Note on the Preliminary Tremor of Earthquake Motion.

By

F. Omori, D. Sc.

Professor of Seismology, Tokyo Imperial University.

With Plates XIII—XVI.

1. It is well known that an earthquake usually begins with movements, whose amplitude of vibrations is much smaller than that of the subsequent motions, which form the principal portion of the shock. These small introductory movements, the "preliminary tremor," whose period is generally very short, are doubtless, in some instances, the cause of the so-called earthquake sound, often heard just before the arrival of the tremblings of the ground. The quickest tremor vibration, which I have ever observed, was one of the after-shocks of the great Mino-Owari earthquake of the 28th October, 1891, instrumentally registered at the temporary seismological observatory set up in the village of Midori in the Néo-Valley, the most central part of the meizoseismal zone, its complete period being only 0.023 second. In the case of some very distant earthquakes, however, the preliminary tremor consists entirely of small slow undulations with a period nearly equal to that in the principal portion.

It has already been pointed out by Professor J. Milne and others that a distant earthquake, as observed by means of delicate horizontal or vertical pendulums, begins with tremors, whose duration increases with the distance of the origin of disturbance from the observing station. What is here discussed is based on the observations of comparatively near earthquakes made in Tokyo and at the Meteorological Observatories of Kagoshima, Fukuoka, Gifu and Miyako, the origins of disturbance being in Japan itself or in the Ocean off its eastern coast.

I may here note that all the earthquake diagrams, from which I have measured the durations of the preliminary tremor, were given, by Ewing's or by Gray and Milne's Seismographs, unless otherwise stated. Each of these instruments, ordinarily at rest, is started on the occasion of an earthquake by means of an electric contact-maker, which is usually made so delicate as to be sensible to a movement of about $\frac{1}{20}$ mm. However, different seismographs at one station, owing to different sensibilities of the contact-makers of the instruments, do not always give one and the same duration for the preliminary tremor of an earthquake, the discrepancy amounting usually to a few seconds. In these cases the longest value of the duration must be regarded as nearest to the truth and is that which has been adopted.

Again, I have excluded all the diagrams of small earthquakes, whose origins were very far off from the observing station, because in these cases, the beginnings of the motion, being slow and extremely small, are very apt to fail to affect the electric contact-maker, and, also because there often exists no well-marked transition from the preliminary tremor to the principal portion of such earthquakes.

By examining the seismographic diagrams of different earthquakes, it will be seen that in general the duration of the preliminary tremor is longer for distant earthquakes than for those of near origins. Its duration in some typical earthquakes, as recorded in the diagrams, I shall now proceed to consider.

2. Observations at the Meteorological Observatory of Gifu (lat. 35°27′, long. 136°46′). The observations at Gifu of the great Mino-Owari earthquake of the 28th October, 1891, and of five of its strongest after-shocks are given in the following table:—

Earthquakes observed at Gifu.

No.	Intensity.	Date.	Time of occurrence.	Duration of the preliminary tremor.
			h. m. s.	
1	Destructive.	28th Oct. 1891	6. 37. 11 a. m.	2. seconds.
2	Rather strong.	28th Nov. 1891	9. 39. 19 a. m.	1.3 „
3	„ „	3rd Jan. 1892	4. 21. 13 p. m.	3. „
4	Violent.	7th Sept. 1892	5. 41. 07 a. m.	1. „
5	Rather strong.	10th Jan. 1894	6. 03. 42 p. m.	1.5 „
6	Violent.	„ „ „	6. 45. 28 p. m.	3. „
			Mean	2.0 seconds.

Of these 6 earthquakes, No. 1 was caused by the formation of a long fault, most remarkably shown in the Néo-Valley, whose central part is about 30 kilometres distant from Gifu. The remaining five earthquakes all originated in the Mino-Owari plain, not far from the same city.

3. Observations at the Meteorological Observatory of Kagoshima (lat. 31°35′, long. 130°33′).

The observations at Kagoshima of the violent earthquake of the 7th September, 1893, and two of its after-shocks were as follows:—

Earthquakes observed at Kagoshima.

No.	Intensity.	Date.	Time of occurrence.	Duration of the preliminary tremor.
1	Very strong.	7th Sept. 1893	h. m. s. 2. 46. 00 a. m.	2.5 seconds.
2	Strong.	8th „ „	7. 10. 20 a. m.	1.2 „
3	Weak.	12th „ „	11. 39. 34 p. m.	0.5 „
			Mean	1.4 seconds.

The origins of these earthquakes were in the southern part of the Satsuma Peninsula, at about 25 kilometers south of the city of Kagoshima.

4. Observations at the Meteorological Observatory of Fukuoka (lat. 33°35′, long. 130°23′).

The observations at Fukuoka of the severe earthquake of the 12th August, 1898, and one of its after-shocks were as follows :—

Earthquakes observed at Fukuoka.

No.	Intensity.	Date.	Time of occurrence.	Duration of the preliminary tremor.
1	Very strong.	12th Aug. 1898	h. m. s. 9. 35. 34 a. m.	0.3 seconds.
2	Strong.	„ „ „	1. 03. 15 p. m.	0. „
			Mean	0.2 second.

The origins of these earthquakes were in the western part of the province of Chikuzen at about 20 kilometres west of Fukuoka.

The duration of the preliminary tremor of No. 1, as recorded by my Horizontal Pendulum in Tokyo, was 122 seconds.

5. Observations in Tokyo. In the following table are given the observations of those earthquakes of comparatively near origin, which were strongly felt in Tokyo.

Earthquakes of near origin observed in Tokyo.

No.	Intensity.	Date.	Time of occurrence.	Approximate position of the epicentre.	Duration of the preliminary tremor.
			h. m. s.		
1	Strong.	15th Oct. 1884	4. 21. 54 a.m.	In the ocean, probably 100 kil. S.W.	4. seconds.
2	„	15th Jan. 1887	6. 51. 59 p.m.	50 kil. S.W.	3. „
3	„	5th Sept. 1887	3. 23. 23 p.m.	In the ocean, E.	15. „
4	Rather Strong.	5th April 1888	2. 30. 29 p.m.	In the Province of Shimotsuke, 100 kil. N.	10. „
5	Strong.	29th April 1888	10. 00. 33 a.m.	Same as No. 4.	14. „
6	„	18th Feb. 1889	6. 09. 32 a.m.	In the Bay of Tokyo.	10.5 „
7	„	24th Dec. 1891	5. 33. 14 a.m.	70 kil. W.S.W.	7.7 „
8	„	31st June 1892	7. 09. 57 a.m.	In the vicinity, E.	7.6 „
9	Violent.	20th June 1894	2. 04. 10 p.m.	In the vicinity, E.N.E.	6.8 „
10	Strong.	7th Oct. 1894	8. 30. 03 p.m.	In the ocean, E. N. E.	16. „
11	Rather Strong.	30th Nov. 1894	8. 30. 57 p.m.	70 kil. S.W.S. (Focal depth taken into account.)	9.3 „
				Mean.....10.0 seconds.	

6. Observations in Tokyo, (*cont.*) I will next give the observations in Tokyo of great earthquakes of distant origin.

Earthquakes of distant origin observed in Tokyo.

No.	Intensity.	Date.	Time of occurrence.	Position of the epicentre.	Duration of the preliminary tremor.
			h. m. s.		
1	Strong.	28th Oct. 1891	6. 39. 11 a.m.	(The great Mino-Owari Eqke.) 288 kil. W.	37. seconds.
2	Weak.	22nd March 1894	7. 27. 49 p.m.	(The great Hokkaido Eqke.) 900 kil. N.E.	109. „
3	Slight.	31st Aug. 1896	5. 09. 33 p.m.	(The great Rikuchu-Ugo Eqke.) 430 kil. N.	56. „

4	Strong.	17th Jan. 1897	0. 49. 28 a. m.	(The severe Nagano Eqke.) 170 kil. N.W.	17.	seconds.
5*	Weak.	5th Aug. 1897	9. 12. 23 a. m.	In the ocean, about 400 kil. N.E.	45.	„
6	Strong.	26th May 1898	2. 59. 57 a. m.	(The severe Echigo Eqke.) 170 kil. N.W.N.	17.	„
7*	Weak.	23rd April 1826	8. 37. 00 a. m.	In the ocean, about 400 kil. N.E.	54.	„

The positions of the suboceanic origins of the two earthquakes, No. 5 and No. 6, (marked with asterisks), have been inferred simply from the forms of their isoseismal lines on land and are, therefore, to be regarded as being only approximate. These two earthquakes have been excluded in deducing equation (1) below. With respect to the remaining five earthquakes, all of which, except No. 2, originated inland, the positions of their origins have carefully been determined from special investigations and are consequently to be regarded as being exact.

I add here the observation at the Meteorological Observatory of Osaka[1] of the great Mino-Owari earthquake of the 28th October, 1891:

$$\left\{\begin{array}{l}\text{(Distance of Osaka from the origin} = 140 \text{ kilometres.)} \\ \text{Duration of the preliminary tremor} = 14 \text{ seconds.}\end{array}\right.$$

7. Comparing the results in §§ 2, 3, and 4 with that in § 6, we see that the duration of the preliminary tremor of an earthquake depends on the distance between the origin and the observing station, the average durations being for the observations at Gifu, Kagoshima and Fukuoka, respectively only 1.4, 2.0 and 0.2 seconds. Whether the duration of the preliminary tremor would actually vanish at the very *centre* (not the

1. At Gifu and Nagoya, much nearer to the origin, the durations of the preliminary tremor of the same earthquake were respectively 2 and 4 seconds.

epicentre) of an earthquake, is a problem which is very difficult to solve. But I believe such must, in some cases, be approximately true. The followiug are some of my own observations relating to the point in question.

8. On the 8th November, 1894, at 8.25 p. m., I experienced one of the after-shocks of the destructive Shonai Earthquake in the town of Fujishima, which is situated quite near to the epicentre of that earthquake. At the time, I was sitting quietly upstairs of a wooden two-storied house, and felt the shock as a sudden blow coming from below, accompanied by a loud noise, such as that caused by the falling of a heavy body on the ground. The motion consisted of a single principal vertical movement, followed by very feeble vibrations, the whole duration being about 30 seconds. Although the effect of the shock was strong enough to cause people to run out of doors, I observed the lamps suspended from the ceiling of my room remaining still and not thrown into oscillations. In this case, the shaking began abruptly and had no preliminary tremor, the origin of disturbance, which was evidently local, being quite near to the place of observation.

9. The observation at Midori. Soon after the great Mino-Owari Earthquake of the 28th October, 1891, a temporary seismological observatory was established at the village of Midori in the Néo-Valley, before referred to (§ 1), and a number of the after-shocks were seismographically registered.

It is to be noted that after the initial great earthquake the principal centre of seismic activity was not in the Néo-Valley, but to the south of it in the vicinity of Gifu. The phenomena of earthquake-sounds were, however, most frequent and intense in the Valley, the sounds being usually like that caused by the

falling of a heavy weight on the ground or by the discharge of a cannon at a distance.

The results of the seismographical observations at Midori, carried out between the 11th and the 28th November, 1891, may be summarised as follows:—Of the 18 earthquakes, whose motion was large enough to be distinctly measured, the strongest was that on the 28th November, 1891, at about 9.39 a.m., (No. 2, Table, § 2), of which the whole duration was 35 seconds and that of the preliminary tremor 4.2 seconds, the origin of this shock being much nearer to Gifu than to Midori. Four other earthquakes also originated at some distances from the observing station, and their movements consisted of comparatively slow undulations; the total duration varied between 7 and 43 seconds, and the maximum duration of the preliminary tremors was 2.7 seconds. The remaining 13 earthquakes were all small local shocks and consisted of very minute vibrations, of periods which varied between 0.023 and 0.17 seconds. All these shocks, whose duration varied between 0.9 and 4.3 seconds, had no preliminary tremor, but began at once with well-pronounced movements, except in one case in which the motion began with a well marked preliminary tremor of 0.1 second in duration.

It may be noted that the subterranean sound was perceived simultaneously with, or very shortly, say 1 or 2 tenths of a second, before the tremblings of the ground.

10. Let us put, for the sake of abbreviation, y=the duration, in seconds, of the preliminary tremor of an earthquake at a given station, whose distance from the origin of disturbance is x kilometres. Then, fig. 1, Pl. XIII, graphically illustrates the relation between x and y for the large distant earthquakes noticed

in § 6,[1] for No. 11, § 5, and for the Fukuoka Earthquake of the 12th August, 1898, as observed in Tokyo, § 4. The curve, $p\ q$, drawn through the mean positions, is approximately a straight line, whose equation is, by calculation, found to be

$$7.51\ y = x - 24.9 \text{ km.} \qquad (1)$$

The straight line, $p\ q$, cuts the abscissa axis at a point p ($x = 24.9$ kilometres) instead of passing through the origin of coordinates. This may be due to the probable fact that the earthquake waves get weakened as they spread out from the origin, the very earliest portion becoming at great distances finally too small to affect the seismograph. For great earthquakes, whose origin is near to the observing station, say under 100 kilometres, such a dissipative effect would not much affect the duration of the preliminary tremor. These cases must be treated separately, taking into account, of course, the depths of the earthquake foci.

The duration of the preliminary tremor does not depend on the magnitude of the earthquake, which may be considered as represented by the extent of the area of disturbance. Thus, no difference of this kind is to be seen between the great Mino-Owari Earthquake and its after shocks, (See § 2). Again, the mean radii of propagation of the sensible shakings of the Mino-Owari Earthquake and the Rikuchu-Ugo Earthquake of the 31st August, 1891, (See No. 1 and No. 3, Table, § 6), were respectively 600 and 520 kilometres: the former earthquake was thus a little greater than the latter, but the durations of their preliminary tremors, observed in Tokyo, were respectively 37 and 56 seconds.

1. The focal depth is assumed to be negligible in comparison with the distance between the observing station and the origin of disturbance.

11. According to equation (1), which is to be regarded as applicable to great earthquakes at distances, say above 100 kilometres, from the observing station, the duration of the preliminary tremor is increased at the rate of 15 seconds per 100 kilometres of the distance y. This, if found to be always true, would enable us to estimate, from the diagram at any station by a sufficiently sensitive seismograph, the approximate distance of the origin of a shock. Or, if the seismographic records be simultaneously taken at two or more stations, we can, from the comparison of the durations of the preliminary tremors, easily fix the approximate position of the origin. I give next a few illustrations of the application of equation (1).

12. The durations of the preliminary tremors of the two large earthquakes of the 5th August, 1897, and of the 23rd April, 1898, recorded instrumentally at the Meteorological Observatory of Miyako (lat. 39°38′, long. 141°59′) were respectively 22 and 13 seconds, the corresponding durations in Tokyo being, as given in § 6, 45 and 54 seconds. According to equation (1), the distances of the origins of these two earthquakes from Miyako would respectively be about 190 and 120 kilometres, while the corresponding distances from Tokyo would be 360 and 430 kilometres. The positions of the origins as determined by the intersections of the circles drawn with radii equal to these distances about Miyako and Tokyo as centres are, as indicated in fig. 2, not very different from those to be inferred from the isoseismal lines.

13. The earthquake of the 8th June, 1898; 9.10 a. m. The earthquake was recorded by my Horizontal Pendulum at Miyako, the machine having been set up there just the day before. It was also signalised by the seismograph at the Miyako

Meteorological Observatory, but otherwise nowhere observed or reported. The duration of the preliminary tremor, as given by the Horizontal Pendulum diagram was 23 seconds, which, according to equation (1), would correspond to a distance of about 200 kilometres between the observing station and the probably suboceanic origin of the earthquake. In cases like this, it is impossible in any other way, to estimate the distance of the origin of disturbance.

14. The earthquake of the 7th October, 1898; 11.0.46 a.m. The earthquake shook moderately Oshima, Rikuoku, Rikuchu and Iburi. The duration of the preliminary tremor in Tokyo, as recorded by my Horizontal Pendulum was 82 seconds, while that at Miyako was 19.5 seconds. According to equation (1), the distances of the origin from Tokyo and Miyako would respectively be about 640 and 170 kilometres. The position of the origin determined by the intersection of the circles described about Tokyo and Miyako with radii respectively equal to these distances is indicated in fig. 3, it being nearly identical with that to be inferred from the isoseismal lines.

15. The fact that the duration at a given station of the preliminary tremor of an earthquake is nearly proportional to the distance of its origin from the station can be explained by assuming two sets of waves, which, originating simultaneously at the centre of disturbance, are propagated with different velocities. If V_1 denote the velocity of propagation of the small preliminary tremors, and if V_2 denote that of the principal waves of an earthquake, we find

$$\frac{1}{V_2}-\frac{1}{V_1}=\frac{x-24.9}{7.51\,x}. \qquad (2)$$

For the cases of the Mino-Owari Earthquake (No. 1, § 6) and the Hokkaido Earthquake (No. 2, § 6), we obtain :—

Mino-Owari Eqke. $V_1=2.1$ km. $V_2=1.6$ km.
Hokkaido Eqke. $V_1=2.3$ km. $V_2=1.8$ km.

It is, however, to be observed that equation (1) has been deduced from the observation of earthquakes, the distances of whose origins from the observing stations do not exceed 900 kilometres, and it would evidently be absurd to apply the same equation to cases of very distant earthquakes, for instance, those originating in Japan and observed in Europe. Such earthquakes give the high values for the transit velocity of 12 to 14 kilometres per second.

16. What was said in the preceding paragraphs seems to show the coexistence in earthquakes of two principal kinds of waves whose velocities of propagation are different. It must not, however, be supposed that the motion of an earthquake consists of only two kinds of waves. On the contrary, an earthquake motion consists, when the origin is not very far distant from the observing station, of several kinds of waves with different periods of vibration, ranging generally between a fraction of a second and several seconds. Short-period vibrations, which always occur most markedly at the beginning of the motion, gradually die away, leaving behind only the vibrations of long periods. Perhaps it may be that waves with different periods are propagated with different velocities.

Fig. 5 is a reproduction of the EW component diagram of the moderately strong earthquake of the 3rd April, 1898, recorded in Tokyo by my long-period Horizontal Pendulum Seismograph, the period of proper oscillation of whose horizontal

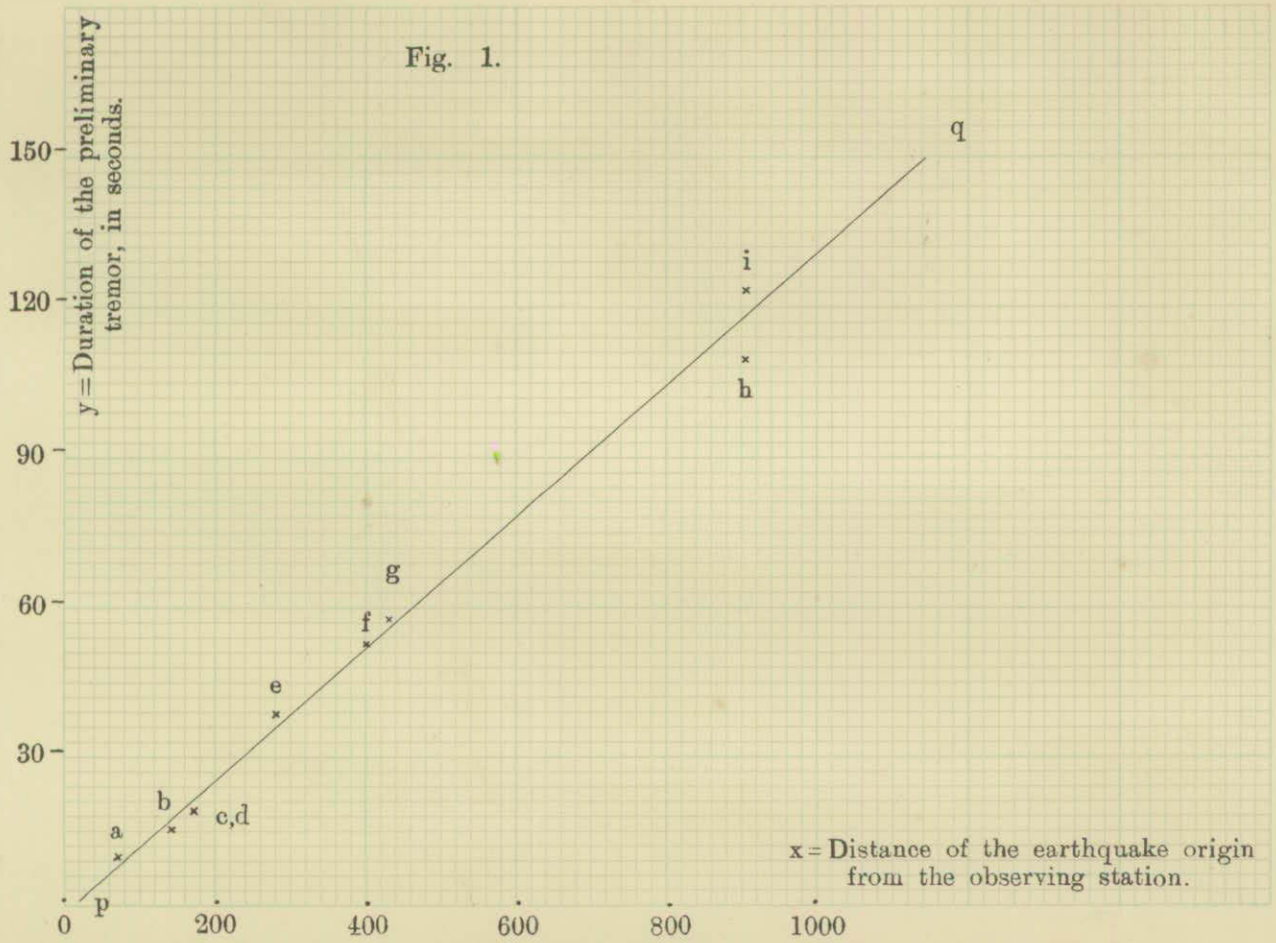
pendulum is 24 seconds. The length of the smoked paper wrapped round a drum, on which the record was taken, is 745 mm., the drum making one complete revolution once in 70 seconds. The proper motion of the horizontal pendulum is not shown in the diagram, and therefore all the waves are to be regarded as indicating real earthquake movements. The motion was here recorded only as far as the 210th second from the commencement, but the real duration was much longer. According to the diagram, there were the following four kinds of waves superposed one upon the others :—

1. Waves, whose average period was 0.36 second, and whose maximum range was 0.6 mm.
2. Waves, whose average period was 0.88 second, and whose maximum range of motion was 0.6 mm.
3. Waves, whose average period was 1.5 seconds, and whose maximum range of motion was 0.9 mm.
4. Waves, whose average period was 3.4 seconds, and whose maximum range of motion was 1.7 mm.

This earthquake, whose origin was about 100 kilometres west of Tokyo, was in the NS component recorded by the Horizontal Pendulum. According to the diagram, the total duration was about 20 minutes, the average period of the principal undulations, whose maximum motion was 2.2 mm., being about 6.3 seconds. The duration of the preliminary tremor was 15 seconds. (In fig. 4 is given the earlier portion of the diagram).

November, 1898. Seismological Institute, Tokyo.

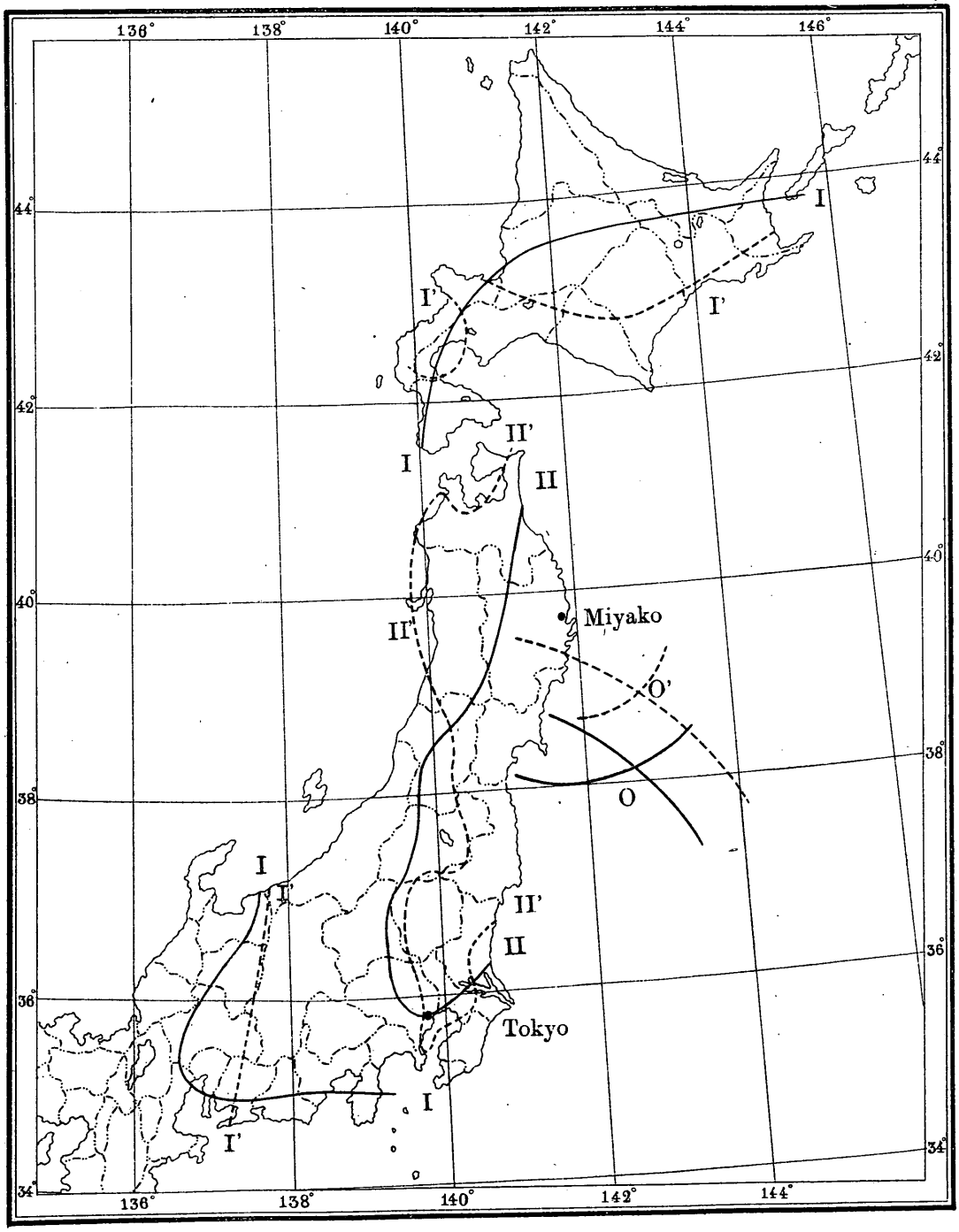
Fig. 1.



a = Eqke No. 11, § 5.
b = Mino-Owari eqke, observed at Osaka.
c = „ No. 4, § 6.
d = „ No. 6, § 6.
e = „ No. 1, § 6.
f = Mean of No. 5 and No, 7, § 6.
g = „ No. 3, § 6.
h = „ No. 2, § 6.
i = Fukuoka eqke of Aug. 12th, 1898, observed in Tokyo, § 5.

Jour. Sc. Coll. Vol. XI. Pl. XIII.

Fig. 2. The Earthquakes of Aug. 5th, 1897, and of April 23rd, 1898.



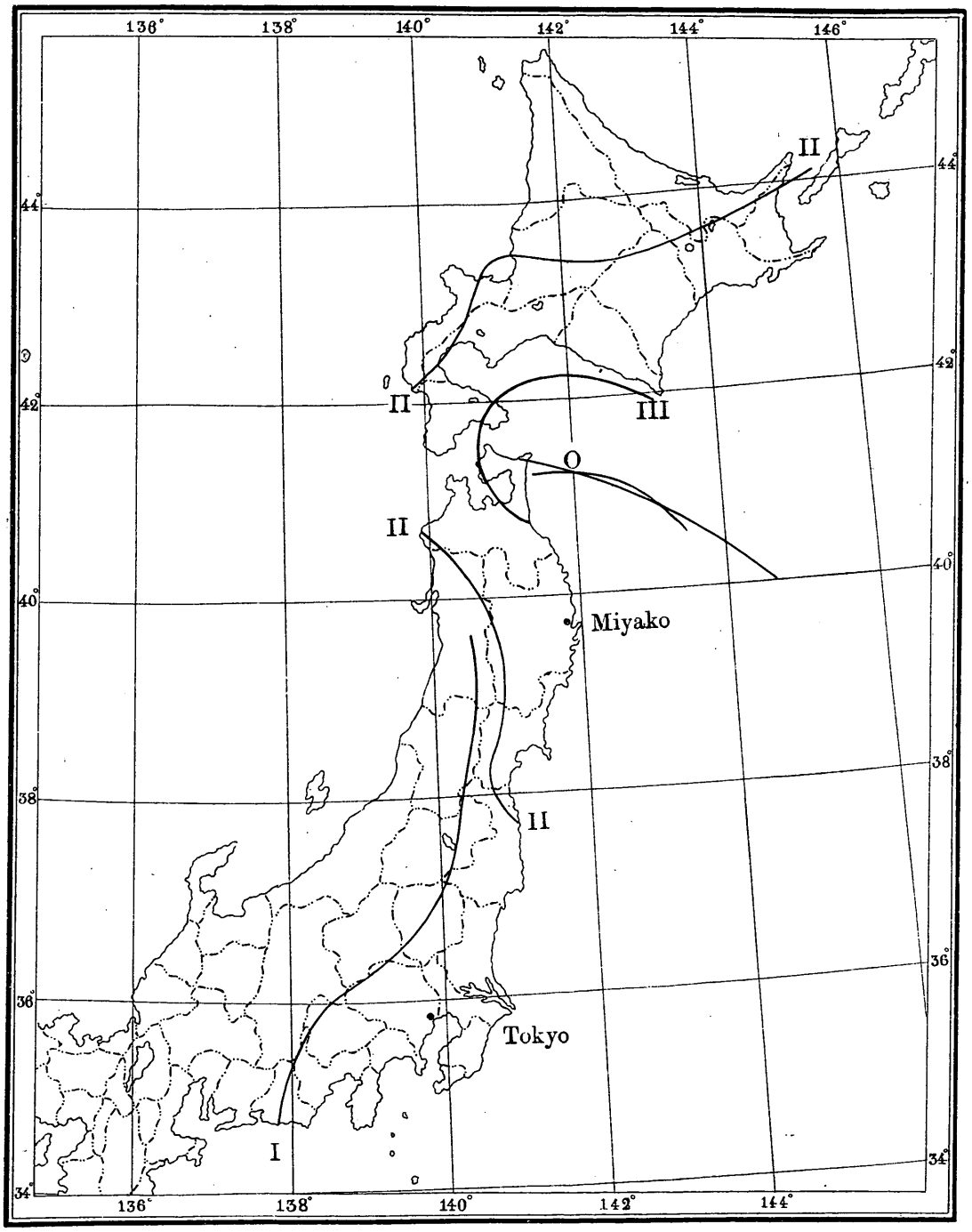
—·—·— Boundary of provinces.

Full curves, I and II, refer to the eqke of Aug. 5th, 1897, and dotted curves, I' and II', to that of April 23rd, 1898.

I, I,' Boundary of the area of slight motion.
II, II,' „ „ „ „ „ strong „

O and O' indicate the approximate positions of the eqke origins.

Fig. 3. The Earthquake of Oct. 7th, 1898.



—·—·— Boundary of provinces

I, Boundary of the area of slightest motion.
II, „ „ „ „ „ slight „
III, „ „ „ „ „ strong „

O indicates the approximate position of the earthquake origin.

Fig. 4. The Earthquake of April 3rd, 1898; NS component. (Recorded by Omori's Horizontal Pendulum.) Multiplication 10 times.

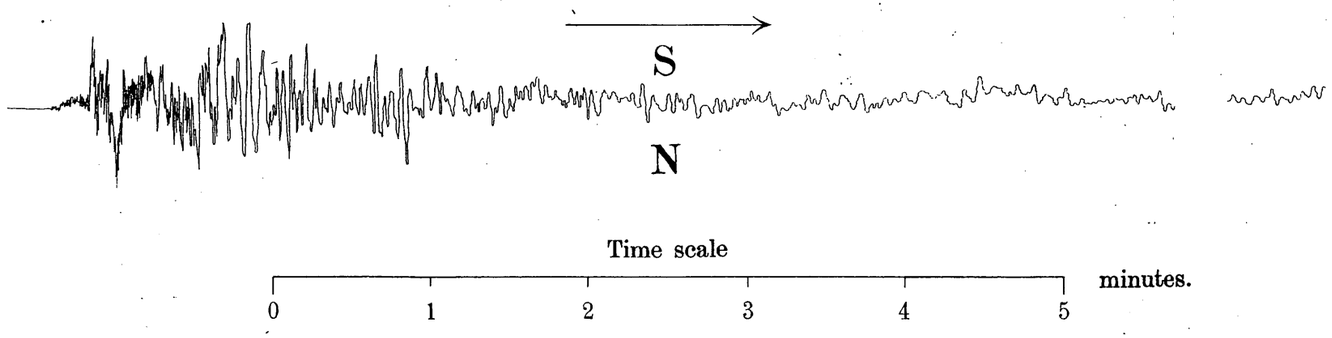


Fig. 5. The Earthquake of April 3rd, 1898; EW component. (Recorded by the long-period Horizontal Pendulum Seismograph.) Multiplication 6½ times.