
357. Nov. 10 .	50	—	—	—	—	—	—	—	—	—	—	—	”
311. July 17 .	—	—	—	—	—	—	19	—	—	—	—	—	”
307. July 11 .	17 ?	—	17	39 ?	—	—	17	21	—	—	—	—	”
306. July 10 .	53	—	—	—	—	48	—	—	—	—	—	—	”
295. June 17 .	—	—	58	—	—	67?	—	—	—	—	—	—	Philippines ?
263. March 7 .	58	58	68	23	—	47	17	42	—	—	—	—	Japan
323. Aug. 3 .	57	—	20	21	—	—	—	—	—	—	—	—	”

The above earthquakes were recorded by seismographs in Japan, and therefore originated in or near that country.

In very many of these entries there must be errors, the reasons for the existence of which have already been explained. The values of these vary between a fraction of a minute and several minutes.

Where origins are known from observations made near to the same these are stated.

The geographical positions of these origins are shown in map (Plate II.). Some of the entries on this, particularly those for the Atlantic and Indian Ocean, are conjectural, whilst others may be taken as correct. The reliance which can be placed upon any particular determination is shown in the table of time intervals on which the same is founded.

263. This earthquake, which is described in the British Association Report, 1899, p. 212, and was recorded in Tokio at 0h. 59m. 29s. G.M.T. March 7, is of interest as showing that the amplitudes of motion recorded at Shide and Kew were greater than those recorded at Toronto, whilst at Victoria, the nearest station to the origin, but reached by a sub-oceanic path, it was the smallest of all (see p. 70).

Other earthquakes, approximately corresponding to entries in the Tokio register, and which may therefore have originated near to Japan, are Nos. 271, 286, 314, and 363. Nos. 351 and 352 may have originated to the east of Japan, about 40° N. lat. and 160° E. long.

TABLE II. *West Equatorial Pacific. East Indies.*

—	Shide	Kew	Toronto	Victoria (B.C.)	San Fernando	Bombay	Batavia	Mauritius	Madras	Calcutta	Cape of Good Hope	Tokio	Remarks
Distance in degrees	121	121	136	105	132	62	22	73	53	50	105	47	These entries relate to the origin.
Expected time intervals	76	73	85	66	84	38	16	45	33	32	66	29	
347. Sept. 29	70 or 57	70 or57	—	73 or 60	30 or 17	28 or15	0	40 or33	—	18 or 5	60 or47	18 or 5	According as the Batavian max. is 17·11 or 17·24
247. Jan. 12 .	63	—	—	—	—	?	0	—	—	—	—	—	—
298. June 24 .	57	—	56	71	—	13	0	15	—	—	—	—	—
299. June 29 .	60	—	—	71	—	7	0	—	9	—	—	—	—
310. July 17 .	63	—	35?	48	—	—	0	—	—	—	—	—	—
324. Aug. 4 .	55	26	21 or41	18 or58	32	13	0	42	11	12	58	—	—
332. Aug. 24 .	71	70	52	35	13	—	0	49	—	—	59	—	—
354. Oct. 19	64 or 68	—	—	56 or 52	—	—	0	40 or36	—	—	50 or46	5	—
355. Oct. 24 .	61	—	91	61	—	—	0	35	—	—	46	—	—

347. Dr. J. P. van der Stok in the 'Kon. Akad. van Wettenschappen te Amsterdam,' Nov. 25, 1899, tells us that in the night of September 29–30, at 1.45 A.M. (September 29, 17h. 9m. G.M.T.), an earthquake, followed by sea waves, damaged the south coast of Ceram, and, in less degree, the islands of Ambou, Banda, and the Ulias Isles. Several villages on the south coast of Ceram were destroyed—in Elpapoeti Bay all except two. The prison at Amahei was completely destroyed, and the fortifications partly so.

Dr. R. D. M. Verbeek gives an account of this earthquake in the

'Javasche Courant,' 1900, No. 21. He gives Amahei time for the shock as 1h. 42·2m., and that for Wahei as ± 1h. 43m. (17h. 7m. G.M.T.). At the former place five to ten minutes after the shock, the coast was flooded by a sea wave. This inundation, to a height of 1·7 to 9 metres, was also experienced at other places along the south coast of Ceram. At Banda, 187 km. south-east from Elpapoeti Bay, the water began to rise about half an hour after the shock. At Kawa, at the west end of Ceram, and at other places, strips of alluvium were submerged. Dr. Verbeek places the centrum a few miles inland to the west of Elpapoeti Bay, on the line of a fault running parallel to the south coast of Ceram.

The time intervals between the shock and the sea wave observed at Amahei indicate an origin at a distance of ·5 to 1 degree from that place. This would probably be sub-oceanic, and on the face of the Webber Deep, where soundings have been obtained of 4,000 fathoms. As it is possible that there may have been a bodily displacement of materials lying between Ceram and the Webber Deep, this does not interfere with Dr. Verbeek's fault line. The time at the origin may therefore be taken as lying between 17h. 7m. and 17h. 9m. If the maximum observed at Batavia took place at 17h. 24m., and the movement took 15 minutes to reach that place, we again reach the conclusion that the time at the origin was about 17h. 9m. G.M.T.

TABLE III. *Mid-Indian Ocean.*

—	Shide	Toronto	Batavia	Madras
288. May 15.	56	—	0	61
313. July 20.	42?	39	0	—
319. July 29.	45	—	0	—

TABLE IV. *North-east Pacific. West of Alaska.*

—	Shide	Kew	Toronto	Victoria, B.C.	San Fernando	Bombay	Batavia	Mauritius	Madras	Calcutta	Cape of Good Hope	Mexico	Tokio	Remarks
Distance in degrees	70	70	40	20	77	100	108	145	105	90	165	49	50	These entries refer to the *origin.*
Expected time intervals	44	44	25	14	48	63	68	92	67	57	104	31	32	
333. Sept. 3 . .	30	30	13 28?	0	36	47	—	81	—	—	100, 89 79	—	17 16	
337. Sept. 10 . .	20	20	0	—	22	34or33	50or48	—	39or38	—	69or67	7	—	Small
338. Sept. 10 . .	20	19	0	—	22	35	53	64	—	—	61	6	—	—
246. Jan. 12 . .	23	—	13	0	—	?	—	—	—	—	—	—	—	—
266. March 19 .	30	—	9	0	—	—	—	—	—	21	—	—	—	—
282. April 16 . .	31	39	15	0	—	—	—	94	—	—	—	—	—	—
334. Sept. 4 . .	—	—	9	0	36	—	—	—	—	—	—	—	—	—
341. Sept. 16 . .	16	18	0	—	21	—	—	—	—	—	64	—	—	—
342. Sept. 17 . .	27	27	10	0	34	47	—	—	48	—	76	—	—	—
344. Sept. 23 . .	25	31	11	0	35	50	60	77?	—	—	72	—	27	—
345. Sept. 23 . .	33	37	17	0	38	63	—	—	—	—	87	—	—	—
309. July 14 . .	11	11	9	0	14	13	—	14?	—	—	35	—	—	Behring Sea
317. July 27 . .	11	—	6	0	—	—	—	—	—	—	—	—	—	—

Nos. 333, 337, and 338. In the 'Toronto World' of September 25 we read that on September 3, about 2.30 P.M., houses in Yakuta Bay were rocked violently, doors were slammed, dishes rattled, and tables moved. On September 10, about eight o'clock, a more violent movement occurred. Trees swayed, and there were slight shakes every few minutes. Just as the earthquake ceased tidal waves came rolling in. There were three of these waves following each other at intervals of about five minutes. The rise was 15 feet from low tide to a foot above the highest tide point. On the island of Kanak, opposite Yakuta, a graveyard sank so that on the next day a boat was able to row over the place where it had been, and the tops of the submerged trees could be seen.

These shocks disturbed the declinometer, duplex, and vertical force magnetographs in Toronto.

Scanty as these notes are, they apparently indicate an origin somewhat to the east of that shown in Plate III.

The period of the earth waves for No. 333 as recorded at Shide was 15 seconds, whilst the maximum angle of tilting was 8″. With a velocity of 3 km. per second, and the assumption that the motion is simple harmonic, so that the height of the waves$=\frac{l}{2\pi}\tan a$, where l=length of wave and a=maximum angle of tilting, we may conclude that these waves were 45 km. in length and 29 cm. in height. With periods of at first 40 and afterwards 15 seconds for the disturbance recorded in the Isle of Wight on September 10, No. 338, it would appear that at first there were waves 120 km. long and 39 cm. high, followed by others 45 km. long and 43 cm. high. Whether we can accept vertical displacements of this order, representing accelerations not unfrequently $\frac{1}{50}$ of gravity is yet *sub judice*, and an experiment to confirm or modify these conclusions is now in progress.

TABLE V. *East Mid-Pacific. West of Mexico.*

—	Shide	Kew	Toronto	Victoria, B.C.	San Fernando	Bombay	Batavia	Mauritius	Madras	Calcutta	Cape of Good Hope	Origin
Distance in degrees	84	84	34	30	86	148	150	168	148	138	138	0
Expected time intervals	52	52	22	20	54	93	95	105	93	87	87	0
250. Jan. 24 .	31	31	3	0	—	—	—	92	—	—	—	Mexico
381. Jan. 20 .	—	32	2	0	—	—	86	—	—	—	—	„
248. Jan. 14 .	37	{31 or 35}	2	0	—	—	—	—	—	—	—	„
321. Aug. 2 .	30	30	0	—	—	—	—	—	—	—	—	Concepcion ?
294 ? June 14 .	32	30	0	34	16	70	—	72	—	—	—	Jamaica ?
371. Dec. 25 .	47	47	16	9	60	—	—	—	—	—	75	S. California

250. The key to the origin of this group is given by earthquake No. 250. From Señor Jose Zandizas, director of the observatory in Mexico, we learn that it took place on January 24, 1889, at approximately 11h. 45.5m. P.M. It was severe, caused some damage, but it cannot be siad

to have been very strong. It was felt over the whole republic. At Colima, on the Pacific side, it had a duration of 1m. 20s., and on the Atlantic side, at Vera Cruz, it lasted 10s.

By the method of circles and by the method of preliminary tremor intervals I place the origin at a point 30° distant from Victoria, and 34° from Toronto, or near to lat. 19° N. and 105° W. long. On January 20, 1900, No. 381 was recorded in Mexico with time intervals similar to those for No. 250. The preliminary tremor intervals for this referring to Victoria, Toronto, and Kew read 13, 15, and 38 minutes, indicating that the Kew reading for No. 250 is the lower of the two values given.

The time readings for 248 clearly correspond with that for an earthquake with a similar origin.

294. An origin S.W. of Jamaica roughly agrees with the time differences between Toronto, Victoria, and Shide, and the preliminary tremors duration for Kew and Toronto.

371. In 'Nature,' April 19, 1900, we read that on December 25, at 12.25, an earthquake took place in S. California. In the villages of San Jacinto and Hermet every brick building was damaged.

Professor F. Stupart sends me the following extract from a newspaper clipping:

Los Angeles, Cal., December 25, 1899.

The towns of San Jacinto and Hernet, in Riverside County, were badly shaken by an earthquake at 4.25 o'clock this morning. In San Jacinto not a brick house or block escaped injury. Nearly all of the business portion is in ruins. The new Southern California Hospital caved in. It was not occupied. At Hernet the Hernet's Company mill is partly down. The front wall fell flat. The rear of the large Johnston block also toppled over. Hernet's new hotel is a ruin. The damage at those places cannot be estimated now. Communication by wire is interrupted. The 'Herald' has received a telegram from San Bernardino saying that six Indians were killed at Hernet by falling walls during the earthquake. The Santa Fé railroad report is to the effect that no lives were lost.

Los Angeles, December 25.—The total damage at San Jacinto and Hernet is estimated at $50,000. No person was injured at either place so far as known. The shock was heavy at Santa Ana, Anheim, San Bernardino, Riverside, and other places, but no particular damage is reported except from San Jacinto and Hernet. In this city no damage was done, though the shock was particularly violent. The houses here are well filled with Eastern tourists, and they were in many instances terrified at the unexpected disturbances, and rushed from their rooms.

San Diego, Cal., December 25.—The most severe shock of earthquake experienced in this city in fourteen years took place at 4.25 A.M. to-day, and was accompanied by a loud rumbling noise. The taller buildings in this city were severely shaken, but no serious damage was done. A high wave struck the beach ocean front, but no damage was done. A slight shock followed the first a few seconds later.

268. The time intervals for Shide, Victoria, Bombay, and Toronto suggest an origin near to that given for 322, with which the preliminary tremors for Victoria and Mauritius accord. In the British Association Report for 1899 this origin was placed on the western side of the Atlantic, but additional data having since been obtained this is now modified.

TABLE VI. *South-East Pacific. West Coast South America.*

	Shide	Kew	Toronto	Victoria, B.C.	San Fernando	Bombay	Batavia	Mauritius	Madras	Calcutta	Origin
322. Aug. 2 .	25	23	0	—	—	—	—	—	—	—	Concepcion.
321. „ 2 .	30	30	0	—	—	—	—	—	—	—	Chili? See W. of Mexico, list V.
268. Mar. 23 .	10	14	0	11	?	41	—	23	—	—	S.E. Pacific.
269. „ 23 .	22	29	0?	20	—	—	—	—	—	?	—
270. „ 25 .	35 or 8	?	0	14	?	—	—	—	—	—	—
278. April 12 .	26	36	0	20	—	—	—	—	43	—	W. of Chili
279. „ 13 .	21	31	0	14	—	—	—	—	44	—	—
291. June 5 .	33?	0	0	15	—	—	11	—	—	—	—
292. „ 5 .	23	30	0	15	—	—	—	—	—	—	—

322. The time intervals indicate a possible origin, about 80° due south from Toronto, or off the south coast of *South America*, *near Concepcion.* As this earthquake is not a large one, the whole of the preliminary tremors have not been recorded, and therefore these indications may be neglected.

The similarity of the seismograms for this earthquake and that for 321, together with the fact that they succeeded each other within two hours, suggest a similar origin, and Professor F. Stupart, of Toronto, writes me to the effect that it is probable that both originated off the South American coast.

TABLE VII. *North Atlantic. North Norway to Spitzbergen.*

	Shide	Kew	Toronto	Victoria, B.C.	San Fernando	Bombay	Batavia	Mauritius	Madras	Calcutta	Cape of Good Hope	Tokio	Origin
252. Jan. 31	0	0	12	16	—	?	—	—	—	—	—	—	—
254. Feb. 23	0	?	15	19	—	—	—	—	—	—	—	—	—
255. „ 26	0	?	—	20	—	—	—	—	—	—	—	—	—

TABLE VIII. *Equatorial Atlantic.*

	Shide	Kew	Toronto	Victoria, B.C.	San Fernando	Bombay	Batavia	Mauritius	Madras	Calcutta	Cape of Good Hope	Tokio	Origin
308. July 12	0	10	8	40	2	36	—	23	34	—	—	—	—

TABLE IX. *Western Central Asia. Turkey in Asia.*

	Shide	Kew	Toronto	Victoria, B.C.	San Fernando	Bombay	Batavia	Mauritius	Madras	Calcutta	Cape of Good Hope	Tokio	Origin
343. Sept. 20	0	2	33	40	10	14	—	34	—	—	29	30	Smyrna
373. Dec. 31	4	0	31	40	5	—	—	14	—	—	26	−6	Tiflis

343. From 'Nature,' January 25, 1900, we learn that more than 1,600 persons were killed, more than 2,000 were injured, whilst 11,000 houses were destroyed. The epicentre was in the Meander Valley, between Aidin and Sarakim. Along a line of sixty miles in this valley there are many

damaged towns and villages. This valley and the Legens Valley have subsided from 2 to 6 feet. The railway line between Aidin and Omourlou was raised fully one yard.

373. From 'Nature,' *January 25, 1900*, we learn that the earthquakes of December 31 destroyed many houses at Akhalkalaki (Transcaucasia). Here and in ten neighbouring villages over 200 people perished. At the Tiflis Physical Observatory the following observations were made. In Greenwich mean time the first shock was at 10h. 51·4m. It was severe in the hilly part of the city, on the right bank of the river Kura. The second shock was feeble and noted at 13h. 39·5m. The third shock was not noted by the seismograph at the observatory on the left bank of the Kura, but was noted at 17h. 45m. on the right bank. At Kalagelan the first was observed at 10h. 49m., and at Sviri and Zugdidi at 11h. 23m. The latter places are on the Kars Railway. At the railway stations, Abastuman and Kobi, the times were 13h. 51m. and 11h. 2m.

TABLE X. *Origins which are extremely doubtful.*

B. A. No.	Shide	Kew	Toronto	Victoria, B.C.	San Fernando	Bombay	Batavia	Mauritius	Madras	Calcutta	Cape of Good Hope	Origin
245. Jan. 6 .	6	?	0	—	?	?	—	—	—	—	—	N. Atlantic, W. side.
249. „ 22 .	4	0	—	—	—	?	—	—	—	—	—	Greece ?
251. „ 30 .	64	?	—	?	—	4	—	—	0	—	—	Indian Ocean, E. side.
253. „ 31 .	16	15	—	—	—	0	—	—	—	—	—	„ „ W. side.
256. Feb. 27 .	?	?	0	5·7	?	?	—	—	—	—	—	W. Indies.
257. „ 27 .	0	0·5	—	—	—	—	—	—	—	—	—	N. Atlantic, E. side.
259. „ 28 .	0	0	13	?	?	?	—	—	—	—	—	N. Atlantic, C. Verde.
260. „ 28 .	0	—	—	—	—	—	—	—	—	—	—	Trieste 13 min. after Shide, N. Atlantic, W. side.
262. Mar. 6 .	22	?	—	—	—	—	—	—	—	—	—	Nicolaiew, before Shide, Caspian Sea.
264. „ 12 .	28	?	0	1	—	?	14?	?	—	?	—	*Origin, S. Pacific.* The magnitude of the seismograms indicates that Toronto was reached before Shide and Victoria. The maximum was not well defined at Victoria, whilst at Batavia the movements were only recorded as a thickening of the line. The position of the origin was apparently in the Mid-South Pacific.
267. „ 21 .	16	?	—	—	?	—	—	—	—	?	—	Trieste, before Shide, Caspian Sea.
273. April 4 .	0	—	—	—	—	—	—	—	?	—	—	N. Atlantic, E. side.
276 „ 6 .	1	0	—	—	—	—	—	—	—	—	—	„ „
281. „ 15 .	—	—	—	—	—	—	—	—	—	—	—	„ „
283. „ 17 .	43	—	34	0	—	—	—	—	—	—	—	N.E. Pacific.
284. „ 28 .	—	—	—	—	—	—	—	—	—	—	—	N. Atlantic, E. side.
289. May 17 .	19	—	—	—	—	—	0	—	—	—	—	Indian Ocean ?
293. June 9 .	1	—	—	—	—	—	—	0	—	—	—	„ „
297. „ 19 .	—	—	—	—	—	—	—	—	—	—	—	N. Atlantic, E. side.
300. July 2 .	—	—	—	—	—	—	—	—	—	—	—	„ „
301. „ 2 .	30	—	—	0	—	?	—	—	—	—	—	E. Pacific Ocean.
302. „ 3 .	—	—	—	—	—	—	—	—	—	—	—	N. Atlantic, E. side.
303. „ 7 .	9	1	0	4	—	—	21	—	—	—	—	N. Atlantic, W. side.
305. „ 9 .	46	50	86	75	—	6	—	—	0	—	—	Equatorial Indian Ocean.
312. „ 10 .	?	—	—	—	?	—	—	—	—	—	—	N. Atlantic, E. side.
315. „ 26 .	4	—	—	—	—	0	—	—	—	—	—	Indian Ocean.
318. „ 28 .	—	—	—	—	—	—	—	—	—	—	—	N. Atlantic, E. side.
220. „ 31 .	—	—	—	—	—	—	—	—	—	—	—	Indian Ocean ?
325. Aug. 7 .	9	9	—	—	—	0	—	—	—	0	—	„ „
326. „ 17 .	?	?	36	17	24	0	—	19	3	—	28	Eastern East Indies.
327. „ 21 .	?	?	—	—	—	—	—	—	—	—	—	N. Atlantic, E. side.
328. „ 23 .	?	?	—	—	—	—	—	—	—	—	—	„ „
329. „ 23 .	?	?	—	—	—	—	—	—	—	—	—	—

TABLE X. *Origins which are extremely doubtful*—continued.

B. A. No.	Shide	Kew	Toronto	Victoria, B.C.	San Fernando	Bombay	Batavia	Mauritius	Madras	Calcutta	Cape of Good Hope	Origin
335. Sept. 6 .	29	—	0	—	—	—	—	—	—	—	—	W. of Mexico. Group V.
336. " 6 .	0	—	1	—	—	—	—	?	—	—	—	Mid N. Atlantic.
340. " 14 .	11	—	0	—	—	—	—	—	—	—	—	N. Atlantic, W. side.
346. " 27 .	6	6	0	15	—	—	—	—	—	—	7	Mid-Equatorial Atlantic ?
349. Oct. 4 .	—	—	—	—	—	—	—	—	—	—	—	N. Atlantic, E. side.
351. " 13 .	36	—	31	7	—	—	0	—	—	—	2	—
352. " 13 .	33	38	—	9	—	—	0	—	—	—	63	E. of East Indies ?
356. " 29 .	0	—	—	—	—	—	5	—	—	—	—	Indian Ocean.
358. Nov. 12 .	11	—	—	27	—	—	0	—	—	—	49	S. Pacific.
361. " 18 .	25	2	0	23	3	—	—	—	—	—	3	Mid-Equatorial Atlantic.
362. " 20 .	42	—	33	0	4	—	—	—	—	—	—	Pacific Ocean.
365. " 24 .	58	—	—	50	63	20	0	38	—	—	9?	Japan ?
370. Dec. 17 .	—	—	—	—	—	—	—	—	—	—	—	N. Atlantic, E. side.
372. " 26 .	27	7?	1	18	0	—	—	—	—	—	35	—
374. " 31 .	51?	25	41	34	33	0	10	—	—	—	48	Japan ?

The origins indicated in the last table are for the most part conjectural. In those instances where a disturbance has only been recorded at Shide and Kew, and we are without evidence showing that the seismograms refer to earthquakes observed in Great Britain and Europe, it seems probable that they represent adjustments in the strata on the eastern side of the North Atlantic. Time entries for these stations, a few minutes later than the corresponding entry for Toronto, suggest that we are here dealing with a disturbance originating on the western side of the same ocean.

Origins indicated by terms like Indian Ocean and Pacific Ocean only show how little information can be derived from certain seismograms.

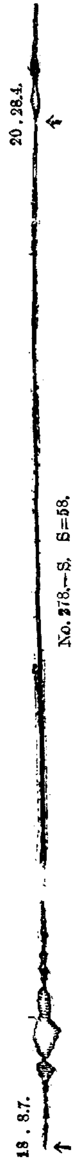
Here and there a few impossible entries are recorded. For example, the greatest interval of time which could elapse between the arrival of an earthquake in Mauritius and Bombay or Madras is thirty minutes, yet for earthquake 326 it will be observed that the entries for the latter places are respectively forty-one and forty-five minutes. To correct such entries it is necessary to compare together the original seismograms, which has not been always possible.

15. *Illustrations of Seismograms.*

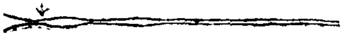
The following illustrations of seismograms are only to be regarded as *sketches* of the original photograms. The accuracy of any given reproduction has been largely dependent upon the clearness of the figure from which it was copied. They show the range of motion and the principal characteristics of wave-groups, but they do not show details like small serrations so clearly exhibited in many of the original records from which they have been reproduced. The numbers correspond with the numbers given for particular earthquakes in the preceding text and those in the Shide records contained in the first circular of earthquake registers issued by the Seismological Investigation Committee. The arrow with its time-mark gives the time for a particular phase of movement, which is usually that of the commencement. The number following the letter S gives the time-scale in millimetres per hour. Thus S=60 means that 60 millimetres equal one hour.

The locality at which a seismogram was obtained is indicated by the following initial or initials :—

Isle of Wight (Shide)	S.
Kew	K.
Toronto	T.
Victoria, B.C.	V.
San Fernando	S.F.
Madras	Ma.
Mexico	Me.
Bombay	B.
Calcutta	C.
Batavia	Ba.
Mauritius	M.
Cape of Good Hope	C.G.H.
Tokio	To.



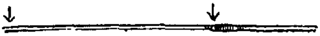
No. 278.—S. S=58.



No. 278.—T. S=59·5.

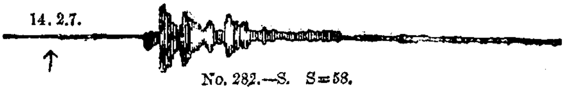
No. 278.—V. S=60·5.

No. 279.—S.

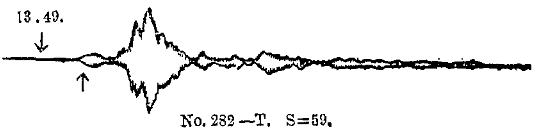


No. 279.—T. S=59·5.

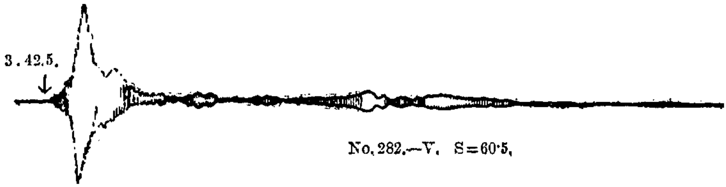
No. 279.—V. S=61.



No. 282.—S. S=58.



No. 282.—T. S=59.



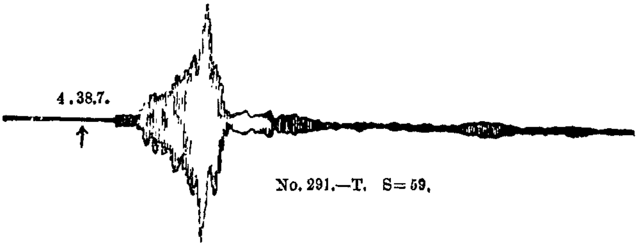
No. 282.—V. S=60·5.

No. 283.—S. S=58.

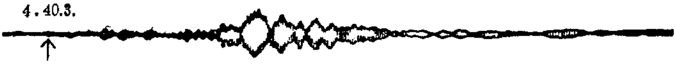
No. 283.—T. S=59.

No. 283.—V. S=60·5.

No. 291.—S. S=58.

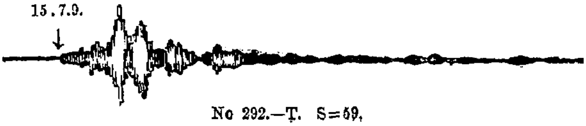


No. 291.—T. S=59.



No. 291.—V. S=60·5.

No. 292.—S. S=58.



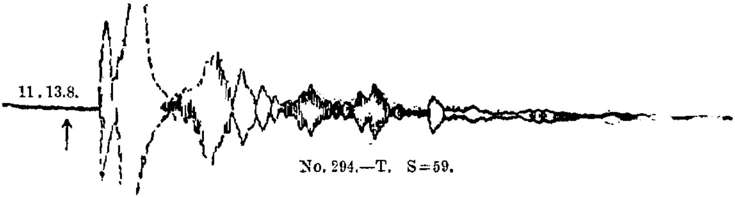
No 292.—T. S=59.

No. 292.—V. S=60·5.

No. 294.—M. S=58.

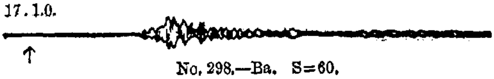
No. 294.—S. S=58.

No. 294.—S.F.

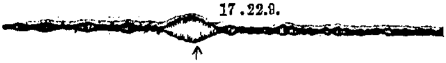


No. 294.—T. S=59.

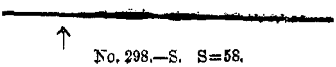
No. 294.—V. S=60.



No. 298.—Ba. S=60.



No. 298.—M. S=58.

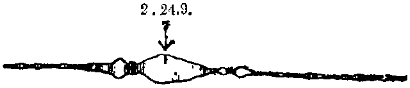


No. 298.—S. S=58.

No. 305.—B. S=60.

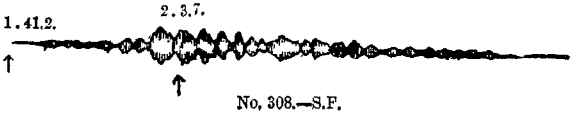
No. 305.—S. S=58.

No. 308.—B. S=59.



No. 308.—M. S=58·5.

No. 308.—S. S=58.

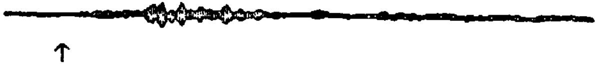


No. 308.—S.F.

No. 309.—S. S=58.

No. 309.—C.G.H. S=59·5.

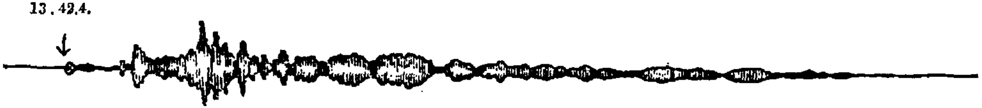
No. 309.—B. S=59·5.



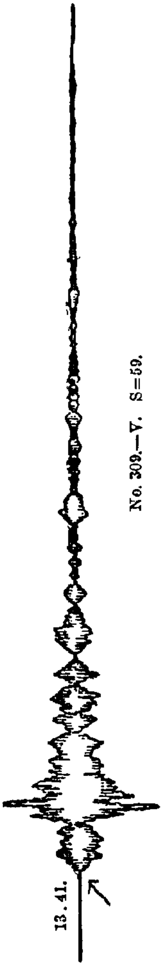
No. 309.—Ba.

No. 309.—K. S=61.

No. 309.—S.F. S=59·5.

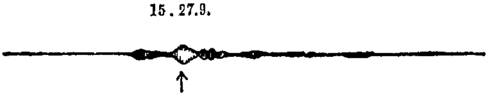


No. 309.—T. S=59.



No. 309.—V. S=59.

No. 321. S=58.

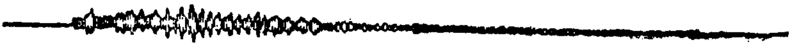


No. 321.—T. S=58·5.

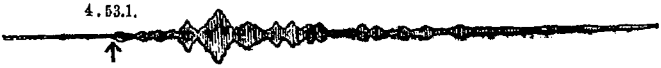
No. 322.—S. S=58.

No. 322.—T. S=58·5.

No. 324.—B. S=59.

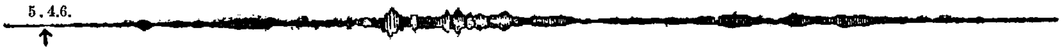


No. 324.—Ba. S=59.



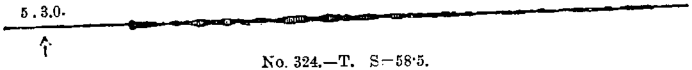
No. 324.—C. S=58·5.

No. 324.—C.G.H. S=59·5.

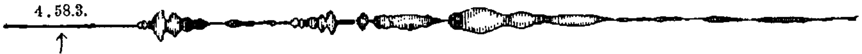


No. 321.—S. S=58.

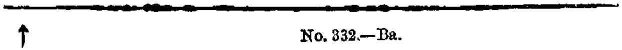
No. 324.—M. S=60.



No. 324.—T. S=58·5.

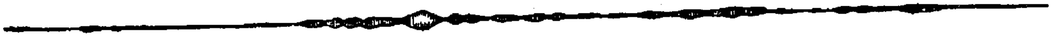


No. 324.—V. S=60.



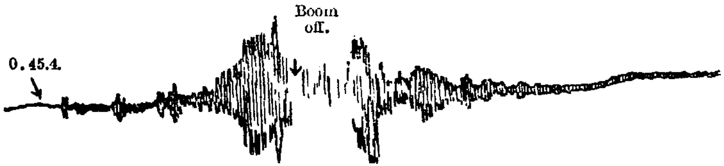
No. 332.—Ba.

No. 332.—M. S=58·5.



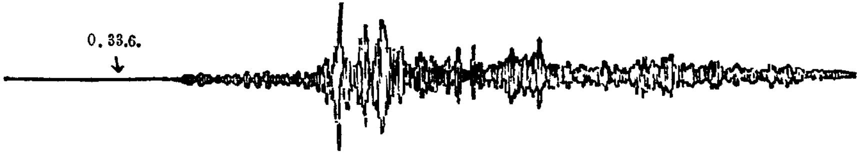
No. 332.—C.G.H. S=59.

No. 332.—S. S=58.

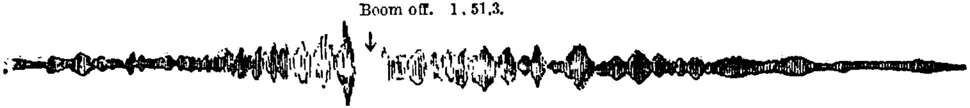


No. 333.—B. S=59.

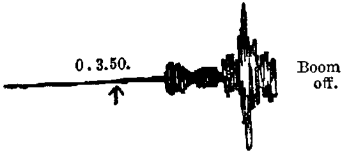
No. 333.—C.G.H. S=59.



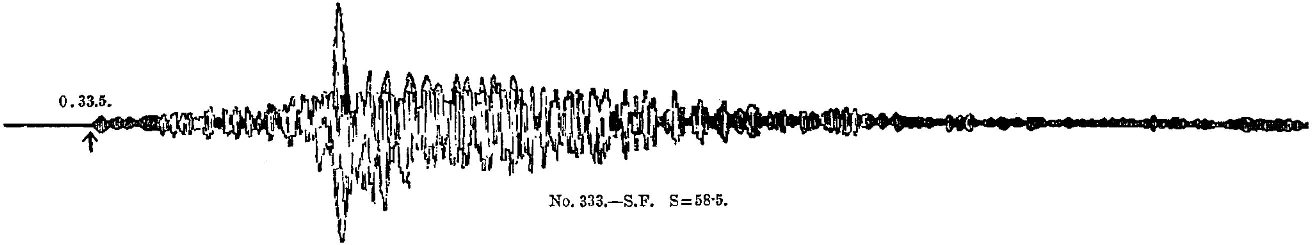
No. 333.—K. S=62.



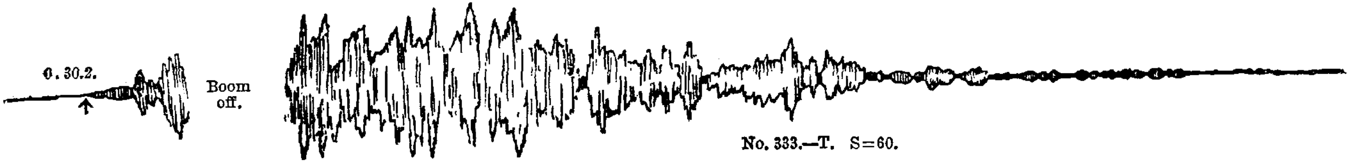
No. 333.—M. S=59.



No. 333.—S. S=58.

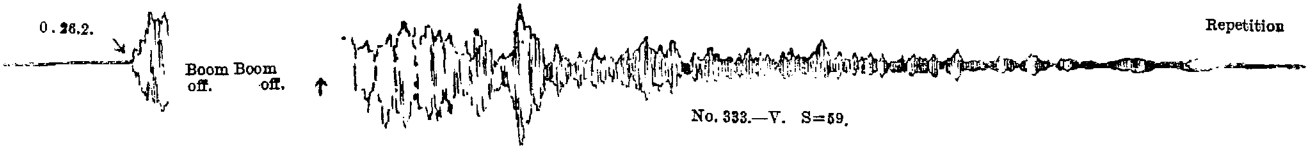


No. 333.—S.F. S=58·5.



No. 333.—T. S=60.

No. 333.—To. S=58·5.

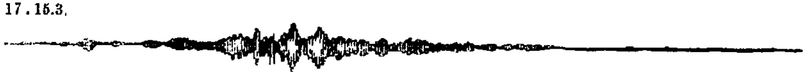


No. 333.—V. S=59.

No. 337.—B. S=58·5.

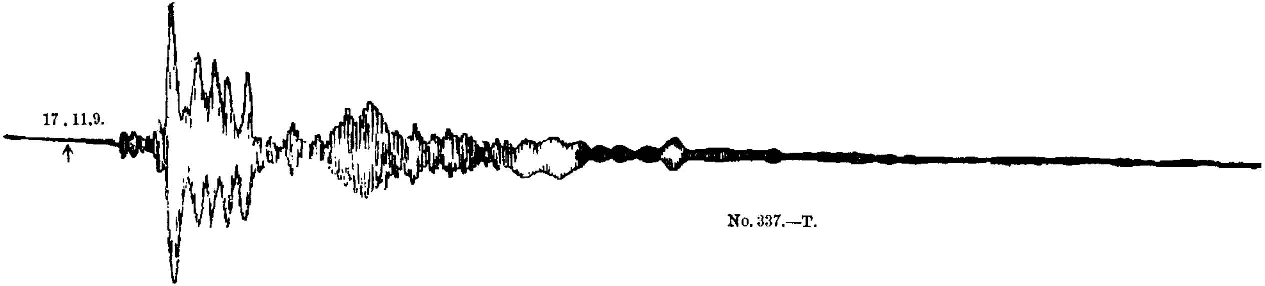
No. 337.—Ba. S=60.

No. 337.—C.G.H. S=59.



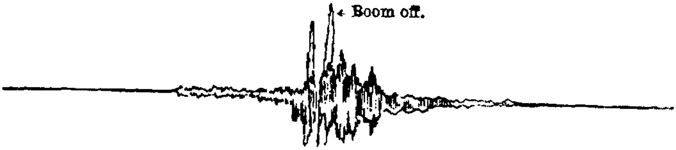
No. 337.—K. S=60.

No. 337.—S.F S=56.



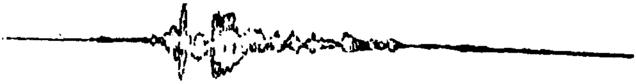
No. 337.—T.

No. 338.—Ba. S=60.



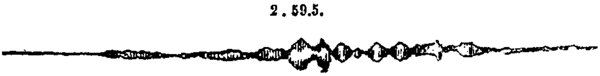
No. 338.—Me. S=59.

No. 343.—B. S=59.

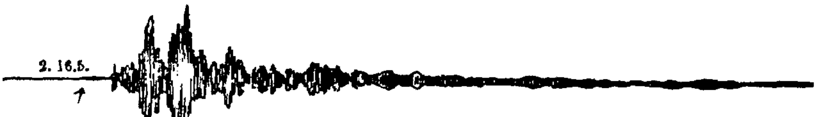


No. 343.—C.G.H. S=59.

No. 343.—K. S=61.

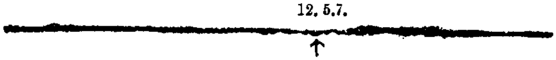


No. 343.—M. =59.



No. 343.—S.

No. 343.—To. S=61.

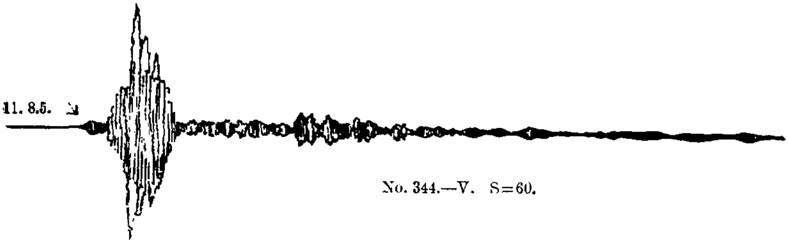


No. 344.—B.

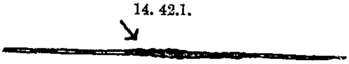
No. 344.—M. S=58.

No. 344.—S. S=58·5.

No. 344.—To. S=58.

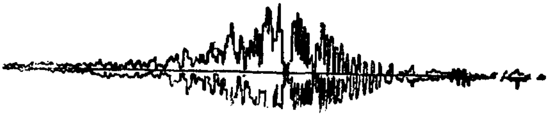


No. 344.—V. S=60.



No. 345.—B.

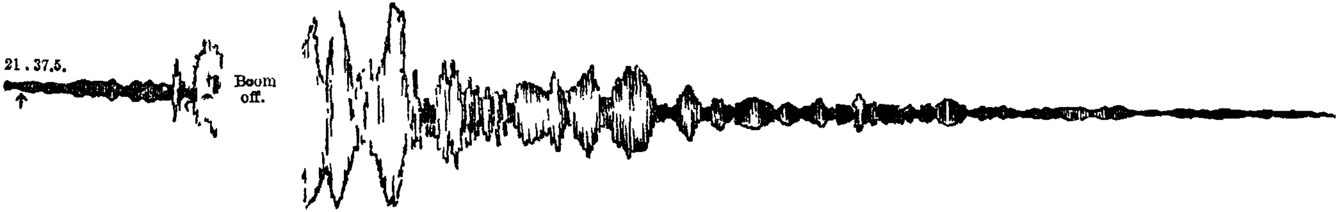
No. 345.—S. S=58·5.



No. 338.—B. S=59.

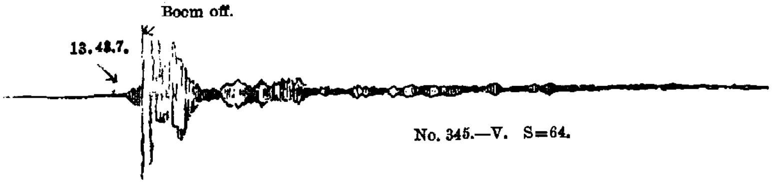
No. 338.—M. S=58.

No. 338.—S.F. S=55·5.



No. 338.—T. S=58·5.

No. 338.—O.G.H. S=59.

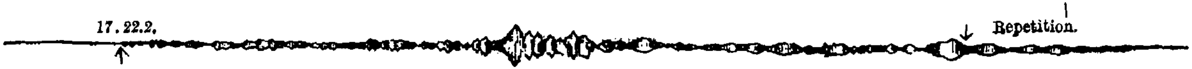


No. 345.—V. S=64.

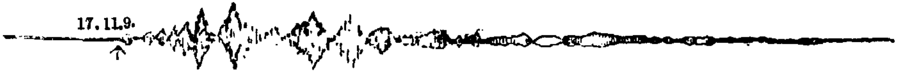
No. 347.—Ba. S=59·5.

No. 347.—K. S=

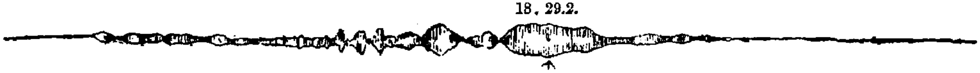
No. 347.—M. S=58·5.



No. 347.—S. S=59.

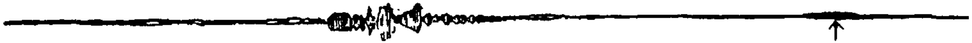


No. 347.—To. S=59.

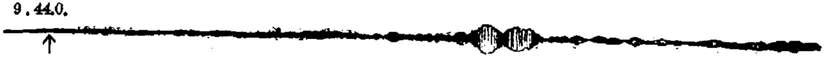


No. 347.—V. S=60.

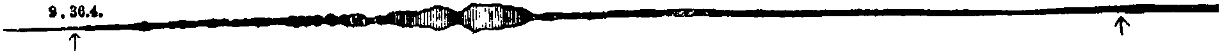
No. 354.—Ba. S=59·5.



No. 354.—C.G.H. S=59.



No. 354.—S. S=58·5.



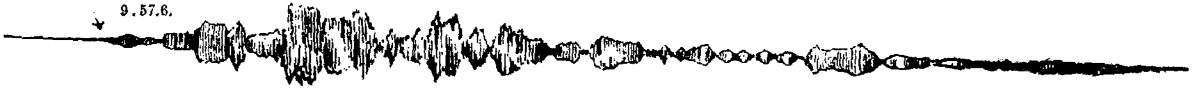
No. 354.—V. S=59·5.

No. 364.—B. S=59.

No. 364.—C.G.H. S=59.

No. 364.—*M*. S=58.

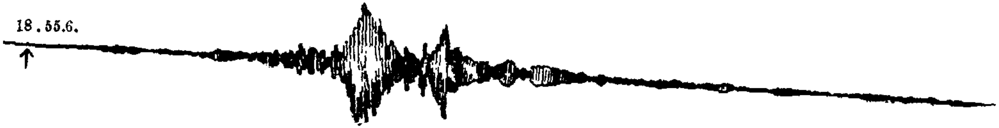
No. 364.—T. S=58·5.



No. 364.—V. S=60.

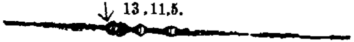
No. 366.—C.G.H. S=59.

No. 366.—M. S=58.



No. 366.—S. S=59.

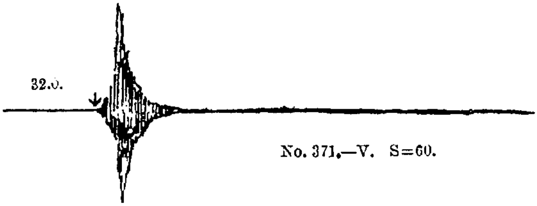
No. 371.—T. S=43.



No. 371.—S. S=58·5.

No. 366.—B. S=59.

No. 366.—Ba. S=59·5.



III. *Earthquakes and Timekeepers at Observatories.*

That earthquakes we can feel frequently accelerate, retard, or stop clocks with pendulums is a fact well known, but the extent to which cryptoseismic disturbances which sweep over the whole surface of our globe many times per year affect this class of timekeepers has not yet been investigated.

Father J. de Moidrey, S.J., of the observatory at Zikawei, gives me the following notes on this subject. On June 12, 1897, 'an excellent clock facing north lost 4m. 44·5s. in the afternoon, whilst another, almost identical, fixed to the same brick pillar, but facing east, was undisturbed (rate 0·1s.). Secchi's barograph shows a slight stroke at 11h. 25m. G.M.T., corresponding to an oscillation of 1 mm. of the quicksilver.

'A fast moving barograph (mercury) shows a spot at 11h. 23m., indicating a swing of the mercury of 0·25 mm. This increased to 0·50 mm. and died out suddenly.

'The magnetographs, declinometer, bifilar and Lloyd's balance were all disturbed, although it was a day of perfect magnetic calm.'

On this day, at 11h. 5m. G.M.T., a violent earthquake took place in Assam. The large waves of this would reach Zikawei at 11h. 21m. G.M.T., or 7h. 26m. 43s. P.M. local time.

In a second letter Father Moidrey writes:

'On June 4, 1898, about midnight, our north clock lost about four seconds. That same night at a watchmaker's in Shanghai several clocks (six, I believe), all facing north or south, were stopped. Nothing else was noticed by the watchmaker, M. Vrard, who in his surprise telephoned to the observatory to ask what was the matter. Nobody in the town felt an earthquake, nor was one referred to in the newspapers. A missionary at Nankin had his clock stopped the same night, but did not notice any other phenomena. Our magnetograph and thermograph recorded a shock at 16h. 24m. 17s., June 3, G.M.T. On that day there was an earthquake at Chemulpo, Corea.'

We are here evidently dealing with an earthquake recorded on June 3 at 17h. 14m. at Shide, and also recorded at Kew, Nicolaiew, and Potsdam.

From the 'Bulletin Mensuel' of Zikawei, third quarter, 1897, we learn that in the night of September 2 the two clocks were stopped and the magnetographs were disturbed at 1.42 (September 1, 17h. 36m. G.M.T.). Nothing was felt. This may refer to an earthquake recorded at Shide, September 1, 18h. 29m. G.M.T.

Although Professor E. C. Pickering writes me that on September 3, 10 and 23, 1898, which are dates for heavy earthquakes in Alaska, and on September 20, when there was a severe earthquake in Asia Minor, there were no noticeable changes in the rates of the clocks at Harvard

University; the observations made at Zikawei indicate that at certain observatories at least the unfelt movements of earthquakes may from time to time have serious effects on timekeepers.

With the object of throwing light upon this subject I shall esteem it a favour if directors of observatories will let me know whether any changes were observed or *not observed* in the rates of pendulum timekeepers on dates corresponding to those of large earthquakes enumerated on p. 108, addressing their communications to me at Shide, Isle of Wight, England.

IV. *Earthquakes and Rain.*

In the British Association Reports for 1899, p. 209, I gave a quotation from Mr. O. H. Howarth respecting a heavy condensation of aqueous vapour which he observed for three hours after the Mexican earthquake of January 24, 1899. This was in the form of a heavy mist which settled over the head of a cañon at an elevation of 8,700 feet.

Mr. Howarth states that in this place such mists are never seen at this time of the year, it being the middle of the dry season.

Something similar to this occurred on June 12, 1897, after the severe earthquake which originated on that day in the highlands of Assam. Mr. H. Luttman-Johnson, I.C.S., in the 'Journal' of the Society of Arts, April 15, 1898, describes the weather before the earthquake as having cleared: the afternoon was lovely, and there was not a cloud in the sky. Five minutes after the earthquake the residents in Shillong were surrounded with cloud and mist, and they sat up all night with rain beating upon all sides.

Captain A. A. Howell, I.C.S., deputy-governor of the Garo Hills, gives the actual rainfall. The records taken at 8 A.M. showed that for the twenty-four hours preceding the 12th there was no rain. There was rain at noon on the 12th, but it cleared off at 2 P.M. The earthquake occurred at about 5 P.M., and after that until next morning 3·26 inches fell.

In considering whether there is any possibility of a connection between the phenomena here considered we must remember that observations showing that rain and cloud have followed closely on the heels of certain earthquakes appear to be confined to tropical and semi-tropical countries; and it is in these countries where sudden showers, indicating the collapse of critical atmospheric conditions, are frequent. Given, therefore, such conditions at no great distance above the surface of the earth, which was probably the condition in the highlands of Assam, and then admit that beneath the gaseous covering consisting of layers of air of different temperatures and with different degrees of saturation 10,000 square miles of mountainous country was moved, or that a much larger area was thrown into violent wave-like movement, we recognise that the relationship of earthquakes and atmospheric precipitation may not be so improbable as is generally supposed. As the ground rose upwards, the air immediately above it would suffer compression, and as the ground fell there would be rarefaction, whilst layers of air differing in their physical state might be mixed, and a vigorous seismic activity might in this way result in precipitation.

V. *Earthquakes and Small Changes in Latitude.*

In vol. xvii. of the 'Seismological Journal of Japan,' 1893, p. 17, I drew attention to the observation that the period of maxima increase in latitude in Berlin apparently coincided with maxima of earthquakes recorded in Japan.

If we compare the wanderings of the pole from its mean position for the years 1895–1898[1] with registers of earthquakes which have disturbed continental areas or the whole world, we find a somewhat similar relationship. This is shown in the accompanying table, the pole displacements being measured from Albrecht's figure.

—	1895		1896		1897		1898	
	Displacement	Earthquakes	Displacement	Earthquakes	Displacement	Earthquakes	Displacement	Earthquakes
1. January 1 to February 5 .	0″·03	1	0″·07	1	0″·14	5	0″·12	4
2. February 5 to March 14 .	0·03	2	0·04	1	0·11	7	0·11	0
3. March 14 to April 19 . .	0·06	0	0·05	1	0·07	1	0·07	4
4. April 19 to May 26 . .	0·07	1	0·08	2	0·11	5	0·08	5
5. May 26 to July 1 . .	0·08	1	0·10	2	0·13	5	0·10	6
6. July 1 to August 7 . .	0·03	1	0·11	0	0·11	6	0·16	5
7. August 7 to September 12 .	0·05	0	0·10	4	0·10	5	0·15	6
8. September 12 to October 19	0·06	1	0·13	3	0·07	5		
9. October 19 to November 24	0·06	1	0·10	4	0·11	4		
10. November 24 to December 31	0·08	1	0·13	0	0·12	1 or 4		
Totals . . .	0·53	9	0·91	18	1·07	44 or 47	0·79	30

A conclusion suggested by this table is that, during intervals when the pole displacement has been comparatively great, large earthquakes have been fairly frequent, and *vice versâ*. In the yearly totals this is marked.

If we turn to a figure given by F. R. Helmert, showing variations in latitude as determined from 353 sets of photographic records made on forty-two days in the months of April, May, and June, 1897 (see 'Bericht über eine neue Reihe von Polhöhen-Bestimmungen, &c., im Jahre 1897,' F. R. Helmert, Potsdam), we see that successive daily means frequently differ from 0″·1 to 0″·2 amongst themselves. Equally large differences exist between the separate observations from which these means are deduced.

That is to say, successive observations may show differences as great as the annual maximum displacement of the pole, which is about 0″·25 from a mean position.

If on Helmert's figure we plot the large earthquakes for these months, it is seen that in the time of their occurrence they closely coincide with

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[1] See *Bericht über den Stand der Erforschung der Breiten-Variation am Schlusse des Jahres* 1898, von Th. Albrecht.

the times at which large deviations in latitude occur. In April, when these deviations were comparatively small, large earthquakes did not occur.

When considering the possibility of any relationship between earthquakes and these extremely frequent and practically oscillatory changes in latitude, there are two points of importance to be remembered.

The first is that with each of these earthquakes there is a sudden shifting of a large mass of material at a seismic origin. The molar displacement for the Indian earthquake of June 12, 1897, is estimated by Mr. R. D. Oldham by an area of 6,000 or 7,000 square miles, and it is not improbable that earthquakes which have caused the Pacific Ocean to oscillate for a period of twenty-four hours were accompanied by displacements of larger magnitude.

The second consideration is that each of the large earthquakes here considered has been accompanied by surface or distortional waves which in many instances affect the whole surface of the globe. These waves, so far as we can infer from their velocity, period, and maximum angle of inclination, vary between twenty and seventy miles in length, and are from a few inches to two or three feet in height. If they attain the magnitudes here given (see p. 83) they seem certainly sufficient to relieve a district in orogenic strain.

A further test of the suggestion that slight nutational effects may result from earthquakes would be to compare observations indicating small changes in latitude made before and after the times of large earthquakes referred to in the report, the more important of which are as follows:

						H.	M.
No. 250.	Origin	Mexico,	January	24,	1899,	23	44
„ 333	„	Alaska,	September	4	„	0	11
„ 337	„	„	„	10	„	16	51
„ 338	„	„	„	10	„	20	21
„ 343	„	Smyrna,	„	20	„	2	9
„ 347	„	Ceram,	„	29	„	17	9
„ 381	„	Mexico,	January	20	1900,	18	31

The times given are the approximate times at the origin. These are expressed in Greenwich mean time (civil). 0 or 24 hrs.=midnight. The times at which the large waves reached any distant station may be calculated by the application of Curve II*a* or II*b* in the table on p. 67.

VI. *Selection of a Fault and Locality suitable for Observations on Earth-Movements. By* CLEMENT REID.

The selection of a favourable site for observations upon differential movement between the two sides of a fault presents many difficulties, and the locality we have chosen is more to be regarded as the best available than as ideally perfect. Leaving out of account for the present considerations other than geological, there are certain conditions, most of which must be complied with if the observations are to be of real value.

The fault selected must be:

1. Of considerable magnitude, and not be merely a branch fault which the next earth-movement may easily leave unaffected.

2. It should be of known date, and belong to a recent geological period. This consideration is important, for a Tertiary movement is far

more likely to be still in progress than is one which can only be shown to affect Palæozoic or Secondary rocks. Not only have the older movements in many cases ceased long since, and have given place to movements in different directions; but a fault which has long remained without movement tends to become closed and re-cemented, so that there is a considerable likelihood that any future movement may not follow exactly the same line, even though the strain be in the same direction.

3. The fault should crop out on ground fairly level, and in hard rocks, otherwise the observations may be masked by the slight irregular 'creep' of the surface downhill, and no firm foundation for the apparatus be obtained.

4. It is desirable that the rocks on the two sides of the fault, though geologically far apart, should be as like as possible in lithological character, so that any surface movements due to change of temperature or absorption of rain-water should affect the two sides alike.

5. In order to avoid complications through slow solution of the rocks by percolating rain, a fault bringing together insoluble silicious rocks would be preferable to any other.

6. As the records to be obtained may throw great light on movements of the earth's crust, it is desirable that the fault selected for observation should be one belonging to a set of disturbances of great magnitude, having common characteristics, and affecting a considerable area. It is therefore important that the district chosen should be one which has been carefully studied geologically, and of which the structure is thoroughly known.

These various conditions, added to the consideration of convenience of access of the locality, availability of a skilled observer, availability of the land, and other minor points, made a series of requirements not easy to satisfy, and I will now indicate in what respects the site finally selected comes up to or falls short of the ideal set before us.

Consideration No. 2 confines us at once to the only area in Britain in which large earth-movements of Tertiary date can clearly be proved to have taken place. This area may be taken to lie between the North Downs and the English Channel, and to extend as far west as Weymouth and Abbotsbury. But only the parts of it in which Tertiary rocks are still preserved will do for our purpose; the reason being that older movements of the same general character affected the Jurassic and Lower Cretaceous rocks. These intra-Cretaceous disturbances cannot always be distinguished from the Tertiary movements, in the absence of the unconformable Upper Cretaceous and Tertiary strata. Thus in the Wealden area a good many faults are believed to affect the Lower Cretaceous rocks; but they are of no great magnitude, and it is impossible at present to differentiate those of Tertiary date from the older series.

We are thus confined, by a process of elimination, to the sharply folded belt which occupies the southern part of the Hampshire Basin and includes the northern half of the Isle of Wight. Even over this area it would only be possible to use Mr. Horace Darwin's apparatus at certain points; for much of the country is sharply folded without faulting, and any earth-movements now in progress could only be measured by careful levelling and triangulation. Thus we are confined ultimately to a limited highly disturbed and faulted belt, which extends east and west through the centre of the Isle of Wight and reappears in Dorset between Studland Bay and Abbotsbury.

Within the area thus selected are various sharp monoclinal folds, all with an east and west axis, and with the strata so bent as to become nearly vertical. In places the lateral pressure and folding have been so violent as to pass into overthrust faulting on a considerable scale. None of the Tertiary disturbances in this part of England is a normal drop-fault; the supposed north and south Tertiary fault in the Medina valley, though often shown in old maps and text books, having no existence.

The date of most violent disturbance in the system of folds above alluded to is clearly later than Middle Oligocene; for in the Isle of Wight the Hamstead Beds, which belong to that period, and are the newest Tertiary strata there preserved, are tilted at a high angle. From various considerations, which need not here be recapitulated, it seems probable that this set of disturbances commenced in Eocene times, became most violent in the Miocene period, and died away in Pliocene times.[1] Though in our south-eastern counties older Pliocene strata to some extent have been tilted, the disturbance has not yet been shown to affect newer deposits, or to be still in progress. This last is one of the principal points which our apparatus should decide.

Consideration No. 1 limits our choice to a small group of faults, not more than half-a-dozen, and as the apparatus employed needs a fairly clean-cut fracture, unless the pipes are to be of unreasonable length, it is only at a few points on these faults that the observations can be made. We have thus so greatly reduced the number of possible points at which the apparatus could be fixed, that it will now be simplest to describe the faults one by one, and point out to what extent they do or do not fulfil the rest of the requirements.

Working from east to west, the first Tertiary fault met with is in the main monocline of the Isle of Wight, which occasionally passes into a thrust-fault of no great extent. In one place the basement bed of the London Clay is brought against Bracklesham Beds; but the strata are too soft and full of water to yield satisfactory fixed points. In the others, plastic Clays of the Reading Series have slid over Chalk, the bedding being vertical and the surface slope very high. At no point in the Isle of Wight could a satisfactory site be found.

Following this disturbed belt westward, we again meet with a sharp monoclinal fold, passing into a slide-fault, at Ballard Cliff in Dorset. This is the well-known 'Isle of Purbeck Fault,' which thrusts Chalk with flints with curved bedding over similar rock with the bedding vertical. The fault itself is very conspicuous in the cliff-face, curving through about a tenth of a circle in a height of 280 feet.[2] This fault might be a good one for observation; but though it is of considerable magnitude, the locality is by no means convenient of access. The disturbance is, however, a valuable one to study, for its character is clearly shown in the section. The other faults with which we are now dealing apparently are all of this type.

The next Tertiary fault met with is close to Corfe Castle, where in the sharpest part of the monoclinal curve the London Clay has been thrust over the Reading Beds and abuts against the Upper Chalk. This slide-fault is of small magnitude, and as in similar slides in the Isle of Wight,

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[1] Reid and Strahan, 'Geology of the Isle of Wight,' chapter xiv. *Memoirs of the Geological Survey*, 1889; Reid, 'Pliocene Deposits of Britain,' chapter v. *ibid.* 1890.

[2] See Strahan, 'Geology of the Isle of Purbeck,' chapter xv. *Mem. Geol. Survey*, 1898.

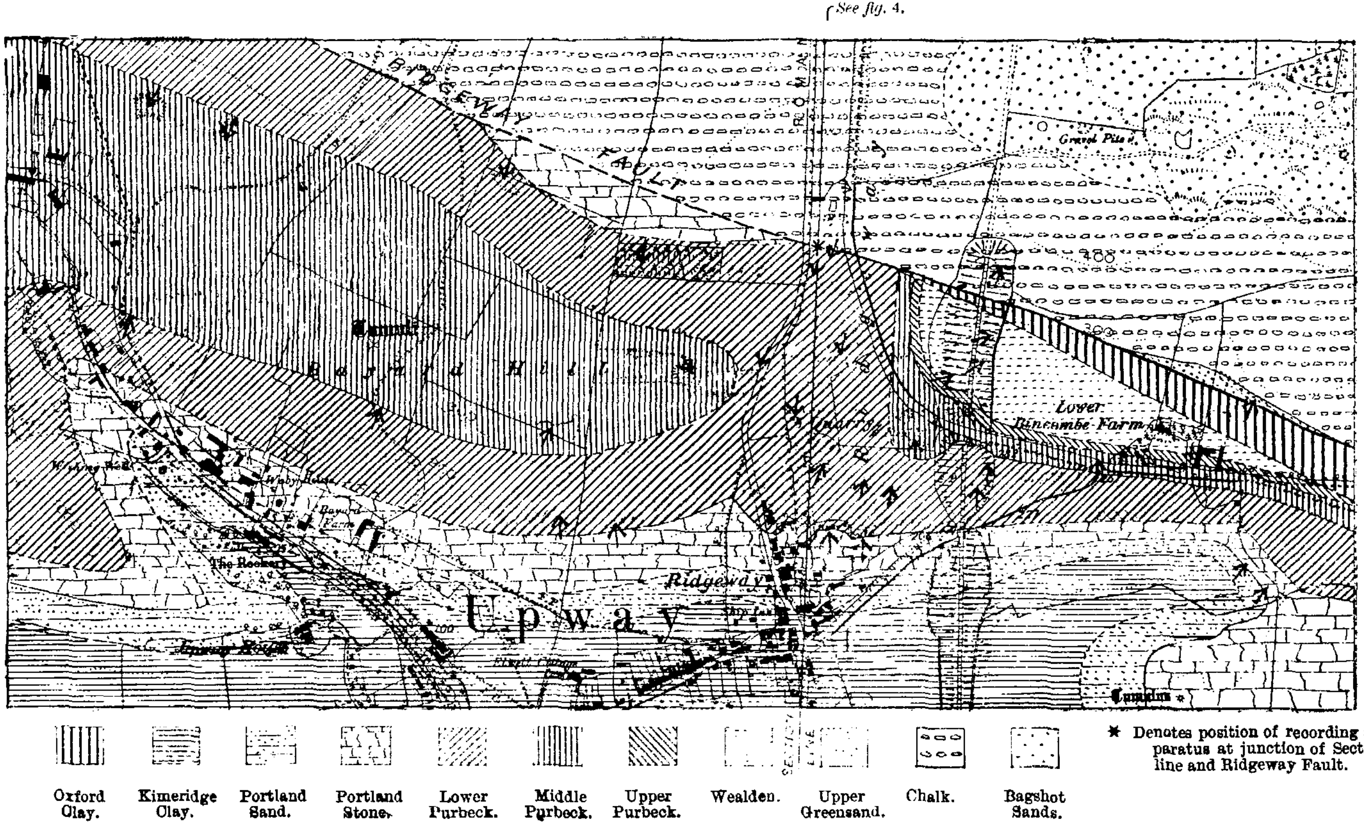
the ground is too steep and the rocks too soft to yield satisfactory fixed points. Along the same line the junction of the Chalk and Eocene is again slightly faulted near Lulworth; but the fault is of small magnitude, and the adjoining rocks are too much shattered for our purpose. The Durdle fault runs parallel with and close to high cliffs, so that delicate observations might be entirely masked by movements caused by the gradual removal of large masses of rock by the sea on the south and the consequent rise of the strata on that side. At Bat's Head the Isle of Purbeck Fault is finally lost beneath the sea, and the shattering of the rocks is too great to allow of exact observations. This fault does not reappear in the Weymouth area.

There still remains one of the most important Tertiary disturbances in the district, that known as the Ridgeway fault. This also is an overthrust fault cutting through a monocline, or through the north limb of a sharp anticlinal fold. Its date is clearly later than the Bagshot period; its magnitude is great, and if any of the Tertiary faults are still undergoing changes, this one is likely to partake in the movement. It brings together rocks of very different ages and of varying character, so that the choice of exact locality for the observations depended on the discovery of a spot where the fault is a clean fracture, where the rocks on each side are hard and of fairly similar lithological character, and where the ground is sufficiently level for the apparatus. Along a good deal of its course there is much fault rock or broken ground, and in most parts the strata on one or both sides are soft. These parts would not be convenient or satisfactory for our purpose. For various reasons the choice narrowed down to the neighbourhood of Poxwell, where Middle or Lower Chalk abuts against Lower Purbeck; or to the district between Upway and Portisham, a distance of four miles, where Upper Chalk is faulted against strata close to the base of the Lower Purbeck, or even against Portland Beds. Of these localities Upway was chosen (fig. 2), for there the deep railway-cutting has laid open the structure of the disturbance, and within a reasonable distance, though not too near, was a piece of fairly level ground, one end of which had been opened for chalk-pits and the other for quarries in the Purbeck Beds. The railway-cutting itself would not have been satisfactory, for in it a wide dyke of 'fault-rock,' composed of Oxford Clay and Cornbrash, occurs, and south of the fault there are soft rocks. Besides this, soft strata in a deep cutting will almost certainly be subject to slow 'creep' to such an extent as entirely to mask any deeper-seated movement.

The site finally selected proved by an unexpected series of coincidences to be particularly convenient. It is broken ground, now only used for rough pasture and not liable to be disturbed by the plough; it belongs to Gonville and Caius College, Cambridge, who have most kindly done all in their power to help us in the experiment. Our thanks are not only due to the College, but also to the tenant for his assistance in carrying out the work. And last, but not least, it was conveniently accessible to the member of the Committee who was prepared to undertake the recording.

While our excavations were being made I examined them, and noted as exactly as possible the geological conditions in the immediate neighbourhood, for the fault varies within very short distances, and has changed completely in the two hundred yards between the railway cutting and our selected site. In that short distance the dyke of Oxford

FIG. 2.—Geological Survey Map of Upway, by A. STRAHAN; with additions by CLEMENT REID
(Scale, 6 inches = 1 mile.)



* Denotes position of recording apparatus at junction of Section line and Ridgeway Fault.

Clay has disappeared entirely, as is the case with the Middle Chalk on the north side of the fracture, as well as the Wealden and Upper and Middle Purbeck on the south side. The fault has also become a fracture of unusual sharpness for one of so great a magnitude.

In discussing the character and extent of thrust of the fault at Ridgeway, it should not be forgotten that it does not pass through a series of conformable strata. The Upper Cretaceous rocks here rest unconformably on a folded and greatly eroded surface of Lower Cretaceous and Jurassic strata, so that the local absence of Wealden and of most of the Purbeck may be due to this unconformity. These intra-Cretaceous folds have an axis approximately parallel with the much later Tertiary disturbances. The most important of them is the wide anticline between Upway and Portland. This is followed northward by a narrow and sharp syncline, which brings in the Wealden and Purbeck between Upton and Bincombe, and passes unconformably under Upper Cretaceous rocks towards the east and towards the north-north-west. Next follows an anticline, which is almost entirely hidden by the newer rocks. It is touched at Poxwell, where the Jurassic strata dip northward at a higher angle than the Upper Cretaceous. It then seems to run beneath the Chalk parallel to the southern boundary just north of the Tertiary overthrust. Its southern limb reappears at Bincombe, but soon disappears again beneath the overthrust mass of Chalk. The position and character of these earlier folds, their relation to the Upper Cretaceous overlap, and the relation of both to the overlap of the Bagshot Beds on to the Oolite,[1] are the factors which produced a continuous plane of weakness extending obliquely downward from the surface deep into the Jurassic strata, as shown in the diagram (fig. 3).

The outcome of this geological structure has been that any subsequent lateral compression in a north and south direction causes the massive Chalk, over 800 feet thick, to be driven against the wide arch of rigid Purbeck and Portland rocks extending towards Portland. Any such movement must tend still more to fold and buckle the already existing small anticlines and synclines; but the main arch of hard Upper Jurassic rocks would offer great resistance, as would the horizontal thick-bedded Chalk. Thus the Chalk must approach the main anticline, overriding the minor folds, taking with it such parts of them as happened to be above the plane of greatest weakness, and smearing the slide-plane with Oxford Clay and Cornbrash caught up in the passage over the northern limb of the anticline.

The above explanation will, I believe, account for the whole of the curious phenomena recorded along this line of fault. Granted north and south compression, any differential movement must be along this plane of weakness. The extent of the differential movement must also be greatest at the surface where the plane emerges, and must rapidly decrease downward and northward until the fault entirely disappears. The extent of the movement in this case is probably about half a mile.

From the data in the memoirs and maps of the Geological Survey, and from my notes made more recently, I have constructed the subjoined geological section across the fault at the point where our apparatus is fixed (fig. 4); but though the underground structure must be not unlike that indicated, the exact curve of the fault, and also the exact character

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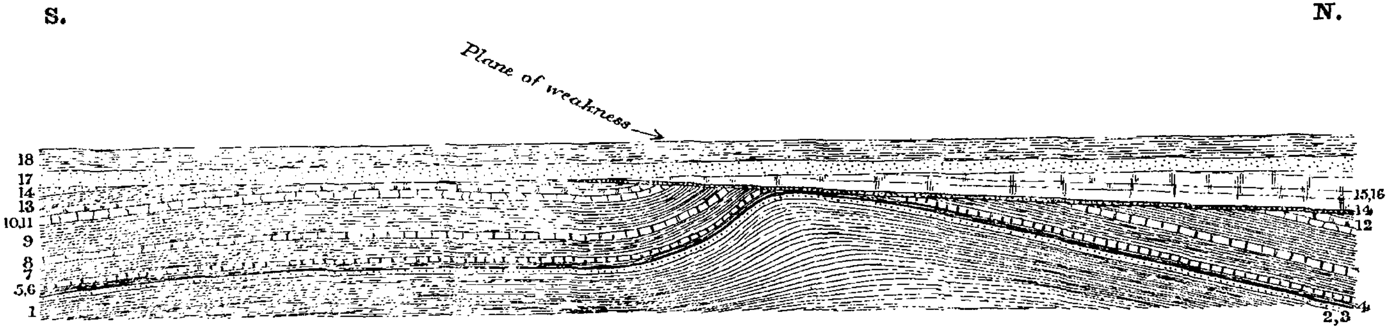
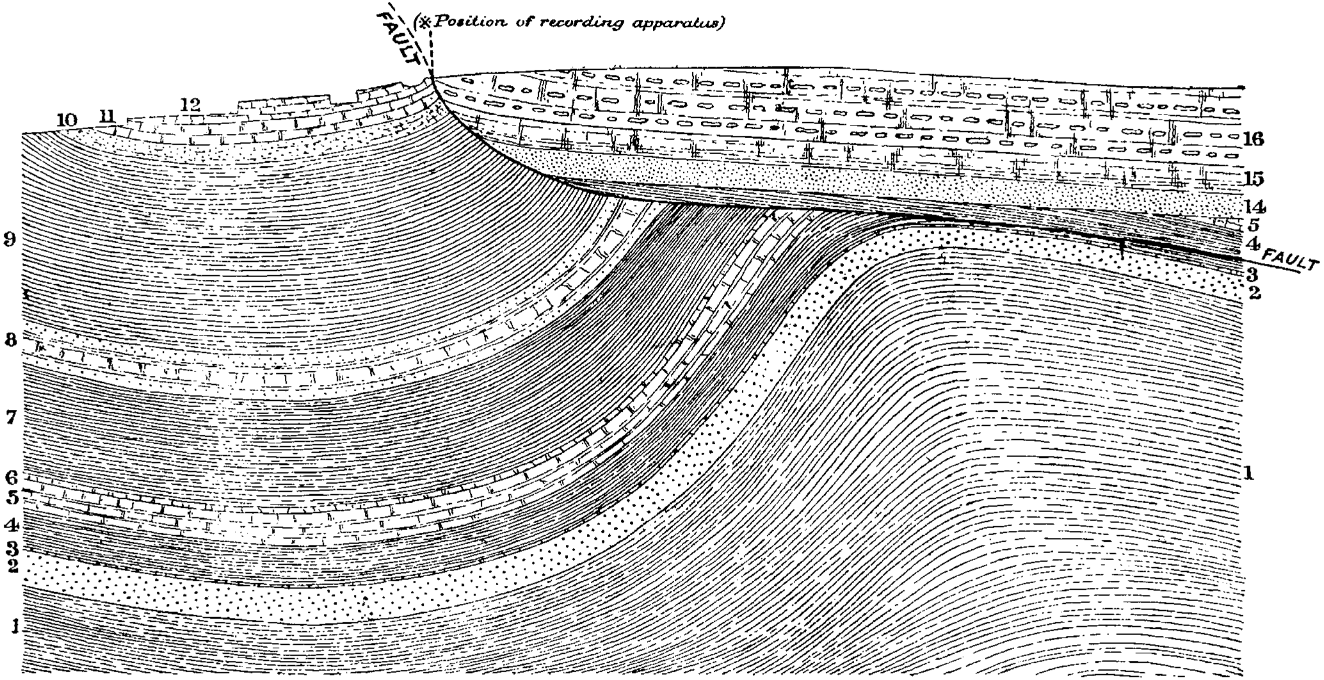
[1] See Reid, 'Geology of Dorchester,' chapter vi., *Memoirs Geol. Survey*, 1899.

FIG. 3.—N. and S. Diagram Section, showing probable structure before the formation of the Ridgeway Fault. (Scale, 1 inch = 1 mile.)



18 Oligocene.
17 Bagshot.
16 Upper Chalk.
15 Middle and Lower Chalk.
14 Upper Greensand.
13 Wealden.
12 Purbeck Beds.
11 Portland Stone.
10 Portland Sand.
9 Kimeridge Clay.
8 Corallian.
7 Oxford Clay.
6 Cornbrash.
5 Forest Marble.
4 Fuller's Earth.
3 Inferior Oolite.
2 Midford Sand.
1 Lias.

FIG. 4.—Section across the Fault at Ridgeway. (Scale, 6 inches = 1 mile.)

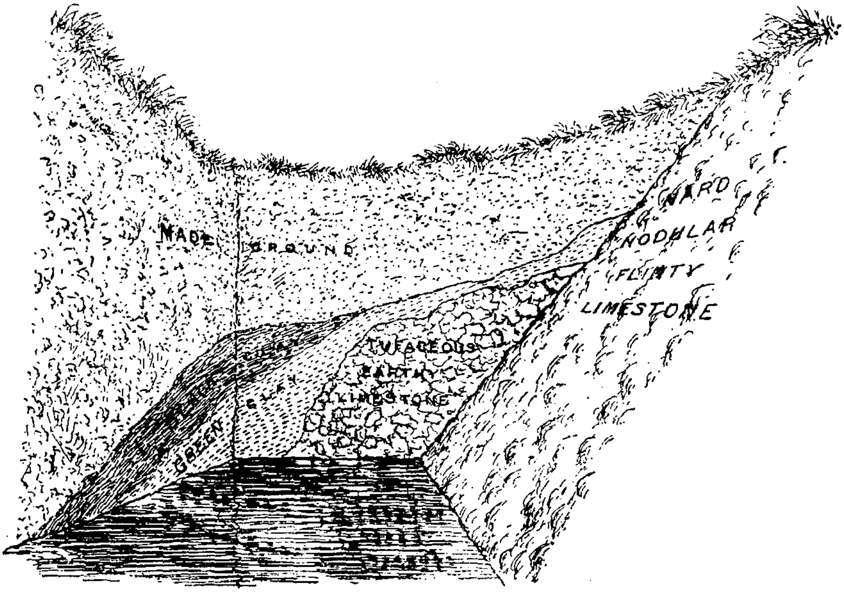


16 Upper Chalk.
15 Middle and Lower Chalk.
14 Upper Greensand.
12 Purbeck Beds.
11 Portland Stone.
10 Portland Sand.
9 Kimeridge Clay.
8 Corallian.
7 Oxford Clay.
6 Cornbrash.
5 Forest Marble.
4 Fuller's Earth.
3 Inferior Oolite.
2 Midford Sand.
1 Lias.

of the hidden folds beneath the Chalk, must remain uncertain. The Eocene deposits are not shown in this section, as they happen to have been denuded along the line selected. They occur only a short distance away out of the line of section. The actual evidence seen at the surface close to our site will now be described.

On the south side of the fault the strata dip northward at varying angles for a distance of about two miles from the crest of the main anticline, the lowest rocks in the district occurring in this anticline north of Radipole, where the Forest Marble appears at the surface. To this succeed in order the Cornbrash, Oxford Clay, Corallian Rocks, and Kimeridge Clay, followed at Upway (at the south border of the map, fig. 2), where the slope becomes steeper, by Portland Sand, Portland Stone, and Lower Purbeck Beds. The lower quarries at Upway are in Portland Rock, dipping north ; the higher are in Lower Purbeck, nearly horizontal, for at that point the lowest part of a synclinal fold is reached and the strata begin to rise again.

FIG. 5.—Section of Lower Purbeck Rocks, dipping at 52°.



Higher up the hill in quarry and road-cutting the sections are nearly continuous, the dip being about S.S.W. at angles varying from 15° to 30°. Signs of lateral compression are also common, this being particularly well seen on the west side of the quarry nearest to the fault, where in a few yards the dip changes from nearly horizontal, with small sharp folds, to an angle of 15°. At the extreme north edge of this quarry the Committee undertook special excavations in order to clear up the geology at a point close to the fault. We followed a particular rock bed to a depth of 9 feet from the surface, obtaining the subjoined section, seen from the east (fig. 5). The strata laid bare belong to the 'dirt-bed' of the

Lower Purbeck, and occur within a few feet of the Portland Rock. The strike is almost parallel to the fault, though more nearly east and west. Thus it becomes almost certain that Portland Beds crop out at the surface immediately east of the Roman road and are probably within less than 10 feet of the surface at the point where the recording apparatus crosses the fault.

Taking now the trench in which the apparatus is placed, we will describe the strata there seen on each side of the fault. The trench is 9 metres long, and at the four observing stations (see Mr. Horace Darwin's Report, p. 119) sections were exposed to a depth varying from 5½ to 7 feet. At Station SS (the southernmost) the depth was 5½ feet, of which the top 3 feet was in disturbed ground, the lower 2½ showing hard brownish fine-grained oolite with fossils, the rock being somewhat shattered, with small open fissures, which were afterwards filled in with concrete. This rock undoubtedly belongs to the Lower Purbeck; it seems to dip at a high angle in a southerly direction, the strike, however, not being parallel with the fault. The shallower trench between Stations SS and S showed similar strata, though no fossils or oolitic grains were observed. At Station S the hole was also 5½ feet deep; the rock being a hard splintery brown limestone, more or less nodular and containing small chert nodules. I believe that this rock corresponds with some cherty limestones which are seen in the large Upway Quarry, just below the 'dirt-bed' and within 5 or 10 feet of the base of the Purbecks. Near the fault, however, they are harder and more crystalline than in the quarry. I was not able to find the earthy and carbonaceous 'dirt-bed' at this point, though it is so well seen only 50 or 60 feet away (see fig. 5). The squeezing-out or thickening of a soft stratum is, however, a phenomenon constantly to be met with near a big disturbance, and the absence of the carbonaceous seam is probably due to this cause. The south cheek of the fault consists of brecciated white limestone with chert. These exposures seem to indicate that the Portland Stone must occur within 5 feet or so of the surface close to the fault, and on the strength of the new evidence I have added an inlier of Portland rock to the map made by Mr. Strahan, who agrees with me that such an addition is necessary.

The fault itself is represented by a band of fault-rock not more than 2 feet in thickness and quite unlike the wide dyke of mingled Oolite and Oxford Clay seen in the railway-cutting. In our trench the fault-rock is a hard mass of breccia consisting of Upper Chalk and fragments of Purbeck Limestone.

The north cheek of the fault consists of very hard shattered and re-crystallised flinty chalk like that associated with the similar disturbances at Corfe Castle and at Ballard Cliff, though at Ridgeway I did not observe actual calcite veins. Two feet north of the fault I dug out a specimen of *Ananchytes ovatus*; but this echinoderm and a few fragments of *Inoceramus* were the only fossils I could find in the Chalk in our trench. The flinty character of the Chalk and the presence of the *Ananchytes* show, however, that we have passed suddenly from Lower Purbeck to Upper Chalk, and the character of the Chalk and of the included flints indicates, I think, that we are at an horizon above the Micraster-zones and probably at least 300 feet above the base of the Chalk.

Between the fault and Station N the Chalk gradually becomes softer and less crystalline and contains small broken flints, black with moderate rinds. The hole at Station NN showed 6 feet of moderately hard Chalk, with numerous brownish-grey flints; the Chalk being fissured but not altered. At Station NN the hole was 7 feet deep and exhibited Chalk with numerous flints, the rock being much slickensided and fissured. It contained a few fragments of *Inoceramus.* I was not able anywhere to get a satisfactory dip in the Chalk in the trench or holes; though the general impression suggested was of an ascending succession northward, and of a high dip in that direction.

The general results of the geological examination may thus be summarised. The fault, at the point where the apparatus crosses it, probably cuts out strata having a thickness of nearly 1,000 feet, made up thus:—

Chalk (part of Upper, whole of Middle and Lower)	300
Greensand and Gault	150
Wealden	350
Upper Purbeck	50
Middle Purbeck	50
Lower Purbeck (to within 5 feet of base)	85
Total feet	985

The break, however, is not caused by a normal fault of 985 feet throw. It is the result of a sliding movement over a cylindrical surface curving downward and northward from nearly vertical to nearly horizontal. This view, as pointed out by Mr. Strahan, explains the presence of a dyke of Oxford Clay and Cornbrash in the railway-cutting; a fact which cannot be satisfactorily accounted for by normal faulting, even to the extent of 2,500 or 3,000 feet. The movement along the curve of the thrust-plane amounts to not less than 2,500 feet, even if the strata are everywhere vertical to the fault. It is just possible, however, that earlier faulting along nearly the same line in intra-Cretaceous times brought up Cornbrash, so that it occurs immediately beneath the Upper Cretaceous rocks just north of the Tertiary fault. On this supposition, and with the most favourable angle of dip throughout, the Tertiary thrust may not exceed 500 feet. The most probable estimate of the extent of the Tertiary displacement is, however, about half a mile; a lower estimate demands an improbable series of fortuitous coincidences, such as we are not justified in postulating.

There is one point that I should like to suggest for future consideration. The disturbances just described result from lateral compression of the strata in a north and south direction, and it is clear that levelling across the fractures will only give us one element in that motion. The horizontal movement must be of much greater magnitude than the vertical, and could be accurately tested by triangulation. As the folds have always an east and west axis, and there is no sign of disturbance in other directions, triangulation across the folds from fixed points lying east and west ought to enable us to test whether any change is now going on over wider areas. Even a comparison of the earlier Ordnance triangulation of the South of England with the later one might throw light on this question, if the stations can be identified with sufficient accuracy. No minute re-measurement of a base-line would be necessary for this test. If the movement is going on at all it must be far greater in a north and south than in an east and west direction—*i.e.*, it will alter the latitude but not the longitude. It must therefore distort every triangle which can be re-observed from two such points as St. Catherine's Down and the top of Portland.

VII. *An attempt to detect and measure any relative movement of the strata that may be now taking place at the Ridgeway Fault near Upway, Dorsetshire.—Preliminary Report by* HORACE DARWIN, *August* 1900.

The Fault for this experiment was selected by Mr. Clement Reid, and is described by him in a separate report. It would have been better if the rock had been harder and more impervious to water; the solubility of the carbonate of lime in the rock is also a disadvantage. The site is easy of access, an essential point in such an experiment; this, together with the advantages pointed out by Mr. C. Reid, justify the selection of the Fault.

The Fault where the apparatus is fixed is a few yards east of the Roman road and about 560 yards north of the cross roads in the village of Upway, Dorsetshire, and is about 360 feet above Ordnance datum. Gonville and Caius College, Cambridge, allowed the apparatus to be fixed on their property and did all in their power to make the experiment successful, and the Committee are most grateful to them. I must thank Mr. Nelson Richardson for the many hours' help he gave me at Upway, and in arranging for the experiment, and for the readings he took afterwards. Thanks are also due to Mr. Loveless, the tenant of the land, for the care he has taken in carrying out the work and the help he gave in every way.

Four positions were taken in a straight line approximately at right angles to the fault; these positions will be denoted by the letters N.N., N., S., S.S.; N.N. is 9 metres and N. 4½ metres north of the *Fault*, and S.S. is 9 metres and S. 4½ metres south of it. The apparatus is arranged to measure the relative vertical movement of the strata at these four stations. There are advantages in selecting four instead of two stations. If there had been only two stations, and the apparatus got damaged at one of them, the experiment must have been a failure; also, if there had been any accidental displacement of the apparatus relatively to the strata at either of the two stations it might have led to misleading results. With four stations such damage or movement will probably be detected, and the results, though less valuable, will not be rendered quite useless, as would be the case with only two stations.

The movement of the strata at the Fault may take place in any or all of the following ways:—

(1) The strata on both sides of the Fault may tilt as a whole without any slip taking place at the Fault.

(2) The strata at the north side may tilt and the south side not tilt, and still no slip at the Fault.

(3) The strata at the south side may tilt and the north side not tilt, and still no slip at the Fault.

(4) There may be slipping at the Fault with no tilting.

These four movements may be all taking place at the same time, and the use of four stations will allow of each movement being separated from the others.

The apparatus has been designed by me and made by the Cambridge Scientific Instrument Company, Limited. I have not been able to give sufficient time this summer to overcome some difficulties which I regret that I did not foresee, and it is for this reason that no numerical results are given in this report. The instrument, however, promises well, and I hope next year to give a description of it and numerical results; now I only propose to explain its general principle.

A brass casting is permanently fixed to the rock at each of the four stations, and it is the relative vertical movement of these castings which is measured. A stand carrying a microscope can be placed on any of these castings; it has three feet, each in the form of an inverted V, and these rest on three cylindrical pieces forming part of the brass casting. This is the usual geometrical arrangement, giving six points of contact, and determining absolutely the relative position of the microscope stand and the casting. The microscope is about 4 feet long, and thus the eye is in a convenient position for taking an observation. The microscope is moved vertically in the stand by a micrometer screw, and carries at its lower end a needle pointing vertically downward. The micrometer screw is turned, the microscope is lowered till the needle point touches the surface of some oil contained in a vessel fixed to the rock, and the position of the micrometer screw noted. The microscope and stand are then removed and placed on the other castings, and the observation repeated; in this way the relative position of the casting at each station to the oil surface is measured. The four oil vessels are connected by a pipe; the surface of the oil is therefore at the same level. The needle point is illuminated by a mirror fixed in the oil vessel, and the light, leaving it in a nearly horizontal direction, is reflected by a vertical mirror nearly directly backwards, and is then again reflected vertically upwards through the object-glass and eyepiece of the microscope. On looking vertically downwards through the microscope, the needle point and its reflection in the surface of the oil are seen as if the eye were placed just above the surface of the oil; and when the micrometer screw is turned the needle point and its image are seen to approach each other. The moment of contact is perfectly evident; the needle and its image appear to run into each other in a confused manner, owing to the distortion of the oil surface when the needle point touches it. The delicacy is considerable; the divisions in the divided head of the micrometer screw correspond to a movement of $\frac{1}{100}$ mm., and it is easy to estimate a tenth of these divisions, but I do not think that the readings can be trusted to this amount, and it is proposed only to read to $\frac{1}{100}$ mm., which is well within the power of the instrument.

The micrometer readings give the height of each station above the oil surface, and from these readings is deduced the movement at each station relatively to a datum plane. This datum plane is taken at the mean level of the four stations. The necessary calculations also prevent any error arising from change of the oil level due to expansion or evaporation, damage to the needle point, or expansion of the microscope.

It is hoped that a very small slip at the Fault will be detected and measured, but even if the movement should ever become as much as 10 mm. to 20 mm., it can still be measured with great accuracy. It is unlikely that such a movement will damage the lead pipe where it crosses the Fault; damage to the pipe, however, can be easily remedied without impairing the accuracy of the readings. Some readings have been taken, but it is feared that they are not perfectly trustworthy; they may, however, be useful in confirming later results.