On the Propagation of Earthquake Motion to Great Distances

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Phil. Trans. R. Soc. Lond. A 1900 **194**, 135-174
doi: 10.1098/rsta.1900.0015

III. *On the Propagation of Earthquake Motion to Great Distances.*

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Communicated by Sir ROBERT S. BALL, *F.R.S.*

Received June 16,—Read November 16, 1899.

§ 1. THE earliest suggestion of the existence of more than one kind of wave motion in an earthquake appears to have been made in 1849 by Wertheim.* After discussing on theoretical grounds the ratio between the rates of propagation of distortional and condensational waves in an infinite solid, he proceeds to say that the only possible experimental verification would be by the use of a very large body, such as the Earth itself. It would hardly be possible to produce, artificially, a disturbance which would be propagated and be sensible at a great distance from the origin, but such disturbances are produced naturally in earthquakes, and he finds in the descriptions of great earthquakes indications of two distinct types of disturbance, which succeed each other in point of time, and which he attributes to the two forms of elastic wave motion.

Suggestive as it is, this memoir seems for long to have been devoid of influence on seismological research. It would not be materially incorrect to say that ROBERT MALLET's classic works were based on the hypothesis that earthquake motion was solely that of a condensational wave.

In 1885, Lord RAYLEIGH published his investigation† of elastic surface waves, that is to say, superficial waves analogous to deep-water waves, but owing their propagation to the elasticity of the substance in which they are propagated instead of to gravity. The concluding passage of this paper suggests that "it is not improbable that the surface waves here investigated play an important part in earthquakes, and in the collision of elastic solids. Diverging in two dimensions only, they must acquire at a great distance from the source a continually increasing preponderance."

In the year 1888, a paper‡ by Professor C. G. KNOTT was published, in which he

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* G. WERTHEIM, "Mémoire sur la Propagation du Mouvement dans les Corps solides et liquides" 'Comptes Rendus,' vol. 29, 1849, pp. 697–700; 'Ann. Chim. Phys.,' 3rd ser., vol. 21, 1851, pp. 19–36).

† "On Waves propagated along the Plane Surface of an Elastic Solid" ('Proc. Lond. Math. Soc.,' vol. 17, 1885, pp. 4–11).

‡ "Earthquakes and Earthquake Sounds as Illustrations of the General Theory of Elastic Vibrations" ('Trans. Seismol. Soc. Japan,' vol. 12, 1888, pp. 115–136).

29.3.1900

shows that no separation of the condensational and distortional waves is to be expected in the records of seismographs. Wave motion of either kind, on passage from one medium to another, is split up into refracted and reflected waves, while each of these is again split up into condensational and distortional waves. The result of this is that, even if earthquake motion were purely condensational or distortional at first, it would soon become converted, in its passage through the heterogeneous materials of the earth's crust, into an extremely complex disturbance, analogous to that registered by seismographs.

He also refers to Lord RAYLEIGH'S paper, but considers that the comparatively large vertical and small horizontal displacements required by the theory are not in accordance with the records of seismographs. Professor MILNE has, however, lately suggested* that the records of the seismographs may be misleading, and the large horizontal displacements registered by them be due to tilting of the instruments, and not to the inertia of the supposed steady points.

Another suggestion in the paper is that the principal disturbance in an earthquake is not purely elastic, but quasi-elastic, and that what are known as the preliminary tremors are truly elastic vibrations, set up by and outracing these.

The same volume of 'Transactions' contains a paper by Professor MILNE,† in which he suggests that the effect of compressional waves propagated direct from the origin to the surface is confined to the neighbourhood of the epicentre, and that beyond this the earthquake motion felt and recorded is due to surface waves, set up at the outcrop of the waves of compression near the origin, and thence propagated outwards.

In 1894, Wertheim's memoir appears for the first time to have influenced seismological research, when it was recalled to notice by Dr. A. CANCANI,‡ who considered that in the records of earthquakes near, and at a distance from, their origin, he could trace the separation of the condensational and distortional waves, having rates of propagation of about 5 and 2·5 kiloms. per second respectively. In his earlier paper he considered that it was only the latter which preserved sufficient energy to make them recognisable, by instrumental aid, at a distance from the origin, while the condensational waves were only recognisable in its vicinity. It is clear, however, from his paper, and from two others subsequently written§ in defence of the ideas promulgated in it, that the disturbance which he attributes to the distortional waves is the phase of great surface undulations, travelling like the waves of the sea, which

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* 'Seismology,' 8vo., London, 1898, p. 117.

† J. MILNE, "On certain Seismic Problems demanding Solution" ('Trans. Seismol. Soc. Japan,' vol. 12, 1888, pp. 107–113).

‡ "Sulle ondulazioni provenienti dei centri sismici lontani" ('Ann. Ufficio Cent. Met. e Geodyn. Italiano,' 2nd series, vol. 15, 1894, Part 1, pp. 13–24).

§ "Intorno ad alcune obbiezioni relative alla velocità di propagazione delle onde sismiche" ('Atti, R., Acc. Lincei,' vol. 3, 1894, Part 2, pp. 30–32); "Osservazioni e risultati recenti sulla forma e sul modo di propagarsi delle ondulazioni sismiche" ('Bol. Soc. Sismol. Ital.,' vol. 2, 1896, Part I., pp. 125–137).

do not appear to be due to distortional waves of the character contemplated by the theory of wave motion in an infinite solid, but rather to be analogous to the elastic surface waves investigated by Lord RAYLEIGH.

The views of Dr. CANCANI have been opposed by Dr. AGAMENNONE, who, in a series of papers devoted to the investigation of the observed rate of propagation of earthquakes, has shown that there is no indication of the velocities grouping themselves round the values 5 and 2·5 kiloms. per second deduced by Dr. CANCANI, but that, on the other hand, the observed values exhibit a great diversity, and not infrequently rise to double of the greater of the two assumed values.

Dr. CANCANI's views have, however, been accepted by other seismologists, notably by Professor GRABLOWITZ, who has, without any marked success, attempted to apply them to the determination of the place of origin of distant earthquakes observed at Ischia. The idea that the surface undulations due to great earthquakes are of the nature of distortional, and the so-called "preliminary tremors" of condensational, waves, seems to have taken root, and in the two most recent papers dealing with the subject by Professor C. G. KNOTT* and Professor J. MILNE,† the former are distinctly treated as distortional waves travelling by a brachistochronic path through the earth.

When investigating the great Indian earthquake of 1897, I found that the numerous diagrams, for which I was indebted to the generosity of the Directors of the Italian Observatories, showed two distinct phases, or periods of disturbance, preceding the advent of the surface undulations of long period. The first of these was marked by the commencement of the disturbance, the second by a sudden increase, accompanied by a change in the period of the waves; these features were more or less distinctly exhibited by all the records, and when preparing my report I suggested‡ that they represented the arrival of the condensational and distortional waves respectively, which had travelled through the earth, while the surface undulations of long period had travelled round the surface of the earth; thus recognising the presence of the three known types of elastic wave motion.

In this report the suggestion had to remain as such. To have entered on an examination of the records of other earthquakes with a view to its confirmation would have been foreign to the task in hand, besides being rendered impossible by the necessity of completing the report, and it is the object of this paper to show that the records of other great earthquakes confirm the suggestion.

§ 2. The rate of propagation of earthquake waves is a subject which has for long attracted much attention and been the subject of many studies and experiments. I found, however, that none of these with which I have become acquainted could be directly used, and that it was necessary to go back to the original descriptions, and

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* "The New Seismology" ('Scottish Geog. Mag.,' vol. 15, 1899, pp. 1–12).

† "Earthquake Precursors" ('Nature,' vol. 59, 1899, pp. 414–416).

‡ "Mem. Geol. Surv. Ind.," vol. 29, 1899.

treat the matter anew. With the exception of some studies of the rate of propagation of earthquakes within the seismic area, the published calculations deal, almost without exception, with isolated observations, not infrequently with earthquakes whose place or time of origin are more or less uncertain, and seldom take any notice of more than the time of commencement of the record, and in some cases also of the maximum displacement.

The very laborious series of researches by Dr. AGAMENNONE I have been unable to make use of, owing to the method of calculation adopted by him. The time, accurately determined at some place away from the origin, is taken, and the distances from the origin of that place, and of the more distant places whence observations have been obtained, are calculated; thence the apparent surface velocity is obtained by dividing the difference of distance by the difference of time. This method would be perfectly legitimate if we were dealing with only one class of wave motion, propagated at a uniform rate round the surface of the earth; if, on the other hand, the wave motion is propagated along a brachistochronic path through the earth, it must necessarily lead to misleading results, owing to the difference between the true and apparent rates of propagation, a difference which varies with the distance from the origin.

The object of this study being to determine whether the three phases recognised in the records of the great earthquake of 1897 are a constant or an accidental feature, as well as to ascertain the forms of wave motion and wave-path represented by each phase, it is essential that the time intervals should be referred to the time of origin, and not of arrival of the shock at some place away from it. It is also necessary that these time intervals, as well as the distances from the place of origin, should be determined with a close degree of accuracy, as without this it would be impossible to decide whether an apparent resemblance in the records of different earthquakes was, or was not, due to the same cause in each case.

To ensure this accuracy, it is necessary to select the earthquakes dealt with. In the *first* place, it is essential that the disturbance should originate in a single effort of short duration. Fortunately all those which fulfil the other conditions fulfil this also, and none have had to be rejected on this score. *Secondly*, the time and place of origin must be tolerably accurately known. The limits of error adopted have been 1 minute of time and 1° of arc. In the case of all the earthquakes noticed below, these limits are not exceeded, and in several cases the limit of error from this cause is much less. *Thirdly*, I have excluded all cases where there were not a sufficient number of independent records to serve as a check on, and confirmation of, each other. *Fourthly*, as a separation of the condensational and distortional plane waves is not to be looked for in the heterogeneous materials near the surface of the earth, the records from places at distances of less than 20° of arc from the origin have not been taken into consideration.

In collecting the facts I have been almost exclusively indebted to the careful and detailed accounts of earthquakes, both sensible and insensible, recorded in Italy, which are regularly published through the enlightened liberality of the Italian Government. Detailed descriptions of the records of most of the more important seismographs established in Italy have been printed, at first in the *Bollettino* of the Central Meteorological Office in Rome, and afterwards in that of the Italian Seismological Society. From these I have extracted the times of (1) the commencement of the record, (2) of any marked sudden increase of movement, and (3) of any change in its character, so far as these are mentioned; the results, in the case of the seven earthquakes which satisfy the conditions laid down, are given below.

Details of the Data.

1. JAPAN, March 22, 1894.

This earthquake has been made the subject of a special study by the late E. VON REBEUR PASCHWITZ,[*] by whom the three-phase character of the record was recognised. The origin is placed by Professor MILNE as in about N. lat. 43°, E. long. 146°. The time was recorded at Tokio, by the Gray-Milne seismograph, at 10^{h} 27·8^{m},[†] and the distance from the epicentre being about 950 kiloms., the time at the epicentre, reckoning the rate of propagation as 3 kiloms. per second, would be 10^{h} 22·5^{m}. As the records are detailed in the paper referred to, it will be unnecessary to reproduce the descriptions, and they may be tabulated at once, the times being minutes after 10^{h}.

Locality.	1st phase.	2nd phase.	3rd phase.	
			Commencement.	Maximum.
Charkow . .	34·5	—	—	—
	35·7	—	—	—
Nicolaiew . .	35·2	—	62·0	—
Pavia	—	—	—	78·0
Siena	37·2	47·8	67·4	—
Rome	37·3	47·0	68·0	80·0
	37·8	—	—	—
Rocca di Papa .	37·0	48·0	68·0	79·5
	37·3	48·0	—	—

The times at Padua (40^{m}) Grenoble (39·7^{m}) and Mineo (42·5^{m}) appear to represent the maximum of the first phase, registered at Rome about 40^{m}, rather than the commencement. Besides this the Charkow and Nicolaiew pendula registered an earlier shock, presumably from the same centre, with an origin at 5^{h} 24^{m}. The times in minutes after 5^{h} are

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[*] 'Petermann's Mittheilungen,' 1895, pp. 14–21.

[†] All times are Greenwich Mean Time.

Locality.	1st phase.	2nd phase.	3rd phase.	
			Commencement.	Maximum.
Charkow . . .	—	48·6	—	—
	—	49·8	60·0	—
Nicolaiew . .	(41·0)	48·0	64·8	70·0

The time of commencement of the record at Nicolaiew is obviously late, and corresponds rather to the maximum than the commencement of the first phase.

Converting these times into intervals, and distinguishing the earlier shock as (1), the principal one as (2), we get

Arc degrees.	Locality.	1st phase.	2nd phase.	3rd phase.	
				Commencement.	Maximum.
68·7	Charkow . . (1) . .	—	24·6	—	—
		—	25·8	36·0	—
	(2) . .	12·0	—	—	—
		13·2	—	—	—
72·9	Nicolaiew . . (1) . .	—	24·0	40·8	46·0
	(2) . .	12·7	—	39·5	—
83·9	Pavia . . . (2) . .	—	—	—	55·5
84·6	Siena . . . (2) . .	14·7	25·3	44·9	—
85·4	Rome . . . (2) . .	14·8	24·5	45·5	57·5
		15·3	—	—	—
85·4	Rocca di Papa (2) . .	14·5	25·5	45·5	57·0
		14·8	25·5	—	—

2. ARGENTINE, October 27, 1894.

According to an account of this earthquake by A. F. NOGUÈS,* the zone of greatest intensity formed an ellipse whose major axis passed by Rioja, San Juan, and Mendoza, while the minor axis reached nearly to the foot of the Andes. The epicentre may be safely placed in S. lat. 28° 30′, W. long. 69° 0′, with an error of less than 1° of arc.

The time of origin is not so easy to determine. It was recorded in the observatory of Santiago de Chile at $4^h\ 7^m\ 40^s$ P.M. local mean time. I have not been able to obtain the exact meridian of this observatory, but it is, according to the best atlases, about 2^m east of Valparaiso, whose local time is $4^h\ 46{\cdot}5^m$ slow of Greenwich. Applying this correction the G.M.T. (civil) at Santiago becomes about $20^h\ 52^m$. The only other time observation of any value is that from Buenos Ayres, where it was recorded at $5^h\ 2^m$ local time, which is about $3^h\ 53{\cdot}5^m$ slow of Greenwich; the time at

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* 'Comptes Rendus,' vol. 120, 1895, pp. 167–170.

which the earthquake was experienced corresponded therefore to about 20^{h} $55{\cdot}5^{m}$ Greenwich time.

Allowing for a rate of propagation of 3 kiloms. per second, the earthquake would have taken about 2^{m} to reach Santiago, and 6^{m} to reach Buenos Ayres. Making these deductions, the time of origin becomes 20^{h} 50^{m} and 20^{h} $49{\cdot}5^{m}$ respectively. As greater value should be attached to the Santiago record, both because it was automatic and because of its greater proximity to the centre, we may take the time of origin as 20^{h} $50^{m} \pm 0{\cdot}5^{m}$.

The records abstracted below, except in the case of Tokio, are taken from the 'Bollettino d. Ufficio Centrale Met. e Geodyn.,' for October, 1894.

Pavia.—21^{h} 46^{m} 55^{s} commencement, 21^{h} 57^{m} 52^{s} end, on the Brassart seismograph.

Siena.—21^{h} 12^{m} commencement on the Vicentini microseismograph, slow undulations distinct at 21^{h} 52^{m}, which continue conspicuous till 22^{h} 8^{m}.

Rome.—21^{h} 7^{m} 35^{s} commencement on both components of the grande sismom. On the N.W.—S.E. component these reach a maximum of 3·5 millims. at 21^{h} 15^{m} 10^{s}; towards 21^{h} 40^{m} slow undulations begin on both components. Maximum at 21^{h} 55^{m} 40^{s}, end about 23^{h}. On the other seismograph the commencement is not till 21^{h} 40^{m}, maximum 21^{h} 55^{m} 40^{s}, end 22^{h} 14^{m} 15^{s}.

Ischia.—21^{h} 33^{m} commencement on the Brassart seismograph; 22^{h} 8^{m} maximum, end at 22^{h} 40^{m}.

Rocca di Papa.—21^{h} 49^{m} 35^{s} commencement, 22^{h} 10^{m} end, on the grande sismom.

Nicolaiew.—Commencement 21^{h} 12^{m} 6^{s}, a sudden increase at 22^{h} 17^{m} 6^{s}, curve disappears from 21^{h} 24^{m} 6^{s} to 21^{h} 32^{m} 6^{s}, fresh disappearance till 22^{h} 2^{m} 6^{s}, end 0^{h} 37^{m} 6^{s} of following day.

Charkow.—Commencement 21^{h} 8^{m} 36^{s}, the curve disappeared for an hour, end at 0^{h} 10^{m} 54^{s} of the following day.

Tokio.—In a letter by Dr. E. VON REBEUR PASCHWITZ to 'Nature' (vol. 52, p. 55, 1895), a letter from Professor MILNE is referred to, in which it is stated that the earthquake was recorded at Tokio by three instruments at 18^{h} 0^{m}, 18^{h} 5^{m}, 17^{h} 41^{m}, respectively. The times were measured from a time signal at about the previous noon, but the record of these was lost by fire. In the case of the first instrument the time signal was always impressed within about $\frac{1}{2}^{m}$ or 1^{m} of noon, consequently the error cannot exceed a few minutes. These times, recorded also in 'Brit. Assoc. Rep.,' 1895, p. 147, where the last is marked as evidently wrong, correspond to Greenwich mean times 21^{h} 0^{m}, 21^{h} 5^{m}, and 20^{h} 41^{m} respectively.

The times, given in minutes after 21^{h} Greenwich mean time, may be classified as follows :—

Locality.	1st phase.	2nd phase.	3rd phase.	
			Commencement.	Maximum.
Pavia	—	—	46·9	—
Siena	(12·0)	—	—	52·0
Rome	7·6	15·2	40·0	55·7
	—	—	40·0	55·7
Ischia	—	—	(33·0)	68·0
Rocca di Papa	—	—	49·6	—
Nicolaiew	(12·1)	17·1	—	—
Charkow	8·6	—	—	—
Tokio	(0·0)	—	—	—
	(5·0)	—	—	—

The times of commencement at Siena and Nicolaiew evidently correspond to the maximum rather than the commencement of the first phase as recorded at Rome. The sudden increase in the disturbance at Nicolaiew at $17 \cdot 1^{m}$ is attributed to the second phase. It is in tolerably, though not close, concordance with the time at Rome.

The times of commencement at Tokio are, in spite of the much greater distance from the origin, much earlier than the corresponding times at the European observatories, and the difference seems greater than can be attributed to instrumental errors. The commencement of the third phase at Ischia is so much in advance of the others that it is probably not strictly comparable with them, and refers to a somewhat different phase.

Converted into intervals these times become

Arc degrees.	Locality.	1st phase.	2nd phase.	3rd phase.	
				Commencement.	Maximum.
102·2	Pavia	—	—	56·9	—
102·7	Siena	—	—	—	62·0
102·8	Rome	17·8	25·2	50·0	65·7
		—	—	50·0	65·7
102·9	Rocca di Papa	—	—	59·6	—
103·0	Ischia	—	—	—	78·0
117·6	Nicolaiew	—	27·1	—	—
120·9	Charkow	18·6	—	—	—

3. JAPAN, June 15, 1895.

This earthquake has been discussed by Professor MILNE,[*] who puts the time and

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[*] 'Brit. Assoc. Rep.,' 1897, p. 157.

place of origin as 10^{h} 31^{m} on 15th June, at about 120 geographical miles east of Migako, or in about N. lat. 39° 30′, E. long. 144° 30′.

The following abstract of the records is taken from 'Boll. Soc. Sismol. Ital.,' vol. 2, Part II.

Padua.—Commencement of rapid vibrations at 10^{h} 46^{m} 57^{s}, which terminate at 11^{h} 4^{m} 27^{s}; at 11^{h} 17^{m} 17^{s} the first groups of slow undulations, period 40^{s}, commences; record ends at 12^{h} 58^{m} 1^{s}.

Rocca di Papa.— 10^{h} 56^{m} 18^{s} commencement of barely perceptible tremors on the N.—S. component of the grande sismom; at 11^{h} 20^{m} commencement of undulations of 18^{s} period, which reach a maximum of 11^{h} 23^{m} 15^{s}, and end at about 12^{h} 30^{m}. On the E.—W. component the tremors begin at 10^{h} 57^{m}, and the long waves at 11^{h} 17^{m} 48^{s}, maximum at 11^{h} 23^{m} 10^{s}, and end at 12^{h} 30^{m}.

Rome.—On the sismom. medio undulations began at 11^{h} 19^{m} 20^{s} and end about 11^{h} 32^{m} 30^{s}. The grande sismom. shows a commencement at 11^{h} 21^{m} 50^{s}, maximum 11^{h} 28^{m} 25^{s}, end 11^{h} 47^{m} 15^{s}, all on the N.E.—S.W. component. The other component shows a commencement at 11^{h} 19^{m} 55^{s}, maximum at 11^{h} 23^{m} 5^{s}, end at 11^{h} 49^{m} 20^{s}.

Ischia.—10^{h} 50^{m} 29^{s}, commencement of record on horizontal pendula (according to 'Brit. Assoc. Report,' 1897, p. 170, the time was 10^{h} 49^{m} 50^{s}) at 10^{h} 57^{m} 21^{s} the movement, which had been minute, became appreciable; at 11^{h} 6^{m} 10^{s} the period of the undulations increased, and the great undulations commenced at 11^{h} 22^{m}, end at 12^{h} 30^{m}.

Catania.—The account is very meagre, but in the 'Atti. Acc. Gioenia di Sci. Nat.,' ser. 4, vol. 10, the following details of the record are given. Commencement 10^{h} 47^{m} 12^{s}; commencement of waves of about 24^{s} period 11^{h} 9^{m}, maximum 11^{h} 29^{m} 15^{s}, end 14^{h} 2^{m}.

At *Shide* the horizontal pendulum is reported to have commenced its record at 10^{h} 30^{m}, and at Nicolaiew the maximum was at 10^{h} ('Brit. Assoc. Report,' 1897, pp. 149, 167), these times being in advance of the time of origin of the shock.

Classifying these, we get the following times in minutes after 10^{h} A.M.

	1st phase.	2nd phase.	3rd phase.	
			Commencement.	Maximum.
Padua	47·0	—	77·3	—
Rocca di Papa	—	56·3	80·0	83·0
"	—	57·0	77·8	83·2
Rome	—	—	79·3	—
"	—	—	81·8	88·4
"	—	—	79·9	83·1
Ischia	(49·8)	57·3	(66·2)	88·0
Catania	47·2	—	(69·0)	89·2

The time of commencement of the first phase at Ischia, 10^{h} $49{\cdot}8^{m}$, is evidently late and corresponds to the maximum rather than the commencement of the same phase at Padua and Catania, while the recorded times of commencement of the slow undulations at Ischia and Catania are so much in advance of these at the other stations that they must be regarded as due to an earlier phase, while the undulations were still too small to be generally registered.

There were two other shocks registered on the same day in Japan, and presumably originating from the same, or practically the same, centre. Making the same time allowance the times of origin would be 19^h 13·25^m and 22^h 58^m of 15th June. From the records published in the 'Boll. Soc. Sismol. Ital.,' vol. 2, Part II., the following details are extracted.

Shock of 19^h 13·2^m.

Padua.—19^h 28^m 41^s commencement of rapid oscillations, at 20^h 3^m 33^s the slow undulations commence, which end at 20^h 22^m 43^s.

Rocca di Papa.—Commencement 20^h 3^m, maximum 20^h 6^m, end 20^h 24^m on N.—S. component; on E.—W. commencement 20^h 4^m, maximum 20^h 6^m, end 20^h 17^m.

Rome.—The first distinct oscillations at 20^h 4^m 15^s on N.W.—S.E. component, maximum 20^h 6^m 55^s, end 20^h 22^m 30^s. On the other component the commencement was at 20^h 8^m 55^s, end 20^h 25^m 10^s.

Ischia.—19^h 38^m 47^s commencement on both the horizontal pendula; oscillations of a period of 22·6^s commenced at 20^h 3^m 7^s on E.—W. component and at 20^h 3^m 33^s on N.—S.; maximum at 20^h 6^m 47^s.

Summary of the above Times, in minutes, after 19^h.

Locality.	1st phase.	2nd phase.	3rd phase.	
			Commencement.	Minimum.
Padua	28·7	—	63·5	—
Rocca di Papa .	—	—	63·0	66·0
	—	—	64·0	66·0
Rome	—	—	64·2	66·9
	—	—	68·9	—
Ischia	—	38·8	63·1	66·8
	—	38·8	63·5	—

Shock of 22^h 58^m.

Padua.—23^h 13^m 27^s commencement of diagram, at 23^h 13^m 46^s the slow undulations began, which terminated at 24^h 0^m 24^s.

Rocca di Papa.—23^h 46^m commencement on N.—S. component, 23^h 49^m maximum, end 24^h. On E.—W. component the commencement was 23^h 48^m, maximum, 23^h 50^m 30^s, end about 24^h.

Ischia.—Commencement of disturbance on E.—W. component 23^h 23^m 23^s; the slow undulations commenced at 23h 49m 15s, and at 23h 49m 31s on the N.—S. The terminations of the diagrams were at 24h 13m 27s and 24h 17m 7s respectively.

Summary of the above Times, in minutes, after 23h.

Locality.	1st phase.	2nd phase.	3rd phase.	
			Commencement.	Maximum.
Padua . . .	13·5	—	49·8	—
Rocca di Papa .	—	—	46·0	49·0
	—	—	48·0	50·5
Ischia	—	23·4	49·2	—
	—	—	49·5	—

Combining these three groups of records, and distinguishing the shocks as (1), (2), (3), respectively, we get the following time intervals:—

Arc degrees.	Locality.	1st phase.	2nd phase.	3rd phase.	
				Commencement.	Maximum.
85·1	Padua . . (1) . .	16·0	—	46·3	—
	(2) . .	15·5	—	50·3	—
	(3) . .	15·5	—	57·8	—
87·7	Rocca di Papa (1) . .	—	25·3	49·0	52·0
	,, . .	—	26·0	46·8	52·2
	(2) . .	—	—	49·8	52·8
	,, . .	—	—	50·8	52·8
	(3) . .	—	—	48·0	57·0
	,, . .	—	—	50·0	52·5
87·7	Rome. . . (1) . .	—	—	48·3	—
	,, . .	—	—	50·8	57·4
	,, . .	—	—	48·9	52·1
	(2) . .	—	—	51·0	53·7
	,, . .	—	—	55·7	—
88·0	Ischia. . . (1) . .	—	26·3	—	57·0
	(2) . .	—	25·6	49·9	53·6
	,, . .	—	25·6	50·3	—
	(3) . .	—	25·4	51·2	—
	,, . .	—	—	51·5	—
90·9	Catania. . (1) . .	16·2	—	—	58·2

4. JAPAN, August 31, 1896.

According to Professor MILNE,* this earthquake had its epicentre in about N. lat. 39° 40′, E. long. 140° 50′. The time of origin was 5h 7m 9s P.M. Japan time or 8h 7m 9s Greenwich time. These data may be accepted as correct, so far as the

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* 'Brit. Assoc. Rep.,' 1897, p. 162.

geographical position of the epicentre is concerned, and the time error is probably under $0{\cdot}25^m$. The time may, therefore, be taken as $8^h\ 7^m$. The abstract of the records in Europe is taken from the 'Boll. Soc. Sismol. Ital.,' vol. 2, Part II., except in the case of the records from the Isle of Wight, which are abstracted from 'Brit. Assoc. Report,' 1896, p. 229.

Nicolaiew.—$8^h\ 7{\cdot}5^m$ commencement, $8^h\ 17^m$ sudden increase; $8^h\ 30^m$, width of trace 10 millim., $8^h\ 33^m$ disappearance of ditto, end at $11^h\ 7^m$.

Strassburg.—Commencement $8^h\ 17^m\ 50^s$, maximum $8^h\ 29^m\ 56^s$, end $11^h\ 38^m\ 2^s$ ('Nature,' vol. 55, p. 558).

Isle of Wight.—Commencement at Carisbrooke Castle $8^h\ 23^m\ 6^s$, exceedingly minute tremors; first decided tremors $8^h\ 31^m\ 46^s$ at Carisbrooke, $8^h\ 31^m\ 42^s$ at Shide; heavy motion commences $8^h\ 57^m\ 6^s$ and $56^m\ 49^s$ respectively, maximum, first at $9^h\ 4^m\ 26^s$, and absolute at $14^m\ 26^s$, both at Carisbrooke; end of disturbance $11^h\ 16^m\ 20^s$, and $10^h\ 59^m\ 36^s$.

Rocca di Papa.—Horizontal pendula; commencement $8^h\ 31^m$; these undulations had a period of 30^s and at 9^h the character of the record changed to undulations of 14^s, attaining their maximum at $9^h\ 4^m$; end of disturbance about 10^h.

Seismograph of 7^m. Commencement $8^h\ 55^m$, maximum $9^h\ 4^m$, end $9^h\ 6{\cdot}5^m$.

Seismograph of 15^m. E.—W. component: commencement $8^h\ 21^m$, disturbance becomes very distinct at $8^h\ 32^m\ 30^s$; $8^h\ 41^m$ commencement of waves of 30^s period, which change to 14^s period at $8^h\ 59^m\ 30^s$, maximum of these $9^h\ 4^m$, end at $10^h\ 16^m$; N.—S. component: first visible tremors $8^h\ 21^m$, which became distinct at $8^h\ 31{\cdot}5^m$; $8^h\ 40^m$ commencement of waves of 30^s period, which change to 14^s period at $8^h\ 58^m\ 30^s$, maximum $9^h\ 4^m$, end $10^h\ 0^m$.

Rome.—Sismom. grande, 16^m, 200 kilogs., N.E.—S.W. component: $8^h\ 21^m\ 15^s$ commencement, after a diminution a group of oscillations recommences at $8^h\ 31^m\ 10^s$, at $8^h\ 58^m\ 20^s$ the slow undulations commence, maximum, $9^h\ 4^m\ 15^s$, end $9^h\ 24^m\ 35^s$; N.W.—S.E. component: commencement not distinctly determinable, but becomes distinct at $8^h\ 24^m$. Somewhat considerable oscillations commence at $8^h\ 29^m\ 55^s$, with a maximum at $8^h\ 32^m\ 20^s$; the slow undulations commence at $8^h\ 58^m\ 40^s$, maximum $9^h\ 3^m\ 55^s$, end $9^h\ 25^m\ 50^s$.

Ischia.—Horizontal pendula; commencement of first phase $8^h\ 20^m\ 30^s$, of second phase $8^h\ 31^m\ 30^s$, of third phase of long undulations $8^h\ 49^m\ 41^s$, maximum $9^h\ 6^m$, end $10^h\ 21^m$.

Catania.—Commencement $8^h\ 25^m\ 24^s$; at $9^h\ 32^m\ 24^s$ commencement of another group of oscillations of greater amplitude; maximum of slow undulations about $9^h\ 4^m$; N.W.—S.E. component gives a much better record, commencement $8^h\ 21^m\ 48^s$; at $8^h\ 32^m\ 33^s$ a decided increase in the disturbance, which had dwindled; commencement of slow oscillation $8^h\ 44^m\ 51^s$, maximum about $9^h\ 3^m$.

Summarising the above abstracts we obtain the following times, in minutes after 8^h A.M.

Locality.	1st phase.	2nd phase.	3rd phase.	
			Commencement.	Maximum.
Nicolaiew . .	17·0	30·0	—	—
Strassburg . .	17·8	29·9	—	—
Shide	23·1	31·8	57·1	64·4
	—	31·7	56·8	—
Rocca di Papa .	—	31·0	60·0	64·0
	—	—	55·0	64·0
	21·0	32·5	59·5	64·0
	21·0	31·5	58·5	64·0
Rome	21·2	31·2	58·3	64·2
	—	29·9	58·7	63·9
Ischia	20·5	31·5	(49·7)	66·0
Catania . . .	—	32·4	—	64·0
	21·8	32·5	(44·8)	63·0

The commencement of the slow undulations on the great seismograph of the Rocca di Papa at 8^{h} 40^{m} obviously represents a different phase to that accepted on the other records as the commencement of the third phase. The same may be said of the times at Catania and Ischia.

The time of commencement of the disturbance at Nicolaiew, 8^{h} 7^{m}, being practically identical with the time of origin, cannot refer to any of the phases here being dealt with, if it is to be connected with this earthquake at all.

Converting the times into intervals we get the following result :—

Arc degrees.	Locality.	1st phase.	2nd phase.	3rd phase.	
				Commencement.	Maximum.
72·7	Nicolaiew	10·0	23·0	—	—
82·5	Strassburg	10·8	22·9	—	—
83·8	Shide	16·1	24·8	50·1	57·4
		—	24·7	49·8	—
85·9	Rocca di Papa . . .	—	24·0	53·0	57·0
		—	—	48·0	57·0
		14·0	25·5	52·5	57·0
		14·0	24·5	51·5	57·0
85·9	Rome	14·2	24·2	51·3	57·2
		—	22·9	51·7	56·9
86·2	Ischia	13·5	24·5	—	59·0
88·2	Catania	—	25·4	—	57·0
		14·8	25·5	—	56·0

5. INDIA, June 12, 1897.

The epicentre of this shock was an area of about 300 kiloms. long and about half as broad ; the centre of this area lay in about N. lat. 26°, E. long. 91°, which may be taken as the epicentre for the purpose of calculating distances. The time of origin was $11^h\ 5^m$ G.M.T., with a maximum error of not more than $0{\cdot}5^m$, and probably not more than half of this.

As the records have been discussed in my report on this earthquake ('Mem. Geol. Surv. Ind.,' vol. 29) it is not necessary to repeat the details here. The times are tabulated here on a slightly different principle to that adopted in the report, and some slight changes have been made where the times as finally determined and published in the 'Boll. Soc. Sismol. Ital.,' vol. 3, Part II., differ from those originally communicated to me. They are given in minutes after 11^h G.M.T.

Locality.	1st phase.	2nd phase.	3rd phase.	
			Commencement.	Maximum.
Potsdam . . .	(18·7)	—	—	—
Catania . . .	17·3	25·8	46·0	49·5
Ischia	17·2	25·8	45·0	47·50
	17·2	25·0	45·0	47·4
	18·0	—	45·0	—
	17·4	26·0	—	(57·3)
	16·8	26·5	46·5	47·6
Rocca di Papa .	17·5	25·3	43·1	47·0
	18·0	26·0	41·8	47·1
Rome	17·1	24·3	43·5	47·5
	17·3	25·3	43·1	47·0
Padua . . .	16·8	26·7	42·5	47·2
Siena . . .	17·0	26·0	46·0	48·0
Pavia	18·8	—	45·7	—
Strassburg . .	18·5	—	—	—
Grenoble . . .	(19·1)	—	—	—
Edinburgh . .	18·0	28·0	—	—

The times of the second and third phases at the Rocca di Papa and Padua are taken from copies of the original traces, they do not appear in the accounts as printed in the 'Boll. Soc. Sismol. Ital.,' vol. 3, Part II. The time at Siena is taken from the account and photograph of the trace sent to me from that observatory. In the 'Boll. Soc. Sismol. Ital.,' it is printed as $7^m\ 48^s$, probably a misprint; the time at Verona is there given as 8^m, also a probable clerical or printer's error.

The time of the maximum of the third phase on the N.—S. component of the three-pendulum instrument at Ischia, $57^h\ 3^m$, is much later than any of the others. This may be due to the direction of its sway; a maximum of 4·5 millims. is recorded at $48{\cdot}1^m$, but is exceeded by that of $57{\cdot}3^m$ which reached 8·4 millims. This record may be excluded from consideration.

The Grenoble and Potsdam records are so divergent from the others that they had best be excluded from consideration. They probably correspond more or less to the maximum of the first phase as registered on the Italian instruments.

The uncertainty of the response of light horizontal pendula with photographic registration to the early phases of the disturbance, as compared with the greater constancy of response on the part of the very heavy pendula used in Italy, is very marked in the case of this earthquake.

Converted into intervals these times become

Arc degrees.	Locality.	1st phase.	2nd phase.	3rd phase.	
				Commencement.	Maximum.
63·9	Catania	12·3	20·8	41·0	44·5
64·0	Ischia	12·2	20·8	40·0	42·5
		12·2	20·0	40·0	47·4
		13·0	—	40·0	—
		12·4	21·0	—	—
		11·8	21·5	41·5	42·6
64·0	Rocca di Papa . . .	12·5	20·3	38·1	42·0
		13·0	21·0	36·8	42·1
64·1	Rome	12·1	19·3	38·5	42·5
		12·3	20·3	38·1	42·0
64·5	Padua	11·8	21·7	37·5	42·5
65·3	Siena	12·0	21·0	41·0	43·0
66·4	Pavia	13·8	—	40·7	—
66·5	Strassburg	13·5	—	—	—
70·9	Edinburgh	13·0	23·0	—	—

6. JAPAN, August 5, 1897.

According to Professor MILNE the focus of this earthquake was practically the same as that of June 15, 1896. The time of origin is determined as 0^{h} $9{\cdot}4^{m}$.

The following times are taken from the detailed account in 'Boll. Soc. Sismol. Ital.,' vol. 4, Part II., except in the case of Shide, for which the authority is 'Brit. Assoc. Rep.,' 1898, p. 192.

Nicolaiew.—0^{h} 17^{m} commencement, 0^{h} 22^{m} increase of amplitude to 8 millims., 0^{h} 31^{m} trace disappears, 3^{h} 52^{m} end of disturbance.

Shide.—0^{h} 22^{m} 25^{s} commencement, preliminary tremors 30^{m}, duration over 3^{h}.

Padua.—0^{h} 24^{m} commencement, end towards 2^{h} 30^{m}.

Rome.—Grande sismom.; 0^{h} 23^{m} 55^{s} commencement on N.E.—S.W. component, a maximum at 0^{h} 28^{m} 25^{s}, after which the disturbance decreases; a sudden increase at 0^{h} 34^{m} 35^{s}, a second maximum at 0^{h} 35^{m} 10^{s}; slow undulations commence at 0^{h} 53^{m} 45^{s}, maximum 1^{h} 8^{m} 45^{s}, end 2^{h} 44^{m} 15^{s}. On the N.W.—S.E. component: 0^{h} 24^{m} 45^{s} commencement, a sudden increase at 0^{h} 34^{m} 55^{s}, slow undulations commence towards 0^{h} 59^{m} 45^{s}, maximum 1^{h} 8^{m} 25^{s}.

Sismom. sotter; N.E.—S.W. component: 0^{h} 24^{m} 20^{s} commencement, a maximum at 0^{h} 27^{m} 55^{s}, after which the disturbance nearly dies out, 0^{h} 59^{m} commencement of slow waves, maximum at 1^{h} 8^{m} 40^{s}, end at 2^{h} 28^{m} 30^{s}. On N.W.—S.E. component, the earlier stages of the disturbance are very ill marked, 0^h 59^m commencement of the slow undulations, maximum between 1^h 3^m 56^s and 1^h 8^m 12^s.

Rocca di Papa.—Hor. pendula ; E.—W : 0^h 24^m 52^s commencement, 0^h 35^m 20^s a maximum, 0^h 45^m another maximum ; 1^h 0^m commencement of a group of great undulations, maximum 1^h 6^m 40^s, end 2^h 15^m ; N.—S. : 0^h 34^m commencement, 1^h 0^m commencement of slow undulations, 1^h 8^m 10^s maximum.

Grande sismom. ; E.—W : 0^h 32^m 10^s commencement, 0^h 45^m 10^s commencement of undulations of 7^s period 1^h 8^m 40^s maximum, end about 2^h ; N.—S. : 0^h 32^m 40^s commencement, 0^h 45^m commencement of slow undulations of 7^s period, maximum 1^h 8^m 30^s, end 2^h 12^m.

Ischia.—Hor. pendula ; N.—S. : 0^h 24^m 33^s commencement, 0^h 35^m 14^s slower oscillations, 0^h 55^m 18^s commencement of very slow oscillations, 1^h 9^m 30^s maximum, 3^h 12^m end ; E.—W. : 0^h 24^m 49^s commencement, 0^h 33^m 20^s resumption, 0^h 35^m 22^s slower oscillations, 0^h 54^m 7^s commencement of very slow oscillations, 1^h 8^m 39^s maximum, 3^h 0^m end.

Catania.—N.E.—S.W. component ; 0^h 24^m 53^s commencement, 0^h 35^m 4^s increase of movement, 0^h 42^m 3^s commencement of slow undulations, 1^h 8^m 38^s maximum, 3^h 3^m 26^s end ; N.W.—S.E. : 0^h 24^m 35^s commencement, 0^h 53^m 49^s commencement of slow undulations, 1^h 11^m 5^s maximum, 3^h 5^m $2·8^s$ end.

Tabulating as before we obtain the following times, in minutes after 0^h, for the different phases of the disturbance :—

Locality.	1st phase.	2nd phase.	3rd phase.	
			Commencement.	Maximum.
Nicolaiew . .	22·0	31·0	—	—
Shide	22·6	—	—	—
Padua . . .	24·0	—	—	—
Rome	23·9	34·6	53·7	68·7
	24·7	34·9	59·7	68·4
	24·3	—	59·0	68·7
	—	—	59·0	65·0
Rocca di Papa .	24·9	(35·3)	60·0	66·7
	—	34·0	60·0	68·2
	—	32·2	(45·2)	68·7
	—	32·7	(45·0)	68·5
Ischia	24·5	(35·2)	55·3	69·5
	24·8	33·3	54·1	68·6
Catania . .	24·9	35·1	(42·0)	68·6
	24·6	—	53·8	71·1

This is a singularly complete record, almost as much so as that of the great earthquake of June 12, 1897, and is besides remarkable for the very well defined maximum of the great undulations. The time of commencement of the disturbance at Nicolaiew, $0^h\ 17^m$, if due to this earthquake appears to indicate a different phase of the disturbance from that here characterised as the first phase. The times for the second phase at Rocca di Papa (35·3) and at Ischia (35·2) are shown by the detailed description to refer rather to the maximum of this phase than to the commencement as registered on other instruments. The "maximum" at the Rocca di Papa at 45^m, the commencement of undulations of 7^s period at $45{\cdot}2^m$, and the commencement of the slow undulations of Catania (42^m) all appear to refer to an earlier movement of this phase than the other records.

Converted into time intervals, these times become

Arc degrees.	Locality.	1st phase.	2nd phase.	3rd phase.	
				Commencement.	Maximum.
74·2	Nicolaiew	12·6	21·6	—	—
85·0	Shide	13·2	—	—	—
85·1	Padua.	14·6	—	—	—
87·7	Rome	14·5	25·2	44·3	59·3
		15·3	25·5	50·3	59·0
		14·9	—	49·6	59·3
		—	—	49·6	55·6
87·7	Rocca di Papa . . .	15·5	—	50·6	57·3
		—	24·6	50·6	58·8
		—	22·8	—	59·3
		—	23·3	—	59·1
88·0	Ischia	15·1	—	45·9	60·1
		15·4	23·9	44·7	59·2
70·9	Catania	15·5	25·7	—	59·2
		15·2	—	44·4	61·7

7. TURKESTAN, September 17, 1897.

On August 15, 1897, an earthquake was felt in Turkestan, and two others of greater severity on September 17. These have been made the subject of a special study by Dr. AGAMENNONE.* In this the epicentre is supposed to have been the same for all three. As the first is not recorded from any other place except Tashkent, this must be regarded as uncertain, and the records will not be taken into consideration. The other two were felt at a number of places, with greatest severity at Jisak and Ura Tube, where the earthquake reached 8 degrees of the Rossi-Forel scale, while the most distant was Kasalinsk, some 800 kiloms. from Jisak.

The epicentre is taken by Dr. AGAMENNONE as being on the northern slope of the mountains south of Ura Tube and Jisak, and the great extent of country over which the earthquakes, which only reached 8 degrees of the Rossi-Forel scale at their epicentre, were felt, is attributed to the depth of the focus from the surface. It seems more reasonable to suppose that the epicentre lay in the western Tian Shan

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* 'Bol. Soc. Sismol. Ital.,' vol. 4, Part I., 1898, pp. 120–123.

Mountains to the southwards of Jisak and Ura Tube, in a region from which information is unattainable. It may be taken as in about 39° N. Lat. and 68° E. Long.; this will certainly be nearer the truth than assuming the position of Jisak as that of the epicentre, and may be taken as correct within a limit of error of 1° of arc.

For the time we have only the observations at Tashkent. According to the director of the observatory there, as quoted by Dr. AGAMENNONE, the times at Tashkent were $8^h\ 7^m\ 30^s$ P.M. and $10^h\ 15^m\ 22^s$ P.M. respectively. As the distance from the epicentre is about 320 kiloms., the time of origin of the shock would be about 2^m before its arrival at Tashkent, taking the rate of propagation as 3 kiloms. per second. This would give the G.M.T. times of origin as $15^h\ 28^m$ and $17^h\ 36^m$ respectively, times which may be taken as correct within one minute of error.

1*st Shock of* $15^h\ 28^m$.

Nicolaiew.—$15^h\ 40^m$ commencement, maximum at $15^h\ 45^m$, end at $16^h\ 24^m$.

Potsdam.—$15^h\ 44^m$ commencement, at 47^m a slight increase, at 50^m, another sudden increase and the trace disappears shortly after; end about 17^h.

Ischia.—The horizontal pendula were disturbed as early as $15^h\ 15^m\ 12^s$, but this was evidently the same disturbance as affected the instrument at Catania. The first decided increase was at $15^h\ 42^m\ 33^s$ on the N.—S., and $42^m\ 36^s$ on the E.—W. component, they decrease after 3 minutes, and at $15^h\ 50^m$ the oscillations are irregular, but grow more regular and longer, reaching a maximum at about 16^h. It is not possible to make out from the description, whether there was a defined maximum, but probably not. End at $16^h\ 35^m$.

Catania.—The disturbance commenced at $15^h\ 15^m\ 50^s$ on the N.W.—S.E. component, and at $15^m\ 15^s$ on the N.E.—S.W.; this is some 13 minutes before the time of origin of the shock, and this disturbance must be attributed either to some other earthquake, or to tremors of a character which were not felt within the seismic area. In either case they cannot be referred to any of the three phases under discussion.

At $15^h\ 42^m\ 53^s$ on the N.W.—S.E., and at $42^m\ 47^s$ on the other component the disturbance becomes well marked. No definite phases are referred to but the maximum departure from normal was attained at $16^h\ 0^m\ 50^s$ on the N.W.—S.E., and at $16^h\ 1^m\ 0^s$ on the N.E.—S.W. component. End at $16^h\ 14^m\ 7^s$ on N.W.—S.E., and at $16^h\ 13^m\ 27^s$ on N.E.—S.W. component.

Rocca di Papa.—Grande sismom.; commencement of disturbance at $15^h\ 50^m$ on E.—W., 52^m on N.—S. component. The horizontal pendulum commenced at $15^h\ 50^m$ on the N.—S. component. Maximum from $15^h\ 55^m$ to 58^m, end at $16^h\ 5^m$. The record of the other component shows nothing.

Rome.—The sismom. medio. showed at $15^h\ 38^m\ 30^s$ some minute undulations and nothing more till $47^m\ 30^s$. A small isolated group appears later with a maximum at $16^h\ 2^m\ 10^s$.

Edinburgh.—Slight disturbance of the bifilar pendulum from 15^{h} 55^{m} to 16^{h} 5^{m}.

Shide.—15^{h} 59^{m} 58^{s} commencement of disturbance lasting 40 minutes. Preliminary tremors 8 minutes.

These times are tabulated below, being given in minutes after 15^{h}.

Locality.	1st phase.	2nd phase.	3rd phase.	
			Commencement.	Maximum.
Nicolaiew . .	—	40·0	45·0	—
Potsdam . . .	—	44·0	50·0	—
Ischia	—	42·5	—	60·0
	—	42·6	—	60·0
Catania . . .	—	42·9	—	60·8
	—	42·8	—	61·0
Rocca di Papa .	—	—	50·0	—
	—	—	52·0	—
	—	—	50·0	58·0
Rome	38·5	—	—	62·2
Edinburgh . .	—	—	55·0	—
Shide	—	—	60·0	68·0

The increase in the displacement of the horizontal pendulum at Potsdam, 47^{m}, does not seem attributable to any of the three phases under consideration.

2nd Shock of 17^{h} 36^{m}.

Nicolaiew.—18^{h} $2·5^{m}$ commencement of disturbance, end at 18^{h} 57^{m}.

Potsdam.—17^{h} $51·5^{m}$ commencement; at $55·5^{m}$ there is a sudden increase of amplitude, and the trace becomes lost shortly afterwards. End at $19\frac{1}{2}^{h}$.

Ischia.—The horizontal pendula were disturbed at 17^{h} 36^{m} 58^{s}, or practically simultaneously with the origin of the shock. As in the case of the previous earthquake, and for the same reasons, this disturbance may be neglected. At 44^{m} 35^{s} on the N.—S. pendulum there was a slight increase, and at 46^{m} 10^{s} on the other a group of eight oscillations of $3·4^{s}$ period. At 50^{m} 40^{s} the disturbance of the N.—S. pendulum was more noticeable, afterwards diminishing, and at 51^{m} on the other is a group of undulations of 6^{s} period. At 54^{m} on the one and 54^{m} 30^{s} on the other the oscillation was more noticeable and slow. At 18^{h} 0^{m} it was very slow, but irregular, reaching its maximum at 18^{h} 5^{m}, and ceasing at 18^{h} 51^{m}.

Catania.—Commencement about 17^{h} 46^{m} 18^{s} of very minute undulations; from 17^{h} 51^{m} 55^{s} to 52^{m} 37^{s} a group of seven very regular undulations of 6^{s} period end at 19^{h} 11^{m} 1^{s}. On the other (N.E.—S.W.) component the time of commencement is the same; the end is at 18^{h} 0^{m} 48^{s}.

Rocca di Papa.—Grande sismom. Commencement of slight oscillations at 17^{h} 48^{m}, which have an easily distinguished maximum at 18^{h} 6^{m}, and end at 19^{h} 17^{m}. The horizontal pendula commenced to oscillate at 17^h 58^m; no marked maximum; end 18^h 10^m.

Rome.—Sismom. sotter. At 17^h 45^m 50^s ± 5^s the seismograph was disturbed; the disturbance decreased, but became once more recognisable at 52^m.

Edinburgh.—18^h 2^m to 18^h 12^m slight disturbance on bifilar pendulum.

Shide.—17^h 59^m 58^s commencement of disturbance, lasting 38^m. Preliminary tremors lasted 8^m.

Summarising these times we get the following, the times being tabulated in minutes after 17^h:—

Locality.	1st phase.	2nd phase.	3rd phase.	
			Commencement.	Maximum.
Nicolaiew . .	—	—	(62·5)	—
Potsdam . . .	—	51·5	—	—
Ischia, N—S .	(44·6)	50·7	60·0	65·0
E—W .	46·2	51·0	—	—
Catania . . .	46·3	51·9	—	—
Rocca di Papa .	—	—	—	66·0
	—	—	58·0	—
Rome	45·8	52·0	—	—
Edinburgh . .	—	—	62·0	—
Shide	—	—	60·0	68·0

The maximum at Shide is put at 8^m after the commencement, the recorded duration of the preliminary tremors.

The time of commencement of slight oscillations on the grande sismometrografo at the Rocca di Papa is not included, as it falls intermediate between the times of the first and second phases, and cannot be recognised as a distinct phase on any other instrument.

The time of commencement at Nicolaiew, as compared with other places, is decidedly late. The instrument does not appear to have commenced to work till a phase more closely corresponding to the maximum, than the commencement of the long period waves.

Besides the phases included in the table, there seems to be another, corresponding to the increased disturbance at 17^h 54^m and 54^m 30^s at Ischia, and at 17^h 55·5^m at Potsdam.

With these exceptions the times of commencement or of sudden increase of the disturbance exhibit a very close concordance, the most serious divergence being the time of commencement on the N.—S. pendulum at Ischia. As this instrument showed tremors continuously from 17^h 36^m 58^s, and the time given is that of a feeble augmentation, it may well be somewhat in error owing to the difficulty of determining the exact time of this commencement. The better marked group of waves on the E.—W. pendulum record seem to afford a more trustworthy time, and the other will be discarded.

Distinguishing the two shocks as (1) and (2) respectively, we get the following table of time intervals in minutes :—

Arc degrees.	Locality.	1st phase.	2nd phase.	3rd phase.	
				Commencement.	Maximum.
27·5	Nicolaiew . (1) . .	—	12·0	17·0	—
39·9	Potsdam . (1) . .	—	16·0	22·0	—
	(2) . .	—	15·5	—	—
41·0	Ischia . . (1) . .	—	14·5	—	32·0
		—	14·6	—	32·0
	(2) . .	—	14·7	24·0	29·0
		10·2	15·0	—	—
42·4	Catania . . (1) . .	—	14·9	—	32·8
		—	14·8	—	33·0
	(2) . .	10·3	15·9	—	—
42·5	Rocca di Papa (1) . .	—	—	22·0	—
		—	—	24·0	—
		—	—	22·0	—
	(2) . .	—	—	—	30·0
		—	—	22·0	—
42·5	Rome . . (1) . .	10·5	—	—	34·2
	(2) . .	9·8	16·0	—	—
48·8	Edinburgh . (1) . .	—	—	27·0	—
	(2) . .	—	—	26·0	—
48·9	Shide . . (1) . .	—	—	32·0	40·0
	(2) . .	—	—	24·0	32·0

§ 3. From the details given above it will be seen that of the eleven shocks, grouped as seven earthquakes, which satisfied the conditions laid down, all gave threefold records similar to that of the Indian earthquake of 1897. This, however, would not of itself prove the correctness of the interpretation suggested in that case, nor even that the three phases referred in each case to the same form of wave motion. To do this it must be shown firstly that the intervals of time and space bear, in each case, such relation to each other as will show that the three phases recognised refer to the same forms of wave motion, and, secondly, that the forms of wave motion to which they refer are those to which they have been assumed to be due.

In carrying out this comparison it will be convenient to group and average the observations in the case of each earthquake, not only in the case of each station, but in each group of stations separated from the origin by approximately the same arc. The limit taken will be 5°, and the records from each group of stations lying within this limit will be averaged. An exception will, however, be made in the case of the instruments with photographic registration; these, in spite, or perhaps because, of their great sensitiveness to minute tilts, do not seem so well adapted for picking up and recording the wave motion represented by the first and second phases. To whatever cause this may be due, the records printed above show that, with regard to these phases, they do not respond with the same constancy or concordance as the heavy weighted pendula favoured in the Italian observatories.

Taking the records of the first phase motion, and separating the records of the heavy pendula with mechanical record from the light photographic pendula, we get the following results :—

First Phase ; heavy pendula.

Earthquake No.	Arc degrees.	No. of observations.	Interval. Minutes.	Rate. Kiloms. per second.	Locality.
7	42·1	4	10·2	7·6	Italy.
5	64·2	13	12·4	9·6	,,
1	85·2	5	14·8	10·6	,,
4	86·3	5	14·1	11·3	,,
3	86·5	4	15·8	10·1	,,
6	88·1	9	15·1	10·8	,,
3	90·9	1	16·2	10·4	Catania.
2	102·8	1	17·6	10·8	Rome.

Here there will be noticed a close accordance in the time intervals and the apparent rate of transmission, both of them increasing as the distance from the origin increases, but not in the same ratio. The only break of any significance in the regular increase is in the case of earthquake No. 4, and even this becomes unimportant when it is remembered that the uncertainty of the exact time and place of origin, combined with the shortness of the interval, may produce an error in the calculated rate of time amounting to nearly 1 kilom. per second.

The photographic records show a greater irregularity, but the general result is the same, as may be seen from the following tabular statement :—

First Phase ; light pendula.

Earthquake. No.	Are degrees.	No. of observations.	Intervals. Minutes.	Rate. Kiloms. per second.	Locality.
5	66·5	1	13·5	9·0	Strassburg.
1	70·1	2	12·6	10·3	Russia.
5	70·8	1	13·0	10·0	Edinburgh.
4	72·7	1	10·0	13·5	Nicolaiew.
6	74·2	1	12·6	10·9	,,
4	82·5	1	10·8	14·1	Strassburg.
4	83·8	1	16·1	9·6	Shide.
6	85·0	1	13·2	11·9	,,
2	120·9	1	18·6	12·0	Charkow.

Turning to the second phase, we see the same features repeated, and as the time intervals are longer, and consequently the effect of a small error less, there is a still more marked steadiness in the increase of apparent velocity with distance, as is shown in the following tabular statements :—

Second Phase ; heavy pendula.

Earthquake. No.	Arc degrees.	No. of observations.	Interval. Minutes.	Rate. Kiloms. per second.	Locality.
7	41·7	8	15·0	5·1	Italy.
5	64·2	11	20·7	5·7	,,
1	85·2	4	25·2	6·3	,,
4	86·5	8	24·6	6·5	,,
3	87·9	6	25·7	6·3	,,
6	88·2	7	24·4	6·7	,,
2	102·8	1	25·2	7·5	Rome.

Second Phase ; light pendula.

Earthquake. No.	Arc degrees.	No. of observations.	Interval. Minutes.	Rate. Kiloms. per second.	Locality.
7	27·5	1	12·0	4·2	Nicolaiew.
7	39·9	2	15·7	4·7	Potsdam.
1	70·1	3	24·8	5·2	Russia.
5	70·8	1	23·0	5·7	Edinburgh.
4	72·7	1	23·0	5·8	Nicolaiew.
6	74·2	1	21·6	6·4	,,
4	82·5	1	22·9	6·7	Strassburg.
4	83·8	2	24·7	6·3	Shide.
2	117·6	1	27·1	8·0	Nicolaiew.

Turning to the third phase and taking first the times at which the slow movement was recognised as commencing, we get a much less closely concordant series of times than in the case of the first or second phase. The interval being also longer, these divergences have but a small influence on the deduced rate of travel, nor do the extreme values depart much from the average value, except in the case of those records which have been rejected as too much in advance of the others to allow of their reference to the same phase.

The average of the observations works out as follows :—

Third Phase. Commencement.

Earthquake. No.	Arc degrees.	No. of observations.	Interval. Minutes.	Rate. Kiloms. per second.	Locality.
7	27·5	1	17·0	3·0	Nicolaiew.
7	41·8	6	22·7	3·4	Europe.
7	48·8	4	27·2	3·3	England.
5	64·3	12	39·8	3·0	Italy.
1	71·5	3	38·8	3·4	Russia.
4	83·8	2	50·0	3·1	Shide.
1	85·1	3	45·3	3·5	Italy.
4	85·4	8	51·0	3·1	,,
6	88·1	9	47·8	3·4	,,
2	102·6	4	54·1	3·5	,,

Here we get a result different from that obtained in the case of the first and second phases, in that the time intervals increase in practically the same ratio as the distances, and there is no indication of an increase of apparent velocity with the distance. The irregularity in the values of the rate of propagation is easily explicable by the difficulty of obtaining an accurate record of the commencement of this phase of motion. Whatever may be the manner of propagation of this form of wave motion, it seems to manifest itself in much the same manner as the ripples which radiate over the surface of a pond. There is a band of larger and distinctly visible ripples, and as these radiate they come to be preceded and followed by an ever widening belt of longer and flatter wavelets whose limits cannot be determined on account of the gradual manner of their decrease in height. In a similar manner the surface undulations which form the last phase of a distant earthquake commence as very long and flat waves, gradually increasing in height, and the exact moment at which these will begin to influence an instrument may be materially delayed or advanced by very slight differences in its sensitiveness.

This may be illustrated by taking the maximum and minimum values for the rate of travel given by the records averaged in the table given above. They are

Earthquake. No.	Mean arc.	Rate of travel. Kiloms. per second.	
		Maximum.	Minimum.
7	41·8	3·6	3·2
7	48·8	3·8	2·8
5	64·3	3·2	2·8
1	75·3	3·5	3·3
4	85·4	3·3	3·0
3	87·3	3·7	2·9
6	88·1	3·8	3·2
2	102·7	3·8	3·2

Here there are evidently very great divergences, which can only be attributed to differences in the sensitiveness of the instruments to this phase. There is no visible relation between distance and rate of travel, while the apparent rates vary from 3·2 to 3·8 kiloms. per second.* In view of these divergences it becomes a question whether some of the records rejected as giving times much too early should not be included, and for this reason they have been tabulated here.

Earthquake. No.	Arc degrees.	Interval. Minutes.	Rate. Kiloms. per second.	Locality.
7	39·9	19·0	3·9	Potsdam.
7	41·0	18·0	4·2	Ischia.
4	85·9	33·0	4·8	Rocca di Papa.
4	86·2	42·7	3·7	Ischia.
6	87·7	35·6	4·5	Roca di Papa.
3	88·0	35·2	4·6	Ischia.
4	88·2	37·8	4·3	Catania.
3	90·9	38·0	4·4	,,
6	90·9	32·6	5·1	,,
2	103·0	43·0	4·4	Ischia.

From this, if the data are accepted, it seems that the first waves of this phase may travel at rates that rise to near 5 kiloms. per second, though those which are ordinarily registered at the commencement of this phase have not a greater apparent rate of travel than about 3·5 kiloms. per second.†

If, instead of the very indeterminate commencement of this phase, we take the more easily determinable time of the maximum movement, we find, as shown in the table below, that greater uniformity of result which might be expected to follow from the fact that the recorded times are less influenced by variations in the sensitiveness of the different instruments.

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* The minimum values may be neglected, as they are evidently due to a tardiness in action of the instruments.

† The Sacramento earthquake of April 19, 1892, recorded at Strassburg, gives a rate of 3·8 kiloms. per second over an arc of 82·5°. The Venezuela shock of April 28, 1894, recorded in Russia, gives 3·5 and 4·0 kiloms. per second over arcs of 93·8° and 93·6° respectively. The earlier phases of these shocks were not recorded.

Third Phase; maximum.

Earthquake No.	Arc degrees.	No. of observations.	Interval. Minutes.	Rate. Kiloms. per second.	Locality.
7	41·8	7	31·8	2·4	Italy.
7	48·8	2	35·0	2·6	Shide.
5	64·2	10	43·1	2·8	Italy.
1	72·9	1	46·0	2·9	Nicolaiew.
1	84·9	3	56·7	2·8	Italy.
3	88·0	12	53·8	3·0	,,
6	88·3	12	59·0	2·8	,,
2	102·8	4	67·8	2·8	,,

Here, if we exclude the results of the Turkestan earthquake of 1897, there is a most striking concordance in the rates of transmission at all distances between 60 and 120 degrees of arc. The lesser velocity in the case of the smaller arc will be considered further on; here it will be enough to say that in itself this cannot be regarded as an indication of a progressive increase of apparent rate of propagation with distance, such as was observed in the case of the first and second phases.

§ 4. Before proceeding further with this investigation it will be necessary to hark back and consider some general principles involved.

Firstly, the rate of propagation may, as is well known, mean one of two things, either (1) the apparent rate of propagation as measured at the surface of the earth, or (2) the true rate of propagation as measured along the actual wave path. These velocities, whose distinction is well recognised and for which distinct symbols are always employed, must, however, be further subdivided, and for the present purpose the four following values recognised:—

v = the apparent rate of propagation at any given point on the surface. This is what is commonly meant by apparent rate of propagation.

v_a = the apparent average rate of propagation as between two points on the surface of the earth. The only average which appears to be of any value is that referred to the origin. It is this value which has been given in the tabular statements above as the rate.

V = the true rate of propagation at any given point of the wave path.

V_a = the true average rate of propagation, obtained by dividing the distance, measured along the wave path, by the time interval.

In the special case of waves propagated along the surface with a uniform velocity these four values are identical; if wave motion is propagated at a uniform speed and along rectilineal paths through the earth the values of V and V_a will be identical but different from v and v_a, which will also differ from each other. In any other case the four quantities must necessarily be different.

The earliest suggestion that the propagation of earthquake movement was along curved, and not straight, wave paths is contained in a paper by Dr. A. SCHMIDT,* of Stuttgart, in which he pointed out that the assumption, made by all previous investigators, of a constant rate of propagation and a rectilinear wave path, was an improbable one. The very different conditions of temperature and pressure in the interior of the earth cannot be without influence in modifying the elasticity and consequently the rate of propagation, and an investigation of the observed rates of propagation of certain earthquakes indicates that this modification results in an increase of the rate of propagation with the depth below the surface.

The problem has been investigated mathematically by M. P. RUDZKI,† for the case of a spherical body, such as the earth. He shows that the wave path which would be straight in the case of a homogeneous solid, or one in which the rate of transmission was constant for all distances from the centre, would be convex towards the centre if the velocity of transmission increased as the distance from the centre diminished, that is as the depth below the surface increased, and concave towards the centre if the opposite were the case. He then investigates the form of the wave paths on the assumption that the velocity of propagation is a constant function of the radial distance from the centre.

On this supposition he finds that the wave paths would form a series of curves intersecting at the focus, the upward path to the surface forming part of the same curve with the path of the wave motion which starts downwards from the focus in the opposite direction. Each of these curves is symmetrical on either side of a radius, drawn from the centre of the earth, which intersects the curve at the point where it approaches nearest to the centre of the earth, and where it is tangent to a circle drawn round this centre. A limiting condition is found where this radius passes through the focus; in this case the curves are symmetrical on either side of the focus, and the circle on which this group of curves intersects the surface of the sphere is taken as the limit between an inner and an outer area.

Turning from the wave paths and the variations in V, or the true velocity, he then deals with the variations of v, or the apparent velocity at the surface. This is infinite at the seismic vertical, and decreases outwards till the limit of the inner area is reached, where it has its minimum value. Passing from this inner area into the outer area, the value of v increases once more, and becomes infinite at the antipodes of the seismic vertical.

It is only the value of v which is investigated, but it is obvious that the value of V_a, or the apparent average velocity of transmission from the centre, must be subject to similar variations. It can never be infinite, but within the inner area it will

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* "Wellenbewegung und Erdbeben. Ein Beitrag zur Dynamik der Erdbeben." 'Jahresheft Ver. f. Vaterland. Naturk. in Württemberg,' vol. 44, 1888, pp. 248–270.

† "Ueber die scheinbare Geschwindigkeit der Verbreitung der Erdbeben" (German translation of paper in Polish, published by the Academy of Krakau). GERLAND'S Beiträge z. Geophysik,' vol. 3, 1888, pp. 485–518.

decrease, and within the outer area increase, as the distance from the epicentre increases.

The depth of the focus is always so small in comparison with the diameter, and the size of the inner area so small in comparison with the surface, of the earth, that they may be left out of consideration in a study of the propagation of earthquake motion to great distances. Consequently we should find, if the disturbance is transmitted through the earth, an increase in the apparent rate of transmission with an increase in distance from the origin. This apparent rate of increase will be proportionate to the ratio between arc and chord if the wave motion is propagated in straight lines, it will be less if the rate of propagation diminishes with the depth and the wave paths are concave towards the centre, and greater if they are convex, and the rate of propagation increases with the depth.

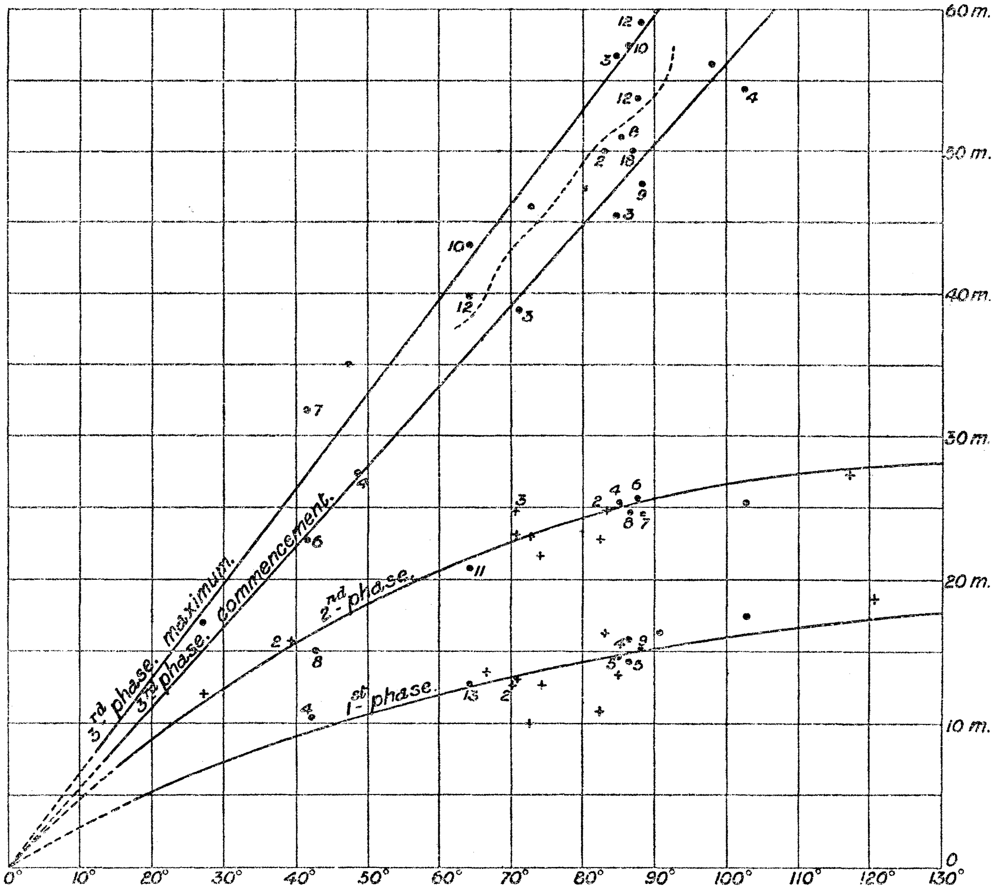
It must further be noticed that the regularity of increase of v and v_a with the distance from the origin only holds good if the increase of V is a constant function of the distance from the centre of the earth. This may reasonably be expected so long as there is no great change in the character of the medium traversed and the change in the elastic constants is principally due to the increase of temperature and pressure. It is, however, very probable that the central core of the earth is metallic, composed principally of native iron, surrounded by an outer shell of magma, which would be stony or glassy in a cooled and solidified form. If this be the case the wave on passing from the one to the other would enter a medium in which the change of elasticity due to temperature and pressure would be complicated by an initial difference in the elastic constants.

If, as is probable, there should be a sudden increase of V when the wave path enters the central core, it is possible that v might become infinite along a circle removed from the antipodes of the origin, and beyond that have a negative value. That is, it is conceivable that the disturbance might emerge at the antipodes before it reached the surface at some point nearer the origin. In any case a sudden change in the rate of increase would exhibit itself as an interruption of the regular curvature of the time curve, this being bent downwards if the change was an increase, upwards if it was a decrease, of the regular rate of increase of velocity with depth below the surface.

Turning to the application of these general principles to the recorded observations, this seems to be most conveniently effected in the graphic manner employed in the accompanying diagram. On this the recorded times of the first, second, and third phases have been plotted against their distances from the origin in degrees of arc, and smoothed curves drawn through them.

It may not be amiss to repeat here that in obtaining these times no selection was exercised. The times of commencement and of any marked change of amount or character of movement were taken from the published record, and the only subsequent selection made was the rejection, in those cases only which have been specially mentioned, of records of individual instruments which were markedly divergent from those of others whose times were in close concordance with each other. To have included these in the general average would not have led to greater, but to less, accuracy in the result.

As, moreover, the light horizontal pendula do not seem to respond with the same consistency to the motion of the first two phases, as the heavily weighted pendula used in Italy, their records have been distinguished on the plate, being indicated by a cross, while the records of the Italian instruments are plotted as circles. A small figure against either cross or dot means that it is the average of a corresponding number of not very divergent instrumental records; where no figure is entered only a single instrumental record is indicated.



Time curves of the three phases of earthquake motion recognisable in distant records.

In the case of the third phase there was no reason for distinguishing between the records of the two types of instruments, but by far the preponderating number of records have been obtained from the Italian instruments. Generally when a light pendulum with photographic record is affected by one of the first two phases, the movement of the pendulum is so great in the third phase that the swing of the spot of light passes the limit of photographic registration, and the record is lost. These remarks do not apply to Professor MILNE'S pattern of instrument, where the displacement of the pendulum is directly photographed without any reflection or magnification of the movement, but, as the time of maximum displacement is not to be found in the published accounts of the records of this instrument, it has not been possible, except in a few cases, to utilise the Shide records.

The two types of instrument differ not only in detail but in the object aimed at in their construction; HORACE DARWIN'S bifilar pendulum, as well as the horizontal pendula of REBEUR-PASCHWITZ, GERLAND and MILNE, were designed to register tilting, and are not primarily intended to respond, by their inertia, to a rapid movement of the ground in a horizontal direction. The heavily weighted pendula are, on the contrary, intended to respond to horizontal shakes, the heavy mass acting as a steady point. Professor GRABLOWITZ has shown,* from a comparison of the records of the instruments at Ischia, which are under his charge, that during the first phase the record is due mainly to inertia, and only to a small extent, if at all, to tilting, while in the latter stage the opposite takes place, and the record is principally due to tilting. The greater constancy of record of the heavy pendula in the case of the first phase, and the greater sensitiveness of the light pendula to the motion of the third phase are, consequently, in accordance with the objects specially aimed at in the construction of each type of instrument.

§ 5. Taking up the consideration of the records of the first two phases, it will be seen that, as plotted on the diagram on page 163, they all lie very close to two curved lines, starting from the origin and proceeding with a regularly decreasing curvature—at any rate to a distance from the origin of 90° of arc. In both cases the only serious divergence of a record from the curve is in a few cases of photographic records, and this is most marked in the case of the first phase. The concordance is so close that the curves drawn may be taken as, in the main, representing the true time curves† of these two phases.

From the construction of these curves they represent graphically the apparent velocity at any point, for this is directly proportional to the cotangent of the angle of inclination. The relation of the apparent velocity to distance is consequently exactly what is required on the assumption that the wave motion is transmitted through the earth, and a simple calculation shows that the increase is markedly greater than what would be due to rectilinear propagation. It follows, therefore, that for the wave motion represented by these two phases, the rate of propagation increases with the depth, and the wave paths are convex towards the centre of the earth.

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* 'Boll. Soc. Sismol. Ital.,' Part II, *passim*. Professor GRABLOWITZ only recognises two phases, corresponding to the first and third of this paper.

† Dr. A. SCHMIDT has proposed ('Jahresheft Ver. f. Vaterland. Naturk. in Württemberg,' vol. 44, 1888), to apply the term "hodograph" to these time curves, but as this term is already used in a very different sense, I think it best to abandon the word, and use the simple expression "time curve."

Having thus two forms of wave motion propagated through the earth, it is natural to regard them as condensational and distortional, and this inference is strengthened if we complete the curves and carry them on to the origin. They then give initial velocities of transmission of about 5 and 3 kiloms. per second respectively.

Little is known of the rate of transmission of elastic waves through rock. Direct experimental determinations, by measuring the rate of transmission of the disturbance set up by an explosion, give little assistance, as the velocities obtained are much less than should result from the elastic constants of the rock, a difference probably due to the weathered and fissured condition of all rocks near the surface. The only experiments of much value are those of Professor GRAY and MILNE,* who measured the elastic constants of certain rocks, and obtained results from which the following rates of transmission of condensational and distortional waves were deduced :—

	Condensational.	Distortional.	Ratio.
Granite	3·95	2·19	1·80
Marble	3·81	2·08	1·83
Slate	4·51	2·86	1·58
Mean	4·09	2·38	1·68

The original records of the experiments have been lost, and some doubts attach to the absolute correctness of the results,† but they are probably not seriously in error.

In Professor KNOTT's paper‡ the same experiments are referred to, but the elastic constants differ slightly from those published in the 'Quarterly Journal.' Combining them with the densities as given by Professor MILNE we get—

	Condensational.	Distortional.	Ratio.
Granite	4·2	2·3	1·8
Marble	4·0	2·2	1·7
Slate	4·7	3·0	1·4
Mean	4·3	2·5	1·7

From the above we may conclude that the rates of transmission of elastic waves through continuous rock such as is met with at a little distance from the surface,

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* 'Quart. Jour. Geol. Soc.,' vol. 39, 1883, p. 140.

† 'Seismol. Jour.,' Japan, vol. 3, 1894, p. 87.

‡ 'Trans. Seismol. Soc.,' Japan, vol. 12, 1888, p. 118.

in other words, the initial velocity of propagation in the case of an earthquake, is not far removed from 4·5 kiloms. per second in the case of condensational, and 2·6 kiloms. per second in the case of distortional waves.

These values are in close accord with the ones obtained from the curve given by distant observations, the difference being no greater than might easily be made to vanish by a slight manipulation of the extrapolated portion of the curve. We may consequently adopt the conclusion that the first phase represents the arrival of condensational, and the second that of distortional waves, which have travelled through the earth from the origin to the place of record.

§ 6. If the curves drawn on the diagram represent the true time curves, it should be possible to deduce from them the relation between the variation of velocity of transmission and depth below the surface. Until a larger number of observations have been collected, and it is certain that the true curve does not exhibit irregularities, not shown by the few records as yet available, it does not seem advisable to attempt this ; but a tentative investigation of the results obtained at a distance of 85°, where, owing to the number of observations available, the curves are fixed with great certainty, will not be unprofitable.

For a distance of 85°, or about 9,500 kiloms. from the origin, the time intervals are very close to 15^{m} and 25^{m} respectively. These intervals give apparent mean velocities of 10·5 kiloms. and 6·3 kiloms per second, and as the wave path is a curve convex towards the centre of the earth, these are probably nearer the true average velocities than the mean apparent velocities as measured along the chord, which are 9·5 kiloms. and 5·7 kiloms. per second respectively.

The maximum velocity is necessarily greater than the mean, and we shall probably be not far wrong in assuming that the maximum excess over the initial velocity is about double the mean excess. To be on the safe side the apparent mean velocities as measured along the chord may be taken ; here the mean excess is 5·0 kiloms. and 3·1 kiloms. per second respectively. Adding the doubles of these to the initial velocities of 4·5 and 2·6, we obtain a maximum velocity of 14·5 kiloms. per second for the condensational, and 8·8 kiloms. per second for the distortional waves respectively.

If we put V_i for the initial velocity, and V_m for the maximum, then

$$V_i/\sin a_i = V'/\sin a' = V''/\sin a'' = V_m/\sin a_m,$$

where a_i is the initial angle of incidence, or what may be called the plunging angle at which the particular ray or wave path leaves the focus, and a_m is the angle of refraction where the maximum velocity is attained. But a_m is necessarily 90°, the maximum velocity being attained where the wave path is tangent to a circle drawn round the centre of the earth. Hence

$$V_i/V_m = \sin a_i.$$

Applying this formula, we find that for the condensational wave a_i is 18° 10′, and for the distortional 17° 10′. Measuring these angles from the horizontal instead of the vertical, they become 71° 50′ and 72° 50′ respectively.

Assuming that the true wave path is an arc of a circle, it is easy to calculate the depth reached by the wave path. For a condensational wave it is close on 2,800 kiloms. The value in the case of the distortional wave is practically the same, though slightly higher.

From this it follows that the disturbances registered in Europe as the first and second phases of earthquakes which originate in Japan, are due to wave motion which, at the origin, has plunged downwards at an angle of about 72° with the horizon, and has penetrated to a depth of about 3,000 kiloms. from the surface, or to about 0·55 of the radius as measured from the centre.

As to approximate indication, the corresponding values for 30° and 60° may be given.

	30°.	60°.	85°.
Plunging angle	65°	69°	72°
Maximum velocity (kilom. per sec.) . . .	10·0	12·5	15·0
Maximum depth from surface (kilom.) . .	1000	2000	3000

These results do not pretend to accuracy, but at any rate they indicate the order of magnitude of the true figures, and indirectly point to the cause of the feebleness of the disturbance due to these waves at a distance from the origin. It will be seen that the waves which are spread over the whole surface of the earth, outside a circle of 30° radius round the origin, are those contained within a cone of 50° apical angle at the origin, that is to say, about $\frac{1}{20}$th of the total energy of the shock is distributed over $\frac{19}{20}$ths of the surface of the earth.

It will not be without interest to form some idea of the elastic constants at the depth reached by the waves of Japanese earthquakes on their path to Europe. Taking the velocities of 14·5 and 8·8 kiloms. per second, and an assumed density of 3·5, the wave modulus of elasticity is

$$m = 5{\cdot}86 \times 10^{12} \text{ for the condensational wave,}$$

$$n = 2{\cdot}16 \times 10^{12} \text{ for the distortional wave.}$$

Here n is the rigidity, and putting $m = k + \frac{3m}{4}$, where k is the bulk modulus, we get the result

$$k = 4{\cdot}24 \times 10^{12} = \text{bulk modulus.}$$

Comparing these values with those of granite, as given in Professor KNOTT's paper, we find that the rigidity is 15 times, and the bulk modulus nearly 12 times, greater than that of granite. If instead of a density of 3·5 we assume the more probable density of 7·0, these values would have to be further increased by about one-half, and would become 17 and 21·5 times the corresponding constants for granite.

According to RUDZKI,[*] if the wave paths are circular arcs, the function of the radial distance which represents the velocity of transmission takes the form

$$V = A - Br^2.$$

Taking the value of V to be 14·5 kiloms. per second at a distance of 0·55 of the radius, and equating this with the assumed initial velocity of 4·5 kilom. per second, we get

$$V = 18 \cdot 5 - 14r^2,$$

r being expressed as a fraction of the radius of the earth. For the distortional wave the formula becomes

$$V = 11 \cdot 5 - 9r^2.$$

These formulæ give results in very fair accordance with those deduced from the observations recorded, but cannot be accepted as more than empirical approximations. They indicate that the maximum velocity of transmission at the centre of the earth should be about 18·5 kiloms. per second for the condensational, and 11·5 kiloms. per second for the distortional wave, if there is no sudden change in the increase of the elastic constants below the depth of 3,000 kiloms. from the surface.

It is, however, by no means certain that a regular increase of the elastic constants to the centre of the earth is to be looked for; on the contrary, a sudden change is to be looked for where the wave path leaves the outer stony shell to enter the central metallic core which may reasonably be supposed to exist.

Though we have no direct knowledge of the constitution of the interior of the earth, we do know not only its average density, but also approximately the rate of increase of density from the surface to the centre. The estimates of this, made by LAPLACE and WALTERSHAUSEN, give values for 0·5 and 0·6 of the radius as follows:—

	0·5	0·6
Laplace	8·23	7·25
Waltershausen . .	7·85	7·08

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[*] GERLAND'S 'Beiträge z. Geophysik,' vol. 3, 1898, p. 518

As the density of iron is about 7·5, and as its density in the interior of the earth is, on the one hand, lessened by increased temperature, and, on the other, increased by pressure, we may take it that the central metallic core extends to about 0·55 of the radius from the centre, or to about the same depth as is reached by the wave paths which emerge at a distance of 90° of arc from the origin.

It will be interesting to see if observations which may be obtained hereafter at distances of more than 90° of arc from the origin bear this out; at present we have only the few observations of the Argentine earthquake of 1894. If the Tokio record of this can be accepted as representing the arrival of the condensational waves, there is a marked fall in the time curve between 90° and 155°, indicating an earlier emergence of the waves at the greater as compared with the lesser distance.

The European records of the same shock do not indicate a drop in the time curve; those of the first phase lie very close to the continuation of the curve for the condensational wave, but to bring the second phase near the continuation of this curve it has to be bent downwards into greater parallelism with the time curve of the first phase, thus indicating a change in the ratio of the elastic constants. The observations are, however, too few for any dependence to be placed upon them.

§ 7. The records of the third phase show no such variation of velocity with distance from the origin as was noticed in the case of the first and second phases. The velocities of propagation as deduced from the times of commencement show a good deal of variation among themselves, but there is no indication of an increase of apparent rate of propagation with distance.

I have already referred to the difficulty there is in determining with certainty the time of commencement of this phase of wave motion, and if we turn to the time of maximum of this phase, usually determinable with greater certainty, we find a close agreement in the rate of propagation at all distances, except in the case of the Turkestan earthquakes and the shortest arcs dealt with. These are slightly but distinctly less than those deduced from observations over longer arcs, but with this exception the observations point to the conclusion that the apparent rate of propagation is uniform at all distances from the origin.

This conclusion is not in concordance with the latest results published by Professor MILNE,* who has deduced as average rates of propagation of the large waves the following values:—

Distance from origin	20°	60°	80°	110°
Velocity of propagation, kiloms. per second . . .	2·1	2·8	2·9	3·3

These values if plotted do not fall into a smooth curve, but such as it is the curve would point to propagation through the earth along brachistochronic paths, slightly concave towards the centre of the earth. If this be the case, the form of

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* 'Brit. Assoc. Rep.,' 1898, p. 220.

wave motion is something very different to any which has yet been investigated, so far as I know, and requiring some form of wave motion whose rate of propagation decreases with an increase of the modulus of elasticity.

Even if some such explanation as has just been suggested were possible, it does not appear to be the true one. The value of 3·3 kiloms. per second given by Professor MILNE for an arc of 110° depends solely on the Argentine earthquake, and, as shown by the times tabulated above, an even higher rate might have been adopted. The values for 60° and 80° also are lower than might have been adopted if the time of commencement was referred to, while the rate for 20°, though lower than that given by the Turkestan earthquake, may represent closely the average rate for that distance.

In interpreting the data, however, it is necessary to remember the circumstances in which they were obtained. All the data available as yet are from observatories situated in Europe, and consequently we have not observations of the same earthquake at varying distances from the origin, but observations of different earthquakes whose origins were at various distances from the group of observatories at which they were recorded.

Now the waves of the third phase, whatever the nature of the molecular movement to which they are due, travel along the surface as distinct undulations with a motion, to use Professor MILNE's simile,* "not unlike the swell upon an ocean." Such being the case, it is not improbable that their rate of propagation may be dependent on their size, as in the case of sea waves; and this is the more to be expected if, as seems probable, their propagation is partly gravitational.

If this be the case, the instruments would only be affected by earthquakes originating at very great distances if they were of very great magnitude and capable of setting up the largest waves, which would not only travel furthest, but at the greatest speed. In the case of earthquakes originating at more moderate distances, a certain proportion would be of lesser magnitude, setting up surface waves of lesser size, and travelling at lesser velocities, by which the average of the apparent rates of propagation would be reduced. Close to the origin, moreover, we come into the region where earthquakes are sensible, and the very low rates of propagation recorded in some cases would further lower the average.

The interpretation which I put on the records is, therefore, that the third phase corresponds to the arrival of a form of wave motion which is propagated round the surface and not through the interior of the earth; that the rate of propagation in the case of each individual earthquake is practically constant; and that the true and apparent velocities of propagation are everywhere the same, but that the rate of propagation varies in the case of different earthquakes, being dependent in some way on the size of the waves set up by it. In the case of the greatest earthquakes, which are recorded at distances of 60° and over, this rate of propagation appears to be practically always about 2·9 kiloms. per second for the principal and largest waves,

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* 'Seismol. Jour. Japan,' vol. 3, 1894, p. 89.

and may rise to over 4·0 kiloms. per second for the long low waves which outrun the principal ones.

The conclusion drawn from the records is greatly strengthened by the fact that, in the case of the great earthquake of 1897, the only one where the rate of propagation has been carefully determined within the seismic area as well as at a distance, it was found that the rate of propagation of the sensible shock, from the origin to distances up to 15° of arc, was practically the same as the rate of propagation of the waves of the third phase to a distance of 65° of arc. The actual difference as calculated is but 0·1 kilom. per second, or about one-thirtieth of the value, a difference which is well within the inevitable limits of error of the observations.

The nature of these waves has yet to be elucidated. The elastic surface waves investigated by Lord RAYLEIGH should travel, in material of the nature of the rocks with which we are acquainted, at a rate of about 0·9 of the rate of propagation of a distortional plane wave in an infinite solid. This for continuous rock of the nature of that which forms the crust of the earth is about 2·6 kiloms. per second, so that if we take the rate of propagation of the greatest surface waves at 2·9 kiloms. per second, the excess is just about what the defect should be.

The form of the molecular movement in the waves investigated by Lord RAYLEIGH, does not seem to be consonant with that recorded in the neighbourhood of the origin. At great distances it may be in closer accord, but apart from this, the rate of propagation of the purely elastic surface waves is not a function of either their length or amplitude, while that of the great surface undulations of an earthquake appears to be a function of one or both of these. This is intelligible if, as was suggested by Lord KELVIN,* the propagation of these waves is accelerated by gravity, and the fact that the rate of propagation seems to be in some way a function of their size is a support to the suggestion.

§ 8. There remain now for notice only those cases where the record has commenced earlier than the time at which the condensational waves, set up by the earthquake to which the record is attributed, would be expected to emerge. In all, seven such cases are included in the records noticed above, and are tabulated below.

Earthquake No.	Arc degrees.	Time of		Interval. Minutes.	Locality.
		Origin.	Record.		
7	41·0	17^{h} $36·0^{m}$	17^{h} $37·0^{m}$	+ 1·0	Ischia.
7	41·0	15 28·0	15 15·2	− 12·8	,,
7	42·4	15 28·0	15 15·0	− 13·0	Catania.
4	72·7	8 7·0	8 7·5	+ 0·5	Nicolaiew.
6	74·2	0 9·4	0 17·0	+ 7·6	,,
3	85·2	10 31·0	10 30·0	− 1·0	Shide.
2	155·2	20 50·0	21 0	+ 10 0	Tokio.

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* 'Seismol. Jour. Japan,' vol. 3, 1894, p. 87.

Of these the two records of the earlier of the two Turkestan earthquakes of 15th August, 1897, being 13 minutes in advance of the time of origin, may very probably be attributed to some local shock. Three of the others are practically simultaneous with the origin, and one, omitting the Tokio record of the Argentine earthquake, about $7\frac{1}{2}$ minutes later than the origin. That is to say, the record begins from 5 to 15 minutes before the arrival of the condensational waves.

It is very difficult to decide whether these early commencements of the record have any real connection with the earthquakes they appear to refer to, or are due to other, possibly local, disturbances which happened to coincide approximately with the greater earthquake.

On the one hand the number of cases in which there is an early commencement of the record seems too great for the connection to be fortuitous. Excluding the second Turkestan shock, where the record began at Ischia and Catania about 13 minutes before the earthquake, and the disturbance may well be attributed to some other cause, we have no less than five out of ten distinct shocks, in which there is a commencement of the record in advance of the disturbance of what I have called first phase.

On the other hand there is the want of accordance in the times, and the fact that the early commencement was in each case only found at a single station; as these are about evenly divided between the light and heavy pendula, there is no guide as to the nature of the disturbance.

If due to the principal shock and not to local disturbances, these early commencements of the record can hardly be attributed to any form of wave motion set up by, and at the same time as, the earthquake. They would, in this case, have to be attributed to premonitory disturbances of a nature very different to that of the main shock, for, though unfelt in the neighbourhood of the origin, the initial energy of the disturbance would have to be great enough to affect instruments at distances ranging from one ninth to one quarter of the circumference of the earth.

On the whole, then, it seems more natural to attribute these early commencements, which show no concordance in their times as compared with each other, to local disturbances, or at any rate to some cause other than the earthquake with which they are approximately coincident. A possible exception to this is the Tokio record of the Argentine earthquake; this, as suggested above, may be due to the earlier emergence of condensational waves which have traversed the central core of the earth, as compared with those which have not penetrated so deep and, though traversing a shorter course, have done so at a lower rate of propagation.

The results obtained in the preceding investigations may be summarized as follows:—

1. The complete record of a distant earthquake shows three principal phases of increase of displacement followed by decrease, the phases being marked by a more

or less well defined change in the character as well as the amount of the displacement. Of these the third phase is the most readily and constantly recorded, the second less so, and the first is the phase most frequently absent.

2. The disturbance of the first and second phases being recorded by heavy pendula, possessing great inertia, with greater constancy and concordance than by light horizontal pendula specially designed to detect surface tilting, we may conclude that the motion is principally of a to-and-fro nature, and that the records are due to the inertia of the pendula, rather than to a tilting of the surface. This conclusion has been come to by previous writers in the case of particular shocks.

3. The times of arrival of the first two phases, when plotted, form a curve of increase of apparent velocity with distance, consistent with the hypothesis that they represent the times of arrival of elastic waves propagated through the earth at rates which increase with the depth below the surface.

4. The increase of rate of propagation with depth appears to be a constant function of the depth, at any rate as far as the greatest depth reached by the waves which emerge at a distance of 90° of arc from the origin. Beyond this depth, which may be put at about 0·45 of the radius, there are some indications of a rapid increase in the rate of propagation.

5. The time curves drawn through the times of commencement of the first and second phases, if continued to the origin, give initial rates of propagation in tolerably close agreement with the probable initial rates of propagation of condensational and distortional waves in continuous rock.

6. We may consequently accept the conclusions, that the first phase represents the arrival of condensational waves, and the second phase of the distortional waves, each of which have travelled along brachistochronic paths through the earth.

7. The disturbance of the third phase differs from that of the first, or second, phase in that the light pendula with photographic registration are even more sensitive to it than the heavy pendula whose freedom of movement is trammelled by the friction of their mechanical record. From this we may conclude, that the record is due not to inertia, but to a tilting of the instrument as a whole; a conclusion which is borne out by the nature of the record in those instruments which trace the displacements on a surface moving with sufficient rapidity to give an open record. This is the phase of the long surface undulations, resembling the swell of the ocean, whose character has been recognised and acknowledged since 1894.

8. The apparent rate of propagation of the waves of this phase shows no sign of varying with the distance from the origin, but is constant at all distances, or at most subject to a very slight and slow change. From this it may be concluded that they are propagated as surface undulations and that, in their case, the true and apparent velocities are everywhere identical.

9. The rate of propagation is not, however, constant in the case of all earthquakes, but the waves set up by the greatest earthquakes travel at a higher speed than

those set up by lesser ones; from this it may be concluded that the rate of propagation is, in some way not yet worked out, a function of the size of the wave.

10. The rate of propagation of the waves of this phase is, in the case of great earthquakes, higher than that which has been calculated for purely elastic surface waves, and from this, and from the fact that their rate of propagation seems to be a function of their size, it is probable that their propagation is, at least in part, gravitational.