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Further studies on earthquake waves

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ness and inability to control a neurotic wife of pronounced German sympathies, he would have remained the idol of his people until the day of his death."

FURTHER STUDIES ON EARTHQUAKE WAVES.

By C. G. KNOTT, D.Sc., LL.D., Secretary R.S.E.

(With Sketch-Map and Diagrams.)

NEARLY twelve years ago (vol. xxi. p. 569), in a review of the late Professor Milne's book on Seismology, I drew attention to the remarkable development of seismology as a mathematical rather than a geological science. Largely through Milne's own efforts, the importance of world-wide seismic surveys had become recognised by all nations. The investigator did not require to be a resident in a so-called earthquake country, such as Italy or Japan or the Caucasus. He could set up his instruments at any point on the earth's surface, and ere long he was certain to be meeting the earthquake face to face. Milne himself established his observatory at Shide, in the Isle of Wight, and the Seismological Committee of the British Association, under the able leadership of Professor Turner of Oxford, have kept it going since Milne's death in August 1913.

Meanwhile the growing importance of seismological observations and studies had led to the establishment of the International Seismological Association, which met every three years at different centres for the interchange of views and the voting of sums to definite lines of research. The last Congress met in Manchester in July 1911, under the presidency of Professor Schuster. Seismologists from all countries gathered together; and it chanced that the most distinguished workers in the subject met each other in this friendly concourse. To name but a few; there was the great pioneer himself, John Milne; there was Prince Galitzin, whose seismometers are second to none for the accuracy of their records; there was Professor Wiechert, whose papers in conjunction with the late Dr. Zöppritz are among the most valuable communications of the last ten years; there was Professor Omori of Japan, whose unwearied labours have shed much light on the behaviour of after-shocks; and many others who, directly or indirectly, have increased our knowledge of the earth as a body subject to change.

At the final social gathering of this Congress, Prince Galitzin, the President-elect for the next three years, proposed, in a racy English speech, the health of John Milne, as the one who had led the way into the unknown fields of seismological research. Milne's reply was one of the features of the meeting—reminiscent, humorous, genial. Yet we all knew that at the back of his mind he cared not for this International Association, with its central bureau at Strassburg. He held it a grievance that this country should have subsidised an International Council, and yet had never found it necessary to support the one great central agency which, with the help of the British Association, he

had established at Shide. Wherever the British flag fluttered in the breeze, there a Milne seismometer had been established to catch the faint flutters of far distant earthquakes. Of course it is the old story. For the sake of scientific research in itself, our wise statesmen would have none of it; but when international politics had a look in, then money was found for the Strassburg Bureau.

However, it was a most enjoyable Congress in 1911. Very valuable papers were read; important votes were made of funds for definite purposes; the University and the city of Manchester treated us kindly; and after the Congress had finished its deliberations, Sir Napier Shaw gathered a goodly company under his personal guidance, and by train and motor car took us to Eskdalemuir to view the Observatory, and especially the Galitzin seismometers.

The next Congress was to have been held in September of 1914; but this, alas, was prevented by the nation which plumes itself on its scientific culture, and within whose territory Strassburg still lies. The place of meeting was what was then known as St. Petersburg, where Prince Galitzin had his seismological laboratory. The invitations had been sent out, and many were looking forward to a delightful experience of Russian hospitality, as well as a renewed discussion of the profound mysteries of the earth's interior, when—crack went the assassin's pistol, and a veritable Teutonic earthquake convulsed Europe. Like all large earthquakes, its tremors were felt to the uttermost bounds of earth.

It was grievous that such a cause should wreck the endeavour for international interchange of thought; but probably many of us felt a more individual grief when, within a year after the outbreak of war, Prince Galitzin died. His death removed one of the most conspicuous and most successful workers at the problem of tracing an earthquake to its origin from a study of the records of tremors at any one station far distant from the source of the disturbance.

The outbreak of the war in 1914 totally disorganised the International Seismological Association. Fortunately, in the widespread distribution of stations which Milne established, there existed an organisation closely approximating to an international character; and good work could still be done in spite of the inaccessibility of the Central European records. Since Milne's death the work of the Shide Observatory has been carried on with great efficiency under the superintendence of Professor H. H. Turner; and the *Reports* presented to the British Association contain important developments and interesting suggestions for new lines of research. I propose to discuss briefly some of the problems attacked in these *Reports*, as well as other aspects of the vast question of the structure of the earth.

These may be treated under two headings: first, the improvement of the instruments for recording the tremors due to distant earthquakes; second, the discussion of the available records.

It may be well to recall at the outset what a seismometer does, and what the general character of an earthquake record is. A seismometer is an instrument suspended or supported in a framework fixed to the earth in such a way as to behave like a "steady point" when the earth

moves. Attached to the steady point is a lever, whose movements relative to the earth are recorded automatically on a steadily moving surface, in most cases a strip of paper, on which rests the end of a fine pen in connection with the lever. In Milne's instruments the record is obtained photographically by means of a light thrown through a hole or slit at the end of the lever or "boom," and focussed on a moving strip of sensitised paper. To obtain a complete record of the relative movement of earth and seismometer, three instruments are needed, two for the N.S. and E.W. components of the horizontal movement, and one for the vertical movement.

The Milne instrument as supplied to the many stations established by the Committee of the British Association all over the world, records only the horizontal movements. It is a simple type of horizontal pendulum which may be briefly described as a horizontal rod suitably weighted, bearing on a pivot point at one end, and supported by a slanting wire, whose upper end is fixed to a point in the framework

nearly in the same vertical as the pivot point. The pendulum rod is continued outwards as a long boom, bearing at its far end the slit through which the beam of light is directed towards the sensitised paper. Any slight relative movement of earth and steady point is magnified by the attached long boom. The framework is adjusted by levelling screws until the periodic time of the free swing of the boom is about seventeen or eighteen seconds.

The boom of one instrument lies E. and W., and records the N.S. component of relative motion; that of the other lies N. and S., and records the E.W. component of motion. When a station is provided with only one instrument it is set so as to record the E.W. movement. When there are two instruments their records are taken side by side on the moving strip of paper.

The merits of the Milne instrument as compared with other forms of horizontal pendulum are given concisely in the British Association *Report* for 1914 in these words:—

"Extreme lightness and compactness characterise it, and no simpler method of optical registration could well be devised. No expensive lenses are needed, and, with the exception of a few parts of the

mechanism, no specially high-class work is required in manufacture. The whole of the apparatus is self-contained, and does not take up much floor space."

All types of instruments agree in giving the same kind of earthquake record, the main features of which are reproduced in the preceding figure (after Omori).

The record begins with *a*, the first preliminary tremor, hereafter represented by the letter *P* (for Primary). In a few minutes a sudden increase of motion is shown at the point *b*, and this marks the advent of the second preliminary tremor, represented by the letter *S*. Following these we have the large waves beginning at *c*, attaining a maximum and then gradually falling off to the end. In the present article the discussion will be restricted mainly to the *P* and *S* tremors and their reflexions.

As established by Oldham and Milne seventeen years ago, the laws governing the transmission of the *P* and *S* tremors on the one hand, and of the large waves on the other, are markedly different. The rapidly growing mass of statistics and the improvement of seismometers have not altered the main facts then established. The distinction between the preliminary tremors and the large waves has been proved beyond all possibility of dispute. The large waves travel round the surface of the earth with a constant speed which has been variously estimated according to the particular part of the large wave record which has been under contemplation. In the recent set of Tables compiled by Dr. Klotz of Ottawa the speed is given as 3·8 kilometres per second (2·36 miles per second) and refers to the advent of the large waves, and not to their maximum.

This simple law of arcual transmission is not satisfied by the *P* and *S* waves. To show this it is sufficient to reproduce, with more recent data, the following table from my book on the *Physics of Earthquake Phenomena* (1908), p. 225. It also gives an epitome sufficient for present purposes of the times of transit of the *P* and *S* curves as given in the Bulletins of the Seismological Committee of the British Association. They are practically identical with the tables prepared by Wiechert and Zöppritz in 1907. The main purpose of the short table here given is to compare the chordal and arcual speeds of the *P* and *S* waves. The arcs are expressed in radians, the chords in earth-radius, and the times in minutes. Hence the speeds are in earth-radius per minute:—

Arc. Degrees.	Times. Minutes.		Chord.	Arc.	Chordal Speeds.		Arcual Speeds.	
	<i>P.</i>	<i>S.</i>			<i>P.</i>	<i>S.</i>	<i>P.</i>	<i>S.</i>
20	4·7	8·4	0·34	0·35	·072	·040	·074	·042
40	7·9	14·1	0·68	0·70	·086	·048	·089	·050
60	10·2	18·4	1·0	1·05	·098	·054	·103	·057
80	12·3	22·4	1·29	1·40	·105	·053	·114	·062
100	14·2	25·9	1·53	1·74	·108	·059	·123	·067
120	15·7	28·8	1·73	2·09	·110	·060	·133	·073
140	17·2	31·1	1·88	2·44	·109	·060	·142	·079

It is obvious at a glance that the P and S tremors do not pass along the surface, since the arcual speeds steadily increase with the length of the arc. The chordal speeds also increase with distance, but not so rapidly. Moreover they tend towards a constant value for the greater distances. Hence the P and S tremors pass neither along the surface nor along the chords; but their paths approximate to the chords as the distances increase. Those P and S tremors which appear at far distant stations pass across the body of the earth. Those which appear at nearer stations pass by curved paths which come nearer to the chordal position than to the arcual position.

These facts were the basis for the next advance in the theory of seismic waves, the general nature of which will be found in the *Physics of Earthquake Phenomena*, Chapter XII. It will suffice to recapitulate a few of the leading conclusions.

The P and S tremors are universally accepted as the compressional and distortional waves started by the earthquake cataclysm and propagated by brachystochronic paths through the body of the earth. What the seismometer at any station measures is the disturbance at the surface due to the outcrop of these waves.

On account of the greater velocity of the compressional or P wave the interval of time between the arrival of the P and S waves will become longer with increasing distance of the station from the earthquake focus. From his early statistics Milne drew up a table giving the relation between this time interval and the arc between the epicentre and the station of observation. Now any good seismogram will show this interval, which is simply the length ab in the diagram expressed in minutes. This single measurement determines the arcual distance of the epicentre from the station of observation. The epicentre must therefore lie on the small circle drawn on the earth's surface with the station of observation as its centre and the arc corresponding to the time interval ($S-P$) as its arcual radius. From his knowledge of where earthquakes usually had their origins Milne was often able to locate the epicentre from this one observation.

When the corresponding datum from the record at another station is obtained another small circle with this station as centre can be drawn on the terrestrial globe, intersecting the former circle at two points, one of which will be the epicentre. The record from a third station should fix the position of the epicentre indisputably.

To quote again from the British Association Report of 1914 :—

"The Milne type of instrument is very sensitive as a mere seismoscope. With the exception of very faint movements indeed, some record of a distant quake can always be obtained by it; this is due to the absence of damping and almost entire absence of solid friction; by altering the period of oscillation of the boom we may make it particularly sensitive to any wave-period desired."

Owing to the absence of damping and the effects of resonance, the maximum movements on the Milne record do not necessarily coincide with the maximum movements of the ground. By slight damping a more faithful record might be obtained; and if the pendulum were

made accurately dead-beat by suitable damping, quite close agreement would no doubt prevail between the actual earth movements and those worked out from the record.

But damping means great reduction in the amplitude of the record. This must, therefore, be greatly magnified before efficient damping can be applied. This has recently been done in the Shaw and Burgess modifications of the Milne instrument; but before considering this I propose to discuss briefly the merits of the Galitzin instruments.

The Galitzin horizontal pendulums are constructed after the Zöllner system. This principle may be very simply illustrated by means of a model made of a rod, say a ruler, and two pieces of string. Attach the strings to the rod at two points on the same side of the centre of gravity. Take hold of the free end of the string which is nearer to the centre of gravity and lift the rod from the table. With the other hand seize the other string and draw it down until the rod is pulled into a horizontal position. The strings will then be found to be inclined to the vertical and to be nearly parallel, while the two hands are approximately in the same vertical line. A slight movement of either hand at right angles to the lie of the rod will cause the rod to swing round through a large angle. The arrangement may be made very sensitive, and is free from pivot frictional resistances. The main features of the Galitzin instruments are very succinctly given in the British Association Report already referred to. After the description of the Milne instrument, Turner continues:—

“The Galitzin instrument, on the other hand, is a very much more complicated affair. It is designed to follow a somewhat elaborate mathematical theory, and high-class workmanship and accuracy are needed in its construction. Its pendulum is shorter than the Milne and much heavier—say, seven kilograms. It is hung by two steel wires (Zöllner system), and has no pivot at all in some cases. Provision, however, is made on the pendulum and frame for a steel point and cup to be inserted if required . . . Close to the outer end of the boom are fixed to the frame four powerful horse-shoe magnets. Between the poles of one pair of these moves a set of wire coils fixed to the boom and coupled in series with a delicate galvanometer placed in any convenient position elsewhere. Between the other pair is a large copper plate, also fixed to the boom, and this last acts as a magnetic clasper. The magnets can be adjusted as desired to vary the magnetic field between the poles.

“The galvanometer is of the moving coil type, and has a long period of oscillation when undamped. This galvanometer is an excellent piece of work, and is electrically damped so that it can be rendered just aperiodic. With the whole instrument in normal working it is necessary that the undamped periods of both pendulum and galvanometer should be the same, and that they both should be damped just to the limit of periodicity.

“The optical registration consists of a collimator with a fine slit powerfully illuminated. The beam is reflected from a mirror in the galvanometer and thence to the sensitive paper on the revolving drum,

where a cylindrical lens condenses the line of light into a point on the paper. . . .

"A good deal of floor space is required, and the room in which the recording parts are placed must be kept dark."

As already pointed out, the Galitzin seismometer does not record the movement of the ground but the movement of a galvanometer coil. This movement is produced when a current flows through the coil; and this current is produced by induction in the floating coil at the end of the boom as it moves across the lines of force in the air gap of a powerful magnet. The strength of the current is proportional to the velocity of the end of the boom, and the galvanometer deflection must also be proportional to this velocity. Hence the Galitzin record is a record of velocities, not of displacements, of the horizontal pendulum. Its zero position is not affected by the wandering of the horizontal pendulum from its position of equilibrium, a trick which often disturbs the record in the other forms of seismometer. On the other hand, the Galitzin record takes no cognisance of slow movements of the horizontal pendulum. There must be a certain rapidity of to and fro movement of the ground to give rise to velocities large enough to produce appreciable currents through the galvanometer.

By attaching to the light boom of the Milne instrument a thin sheet of aluminium moving within the air gap of a magnet, J. J. Shaw has successfully applied the magneto-electric damping to this type of seismometer. At the same time by an optical arrangement of great lightness and delicacy he has magnified the record of the undamped instrument 300-fold; and obtained in combination with the damping arrangement a record with magnification about forty times that of the ordinary type of Milne instrument. The records obtained with this modified instrument are comparable with those obtained with the Galitzin form. The results are of great interest as proving that massiveness is not essential in a seismometer yielding precise records. With the increased magnification, however, other troubles arise which are difficult to cope with.

One fact which will militate against the Galitzin instruments being installed in other than first-class observatories is the expense of the equipment. Another is that it requires the attention of a highly trained scientific observer with a good working knowledge of dynamical mathematics. "The interpretation of its records is not a very simple matter, but by those prepared to spend the time a vast amount of information can be obtained. The scale of magnification varies widely with different wave periods, being in general approximately 800 as a maximum for periods of about fourteen seconds, and falling off for either longer or shorter periods." Thus neither slow movements nor rapid vibrations leave any record.

An instructive account of Galitzin's instruments, of their mode of action and the interpretation of their records, is given by G. W. Walker in his *Modern Seismology*. Dr. Walker was for several years superintendent of the Eskdalemuir Observatory, the one station in Great Britain possessing a complete installation of Galitzin's seismometers. He

had, therefore, ample opportunity of becoming acquainted with the instruments in all their moods.

As an instrument of precision the Galitzin seismometer is certainly superior to any other. Galitzin showed how the records of one set of instruments at one locality could lead to the determination of the position of the epicentre of the distant earthquake. The success of this determination depends on certain conditions being satisfied. The *P* tremors must begin distinctly, and not be mingled with tremors due to other causes. Both the horizontal instruments must be of the same sensitiveness, so that the first displacements of the record are proportional to the north and east components of the velocity of the ground produced by the initial impulse. The ratio of these first displacements in the record will then give the azimuth from which the compressional wave has come—that is, the azimuth of the epicentre referred to the station. The epicentre will lie on the great circle having this azimuth as it passes through the station. The distance of the epicentre along this great circle will be given by the interval of time the *P* tremor lasts before the *S* tremor comes on. All that is now needed is to know in which direction along this great circle the epicentre is; and that is given by the up or down direction of the first impulse shown on the vertical motion seismogram. Thus in favourable cases the three records of the Galitzin instruments at any one locality suffice to determine the situation of the epicentre. It has never been claimed that this could be effected by any other form of instrument.

There is no doubt that the ingenious combination of electric and optical methods used by Galitzin gives great scope for magnification of the records. The only limit is the delicacy of the galvanometer. Nevertheless it is a disadvantage that the velocity, and not the displacement of the ground, is what is given directly. It is conceivable that the improvements recently effected by J. J. Shaw and J. H. Burgess in the Milne instrument may lead to further improvements, and give us an instrument of precision comparatively easy to manage.

With the ever-increasing number of observations the times of transit of the *P* and *S* waves to various distances should be gaining in accuracy. There are, however, great difficulties in co-ordinating the data. Of the numerous large earthquakes which produce clear-marked records at the majority of the stations, comparatively few occur in populous regions, where alone accurate times are determinable. This is, no doubt, a fortunate circumstance as regards destruction of life and property. The position of an epicentre and the time of the disturbance there are generally estimated from the records of *P* and of *S* at fairly distant stations. It was by this method that Milne discovered the positions of the epicentres of many large earthquakes, and was thus able to lay down on the terrestrial globe or map his areas of origins of large shocks. Year by year these were indicated on a map of the world, published along with the British Association Report, for each year. This map was on Mercator's Projection, which is not at all convenient for indicating great circles other than the equator and the meridians. The other familiar projections of the hemispheres are even more

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on faces of the octohedron which may be unwrapped into a plane in various ways. The particular set of great circles was chosen so as to bring out the striking symmetry of the earth both seismological and geographical. The projection is reproduced p. 414, with the permission of the author, from the British Association Report of 1916. Six of the triangles are immediately recognisable. The other two have been divided into halves, *ACB* and *DCB*, *GKH* and *LKH*, so as to retain symmetry with compactness.

The continents are slightly shaded. The dots represent earthquake origins, as recorded by Milne, from 1899 to 1910. All small islands have been omitted so as to prevent possible confusion. The line *GKECA* represents one of the original great circles, and about it a large number of earthquake origins cluster. The similar great circle, *LKFCD*, is not at present a conspicuous line of earthquake activity, but it may have been so in the past. The third great circle is formed by *EF* and the boundaries of the map, but there is no evidence of this being or having been a line of seismic disturbance. If, however, we draw *LFW* with *ZD* half way between the two circles we find another line about which epicentres cluster. These two great circles, near which earthquake origins crowd, are distinguished by triplets of lines. The "Libbey's Circle," which was drawn by Milne on the earthquake maps, in the Reports for 1903-1909, is a small circle parallel to *WFL*, and would fall in fully better with the distribution of origins. Still the rough grouping of these origins about two great circles is an interesting point.

It will be noticed that the great majority of these origins lie under the ocean waters. They were therefore estimated entirely from the *P* and *S* phenomena in the records of three or more stations. And this is the method which has still to be used. The tabulated times of transit of *P* and *S* waves are means, and the probable errors are considerable. No single earthquake, however fully detailed as regards the position of the epicentre and the times of arrival of the important impulses at the various stations, gives numbers in accurate agreement with the tables. A particular instrument may not catch the first impulses; the times recorded at some stations may not be accurate; the tremors may travel more quickly in some azimuths than in others (Milne indeed believed he had found evidence of this); the initial impulses of the earthquake disturbance may produce larger effects in some directions than in others; the decay of motion may vary with the azimuth so that records at different places may not catch corresponding movements; the geological formation in the neighbourhood of a station may deflect a large portion of the wave energy; the reflexion and refraction of elastic waves at surfaces of discontinuity may, as I pointed out thirty years ago, produce such changes as to alter entirely the subsequent propagation of the wave motion. When we have regard to all the possibilities, it is not surprising that our data for the transmission of the *P* and *S* tremors are still lacking in absolute certainty.

Consider for a moment the question of the reflexion of an elastic wave at the outer boundary of the vibrating rock. This is a purely

elastic problem, and was worked out mathematically in a paper communicated to the Seismological Society of Japan of 1888, republished with extensions in the *Philosophical Magazine* for July 1899.¹ There it was shown that when a compressional or *P* wave is reflected within the transmitting medium there is also reflected a distortional or *S* wave which sets off with a definite direction of propagation and carries with it a definite fraction of the original energy. The value of this fraction depends on the original angle of incidence. The numerical details will vary with the elastic constants and the density of the material. Recently I have calculated the case in which the material is such as to transmit the *P* and *S* elastic vibrations with a velocity of 7.18 and 3.98 kilometres per second, nearly 4.5 and 2.5 miles per second.² At high incidences, that is for low values of what is usually called the angle of emergence (the angle between the direction of the ray and the surface) the energy carried off by the reflected *S* wave is much greater than those carried off by the reflected *P* wave. A few of the numbers are given in the following table for the two cases of rock backed by air and rock backed by water :—

P = original energy of compressional wave.

P_1 = energy of reflected compressional wave.

S_1 = energy of reflected distortional wave.

P' = energy of refracted compressional wave in water.

$e = 90^\circ$ — angle of incidence (or reflexion) of *P* wave.

$e_1 = 90^\circ$ — angle of reflection of *S* wave.

Angles of incidence and reflexion in degrees.		Material backed by							Arc in degrees.
		Water				Air			
		P	P_1	S_1	P'	P	P_1	S_1	
e	e_1								
0	...	1	...	...	...	1	1.000	...	...
10	56.7	1	.040	.845	.117	1	.066	.934	3°
20	58.6	1	.0002	.871	.128	1	.008	.992	8°
40	64.8	1	.033	.798	.167	1	.073	.927	20°
60	74	1	.302	.476	.219	1	.445	.555	40°
70	79	1	5.13	.245	.241	1	.711	.289	98°
80	84	1	.677	.070	.259	1	.977	.022	170° ?

The general character of the distribution of the energy in the various secondary waves is very similar in the two cases. It will be seen that when e is about 20° the *S* reflected wave reaches a maximum. Now for emergence angle of 20° at the earth's surface the arcual distance between the epicentre and the point where the wave is emerging is 8° ; when the emergence angle is 40° the arcual distance is 20° ; and when the emer-

¹ See also *Physics of Earthquake Phenomena*; Clarendon Press, 1908; chapters x. and xii.

² These numbers, which differ slightly from those hitherto used, are the results of some recent calculations.

gence angle is 60° the arcual distance is 40° . For higher emergence angles and greater arcual distances the energy in the distortional or S wave falls off and the energy in the reflected condensational or P wave increases.

Suppose now that at a station distant A° from the epicentre we are studying the inflow of the P and S tremors. The first tremor to appear is the P wave, passing brachystochronically through the earth and emerging at distance A ; the PP wave which after one reflexion at the point half way between the epicentre and the station emerges at the station and produces on the seismogram possibly an increased disturbance; the PP wave which after two reflexions from points one-third and two-thirds the distance A from the epicentre. But in addition to these reflected waves there is the case of a wave P giving rise to a reflexion S , and this PS wave will emerge at a slightly later time than the direct S wave from the epicentre. The reflected rays produce appreciable effects at the recording station for the same reason

that rainbow colours are produced. There is a turning value in the time of transmission with a consequent crowding of the rays.

The relations are shown in the rough diagram in which E is the epicentre, M the station where the record is being produced, and the arc AB represents the surface of the earth. The direct P wave travels from E to M by the path E, P, M ; the once reflected wave PP is indicated by the double arc ERM ; the twice reflected wave PPP by the triple arc $Err'M$; and the reflected wave PS by the double arc ESM .

For certain angles of incidence the energy carried off by the reflected S wave at any position will be a greater proportion of the incident energy than the amount carried off by the P wave.

For example at R the reflected S wave will pass away in the direction RS' and will have no influence on the record at M . But if the arc EM is of moderate size most of the reflected energy goes away in the distortional S form and only a very small fraction passes from R to M . What comes to M in the distortional form is the energy reflected at S , SM being the reflected S wave: and this may easily be greater than the amount associated with the reflected waves ERM and $Err'M$.

The point I wish to accentuate is that for small and moderate values of the arc A_1 less (say) than 60° we cannot expect the PP and the PPP

reflected waves to bring in much energy with them. The *PS* wave will bring in more and will materially add to the increase of the motion after the *S* tremor has begun to appear. In many cases the *S* and *PS* will be indistinguishable.

On the other hand when A is larger, say, greater than 80° , the energy in the reflected *P* wave becomes comparatively larger and increases for greater arcual distances. We should therefore expect to find in the seismogram indications of the arrival of the *PP* and the *PPP* waves.

The *PS* wave which reaches a station at a distance, say, of 120° from the epicentre may still bring with it more energy than the *PP* wave for this distance. For its point of reflexion is not half way but at a point about 25° from the epicentre. Now the particular *P* wave which starting from the epicentre impinges at the point 25° distant has most of its energy passed over into the reflected *S* wave. The other particular *P* wave which impinges at the point distant 60° from the epicentre has fully half of its energy passed over into the reflected *P* wave; and the reflected *S* wave at this point emerges at a position far beyond the distance 120° , and therefore does not affect the seismogram obtained there.

According to the tables at present in use the times of transit of these various waves over an arcual distance of 120° are as follows:—

Character of wave.	Time of transit over 120° .
<i>P</i> direct	15·7 minutes.
<i>PP</i> once reflected	20·4 „
<i>PPP</i> twice reflected	23·8 „
<i>S</i> direct	28·8 „
<i>PS</i> once reflected	30·7 „
<i>SS</i> once reflected	36·7 „

This *PS* wave following so closely on the *S* wave has no doubt been mistaken for the latter—a possible contingency which should be kept in view when statistics are being made up.

The *PP* and *PPP* waves are occasionally very clearly marked, especially on the Galitzin seismograms. According to the views here expressed these reflected tremors should be visible in all large earthquakes at distances greater than 70° ; but at distances less than 50° we should not expect to find any very strong trace of them.

There is no reason why more frequently reflected waves should not also exist. The inevitable loss of energy during the process of reflexion may, however, so diminish the amplitudes of these multiple-reflected waves as to make them practically inappreciable. It is well to note, however, that as the incident compressional wave approaches grazing incidence with very small angle of emergence e , the reflected compressional wave *PP* begins to have associated with it more energy than for greater angle of emergence. This has already begun to appear in the table given above; for with $e=10^\circ$, the energy of *PP* though still small is greater than when $e=20^\circ$. And as e diminishes towards zero the energy of *PP* rapidly rises, while that of *PS* rapidly falls. It is

consequently quite a possibility that although PP (or briefly P_2) or PPP (or P_3) may carry with them a comparatively small amount of energy, P_{10} or P_{20} may carry more, and the greater proportionate amount of energy associated with the reflected compressional wave for small angles e may balance the loss due to the successive reflexions.

This conception of multiple reflexions over small arcs has been developed in a novel way by H. H. Turner in the British Association Report for 1915, as a suggested explanation of what he calls the Y phenomenon. In some seismograms in the neighbourhood of the S impulse which marks the advent of the S tremors, there are two well-marked disturbances a minute or two apart. The observer naturally regards the first maximum as the true S and the second as the reflected wave PS . But a careful analysis of the whole record in certain cases has convinced Turner that in these cases the second maximum is the true S ; and the first maximum is what he calls the Y phenomenon.

In suggesting that this Y phenomenon might be explained as being due to multiple reflexions, Turner pointed out that the time of transit of these reflexions tends to a maximum as the reflexions are taken over shorter and shorter arcs. For example for an arc of 60° , sixty reflexions over arcs of 1° take 900 seconds to reach the position 60° , thirty over 2° take 930, twenty over 3° take 940, fifteen over 4° take 930, twelve over 5° take 924, and so on. This maximum means a crowding together of the reflected rays, and this might show as an increased displacement on the seismogram. The following short table compares the time transits of the multiple-reflected P and the S waves.

Arc	=	60	80	100	120 degrees
P_n	=	940	1240	1550	1880 seconds
S	=	1103	1343	1556	1729 seconds
$P_n - S$	=	-163	-103	-6	+151 seconds

This phenomenon of the multiple reflexion, if it exists in sufficient prominence to be appreciable, precedes the S displacement for arcs less than 100° , after which it follows later. If this is the Y phenomenon, then it should be apparent as a kind of prelude to the S displacement for arcs less than 100° . Further investigations have led Turner to give up this explanation as not applicable to all cases. The Y phenomenon still awaits explanation. It is interesting to note that in two examples figured in the Report the Y phenomenon is extraordinarily similar to the S impulse, but *is in opposite phase*. This suggests an origin at the prime source of the disturbance—perhaps a double or recoil shock or a reflexion at the source.

By several lines of argument, Turner has come to the conclusion that the tables of times of transit for P and S at present in use require correction in certain parts. When all the available records of any large earthquake are considered in detail, and the observed times of advent of the characteristic phases are compared with the times according to the accepted tables, considerable discrepancies appear. A shift of the epicentre in position, or a correction to the estimated time of occurrence, or both combined may improve matters; but generally

such changes do not bring improvement all round. The corrections which have been suggested as likely to bring greater consistency into the comparisons between observed and estimated times do not amount to more than half a minute one way or the other. I do not propose at this time to do more than mention these suggested corrections, the whole question being still *sub judice*. When we bear in mind the heterogeneity of the earth's crust and the certain asymmetric nature of an earthquake shock, it is rather matter of surprise that there is after all so good an agreement in the times of transit as obtained from the various records. Any discrepancies in the records obtained at stations within a quadrant distance from the epicentre, might easily be assigned to the causes just named, without an appeal to more recondite theories.

The discussion is on a different footing, however, when we try to co-ordinate the results obtained from records at very distant stations. It has long been recognised that the observed transit times for epicentral distances greater than 110° do not fit in well with the times for smaller distances. The question was discussed in some detail, in the light of the data then available, in Chapter xii. of my book on the *Physics of Earthquake Phenomena*. The difficulties in the way of obtaining satisfactory records at very distant stations a dozen years ago were (1) the comparative imperfections of the seismometers then in use; (2) the natural decay of disturbances as they travelled to more distant points; (3) the spreading out of the wave front so that the energy per unit surface was greatly diminished; (4) the small horizontal component of the compressional impulse P as it impinged on the surface.

As examples of these general statements it was shown (p. 219 *loc. cit.*) that, as estimated from records of large earthquakes containing the trace of the large waves passing round the earth by the longer as well as by the shorter route, the amplitude of the maximum motion was cut down to one half within an arcual distance of 41° . It was also shown (p. 254 *loc. cit.*) that, in the case of the P and S waves, about 50 per cent. of the whole original energy was "distributed over the small surface whose boundary lies about 7° from the epicentre, and that 75 per cent. was distributed over a surface which does not extend to 18° from the epicentre." Finally as regards the direction of the impulse emerging at great distances it will suffice to point out that at an epicentral distance of 120° the emergence angle is 71° . Hence only about one-third of the amplitude of the P disturbance is horizontal.

All these causes necessarily led to great uncertainty in the appearance of the P tremor. There was a better chance for the S tremor to make its appearance; for in the first place it is generally more conspicuous than the P tremor, and then at a distance, say of 120° , the horizontal component of the displacement, which is transverse to the direction of propagation of the wave, is 0.95 of the whole displacement.

It was hoped that as time went on the improvement in the sensitiveness and accuracy of the seismometer would surmount these various difficulties in obtaining satisfactory far-off records. This, however, does not seem to be the case. In the British Association Report for 1916 Turner writes as follows:—"At distances from the epicentre greater than 110°

the times recorded for the arrival of P and S are such as cannot be reconciled with adopted tables by any reasonable extrapolation, and to explain the anomalies various hypotheses of discontinuity in the interior of the earth have been suggested. It is believed that these are unnecessary, and that the hypothesis outlined below will fit the facts. It calls for a modification of existing tables between the origin and 40° distance; and until it is disposed of in one way or the other, the improvement of these adopted tables cannot be satisfactorily undertaken."

Led by these considerations Professor Turner has done great service in gathering together all available material in a form convenient for statistical investigation. The Shide Bulletins are now issued in such a form that the records from the various stations for each single earthquake are grouped together. At present, unfortunately, the Central European stations supply no records. This, however, is not such a serious matter, since they form a cluster generally having much the same azimuth and the same average distance from epicentres. It is a curious fact that the well-equipped European stations are in the vast majority of cases about a quadrant distant from the usual run of earthquake origins. What we wish now are more numerous and more consistent and accurate records from stations with epicentral distances of 120° and greater. There is still extraordinary uncertainty in diagnosing the advent of the P and S tremors in these far distant seismograms. The most recent data from the highly perfected seismometers of the present day have not simplified the interpretation. What appears as the first disturbance in the trace as recorded at these distant stations is probably a later phenomenon than the true P . It cannot always be identified with P_2 , which according to the theory of the reflexion of elastic waves should be specially prominent for arcs greater than 100° .

In attempting to identify the observed phenomenon with P_2 or P_3 , Turner finds discrepancies which seem too large to be errors of observation. He has, therefore, speculated on the existence of a new phenomenon which he distinguishes as PX ; and in the British Association Report for 1916 has developed an ingenious explanation of this phenomenon. He regards it meanwhile as a purely tentative effort; and we shall do well to await further investigations into this problem.

It is of the utmost importance to obtain the time transits of the various types of disturbance as accurately as possible, for these are the data from which we deduce the manner in which the seismic radiations pass through the body of the earth. In 1907, basing on a certain hypothesis as to the change of velocity of the compressional and distortional wave with depth below the earth's surface, I showed how the times of transit as observed at the surface could be explained.¹ Wiechert and Zöppritz about the same time solved the same problem on different assumptions, and their investigations are among the most valuable contributions that have been made to the theory of seismic radiations. Following up this line of investigation there appeared in the *Göttingen*

¹ See "Seismic Radiations," *Proc. R. S. E.*, 1907-8; also *Physics of Earthquake Phenomena*, p. 248.

Nachrichten in 1912¹ a paper by "Zöppritz, Geiger and Gutenberg," forming No. v. of the series on "Erdbebenwellen," and specially dealing with the constitution of the earth's interior as deduced from the relation of the surface displacements associated with the longitudinal wave *P* and the once reflected wave *P*₂, with several other observations on earthquake waves. This paper is essentially the work of Zöppritz, whose early death at the age of twenty-seven robbed the scientific world of an investigator of great promise. The paper is partly edited by Wiechert, the mathematical notes left incomplete by Zöppritz being worked up into final form and applied to the data of observation by Geiger and Gutenberg.

In this paper Zöppritz, beginning from certain assumptions as to the law of change of velocity with depth, shows how closely the conclusions based on these assumptions agree with the data of observation of the times of transit of the *P* waves. The final results point to the existence within the earth of three surfaces of discontinuity at which the velocities of the seismic waves do not change continuously. This method, however, of assuming the law of change of velocity with depth and then making it fit the observed values of the times of transit of the *P* and *S* waves to points on the earth's surface is not convincing, although it is the only method which so far has been adopted. Recently I have discovered a method of directly calculating from the observations, without any assumptions whatsoever, all the properties of the seismic radiations through the earth. It is a laborious process, and should be used only when we have the best possible data to hand. Unfortunately, on account of the uncertain values of the times of transit to epicentral distances greater than 110°, it is not possible to calculate the velocities of the seismic waves to a depth greater than half the value of the earth's radius. For example, the path by which the *P* radiation passes from the epicentre to an epicentral distance of 100° is a curve concave outwards whose vertex is distant from the earth's centre by 0·55 of the earth's radius. The velocity of the *P* waves at this depth is 12·8 kilom. or 8·48 miles per second; and the most obvious conclusion is that the same velocity holds for all regions nearer the earth's centre. The velocity of the *S* waves is 6·84 kilom. or 4·53 miles per second at the same and greater depths. The ratio of these velocities is 1·87.

If *k* is the incompressibility and *n* the rigidity of the earth's substance at these depths,² then the well-known theory of the propagation of elastic waves gives

$$\frac{k + \frac{1}{3}n}{n} = (1.87)^2 = 3.5 \text{ or } k = 2.17 n.$$

Poisson's ratio has therefore the value 0·3.

Errata.—"TRAVEL MEMORIES."—On p. 339 of the last issue the lettering of the illustration should read "Orange Garden at Kazerun with Bagh-i-Nazar to right seen from the Telegraph House," and not as printed. Further, on pp. 342, 347 and 348 Dr. Odling's name was by mistake given as Oddling.

¹ "Ueber Erdbebenwellen," *Nachrichten* von der Kön. Ges. d. Wissenschaften zu Göttingen, 1907.

² See *Physics of Earthquake Phenomena*, p. 251; also *Phil. Mag.*, 1889, p. 67.