Horizontal Pendulums for the Mechanical Registration of Seismic and Other Earth Movements.

By

F. Omori, D. Sc.

Professor of Seismology, Tokyo Imperial University.

With Plates II—XII.

I.

1. Observational seismology requires not only seismographs to record the comparatively sudden and violent movements of the ground, which constitute earthquakes, but also much more sensitive instruments, to record those imperceptible seismic disturbances and other earth movements, which are always proceeding. The seismometrical work, which has been done in Japan during the last 20 years, has related chiefly to earthquakes of comparatively near origin, the seismographs used being those of Ewing, and Gray and Milne. Each of these instruments registers the more sudden vibrations of the earthquake motion, but is almost incapable of measuring earth undulations of long period, owing to the want of a sufficient approach of the so-called "steady mass" to the neutral equilibrium, and to the existence of a considerable amount of friction between the writing pointer and the record-receiver and elsewhere.

2. It is unnecessary to repeat here the historical sketches of seismographs, horizontal pendulums, etc., which have already

been given by Ewing[1], Davison[2], Hecker[3], Pacher[4] and others. But with regard to the registration, it must be pointed out that there are two methods of doing this, photographic and mechanical, of which the latter, so far as the observation of earthquakes and similar earth movements is concerned, seems to be the best. Thus, for instance, the Horizontal Pendulum Apparatus of Paschwitz is well adapted for observing the level change of the ground, but, when seismometrically used, it is merely a species of very delicate seismoscope, unless the rate of motion of the photographic paper is very rapid. For, with such a small rate of motion of the paper as was adopted by Paschwitz, about 2 cm. per hour, the photogram shows only the extent of motion of the light point, and tells nothing about the period of vibration of the earthquake motion. In fact it is, I think, a great mistake to take the range of motion in such photograms as the representative, or direct result, of any tilting motion of the ground: firstly, because, in an earthquake, the horizontal pendulum of Paschwitz is usually thrown into its proper oscillations of considerable amplitude, and, secondly because the earthquake movements registered by such pendulums are probably due to the horizontal motion, and not to the tilting of the ground. (See § § 16,26). With a quick rate of motion of about 30 cm. per hour of a very sensitive photographic paper, we can obtain open earthquake diagrams clearly showing individual movements of the pendulum, as well as the "pulsatory oscillations" or small earth movements

1. *J. A. Ewing.* Earthquake Measurement. *Memoirs of the Science Department, Tokio Daigaku, No.* 9. 1883.

2. *C. Davison.* The Horizontal pendulum. *Natural Science Vol. VIII.* 50. *April,* 1896.

3. *O. Hecker.* Das Horizontalpendel. *Zeitschrift für Instrumentenkunde,* 1896, *Januar.*

4. *Giulio Pacher.* I Microsismografi dell'Istituto di Fisica della R. Università di Padova. *Atti del R. Istituto Veneto di Scienze, etc. Tomo VIII, Serie VII.*—1896-97.

of long period. But the method is expensive, and, besides, the inertia of the mass of the pendulum is too small to be suitable for observing ordinary earthquakes, which throw the pendulum into motion with its own period.

3. With regard to the mechanical method of registration, we can render the instruments as sensitive as we please, by making the "steady mass" sufficiently heavy, say 100 or 200 kilogrammes in weight, as has been done by several Italian observers; or, by greatly lessening the friction between the parts of the machine, as in my Horizontal Pendulum, whose heavy mass is only 3 kilogrammes in weight. (See section III). Further, the definition of the diagram can be made quite sharp, and the rate of motion of the smoked paper, which serves as the record-receiver, can, without expense and trouble, be increased to any extent.

Horizontal Pendulums adapted for mechanical registration have already been successfully tried by Grablovitz[1] and by Cancani[2]. In the horizontal pendulum of Grablovitz the vertical height between the points of suspension and of support is 2 m., while the horizontal distance between the vertical axis and the centre of the heavy mass is only 10 cm., the weight of the latter being 12 kgm. The vertical height in Cancani's apparatus is 5.25 m., and the horizontal distance between the upper point of support and the writing pen 2.7 m., the weight of the heavy mass being 25 kgm. and the complete period of vibration of the pendulum 24 seconds.

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1. *Giulio Grablovitz.* Pendoli orizzontali a registrazione meccanica continua. *Boll. d. Soc. Sism. Italiana. Vol. II.*

2. *A. Cancani.* I Pendoli orizzontali, etc. *Boll. d. Soc. Sism. Italiana. Vol. III.*

II.

4. The building, in which my Horizontal Pendulums have been set up, is a brick "Earthquake-proof House,"[1] erected in the grounds of the University (Hongo, Tokyo) by the Imperial Earthquake Investigation Committee, as a sort of a seismological observatory. (See fig. 5.) The structure, which covers an area of 83 sq. m., simply consists of four walls of parabolic section covered with a tiled roof furnished with a skylight, each wall being $5\frac{1}{2}$ m. high, 0.7 m. thick at top and 2.4 m. thick at the ground level. The entrance is the only opening in the walls.

The house, thus forms a kind of a stout hollow column, and its walls, from which the Horizontal Pendulums are suspended, may be considered to be unaffected by the direct impact of winds.

5. My Horizontal Pendulums for recording earthquakes and other earth movements mechanically and continuously, are constructed on the principle of keeping the heavy mass comparatively small and reducing friction to a minimum. As each Pendulum records only the motion normal to its plane, we want, for the complete observation of earth movements, a pair of these machines to be placed at right angles to each other.

The reference letters apply to Pl. II, which illustrates the mechanical details of one of the Horizontal Pendulums, fig. 1 and fig. 2 giving respectively side and front elevations.

The Pendulum consists of a thin brass cylinder, *a*, filled with lead, 16 cm. in height, 10 cm. in diameter and about 14 kgm. in weight, attached a little above its centre of gravity to

1. Designed by Prof. K. Tatsuno, member of the Imperial Earthquake Investigation Committee.

a strut, *b*, which consists of an iron tube 1.5 cm. in diameter, and of such length that the distance between its end and the axis of the cylinder is 1 m.

The heavy-bob, *a*, is hung by a fine steel wire, *c*, from an inside projection of one of the walls of the "Earthquake-proof House," the lower end of the wire being attached to a stirrup, *d*, pivoted at *e*, a little above and in front of the centre of gravity of the bob. The tubular strut, *b*, is furnished at the end with a sharp conical steel point of about 50°, which is pivoted in a conical steel socket, *f*, of about 120°, fixed to a step-like projection in the lower part of the wall.

The upper end of the wire, *c*, is attached, by means of a screw, *g*, to a triangular steel prism, *h*, whose knife-edge, reduced to two small portions, *i* and *j*, works on a steel V-groove, *k*, properly perforated to allow the passage of the screw *g*. The V-groove is mounted on a stout arm of hard wood bolted to the upper projection of the wall in such a way that the wire and the knife-edge, whose intersection determines the upper point of suspension of the pendulum, stand at right angles to each other. The pendulum can thus swing freely about its axis, the vertical distance between the points of suspension and of support being $2\frac{1}{2}$ m. The vertical adjustment of the heavy-bob, *a*, is made by the screw, *g*, while its horizontal adjustment is made by a screw (not shown in the figures) moving the point of support in the direction normal to the pendulum plane.

As the period of free vibration of the Pendulum is slow, and as the strut, *b*, is sufficiently long, the axis of the heavy cylinder may be considered as being "steady" not merely with respect to infinitesimal and quick vibrations of the ground, but also with respect to considerable pulsatory or very slow undulations, since the real earth movements will at least be distinguishable from the proper vibrations of the pendulum.

6. The writing pointer, shown in plan and elevation in fig. 3, consists of a small steel axis, *l*, 3 mm. in diameter and 5 cm. in height, rigidly attached to a light lever, *m n*, whose shorter forked arm, *m*, is of brass, and whose longer grooved arm, *n*, is of alminium. The axis is pivoted in a vertical position between two small conical sockets fixed in an inverted stirrup, *o*, which is adjustable along the horizontal metal bridge, *p*, supported on two stout wooden posts, *q*, in rigid connection with the ground. (See fig. 4).

Between the two limbs (fig. 4) of the shorter arm, *m*, of the pointer there is fitted exactly a highly polished small axis, *r*, 3 mm. in diameter and 3 cm. in height, which forms the prolongation of the central line of the heavy cylinder, *a*, and which is pivoted in a stirrup, *s*, fixed to the latter.

To a small U-shaped frame of brass, *t*, at the end of the alminium arm of the pointer is hinged an exceedingly light writing index, *u*, made of a thin triangular piece, about 5 mgm. in weight, cut from a watch spring. The point of the index rests on the record-receiving smoked paper wrapped round a light wooden drum. (See § 7).

The effective lengths of the two arms, *m* and *n*, of the writing lever are respectively 28 and 280 mm., the pointer thus multiplying 10 times the horizontal motion of the ground.

It will be observed that the pressure, which the writing index exercises on the record-receiving smoked paper, is a small weight of only $\frac{5}{3}$ mgm., equivalent to one-third of the weight of the index, and this circumstance reduces the friction between the index point and the paper to a minimum. Again, the capability of free rotation of the axis, *r*, which serves as the "steady line," very effectually prevents friction coming into play between itself and the limbs of the forked arm, *m*, of the pointer when the pendulum is recording earth movements. Both of these details are indispensable in making the Horizontal Pendulum sufficiently sensitive to small *pulsatory oscillations.* (See § 13).

7. The record is taken on a smoked smooth paper wrapped round a light wooden drum, *v*, 942 mm. in circumference and 350 mm. in length, whose axis is formed by a brass rod 8 mm in diameter. The drum, which is turned by clock work[1], *w*, at the rate of one revolution in an hour, has at the same time a slow motion of translation in the direction of its axis, one of the external prolongations of the latter being screw-cut.

The time-marks on the record-receiver are given by the electric time-ticker, *x*, connected with a good clock, a signal being made once in a minute.

The drum, which together with its brass axis weighs about $\frac{1}{2}$ kgm. consists of a thin mantle of wood, strengthened by an inner hoop at the middle of its length. Further, to prevent the deformation of the mantle, each end is composed of a frame of the same wood, made up of exactly similar radial pieces, as shown in fig. 1.

8. The above description of the mechanical details applies equally well to each of the EW and NS component Horizontal Pendulums, which differ from each other only in the following two respects.

Firstly, the rate of translation of the drum is, for the EW component apparatus, 4 mm. per revolution, while for the NS component apparatus it is 3 mm. per revolution.

1. Provisionally a pendulum clock has been adopted. It would unquestionably be much better to employ a motor, which drives on continuously, regulated by a governor.

Secondly, the complete periods of vibration of the EW and NS component horizontal pendulums are at present, for a special purpose, set unequal to each other, being respectively 28 and 17 seconds. The period of each pendulum can be raised much above these values, but it was found convenient not to make it much above 30 seconds, in order to prevent the pendulums assuming too great deviations in their daily oscillations and other slow movements.

III.

9. Pl. III illustrates the portable form of my Horizontal Pendulum, recently set up in the Seismological Institute, fig. 6 and fig. 7 giving its front and side elevations.

The heavy-bob of the pendulum is a thin brass cylinder, *a*, filled with lead, $6\frac{1}{2}$ cm. in diameter, 9 cm. in height and about 3 kgm. in weight, attached at a little above its centre of gravity to a strut, *b*, which is an iron rod, 8 mm. in diameter, furnished at the end with a sharp conical point. The strut is pivoted in a conical steel socket, *c*, fixed to the base of a strong cast iron stand, *d*, which is bolted to a foundation column, and from whose top the pendulum is hung by means of a fine wire, *e*. The vertical distance between the points of support and suspension is 1 m., and the horizontal distance between the point of support and the axis of the heavy cylinder 75 cm. The lower end of the wire, *e*, is attached to the cylinder in a manner similar to that in the case of the instrument described in the preceding section.

10. Fig. 8 shows in section and plan the details of the mechanism applied to the top of the cast iron stand, by means of which the necessary adjustments can be effected.

The strut, *b*, is adjusted to a nearly horizontal position by means of a screw, *f*, to which the suspension wire is attached, and which passes normally through a closely fitting hole in a steel triangular prism, *g*. The edge of the knife has all been cut away except two small portions, *h* and *i*, on which the prism rests in a V-slot, *j*, in the inclined hypothenuse face of an isosceles right-angular iron prism, *k*, soldered to a large square screw, *l*. The latter passes through two closely fitting stirrups, *m*, attached to a thick brass plate, *n*, and the azimuthal position of the heavy cylinder, *a*, can be adjusted by appropriate movements of the screw, *l*, by means of the two nuts, *o*. For properly adjusting the period of vibration of the horizontal pendulum, the whole system is, in its turn, made to move forward and backward on the basal plate, *p*, by means of a screw, *q*. Finally, the two screws, *r*, fixed in the stirrup, *s*, rising from the basal plate, secures the plate, *n*, to the latter.

The right-angled prism, *k*, is so perforated as to allow the free passage through it of the screw, *f*. Rectangular cuttings, *t* and *u*, have also for the same purpose been made in the two plates, *n* and *p*.

The basal plate, *p*, is to be fixed to the top of the cast iron stand, *d*, with such an angle of inclination that the suspension wire is at right angles to the knife-edge.

11. The complete period of vibration of this form of the horizontal pendulum has been set at 20 seconds, but it can be raised much above this value, if desired, the maximum length of the complete period, with which the pendulum can be kept stable, being about 90 seconds. The comparatively low value of 20 seconds has been chosen for the sake of preventing the deviation of the pendulum becoming inconveniently great, the purpose here

being to observe only seismic and similar slight movements. The writing pointer and the record-receiver are precisely similar to those described in the preceding section, with the difference that the diameter of the wooden drum, which makes one revolution in about 40 minutes, is here 23 $\frac{1}{2}$ cm.

IV.

12. I shall now describe some typical diagrams given by my Horizontal Pendulums, the observations having been made, unless otherwise stated, with the instruments set up in the "Earthquake-proof House."

The ground is generally in movement of one kind or other, even when there is no earthquake, but sometimes it is almost still. (See fig. 19.) The duration of the calm epoch varies from a few days to a month or more.

13. The movements of the ground recorded by the Horizontal Pendulums may be divided into two classes, according as they are or are not of seismic origin. A non-seismic disturbance consists of small *pulsatory oscillations*, or movements of slow period[1], which varies usually between 4 and 8 seconds, the maximum range of motion yet observed by me being about 0.2 mm. in each horizontal component.

It is to be noted that in some pronounced storms of pulsatory oscillations, the range of motion is quite as wide as in small earthquakes, although these oscillations are quite imperceptible to the senses, on account of the slowness of period. It is also remarkable that the ground is so often disturbed by such storms,

1. The term *period* is used throughout the paper in the sense of the *complete period*.

each of which generally lasts for some days. Their effects must not be overlooked in determinations of the force of gravity and in other delicate measurements of geo-physics.

The period of the pulsatory oscillations seems to depend, to a slight extent, on the range of motion, the period of the larger movements in a given interval of time being usually a few tenths of a second longer than that of the smaller movements in the same interval. Again, the general average period of the pulsatory oscillations seems to remain nearly constant for a certain length of time, it may be even for several days.

The rate of motion of the smoked paper is, in the present forms of my Horizontal Pendulums, too rapid to allow of pulsations of several minutes period, as observed by Paschwitz, Milne, and others, being discerned.

Pronounced storms of pulsatory oscillations have been generally observed, when strong winds prevailed in Tokyo or its vicinity, as was the case from the 6th to the 7th, September 1898. (See fig. 9). Nevertheless, these movements have been met with in very quiet weathers, as was the case on the 14th and 15th October, 1898. (See fig. 10). For the sake of reference, I give, in Pl. XII, the weather maps for these days.

In the storm of pulsatory oscillations on the 6th and 7th September, 1898, the maximum range of motion was 0.2 mm. in each component. The average period of the oscillations of larger amplitude was 6.0 seconds, while that of the oscillations of smaller amplitude was 5.6 seconds.

In the storm of pulsatory oscillations on the 14th and 15th October, 1898, the maximum range of motion was 0.1 mm. in each component, the general average period being 6.8 seconds.

It must be understood that the period of the pulsatory oscillations is naturally the same always in both horizontal components.

14. I will next notice three more instances of storms of pulsatory oscillations.

Pulsatory oscillations on the 21st and 22nd May, 1898; EW component. The range of motion of one of the greatest movements was 0.16 mm. and its period 5.6 seconds. The motion was not uniform but presented, as is usually the case, alternations of maxima and minima, whose average interval was about 1 minute. The average period of the larger oscillations was 5.5 seconds, while that of the smaller in the same epoch was 5.2 seconds, the general average period being 5.4 seconds.

Pulsatory oscillations on the 5th and 6th June, 1898; EW component. The maximum range of motion was 0.15 mm. The average period of the larger oscillations was 5.7 seconds, while that of the smaller was 5.2 seconds, the general average period being 5.4 seconds.

Pulsatory oscillations on the 14th and 15th November, 1898. The average period of vibration was 4.5 seconds, the maximum range of motion being about 0.07 mm. in each horizontal component. The diagram of the NS component is given in fig. 11.

15. The pulsatory oscillations, as to whose reality there can be no doubt, have also been observed by myself with a Paschwitz Horizontal Pendulum newly constructed by Messrs A. Repsold and Sons for the Imperial Earthquake Investigation Committee. Fig. 13 (Pl. VI) exhibits a typical specimen of such movements obtained on the 10th April, 1898, in the University grounds (Hongo, Tokyo), the rate of motion of the photographic paper being 30 cm. per hour, and the proper

periods of oscillation of the EW and NS component horizontal pendulums being respectively 18.8 and 35.5 seconds. It will be observed that, in each component, pulsatory oscillations of period 4.0 seconds are superposed on the proper vibrations of the pendulum, the motion assumed to be horizontal (see § 16) being multiplied 37 times.

Fig. 14 is a similar diagram, with the same multiplication ratio, obtained on the 28th January, 1898, showing one of the most remarkable storms of pulsatory oscillations, which I have so far observed. The average period of vibration of the oscillations was 5.5 seconds, while the maximum range of motion in each horizontal component was 0.15 mm.

16. *On the nature of the pulsatory oscillations.*

The small slow movements, termed here pulsatory oscillations, are not, in general, identical with the microseismic disturbances indicated by ordinary short-period simple pendulum tromometers; or those indicated by a Paschwitz Horizontal Pendulum, when the rate of motion of the photographic paper is small, say a few centimetres per hour. The movements in these cases are simply the proper oscillations of the pendulum, and they have apparently no connection, at least no simple and general connection, with the pulsatory oscillations. Fig. 15 represents an instance, in which the proper motion of the Paschwitz Horizontal Pendulums was great, yet unaccompanied with any pulsatory oscillations.

It is a very important matter to determine whether the pulsatory oscillations are purely horizontal movements or components of tiltings due to undulations of the ground like waves of water. If horizontal movements only, their recorded amplitude would not depend on the proper period of vibration of the horizontal pendulum, but simply upon the ratio of the multiplication by the writing pointer. On the other hand, if the pulsatory oscillations be due to tiltings of the ground, the recorded amplitude of motion would depend both on the multiplication ratio of the writing pointer and on the proper period of the pendulum. Thus, if n be the multiplication ratio of the pointer; l, the distance between the end of the strut and the centre of the heavy-bob; φ, the angle of inclination of the axis of support of the pendulum to the vertical; α, the angular amount of the change of level of the ground in direction normal to the plane of the pendulum; and r, the motion of the point of the writing pointer, we have —

$$r = n\, l\, \frac{\alpha}{\varphi}$$

or

$$r = n\, l\, \alpha\, \frac{T^2}{T_0^2},$$

in which T is the complete period of vibration of the horizontal pendulum, and T_0 its period when the pendulum swings vertically. In our case, the EW and NS component Horizontal Pendulums are exactly similar to each other, except in the values of the T's, which are respectively equal to 28 and 17 seconds (§ 8). The ratio of the range of motion as recorded by these two apparatus would, for a given value of α, be as $28^2 : 17^2$, that is to say, as 2.7 : 1. If, therefore, the pulsatory oscillations be due to the tiltings of the ground, the range of motion would, allowing for the alternations of maxima and minima, be shown, on the whole, nearly three times greater in the EW component apparatus than in the NS one. Such, however, is not the case, the range of motion being always equal in the simultaneous diagram of the two component pendulums.

Fig. 12a and fig. 12b are the EW component diagrams of the pulsatory oscillations on the 14th December, 1898, the former given by the Horizontal Pendulum of the portable form described in section III, and the latter given by the EW component apparatus in the "Earthquake-proof House." It will be observed that the range of motion is the same in the two diagrams, although the too instruments had different periods of proper oscillation and different lengths of struts, and conseqently were differently sensitive to tilting movements. (See also § 26).

Again, with respect to the Paschwitz Apparatus diagrams, fig. 13 and fig. 14, the periods of free oscillation of the NS and EW component pendulums were respectively 35.5 and 18.8 seconds, the ratio of the squares of these two numbers being nearly as 4 : 1 ; but the range of motion of the pulsatory oscillations was the same on the whole, in the two components.

I conclude, therefore, that the pulsatory oscillations, at least those of the kind here considered, are *horizontal movements* and not tiltings of the ground. The direction of motion of these oscillations is evidently changing from time to time.

V.

17. *Seismic disturbances.* Seismic disturbances, or the movements due to earthquakes, are frequently recorded by Horizontal Pendulums in Tokyo, which is evidently a very favourable place for seismological observation.

They may conveniently be divided into two classes, namely, those of near origin, and those of distant origin. Some typical examples of the former class shall first be given.

18. Every small local shock, as shown in fig. 19, begins with a *preliminary tremor* of a few seconds duration, the motion consisting of vibrations of short period superposed on more or

less distinct slow undulations. The duration of such shocks is short, being, when recorded by ordinary seismographs, usually less than 1 minute. But, when recorded by the Horizontal Pendulums, their duration is found generally to be longer than 10 minutes.

In local shocks, movements of a very long period, say much above 10 seconds, seem not to exist.

19. Fig. 19 gives the NS component diagrams of three small shocks, marked A, B and C, which happened in the night of the 15th and in the morning of the 16th September, 1898.

A. The 16th September, 1898; 8.32.31 a.m. The total duration was about 12 minutes, and the duration of the preliminary tremor about 16 seconds. At first quick movements were superposed on slow ones, the average period of vibration in the end portion of the shock being 3.8 seconds. The maximum range of motion was 0.3 mm. in each horizontal component.

B. The 16th September, 1898; 4.48.23. a.m. The total duration was about 17 minutes, and the duration of the preliminary tremor about 27 seconds. In the principal portion of the earthquake, there seems to have existed traces of slow undulations, whose period was 5.3 seconds. The average periods of vibration for three successive series of 40 vibrations, measured from about $3\frac{1}{2}$ minutes after the beginning, were found to be 3.5, 3.9 and 5.5 seconds. The maximum range of motion was 0.4 mm. in the EW and 0.5 mm. in the NS component.

C. The 15th September, 1898; 4.57.35 p.m. A very small shock, whose total duration was $8\frac{1}{2}$ minutes. The average period of the prevailing waves was 4.3 seconds, these being superposed by others still smaller.

20. The earthquake of the 23rd April, 1898. This was a large earthquake, whose centre was not very distant from the observing station, being under the ocean about 400 km. NE by N of Tokyo. The area of disturbance, within which the shock was strong enough to be felt without instrumental aid, was very extensive, its longest and shortest axes being respectively about 650 and 380 km. Along the east coast of the northern part of the Main Island the shock was sufficiently strong to damage some buildings. In Tokyo itself the earthquake was felt as mild shakings of long duration.

The NS component diagram of the earthquake is shown in fig. 16. (The EW component apparatus was then not ready). The shock began at 8. 37.0 a.m., and, after about 50 seconds of preliminary tremor, the motion became large, till at 1 m. 14 s. from the commencement the pointer got off (at *A*) the record-receiver. At 8 m. 41 s. from the commencement, I put (at *B*) the pointer again on the smoked paper. The motion was then still pretty large, but standing perfectly still, I could feel absolutely nothing of it. The subsequent motion was recorded to the end, the pointer having been purposely displaced from *E* to *E′* and again at *H* in order to avoid the overlapping and confusion of several lines. The total duration of the earthquake was about 2 hours.

The earthquake motion may be considered to have consisted of two kinds of vibrations: firstly, of waves whose periods were short and included between a fraction of a second and about two seconds; and secondly, of waves whose periods were long and varied from 5 seconds to about 12 seconds. Ordinary seismographs would have recorded the waves of the first order, but would have been incapable of recording those of the second.

At first, waves of both kinds occurred together (superposed by some traces of the proper motion of the horizontal pendulum, which, however, are easily distinguishable, on account of the great length of the period of the pendulum itself). The small movements, *p*, *q*, *qr*, *st*, etc., belong to the first kind, while the large displacements, *a b c*, *c d e*, etc., belong to the second kind. It will easily be observed that the waves of the first kind soon disappeared, leaving behind only those of the second.

The range of motion of the principal displacements of the waves of the second kind, which I assume to be horizontal movements and not tiltings of the ground, (see § 26 below) were as follows :—

Displacement.	Range of Motion.
a b	5.1 mm.
b c	5.0 ,,
d e	6.4 ,,
f g	12.6 ,,

Again, the periods of vibration of the two waves, *a b c* and *c d e*, were respectively 5.8 and 7.9 seconds. If the period of the motion *f g* be assumed to be 8 seconds, we find by calculation

maximum velocity=5 mm. per sec.,

maximum acceleration=3.5 mm. per sec. per sec.

These values of the maximum velocity and the maximum acceleration are very low, a fact which explains why we do not feel such movements. The range of motion of one of the principal displacements of the first kind, *s*, was 2.3 mm.

This earthquake enables us on account of its great duration to calculate the average periods in several portions of its motion. Beginning with a point marked *B* in the diagram, I find for the average periods of five series of successive 60 complete vibrations —

Succcssive values of the average period.	Difference.
6 . 6 seconds.	
	0 . 7 second.
7 . 3 ”	
	0 . 8 ”
8 . 1 ”	
	0 . 8 ”
8 . 9 ”	
	0 . 8 ”
10 . 7 ”	

There is thus in this case an apparent arithmetical increase in the average period of vibration, which was in the beginning about 6 seconds and at the end about 11 seconds, the rate of increase of the period amounting to about 0.8 second in every 60 complete vibrations, that is to say, to about 7.5 seconds every hour of the duration of the disturbance. Such an increase in period during an earthquake, which can only be definitely ascertained in shocks of long duration, should be, I belive, hardly perceptible at very great distances from the origin of disturbance.

From the diagram of this earthquake, it is evident that the movements of a great earthquake consist generally of slow undulations superposed upon quick vibrations, different waves being probably generated simultaneously at the centre of disturbance.

One of the after-shocks of this earthquake is also shown in the diagram (fig. 16). The total duration was about 12 minutes, and the average period of the prevailing vibrations in the principal portion was 6.0 seconds, the maximum range of motion being 0.3 mm. Measuring 3 minutes after the commencement, the average period of slow undulations was found to be 7.0 seconds. Near the end the average period was 5.3 seconds.

21. The earthquake of the 26th May, 1898.

This earthquake originated in the province of Echigo, near the town of Tokamachi, about 140 km. NW of Tokyo. In the meizoseismal area, the shock caused much damage to buildings, although it levelled none to the ground. In Tokyo the motion was strong enough to cause people to run out of doors.

The diagram obtained from the two component Horizontal Pendulums are reproduced in fig. 17 and fig. 18. The earthquake began at 3.0.0 a.m., and after 17 seconds the motion became large, till at 90 seconds from the commencement, the EW component pointer went off the record-receiver. The motion in the NS component, which was not so large as in the other component, was successfully recorded to the end. The total duration, notwithstanding the violence of motion, was short, amounting to only about 30 minutes.

The NS component. The motion began with long-period vibrations, of which there were 8 well-defined ones with an average period of 10.4 seconds. The range of motion of one of the most prominent of these vibrations was 5.6 mm., its period being 10.8 seconds. Then followed a great number of well-defined vibrations, whose period, averaged from the first 50 vibrations, was 4.0 seconds. The two maximum movements belonging to this group, which occurred respectively at 62 and 96 seconds from the commencement were the following:—

{range of motion 11.7 mm., period 4.8 seconds;
{range of motion 11.7 mm., period 4.2 seeonds.

This epoch of the most active motion was followed by a short interval of time, during which the motion was small and superposed by ripples. Then followed again rather well-defined waves of a slightly longer period, interrupted sometimes by a short interval of irregular movements, the period, averaged from 103 vibrations, being 6.0 seconds. Later on, the period averaged from 68 vibrations was 7.0 seconds.

The EW component. The motion was small and complex during the first 50 seconds, quick vibrations being superposed on slow undulations. The motion became then regular and larger, till at 90 seconds from the commencement the writing pointer went off the smoked paper, when the amplitude became greater than 13.5 mm. and therefore the range of motion greater than 27 mm. The period of this vibration being about 8.5 seconds its maximum velocity and maximum acceleration would be respectively greater than 10 mm. per sec. and 7.4 mm. per sec. per sec.

One of the after-shocks of this earthquake, which took place at 4.54.0. a.m., is shown in figs. 17 and 18. The total duration was about 9 minutes. The motion began with 6 undulations of the average period of 10 seconds, the maximum range of motion being 0.3 mm. in the EW and 0.2 mm. in the NS component. The next 9 undulations were a little quicker, their average period being 6.1 seconds. The average period near the end was 4.6 seconds.

22. As examples of earthquakes, whose origins are at such distances from the observing station that the movements can no longer be registered by ordinary seismograghs, I take those shocks which occurred on the 10th and the 12th August, 1898, and on the 7th October, 1898.

23. The earthquake of the 10th August, 1898; 10. 0. 41 p.m.

The meizoseismal area, in which buildings were damaged, landslips produced, etc., was a limited portion of the west of the Province of the Chikuzen (in the Island of Kiushiu), about 900 km. W SW of Tokyo. The total duration was about

$9\frac{1}{2}$ minutes. The average period of vibration in the preliminary tremor, whose duration was about 22 seconds, was 3.7 seconds. The average period of vibration in the principal portion was 7.2 seconds, the maximum range of motion being 0.15 mm. in each component. Towards the end, the average period was 3.7 seconds.

24. The earthquake of the 12th August, 1898 ; 8.38.33 a.m.

The total duration of this earthquake, whose origin was approximately in the same locality as in the preceding case was about 30 minutes. The average period of vibration in the preliminary tremor, whose duration was 122 seconds, was 3.7 seconds. Then followed 15 larger undulations of the average period of 3.7 seconds, the maximum range of motion being in the EW component 0.2 mm. and in the NS 0.1 mm. The average period of the next 30 vibrations was 7 seconds, the maximum range of motion being in the EW component 0.4 mm. and in the NS 0.2 mm. Towards the end, the average period of 60 vibrations was 7 seconds, and that of the next 60 vibrations 8.1 seconds. The diagrams are given in figs. 20 and 21.

25. The earthquake of the 7th October, 1898 ; 11.1.1 a.m.

This earthquake, which shook, with varying force, the northern part of the Main Island and the southern part of Hokkaido, had its origin in the Pacific, off the eastern coast of the Province of Rikuoku, about 640 km. NE by N of Tokyo. The total duration was about 30 minutes, while the duration of the preliminary tremor was 82 seconds. The average period of the prevailing slow undulations in the principal portion was 6.0 seconds, the maximum range of motion being in the EW component 0.3 mm. and in the NS 0.45 mm. The average period later on varied between 3.9 and 6.1 seconds, becoming longer towards the end.

26. The earthquake of the 7th November, 1898 ; 2. 57.11 a.m.

The origin of this earthquake is unknown, but its distance from Tokyo was probably not above 1000 km. The total duration was 20 minutes, while the duration of the preliminary tremor was about 18 seconds. The average period of the prevailing slow undulations, of which there were six, in the principal portion, was 8.2 seconds. From about 2 minutes after the commencement, waves became prominent, whose average period was 4.0 seconds, and whose maximum range of motion was in the EW component 0.7 mm. and in the NS 0.5 mm. Near the end, the average period was 6.6 seconds, the waves being superposed on others with an average period of about 4 seconds.

In fig. 22*b*, is reproduced the EW component diagram of the earthquake as given by the Horizontal Pendulum of the portable form. It will be observed that the diagram, allowing for some insignificant traces of the proper motion of the pendulum, is identical with that in fig. 22*a*, which was given by the EW component Horizontal Pendulum in the "Earthquake-proof House."

The question whether the slow undulations of earthquakes are horizontal movements or due to tiltings of the ground may be discussed from a point of view similar to that stated in § 16 in connection with non-seismic movements. Thus, the groups of undulations marked *a* in the two diagrams are identical with one another. Now the periods of free vibrations of the large and the portable horizontal pendulums were respectively 28 and 20 seconds, while their struts were respectively 1 m. and 75 cm. long, the multiplying ratio of the writing pointer being for each of the instruments equal to 10. If, therefore, the undulations, *a*, be due to the tilting of the ground, the ranges of motion in the two apparatus would be to each other as 784 : 400, or nearly as 2 : 1. Such, however, is not the case, the range of motion being equal in the two diagrams. Hence I conclude that the undulations in question, as probably also most of the movements of this earthquake recorded by the Horizontal Pendulums, are *horizontal movements*, rather than tiltings, of the ground.

The slow undulations, which occur in the Horizontal Pendulum records of earthquake disturbances emanating from very distant origins, and whose periods are sometimes as long as 20 seconds or even more, are also probably due to horizontal movements of the ground, being evidently of the same nature as the group of undulations marked *a* in the diagrams of figs. 22 *a* and 22 *b*.

VI.

27. *Earthquake disturbances proceeding from distant origins.*

I have already stated in the preceding section that short-period vibrations occur only in the earliest portions of an earthquake, these becoming probably dissipated, by the viscosity of the material constituting the earth's crust, more rapidly than the long-period undulations, which alone remain in the later portion of the shock. Hence it is to be expected that the disturbance coming from a very distant source would consist of only slow undulations.

The duration of a great, distant, seismic disturbance amounts not seldom to $2\frac{1}{2}$ or even 3 hours. The following is an example of such an earthquake.

28. Earthquake of the 17th November, 1898; 9. 54.44p.m.

For the diagram see figs. 23 and 24. The total duration of the earthquake was about $2\frac{1}{2}$ hours. The preliminary tremor, whose duration was about 4 minutes, consisted of vibrations of an average period of 8.4 seconds, with some traces of small movements of a shorter period imposed upon it. Then followed 13 large slow undulations, whose maximum range of motion was in the EW component 1.6 mm., and in the NS 3.0 mm., the average period being 22 seconds. In the next epoch, the period became shorter, the value averaged from 38 vibrations during about 9 minutes being 13 seconds. In the following portion of the shock, the range of motion became small, the value of the period, averaged from successive series of 50 vibrations, being 13, 13, 12, 10, 11, 11 and 10 seconds. Near the end, the average period was 11 seconds.

To estimate the lengths of the waves constituting this earthquake, I shall assume the velocities of propagation of the very first tremors and of the principal undulations to be respectively 13.0 and 3.6 km. per second, these values being the mean results deduced from observations in Europe of the Japan Earthquake (origin in the Pacific) of the 20th Feburary 1897 and of the great Indian Earthquake of the 12th June, 1897. In our case, the period of waves in the preliminary tremor and in the principal portion being respectively 8.4 and 22 seconds, the corresponding wave-lengths come out as about 110 and 80 km.

December, 1898. Seismological Institute.

Fig. 4. Scale about 1/4

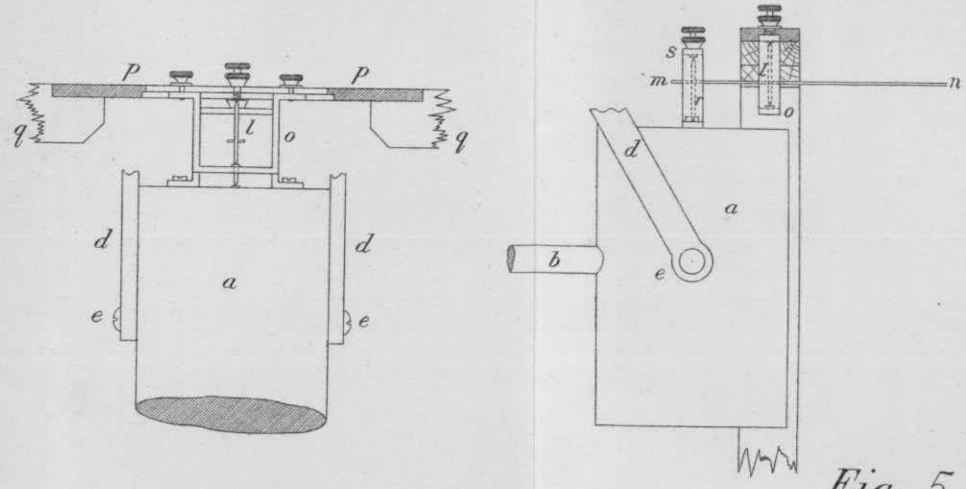


Fig. 5.

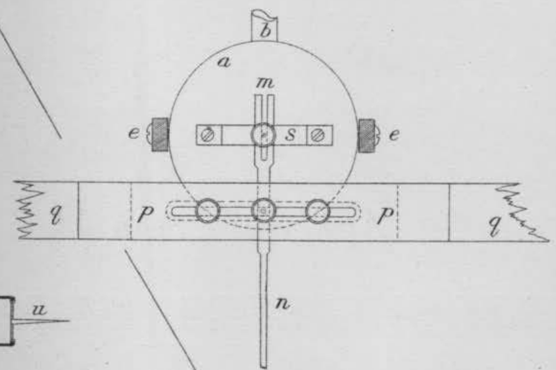
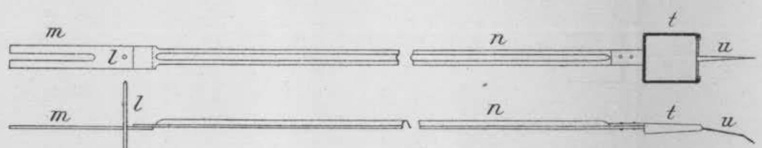


Fig. 3. Scale 1/2



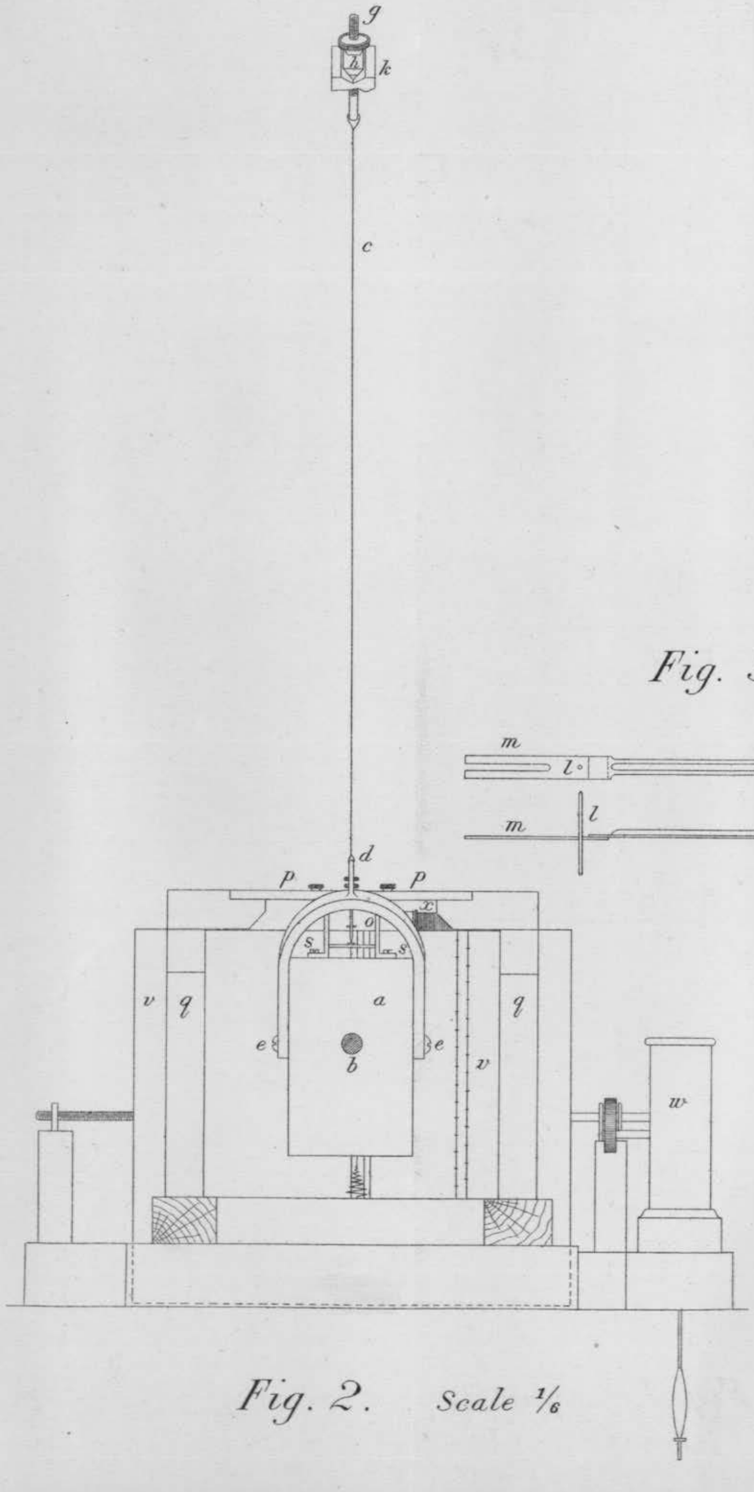
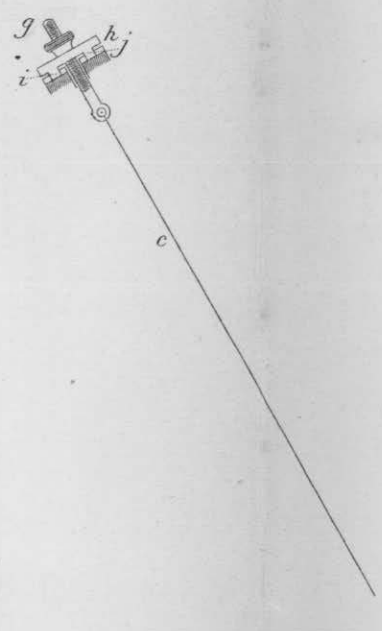


Fig. 2. Scale 1/6



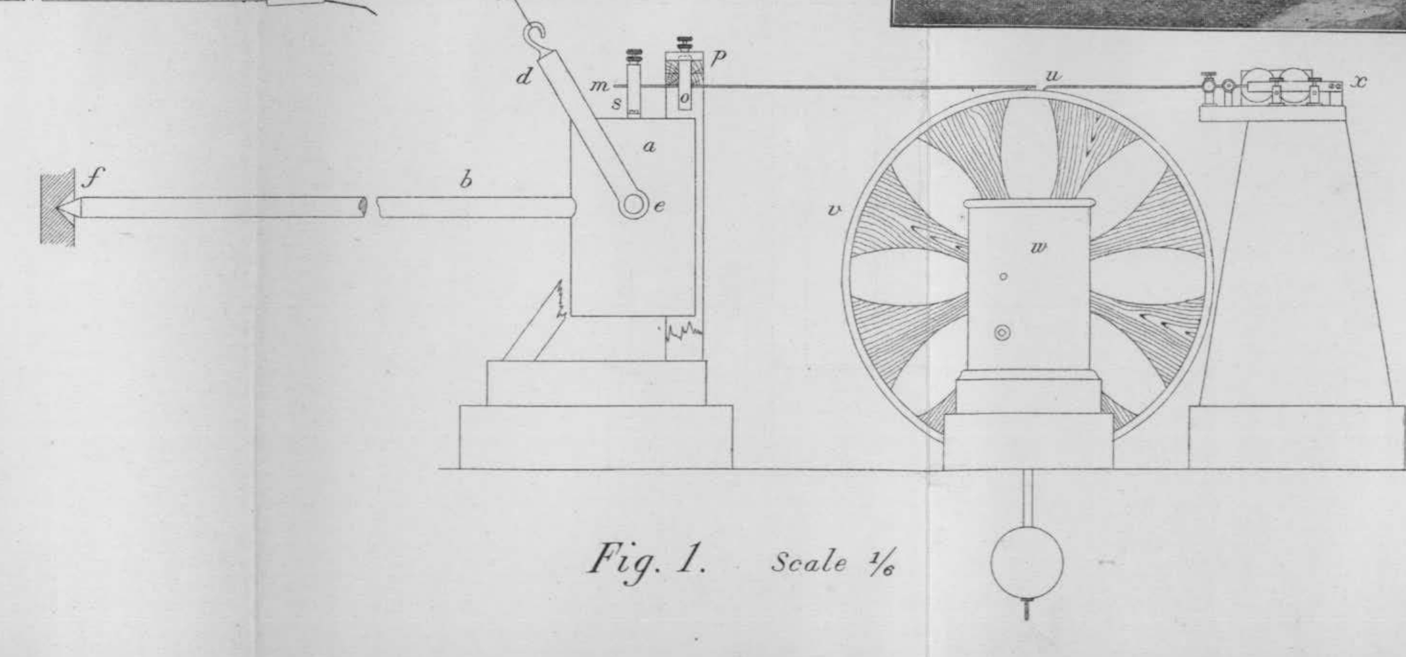


Fig. 1. Scale 1/6

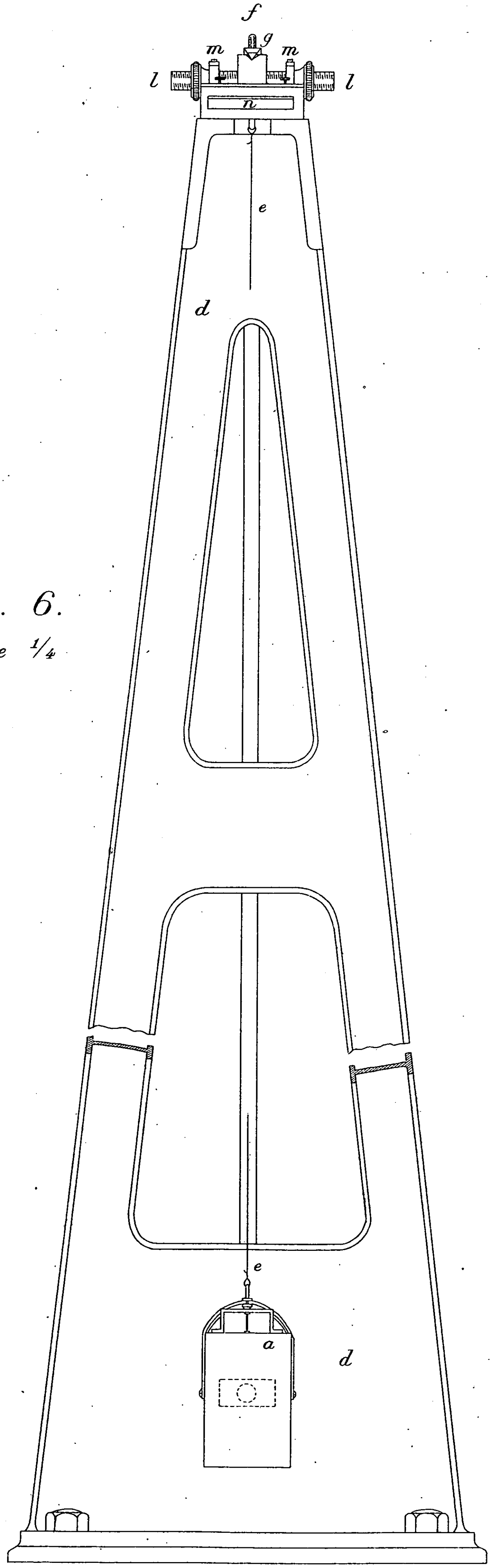


Fig. 6.
Scale 1/4

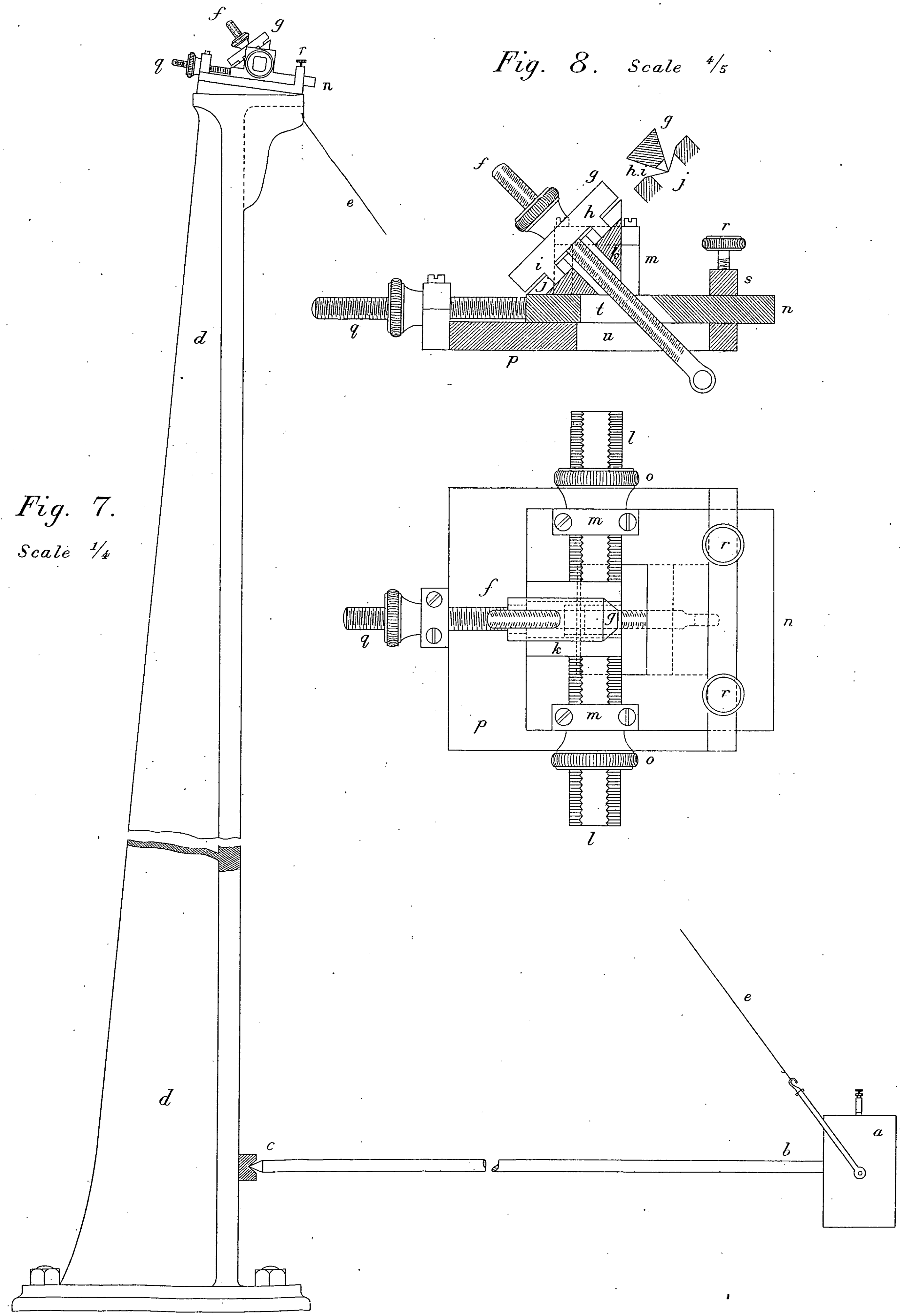


Fig. 7.
Scale 1/4

Fig. 8. Scale 4/5

Fig. 9. Pulsatory Oscillations on Sept. 6th—7th, 1898. (NS component).

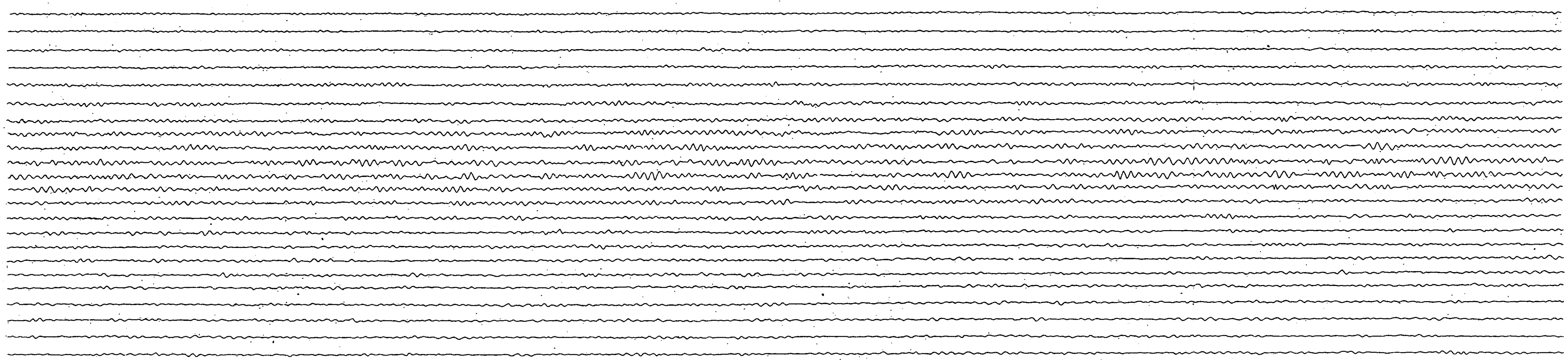


Fig. 10. Pulsatory Oscillations on Oct. 14th—15th, 1898. (NS component).

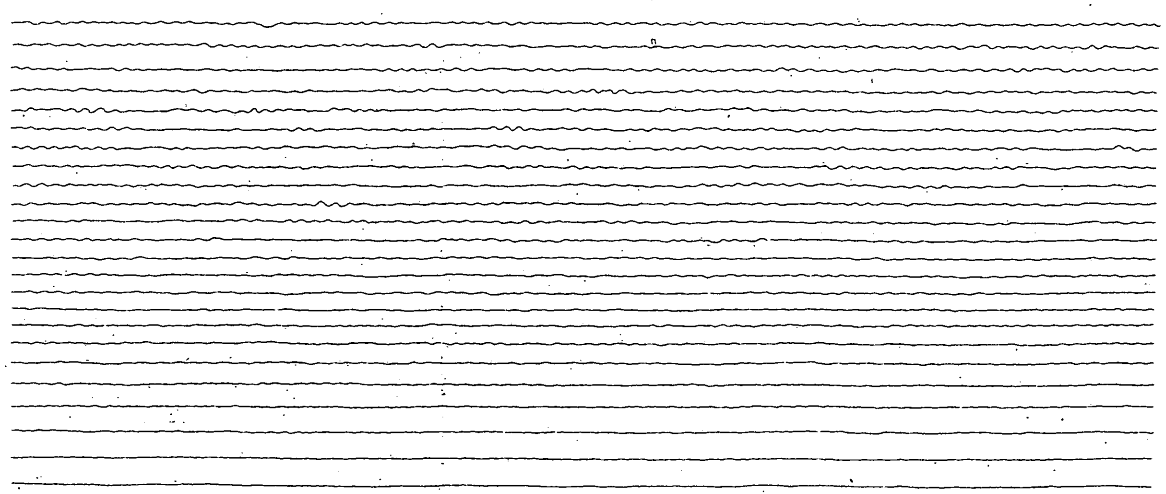
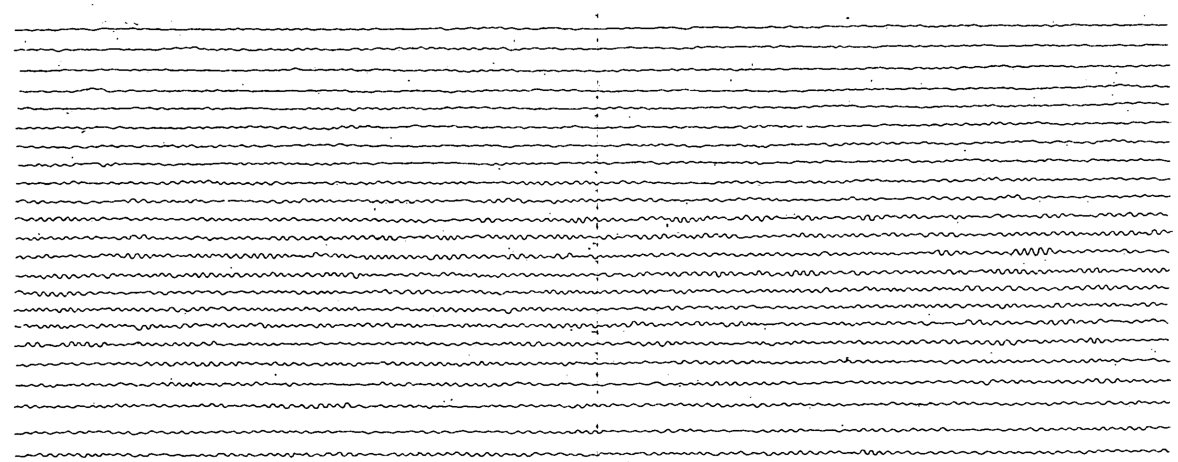
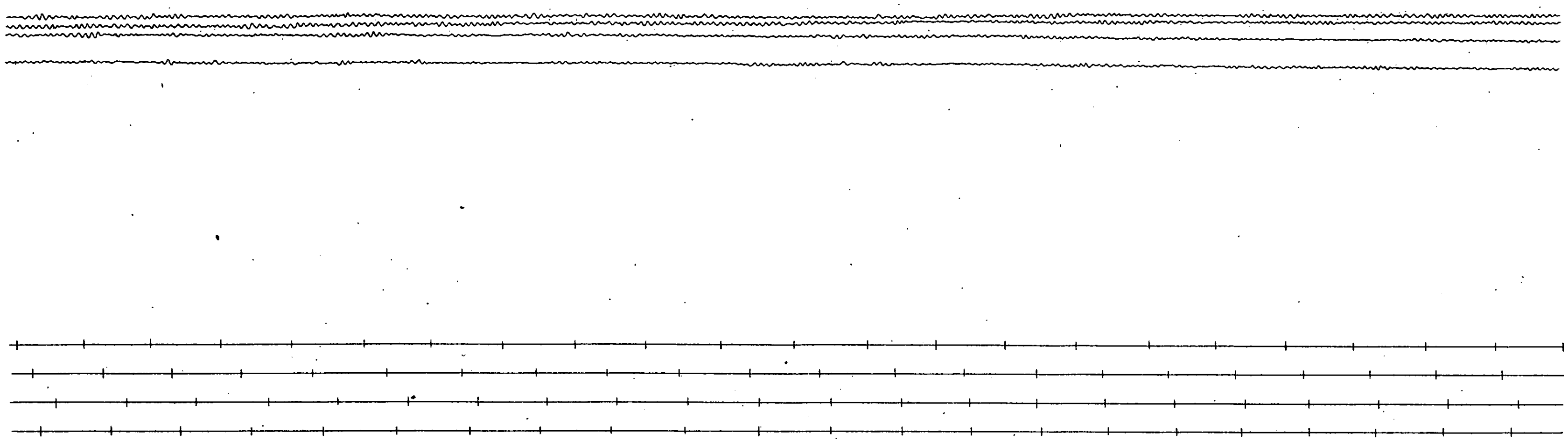


Fig. 11. Pulsatory Oscillations on Nov. 14th—15th, 1898. (NS component).



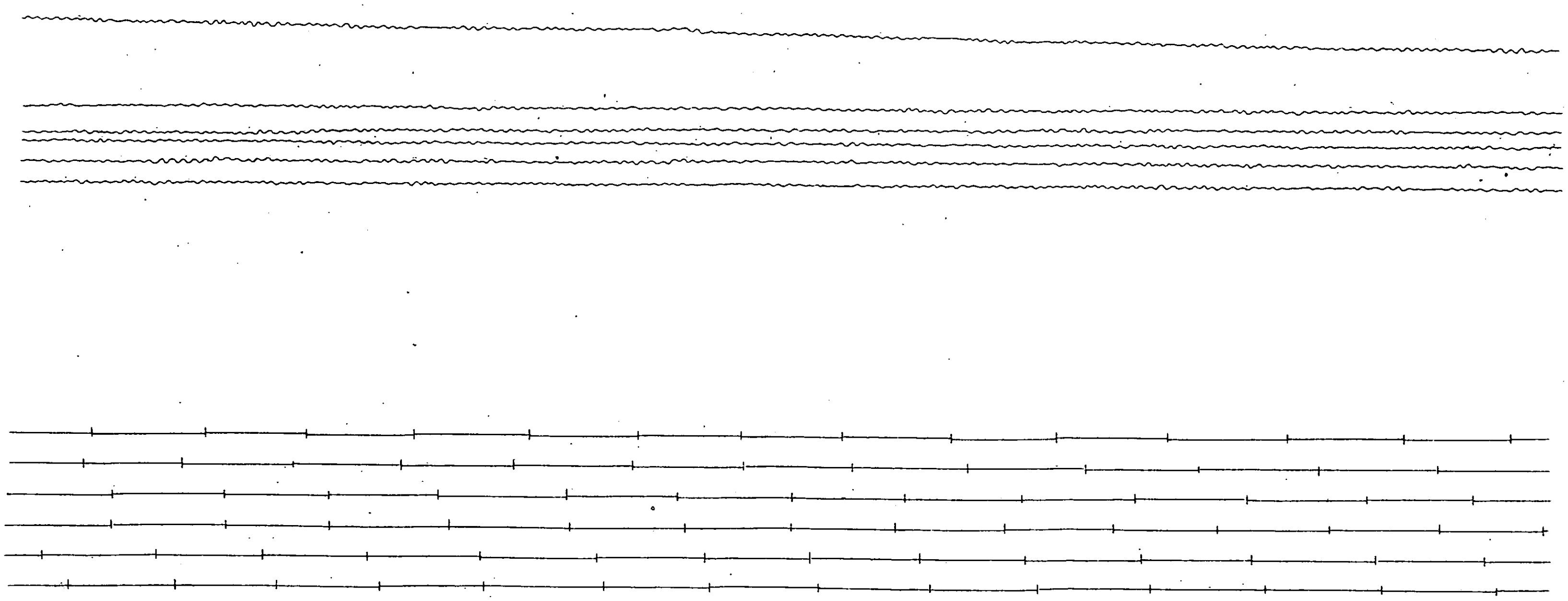
Time scale (1 mm = 3.7 sec.).

Fig. 12a. Pulsatory Oscillations on Dec. 13th—14th, 1898. (EW component).



Time : 1 tick interval = 1 minute.

Fig. 12b. Pulsatory Oscillations on Dec. 13th—14th, 1898. (EW component).



Time : 1 tick interval = 1 minute.

Fig. 13.

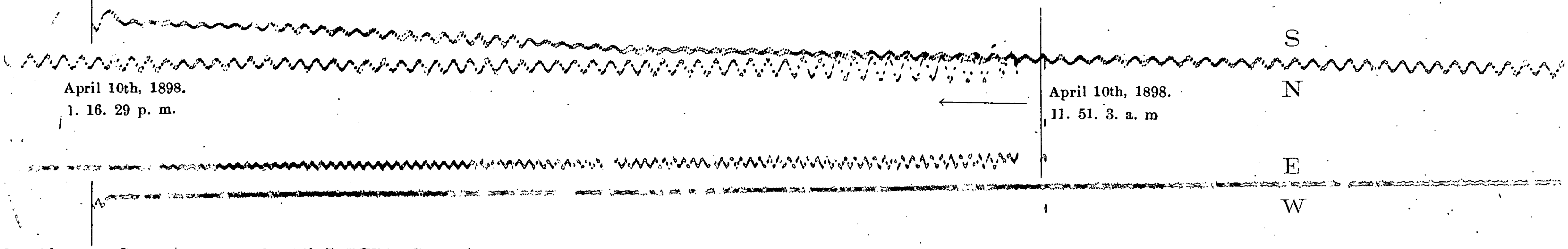


Fig. 14.

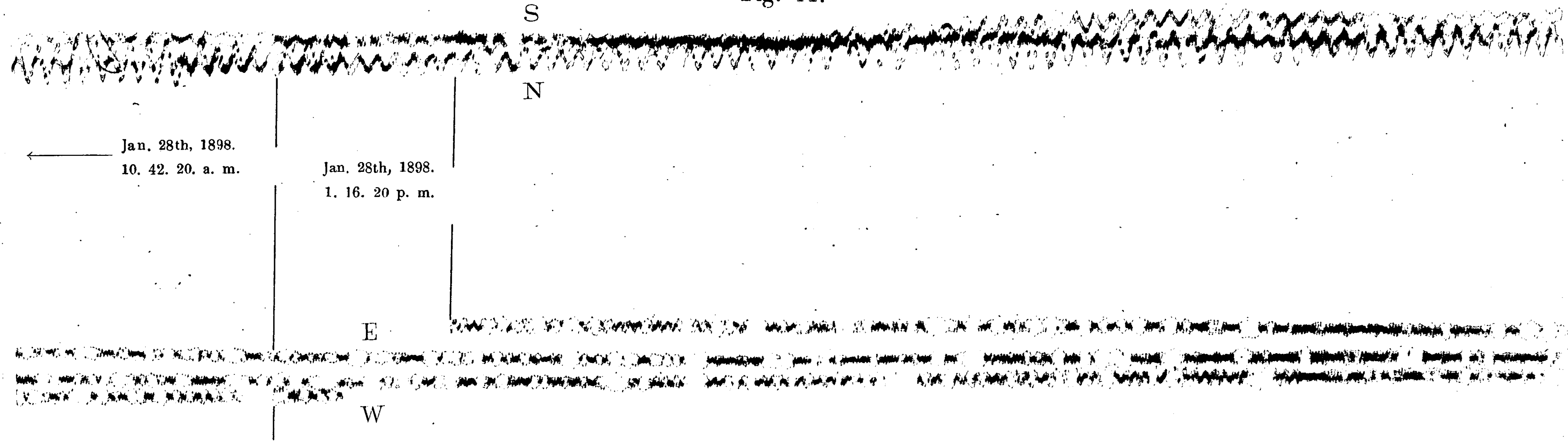
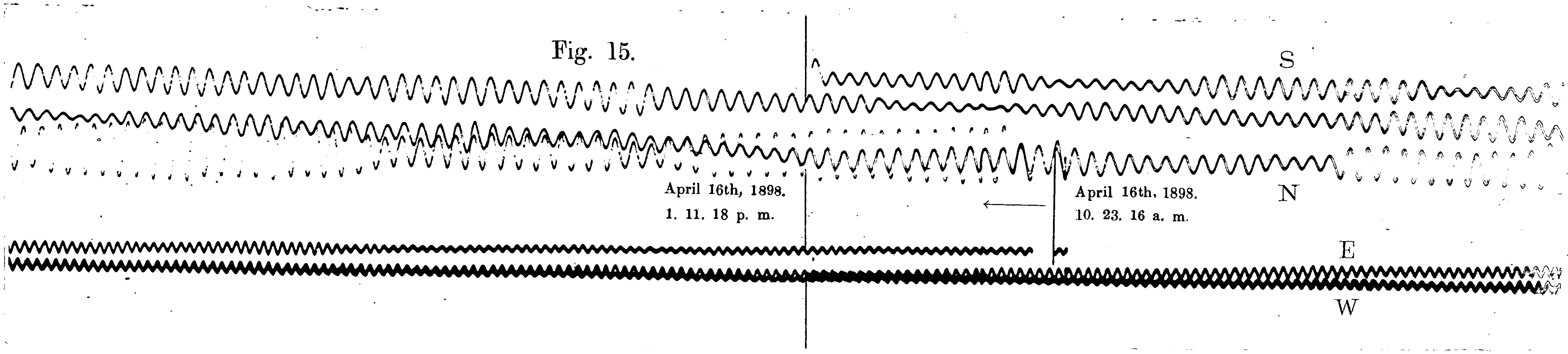


Fig. 15.



Time scale

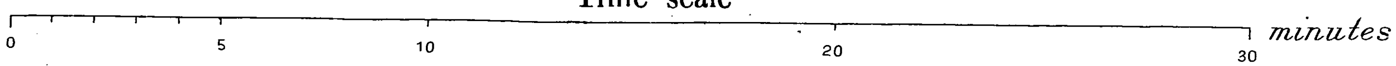


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Fig. 16. The Earthquake of April 23rd, 1898, and its after–shock. (NS component)

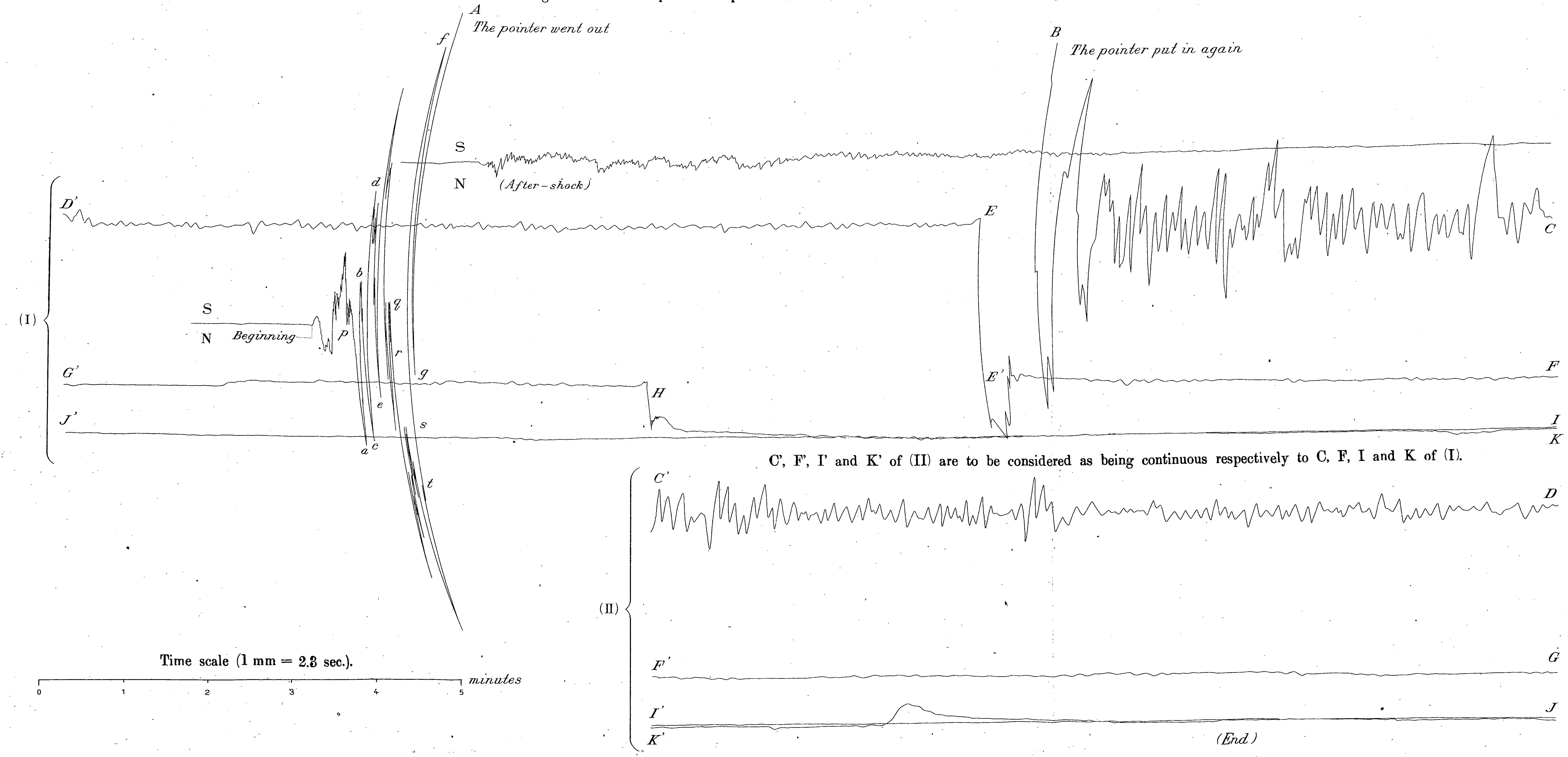


Fig. 17. The Earthquake of May 26th, 1898, and its after-shock. (NS component).

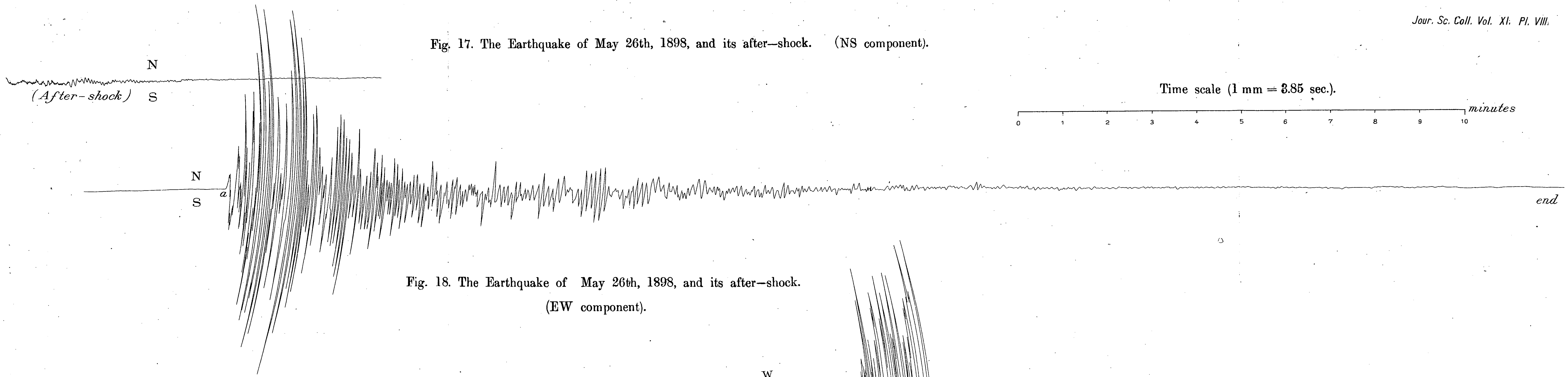


Fig. 18. The Earthquake of May 26th, 1898, and its after-shock. (EW component).

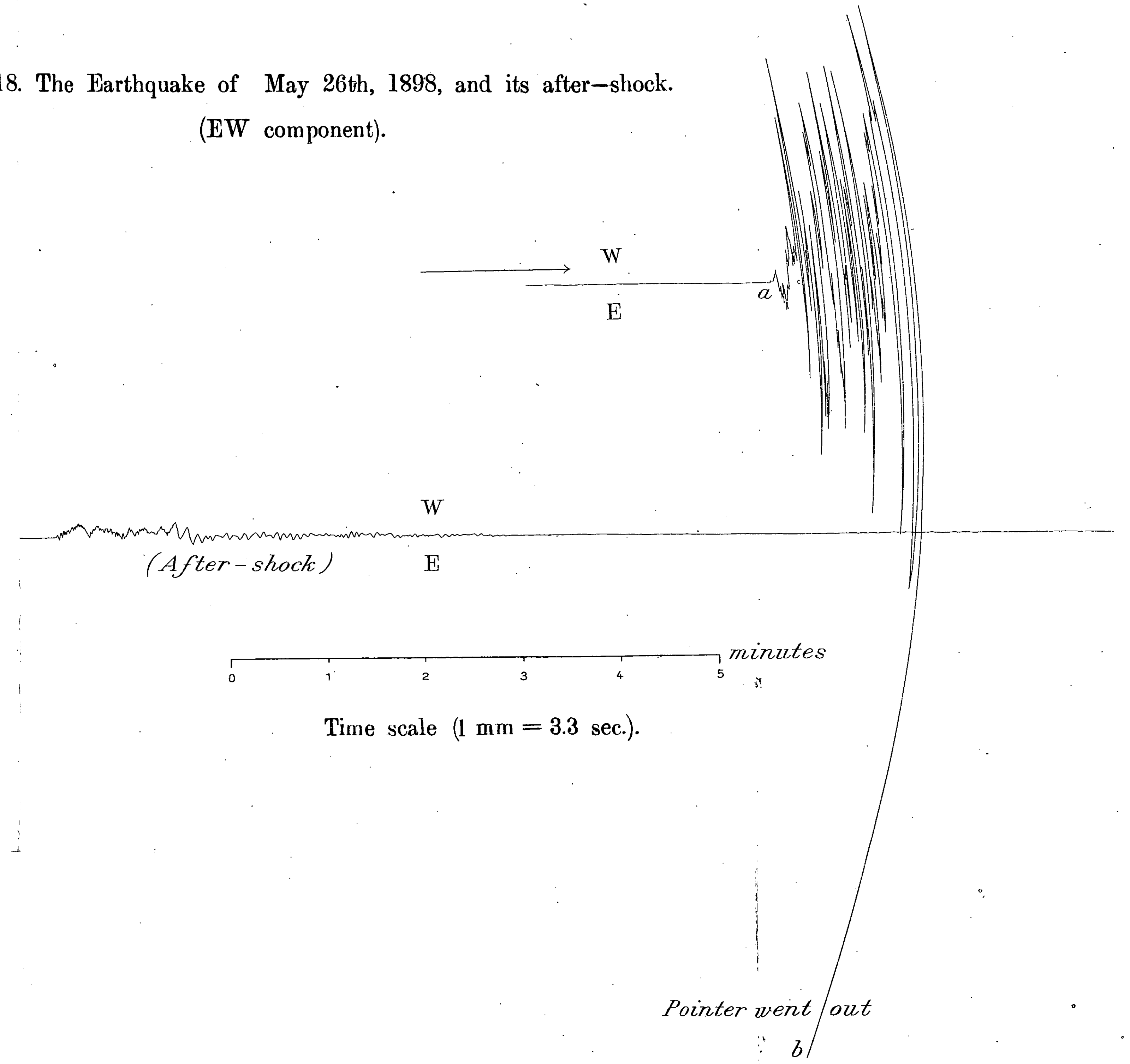
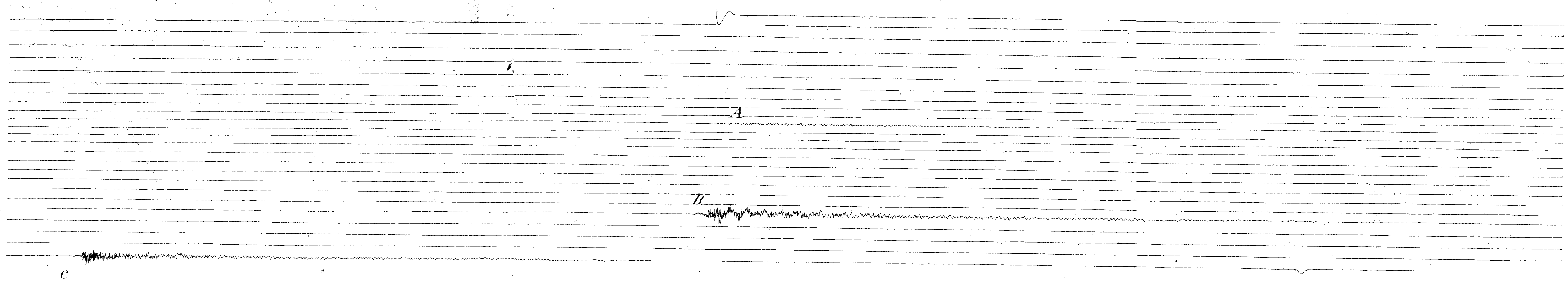


Fig. 19. Three local shocks (A, B and C) of Sept. 15th—16th, 1898. (NS component).



Time scale for fig. 19 and fig. 20. (1 mm=3.8 sec.).

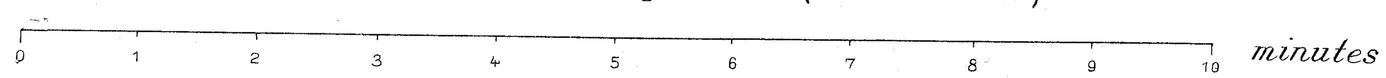


Fig. 20. The Earthquake of August 12th, 1898. (NS component).

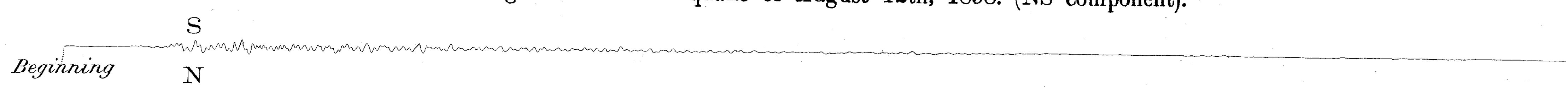
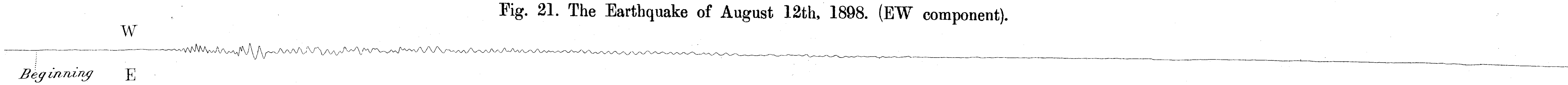


Fig. 21. The Earthquake of August 12th, 1898. (EW component).



Time scale (1 mm = 3.3 sec.).

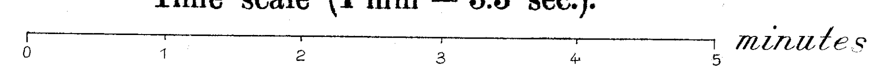
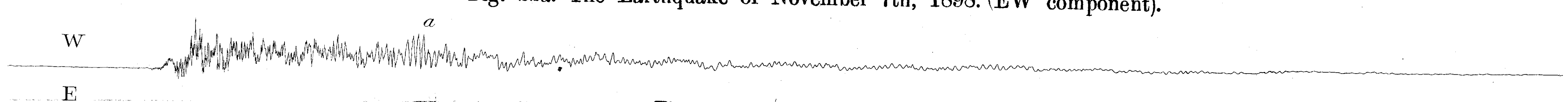


Fig. 22a. The Earthquake of November 7th, 1898. (EW component).



Time scale (1 mm = 3.72 sec.).

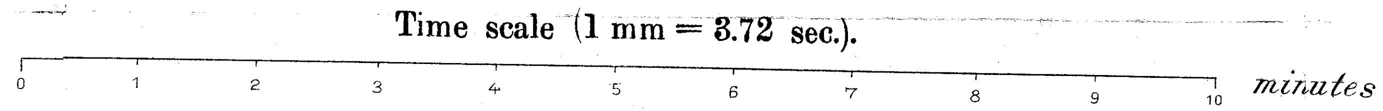
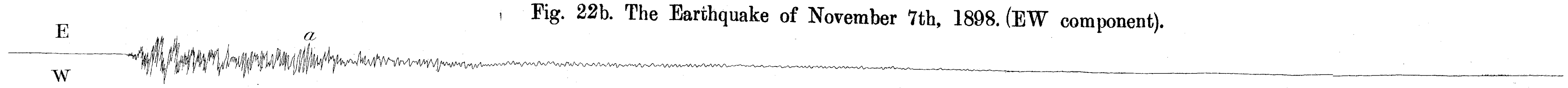


Fig. 22b. The Earthquake of November 7th, 1898. (EW component).



Time scale (1 mm = 5.03 sec.).

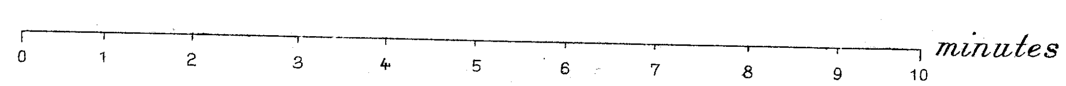
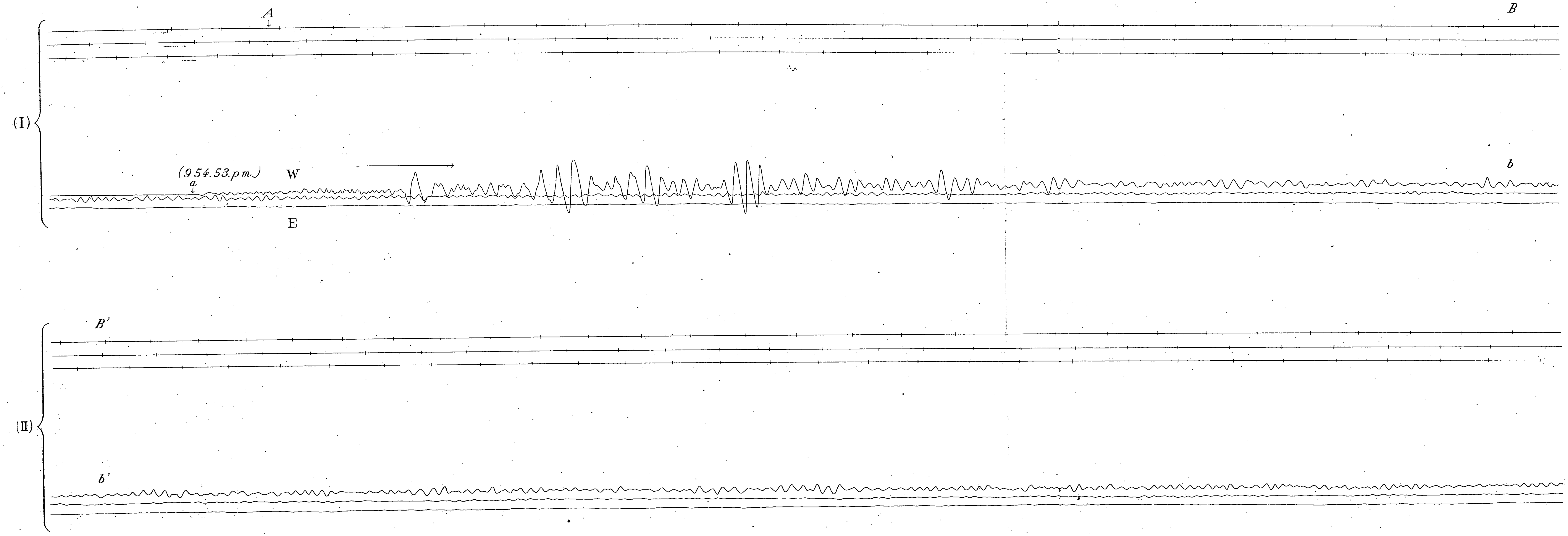
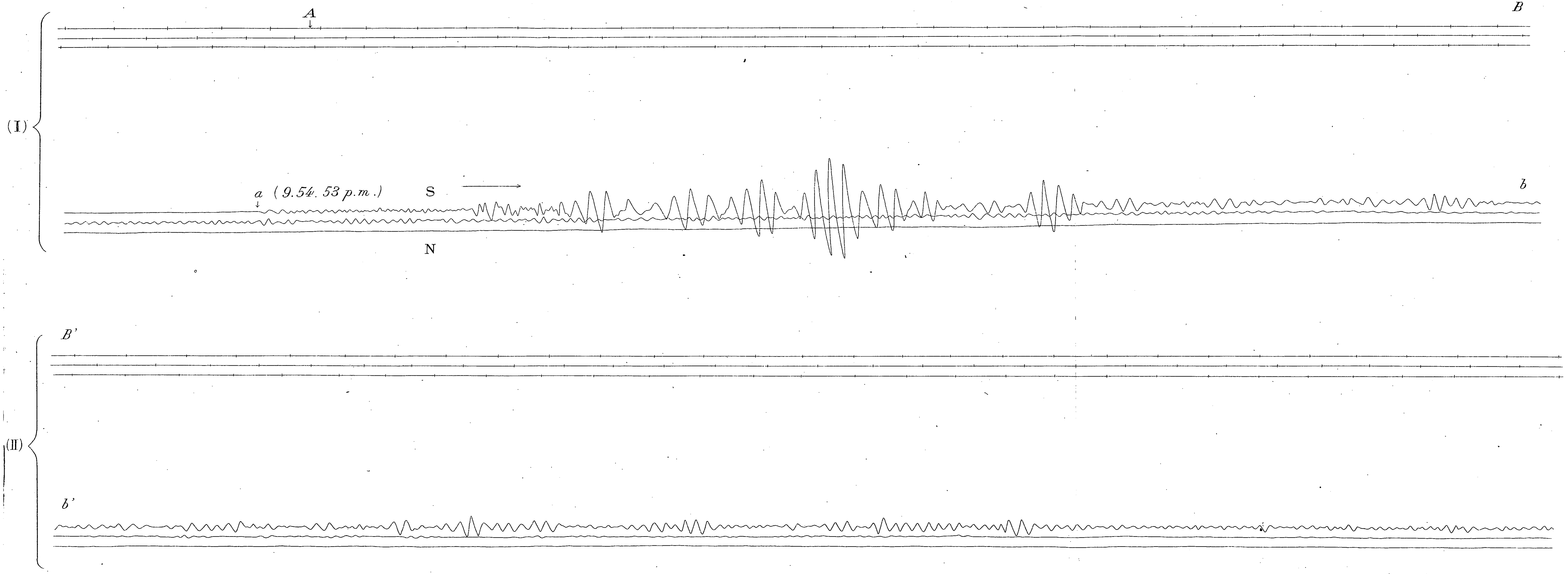


Fig. 23. The Earthquake of November 17th, 1898. (EW component).



B and b of (I) are to be considered as being continuous respectively to B' and b' of (II). Time : 1 tick interval = 1 minute.

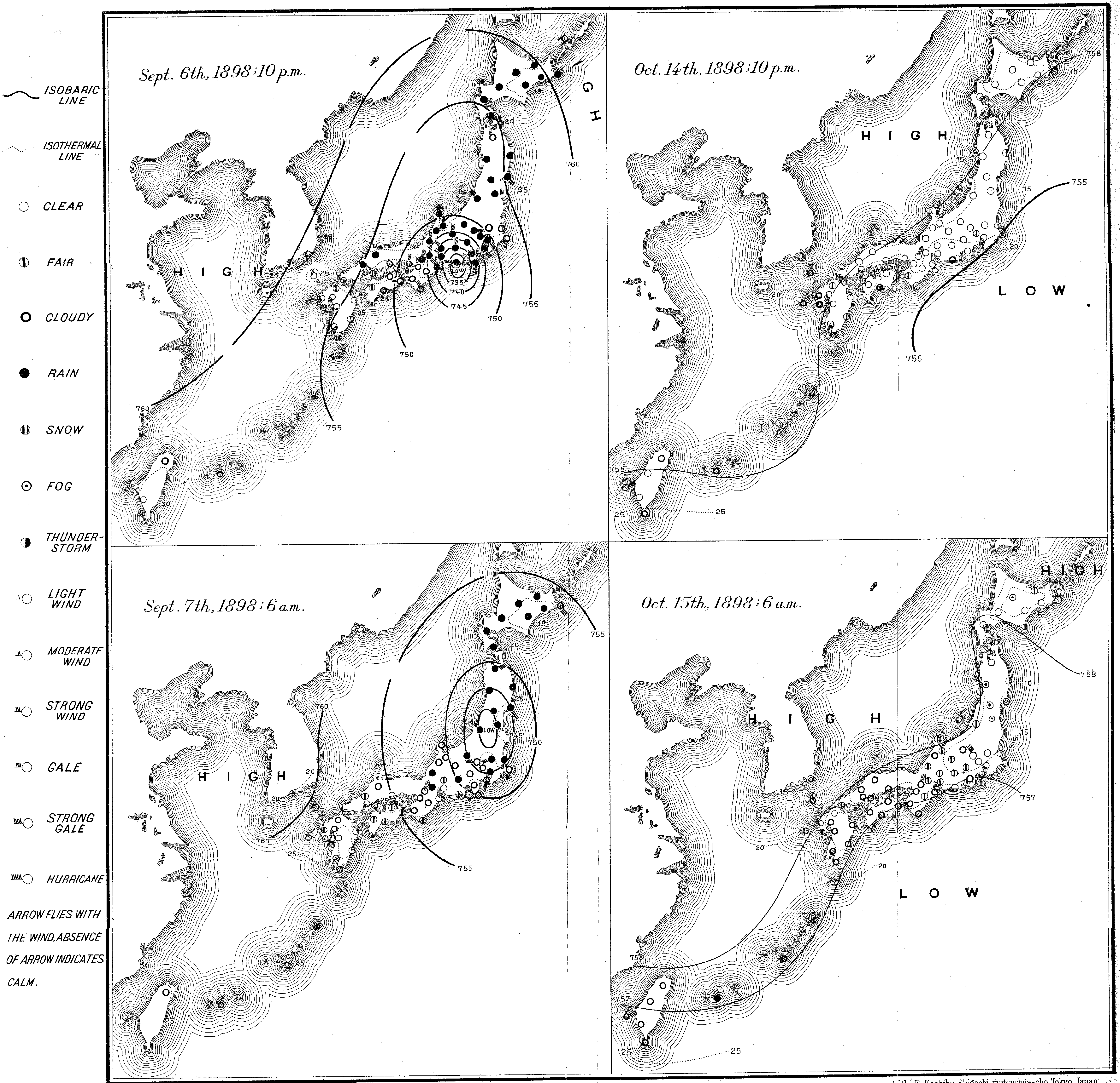
Fig. 24. The Earthquake of November 17th, 1898. (NS component).



B and b of (I) are to be considered as being continuous respectively to B' and b' of (II). Time : 1 tick interval = 1 minute.

Weather Maps

Oct. 6th-7th, 1898. Nov. 14th-15th, 1898.



Lith' E. Koshiba. Shigashi-matsushita-cho. Tokyo. Japan.