The Great Japanese Earthquake of October 28, 1891
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THE GREAT JAPANESE EARTHQUAKE OF OCTOBER 28, 1891.

By CHARLES DAVISON, Sc.D., F.G.S.

Although nearly ten years have elapsed since the occurrence of the greatest of Japanese earthquakes, the final report that will embody the labours of all its investigators has not yet been published. We possess a series of partial reports by Japanese seismologists, and others have studied special features of the case. The following account, which is based on these memoirs, is therefore to a certain extent incomplete. There are several points on which we have little or no information; but, with regard to those of general importance, the main results are already known.

The complicated nature and effects of the earthquake naturally rendered some division of labour necessary or advisable. Prof. Koto undertook the examination of the remarkable fault-scarp; the investigation of the numerous after-shocks was allotted to Prof. Omori, who also paid several visits to the epicentral area and made inquiries on various points; Mr. Conder studied the damaged buildings from an architect's point of view; while Prof. Tanakadate and Dr. Nagaoka devoted themselves to a re-determination of the magnetic elements of the central district. By the compilation of his great catalogue of Japanese earthquakes during the years 1885–1892, Prof. Milne has also provided the materials for a further analysis of the minor shocks which preceded and followed the principal earthquake.

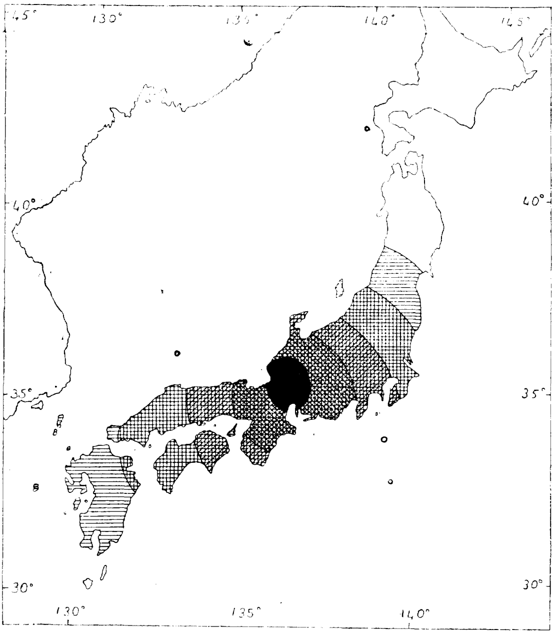

FIG 1.—SKETCH-MAP OF DISTURBED AREA AND ISOSEISMAL LINES. MASATO (7).

The part of Japan over which the earthquake was sensibly felt is shown in Fig. 1. The small black area in the centre is that in which the shock was most severe and the principal damage to life and property occurred. The other bands, more or less darkly shaded according to the greater or less intensity of the shock, will be referred to afterwards. Fig. 5 represents the meizoseismal area on a larger scale; and, as the greater part of it lies within the two provinces of Mino and Owari, the earthquake is generally known among the Japanese themselves as the Mino-Owari earthquake of 1891.

The Meizoseismal Area.

More than half of the meizoseismal area occupies a low flat plain of not less than 400 square miles in extent. On all sides but the south, the plain, which is a continuation of the depression forming the Sea of Isé, is surrounded by mountain ranges, those to the west, north, and north-east being built up mainly of Palæozoic rocks, and those on the east side of granite. A network of rivers and canals converts what might otherwise have been unproductive ground into one of the most fertile districts in Japan. A great garden, as it has been aptly termed, the whole plain is covered with rice-fields, and supports a population of about 787 to the square mile—a density which is exceeded in only six counties of England. As a rule, the soil is a loose, incoherent, fine sand, with but little clayey matter; and it is, no doubt, to its sandy nature that the disastrous effects of the earthquake were largely due. In the northern half of the district, the meizoseismal area is much narrower, and here it crosses a great mountain range running from south-west to north-east and separating the river-systems of the Japan sea from those of the Pacific. To the north, the meizoseismal area terminates in another plain, in the

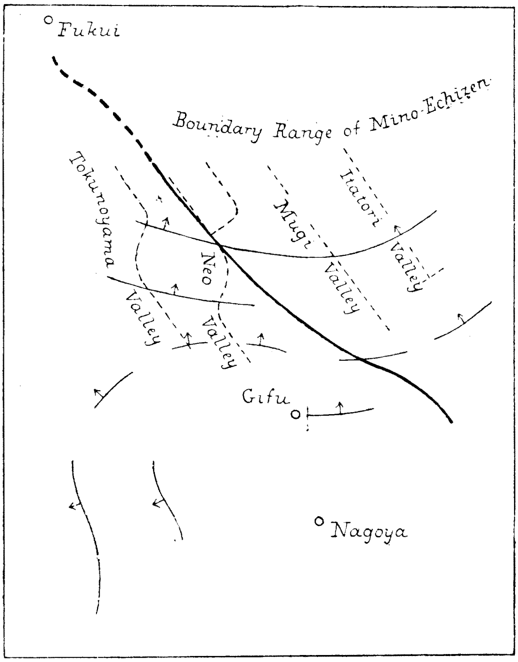

FIG. 2.—GENERAL PLAN OF GEOLOGICAL STRUCTURE OF MEIZOSEISMAL AREA. KOTO (6).

centre of which lies the city of Fukui, where the destructiveness of the earthquake was only inferior to that experienced in the provinces of Mino and Owari. There is also a detached portion of the area lying to the east of Lake Biwa, but it is uncertain whether the exceptional intensity there was due to the nature of the ground or to the occurrence of a secondary or sympathetic earthquake in its immediate neighbourhood.

The general plan of the geological structure of the central district is represented in Fig. 2. The thick line, partly continuous and partly broken, shows the course of the great fault, to the growth of which the earthquake chiefly owed its origin; while the thin continuous lines represent the changing direction of strike of the Palæozoic rocks which surround the Mino-Owari plain, and the arrowheads the direction of the dip. It will be seen that the direction of the strike forms an S-shaped curve, and it is clear that the present torsion-structure of the district could not have been produced without the formation of many fractures at right angles and parallel to the lines of strike. Prof. Koto points out that the regular and parallel valleys of the rivers Tokuno-yama, Neo, Mugi, and Itatori, indicated by broken lines in Fig. 2, have probably been excavated along a series of transverse fractures running from north-west to south-east; while fractures which are parallel to the line of strike may be responsible for the zigzag course of the valleys.

DAMAGE CAUSED BY THE EARTHQUAKE.

The great earthquake occurred at 6.37 a.m., practically without warning, and in a few seconds thousands of houses were levelled with the ground. Within the whole meizoseismal area there was hardly a building left undamaged. The road from Nagoya to Gifu, more than 20 miles in length, and formerly bordered by an almost continuous succession of villages, was converted into a narrow lane between two long drawn-out banks of *débris*. "In some streets," says Prof. Milne, "it appeared as if the houses had been pushed down from the end, and they had fallen like a row of cards." Or, again, a mass of heaped-up rubbish might be passed, "where sticks and earth and tiles were so thoroughly mixed that traces of streets or indications of building had been entirely lost." At Gifu, Ogaki, Kasamatsu, and other towns, fires broke out after the earthquake. In Kasamatsu the destruction was absolutely complete; nothing was left but a heap of plaster, mud, tiles, and charred timbers. At Ogaki, not more than thirty out of 8000 houses remained standing, and these were all much damaged. Within the whole district, according to the official returns, 197,530 buildings were entirely destroyed, 78,296 half destroyed, and 5934 shattered and burnt; while 7279 persons were killed, and 17,393 were wounded.

Next to buildings, the embankments which border the rivers and canals suffered the most serious damage, no less than 317 miles of such works having to be repaired. Railway-lines were twisted or bent in many places, the total length demolished being more than 10 miles. In cuttings, 20 feet or more in depth, both rails and sleepers were unmoved; it was on the plains that the effects of the earthquake were most marked. The ground appeared as if piled up into bolster-like ridges between the sleepers, and in many places the sleepers had moved endways. When the line crossed a small depression in the general level of the plain, the whole of the track was bowed, as if the ground were permanently compressed at such places. "Effects of compression," says Prof. Milne, "were most marked on some of the embankments, which gradually raise the line to the level of the bridges. On some of these, the track was bent in and out until it resembled a serpent wriggling up a slope. . . . Close to the bridges the embankments had generally disappeared, and the rails and sleepers were hanging in the air in huge catenaries."

DISTURBED AREA AND ISOSEISMAL LINES.

The land area disturbed by the earthquake and the different isoseismal lines are shown in Fig. 1. The "most severely shaken" district, that in which the destruction of buildings and engineering works was nearly complete, contains an area of 4286 square miles, or about two-thirds that of Yorkshire. This is indicated on the map by the black portion. Outside this lies the "very severely shaken" district, 17,325 square miles in area, extending from Kōbe on the west to Shizuoka on the east, in which ordinary buildings were destroyed, walls fractured, embankments and roads damaged, and bridges broken down. The third or "severely shaken" district contains 20,183 square miles; and in this some walls were cracked, pendulum clocks stopped, and furniture, crockery, etc., overthrown. Tokio and Yokohama lie just within this area. In the fourth region the shock was "weak," the motion being distinctly felt, but not causing people to run out of doors; and in the fifth it was "slight," or just sufficient to be felt. These two regions together include an area of 51,976 square miles.

Thus, the land-area disturbed amounts altogether to 93,770 square miles, *i.e.* to a little more than the area of Great Britain. According to Prof. Omori, the mean radius of propagation was about 323 miles, and the total disturbed area must therefore have been about 330,000 square miles, or nearly four times the area of Great Britain. Considering the extraordinary intensity of the shock in the central district, this can hardly be regarded as an over-estimate.

The isoseismal lines shown in Fig. 1 are not to be regarded as drawn with great accuracy; for there is no marked separation between the tests corresponding to the different degrees of the scale of intensity. The seismographs at Gifu and Nagoya were thrown down within the first few seconds, and failed to record the principal motion. But a great number of well-formed stone lanterns and tombstones were overturned, and, from the dimensions of these, Prof. Omori calculated the maximum horizontal acceleration necessary for overturning them at fifty-nine places within the meizoseismal area.* At five of these it exceeded 4000 millimetres per second per second, an acceleration equal to about five-twelfths of that due to gravity. Making use of these observations, Prof. Omori has drawn two isoseismal lines within the central district, which are shown in Fig. 4. At every point of the curve marked 2, the maximum acceleration was 2000 millimetres per second per second, and of that marked 1, 800 millimetres per second per second. The dotted line within the curve marked 2 represents the boundary of the meizoseismal area, which, it will be observed, differs slightly from that given by Prof. Koto (see Fig. 5). The difference, however, is apparently due to the standard of intensity adopted, Prof. Koto's boundary agreeing rather closely with the curve marked 2 in Fig. 4.

NATURE OF THE SHOCK.

Little has yet been made known with regard to the nature of the shock, and the published records of the accompanying sound are so rare that it seems as a rule to have passed unheard. The seismographs at Gifu and Nagoya registered the first

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* From the formula $a = \frac{xg}{y}$, where a is the maximum horizontal acceleration, g the acceleration due to gravity, y the height of the centre of gravity, and x its horizontal distance from the edge about which the body was overturned.

half-dozen vibrations, and were then buried beneath the fallen buildings. In the following table, the data from these two stations are therefore incomplete :—

PRINCIPAL MEASUREMENTS OBTAINED FROM SEISMOGRAPHIC RECORDS.

	Gifu.	Nagoya.	Osaka.	Tokio (Imp. Univ.).
Maximum horizontal motion ...	> 18 mm.	> 26 mm.	30 mm.	> 35 mm.
Period of ditto	2·0 secs.	1·3 sec.	1·0 sec.	2·0 secs.
Maximum vertical motion ...	> 11·3 mm.	6·2 mm.	8 mm.	9·5 mm.
Period of ditto	0·9 sec.	1·5 sec.	1·0 sec.	2·4 secs.

If the period of the principal vibrations were known, the observations of Prof. Omori on the overturning of bodies would enable us to determine the range of motion at different places. For instance, the maximum acceleration at Nagoya was found by these observations to be 2600 millimetres per second per second, and if we take the period of the greatest horizontal motion to be the same as that of the initial vibrations, namely, 1·3 second, the total range (or double amplitude) would be 223 millimetres, or 8·8 inches. With the same period, and the maximum acceleration observed (at Iwakura and Konaki) of more than 4300 millimetres per second per second, the total range would be greater than 14·5 inches.*

In the meizoseismal area, many persons saw waves crossing the surface of the ground. At Akasaka, according to one witness, the waves came down the streets in lines, their height being perhaps 1 foot, and their length between 10 and 30 feet. To the north of the same area, we are told that "the shore-line rose and fell, and with this rising and falling the waters receded and advanced." Even at Tokio, which is about 175 miles from the epicentre, the tilting of the ground was very noticeable. After watching his seismographs for about two minutes, Prof. Milne next observed the water in an adjoining tank, 80 feet long and 28 feet wide, with nearly vertical sides. "At the time it was holding about 17 feet of water, which was running across its breadth, rising first on one side and then on the other to a height of about 2 feet." Still clearer is the evidence of the seismographs in the same city. Instead of a number of irregular waves, all the records show a series of clean-cut curves. The heavy masses in the horizontal pendulums were tilted instead of remaining as steady points. They were not simply swinging, for the period of the undulations differed from that of the seismograph when set swinging, and also varied in successive undulations. It was ascertained afterwards,

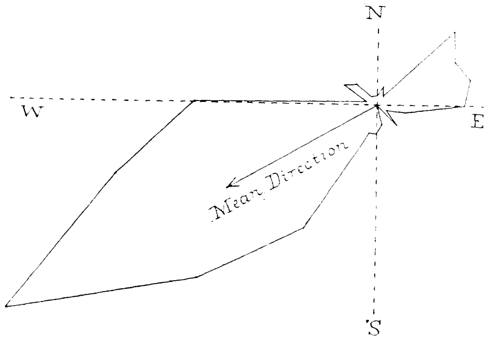

FIG. 3.—PLAN OF DIRECTIONS OF FALL OF OVERTURNED BODIES AT NAGOYA.

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* These estimates are made, on the supposition of simple harmonic motion, from the formula $2a = \frac{at^2}{2\pi^2}$, where $2a$ is the total range or double amplitude, a the maximum acceleration, and t the period, of the vibration.

by measurement with a level, that to produce these deflections, the seismograph must have been tilted through an angle of about one-third of a degree.

Direction of the Shock.—Shortly after the earthquake, Prof. Omori travelled over the meizoseismal area and made a large number of observations on the directions in which bodies were overturned, taking care to include only those in which the direction of falling would not be influenced by the form of the base, such as the cylindrical stone lanterns so frequently found in Japanese gardens. At some places these bodies fell in various directions, at others with considerable uniformity in one direction. For instance, at Nagoya, out of 200 stone lanterns with cylindrical stems, 119 fell between west and south, and 36 between east and north; the numbers falling within successive angles of 15° being represented in Fig. 3. The mean direction of fall is W. 30° S., coinciding with that in which the majority of the lanterns were overturned. Similar observations were made at forty-two other places within and near the meizoseismal area, and the resulting mean direction for each such place in the Mino-Owari district is shown by short lines in Fig. 4, the arrow indicating the direction towards which the majority of bodies at a given place were overturned. It will be seen from this map that the direction of the earthquake motion was generally at right angles, or nearly so, to that of the neighbouring part of the meizoseismal zone, and that on both sides of it, the majority of overturned bodies at each place fell towards this zone.

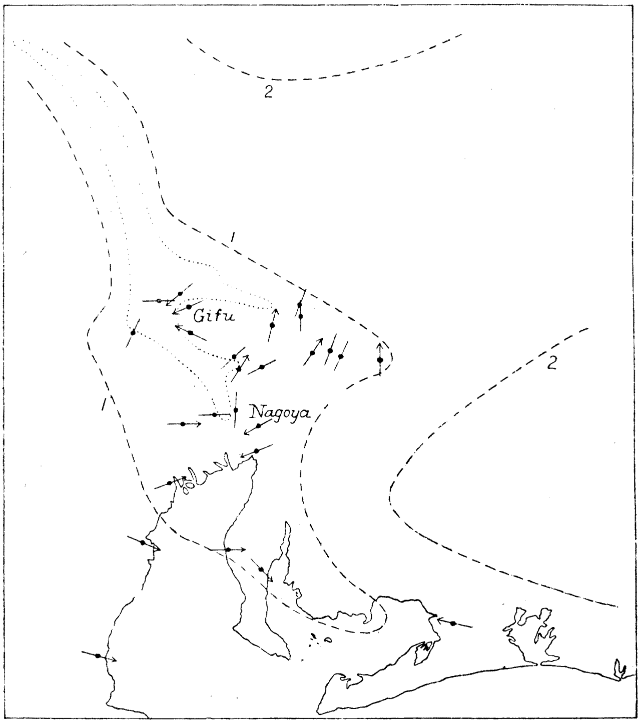

FIG. 4.—MAP OF MEAN DIRECTION OF SHOCK AND ISOSEISMAL LINES IN CENTRAL DISTRICT. OMORI (13).

VELOCITY OF THE EARTH-WAVES.

The times of the great earthquake and of sixteen minor shocks on October 28 and 29 and November 6 were determined at the Central Meteorological Observatory at Tokio, and at either two or three of the observatories of Gifu, Nagoya, and Osaka, each of which is provided with a seismograph and chronometer. The after-shocks referred to originated near a point about 6 miles west of Gifu, and the difference between the distances of Tokio and Osaka from this point is 89½ miles, of Tokio and Nagoya 147 miles, and of Tokio and Gifu 165 miles. The mean time-intervals between these three pairs of places were 67, 111, and 128 seconds respectively, and these give for the mean velocity for each interval 2·1 kilometres (or 1·3

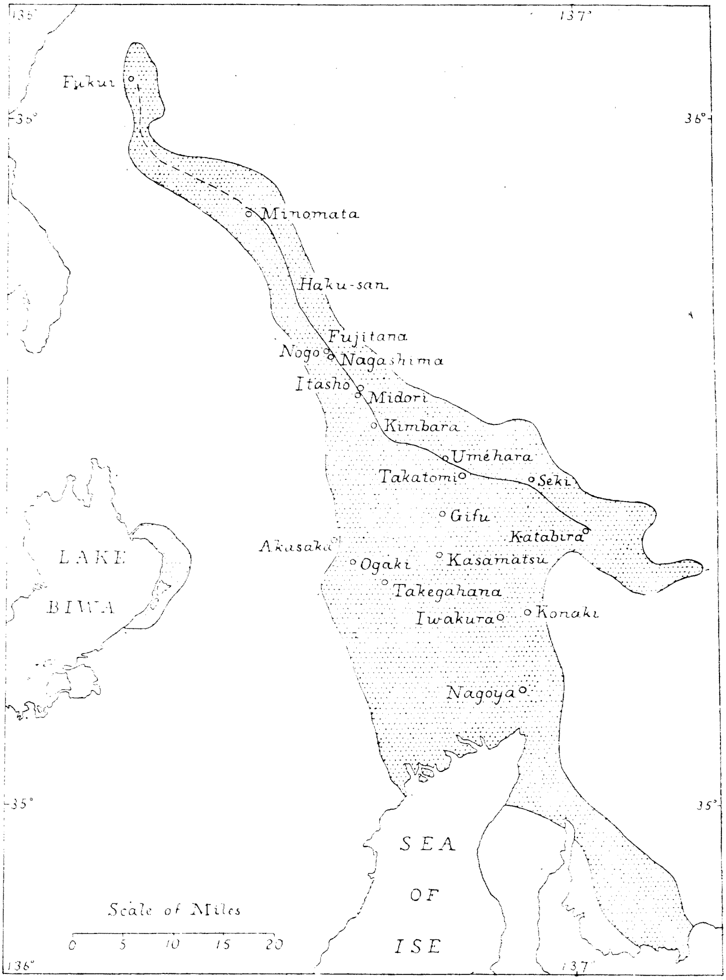

FIG. 5.—MAP OF MEIZOSEISMAL AREA. KOTO (6).

miles) per second. Thus there appears in these cases to be no sensible variation in the velocity with the distance from the origin.

As might be expected, an earthquake of such severity was recorded by magnetometers at several distant observatories. Disturbances on the registers of Zikawei (China), Mauritius, Utrecht, and Greenwich have been attributed to the Japanese earthquake, but the times at which they commenced are too indefinite to allow of any determination of the surface-velocity of the earth-waves to great distances from the origin.

THE GREAT FAULT-SCARP.

As in all disastrous earthquakes, the surface of the ground was scarred and rent by the shock. From the hillsides great landslips descended, filling the valleys with *débris;* and slopes which were formerly green with forest, after the earthquake looked as if they had been painted yellowish-white. Innumerable fissures cut up the plains, the general appearance of the ground, according to Prof. Milne, being "as if gigantic ploughs, each cutting a trench from 3 to 12 feet deep, had been dragged up and down the river-banks." But by far the most remarkable feature of the earthquake was a great rent or fault, which, unlike the fissures just referred to, pursued its course regardless of valley, plain, or mountain. Although

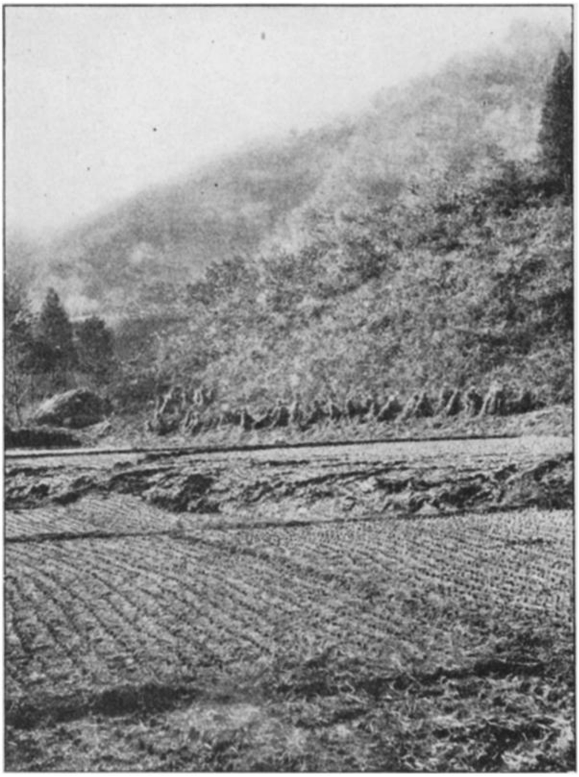

FIG. 6.—PLOUGHSHARE APPEARANCE OF THE FAULT NEAR FUJITANI. KOTO (6).

at first sight quite insignificant in many places, and sometimes hardly visible to the untrained eye, Prof. Koto has succeeded in tracing this fault along the surface for a distance of 40 miles, and he gives good reasons for believing that its total length must be not less than 70 miles.

The general character of the fault-scarp changes with the surface features. On flat ground, where the throw is small, it cuts up the soft earth into enormous clods, or makes a rounded ridge from 1 to 2 feet high, so that it resembles, more than anything else, the pathway of a gigantic mole (Fig. 6). When the throw is considerable—and in one place it reaches from 18 to 20 feet—the fault-scarp forms a terrace, which from a distance has the appearance of a railway embankment (Fig. 7). Or, again, where the rent traverses a mountain ridge or a spur of hills, "it caused extensive landslips, one side of it descending considerably in level, carrying the forest with it, but with the trees complicatedly interlocked or prostrate on the ground."

FIG. 7.—THE FAULT-SCARP AT MIDORI. KOTO (6).

At its southern end, the fault was seen for the first time crossing a field near the village of Katabira. The field was broken into clods of earth, and swollen up to a height of 5½ yards, while a great landslip had descended into it from an adjoining hill. A little further to the north-west, the ground was sharply cut by the fault, the north-east side having slightly subsided and at the same time been shifted horizontally through a distance of 3¼ to 4 feet to the north-west. Adjoining fields were formerly separated by straight mounds or ridges running north and south and east and west, and these mounds were cut through by the fault and displaced, as shown in Fig. 8. From this point the fault runs in a general north-westerly direction, the north-east side being always slightly lowered with respect to the other and shifted to the north-west. Near Seki it takes a more westerly direction, and continues so to a short distance east of Takatomi, where the north side is lowered by 5 feet, and moved about 1¼ feet to the west. At the north end of Takatomi, a village in which every house was levelled with the ground, the fault is double, and the continuous lowering towards the north has converted a once level field into sloping ground. At this point, the small river Toba, flowing south, is partially blocked by the fault-scarp, and an area of about three-quarters of a square mile, on which two villages stand, was converted into a deep swamp (Fig. 9), so that, as the earthquake occurred at the time of the rice-harvest, the farmers were obliged to cut the grain from boats. After passing Takatomi, the fault again turns to the west-north-west, but, the throw being small, it resembles here the track of an enormous mole. At Uméhara it crosses a garden between two persimmon trees, appearing on the hard face of the ground as a mere line; but the trees, which were before in an east-and-west line, now stand in one running north and south, without being in the least affected by the movement (Fig. 10). From here to Kimbara, where the fault enters the Neo valley, the north side is always depressed and shifted eastwards by about 6½ feet.

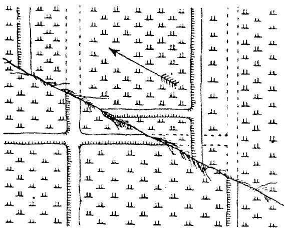

FIG. 8.—DISPLACEMENT OF FIELD DIVISIONS BY THE FAULT NEAR NISHI-KATABIRA. KOTO (6).

It was in the Neo valley that the supreme efforts of the earthquake were manifested. Landslips were so numerous that the greater part of the mountain slopes had descended into the valley, the whole appearance of which had changed. "Unfamiliar obstacles," remarks Prof. Koto, "made themselves apparent, and small hills covered with forest had come into sight which had not been seen before." But the ground was not only lowered and shifted by the fault; it was permanently compressed, plots originally 48 feet in length afterwards measuring

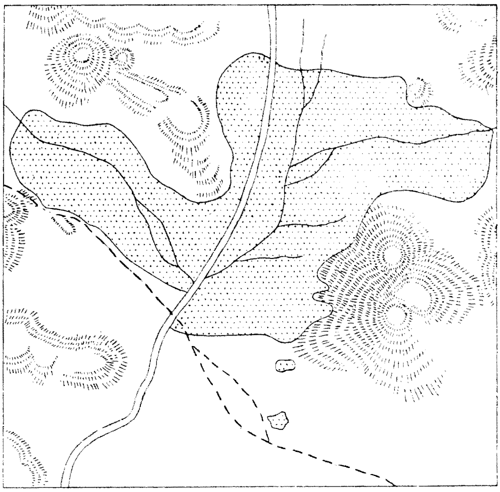

FIG. 9.—MAP OF SWAMP FORMED BY STOPPAGE OF RIVER TOBA BY FAULT-SCARP. KOTO (6).

only 30 feet. In fact, "it appears," in the words of Prof. Milne, "as if the whole Neo valley had become narrower."

A few miles after entering the Neo valley, the throw of the fault reaches its maximum at Midori. But instead of the relative depression of the east side, which prevails throughout the rest of the line, that side is here about 20 feet higher than the other. It is, however, shifted as usual towards the north by about 13 feet; and this displacement is rendered especially evident by the abrupt break in the line of a new road to Gifu (Fig. 7). That the east side has really risen is clear, for, a little higher up, the river has changed from a shallow rapid stream 30 yards wide into a small lake of more than twice the width, and so deep that a boatman's pole could not reach the bottom. At Itasho, about a mile north of Midori, both sides are nearly on the same level, the fault appearing like a mole's track; and 7 miles further, at Nagoshima, the east side is relatively depressed by more than a yard, and at the same time shifted about 6½ feet to the north.

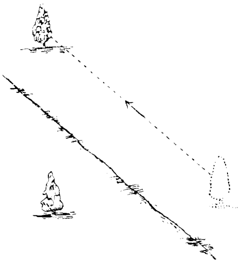

FIG. 10.—SHIFTING OF TREES BY FAULT AT UMÉHARA. KOTO (6).

At Nogo, the main Neo valley turns off at right angles to the east, and the fault continues its course up a side valley, the east side, with respect to the other, being continually depressed and shifted towards the north. It was traced by Prof. Koto through Fujitani (Fig. 6), where there were many unmistakable evidences of the violence of the shock, as far as the eastern shoulder of Haku-san; and here, after following the fault for 40 miles, the lateness of the season compelled him to return. There can be no doubt, however, that it runs as far as Minomata; and it is probable, from the linear extension of the meizoseismal area, that it does not entirely die out before reaching the city of Fukui, 70 miles from its starting-point at Katabira.

MINOR SHOCKS.

For some hours after the earthquake, shocks were so frequent in the meizoseismal area that the ground in places hardly ever ceased from trembling. Without instrumental aid, detailed record was of course impossible; but fortunately the buried seismographs at Gifu and Nagoya were uninjured, and in about seven hours both were once more in working order. To the energy by which this result was accomplished, we owe our most valuable registers of the after-shocks of a great earthquake.

Until the end of 1893, that is, in little more than two years, the total number of shocks recorded at Gifu was 3365, and at Nagoya 1298. None of these approached the principal earthquake in severity. Nevertheless, of the Gifu series, 10 were described as violent, and 97 strong; while of the remainder, 1808 were weak, 1041 feeble, and 409 were sounds alone without any accompanying shock. The slight intensity of most of the shocks is also evident from the inequality in the numbers recorded at Gifu and Nagoya, from which it appears that nearly two-thirds were imperceptible more than about 25 miles from the chief origin of the shocks. Only 70 of the after-shocks during the first two years were registered at Osaka, and not more than 30 at Tokio.

Distribution of After-shocks in Time.—The decline in frequency of the after-shocks was at first extremely rapid, the numbers recorded at Gifu during the six days after the earthquake being 303, 147, 116, 99, 92, and 81, and at Nagoya 185, 93, 79, 56, 30, and 31; in fact, half of the shocks up to the end of 1893 occurred by November 23 at Gifu, and by November 6 at Nagoya. The daily numbers at these two places are represented in Fig. 11, in which the crosses correspond to the numbers at Gifu, and the dots to those at Nagoya; and the curves drawn through or near the marks represent the average daily number of shocks from October 29 to November 20. It will be seen that these curves are hyperbolic in form, the change from very rapid to very gradual decline in frequency taking place from five to ten days after the great earthquake. Fig. 12 illustrates the distribution in time of the after-shocks at Gifu to the end of 1893, the ordinates in these cases representing the number of shocks during successive months.*

A similar rapid and then gradual decline in frequency characterizes the strong and weak shocks recorded at Gifu. Of the ten violent shocks, only one occurred after the beginning of January, 1892; and of the 97 strong shocks, only three after April, 1892. But at the commencement of the series, feeble shocks (*i.e.* shocks that could just be felt) and earth-sounds without any accompanying movement were comparatively rare, and did not become really prominent until two months had elapsed. Of the 308 after-shocks recorded in 1893, none could be described as strong, only 10 were weak, while 263 were feeble shocks and 35 merely earth-sounds.

The last two diagrams show at a glance that the decline in frequency of after-shocks is very far from being uniform. Some of the fluctuations are due to the occurrence of exceptionally strong shocks, each of which is followed by its

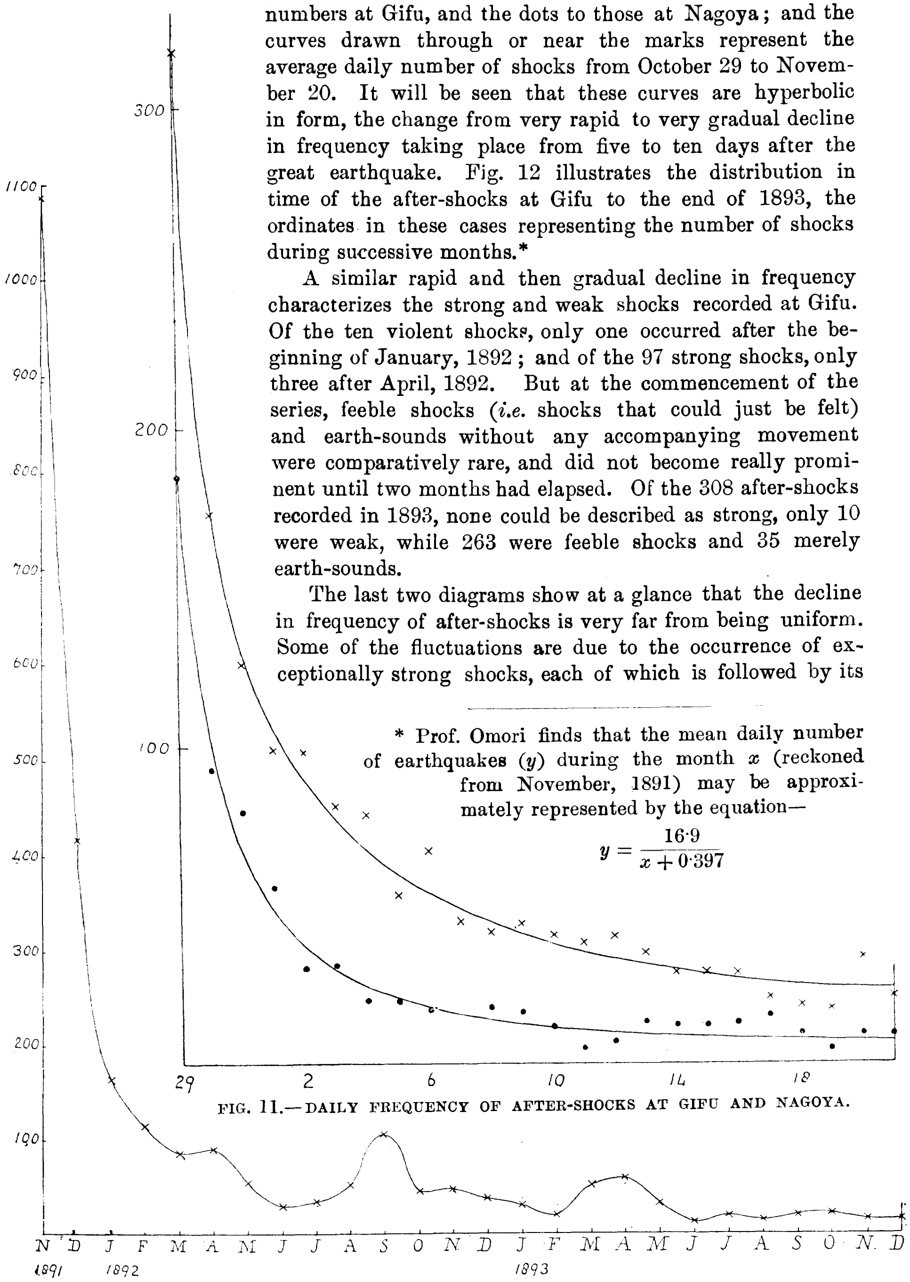

FIG. 11.—DAILY FREQUENCY OF AFTER-SHOCKS AT GIFU AND NAGOYA.

FIG. 12.—MONTHLY FREQUENCY OF AFTER-SHOCKS AT GIFU. OMORI (12).

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* Prof. Omori finds that the mean daily number of earthquakes (y) during the month x (reckoned from November, 1891) may be approximately represented by the equation—

$$y = \frac{16{\cdot}9}{x + 0{\cdot}397}$$

own minor train of after-shocks.* Others seem to be periodic, and possibly owe their origin to external causes unconnected with the earthquake.†

Method of representing the Distribution of After-shocks in Space.—The maps in Figs. 14–17 show the distribution of the after shocks in space during four successive intervals of two months each. They are founded on Prof. Milne's great catalogue of Japanese earthquakes, which give, among other data, the time of occurrence and the position of the epicentre for every shock until the end of 1892. For the latter purpose, the whole country is divided by north-south and east-west lines into numbered rectangles, each one-sixth of a degree in length and breadth; and the position of an epicentre is denoted by the number of the rectangle in which it occurs. The area included within the maps is bounded by the parallels 34° 40′

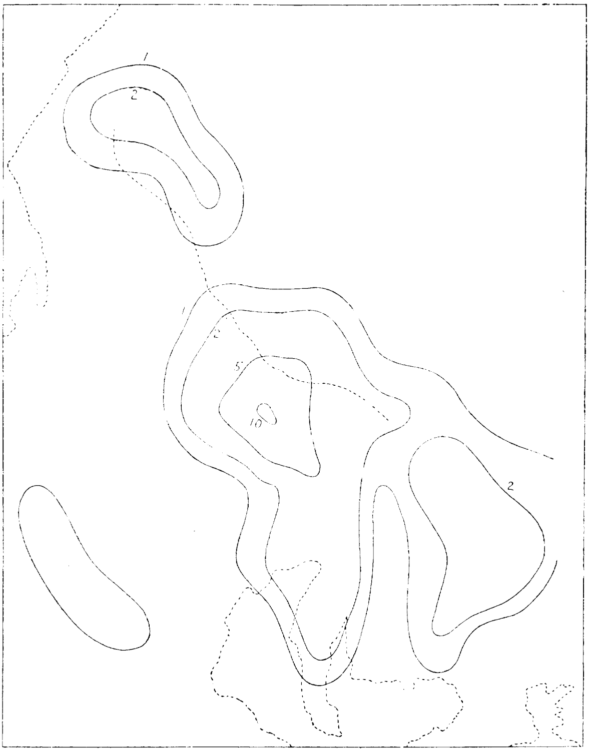

FIG. 13.—DISTRIBUTION OF PRELIMINARY SHOCKS IN SPACE. DAVISON (2).

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* The last violent shock before the end of 1893 occurred on September 7, 1892, and its effects on the frequency of after-shocks is shown by the daily numbers recorded at Gifu during the first fortnight in September. These are—2, 2, 2, 3, 5, 5, 28 (on September 7), 8, 8, 5, 4, 3, 2, 4, 3.

† The periodicity of after-shocks is discussed in the papers numbered 4 and 12 at the end of this paper. There can be little doubt as to the existence of daily and other periods, but the results are not sufficiently established for inclusion here.

and 36° 20′ lat. N., and by the meridians 2° 10′ and 3° 50′ long. W. of Tokio, so that ten rectangles adjoin each side of the map. The number of rectangles lying within each rectangle having been counted, curves are then drawn through the centres of all rectangles containing the same number of epicentres, or through points which divide the line joining the centres of two rectangles in the proper proportion. Taking, for example, the curve marked 5, if the numbers in two consecutive rectangles are 3 and 7, the curve bisects the line joining their centres; if the numbers are 1 and 6, the line joining their centres is divided into five equal parts, and the curve passes through the first point of division reckoned from the centre of the rectangle in which six epicentres are found. Thus the meaning of the curve marked, say, 5 may be stated as follows: Let any point in the curve be imagined as the centre of a rectangle whose sides are directed north-south and east-west, and are respectively one-sixth of a degree of latitude and longitude in length; then the number of epicentres within this rectangle is at the rate of 5 for the time considered.

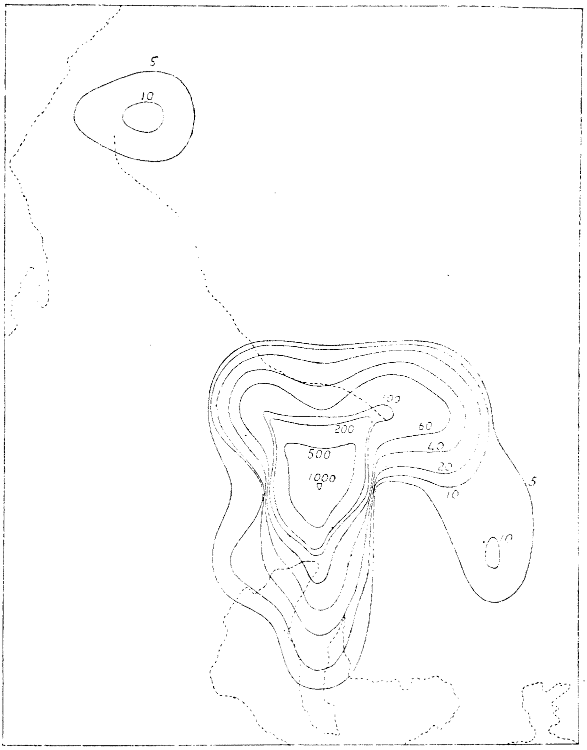

FIG. 14.—DISTRIBUTION OF AFTER-SHOCKS IN SPACE (NOVEMBER–DECEMBER, 1891). DAVISON (2).

Preparation for the Great Earthquake.—At first sight, there appears to have been but little direct preparation for the great earthquake. Except for a rather strong shock on October 25, at 9.14 p.m., it occurred without the warning of any preliminary tremors. But a closer examination of the evidence shows, as we should indeed expect, that there was a distinct increase in activity for many months beforehand. The region had become "seismically sensitive." Of the hundred rectangles included in the maps in Figs. 13–17, there are thirteen lying along the meizoseismal area of the earthquake of 1891, in which nearly all the after-shocks originated. During the five years 1885–1889, 53 out of 125 earthquakes (or 42 per cent.) had their epicentres lying within the thirteen rectangles; or, in other words, the average frequency in one of the rectangles of the meizoseismal area was five times as great as in one of those outside it. In 1890 and 1891 (until October 27), the percentage in the thirteen rectangles rose to 61, and the average frequency in one of them to ten times that of one of the exterior rectangles.

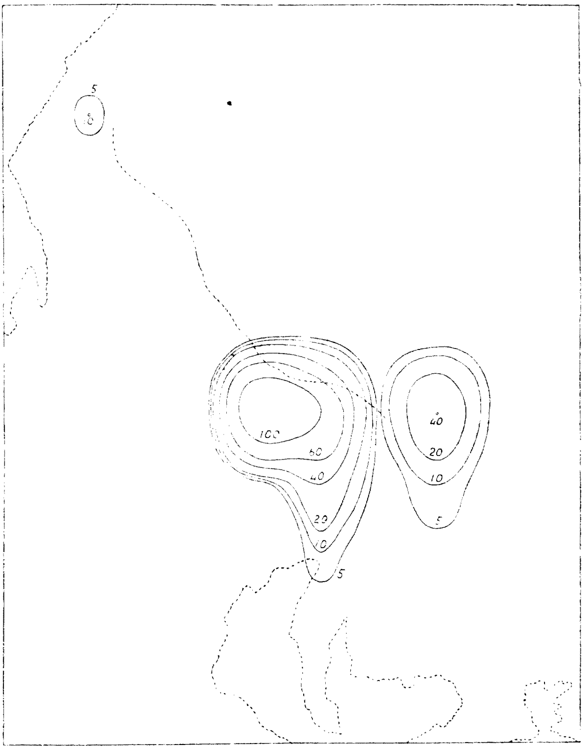

FIG. 15.—DISTRIBUTION OF AFTER-SHOCKS IN SPACE (JANUARY–FEBRUARY, 1892). DAVISON (2).

The curves in Fig. 13 illustrate the distribution of epicentres during the latter interval. It will be seen that they follow roughly the course of the meizoseismal area southwards to the Sea of Isé, and that to the south-east they continue for several miles the short branch of the meizoseismal area which surrounds the southern end of the fault-scarp.

Thus the preparation for the great earthquake is shown, first, by the increased frequency of earthquakes originating within its meizoseismal area; and, secondly, by the uniformity in the distribution of epicentres throughout the same region, the marked concentration of effort which characterizes the after-shocks being hardly perceptible during the years 1890–1891.

Distribution of After-shocks in Space.—We have seen that the after-shocks were subject to a fluctuating decline in frequency, rapid at first, and more gradual afterwards. It is evident, from Figs. 14–17, that a similar law governs the area within which the after-shocks originated. During the first two months, epicentres occur over nearly the whole of the meizoseismal area, but afterwards they are confined to a smaller district, which slowly, though not continually, decreases in size.

The most important feature in the distribution of the epicentres is the central region of extraordinary activity; but there are also districts of minor and more short-lived activity near the three extremities of the meizoseismal band. The seat of chief seismic action shifts slightly from one part to another of the epicentral region, especially about the end of 1891, as will be seen by comparing the innermost curves of Figs. 14 and 15. Thus, with the decline in frequency of the after-shocks and the decrease in their sphere of action, there took place concurrently a gradual but oscillating withdrawal of that action to a more or less central region of the fault.

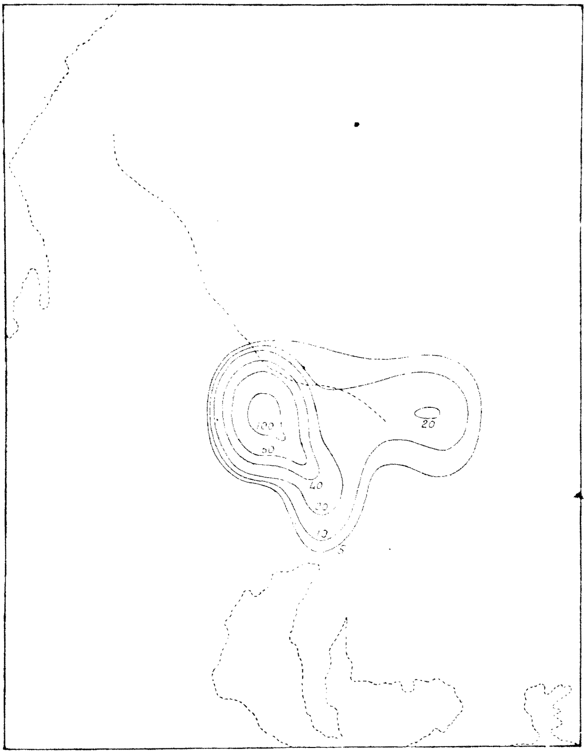

FIG. 16.—DISTRIBUTION OF AFTER-SHOCKS IN SPACE (MARCH–APRIL). DAVISON (2).

Sound-phenomena of After-shocks.—While comparatively few observers seem to have noticed any noise with the principal earthquake, many of the after-shocks were accompanied by sounds. Prof. Omori describes them as belonging to two types. They were either rushing feeble noises like that of wind, or loud rumbling noises like those of thunder, the discharge of a gun, or the fall of a heavy body. In the Neo valley, sounds of the second type were most frequent and distinct, but they either occurred without any shock at all, or the attendant tremor was very feeble; while, on the other hand, severe sharp shocks were generally unaccompanied by distinctly audible sounds.

It is remarkable, also, that sounds were less frequently heard with the early than with the later after-shocks. In November, 1891, the percentage of audible shocks was 17, and from December to the following April always lay between 10 and 12. In May the percentage suddenly rose to 39, and until the end of 1892 was always greater than 32, while in November, 1892, it rose as high as 49. This, of course, agrees with Prof. Omori's observation that sounds attended feeble shocks more often than strong ones.

FIG. 17.—DISTRIBUTION OF AFTER-SHOCKS IN SPACE (MAY–JUNE, 1892). DAVISON (2).

The distribution of the audible after-shocks in space is shown in Fig. 18. These curves are drawn in the same way as those in Figs. 13-17, but they represent the percentages, not the actual numbers, of shocks accompanied by sound. It will be noticed that all three groups of curves lie along the meizoseismal area, or the continuation of the south-east branch; while the axis of the principal group of curves lies to the west of the central regions in which most after-shocks originated.

The explanation of these peculiarities is no doubt connected with the comparative inability of the Japanese people to perceive the deep sounds which in Europe are always heard with earthquake shocks. The sounds are rarely heard by them more than a few miles from the epicentre.* We may therefore conclude that slight after-shocks originated nearer the surface than strong ones, that the mean depth of the foci decreased with the lapse of time, and that the axes of the systems of curves in Fig. 18 mark out approximately the lines of the growing faults. The separation of the two westerly groups of curves appears to show that the main branch of the meizoseismal area is connected with a fault roughly parallel to that traced by Prof. Koto, but of which no scarp (if it existed) could be readily distinguished among the superficial fissures produced by the great shock.

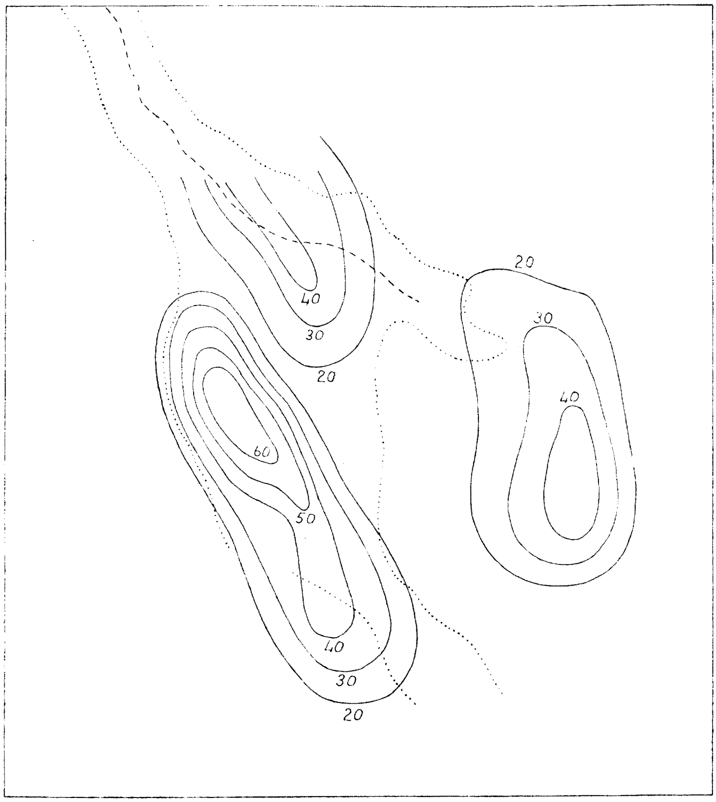

FIG. 18.—DISTRIBUTION OF AUDIBLE AFTER-SHOCKS IN SPACE (NOVEMBER, 1891–DECEMBER, 1892). DAVISON (5).

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* Of the Japanese earthquakes of 1885–1892 originating beneath the land, 26 per cent. were accompanied by a recorded sound; but less than 1 per cent. of those originating beneath the sea and not more than 10 miles from the coast.

EFFECT OF THE EARTHQUAKE ON THE SEISMIC ACTIVITY OF THE ADJOINING DISTRICTS.

So great and sudden a displacement as occurred along the fault-scarp could hardly take place without affecting the stability of adjoining regions of the earth's crust, and we should naturally expect to find a distinct change in their seismic activity shortly after October 28. In Fig. 19 two such regions are shown, bounded by the straight dotted lines. The district in which the principal earthquake and its after-shocks originated is enclosed within the undulating dotted lines. The continuous lines inside all three districts are the curves corresponding to 10 and 5 epicentres for the years 1885–1892. Not far from the axes of the outer groups of curves there are probably transverse faults, approximately parallel to the great fault-scarp and the main branch of the meizoseismal band, and distant from them about 45 and 55 miles respectively.

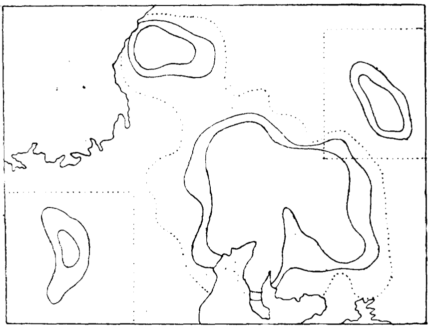

FIG. 19.—MAP OF ADJOINING REGIONS IN WHICH SEISMIC ACTIVITY WAS AFFECTED BY THE GREAT EARTHQUAKE. DAVISON (3).

In the district represented in the north-east corner of Fig. 19, 29 earthquakes originated between January 1, 1885, and October 27, 1891, and 30 between October 28, 1891, and December 31, 1892, 7 of the latter number occurring in November, 1891. In the south-west district, the corresponding figures before and after the earthquake are 20 and 36, 8 of the latter occurring in November, 1891. Thus, in the north-east district, for every shock in the interval before the great earthquake there were six in an equal time afterwards, and at the rate of 10 during November, 1891; and in the south-west district, for every shock before the earthquake there were 10 afterwards, and at the rate of 16 during November, 1891.

Now, it is unlikely that the gradual increase of stress should be so nearly proportioned everywhere to the prevailing conditions of resistance as to give rise to a marked and practically simultaneous change in seismic activity over a large area; whereas the paroxysmal occurrence of a strong earthquake might alter the surrounding conditions with comparative rapidity, and so induce a state of seismic excitement in the neighbourhood. It therefore seems very probable that the increased activity in the two districts here described was a direct consequence of the occurrence of the great earthquake.

ORIGIN OF THE EARTHQUAKE.

The preponderance of preliminary earthquakes within the meizoseismal area and the outlining of the fault-system by the frequency curves of 1890–1891 (Fig. 13) point to the previous existence of the originating fault or faults, and to the earthquake being due, not to the formation of a new fracture, as has been suggested, but to the growth of an old fault.

The last severe earthquake in the Mino-Owari plain occurred in 1859, so that for more than thirty years there had been but little relief to the gradually increasing stresses. Now, the distribution of stress must have been far from uniform throughout the fault-system, and also the resistance to displacement far from proportional to the stresses at different places. At certain points, therefore, the effective stress would be greater than elsewhere, and it would be at these points that fault-slips would first occur. Such slips tend to remove the inequalities in effective stress. Thus, the function of the slight shocks of 1890 and 1891 was, briefly, to equalize the effective stress over the whole fault-system, and so to clear the way for one or more great slips throughout its entire length.

As to which side of the fault moved during the great displacement, or whether both sides moved at once, we have no direct evidence but as regards the neighbourhood of Midori, and there the conditions were exceptional. Prof. Koto thinks that it was probably the rock on the north-east side that was generally depressed and always shifted to the north-west. But the disturbance in reality seems to have been more complicated. That this was the case, that displacement occurred along more than one fault, is probable from the branching of the meizoseismal area, the isolation of the audibility curves of the after-shocks (Fig. 18), and the sudden increase in seismic activity both to the north-east and south-west of the epicentre. The detached portion of the meizoseismal area near Lake Biwa may also point to a separate focus. The whole region, indeed, was evidently subjected to intense stresses, and the depression on the north-east side of the fault-scarp can hardly fail to have been accompanied by other movements, especially along a fault running near the western margin of the main branch of the meizoseismal area.

The later stages of the movements are somewhat clearer. From a study of the after-shocks, we learn that the disturbed masses began at once to settle back towards the position of equilibrium. At first the slips were numerous and took place over the whole fault-system, but chiefly at a considerable depth, where no doubt the initial displacement was greatest. After a few months, stability was nearly restored along the extremities of the faults; slips were confined almost entirely to the central regions, while a much larger proportion of them took place within the superficial portions of the faults.

The official records bring down the history to the end of 1893. Since that time more than one strong shock has been felt in the Mino-Owari plain; but the stage of recovery from the disturbances of 1891 is probably nearly or quite at an end, and we seem rather to be entering on a period in which the forces are once more silently gathering that sooner or later will result in another great catastrophe.

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THE MONTHLY RECORD.

EUROPE.

The River Spey.—Some interesting questions connected with the geological history of the river Spey are touched upon in the April number of the *Scottish Geographical Magazine* by Mr. L. W. Hinxman of the Geological Survey. After pointing out that the southern tributaries, flowing as they do from a more mountainous and humid region than those on the north, have been able to cut a long way back into the original plateau, and thus drain a larger area, the writer points out a striking example of river-capture in the case of the upper Feshie, one of the largest tributaries of the Spey. For the first 6 miles of its course the Feshie flows to the east, but on touching the boundary between the counties of Aberdeen and Inverness, suddenly bends round and flows in a directly opposite direction. The watershed towards the Dee is here only a few feet above the bed of the stream, and to the east is a wide peat-filled valley, down which the upper Feshie must once have flowed. The Eidart, which joins the Feshie a mile below the bend, was once the headstream of that river. Mr. Hinxman next points out that the profile of the course of the Spey is very far from being that of an orthodox river, and that its total fall is less than that of the Dee or Tay. It is