3. *A* SEASONAL VARIATION *in the* FREQUENCY *of* EARTHQUAKES. By RICHARD DIXON OLDHAM, F.R.S., F.G.S. (Read February 6th, 1918.)

[PLATE XII.]

WHEN investigating the aftershocks of the great Indian earthquake of 1917, I found that the ratio of shocks occurring during the day half of the twenty-four hours, between 6 A.M. and 6. P.M., to those occurring during the night half, was somewhat greater than the general average during the summer months, when the sun is in north declination, and somewhat less during the winter months, when the sun is south of the equator. As this relation was found not only in the whole record, but also in the natural groups of observations, it seemed probable that the variation was a real one, and not fortuitous; while the fact that the record of the Shillong seismograph, when tabulated by lunar times and seasons, gave a similar variation suggested that the cause was not climatic, but in some way connected with the tidal stresses set up by the attraction of the sun and the moon.[1]

At a later date I made a tabulation (which has not been published until now) of Milne's catalogue of Japanese earthquakes,[2] and again found a similar relation between the ratio of day to night shocks in the two halves of the year; and a similar tabulation of the records from a number of observatories,[3] mostly independent of and covering a later period than Milne's catalogue, again gave the same result.

Recently there has appeared an abstract tabulation of twenty years' records of observations, carried on by the Italian seismological service, which enables the subject to be more completely studied than was possible with the more limited and imperfect records previously available.[4] In this, once more, the relatively greater frequency of earthquakes during the day in summer and the night in winter is shown by a tabulation of the two halves of the year, and the completeness of the record enables a further test to be applied, based on the consideration that, if the observed variation is not accidental but due to some cause, whether climatic or physically dependent on the variation in the position of the sun, it should be greater at the height of each season than the average of the whole of each half-year. The months June and July were, therefore, taken as representing midsummer conditions, and the comparison of day and night frequency showed a divergence from the average of the year in the same direction as that of the season as a whole, but greater in amount. Similarly, the months of

[1] Mem. Geol. Surv. Ind. vol. xxxv, pt. 2 (1903) pp. 117–45.
[2] Seismol. Journ. Japan, vol. iv (1895).
[3] Publ. Earthq. Invest. Committee, No. 8, 1902.
[4] Boll. Soc. Seismol. Ital. vol. xx (1916) pp. 9–31.

December and January, as representing midwinter conditions, showed a larger excess of night shocks than the general average of the winter half-year.

The actual figures and ratios referred to above are set forth in detail in tabular statement No. 1 (p. 101), and in this each group of half-yearly ratios of frequency may be taken as a single event. In any division of the year into two halves the ratio of day to night shocks would very improbably be exactly the same as for the whole: the actual divergence is in no case greater than might reasonably be expected if the variation were purely fortuitous, and the odds are even that the variation would be in either direction. No conclusion can, therefore, be drawn from any one group taken separately; but the probability that the variation would be in the same direction in each of the three groups is only one-eighth. Similarly, the two extremes in the Italian record may be taken as independent events; in each case, if merely accidental, the variation might, with equal probability, be such as to make the ratio either greater or less than the average of the whole of each half-year, but the probability of their being in both cases greater is only one-quarter, reducing the probability of the whole series falling in the order actually found to one thirty-second. In other words, the odds are 31 to 1 that the variations are not accidental but due to some common cause, and, if the lunar tabulation of the Shillong seismograph can be accepted as another event, the odds become 63 to 1.

From these considerations it may safely be laid down as a general principle that earthquakes are rather more frequent during the day in summer and less frequent in winter than the general averages, with an opposite variation in frequency during the night; and that this relation may be expected wherever the record is sufficiently complete, covers a sufficiently long period, and contains not less than about 1000 separate shocks. This last proviso is necessary, for, with so irregular a phenomenon as an earthquake, a good average can only be obtained where a sufficiently large number of separate records is dealt with. Experience has shown that 400 is about the lowest limit which can be safely used, a larger number is better; but the irregularities become so great, when the number in each separate group dealt with falls below 400, that small variations cease to be traceable.

The extent of the Italian record makes it possible to carry the investigation farther, by considering, separately, each of the two-hour periods in which the record is tabulated. This has been done in tabular statement No. 2 (p. 102), from which it will be seen that the relation between day and night shocks which was found in the case of the half-days is also met with in each of the two-hour periods of each half. A similar tabulation of the Japanese catalogue gave results in substantial agreement with the Italian, with irregularities for the periods between 2 and 6 A.M. and 4 to 6 P.M.; the Japan record, however, is much less homogeneous than the Italian, for, of the total number of shocks recorded, more than three-fifths are

after-shocks of the Mino-Owari earthquake of October 28th, 1891, and of these three quarters fall in the winter half-year. As a result, the mean number of shocks in the two-hour periods of the summer half-year is only 255, a number much too small to give a good average, with the result that the curve of frequency shows great irregularity. This could be obviated by enlarging the groups by a series of overlapping periods; but the method seems less legitimate than that of simply enlarging the periods to three hours each, by which a series of numbers close to the minimum admissible is obtained. The result of this tabulation is given in statement No. 3 (p. 102), and this and the Italian record are shown graphically in the accompanying diagram (Pl. XII).

An examination of these curves shows that the variation in frequency is distributed symmetrically with regard to the time of meridian passage of the sun, but oppositely in each half-year. In other words, it is represented, for each season, by a curve of 24-hour period, with its maximum and minimum, at the times of meridian passage, superimposed on the general curve of variation in frequency—this superimposed curve being similar in each half-year, but with the maximum of one half coincident in time with the minimum of the other. As the variation in the gravitational stresses set up by the sun follows precisely the same course, it is not unnatural to suppose that the two may be connected as cause and effect, and the suggestion obtains some support from the lunar

I. Day and Night Frequency of Earthquakes.

	Number of Shocks.		*Ratio.*
	Day.	*Night.*	*Day : Night.*
Italy, 1891–1910.			
June-July	791	967	90 : 110
Summer half-year	2057	2615	88 : 112
Whole year	3828	5238	84 : 116
Winter half-year	1771	2623	81 : 119
December–January	583	928	77 : 123
Japan, 1885–1892.			
Summer half-year	1522	1537	98 : 102
Whole year	3872	4456	97 : 103
Winter half-year	2350	2919	93 : 107
Assam Aftershocks.			
Sun's declination over 9° N.	1476	1126	113 : 87
Whole year	3839	3329	107 : 93
Sun's declination over 9° S.	1175	1147	101 : 99
Shillong Seismograph Lunar.			
Moon's declination over 9° N.	260	250	102 : 98
Whole record	632	642	99 : 101
Moon's declination over 9° S.	194	237	90 : 110

II. DIURNAL DISTRIBUTION OF EARTHQUAKES (ITALY, 1891–1910).

Hours.	Number of Shocks.			Ratio to Mean.		
	Year.	*Summer.*	*Winter.*	*Year.*	*Summer.*	*Winter.*
0– 2	1001	500	501	1·32	1·29	1·37
2– 4	1094	556	538	1·45	1·43	1·47
4– 6	903	448	455	1·20	1·15	1·24
6– 8	735	386	349	·97	·99	·95
8–10	582	316	266	·76	·81	·73
10–12	623	329	294	·83	·85	·80
12–14	603	335	268	·80	·86	·73
14–16	666	351	315	·88	·90	·86
16–18	619	340	279	·82	·87	·76
18–20	627	312	315	·83	·80	·86
20–22	755	361	394	1·00	·93	1·08
22– 0	858	438	420	1·14	1·12	1·15
Totals ...	9066	4672	4394	12·00	12·00	12·00

III. DIURNAL DISTRIBUTION OF EARTHQUAKES (JAPAN, 1885–1892).

Hours.	Number of Shocks.			Ratio to Mean.		
	Year.	*Summer.*	*Winter.*	*Year.*	*Summer.*	*Winter.*
0– 3	1086	378	708	1·04	·99	1·08
3– 6	1016	365	651	·98	·95	·99
6– 9	975	396	579	·94	1·04	·88
9–12	926	355	571	·89	·93	·87
12–15	1049	425	624	1·01	1·11	·95
15–18	922	346	576	·89	·91	·88
18–21	1079	353	726	1·04	·92	1·10
21– 0	1265	441	824	1·21	1·15	1·25
Totals ...	8318	3059	5259	8·00	8·00	8·00

tabulation of the Shillong seismograph, though the number of shocks dealt with in this case is too small to give it much weight. For the present this must remain a mere suggestion; all that can be asserted is that, whatever may be the actual ratio of day to night shocks in any district and any period, it will be rather greater in summer, and rather less in winter, than the average of the whole year and period.

[In this paper no attempt has been made to apply the method of harmonic analysis because the applicability to earthquake frequency seems doubtful, for reasons which cannot be discussed in detail. As, however, something of the kind seems expected, and as the Italian record, by reason of its completeness and of the fact that the period covered is nearly coincident with the lunar cycle of 19 years, is less unsuited to this method of treatment than the

records which had been previously available, it may not be without interest to point out that the observed frequency is closely approximated by the formula

$$N = 755{\cdot}5 + 212 \sin. (t + 61° 45') + 122 \sin. (2t + 14°), \quad (1)$$

where N represents the number of shocks occurring in any period of two hours' length, and t the time of the middle of the two hours, reckoned from midnight. This formula may be more conveniently put in the form

$$R = 1{\cdot}0 + {\cdot}28 \sin. (t + 61° 45') + {\cdot}13 \sin. (2t + 14°), \quad (2)$$

where R represents the ratio of the actual to the mean number of shocks in a two-hour period, and from this we get the true harmonic frequency [1] as

$$F = 1{\cdot}0 + {\cdot}28 \sin. (t + 61° 45') + {\cdot}14 \sin. (2t + 14°). \quad (3)$$

In other words, we have a diurnal period with a maximum at 1h. 53m. after midnight and a minimum twelve hours later, combined with a semidiurnal period having maxima at 2h. 32m. after midnight and midday, and minima six hours later. The semidiurnal period may be connected with the gravitational stresses set up by the sun, if the correlation is, as it should be, with the rate of change, not with the actual amount, of the stress. The diurnal period is less easy to explain; there is no apparent connexion with the distribution of the gravitational stresses, nor with the diurnal variation in the height of the barometer; there is some apparent connexion with the diurnal variation in temperature, but it is difficult to see how this could affect the frequency of earthquakes. The last named seems to have a real periodicity, for each of the two decades gives a formula closely corresponding to that of the whole period, and the variation in frequency cannot be attributed, in any appreciable degree, to variation in the perfection of the record, by feeble shocks being recorded at some times of the day, and passing unnoticed at others. This is shown by the separate tabulation of shocks of over V° of the Mercalli scale, that is, shocks of such a degree of violence that they could not pass unnoticed and unrecorded, at whatever hour of the day or night they might occur, in a country where the observation of earthquakes is so well organized as in Italy. This tabulation gives an harmonic frequency of

$$F = 1{\cdot}0 + {\cdot}28 \sin. (t + 61° 15') + {\cdot}17 \sin. (2t + 19°), \quad (4)$$

which does not differ materially from (3).

The seasonal variation in frequency dealt with in the paper involves the introduction of a fourth term which makes the approximate representation of the diurnal periodicity in each half year

$$F = 1{\cdot}0 + {\cdot}28 \sin. (t + 61° 45') + {\cdot}14 \sin. (2t + 14°) \pm {\cdot}04 \sin. (t + 90°), \quad (5)$$

[1] C. Davison, Phil. Trans. Roy. Soc. vol. clxxxiv (1893) p. 1111.

the negative sign of the fourth term being used for the summer, and the positive for the winter, half of the year.

The Japanese record, treated similarly, gives the formula

$$F=1{\cdot}0+{\cdot}10 \sin. (t+107° 15')+{\cdot}04 \sin. (2t+130°), \quad . \quad . \quad . \quad (6)$$

which, compared with (3), shows amplitudes of about one-third of those in the Italian record, and epochs which precede midnight by 1h. 9m. and 1h. 20m. respectively. The meaning and interpretation of this difference being at present under investigation, further reference to it must be deferred.]

EXPLANATION OF PLATE XII.

Diagram illustrating the diurnal and seasonal frequency of earthquakes in Italy and Japan.

Discussion.

Dr. J. W. Evans congratulated the Author on the clearness of his exposition of the intricate relations with which his communication dealt. He seemed to have established satisfactorily the reality of the diurnal and seasonal variations in earthquake frequency for which he contended, and their relation to the diurnal inequality of the solar tides in the earth's crust. One naturally compared these results with the pendulum observations by Hecker at Potsdam in a chamber excavated at more than 80 feet below the surface of the ground. These indicated variations in the conformation of the earth's crust, which, like those in the frequency of earthquakes, must be due to stresses of a periodic character. The diurnal variation is, however, attributed to changes of temperature, partly because it is too large in comparison with the semidiurnal and lunar variations to represent the diurnal tidal inequality, and partly because it is greatest in summer and least in winter. It is difficult to understand how the variations in temperature which mainly occur in the outer 6 or 8 inches of the earth's crust and have practically ceased to exist at a depth of 2 feet could have such a result; but there is no other known cause that can be suggested, except the light pressure of the sun's radiation, and that only amounts to 75,000 tons for the whole hemisphere exposed to sunlight. The diurnal variation in earthquake frequency described by the Author cannot be due to the daily changes of temperature, for it is least in summer when these are greatest.

By permission of the President, Dr. Evans then read the following extracts from a letter by Mr. Harold Jeffreys, who had seen the abstract, but was prevented from being present at the discussion:—

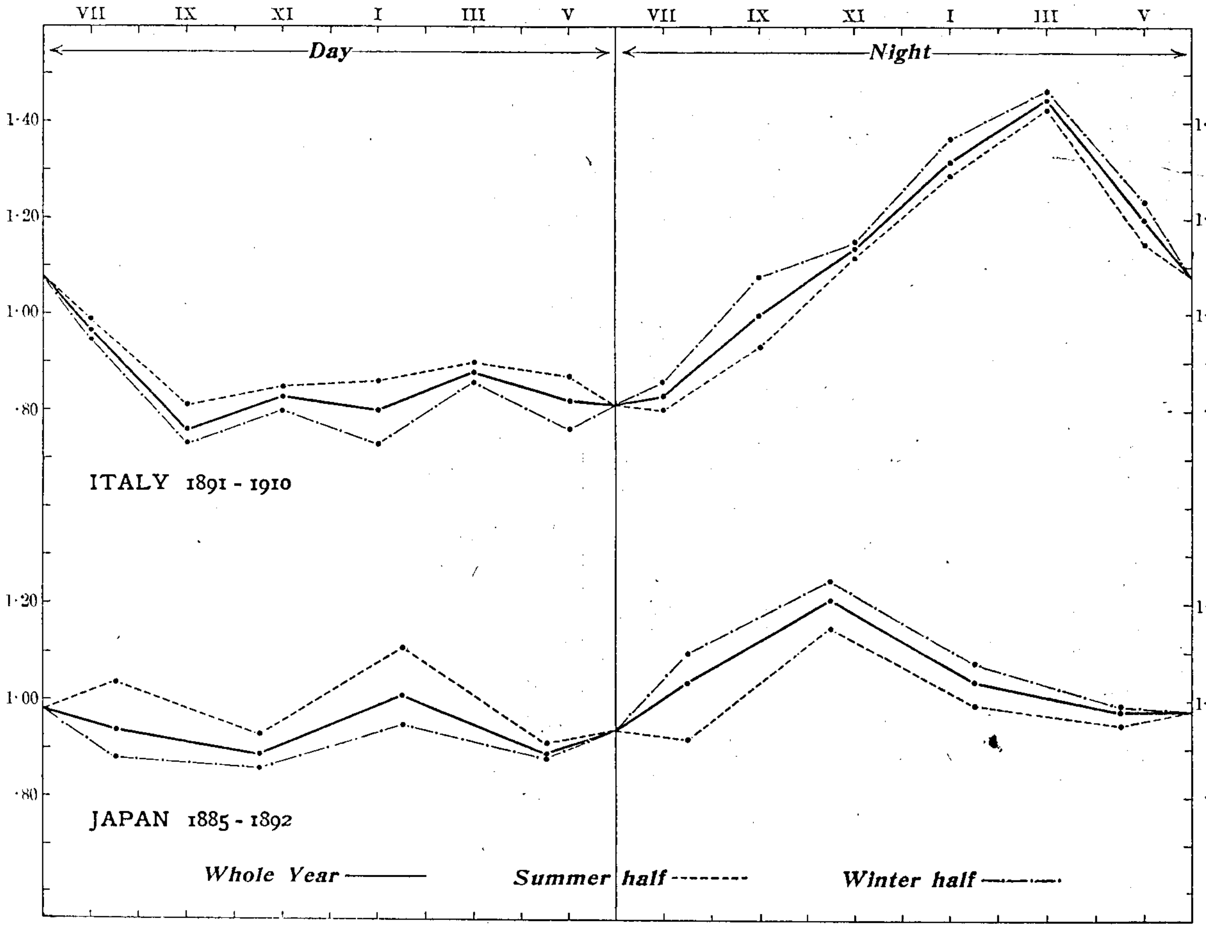
The dynamical explanation of these observations is likely to be somewhat difficult. The diurnal effect (period 24 hours) might arise, either from the diurnal bodily tide, or from heating. The former is rather small, depending on the inclination of the Equator to the ecliptic, and should have opposite signs in winter and summer at the same plane, and in the Northern and Southern Hemispheres at the same time. Its amplitude is only about a

quarter of that of the solar semidiurnal tide, but this has a node in latitudes $\pm \sin^{-1} \frac{1}{\sqrt{3}}$ — not far from Italy and Japan. From the fact that the difference between day and night persists throughout the year without change of sign, only of amplitude, I should conjecture that the explanation is partly thermal and partly tidal, although I admit that I do not know how heating could produce any effect at such depths, unless it could penetrate in some way down the fault-planes. It is very difficult, for instance, to exclude the direct effect of the surface in finding temperatures in borings.

If the diurnal bodily tide is important in Japan, then the solar semidiurnal tide should produce a far greater effect at the Equator and in high latitudes, and the lunar semidiurnal tide a greater one still; the action of the two together would give a strong fortnightly term. The absence of these would indicate that the effect is mostly thermal.

Mr. W. H. Booth suggested that the Earth's temperature, which increases about 1° Fahr. per 50 feet of depth, was due solely to the friction set up by the work of the sun and moon in bending the Earth's outer surface, and that the temperature probably attains a maximum at a comparatively small depth. This is supported by the high temperatures found in boring the Simplon Tunnel, when boiling water was met with several thousand feet above sea-level. Mountains, of course, standing above the general level, are particularly subject to tidal action. All work is dissipated as heat, and, when the rock-temperatures attain a certain limit, the rocks may be so weakened as to give way: as the Author of the paper suggests, the tendency would be to give way at times of maximum effort of tide-producing agents.

The Author, replying, said that he was by no means satisfied that the variations in frequency were really consequences of the hypothesis on which they had been discussed. All that could be said was that the results were quite concordant and in agreement with the supposition that the tidal stresses set up by the sun were not without effect on the frequency of earthquakes. Some of the results were of interest and value apart from the truth or otherwise of the hypothesis, which was being tested by a discussion of the shocks by lunar as well as solar time.



THE DIURNAL AND SEASONAL FREQUENCY OF EARTHQUAKES IN ITALY AND JAPAN.