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List of the Scientific Contributions by Leo A. Cotton which have not been previously presented as a thesis for any degree

(1) Metasomatic Processes in a Cassiterite Vein from New England.

Proc. Linn. Soc. N.S.Wales, Vol.XXXIV, 1909.

(2) Note on the Guyra Lagoon, N.S.W.

Proc. Linn. Soc. N.S.Wales, Vol.XXXIV, 1909.

(3) The Tin-deposits of New England, N.S.W.

Proc. Linn. Soc. N.S.Wales, Vol.XXXIV, 1909.

(4) The Ore-deposits of Borah Creek, New England District, N.S.W.

Proc. Linn. Soc. N.S.Wales, Vol. XXXV, 1910.

(5) (With A.B.Walkom).

Note on the Relation of the Devonian and Carboniferous Formations west of Tamworth.

Proc. Linn. Soc. N.S.Wales, Vol.XXXVII, 1912.

(6) The Diamond Deposits of Copeton, N.S.W.

Proc. Linn. Soc. N.S.Wales, Vol.XXXIX, 1914.

(7) Petrological description of some rocks from South Victoria Land.

Brit. Antarctic Expedn. 1907-9

Reports on Scientific investigations; Geology, 1916, ii part 13, appendix.

Earthquake Frequency with
special reference to Tidal Stresses
in the Lithosphere.

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PART I.

Introduction.

From the very earliest times the attention of man has been arrested by earthquake phenomena. This is particularly the case in those countries which have been tormented by disastrpus shocks. The Chinese and Japanese records contain frequent references to the destructive effects of the larger shocks and these have provided material for the comprehensive catalogues published by Drake[16] and Milne[39] for these countries. The importance attributed to such events may be well illustrated by reference to the chronology of the Jews. The great earthquake which occurred in the reign of Uzziah[95] was used as a datum point to which subsequent events were long after referred.

Such events could not come and go without arousing curiosity and speculation as to their origin. In uncivilised or semi-barbarous communities these speculations either attributed the cause of earthquakes to the movements of some subterranean monster or to supernatural agencies. Amongst more enlightened peoples a more rational attitude of mind prevailed. For example Aristotle, Pliny and others held the view that the movements were due to imprisoned wind or vapours seeking to escape from beneath the earth[22] - a view, after all, not far removed from the more modern theory of a volcanic origin for earthquakes.

As the horizon of man became wider through geographical discovery the intimate relation between the distribution of volcanoes and earthquakes became apparent, and it was natural that earthquake phenomena should be attributed to volcanic energy. This has been the dominant view of the last century and prevailed until its last decade. This may be seen from the view expressed by Milne,[40] the father of modern seismology, as late as 1886. He says, in summarising a discussion on the causes of earthquakes, "Although it would be an easy matter to discuss the relationships of earthquakes and other phenomena, we must conclude that the primary cause of earthquakes is endogenous to our earth, and that exogenous phenomena, like the attractions of the sun and moon and barometric fluctuations play but a small part in the actual production of these phenomena, their greatest effect being to cause a slight preponderence in the number of earthquakes at particular seasons. They may, therefore sometimes be regarded as final causes. The majority of earthquakes are due to explosive efforts at volcanic foci. The greater number of these explosions take place beneath the sea, and are probably due to the admission of water through fissures to the heated rocks beneath. A smaller number of earthquakes originate at actual volcanoes. Some earthquakes are produced by the sudden fracture of rocky strata or the production of faults. This may be attributable to stresses brought about by elevatory pressure. Lastly, we have earthquakes due to the collapse of underground excavations."

(N.B. The italics are not Milne's but mine L.A.C.) Milne, of course, subsequently modified this view but it is here quoted as evidence of the opinion of the most eminent seismologist at that date.

The volcanic theory is now generally abandoned as the chief or even as a very important cause of earthquakes, though it is, of course, admitted in special cases. Some, however, still adhere to the volcanic theory and its chief advocate would now appear to be See[88a] who attributes volcanic and earthquake phenomena to the penetration of sea water to the heated rocks below, and the consequent development of vapour pressure.

Earthquakes are now, however, almost universally recognised as being of tectonic origin. This change in opinion has been brought about chiefly through the labours of M. de Montessus de Ballore[53] and the late Edward Suess.[90a] Both these authorities have demonstrated the intimate relations between lines of crustal weakness and the distribution of earthquake foci. M. de Montessus de Ballore has attacked the problem on a grand scale taking the world for his province. Suess has particularised and demonstrated the relation for such districts as the Murz Line,[90b] Calabria[90c] and other centres.

The most striking demonstrations of the truth of the tectonic theory were afforded by the surface desplacements along fault lines during the Mino-Owari,[32] the Assam and the San Francisco[33] Earthquakes.

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A great many other workers, amongst whom perhaps Omori and Davison are pre-eminent,[10, 10a,b,c,d] have since investigated the relation of earthquake centres to fault planes and the tectonic origin of earthquakes may now be regarded as being firmly established.

Although the prime cause of earthquakes is now apparent much remains to be done. One of the chief incentives to the study of earthquakes is the possibility of predicting their occurrence.

The appalling loss of life caused by ~~destruction~~ destructive earthquakes claims the sympathy of all and makes an imperative demand on seismologists to discover ways and means of mitigating their disastrous effects.

Davison[12] has compiled statistics on the death rate of earthquakes and his paper records no less than 1,249,590 deaths due to destructive shocks. Drake[16] records a similar number, 1,430,000 from the records of China alone. Only one earthquake, the Pekin earthquakes of 1731 A.D. which caused 100,000 deaths is common to both Davison's and Drake's lists, so that more than two and a half million people are known to have perished as the result of earthquakes. Most of the lives have been lost through the collapse of dwellings and the imprisonment and crushing of the unfortunate victims beneath the ruins. In many cases the mortality is very high, often exceeding 50 per cent of the population. Nor are the more recent earthquakes the least disastrous. Two of the highest death rates are recorded for the Messina earthquakes of 1908 and the Avezzano[1] earthquake of 1915 in which 65 and 96 per cent of the respective populations perished.

The national importance of research in connection with seismology has been recognised by the Government of Japan which in 1892 established the Imperial Earthquake Investigation Committee of Japan. The work of this institution has done much to advance our knowledge of seismology. The objects which it seeks are set forth as follows:-[26]

"In the first place to investigate whether there are any means of predicting earthquakes; and in the second place to investigate what can be done to reduce the disastrous effects of earthquake shocks to a minimum, by the choice of proper structures, materials, position, etc.."

A very large measure of success has crowned the second of these endeavours, and it is now possible to design buildings which are practically earthquake proof. Hand in hand with this work the mapping of seismic areas has gone on, and the admirable charts of M. de Montessus de Ballore,[53] Davison[10a] and others now serve to indicate the more dangerous seismic regions. Nevertheless the enormous majority of dwellers in earthquake countries still live in houses which are potential tombs in the event of the occurrence of a destructive earthquake; and, since it is not possible for most people to pull down their homes and rebuild earthquake houses, this will undoubtedly remain the case for many years.

It is then on the first object ~~that much~~ of the Earthquake Investigation Committee that such people may depend their hopes. Nor is the future without such hope. For example Hayes and Lawson predicted with some success the Mexican Earthquake of 1907[20]; and Omori has shown by his prediction of the Valparaiso[20] and Formosa[74] earthquakes how, in a very general way, it may be possible within rather wide limits to to approximate both the time and place of an earthquake. He has also pointed out[76] that in a number of cases there is an increase in seismic activity preceding a disastrous shock so that the study of instrumental seismology may contribute its share to the solution of the problem of the prediction of earthquakes.

Gilbert[20] has writen on this subject but, although admitting the feasibility of earthquake prediction, he is disposed to doubt the value of such a prediction should it be found practicable. He assumes that ~~it would result~~ the prediction could never be precise and that it would result in keeping people ~~on~~ in a state of uncertainty and high nervous tension for considerable periods of time. This, however, would scarcely be the case if the time of the event could be predicted with precision, and its occurrence with a high degree of probability.

Schuster[88] too is inclined to doubt the value of earthquake prediction, but for other reasons. It is "the fear of creating panics by premature forecasts" that he conceives to be the difficulty. He says "even if our knowledge should allow us in the future to form predictions of equal certainy (to those of meteorological prediction L.A.C.) the dangers accompanying such predictions may overbalance its benefits". Such a view appears unduly pessimistic. It is based mainly on the possible dislocation of trade and of the manner in which financial interests might be affected. These considerations, however, are surely of minor importance when contrasted with loss of life and physical suffering. One is tempted to think, from the rather ~~humourous~~ Jocular setting in which Schuster has placed these views that he did not intend them to be taken too seriously.

Davison,[14] too, has discussed the subject of earthquake prediction. He considers that ~~the~~ to be effective both the time and the place of the earthquake must be predicted with accuracy. He recognises however that the problem is one of great importance and states "its solution would possess such untold value for the dwellers in seismic countries that it does seem worth while to examine the progress that has been made in the hope that further knowledge and greater experience may in time to come ~~be~~ lead us to the desired goal". From his consideration of the progress already made Davison concludes that the chief hope appears to lie in the mechanical registration of some phenomena which precede earthquake shocks. Such mechanical measurements may either be trigonometrical revealing earth movements leading to strain, or they may be made by seismographs recording actual movements in progress. It is conceivable that the former method might have yielded important information with regard to the San Francisco earthquake of 1906. The latter method, as subsequently investigated by Davison,[13] would clearly have indicated the probable position of the Mino-Owari earthquake of 1891 and would also have furnished some ~~import~~ information as to the possible time of its occurrence.

Again, Milne[41] has recognised both the possibility and value of earthquake forecasts. He says "Ever since seismology has been studied one of the chief which would enable them to foretell the coming of an earthquake, and the attempts which have been made by workers in this country to correlate these occurrences with other well marked natural phenomena, may, I think, be regarded as attempted in this direction.

Ability to herald the approach of these calamities would unquestionably be an inestimable boon to all who dwell in earthquake shaken countries, and the attempts which have been made both here and in other places are extremely laudable".

Words such as these from the Father of modern seismology are an inspiration to those who labour in this field of research.

The problem of earthquake prediction raises immediately that of earthquake frequency and periodicity. In the search for such phenomena one is naturally led to the consideration of the periodicity of other natural phenomena. Thus we have the rise and fall of the tides, the variations of temperature, barometric pressure, ~~and~~ wind velocity and direction ~~of~~ and rainfall. Thes can all of them be related to the movements of the earth with regard to the sun; or of the moon with regard to the earth. A great many distinguished scientific men have investigated these questions and are still engaged in so doing; and there is little doubt that each of the above mentioned phenomena has, in special cases at least, contributed an element affecting earthquake frequency.

Before presenting his own contribution to this interesting investigation the author proposes to give a critical review of what has so far been accomplished and so present the position as it stands to-day.

EARTHQUAKE FREQUENCY and PERIODICITY.

Prior to the middle of the nineteenth century there were no very comprehensive earthquake catalogues available for study. The foundations for a statistical investigation of earthquakes frequency were laid by the labours of Perrey and Mallet[36] in the catalogues which they prepared during the period 1840-1860. This work has since been carried on by M. de Montessus de Ballore, Milne, Omori and many others.

Most of the records earlier than the last decade of the nineteenth century were not instrumentally recorded - a fact which emphasises the rapid growth of modern seismology.

Numerous attempts have been made to correlate the occurrence of earthquakes with other natural phenomena the chief efforts being included under one or more of the following:-

1. Auroral displays and ~~the~~ luminous phenomena
2. Magnetic and electrical disturbances
3. Planetary influences.
4. Sun Spots
5. Temperature
6. Barometric Pressure
7. Wind Velocity
8. Rainfall and Snowfall
9. Seasonal periodicity
10. Diurnal periodicity

(4-10) Solar effects

11. Ocean Tides
12. Earth tides

(11-12) Solar and lunar effects.

13. Other Periodicities

Earthquakes and the Aurora and luminous phenomena.

The possible relation of earthquakes with the aurora has been discussed by Milne,[40] who apparently does not attach much significance to the evidence so far available. Although a number of striking examples of the simultaneous occurrence of an aurora with an earthquake are recorded, a more extended statistical investigation than has hitherto been made seems desirable. The most comprehensive statistical investigation undertaken so far appears to be that of Boue[3] comprising data for the period 1834 to 1847. He records in this interval 457 earthquakes and 351 notices of aurora. On 48 occasions an earthquake and an aurora occurred on the same day; on 30 of these occasions approximately at the same time; and on 5 occasions at the same hour of the day. This degree of coincidence is perhaps, suggestive but does not point to a very intimate relation between the phenomena.

M. de Montessus de Ballore[62] has discussed the relation of earthquakes and luminous phenomena. He points out that such phenomena have been observed on the occasion of about 200 earthquakes, and that these have usually been destructive earthquakes. As 4136 destructive earthquakes have been recorded by Milne for the Christian Era, the degree of coincidence of these two sets of phenomena is not striking. Probably, in many cases, as in the Chilian earthquake of August 16th, 1906, a storm has coincided with the earthquakes and the luminous phenomena are due to that circumstance.

It is at least significant that in the extensive and elaborate catalogues of the Chinese no such phenomena have been recorded.

Ballore concludes as follows:-

"At the present stage of our observations it is not scientific or rational either to affirm or deny the existence of luminous earthquake phenomena; but all the arguments and facts at our command bear us out in a negative conclusion".

Magnetic and electrical disturbances.

The synchronism of earthquakes with magnetic and electrical disturbances has prequently been noted and is probable that the phenomena are interrelated. It seems more feasible, however, that such disturbances are the result of electrical energy generated by the slipping of the rocks along a fault during an earthquake than that they have an influence in bringing about the earthquake. The question has been discussed by Milne[40] who concludes that such disturbances are more likely to be the result than the causes of earthquakes.

Planetary influences.

Delaun~~a~~ey[15] on analysing Perrey's catalogue of earthquakes embracing the period 1750 to 1842 found two sets of maxima for earthquake frequency commencing in 1756 and 1759 respectively, ~~and~~ each having a period of about ~~21~~ 12 years. These groups he states coincide with the times when Jupiter is in 265° and 135° celestial longitude, and is passing through meteor streams in those longitudes. He also finds evidence of two other ~~were~~ groups of maxima commencing in 1756 and 1773 respectively, each having a period of 28 years. These maxima of earthquake frequency he states coincide with the times when Saturn is passing through the meteor streams in longitudes 265° and 135° respectively.

He also attributes the maximum earthquake frequency recorded by Perrey for November to the earth's passage through a meteor stream during that month.

It seems scarcely credible that the stresses set up by the gravitational attraction of planets and meteors should be of sufficient magnitude to affect earthquake frequency, since such an effect would be masked by the enormously greater attraction of the sun and moon; and also indeed by other influences.

Temperature.

Kluge[27] and others have indicated a relation between temperature and earthquake frequency. This conclusion appears to rest upon the evidence of a winter maximum for earthquake frequency and ~~that~~ the fact that a greater number of earthquakes have been recorded by night than by day. The validity of the winter and night maxima have however been seriously challenged by M. de Montessus de Ballore who attributes these maxima to physiological conditions. It is well known that many earthquakes felt by people at rest are not noticed by persons in motion; and the hours of rest are more frequent in winter and at night.

The solution of this problem must therefore rest upon the evidence of instrumental records, and no comprehensive investigation on this basis has yet been attempted.

It is, however, difficult to imagine that any diurnal variation in temperature can directly affect the frequency of earthquakes by strain of the rocks under expansion and contraction; for the diurnal temperature wave affects only the mere surface of the earth's crust.

Sun-Spots and Earthquake Frequency.

A number of seismologists and others have sought for a relation between periods of sunspot maxima and minima and those of earthquake frequency. Some of these attempts have been discussed by Milne[40] who referred to the works of Naumann, Schmidt, Wolf, Kluge and Poey.

Naumann and Schmidt did not reach a result favouring a relation for these phenomena.

Wolf apparently considers that periods of earthquake maxima coincide with those of sunspots.

Kluge, on the other hand, came to the conclusion that the maxima of earthquake frequency coincide with the sun-spot minima.

Poey, again, from an examination of the earthquakes of Mexico and the Antilles stated that earthquake frequency was at a maximum for the period of both maximum and minimum sun-spot activity. He examined thirty-eight groups of records and found that seventeen occurred at the maximum and seventeen at the minimum of sun-spot frequency. The remaining four groups formed exceptions to the rule.

Bayles[91] concluded that both volcanic and seismic activity reached a maximum at periods of sun-spot minima, and a minimum at periods of sun-spot maxima. He later modified this view and concluded that the relation was true for volcanic rather than for seismic activity.

Jensen[25] from the examination of the question reached the conclusion that the maximum earthquake frequency is associated with the minimum sun-spot activity. He does not however attribute this to a temperature effect, pointing out that the annual variations of temperature due to solar energy are almost imperceptible at a depth of 30 feet from the earth's surface.

Huntington[23] too, has reviewed the question dealing chiefly with the work of Sayles and Jensen, and apparently accepting their conclusions.

The problem was again examined by Taber[91] for the earthquakes of the Charleston district. The period over which his investigations extended, 1882-1913, embraced three sun-spot maxima, but on only one of these occasions (the year 1893) was there a maximum of earthquake frequency.

Taber regards this as a coincidence and concludes that his results do not furnish any evidence of such a relation as that noted by other workers for different seismic regions.

There is however other evidence of a collateral nature which may possibly have some bearing on the subject. In an earlier part of this paper it was noted that Delauney indicated a maximum of seismic frequency coincident with the periodic revolution of Jupiter about the sun - and this period of about 11 years coincides with that of the sun-spot maxima.

Again, Milne has indicated a period of 33⅓ years for the earthquake frequency of Japan extending over the interval from 666 A.D. to 1800 A.D. Such a period would coincide with three cycles of sun-spot activity.

As will be seen later there is some evidence of a relation between rainfall and earthquake frequency, and if this be the case the Bruckner cycle of rainfall being closely equal to three cycles of sun-spot frequency may have some bearing on the subject.

At present the evidence is not conclusive but is certainly sufficiently suggestive to warrant further investigation.

Earthquakes and Barometric Pressure.

At the time when the conception of a fluid nucleus for the earth dominated geologic thought it was very natural that an enquiry into the effect of changes in barometric pressure in relation to earthquake frequency should have been made. Both Perrey and Mallet examined the evidence and the former connected maximum seismicity with minimum barometric pressure accompanied by a maximum range of barometric oscillation.

Merian[40] as early as 1834 pointed out that there was an annual period of earthquake frequency.

Mallet investigated the frequency of earthquakes in relation to the rise and fall of the barometer and concluded that the frequency was about the same in each case.

Similar investigations are discussed by Milne[40] but the data employed in most of these cases have been too meagre to furnish any reliable conclusion.

The problem has however been investigated since by some of the most eminent seismologists, and in spite of the relatively small forces involved in barometric fluctuations there does appear to be good reason for believing that in a number of cases such changes in pressure have contributed towards the precipitation of an earthquake.

A new method of studying earthquake frequency was indicated and employed by Knott[28] in 1886. He pointed out that a simple arithmetical process could be used to accentuate the frequency of any given period by a suitable choice of grouping and averaging the records.

He examined the records of many countries and gave both a tabular and graphical representation of his results. His analysis showed that for all the districts considered there was an annual maximum of earthquake frequency which occurred during the winter months for that district; and that except in the case of the East Indies there is also a well marked semi-annual maximum of earthquake frequency. After discussing the possible cause of such frequency Knott concluded that it was probably due to meteorological influences - particularly snowfall and barometric pressures.

Although the manner in which the annual periodicity might be due to such a variation from the high pressure of winter to the low pressure of summer is readily intelligible, Knott does not show how the barometric variations could be harmonised with the observed semi-annual period of earthquake frequency.

Davison[9] too has taken up the question of earthquake frequency and in 1893 contributed a most comprehensive and important memoir on the subject. His method of analysis resembles that of Knott with slight modifications. One innovation is the examination of seismic activity according to its intensity. He effected this by dividing the earthquakes into slight shocks and those sufficient to damage buildings. This part of the investigation is limited to earthquakes felt only in the northern hemisphere, the data being taken from Mallet's catalogue. The analysis indicated both an annual and a semi-annual period. The annual maximum for slight earthquakes fell in the last fortnight of June; and the semi-annual maximum during the last fortnight of January and July. On the other hand in the case of the destructive earthquakes the annual maximum fell in the last fortnight of January and the semi-annual maximum occurred during the last fortnight of February and August. Hence it appears that the annual maxima for ~~slig~~ slight and strong shocks are opposite in phase; but this is not the case for slight shocks.

In the second part of his investigation no distinctio is made between the slight and strong shocks, but the earthquakes are considered in groups according to their areal distribution. Altogether 62 seismic records were considered, 45 from the northern and 14 from the southern hemisphere. The remaining 3 relate to equatorial countries. The analysis showed that only five of these sixty-two records failed to exhibit a well marked annual period, and in each of the anomalous cases the failure was considered to be probably due to incompleteness in the records. Davison remarks that these results "strongly support the view that the maximum of the annual period occurs during the local winter in each hemisphere".

Again "of the 62 records examined, only three fail to show a fairly well marked semi-annual period, namely, France (Fuchs), Spain and Portugal (Perrey) and Chili (Fuchs); these failures are probably due to incompleteness of the seismic records." After a comparison of the amplitudes of the annual and semi-annual periods and this district grouping Davison concludes "that the annual and semi-annual periods must have entirely different origins".

In a discussion dealing with the origin of the Annual Seismic Period Davison recognises that probably the majority of earthquakes are occasioned by the growth of faults, and that ~~periodically~~ periodicity may be impressed on these by external causes. He suggests that the annual variation is of a seasonal character and that it is affected by the barometric pressure.

In the case of 31 of the districts dealt with in his paper a comparison between the epochs of the seismic and barometric maxima can be made. In 10 of these districts there is an approximate coincidence in the times of the maxima; in 9 cases the seismic maximum follows the barometric maximum after an interval of one month; and in 4 other cases after an interval of two months. In the remaining 8 districts there are special circumstances which may mask such a relation. Davison concludes that" as a general rule, the epoch of the seismic maximum either coincides with that of the barometric maximum, or follows it by a month or two."

He points out that barometric pressure cannot affect the frequency of submarine earthquakes as the pressure on the sea floor will be unaltered owing to a displacement of the sea waters under such pressure; and hence ~~h~~ he explains the anomalies in the case of insular countries such as Japan and New Zealand.

The semi-annual period remains an unsolved problem for Davison concludes "With regard to the origin of the semi-annual period, I regret that I am unable to offer any definite suggestion".

The discussion on the semi-annual period will be considered later under the section dealing with tidal stresses.

Seidl[89] in 1895 attacked the problem from a different point of view. He prepared a table showing the monthly earthquake frequency of Europe for the period 306 A.D. to 1842 A.D. He also found the average monthly distribution of atmospheric pressure but instead of comparing this with the monthly earthquake frequency he adopted a different method. His plan was to calculate the average barometric gradient for each month and to compare this with the earthquake frequency. He expressed the barometric gradient in terms of millimetres per 2820 kilometres and measured from the continent towards the Atlantic Ocean. The table given by him is quoted below.

	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Earthquakes	147.7	138.6	119.4	104.6	94.7	95.4	104.4	101.8	110.2	110.9	123.7	136.4
Gradient	12.6	8.0	4.2	1.6	-0.2	0.6	0.4	1.5	5.3	9.2	6.0	9.3

In view of the genesis of earthquakes by dislocations of the earth's crust, this method of analysis is more rational than that which considers only barometric maxima and minima; for the consideration of barometric gradient implies or may imply differential stresses on opposite sides of the fault plane which gives birth to the earthquake.

The problem has been further considered by Becke[2] in his examination of the earthquakes of Graslitz for the period 24th October to 25th November 1897. He prepared a table and graphs to represent the average daily barometric pressure and also the daily earthquake frequency, and concluded that there was no obvious relation between these phenomena. The limited nature of the investigation, however, rather detracts from its value.

Omori, the foremost of the Japanese seismologists, has also directed his attention to this aspect of earthquake frequency.[71] He took as the basis of his discussion a catalogue of 18,279 earthquakes obtained from 26 stations, and the majority of the records had the merit of being instrumentally observed. Recognising that the time distribution might not be the same for the whole of Japan he subdivided the island into two more or less natural divisions. The first of these comprised that part which trends in a general north and south direction and the second that which trends about E 30°N and which comprises the southern portion of the Japanese Empire. He concluded that for the northerb part of Japan "the annual variation of the seismic frequency follows that of barometric pressure"; amd that for western Japan " "the annual variation of the seismic frequency is the reverse of that of the barometric pressure on the land".

In the same investigation Omori examined the diurnal variations in seismic activity. He found these to vary very considerably with different stations and arranged the stations into groups characterised by 12, 8 and 6 hour periods of frequency respectively. He next discussed the diurnal variations of barometric pressure and attributed the variations in seismic frequency to such barometric influences.

It should be pointed out that the diurnal wave of barometric pressure is very constant for the different stations considered and is quite normal in character, resembling that which characterises most meteorological stations. On the other hand the seismic frequency varies considerably in itsepochs for different districts It would appear therefore that Omori's conclusions with regard to the correspondence of the diurnal barometric and earthquake frequency are scarcely justified by the evidence.

Some six years later, in 1908, Omori[76] again took up the question of annual variation in seismic frequency, restricting his investigation to the earthquakes of Tokyo and Kyoto. He showed that the seismic maxima occurred at different epochs for large and small earthquakes and concluded as follows:-

"From the foregoing it is evident that we must treat small and large earthquakes separately, in the discussio of seismic frequency with respect to the atmospheric pressure, the position of the moon, etc."

In another paper on the "Secondary Causes of Earthquakes"[78] Omori deals more fully with the subject. He gives a table showing the hourly distribution of 2,208 earthquakes instrumentally observed at Tokyo during the 24 years 1876-1899. A curve plotted to illustrate the diurnal earthquake frequency shows four maxima. The diurnal barometric curve was also plotted and shows a close correspondence in the times of its two maxima and two minima with the times of the four seismic maxima.

Another curve is drawn showing the earthquake frequency for 3 hourly periods and this follows closely the barometric curve. Hence Omori concludes that "The ordinary (non-destructive) earthquakes felt in Tokyo happen more frequently with the high barometer than with the low."

Another piece of evidence is furnished by an examination of the records of the general weather conditions associated with the 18 destructive earthquakes recorded in Japan from 1361 to 1891 A.D. The weather conditions for these are as follows:-

Fair or clear weather	12	earthquakes
Cloudy	2	earthquakes
Rainy or Snowy	3	"
Rainy and Windy	1	"
Wet and Sultry	0	"

Omori concludes from this investigation that the great majority of destructive earthquakes appear to have been associated with fine clear weather - anticyclonic conditions involving increased barometric pressure.

It might, perhaps, have been worth while to have compared these figures with the meteorological data giving the average number of fine, cloudy, rainy, etc. weather for Japan; but this Omori does not appear to have considered.

e also made an examination of the stronger earthquakes from the Izu Island zone. Fourteen such earthquakes were considered and Omori ~~concluded~~ concludes that of these twelve are closely related in time to the two maxima and two minima of the diurnal barometric wave.

The recent strong earthquakes of Tokyo were also examined. These are fourteen in number. Omori finds that eight of these earthquakes were accompanied by marked barometric depressions ranging only from 741.5 to ~~t~~ 754.7 mm., while a ninth was accompanied by a very high barometric pressure of 774 mm. He does not in this case discuss the relation of these earthquakes to the diurnal barometric wave. An examination of the data indicates that there is a correspondence with the diurnal barometric wave in only six of the fourteen earthquakes.

Again, in considering the sixteen earthquakes of coastal and submarine origin in the neighbourhood of Tokyo Omori points out that these occur exclusively between 6 and 12 p.m. He takes the average time of occurrence of the earthquakes for each of these groups and finds these times to correspond with those of the barometric maxima. As, however, a considerable range of time is involved in each case, it is very doubtful if such a method is valid.

In his book "The Physics of Earthquake Phenomena" (1908) Knott[31] again returns to the problem of earthquake frequency and barometric pressure. He reviews his own earlier work and the later papers of Omori and Davison. He points out that both these seismologists correlate earthquake frequency with barometric maxima and minima. His own view is that the barometric gradieht is more likely to be the determining factor and he interprets the results of the investigations in that light. He points out that the differences in barometric pressure in a steep barometric gradient may disturb the isostatic balance and so give rise to earthquakes along the margins of the continents. Undoubtedly this view is more in keeping with our knowledge of the physics of earthquake phenomena, as it may involve a stress co-operating with the prime forces giving rise to an earthquake. It is, on the other hand, difficult to see how the mere increase or decrease of pressure uniformly distributed across the earthquake area could produce such a result.

In his final summary, however, Knott appears to think that the evidence at present available indicate that earthquake frequency depends very slightly, if at all, upon such influences as barometric phenomena.

The search for such a relation has not, however, been abandoned, and two very important contributions on this subject have been made since Knott's book was published.

The first of these is a paper by Drake[16] on the earthquakes of China. The author of this paper has prepared a catalogue of 528 destructive earthquakes extending over the last 4000 years. Of these 505 have occurred during the Christian Era. These are grouped in a dual fashion according to districts and according to their monthly frequency. A diagram is given showing the monthly frequency for districts to the north of the Yang-tse-Kiang, to the south of that river and for the ~~wheel~~ whole of China. The three curves have essentially the same features in common. The most prominent feature is the very large maximum for July and August. The maximum is far too large to be explained by a chance distribution of earthquake frequency. The study of the meteorological data discloses the fact that the dominant feature for South China is the annual recurrence of the Summer Monsoon. Speaking of these Drake says "The typhoons or summer monsoons come during summer and early fall; they strike the south and south-east coast of China, more towards the northwest and north, and gradually lose force as they pass over China; they are preceded by intense heat for several days and a falling barometer and are accompanied by heavy rains and a rising barometer the barometric variation during the storm is often over two inches. Speaking of the typhoons of Southern China Williams says the barometer not infrequently falls below 28 inches. This great variation in the air pressure applies more especially to a hundred mile wide strip along the south coast of China. The typhoons are practically confined to July, August and September, and are somewhat more common and severe during August and September".

Northern China on the other hand is principally affected by the winter monsoon which occurs during winter and early spring.

It would therefore naturally be expected that the summer maximus of earthquake frequency would be more marked in the case of South China than North China. The contrary, however, is actually the case.

Drake records but does not appear to have considered this anomaly. He has however considered other aspects of the problem of earthquake frequency and these will be subsequently discussed. With regard to barometric changes however he concludes "the rapid and strong atmospheric variations, assisted to some extent by rain, are the forces most effective in the final stage of earthquake activity".

The second paper referred to above is that by Taber[91] dealing with the earthquakes of the Charleston district. This investigation is probably the most complete enquiry into earthquake frequency that has ever been made for a single district. Many aspects of the question in relation to other natural phenomena are examined and some of these will be considered in other sections of this paper. At this stage however only the question of barometric variations and earthquake frequency will be discussed.

Taber, partly from geological and partly from seismological evidence has indicated the position of a large fault trending in a general north-eastern direction and passing between the towns of Summerville and Charleston. He recognises that if barometric variations are at all effective in promoting earthquake frequency a relation must be sought with the barometric gradient rather than with the maximum and minimum barometric pressures. An examination was made of the state of the barometric gradient for 75 earthquakes recorded in the period 1898-1913. He found that 43 of the earthquakes occurred on days when the barometric gradient decreased from north-west to south-east; fifteen shocks occurred when the gradient sloped in the opposite direction; and on the remaining seventeen occasions the barometric gradient was slight or indeterminate. The meteorological record for the years 1886-1897 was not fully available and could be ascertained for only twenty-eight earthquakes. For these the barometric gradient sloped from north-west to south-east on twenty seven occasions and was only in the opposite direction on one occasion.

Taber also found that for the period 1898-1913 "the atmospheric pressure on earthquake days was above normal for 58 per cent of the days and below normal for 41 per cent; and normal for one per cent. During the period 1886-1897 the percentages were above normal 61, below normal 37 and normal 2". This might at first seem to favour a relation between earthquake frequency and the times of maximum barometric pressure; but Taber found that by taking meteorological data extending over four years, the barometric pressure was above normal for 55 per cent and below normal for 43 per cent of the time This then leaves but a very small excess of earthquake frequency at the times of barometric maxima.

It should be remarked that the direction of the downthrow of the assumed fault in relation to the barometric gradient agrees with that indicated by other collateral evidence.

The foregoing review has indicated the directions in which attempts have been made to correlate earthquake frequency with barometric pressure. The results are not, perhaps, conclusive; but they do appear to render it highly probable that the state of the barometric gradient exercises some influence on earthquake frequency or, at the very least, that both these sets of phenomena are influenced by some common cause. It seems very desirable that the investigation should be carried further - particularly for small districts in which the fault zone giving rise to the local earthquakes is definitely located by geological evidence.

Wind Pressure and Earthquake Frequency.

During storms accompanied by a high wind velocity the wind pressure is often considerable and it has been suggested that such an increase in pressure may be competent to ~~fi~~ fire, as it were, the earthquake gun. Milne[41] has discussd the possible relation of earth tremors and wind velocity and there appears to be a body of evidence in support of such a relation. He says, "For example, in 1887 strong winds were blowing in Central Japan eighty-six times, and it was only in six of these cases that tremors were not observed. On the contrary, when it was calm in Central Japan, only extremely small tremors were noted, and even this was of rare occurrence. An analysis of the tromometric records from Rome showed that for sixty-three increases and decreases in microseismic intensity, there had been forty-six increases and decreases in the intensity of the wind; the corresponding numbers for Rocco de Papa being sixty-four and forty-six".

If such a relation exists for earth tremors it may well be that wind velocity contributes a component to earthquake frequency. This question is however only one phase of the possible relation of earthquake frequency and barometric pressure; for steep barometric gradients are unstable and must inevitably give rise to strong winds. It may well be, of course, that the momentum of a large body of the atmosphere, ~~as~~ if suddenly arrest~~s~~ed would contribute an additional factor to that of the static pressure due to a barometric gradient.

Rainfall and earthquake frequency.

In countries where earthquakes are of frequent occurrence it is natural that many speculations as to the cause of earthquakes should arise. The coincidence of a storm, an oppresive day etc. with an earthquake is sufficient to establish in many untrained minds a causal relation between two such events. Consequently many persons have believed that earthquakes are associated with certain types of weather-earthquake weather - as it is described.

Milne[39] in 1881 states that a relation between the rainfall and earthquakes of Japan has been sought but with no satisfactory result. His own conception of such a relation was, at that time, strongly coloured by his belief in the volcanic origin of earthquakes. He says:-

"It does not seem to be altogether beyond the pale of possibility that the rain which falls upon a volcanic country may have an influence either in soaking downwards and becoming converted into steam, or in simply loosening the ground". He records that he has noted that "microphones buried in pits during a heavy shower of rain are sometimes very active". Although some coincidence between rainfall and earthquake frequency has been noted Milne thought that this being dependent on temperature, barometric pressure, etc. is a "congruent effect of more general causes".

Knott[28] after an investigation on annual periodicity suggested snowfall as a possible factor in determining earthquake frequency. After a lapse of twenty-two years in a comprehensive review of the subject of earthquake periodicity Knott again suggests that rainfall and snowfall may play some part in affecting the ~~p~~frequency of earthquakes. Shortly after this opinion had been expressed there appeared a very important memoir ~~od~~ by Omori on what he calls "secondary causes of earthquakes."[78] This contains what was probably at that time the most systematic enquiry into rainfall and earthquake periodicity, and indeed into secondary causes in general. Omori examined the records of earthquakes which were instrumentally recorded at Tokyo for the period 1876-1907. He found that the earthquake frequency at Tokyo bore "no marked general relation to that of the amount of precipitation"~~,~~ at Tokyo itself. On the other hand when the rainfall curve for the mean of the yearly precipitation at Akita and Niigata was examined for the period 1882-1907 (no earlier records were availab~~l~~le there was found to be a striking degree of correspondence between the curves illustrating yearly earthquake frequency and precipitation. The city of Niigata is about 260 kilo~~-~~metres north west, and that of Akita is about 440 kilometres north of Tokyo. Omori concludes that "This coincidence is probably not accidental, and the variation of the yearly number of earthquakes felt in Tokyo may be taken as approximately proportional to the amount of precipitation along the north western side of the main island".

M. de Montessus de Ballore in 1912 made an enquiry into a possible relation between earthquake frequency and long period variations (Bruckner Cycles) of precipitation.[58] This will be considered later in more detail. He concluded that there was no evidence of any relation between earthquake periodicity Knott again suggests that rainfall and snowfall may play some part in affecting the ~~p~~frequency of earthquakes. Shortly after this opinion had been expressed there appeared a very important memoir ~~od~~ by Omori on what he calls "secondary causes of earthquakes."[78] This contains what was probably at that time the most systematic enquiry into rainfall and earthquake periodicity, and indeed into secondary causes in general. Omori examined the records of earthquakes which were instrumentally recorded at Tokyo for the period 1876-1907. He found that the earthquake frequency at Tokyo bore "no marked general relation to that of the amount of precipitation", at Tokyo itself. On the other hand when the rainfall curve for the mean of the yearly precipitation at Akita and Niigata was examined for the period 1882-1907 (no earlier records were available there was found to be a striking degree of correspondence between the curves illustrating yearly earthquake frequeny and precipitation. The city of Niigata is about 260 kilometres north west, and that of Akita is about 440 kilometres north of Tokyo. Omori concludes that "This coincidence is probably not accidental, and the variation of the yearly number of earthquakes felt in Tokyo may be taken as approximately proportional to the amount of precipitation along the north western side of the main island".

M.de Montessus de Ballore in 1912 made an enquiry into a possible relation between earthquake frequency and long period variations (Bruckner Cycles) of precipitation.[58] This will be considered later in more detail. He concluded that there was no evidence of any relation between earthquake frequency and these cyclic variations in rainfall.

In the following year he published another paper[61] on the subject in which he examined the data with regard to seasonal changes in rainfall. He used as the basis for his investigation Milne's[45] then recently published catalogue of destructive earthquakes. Altogether 4136 earthquakes are recorded in this invaluable catalogue, which covers the period from A.D. 79 to A.D. 1899. Montessus de Ballore first prepared tables in which each main district was considered separately and for which the monthly earthquake frequency and precipitation were compared. He does not furnish any details of his results but states that the tables so compiled were so irregular as to indicate no relation.

He next grouped the observations into three monthly periods and found the results to beas follows:-

(1) The seismic maximum falls in the quarter (3 months) of maximum precipitation for Manchuria, Oceania, Peru and Soudan, the number of earthquakes recorded in these countries totalling 527 altogether.

(2) The seismic minimum falls in the quarter of minimum precipitation for the Amazon Valley, Breton, Mexico and Ukraine. The total number of earthquakes being 836 for these districts.

(3) The seismic maximum falls in the quarter of minimum precipitation for the Andes, Paris and the Punjab, with a total of 225 earthquakes.

(4) The seismic minimum falls in the same quarter as the maximum precipitation for the Arctic region, the danube, India, Norway, Portugal, Polynesia, Sahara,

Senegal, Siam and Syria, with a total of 1783 earthquakes.

(5) Neither the maximum nor the minimum of seismic frequency falls in either the quarter of maximum or minimum precipitation in the case of Arabia, Bengal, China, Greece and Siberia, with a total of 653 ~~earthqua~~ earthquakes.

Montessus de Ballore points out that the climatic conditions of the countries above considered are distributed at random in the five groupings given. He points out moreover that if one takes the difference between the seismic maxima and minima and expresses this as a percentage of the total earthquakes the result is always small, and it is further diminshed by taking into consideration more and more data. This, he considers, indicates the lack of any relation such as that sought after. His conclusion is as follows:-

"En résumé, il n'y a aucune relation de cause à effet entre les tremblements de terre destructeurs et les précipitations atmosphériques, et cela ne présente aucun intérêt de constater par exemple que tel grand événement sismique a suivi une période d'inondations, ainsi qu'on l'a souvent fait".

The rainfall data used by Montessus de Ballore for this investigation were taken from the rainfall maps in de Martonne's book on Geographie Physique.

The conclusion reached by Montessus is, the author believes, open to question, and will be discussed later on

At the time of the publication of ~~this~~ the above paper Montessus de Ballore has apparently not seen the work of Drake[16] which was published a little earlier. This

~~[illegible]~~ important memoir contains a most extensive catalogue of the destructive earthquakes of China; and the author has discussed the data in a most illuminating fashion. Amongst other investigations he enquires into the question of rainfall. After grouping the earthquakes according to the months in which they occur he finds evidence of a very strong annual maximum of earthquake frequency for the months of July and August. This he regards as a seasonal periodicity associated with the summer monsoon which is of ~~of~~ course a period of heavy rainfall. While regarding the the changes in barometric pressure as the chief factors influencing the periodicity he considers that the rainfall contributes an important part of the changes in pressure involved. It is not so much the static pressure, he considers, as the rapid rate of loading and unloading which affects the earthquake ~~pressure~~ frequency.

In the following year Sayles[85] attacked the problem using as the sources for his earthquake catalogues the account of destructive earthquakes given in the following publications and for the periods stated:-

(1) Nature - from 1871 to 1910.

(2) The London Times from 1871 to 1910.

(3) Whitaker's Almanac from 1871 to 1909.

He has illustrated his paper by drawing a curve for the total earthquake frequency, and also an additional curve for earthquakes having an intensity greater than VII on the Rossi-Forel scale.

He has also drawn a curve illustrating the differences from the average for the rainfall of the United States for the corresponding period.

There appears to be a general similarity between these curves and Sayles, while being somewhat guarded in his conclusion, considers that the subject is certainly worthy of further investigation.

The question was again taken up by Taber[91] in 1914. He focussed his attention upon a relatively small area and attacked the problem in a most systematic manner. There can be little doubt that his work marks the most distinct advance yet made in this direction. Previous investigations have sought to correlate the seismic maxima and maxima of precipitation. Taber rightly points out that ~~of~~ if an earthquake is caused by movement along a fault plane the most ~~approximate~~ appropriate stress to ~~give~~ give rise to movement will be a differential one operating in conjunction with the prime earthquake forces. It does not follow that the time of maximum precipitation will coincide with that when the <u>differential</u> stresses on opposite sides of the fault plane are a maximum; but it is with such a differential stress, if at all, that the earthquake frequency should be correlated. After submitting geological and seismographical evidence for a fault passing between Summerville and Charleston and trending in a north-east direction Taber commences to analyse the rainfall data. He found that there was a close correspondence with the three curves representing the railfall at Summerville and at Charleston, and the earthquake frequency. The rainfall at Summerville was constantly in excess of that of Charleston and this excess increased with the total precipitation. It is to the excess of rainfall along the north western (Summerville) side of the fault that Taber attributes the greater part of the corresponding excess in the earthquake frequency. This reasoning is certainly sound and furnishes strong evidence of a relation between earthquake frequency and rainfall. This conclusion is further supported by his examination of the conditions influencing the level of the water table and by collateral evidence with regard to the distribution of atmospheric pressure. The fact that the total rainfall curves also follow the curve for earthquake frequency is incidental,~~[illegible]~~ and is a natural enough relation ~~[illegible]~~ between the total rainfall and the excess of rainfall at the two centres. The causes which control a difference in precipitation at two adjacent centres must be chiefly topographical or related to their proximity to a coast line; as such geographical factors remain constant the difference in rainfall will naturally be closely proportional to the total rainfall. For this reason it may well be that the converse is true and that where earthquake frequency has been directly correlated with total precipitation the reason is that there exists a difference in rainfall over some ~~[illegible]~~ critical zone and that this has also been increased. It will be obvious enough that if the differenc in rainfall across a fault zone operate in the opposite direction to the natural earthquake forces an increased precipitation will be unfavourable to the occurrence of earthquakes; and in this case the maximum rainfall may correspond to a minimum ~~rainfall~~ of earthquake frequency.

If one now returns to the evidence assemble~~s~~d by Montessus de Ballore[61] and examines it in the light of Taber's work it appears that in 21 out of 26 districts which Montessus has considered, either the maximum or minimum earthquake frequency falls in one or other of the quarter year intervals corresponding to a maximum or minimum of total rainfall; and that to these 21 districts are to be referred 3371 ~~out of the~~ or more than 80 per cent of the 4024 earthquakes considered. Since it has been shown that according as the stress difference due to an excess of rainfall on one side of the fault may assist or oppose the natural earthquake forces so the maximum earthquake frequency may coincide either with maximum or minimum difference in rainfall; and since the difference in rainfall is probably in most cases proportional to the amount of rainfall; it follows that the data used by Montessus to refute any relation between rainfall and earthquake frequency has actually, in the light of later research, furnished strong support in favour of the relation postulated. It is true that the differences between the maxima and minima of the earthquake frequencies examined by him are stated to be small, but, on the other hand, this is certainly to be anticipated, since the influence of excess pressure due to differential rainfall is itself small and is not the prime cause of earthquakes; but at best only one of several secondary causes.

The investigations of Omori[78] for Japan, of Drake[16] for China and the more general work of Sayles[85] each take on an added significance in the light of Taber's work.[91]

There can now be little doubt that rainfall exercises an important influence on the earthquake frequency of certain districts

Seasonal Frequency of Earthquakes.

The search for a seasonal frequency for earthquakes is, of course the same as for an annual period. The earliest systematic work is that of Perrey[36] who grouped 2299 earthquakes according to their monthly frequency. These he considered for each district in which they were recorded a and drew up tables to show the monthly frequency for the particular districts.

He next grouped the earthquakes according to the seasons taking January, February and March for the winter period, April, May and June for the Spring, July, August, Septembr for Summer and October, November and December for ~~Winter~~ Autumn. As the result of his labours do not appear to have been presented in an abbreviated form they are here condensed in the following Table:-

District	Winter	Spring	Summer	Autumn
Scandinavia and Iceland	74	39	48	53
British Isles & Northern Isles	56	42	52	67
Spanish Peninsula	55	41	46	59
France, Belgium and Holland	200	133	137	186
Basin of the Rhone	62	32	37	53
Basin of the Rhine & Switzerland	160	103	101	165
Basin of the Danube	76	60	67	67
Italian Peninsula with Sicily, Sardinia and Malta	298	250	203	233
Algeria and Northern Africa	13	12	8	13
Turco-Hellenic Territory, Syria, the Aegaean Islands & Levant	106	102	115	100
United States and Canada	40	16	32	46
Mexico and Central America	16	16	10	10
The Antilles	54	49	65	53
Cuba	13	10	13	15
Chili and basin of La Plata	43	41	48	46
Resume of the Earthquakes of Europe and adjacent parts of Asia from A.D. 306 to 1843.	589	404	442	526
Northern Zone of Europe	54	30	25	39
Northern Zone of Asia	27	13	23	18

It will be noted that of the eighteen groupings considered fourteen exhibit a maximum for the autumn and winter i.e. for the months October to March. This work has been generally regarded as establishing a winter frequency for earthquakes.

Mallet[36] examined an even larger number of earthquakes and found a distribution indicated in the following table:-

Month	Northern	Southern	Seasons North	Seasons South.
January	627	19		
February	539	14		
March	503	9	1669	42
April	489	17		
May	438	20		
June	428	19	1355	56
July	415	18		
August	488	12		
September	463	17	1366	47
October	516	25		
November	473	32		
December	500	21	1489	78
	5879	223	5879	223

Here again the law of a winter maximum frequency for earthquakes is predominant. This frequency Perrey regarded as being worthy of acceptance as an empiric law for Europe at least having some doubt if it can be extended to the Southern hemisphere.

Kluge[27] investigated the seasonal frequency for earthquakes of the northern hemisphere recorded during 1855 and 1856. He found the distribution as follows:-

Spring 51; Summer 57; Autumn 77; Winter 91.

As his seasonal groupings correspond with those of Perrey and Mallet this again confirms the law of a winter maximum for earthquake frequency in the northern hemisphere.

The problem of seasonal periodicity was later investigated by Milne[39] for the chief earthquakes of Japan recorded during the period from 295 B.C. to 1872 A.D. Using the same seasonal gouping Milne's results are as follows:-

Winter 74; Spring 95; Summer 93; Autumn 90.

It is clear that the earthquakes of Japan do not conform to the supposed law.

Milne noted that the exceptions to the supposed law in Mallet's Table occur only in equatorial countries where the seasons are fairly uniform throughout the year. He attributes the winter maximum for countries in higher latitudes to the fact that people are more indoors in winter and are consequently more likely to notice earthquakes. Discussing the problem again in 1886 Milne[40] briefly reviews the work of Perrey and Mallet accepting Mallet's evidence as the most complete statement at that date. He notes that the maximum frequency for the northern hemisphere occurs near the time of perihelion, and the minimum near aphelion. He also notes that Kluge's statistics and those of Mérian for the earthquakes of Basle follow the same law of distribution.

Knott,[28] writing in the same year as Milne, noted the law of winter maximum promulgated by Perrey and Mallet. He pointed out, however, that the choice of the winter season might be improved by including the months December, January and February instead of January, February and March. He then subjected the data to harmonic analysis with a view of finding if real annual and semi-annual periods do exist. Forthis purpose he made use of Milne's Catalogue of Japanese earthquakes for the period 1872 to 1880. Other catalogues were also employed later. He found that there existed an annual periodicity for the earthquake frequency, and considered that it might be due to some meteorological cause.

A few years later (1891) Montessus de Ballore undertook a critical examination of the whole subject of the seasonal frequency of earthquakes and published two important memoirs on the subject.[49,50] He pointed out that ~~[illegible]~~ hitherto the investigation had rested upon scanty evidence which was insufficient either to establish or refute the law of a winter maximum. ~~[illegible]~~ As, however, he had at that time assembled records of 63,555 earthquakes from 309 districts he concluded the time was ripe for a more complete investigation of the subject. As seasonal periodicity was the matter in question it was necessary to reject all records which did not extend over a whole year. Again in many cases the same earthquake was recorded in the records of different districts. To meet this difficulty he decided to record only the days on which the earthquakes occurred, so that an earthquake recorded at several near stations on the same day would be recorded as one "earthquake day".

The limitations so imposed reduced the available records to 38,967 earthquake days from 165 districts.

He divided the year into summer and winter from the equinoxes. He found that a first glance at the statistics suggested that if there was any law it should be extended by stating that it would appear that earthquakes occur more frequently in autumn and winter than in spring and summer. On examining the statistics he found that there were 85 series of records including 20,258 earthquake days which favoured the law and 80 series of records with 18,709 earthquake days which were opposed to it. The difference he pointed out is only $\frac{1}{19}$ of the total.

He next examined each district separately and has given graphical representations of 39 districts. ~~These are reproduced in plate~~ . As the records are not all of equal reliability he has grouped them into seven categories according to their scientific value. These are as follows:-

(1) Series of historical records - sporadic in character
(2) Observations from meteorological records
(3) Records of careful observers residing in earthquake centres.
(4) Seismological records from countries where earthquakes are the object of special study by learned societies.
(5) Series from geodynamical observatories
(6) and (7) Series of ~~microseismic~~ Microseisms or shocks sensible only to instruments - corresponding to intensities I and II on the Rossi-Forel scale

Montessus pointed out that if any seasonal law exists it should be strengthened by support from the records of higher rather than lower scientific value. He states that this was not found to be the case. His results may be tabulated ~~thus~~ as follows:-

	Supporting Perrey's Law		Opposed to Perrey's Law	
Series	No. of Records	No. of Earthquake days	No. of Records	No. of Earthquake days.
Series (1) Historical records	59	12,012	52	9,328
Series (2) Meteorological records	—	—	8	4,353
Series (3) Competent observers in Earthquake districts	9	2,947	3	1,544
Series (4) Seismological records	7	2,315	10	1,660
S Series (5) Geodynamical ~~records~~ observations	4	727	2	526
Series (6) Instrumental	—	—	3	691
Series (7)	6	2,263	2	601
Totals	85	20,264	80	18,703

Montessus states that there is some reson to discredit the evidence of the instrumental records but this statement appears open to question. The geographical representations which he has given, however, indicate that in many cases an annual periodicity is well marked. It does not, it is true, ~~wh~~ always ~~to~~ fall in the winter season so that in the statistical grouping of the records adopted by Montessus the annual periodicity as distinct from Perrey's law of winter frequency, is obscured; though it is well represented by his frequency diagrams. Altogether it appears to the author that the evidence presented by Montessus furnishes strong support to the hypothesis that there is in general an annual periodicity of earthquake frequency that each district has its own characteristic epoch.

Montessus also noted that the difference between the seasonal maxima and minima of earthquake frequency diminished with the increase in the total number of records. This is certainly opposed to the application of Perrey's law of a winter maximum for the whole world but is still in harmony with an hypothesis of a seasonal frequency with a characteristic epoch for each earthquake district. In conclusion Montessus expresses his views.as follows:-

"Toutes ces considérations concordantes entre elles montrent bienque la répartition saisonnière des séismes énoncée par Perrey et toutes celles du mêmre genre, doivent être definitivèment abandonnées et considérées comme de simples accidents de statistiques insuffisantes. Ce ne sont pas des lois naturelles".

It is difficult to see, on the evidence presented by these records, that Montessus is justified in making so strong a statement. It appears to the author that although the world wide application of Perrey's law of a winter maximum is challenged the occurrence of seasonal or annual periodicity is evident in most of the groups represented.

Davison[9] in 1893 approached the subject from a mathematical point of view. ~~He~~ After reviewing Knott's investigation of 1886 he pointed out that although this had indicated both an annual and semi-annual period his data were lacking in completeness. Th method of harmonic analysis employed by Davison is essentially the same in principle as that used by Knott but is somewhat simpler in form.

Davison ~~next~~ first examined the records with regard to their intensity using Mallet's world catalogue and that of Milne for the earthquakes of Japan during the period 1885-1889. For the

the purpose of this review his results may be summarised as follows~~,~~-

Sources of Earthquake Records.	Number of Earthquake	Annual Periods Amplitude of Maximum	Time of Year	Semi-Annual Periods Amplitude of Maximum	Time of Year.
Mallet's Catalogue					
(i) slight earthquakes	187	·16	June b	·27	January b July b ~~February b~~ March a September a
(ii) Destructive Earthquakes.	641	·13	January b	·08	February b August b
Milne's Catalogue Japanese Earthquakes					
(i) Slight earthquakes	2256	·14	September b October b	·12	March a September a
(ii) Earthquakes of medium intensity	565	·17	February b March b	·16	June a ~~September~~ December a
(iii) Strong Earthquakes	176	·17	March b	·12	March a September a

He next made a comprehensive survey of 62 seismic records 45 of which relate to the northern hemisphere, 14 to the southern and 3 to equatorial countries. The results of his work I have summarised in the following tables:-

Seismic Periodicity in the Northern Hemisphere.

		Annual Periods		Semi-Annual Periods.	
arthquake Districts	Number of Earthquakes	Amplitude of Maximum	Time of Year	Amplitude of Maximum	Time of Year
emisphere (Mallet)	5879	·11	December b	·07	February a August a
.Hemisphere (Fuchs)	8133	·29	December b	·11	Aprilbb October b
urope	5499	·35	December b	·11	April October
candinavia & Iceland	214	·30	December b	·22	February a August a
reat Britain (Perrey)	217	·32	October b	·08	April a October a
reat Britain (David Milne)	205	·49	November b	·16	March a September a
Great Britain (Roper)	297	·29	January b	·11	March a September a
France (Fuchs.)	193	·41	December b	none	
France (Perrey)	656	·33	January b	·10	January a July a
Spain and Portugal	201	·21	December b	Probably none	
Austria	461	·37	January b	·22	May b June a Nov.b Dec.a
Hungary, Croatia & Transylvania	384	·31	December b	·30	June a December a
Switzerland & Tyrol	524	·56	January b	·37	June b December b
Basin of Rhone	184	·46	November b	·13	Jan.a Feb.a July a Aug.a
Basin of Rhine & Switzerland	529	·38	January b	·15	June a December a
Basin of Danube	268	·14	November b	·30	January a July a
Italy (Perrey)	984	·19	March b September b	·08	March a September a
Italy (Fuchs)	2350	·14	December b	·14	April b October b

Seismic Periodicity of Northern Hemisphere (Continued).

Earthquake District	Number of Earthquakes	Annual Periods Amplitude of Maximum	Annual Periods Time of Year	Semi-Annual Periods Amplitude of Maximum	Semi-Annual Periods Time of Year.
Italy - Excluding Sicily & Vesuvius.	1513	·21	Sept. b Nov. b	·17	April October
Italy - Vesuvius district ~~Sicily~~.	513	·25	Aug. b	·25	June a Dec.a
Sicily	324	·67	May b	·46	Feb.b Aug.b
Sicily - omitting March 1883	242	·50	July b	·19	June b Dec.b
Florence - Tromometer observations (1872-1887)	61,732	·49	Dec. b	·08	May a June Nov.a Dec.
do. 1876-1887	38,546	·46	Dec. b	·04	May a Nov.a
do. 1876-1887	38,546	·49	Dec. b	·03	May a Nov.a
South-east Europe (Perrey)	423	Irregular		·08	Feb.a Aug.a
S.E.Europe (Schmidt)	3470	·21	Dec. b	·25	March a Sept. a
Balkan Peninsula & adjacent islands	624	·27	Dec. b	·37	Feb.b Aug.b
Zante (Barbiani)	1326	·10	Aug. b	·19	June a Dec. a
Zante (do)	1663	·29	Aug. b	·35	May a Nov.a
Zante (schmidt & Fuchs)	246	·29	~~Aug. b~~ Dec. b.	·33	March a Sept. a
Algeria	135	·67	Dec. b	·30	June Dec.
Asia	458	·33	Feb.b	·14	Feb. a Aug. a
Caucasia	152	·56	Jan. b	·38	Feb.a Aug.a
Japan	2997	·08	Oct. b	·07	March a Sept.a
Tokio	1104	·19	Feb. b	·21	May a Nov.a
Tokio - omitting the record for 1885.	1039	·19	Feb. b	·22	May a Nov.a
Tokio	246	·46	Dec. b	·19	Jan.b July b
Yokohama	130	·41	Dec. b	·29	Jan. b July b
India	320	·25	March b Oct. b.	·38	Jan. a July a.

Seismic Periodicity in the Northern Hemisphere (Continued).

Earthquake Districts.	Number of Earthquakes	Annual Periods Amplitude of Maximum	Time of Year	Semi-Annual Periods Amplitude of Maximum	Time of Year.
North America	552	·35	Nov.b	·14	April a Oct. a
United States & Canada.	134	·46	Dec. B	·15	Jan. a July a.
New England	212	·51	Dec. b	·25	June b Dec. b
California	949	·30	Oct. b	·16	April a Oct. a
California ~~San-Francisco~~	768	·19	Oct. b	·16	April a Oct. a
San Francisco	254	·41	Dec. b	·21	April a Oct. a
San Jose and Santa Clara	54	·56	Dec. b	·33	March a Sept. a
Mexico	86	·43	Dec. b	·79	April a Oct. a
Central America	190	·32	April b	·25	April a Oct. a
West Indes (Fuchs)	205	·59	Oct. b	·59	June b Dec. b
West Indes (Perrey)	221	·11	Aug. b	·16 ~~25~~	Mar. a Sept. a
Sandwich Islands	245	·33	June b	·25	Feb. b Aug. b

Seismic Periodicity in Countries near the Equator.

Malay Archipelago (Fuchs)	598	·19	May b	·25	Jan. a July a
Malay Archipelago (Knott)	515	Irregular		·11	Mar. a Sept. a
New Granada and Venezuela	272	·64	Feb. b	·27	March Sept.

Seismic Periodicity in the Southern Hemisphere.

Earthquake Districts.	No. of Earthquakes	Annual Period		Semi-Annual Period.	
		Amplitude of M Maximum	Time of Year	Amplitude of Maximum	Time of Year
Southern Hemisphere (Mallet)	223	·24	Nov. b	·33	May a Nov. a
S.Hemisphere (Fuchs	751	·37	Aug. b	·06	Jan.a Mar.a July a Septa
New South Wales, Victoria and South Australia.	159	·48	May b	·43	Feb.a Aug.a
New Zealand (Hector)	641	·05	Mar.b May b	·13	Feb.a Aug.a
do.do. Central N. Island.	184	·22	~~May~~ April b	·30	March a Sept.a
do.do.E.coast do.do.	188	·11	May a	·26	Feb.a Aug.a
do.do W.coast S.Island	88	·32	July b	·20	Mar.a Sept.a
do.do.E.coast do.do.	98	Irregular		·28	Mar.a Sept.a
do.do.S.part do.do.	30	Irregular		·56	May a Nov.a
New Zealand (Hogben)	737	·06	between June b & Oct.b	·21	Feb.a Aug.a
do.do. - do.	745	·14	July b	·23	Feb.a Aug.a
Chili (Fuchs)	178	·14	Aug. b	Irregular	
Chili (Knott)	212	·48	Aug.b	·17	June a Dec. a
Peru, Bolivia & Quito	350	·48	July b	·24	Jan. a July a

In the above tables the letters a and b placed after the months signify the first and last fortnights respectively.

The amplitude of the maximum is calculated from the monthly Harmonic analysis. The average earthquake frequency is represented by unity so that an amplitude of ·25 sugnifies a 25 per cent increase in frequency for the month of the maximum and a correspoding decrease of 25 per cent for the month of the minimum. The figures of course referring to the result of the harmonic analysis and not to the actual number of earthquakes for the months concerned.

Davison has summarised these results for the annual and semi-annual maxima in the following tables which are quoted from his memoir.

Annual Period.

Month	Northern Hemisphere	Equatorial Countries	Southern Hemisphere.
January	6	0	0
February	1	1	0
March	0	0	0
April	1	0	2
May	1	1	2
June	1	0	0
July	0	0	3
August	1	0	2
September	0	0	0
October	3	0	0
November	4	0	0
December	16	0	0
Total	34	2	9

The numbers indicate the number of times in which the annual maxima fall in the months indicated.

Semi-Annual Period.

Half-months	Northern Hemisphere	Equatorial Countries	Southern Hemisphere.
January a and July b	4	1	1
January b and July b	0	0	0
February a and August a	4	0	4
February b and August b	3	0	0
March a and September a	5	1	3
March b and September b	0	0	0
April a and October a	5	0	0
April b and October b	2	0	0
May a and November a	0	0	1
May b and November b	0	0	0
June a and December a	3	0	1
June b and December b	2	0	0
Totals	28	2	9

In the above tables for the annual and semi-annual periods the records for Italy, Zante and Japan the West Indes and the Southern Hemisphere (as a whole) are excluded by Davison as being anomalous. Speaking of the table for the Annual Period he says "These figures strongly support the view that the ~~maxim~~ maximum of the annual period occurs during the local winter in each ~~case~~ hemisphere.

The average amplitude obtained from 57 records is ·33 and this indicates that the ratio of the maximum to minimum frequency is about 3 : 2. The average amplitude for the semi-annual period is·24."

Davison points out that the barometric pressure reaches its maximum in most parts of the Northern Hemisphere during November or December and he attributes the annual seismic maxima to its influence. The explanation of the semi-annual period is less obvious. Davison says "With regard to the origin of the semi-annual period, I regret that I am unable to offer any definite suggestion."

Schuster[87] in 1897 made a rigorous examination of earthquake periodicities with a view of testing whether the frequencies recorded were greater than could be anticipated for random events. He discussed, amongst other work, that of Davison and concluded that there is a well-marked annual period which cannot be explained by probability for random events. This investigation lends strong support to Davison's work.

The next important contributions to this subject were made by Omori.[69] He noted first in his examination of the after shocks of the Kumamoto earthquake that these were characterised by an annual periodicity having three maxima in the months of March, May and October and three minima in April, September and December. The ordinary earthquakes recorded at Tokyo he found also to have annual maxima in March, May and December and minima in January, April and August-September.

He then examined the frequency of ordinary earthquakes for the whole of Japan for the interval 1885-1890 and found three annual maxima in February, May and November and three minima in April, August and December.

The results of this investigation so impressed Omori that he wrote as follows:-

"I believe that periodicity plays a very important part in the frequency of earthquakes, and its attentive study may be of help in the prediction of changes in seismic activity and other events."

Milne[41] some four years later reviewed this subject and after referring to the work o~~n~~f Knott and Davison in particular says "From the little that has been said it appears, therefore, that the only pronounced periodicities which earthquakes present are the annual and semi-annual maxima periodicities." Milne in this paper makes a valuable observation which is ~~not~~ now being confirmed by later work. His words, which, ~~x~~ are worthy of quotation, are, "Considering the labour expended upon the analysis of earthquake catalogues, at first sight it appears strange that the definite results have been so few in number. To explain this, however, we have not far to seek. Although intervals of time approximately following some definite law may be occupied before and area under secular geologic influences may repeatedly reach a state of seismic sensibility, there does not appear to be any valid reason to suppose that in widely separated districts these times should be coincident or necessarily follow the same law, If we, therefore, hope to discover any law bearing upon the recurrence of earthquake susceptibility, itseems necessary that we should first obtain sets of records the entries in each of which refer to the same orogenic fold."

The truth of this statement was well illustrated by an investigation carried out by Omori[70] and published in the following year (1899). In this paper Omori tabulated the monthly frequency for 222 destructive earthquakes recorded in Japanese history. He also tabulated in the same way the

228 strong shocks felt at Kyoto. These results are given in the following table:-

Monthly Grouping			Seasonal Grouping		
Month	Japan .	Kyoto	Season	Japan	Kyoto.
March	18	22			
April	12	14	Spring	48	54
May	18	18			
June	19	16			
July	23	20	Summer	74	65
August	32	29			
September	16	13			
October	19	17	Autumn ~~October~~	49	52
November	14	22			
December	22	28			
January	10	16	Winter	45	57
February	13	13			

Omori pointed out for Japan as a whole the warmer months from April to September have 120 shocks as against 96 for ~~t~~ colder months from October to March. On the other hand for Kyoto the number for the warmer months is only 110 and reaches 118 for the colder months.

Again in examining the frequency of the ordinary small earthquakes for both district groupings he ~~[illegible]~~ finds that ~~the~~ for the same district the frequency of the small shocks is the reverse of that of the strong or destructive shocks. This holds ~~the~~ both for Kyoto and for Japan as a whole.

About three years later (1902) Omori[71] followed up this line of research by a much more extensive investigation. For this purpose he employed the records of some 18,279 earthquakes the majority of which were instrumentally observed at 26 Japanese stations. Recognising that the time distributiom might not be the same for different stations he examined each record ~~separatery~~ separately. The whole work constitutes a very detailed and elaborate piece of research. ~~representing these two groups. The~~ Omori found it possible to arrange the 26 districts into two groups in each of which there was a certain degree of ~~internal~~ inter~~v~~nal harmony. The chief results with regard to seasonal and annual frequency he has tabulated in the following tables representing these two groups:-

Group A.

District	Month of the Maximum	Month of the Minimum	Season of the Maximum	Season of the Minimum.
Sapporo	October	January	Autumn	Summer
Hakodate	October	September	Autumn	Summer
Tokyo	May	September	Spring	Autumn
Niigaya	April	December	Spring	Winter
Nagano	May	August	Spring	Summer
Numazu	January	August	Spring	Summer
Hamamatsu	November	July	Winter	Summer
Nagoya	~~November~~ January	November	Spring	Autumn
Gifu	April	August	Spring	Summer
Tsu	January	July	Spring	Autumn
Wakayama	May	February December	Spring	Winter
Hiroshima	January	June	Winter	Summer
Oita	November	May	Autumn	Summer
Kumamoto	January	July	Spring	Summer
Kagoshima	April	July	Spring	Summer

Seasonal Distribution of Maxima and Minima	Spring - 10	Summer - 10
	Autumn - 3	Autumn - 3
	Winter - 2	Winter - 2

Group B.

District	Month of the Maximum	Month of the Minimum	Season of the Maximum	Season of the Minimum
Nemuro	May July	January February	Summer	Winter
Akita	October	September	"	"
Yamagata	August	November	"	Autumn
Miyako	July	February	"	Winter
Ishinomaki	August	January	"	"
Fukushima	April	December	"	"
Utsunomiya	August	September	"	Autumn
Maebashi	March	January	Autumn	Winter
Hikone	August	September	Summer	Autumn
Hamada	October	(April to (July	Autumn	Spring
Kochi	February	May	Winter	Autumn
Seasonal distribution of Maxima and Minima			Summer - 8	Winter - 6
			Autumn - 2	Autumn - 4
			Winter - 1	Spring - 1

The results are obviously variable. Group A comprises districts forming the western and southern portion of Japan; and Group B the eastern and northern parts. It appears from the location of the epicentres that the earthquakes of Group A mostly have an inland origin; while those of Group B are chiefly of submarine origin. Omori concludes that Group A have ~~thie~~ their maximum seismic frequency in winter and Group B a maximum in summer.

It is interesting to carry the analysis a step further and tabulate the number of times in which the maxima fell into the different months for the 26 groups. This gives the following result:-

	Group A	Group B		Group A	Group B
January	5	0	July	0	2
February	0	1	August	0	4
March	0	1	September	0	0
April	3	1	October	2	2
May	3	1	November	2	0
June	0	1	December	0	0

This arrangement chows 9 summer and 6 winter maxima for Group A, and 6 summer and 9 winter maxima for Group B. Hence as Omori points out the periods of maxima and minima have opposite relation for the two groups.

After a study of the seasonal distribution of barometric pressure Omori concludes as follows:-

"(A) region: The earthquakes are mostly of inland origin and the annual variation of the seismic frequency follows that of barometric pressure.

(B) region: The earthquakes are mostly of suboceanic origin and the annual variation of the seismic frequency is the reverse of that of the barometric pressure on land ".

Milne[43] subsequently reviewed this paper and endorsed the views put forward by Omori.

The question of annual periodicity was touched upon from a different point of view by Oldham[66] in the following year. Oldham investigated the aftershocks of the great Assam Earthquakes for diurnal and lunar periodicity. This work will be discussed subsequently in an appropriate place. For the present it may be noted that Oldham found that "earthquakes were proportionately more frequent during the night in winter and during the day in summer, a results which agrees with what would be anticipated if the tide-producing forces, set up by the sun, had some effect in determining the time of origin of earthquakes.
the time of ~~origin of earthquakes~~".

In the following year (1904) Baron Kikuchi[26] published a full and most useful summary of the seismological work which up to that date had been accomplished in Japan, and apparently accepts the reality of the annual seismic period.

In his Bakerian lecture to the Royal Society of London (1906) Milne[44] again reverts to the subject of seasonal periodicity. He points out that for the six years ending in 1904 there were off the west coast pf North America 51 earthquakes during the winter and 35 during the summer months. Again off the east coast of Asia the winter number was 49 and that of the summer 43. Hence for the North Pacific border we have in this period 100 earthquakes during the winter and 78 during the summer halves of the year.

In the Central Asian and Himalayan region there were 25 earthquakes in winter and 27 in summer. Reviewing these facts he says" Beneath the ocean, therefore some indication has been obtained of seasonal seismic frequency, while on a continental surface no such frequency has yet been indicated". Unless this conclusion is intended, as is probable, to refer only to the above investigation it is clearly strongly at variance with the results previously obtained by Davison, Knott and Omori.

It was now (1906) some fifteen years since Montessus de Ballore had attacked Perrey's law of a winter maximum od seismic activity and had expressed his opinion that there was no evidence of seasonal periodicity in general. In view of the amount of work which had been published ~~and~~ since his last memoir on this subject Montessus felt justified in again examining the question. He says[54] that the persistence with which these laws are still promulgated justifies another attempt to refute them. By this time his immense catalogue of earthquakes had grown to include 75.737 records of earthquakes representing about 60.000 different shocks. He employed 81 catalogues which were sub-divided into two groups according as they related to countries lying to the north or south of latitude 45°. He found that there were apparent maxima of earthquake frequency distributed as follows:-

Latitude	Apparent Maxima falling in the period	
	October-March	April-Septembe
greater than 45°	~~October-March~~ 90 per 100	10 per 100
Less than 45°	47 " 100	49 " 100

This result he believes to have a ~~simple~~ simple interpretation. In northerly latitudes people are much more indoors and at rest during the winter than the summer months. This is not the case in temperate and tropical regions. Again slight shocks are much more frequent than heavy ones and hence woud be recorded under the most favourable conditions during the winter period. The more or less equal distribution during summer and winter of earthquakes occurring in latitudes less than 45° lends strong support to this view; and indeed his earlier paper in 1891 showed that the general application of Perrey's winter law was rendered less probable as the statistics increased in number. But Milne and Omori have pointed out the importance of district groupings in considering any relation of natural phenomena with earthquake frequency and have shown that even prominent maxima may be neutralised when compared with statistics from a differeht area. Keeping this in view one must disagree with Montessus' conclusion that earthquakes exhibit no seasonal or annual periodicity but are equally liable to occur at any time of the year.

Knott[31] again returned to the subject in his book published some two years ~~ago~~ later on the Physics of Earthquake Phenomena. Here he reviewed his own earlier work and the later investigation of Davison. After correcting an accidental error in his earlier paper he accepts Davison's work as confirming his own views as to

Knott considers that this change in barometric pressure is sufficient to disturb the isostatic balance along the margins of the continents and this becomes effective in accentuating earthquake frequency. He suggests that the difference between the average summer and winter barometric gradients may account for the semi-annual earthquake periodicity indicated by the analysis. He next reviewed Omori's work on the seasonal periodicity of Japanese earthquakes. He states that there was a good deal of arbitrariness in the manner in which Omori selected his earthquake data - excluding as he did a certain number as representing the after shocks of large earthquakes. He therefore subjected Omori's data to reinvestigation but concluded that the general conclusion, after all, is trustworthy.

Omori published in the same year (1908) the results of a further study in seasonal periodicity, taking for his data the earthquakes of Tokyo and 7Hb. Kyoto. As his previous work had indicated that the ordinary and destructive earthquakes appear to have an inverse relation in frequency he separated the earthquakes for these districts on the basis indicated, and gave his results in the following tables:-

the reality of an annual and semi-annual periodicity for earthquakes. He then discussed the application of Fourier's series to such problems and stated that his opinion as to the value of such a process for this purpose has considerably changed; and concluded that "sufficient accuracy is attained by use of the purely arithmetical overlapping summations over suitable intervals". He then illustrated the application of this simple method the Milne's catalogue of Japanese earthquakes for the period 1872-1880. After applying the criteria suggested by Schuster[87] for testing the relative values of the amplitude and "expectancy" to his earlier investigations for 1884, he concluded that for earthquake records there is evidence of a marked annual periodicity giving in each case a maximum earthquake frequency in the winter season. The only exception is the case of the East Indes, which has no real winter season.

The statistics employed by Davison[a] he considered to be in many cases too meagre? He says "of the 62 different sets of records made use of by Davison only 23 may be regarded as satisfactory, and about 7 others barely admissable". After a review of these data he concluded that the annual winter maximum is well established but the semi-annual maximum is too weak to be accepted as characteristic.

Knott's views as to the cause of this winter frequency differ somewhat from those of Davison. The latter considers that the change of barometric pressure over the seismic area itself is the principal factor, while the former attributes the frequency rather to "the whole manner in which the pressure varies across the seismic region".

There can be little doubt that Knott's view is the more sound as it introduces differential pressure across the fault plane.

Seasonal Seismic Frequency in Tokyo.

Season	Mean Seasonal number of ordinary earthquakes. Period 1876-1899.	Number of destructive and semi-destructive earthquakes. Period 1615-1894.
Spring (March-May)	25·5	3
Summer (June-August)	19·1	7
Autumn (September-November)	18·3	5
Winter (December-February)	23·9	3

Monthly Seismic Frequency in Kyoto (797-1867).

Month	Ordinary Small Earthquakes 1088 shocks	Destructive and Semi-destructive earthquakes -32 shocks
January	79	3
February	82	0
March	110	0
April	102	0
May	95	3
June	91	4
July	87	5
August	95	7
September	74	3
October	87	2
November	95	1
December	91	4

The small earthquakes give a maximum in March and a minimu in September.

The larger give a minimum for the period February to April and a maximum in August.

Shortly after the appearance of 1718 paper Omori published; in the same journal, one of his most important contributions to seismology. This paper deals with what Omori calls "secondary causes of earthquakes."[18] ~~It~~ In it he ~~just~~ first called attention to remarkable examples in which strong or great earthquakes, in a given region have occurred approximately in the same part of the year and even on the same day in different years. This he regards as more than a coincidence and attributes it to seasonal influences depending on barometric pressure. The remainder of this important paper refers to other aspects of earthquake frequency and is discussed under other sections of this review.

Under the section dealing with rainfall and earthquake frequency reference was made to the work of Drake[16] in connection with the destructive earthquakes of China. Here again there is strong evidence of an annual periodicity which is associated with the time ofn the recurrence of the monsoon and which Drake has therefore regarded as being caused by the influence of barometric pressure and rainfall.

After an interval of seven years since his last communication Montessus de Ballore in ~~19~~ 1913 again discussed the question of seasonal periodicity.[60] He claims to have demonstrated in his last memoir on the subject that the law of a winter seismic maximum is really due to a physiological cause affection[70] the observations, and rendering the conditions more favourable for recording small earthquakes in high than in low latitudes. As such an influence cannot enter into the catalogue of megaseisms recently prepared by Milne he undertakes an investigation with the materials of this catalogue. He tabulated the monthly frequency for each district concerned but unfortunately did not appear to consider it worth while to publish the numerical details of this work. He states, however, that as the result of such analysis he found the periods of maximum and minimum earthquake frequency distributed as represented in the following table:-

Table showing the number of times that the annual maxima and minima of earthquake frequency for different districts fell in each month of the year.

Month	No. of Maxima	No. of Minima.
January	8	2
February	2	3
April	1	3
May	1	2
June	2	8
July	0	7
August	1	0
October	6	0
November	0	3
December	2	1

It is rather curious that Montessus de Ballore has omitted the ~~number~~ months of March and September from his table without any comment. It would constitute a strong error if due to an accidental omission; and on the other hand it would be very remarkable if not a single maximum nor minimum was recorded for these two months. There is nothing in Montessus' paper to indicate the reason for the non-inclusion of these months ~~and~~ in his published table. His comment on the above table reads as follows:—

"Les maxims prédominent nettement en janvier et en octobre et les minimums en juin et juillet. Mais le fait que des maximums et des minimums se recontrent dans de nombreux âutres mois et que certaines régions présentent plusieurs maximums et minimums, semble prouver qu'un maximum hivernal et un minimum êstival ne correspondent pas a une ~~bole~~ loi naturelle générale".

Montessus then carried his investigation further by tabulating the percentage ratio of the numerical difference between the averages for the annual maxima and minima to th average yearly number of earthquakes for each district. He then arranged the districts in order of the number of earthquakes recorded for each district, as represented in the following table:-

District	No. of Earthquakes	Ratio $\frac{M-m}{M+m} \times 100$
Moluques et Insulinde	144	9·70
Regions tropicales de l'hemisphere australe	180	3·89
Amerique temperee du Sud	203	5·42
Amerique temperee du Nord	204	9·80
Amerique tropicale du Nord	217	5·99
Bassin oriental de la Mediterranee	238	6·72
Amerique du Sud	239	3·77
Europe centrale et Septentrionale	249	6·23
Bassin occidental de la Mediterranee (1850-1899)	265	5·66
Asie anterieure	292	4·55
Hemisphere austral	383	2·87
Amerique du Nord	421	4·75
Bassin occidental de la Mediterranee jusqu'a 1849	545	4·76
Amerique	624	4·49
Bassin occidental de la Mediterranee	810	3·46
Bassin de la Mediterranee	1051	2·86
Extreme-Orient	1081	3·24
Europe	1300	3·46
Asie	1373	2·69
Le vieux monde	2673	1·95
Hemisphere boreal	3094	1·84
Le monde	3441	1·42

Montessus then directed attention to the percentage ratio pointing out thatvthe value of the ratio decreased as the number of earthquakes increased and hence concluded his investigation by the following remarks:-

"Cet asymptotisme vers zéro, ajouté à l'argument plus haut invoqué, donne le droit de penser que, en vertu de la loi des grands nombres, les maxima hivernaux et les minimums estiraux ne sont qu'une apparence fortuite due au simple hasard, autrement dit que les mégaséismes sont indépendants des mois ou des saisons."

This conclusion does not appear to be the only, or even the most probable interpretation of the facts presented in the foregoing tables. A closer examination of the second table~~l~~. ~~A closer~~ shews that, in all those cases where the percentage ratio is small the area in which the earthquakes are recorded is large, in most cases at least continental in extent, and hence embraces many diverse regions. Again both Milne and Omori have emphasised the necessity for considering the evidence for small areas separately in order to avoid obscuring the special characteristics of each area by merging its data into a large body of statistics. It may very well be, and the detailed examination of separate districts by Knott, Davison and Omori strongly supports. ~~indicate~~ ~~support~~ the view, that a seasonal periodicity is to be found for the earthquakes of most districts. Nevertheless as the month of the seasonal maximum varies the amalgamation of all the records might and generally would reduce the maximum; and the more extensive the group the less apparent would become the maximum. This is probably the reason of the low value of the percentage ratio for records referring to large areas; and if so the chief argument of Montessus against the existence of seasonal frequency of earthquakes fall to the ground. It is one thing to state that the Perrey's law of a winter maximum does not hold for all districts, and quite another to deny seasonal periodicity of any kind whatever; and Montessus appears to have overshot the mark in the latter direction.

In one of the most recent books on seismology Walker[94] also reviews the question of periodicity. He concludes that "the annual periodicity with a maximum in winter.......... obtained by Davison from earthquake statistics may be regarded as fairly well established." Walker also offers a contribution to the subject from the result of his own observations at Eskdalemuir. He applied Schuster's criteria to 235 records of which 16 are megaseismic, and concluded that "the semi-annual term is worthless while the annual term with its maximum at the end of August is important.

The work of Taber[91] on the earthquakes of the Charleston district has already been referred to in connection with rainfall and barometric pressure; but in addition he also analysed his data for annual and semi-annual periodicity. For this purpose he used the method adopted by Knott and now generally approved as being simple and effective. He used two methods of grouping. In the first method he took the actual number of earthquakes, but counted as one any two shocks occurring within 15 minutes of each other. In the second method he took account only of the "earthquake days" thus counting as one all the earthquakes occurring on any one single day. Both methods indicated an annual periodicity with a maximum in September and a minimum in April, with a well marked secondary maximum in March. There is also a semi-annual period with maxima in February and August, and in addition a quarter-yearly periodicity with maxima in the months of March, June, September and December.

Using the criterion suggested by Schuster that a periodicity may be regarded as real when it has an amplitude equal to four times the expectancy, he found that this is the case for both the annual and the quarterly periodicities; but the probability, though favouring, does not support the semi-annual periodicity to the same degree.

Spalding[90] re-examined Taber's statistics and regrouped them ~~with~~ into three monthly periods, one about each of the ~~equinoxed~~ equinoxes and solstices. He found a very high maximum in the quarter of the autumnal equinox and three subsidiary maxima, one in each of his other subdivisions of the year. He then carried his investigation further by examining four other earthquake records which are listed as follows:-

(1) German Empire - 882 earthquakes ~~quoted from Kikuchi's report~~ taken from Mallet's catalogue.

(2) Japanese Empire - 216 earthquakes quoted from Kikuchi's report.

(3) Pacific Coast of U.S.A. - 768 earthquakes from Holden's catalogue.

(4) Pacific Coast of U.S.A. - McAdies catalogue.

He found that in each of these groups there is a well marked annual period about the time of the autumnal equinox-ranging from August to October.

He next examined the data relating to 5155 earthquakes taken from Mallet's catalogue in the same manner. This group shows two pronounced maxima, the principal one about the winter solstice and the other about the vernal equinox. There is also a small maximum about the autumnal equinox and a strong minimum about the summer ~~equinox~~ solstice.

Spalding concludes that there is strong evidence of seasonal periodicity but for the present is content to record the facts without assigning any definite physical cause other than suggesting some general astronomical relation with the earthquake frequency.

67, 68.

The most recent work on this subject is that of Oldham who after an interval of some fifteen years, has again taken up the subject of earthquake frequency. Oldham's work is, I believe, the most important contribution yet made to the subject of earthquake frequency in relation to the tidal stresses set up by the sun and moon. His paper will be discussed more fully under the section of this paper dealing with that subject. At this stage, however, it is important to note that Oldham's results indicate a marked seasonal periodicity in which the ratio of day and night shocks is the periodic element. This ratio he has shown to be a maximum in summer and a minimum in winter. He has recently published two papers dealing with this phase of the subject and is still engaged in a further study of the subject.

It will be seen from the foregoing discussion that the uqestion of the seasonal periodicity of earthquakes has received a considerable amount of attention from the most eminent seismologists. While the conclusion of Montessus de Ballore that Perrey's law of winter frequency does not apply to all districts may be accepted, it is clear that he has been carried too far by denying the existence of seasonal periodicity. His refutation of seasonal periodicity rests upon the assumption that the seasonal of the maximum earthquake frequency must be the same for all earthquake districts, and depends for its conclusion on the massed results of many districts. This method tends to obscure the laws which may separately characterise each district, The detailed work of many workers has now demonstrated beyond any reasonable doubt that seasonal periodicity exists but that the time of the seasonal maximum is a function of topographical elements and geographical position; and probably also of geological structure.

Diurnal Periodicity of Earthquakes.

A diurnal periodicity like an annual one implies some relation direct or otherwise with the sun. The following discussion will be limited to the actual record of such periodicity and the consideration of indirect solar influences such as t temperature and barometric pressure . The possible effect of tidal stresses will be dealt with under a special section.

The first systematic search for a diurnal periodicity appears to have been undertaken by Kluge.[27] He prepared a catalogue of 472 shocks and arranged them according to the hours of their occurrence. The table given by him is given below:-

	Hours A.M.	No. of Earthquakes	Hours P.M.	No.of E'qks.	Hours P.M.	No. of E'qks.	Hours A.M.	No. of Earthquakes.
	6-7	8	12-1	16	6-7	18	12-1	22
	7-8	8	1-2	10	7-8	9	1-2	44
	8-9	24	2-3	18	8-9	18	2-3	38
	9-10	11	3-4	18	9-10	16	3-4	18
	10-11	13	4-5	14	10-11	25	4-5	27
	11-12	17	5-6	15	11-12	33	5-6	32
tals		81		91		119		181

Total from 6 p.m. to 6 a.m. .... 188 + 119 = 300

" " 6 a.m. to 6 p.m. ...... 81 +

In addition to these he has record of 157 shocks which occurred during the night and 4 shocks during the day. The hours at which these occurred are not recorded so that they could not be placed in the table given ~~below~~ below.

This makes a total of 457 night shocks against 176 day shocks. Kluge appears to think that this night frequency is is a function of the temperature but was apparently unable to indicate precisely how the supposed cause operated.

Milne[40] reviewed the question some thirty years later. He pointed out that Fuchs used ~~of~~ Kluge's catalogues for the period 1850-1857, and found the distribution to be as follows:-

Northern hemisphere	.... day -	938;	night 1592
Southern "	.... "	292;	" 357
Totals		1230;	1949

In the northern hemisphere a maximum frequency of 360 earthquakes was recorded between 10 and 12 p.m. and a minimum frequency of 139 between 12 to 2 p.m.

In the southern hemisphere the maximum occurred between midnight and 1a.m. and there were minima from 1 to 2 p.m. and 4 to 5 p.m. These distinctions were found to be less marked in equatorial regions.

Schmidt[96] found a maximum at 2:30 a.m. and a minimum at 1p.m.for the earthquakes of the Orient recorded for the period 1774 and 1873.

Milne comments on these night frequencies as follows:- "With regard to these conclusions, which have been reached with much labour, we might be inclined to think that they are partially to be explained on the supposition that more observations are made during the night than during the day. The personal experience of residents in an earthquake country being, that many earthquakes which occur during the day are passed by unnoticed, whilst those which occur during the night are recorded by thousands of observers. Such a view is certainly confirmed by the instrumental records obtained in Japan. From 1872 to 1880 inclusive there were 261 shocks recorded 132 of which occurred between the hours of 6 p.m.

This conclusion of Milne's is also supported by Montessus de 47.48. Ballore who examined the question for over 45,000 earthquakes. These records he divided into seven groups partly according to a district grouping and partly to the nature of the records He then tabulated for each group the hourly frequency for the whole period of 24 hours. Except in the case of groups V and VII which he discussed separately the records have a similar diurnal periodicity. He therefore combined groups 1,2,3,4,and 6 into one statistical summary. The frequencies are illustrate graphically and indicate a maximum from3 to 4 a.m. the frequency curve then descends rapidly to 7 or 8 a.m. and remains fairly constant till midday. A minimum occurs at aboutlp.m. and this is followed by a distinct maximum from 3 to 4 p.m. The principal minimum is recorded at about 6 p.m. and from this time onward there is a steady increase in the frequency up to the maximum at 3 to 4 a.m.

The interpretation of this curve of diurnal frequency Montessus considers is to be explained by human activities. The maximumat about 3 to 4 a.m. he explains in the following words:-

"Vers 3 heures du matin les sens sont déjà bien reposés et percoivent rapidement les ondulations du sol d'autant mieux que la majeure partie des populations est still couchée".

There is probably a good deal of reason in this explanation but it does not appear to be wholly satisfactory. It is not very clear for example why persons should be more readily awakened or should more readily notice earthquakeshocks between 3 and 4 a.m. than between 4 and 5 a.m. or from 5 to 6 a.m.

With increasing activities Montessus points out that fewer shocks would be observed and thus explains the morning minimum. He finds himself unable to explain the minimum which occurs from 1 to 2 p.m. as this is certainly not the period of maximum human activity. Of the maximum which occurs from 3 to 4 p.m. he writes "C'est l'heure d'un repos relatif dans le pays tempérés, de la sieste dans les pays chauds". This physiological explanation is again unsatisfactory in that it fails to explain the principal minimum at 6 p.m. Montessus suggests rather vaguely that the relative minimum of the early part of the night may be attributed "aux heures du premier et plus profond sommeil les sens sont trop fatigues pour ne pas laisser perdre un grand nombre de petites secousse But this explanation obviously cannot apply to the minimum at 6 p.m.

The fifth goup drawn up by Montessus exhibits a maximum at about 3 a.m. This he attributes to faulty observation assuming that the night observations were not carried out so carefully as those during the day.

The seventh group comprises the instrumental records of the Italian geodynamical observatories extending over the 21 years from 1863 to 1885. These records indicate that the day frequency exceeds that of the night. A closer examination however shows that this relation only holds for the period 1875-1885. Montessus points out that it was about 1875 that the ~~fact~~ first sensitive seismographs were established; and he attributes the day maximum to the influence of such human activities as vehicles, trains, mine explosions, etc. The frequency curve for this group he considers supports this view as it reaches a maximum about midday. It is clear that the conclusion reached by Montessus was not accepted by all seismologists for several important investigations into this question have since been made. The first of

this question have since been made. The first of these appears

in connection with an examination made by Omori on the aftershocks of earthquakes. He pointed out that previous investigation into diurnal frequency rested upon non-instrumental records, and were therefore of doubtful value. The records used by Omori were recorded at meteorological stations provided with seismographs as he states "should have therefore far greater weight than those hitherto obtained". As the journal in whivh Omori has published these records is not commonly available I have summarised his results and have tabulated them as follows:-

Earthquake	Kumamoto	Mino-Owari		Kagoshima
Seismological Station	Kumamoto	Gifu	Nagoya	Chiran
Period	July 31-August 31. 1889	October 28-Nov. 10 1891		September 8- 21st. 1893.
Hours	Number of Earthquakes.			
0-1 a.m.	7	56	51	3
1-2 "	13	64	44	15
2-3 "	18	58	25	12
3-4 "	12	62	34	9
4-5 "	11	92	32	9
5-6 "	11	63	25	17
6-7 "	3	47	16	9
7-8 "	6	53	22	12
8-9 "	4	49	26	10
9-10 "	2	41	20	15
10-11 "	4	42	14	6
11-12 "	3	58	21	11
0-1 p.m.	11	54	18	4
1-2 "	5	48	17	12
2-3 "	2	38	15	13
3-4	1	36	23	8
4-5	4	36	16	10
5-6	3	47	18	4
6-7	8	51	15	10
7-8	4	77	24	11
8-9	5	58	22	3
9-10	2	51	23	8
10-11	4	42	27	12
11-12	5	35	24	10
Totals	148	1258	572	233

The day and night frequencies from 6 a.m. to 6 p.m. and 6 p.m. to 6 a.m. respectively are as follows:-

District	Kumamoto	Gifu	Nagoya	Chiran
Day	48	549	226	114
Night	100	709	346	119
Totals	148	1258	572	233

It is interesting to note that in each of the four cases there is a distinct preponderance of night over day shocks. As these shocks were instrumentally recorded and as the excess occurred during the night in each case the criticisms of Montessus de Ballore do not apply to this series of records.

Omori has illustrated the diurnal frequencies by graphical methods using a smoothing process which actually amounts to a summation of overlapping means for two hourly periods. He found that for Gifu there were three diurnal maxima occurring between 4-5 a.m.; and three minima which occur respectively between 9 and.10 a.m., between 3 and 4 p.m. and at 11 p.m. The intervals between the maxima ~~and~~ are 7,8 and 9 hours, and between the minima 6,8 and 10 hours.

At Nagoya he found that there were 6 more or less distinct oscillations having a mean period of 4 hours. He says "It is evident ~~they~~ that both the 4-hour and the 8 hour periods existed ~~altogether~~ together, but that the longer period predominated in the diurnal earthquake frequency for Gifu and the shorter one in that ~~of~~ for Nagoya".

At Kumamoto and Chiran the hourly distribution of shocks was he considers"very similar respectively to those of Gifu and Nagoya.

Omori next extended his observations and examined the diurnal frequency for Tokyo and then for all Japan. His results are summarised and tabulated below:-

District	Tokyo	Japan	Japan
Period	1876-1891	1885-1890	including the afte shocks at Gifu and Chiran.
Hours	Number	of	Earthquakes.
0-1 a.m.	47	133	1 92
1-2 "	28	153	232
2-3 "	49	211	281
3-4 "	3 3	176	247
4-5 "	42	139	240
5-6 "	46 46	153 166	246
6-7 "	52	153	209
7-8 "	52	162	227
8-9 "	44	151	210
9-10 "	64	157	213
10-11 "	45	139	187
11-12 "	38	155	224
0-1 p.m.	49	151	209
1-2 "	55	186	246
2-3 "	50	188	239
3-4 "	67	162	206
4-5 "	54	144	190
5-6 "	44	132	183
6-7 "	44	135	196
7-8 "	43	156	244
8-9 "	65	153	214
9-10 "	58	184	243
10-11 "	53	185	239
11-12 "	52	171	216
Totals	1168	3842	5333

The disposition of day and night shocks is as follows:-

District	Tokyo	Japan	Japan and Gifu and Chiran.
Day	608	1880	2543
Night	560	1962	2790
Totals	1168	3842	5333

Omori concluded that the earthquakes observed at Takyo exhibit three diurnal maxima occurring respectively between 9 and 10 a.m.; between 3 and 4 p.m. and between 8 and 9 p.m.; and three minima occurring respectively bewteen 2 and 3 a.m. between 11 a.m. and noon and between 6 and 7 p.m. the intervals between the successive maxima are 6,5,and 13 hours and between the minima 9,7 and 8 hours.

For the 3842 earthquakes of Japan as a whole he found again three diurnal maxima occurring between 2 and 3 a.m.; between 2 and 3 p.m. and between 10 and 11 p.m.; and three minima between midnight and 1 a.m., between 8 and 9 a.m. and between 5 and 6 p.m. The intervals between the maxima being 12,8 and 4 hours, and between the minima being 8,9 and 7 hours.

In conclusion Omori says "Three distinct maxima and minima occur in the diurnal fluctuation of the frequency of after-shocks as well as in that of ordinary earthquakes. The hours at which these occur seem to be different for different localities and therefore these may not each be shown, when we mix up earthquakes records from distant places of the world together.

Whether there are more earthquakes during the night than during the day is not certain".

In discussing the possible cause of the periodicity Omori says "To investigate the relations, if any, between earthquakes and the phases of the moon, sun-spots, temperature of the atmosphere, etc. seems not likely to lead to valuable results and would be, as Mallet remarked, a waste of scientific time and labour. With atmospheric pressure it may be different."

After briefly discussing the question he concludes as follows:- "A single abrupt change in the atmospheric pressure is not likely to be accompanied by any fluctuations in the frequency of earthquakes. If however, barometric changes whether small or great, occur at regular intervals then the earth's crust may finally assume certain corresponding oscillations. Thus the daily and annual fluctuations in the seismic frequency may partly be due to those in the atmospheric pressure. Especially are the curves of the annual barometric and seismic fluctuations very similar to each other".

From the above statement it is clear that Omori recognised that the diurnal barometric wave which has two maxima and minima is not capable of affording a full explanation of the seismic frequency in which there are three maxima and minima. It may well be as he says that barometric fluctuations may partly affect the frequency. He has not however indicated how such a relationship might be specifically correlated in the case of the diurnal wave. It is clear that other agents must be active - possibly some which he has rejected as unprofitable lines of investigation. Such apparently has been the view of Davison, Knott, Schuster and Oldham who shortly afterwards sought for solar and lunar periodicities in earthquake frequency. Davison[10] first led the way by an investigation with diurnal periodicity. He first reviewed the work of Montessus de Ballore and of Omori and then proceeded to attack the problem by means of harmonic analysis. In order that the earthquake frequency for different districts may be more easily compared he represented the average hourly number of earthquakes for any given district as unity and calculated the frequency of the maxima and minima and the amplitude as decimals. The amplitude is one half of the difference between the maximum and minimum values of the frequency as determined by the harmonic analysis. He investigated in several cases the first 6 harmonic components of the frequency representing the hourly periods indicated in his tables. His examination comprises a study of several districts. He re-examined by the method of harmonic analysis the records which Omori had discussed in connection with the Kumamoto, Mino-Owari and Kagoshima earthquakes, and also those pertaining to Tokyo and Japan as a whole. In addition he analysed earthquake catalogues for the ~~Philippine~~ Phillipine Islands and Italy. The results of his analysis of Omori's data are very interesting and Davison's tables for these are here reproduced for comparison.

I. After-shocks of Japanese Earthquakes.

Earthquake	Kumamoto		Mino-Owari				Kagoshima	
District	Kumamoto		Gifu		Nagoya		Chiran	
Period	July 31st to Aug.13,1889		Oct. 29 - Nov.10 1891				Sept. 8-21 1893	
Harmonic Component	Ampl.	Epoch h.m.	Ampl.	Epoch h.m.	~~Ee~~Ampl.	Epoch h.m.	Ampl.	Epoch h.m.
1st - 24 hours	•623	0-3	•163	2-19	•505	0-15	•096	4-35
2nd - 12 "	•456	2-35	•089	5-29	•171	1-25	•069	3-58
3rd - 8 "	•430	2-57	•229	3-58	•111	1-17	•075	6-52
4th - 6 "	•214	1-56	•069	1-12	•068	1-41	•086	2-18
5th - 4$\frac{4}{5}$ "	•239	1-12	•051	0-50	•072	1-33	•121	0-40
6th - 4 "	•088	0-52	•121	0-32	•210	0-37	•239	1-57

II. Ordinary Earthquakes of Japan.

(a) 1204 Earthquakes recorded at Tokyo 1876-1881 and 1883-1892.

Harmonic Component	Whole Year Ampl.	Whole Year Epoch h.m.	Winter Ampl.	Winter Epoch h.m.	Summer Ampl.	Summer Epoch. h.m.
1st - 24 hours	.130	10-14	.093	10-39	.176	9-58
2nd - 12 "	.082	10-22	.123	9-26	.085	0-12
3rd - 8 "	.098	6-28	.086	6-31	.111	6-25
4th - 6 "	.118	3-7	.143	2-56	.096	3-26
5th - 4⅘ "	.030	1-8	.059	1-49	.060	4-2
6th - 4 "	.024	3-27	.097	3-11	.058	0-58

(b) 1175 earthquakes recorded for all Japan for the years 1885-1890

Harmonic Component	Ampl.	Epoch h.m.	Ampl.	Epoch h.m.	Ampl.	Epoch h.m.
1st - 24 hours	.147	11-53	~~11-~~ .239	11-50	.061	0-2
2nd - 12 "	.004	9-8	.035	9-48	.028	3-58
3rd - 8 "	.064	6-31	.045	6-12	.083	6-40
4th - 6 "	.100	2-39	.067	2-8	.146	2-53

In discussing the Italian records Davison admits the weight of the argument of Montessus concerning the mid-day maximum for the instrumental records at the geo-dynamical observatories. But he points out that there is however one station - Rocca di Papa which according to Cancani is wholly uninfluenced by vibrations due to human activities; and that the harmonic analysis of the records of this station too indicate a midday maximum. As it is found moreover that the records of ~~th~~ some of the stations questioned by Montessus agree closely with those of Rocca di Papa, the force of his argument with regard to human activities is considerably weakened.

Davison provides a succinct summary of his results as follows:-

"The following conclusions may, I think, be drawn from the results of the above analysis:-

(1) The reality of the diurnal variation of ~~the~~ earthquake-frequency seems to be proved by the approximate agreement in epoch (mean local time) of the first from components for the whole year at Tokio and Manila, and for the winter and summer halves of the year at Tokio.

(2) In ordinary earthquakes there is in nearly every case a marked diurnal period, the maximum generally occurring between 10 a.m. and noon. The semi-diurnal period, though less prominent is also clearly marked, the maximum occurring, as a rule, between 9 a.m. and noon and between 9 p.m. and midnight. Other important - the first maximum of the eight-hour component probably occurring about 6:30 a.m. and that of the six-hour component about 3 or 4 a.m.; but in these two epochs the results are not always concordant.

(3) Though the materials are insufficient for any general ~~conclu~~ conclusion, a comparison of the results for Tokio and Rocca di Papa seems to show that the slighter disturbances at the latter place are subject to a more marked diurnal periodicity.

(4) In the after-shocks of great earthquakes the diurnal periodicity as a rule, is strongly pronounced. The maximum of the diurnal period occurs within a few hours after mid-night, but the epochs of the other components are subject to wide variance. A special feature of after-shocks is the prominence of eight-hour and four-hour components. After a year or two there is some return to ordinary conditions; but even when the average hourly-number number of shocks is reduced to one-

hundredth of that during the first few days, the characteristics of after-shocks are still perceptible".

Davison then undertook an harmonic analysis of barometric pressure records in order to ascertain whether any periodicity similar to that of earthquake periodicity might exist in such records his results show some similarilty but many anomalies he concludes as follows:-

"It seems evident, therefore, that we cannot attribute the diurnal variation of seismic frequency exclusively to that of barometric pressure or of wind velocity but it is not improbable that it may result from a combination of both phenomena, that the diurnal periodicity of ordinary earthquakes may be due chiefly to that of wind velocity and the diurnal periodicity of after-shocks chiefly to that of barometric pressure." The real conclusions from Davison's paper appears to be that diurnal periodicity really exists in earthquake frequency; that there is strong evidence that it is influenced by variations in barometric pressure at that probably other influences at present undetermined are also operative.

The conclusion of Davison that real diurnal periodicity exists is confirmed by Schuster[87.] in a critical examination in which he deals with the probability of such earthquake frequency resulting from the random occurrenceof shocks. Schuster says " The reality of the daily period must be considered established unless the evaluation of the expectancy is faulty owing to the fact that the tremors occur in groups the good agreement between the phases of periodicity disposes of that doubt".

In the year following Schuster's criticism Becke[2.] published an account of the Graslitz earthquakes he tabulated some 300 shocks grouping them first into 2 gourly periods and [illegible] in three-hourly intervals. The graphical representation of both methods are similar and indiate a maximum frequency in the early hours of both morning and evening he further analysed ~~his method of data~~ his ~~grouping~~ ~~data~~ data by several methods of ~~data~~ grouping according to the intensity of the shock and found that the distribution was much the same in each case. He also considered the suggestion that the ~~pure~~ fewer shocks at about mid-day might be due to weak shocks passing unobserved and the minimum about midnight might be due to the omission from the record of weaker shocks not sufficiently strong to awaken the sleepers. The strong shocks however also exhibit the same frequency as the weaker ones and hence the force of the physiological argument is weakened. Becke considered the possibility of the frequency being affected in the same way by the sun's position. He pointed out that if this was the case the same relations should be manifest for the moon. He therefore analysed the records according to the lunar day but did not consider the results confirmed as hypotheses. There are however some important aspects which he overlooks and these will be discussed later under the section dealing with lunar periodicities.

Becke also examined but on account of lack of data ~~,~~ in a not very satisfactory way the possible relations of the earthquake frequency and barometric variation; and he concluded that there was no very obvious relation between these two sets of phenomena.

Milne[41] in his book on seismology has also discussed the question of diurnal periodicity. He took up the disputed question of the preponderance of night shocks and reviewed the work of Montessus de Ballore. In order to escape the disturbing records. He selected those used by Omori - the shocks recorded at Tokyo from 1876-1891 and concluded that these indicate that earthquakes are as frequent during the night as during the day. He makes a very interesting observation which deserves further study, this reads as follows:-

" If however we tabulate the same earthquakes in vertical columns according to the hours of the day each column corresponding to a month of the year, an inspection of this table shows that especially for the winter months there appears for each 24 hours a maximum and minimum; and passing from month to month the time of the maximum, commences at midnight in January, grows later until July when it reaches midday, while from July to December the time of the maximum grows earlier".

After the review of the work of Omori and Davison already discussed in the paper he conceived:- "Since it is likely that along a fault, possibly a hundred miles in length, for many months after its formation there are points at which critical condition are rapidly being produced, it is not improbabl that yielding or accelerated settling should be effected by diurnal barometrical changes.

It must, however, be noted that in Japan these changes, with a range of two millimetres have their maximum and minimum about 9 a.m. and between 2 and 4 p.m., which are hours far removed from those at which the maximum of the weaker and after-shocks chiefly take place."

In 1902 Omori took up the question for the earthquakes of Japan.[71] In this investigation he made a very detailed examination of 18,279 earthquakes recorded at 26 different stations. Recognising that the same laws of frequency may not apply to all areas he has considered separately the records of each of the 26 recording stations. The majority of the earthquakes were observed instrumentally the seismographs used being of the Gray Milne type.The records are assembled in tabular form which shows clearly the frequency for each hour of the day and also for each month. In the case of each district Omori found a marked diurnal frequency which however is not the same for the different stations. He found that it was possible to arrange the stations into four groups characterised respectively by a twelve, an eight a six and a four hour periodicity. In the case of those stations at which the total number of shocks for each exceeded 400 he tabulated the hours of the absolute maximum and minimum as follows:-

Hours of occurrence of the absolute maximum and minimum in the diurnal seismic variation.

Stations	Hours of occurrence of Maximum	Minimum.
Nemuro	11 a.m. - noon	2-3 p.m.
Miyako	5-6 p.m.	2-3 p.m.
Ishinomaki	2-3 p.m.	0-1 a.m.
Fukushima	9-10 p.m.	4-5 a.m.
Utsunomiya	6-7 a.m.	11 p.m.-midnight
Tokyo	9-10 a.m.	4-5 p.m.
Nagoya	1-2 a.m.	(0-1 p.m. 6-7 p.m.
Gifu	10-11 p.m.	4-5 p.m.
Tsu	10-11 a.m. (7-8 p.m.	0-1 p.m.
Wakayama	5-6 p.m.	2-3 p.m.
Kumamoto	9-10 a.m.	2-3 a.m.
Kagoshima	1-2 p.m.	4-5 a.m.

Commenting on the above table Omori remarks "From this table, it will be seen that the hours of occurrence of the absolute maxima and minima in the diurnal seismic variation are very different for the different places. This may partly be due to the fact that earthquakes observed at some of the stations are not sufficiently numerous. The probable cause is, however, the predominance of different periodicities at the different stations."

Even in those cases where stations have the same period the epoch is often quite different. This will be seen from the following tables which are also quoted from Omori's paper:-

Stations with 12 hours period.

Station Max. or Min.	Fukushima	Utsunomiya	Wakayama	Kumamoto.
1st Max.	9-10 a.m.	9-10 a.m.	4-5 a.m.	9-10 a.m.
2nd. "	8-9 p.m.	8-9 p.m.	5-6 p.m.	9-10 p.m.
1st Min.	2-3 a.m.	2-3 a.m.	0-1 a.m.	2-3 a.m.
2nd "	at 2 p.m.	3-4 p.m.	10-11 p.m.	6-7 p.m.

Stations with 8 hours period.

Station Max. or Min.	Nemuro ~~Miyako~~	~~Gifu~~ Miyako	~~Tsu~~ Gifu	Tsu
1st Maximum	at 4 a.m.	1-2 a.m.	4-5 a.m.	2-3 a.m.
2nd "	11 a.m.- noon	9-10 a.m.	0-1 p.m.	10-11 a.m.
3rd "	~~597~~ 5-7 p.m.	6-7 p.m.	at 9 p.m.	7-8 p.m.
1st Minimum	8-9 a.m.	at 5 a.m.	9-10 a.m.	at 7 a.m.
2nd "	2-3 p.m.	at 2 p.m.	3-4 p.m.	1-2 p.m.
3rd "	10-11 p.m.	at 11 p.m.	10-11 p.m.	0-1 a.m.

Stations with 6 hours period - Tokyo.

1st Maximum	2-3 a.m.	1st Minimum	1-2 a.m.
2nd "	9-10 a.m.	2nd "	4-5 a.m.
3rd "	3-4 p.m.	3rd "	0-1 p.m.
4th "	9-10 p.m.	4th "	5-6 p.m.

The above tables emphasise the individuality of the records for each station, and furnish a strong argument against their correlation with barometric pressure alone; which is the only correlation attempted by Omori.

The next to take up the problem of diurnal periodicity was Oldham.[66] He pointed out that after a great earthquake there usually follows a long train of after shocks due to minor readjustments, before equilibrium is reached; and he considered that such a series of shocks was well suited for an investigation into diurnal periodicity. He therefore inquired into the after-shocks of the Great Assam earthquake with this object in view. In order to eliminate errors due to physiological causes he examined the records furnished by the Shillong seismograph. He tabulated the earthquakes for each hour of the day and found two maxima, one between 8 and 11 p.m. and the other between 3 and 6 a.m. He acutely remarks that if this distribution be due to the sun's attractive force, a corresponding effect should also be noted for the moon. He therefore subdivided the lunar day into 24 equal parts and graphically represented the earthquake frequency for each part for a period of 4½ years. He found however that the result exhibited little resemblance to the solar curve and hence made the following statement:- "Hence we may conclude that the observed irregularity of distribution of earthquakes through the 24 hours of the day and night, is not directly due to the attraction of the sun. .... Through the observed irregularity in distribution of the after-shocks over the twenty-four hours of the day cannot be attributed to the direct attraction of the sun, it does not necessarily follow that this is without effect, and it will be of interest to see whether the attraction of the sun and moon have any effect in determining the time of occurrence of earthquakes".

A fuller discussion of this investigation will be given under the section dealing with earth tides.

Although the frequency during the lunar day does not correspond to that of the solar day Oldham thinks that the same fundamental relation may exist in both cases but that the period of observations may not have been sufficiently long to eliminate the solar influence from the lunar observations.

Certainly, however, a diurnal periodicity seems to be present and Oldham is disposed to attribute it indirectly to the tidal forces.

Knott[31] has critically reviewed Omori's, Oldham's and Davison's work in this connection. He discussed the periodicities indicated for the Tokyo and Nagoya districts given by Omori and found no evidence of a daily maxima though he believes there is some ground for the half and quarter daily periods. He has also criticised the methods adopted by Omori, pointing out that he did not use the method of overlapping means which Knott considers essential to the investigation.

In reviewing Oldham's work Knott has calculated the amplitudes and expectancy for the earthquake frequency and concluded that the results were negative in character.

In reviewing Davison's work he considers that more definite results appear from the examination of the Italian records. In reference to these Knott writes "In the case of Italy with its 8177 shocks the daily, half-daily, and quarter daily amplitudes are all comparatively large, and to that extent support the hypothesis of a true solar daily period".

In general he says "where comparison is possible the results agree sufficiently well with the results given by Davison, at least as regards the phases of the assumed periodicities."

In the case of the earthquakes of Japan however Knott has examined a larger number (3842) of shocks than those available (1175) at the time of Davison's investigation.

Comparing the results for this group Knott writes "Davison finds for the times of maxima in the daily, half-daily, third daily and fourth-daily harmonic the following values:- noon, 9 a.m., 6·5 a.m. and 2·5 a.m.; while my values for the corresponding quantities as given by Omori's larger list are 2 a.m.; noon, 6 a.m. and 3·5 a.m. There is agreement in one case only and that is the eight-hours periodicity, for the existence of which there is absolutely no physical basis. The daily and half-daily periodicities are quite different."

It must be kept in mind however when one reads the above statement that Omori had already demonstrated how important it is in investigating earthquake frequency to deal with each district separately; and it may well be that the larger number of earthquakes investigated by Knott involved a different district grouping from that of the list employed by Davison. Again after a perusal of part II of this paper dealing with "Tidal stresses in the lithosphere" most readers will probably be prepared to admit that there may be after all, a physical basis for an eight-hour periodicity in certain cases. Shortly after Knott's review appeared Omori published a further contribution to the subject in his paper dealing with the "Secondary causes of earthquakes". 78 He has given the hourly frequency for 2208 earthquakes instrumentally observed at Tokyo for the 24 years 1876-1899. ~~As Tokyo for the 24 years~~ The frequency curve has four maxima, the two principal ones occurring at 9-10 a.m. and 9-10 p.m. and the two minor ones at 2-3 a.m. and 3-4 p.m. When the earthquakes are grouped in 3 hourly periods the frequency curve has only two maxima and agrees well with the curve for the barometric pressure.

Another illustration of a remarkable diurnal distribution of the frequency is given by Omori in the following table:-

Hour	A.M.				P.M.			
	(a) Eqkes. of Groups I to IV (Inland Origin)		(b) Eqkes. of Groups V to X		(a) Eqkes. of Groups I to IV (Inland Origin)		(b) Eqkes. of Groups V to X.	
0-1	0	14	6	28	0	10	5	24
1-2	1		4		1		5	
2-3	4		4		3		6	
3-4	3		4		2		2	
4-5	4		4		1		1	
5-6	2		6		3		5	
6-7	0	1	5	35	0	1	7	32
7-8	1		5		0		6	
8-9	0		10		1		2	
9-10	0		6		0		11	
10-11	0		5		0		1	
11-12	0		4		0		5	

The periodicity indicated in the above table is of course of a semi-diurnal character.

On the whole then it appears that diurnal periodicity has been noted for many earthquake districts, but that the epoch of the maximum is not the same for all districts but appears to be a characteristic of each particular locality. The attempts which have been made to correlate the periodicity with barometric changes while furnishing a partial explanation do not by any means wholly account for the observed periodicities.

Ocean Tides and Earthquakes Frequency.

It might be thought at first sight that the investigation of tidal forces would be the same for both the water and land areas. This however is not the case for two reasons. In the first place there is involved in the motions of the water tides the bodily transference of large amounts of water from one area to an adjacent one; and in the second plave the phases of the high and low tides vary very considerably for different districts as may be seen by tables giving the "establishment of the port". Moreover there are those who are willing to admit the influence of ocean tides as a factor in determining earthquakes frequency, and who do not attach a similar importance to the corporeal tides. For these reasons then, it was considered advisable to discuss the water tides and the earth tides separately.

Probably the earliest reference to a possible relation between tides and earthquake frequency is an extract from the diary of Richard Cocks under the date November 7th, 1618. The quotation is by Milne[40] and refers to the popular belief that earthquakes are apt to occur at the times of high water.

The stresses set up by fluctuations of the water level are considerable and greatly exceed those due to variations in barometric pressure. Darwin[6] has calculated that the tides having a range from high to low water of about 16 feet, actually operating on the coast of the Atlantic, are capable of causing a vertical displacement of the solid earth's crust amounting to 11·37 c.m. or nearly 5 inches. The careful enquiry into this problem however is of recent date. This may be gathered from the following statement made by Milne[40] in 1886:-

"To determine how far tides may directly be connect earthquakes, the necessary records have yet to be examined".

The absence of any reference to such an investigation in Kikuchi's comprehensive review[26] of the Japanese work in Seismology indicates that even at this date (1904) nothing of importance had been done.

About the same time (1904) Omori, in an investigation into the subject of the lunar-daily distribution of earthquakes,[70] was led to the conclusion that "the effect due to the weight of the sea waters in the tidal motion" was an effective agent in influencing earthquake frequency.

Imamura, too in an investigation into Synodic monthly frequency[24] reached the conclusion that the sea tides contributed a component, in conjunction with barometric pressure, which influenced the earthquake frequency.

The problem appears to have been first systematically examined by Omori, who has discussed it in his paper on the "secondary causes of earthquakes".[78] He investigated four distinct series of records which are as follows:-

(1) List of the recent stronger submarine earthquakes which originated along the Fuji volcanic chain.
(2) List of strong earthquakes felt in Tokyo
(3) Stronger earthquakes whose centres were not much distant from Tokyo. Inland origin.
(4) Stronger earthquakes whose centres were not much distant from Tokyo - submarine origin.

The tables prepared by Omori give the date and time of each earthquake and the nearest time of high or low water. A column is also given expressing the difference between the times of each earthquake and the corresponding time of high or low water. From these statistics Omori records the number of earthquakes which occur near the times of high water, of low water and between tides.

For the first series relating to the Fuji volcanic chain and containing 14 earthquakes, he draws the following conclusion. "The difference between the time of earthquake occurrence and the nearest moment of high or low water of the tide varied, except in the case of the 4th earthquake, between 0 h. 12 m. and 2 h. 15 m. giving the average value of 50 m."

The second series contains 14 strong shocks felt in Tokyo. Of these he writes, "The difference between the time of earthquake occurrence and that of the corresponding high and low water of the tide varied in 11 out of the 14 cases, between 0 h. 0 M. and 2 h. 21 m.; only in the 3 remaining cases, earthquakes happened midway between the high and low waters".

The third series he has subdivided into five groups. He considers together groups I to IV as referring to earthquakes of inland origin, and states the relation of the 26 earthquakes concerned to the phases of the tide as follows:-

"(a) 11 occurred with the high tide

(b) 12 occurred with the low tide

(c) 3 occurred between the high and low tides.

The earthquakes of Group V refer to coastal or submarine regions. The total number of these earthquakes is 39 of which "21 occurred with the high water, 15 with the low water, and the remaining 2 between the high and low waters".

The earthquakes of the fourth series comprise groups VI to X and contain 80 earthquakes. Of these "33 each occurred with the high and low waters, while the remaining 14 occurred between these two phases of the tide".

He has also given the distribution throughout the day of the earthquakes of the third and fourth series in a condensed table which is reproduced as follows:-

Diurnal variation of the seismic frequency in relation to the phases of the tide.

Hour	Earthquakes occurring					
	with high water		with low water		between high and low waters.	
0-1 A.M.	4	20	2	20	0	1
1-2	3		1		1	
2-3	3		5		0	
3-4	3		4		0	
4-5	3		4		0	
5-6	4		4		0	
6-7	3	18	1	11	1	8
7-8	3		3		1	
8-9	5		3		2	
9-10	4		0		2	
10-11	1		2		2	
11-12	2		2		0	
0-1	1	11	4	21	0	2
1-2	2		4		0	
2-3	3		6		1	
3-4	2		1		0	
4-5	0		2		0	
5-6	3		4		1	
6-7	2	15	2	10	3	8
7-8	4		1		1	
8-9	3		0		0	
9-10	4		5		3	
10-11	0		1		0	
11-12	2		1		1	
SUM		64		62		19

From the above table there appears to be a great preponderance of earthquakes occurring with the maximum and minimum loading of the coastal area of Japan in the neighbourhood of Tokyo.

There is however a strange lack of precision in Omori's grouping of the records in relation to the times of high and low water. The lunar day consists of about 24 hours and 50·5 minutes so that the average time between high and low water is 6 hours 12·6 minutes. In order to group the earthquakes according to the times of high and low water and between high and low water this interval should be subdivided into four equal parts each 1 hour 33 minutes in length. Earthquakes occurring within this period of the times of high, low or middle water should be referred to those standards respectively. Omori, however, has included earthquakes occurring ~~as~~ far off ~~as~~ from the times of high and low water as referring to these periods.

Applying the new criteria to Omori's tables the following results have been derived:-

(1) The 14 earthquakes of the Fuji volcanic zone.

With high water 4 earthquakes
" low " 7 "
" middle tide 3 "

(2) The 14 strong shocks felt in Tokyo

with high water, 5 earthquakes
" low " 4 "
" middle tide, 5 "

(3) The 26 stronger earthquakes near Tokyo - Inland origin

(a) Groups I to IV of Omori's table.

with high water, 9 earthquakes

" low " 8 "

" middle tide 9 "

(b) The 39 earthquakes of Group V of Omori's table

with high water, 16 earthquakes

" low " 10 "

" middle tide 13 "

(4) The 80 earthquakes of submarine origin near Tokyo

with high water, 20 earthquakes

" low " . 21 "

" middle tide 39 "

From the manner in which the time intervals are subdivided the number of earthquakes occurring at middle tide should be equal to the sum of those at high and low tide unless the frequency of the earthquakes is affected by the ebb and flow of the tides. It will be seen that the sum of the numbers for high and low tide exceeds that for middle tide by considerable amounts except in the case of the submarine earthquakes. These results may now be tabulated for comparison with Omori's as follows:-

Series	Sum for High and Low tide according to Omori	Cotton	No. for Middle tide. according to Omori	Cotton
1	13	11	1	3
2	11	9	3	5
3a	23	17	3	9
b	36	26	2	13
4	66	41	14	39
	149	104	23	69

Thus according to Omori the ratio of the number of earthquakes occurring at high and low tide to the number occurring about middle tide is 149:23 and according to my calculations 104:69. In spite of this serious discrepancy both sets of figures favour a relation between earthquake frequency and the times of high and low tide. If, moreover, we put on one side the earthquakes of submarine origin the corresponding ratios are-Omori 83:9 and Cotton 63:30, both of which strongly support some such relation as that suggested by Omori. More extended work is however required on this subject.

The only other systematic enquiry into the relation of ocean tides and earthquake frequency appears to be that made by Taber in connection with the earthquakes of the Charleston district.[91] He plotted the earthquake frequency for hourly periods corresponding to the phases from high water to the next period of high water and concludes as follows:- "A careful examination of the curve shows that the times of earthquake shocks are distributed without reference to the hours of high and low water; and when it is tested mathematically for a harmonic periodicity, the maximum number of shocks is found to occur about seven hours and the minimum about one hour before high water, but the amplitude is less than twice the expectancy. This proves that the tides have had little if any influence in determining the time of earthquake shocks. It is interesting, however, to note that the slight maximum occurs near the time of low water, that is to say, when the effect of sea-level height is to reduce to a minimum the load on the south-east side of the assumed fault.

The distance of the fault from the sea coast is possibly the explanation of the fact that tides seem to have little or no influence in determining the time of the shock."

From the foregoing discussion it would appear that the question is still an open one and is worthy of further investigation. It may well be, and indeed is highly probable that any component of earthquake frequency connected with ocean tides is due to differential loading of adjacent areas rather than to the maximum and minimum pressures across the earthquake region.

Earthquake Frequency and Earth Tides.

The possible relation between earthquake frequency and tidal stresses in the lithosphere was first investigated by the famous Alexis Perrey of Dijon.[19] Indeed this question formed the principal subject of his researches and his methods of attacking the problem have influenced most subsequent workers. Perrey accepted the then current doctrine of a fluid nucleus for the earth. He argued that this fluid mass, like the ocean waters, must be subjected to tidal movements, and hence would disturb the solid crust of the earth which they supported. Although this view of the constitution of the earth's interior has now been demonstrated to be untrue, by virtue of the high rigidity of the earth as a whole, the work of Perrey cannot be set aside on this account; for his work is largely based on statistical methods. His conception of the earth's interior influenced the plan of his investigations and was used to interpret his results; but the results themselves are not in any way dependent upon the theory in which he believed. It is well to keep this in mind for it has been contended that, as Perrey's fundamental postulate with regard to the earth's interior has been shown to be false, ~~that~~ the laws which he promulgated with regard to earthquake frequency must be equally untrue.

Perrey's methods appear to have been followed by most subsequent investigators and it almost seems as if his genius has so dominated the trend of thought as to render difficult the development of a fresh point of view.

Perrey's work was communicated chiefly to the French Academy of Science and was discussed and approved by a special committee of that body. The full details of his earlier works do not appear to have been published, work do not appear to ~~have been published~~ but his conclusions with regard to several aspects of the question have been published in several of his later memoirs. In 1853 Perrey presented to the Academy a memoir entitled "Sur les rapports qui peuvent exister entre la fréquence des tremblements de terre et l'âge de la lune"; and in the following year a second memoir entitled "Sur la fréquence des tremblements de terre relativement aux passages de la lune au méridien". 81

These reports were not printed but the substance of their contents was published in a report by a select committee ~~ap~~ appointed to review Perrey's work. This report accepts the view of a fluid nucleus for the earth and regards this hypothesis as competent to explain the results of Perrey's investigations.

Perrey found himself confronted with an initial difficulty in his statistical work. The records were not, of course, at that time instrumentally made, and the times of the earthquakes were not, in consequence, recorded with precision. It therefore happened, that on many occasions when earthquakes were recorded on the same day from different districts, there was a doubt as to whether one or more distinct earthquakes had actually taken place. To overcome this difficulty he undertook two methods of investigation.

In the first case he took as an "earthquake day" a day in which one or more earthquakes occurred regardless of other circumstances. This gave a list of 2735 earthquake days for the period 1801-1845 and a total of 5388 earthquake days for the period 1801-1850.

In the second case he reckoned as an "earthquake day" each shock which could be established as independent of others as for example, two shocks which though simultaneous in time were separated by regions unaffected by either shock. This raised the numbers from 2735 to 3041 and from 5388 to 6596 for the periods abovementioned.

In both the first and second methods he referred each earthquake day to the corresponding lunar day and found a preponderance at the syzygies as compared with the quadratures He found moreover that this law held for each of the quarter centuries comprising the interval from 1801 to 1850.

Perrey also employed a third method in which he regarded as separate each of the individual shocks comprised in a single earthquake. He had not the necessary data for this in general and confined his attention to a list of 913 shocks recorded by Castel~~man~~nau from South America. The results of this third method confirmed those previously obtained by his other methods. The investigation was carried further by examining separately some 422 earthquake days for the period 1841-1845. Even in this limited period the same conclusion is indicated.

Perrey next investigated the question of effect of the variable distance of the moon in describing its elliptical orbit. For this investigation he calculated, according to the different methods of tabulation employed for his former tables, the number of times an earthquake has occurred on the second day before, the day before, the day of, the day following and the second day following perigee and apogee. He found in each case that there was a preponderance of earthquakes at perigee. He next took the differences of the earthquake days between those of perigee and apogee and divided them by their corresponding sums thus obtaining the following quotients, $\frac{1}{16{\cdot}5}$, $\frac{1}{23{\cdot}6}$, $\frac{1}{23{\cdot}5}$, $\frac{1}{24{\cdot}4}$, $\frac{1}{29{\cdot}2}$, $\frac{1}{18{\cdot}6}$, $\frac{1}{21{\cdot}2}$, $\frac{1}{10{\cdot}75}$

The investigation into the relation of earthquake frequency and the times of the moon's passage across the meridian was more restricted in character. For this purpose Perrey requir the actual times of the earthquakes and the only list which he found possible to make use of was that of Castâ~~m~~zoun. He examined 824 shocks recorded at Arequipa and found their distribution throughout the lunar day. He subdivided the lunar day into 16 equal parts which he arranged in pairs forming groups. The report of the commissioners with regard to this part of Perrey's work reads as follows:-

"Sous ces deux formes, et malgré d'assez fortes anomalies qui ne pouvent guère manquer de se présenter dans un nombre de faits aussi restreint encore que 824, les chiffres obtenus, dans l'un et l'aûtre mode de groupement, mettant en évidence l'existence dans la durée du jour lunaire, de deux époques de <u>maximum</u> pour la fréquence des nombres des secousses, et de deux époques de <u>minimum</u>. Les deux époques de <u>maximum</u> se rapprochent des passages de la lune aux méridiens supérieur et inférieur. Les époques de minimum tombent vers le milieu des intervalles".

The commission further reports as follows:-

"M.Alexis Perrey est ainsi parvenu, par la simple discussion des catalogues qu'il avait préalablement formés, à constater, sous trois formes diverses et <u>indépendantes l'un de l'aûtre</u>. l'influence de la marche de la lune sur la production des tremblements de terre, en faisant voir:

"1°. Que la fréquence des tremblements de terre augmente vers les syzygies;

"2°. Que leur fréquence augmente aussi dans la voisinage du périgée de la lune, et diminue, au contraire, vers la l'apogée;

"3°. Que les secousses de tremblements de terre sont plus fréquentes lorsque la lune est dans le voisinage du méridien que lorsqu'elle en est éloignée de 90 degrés." The importance of Perrey's work was recognised by his contemporaries and Mallet was so impressed with its value that he incorporated a translation of the report of the French Commission in the classical paper[36] which he presented to the British Association for the Advancement of Science in 1858.

The French Academy of Science granted Perrey financial assistance to continue his research and in 1861 he furnished a further report[82] on the subject. In this memoir he discarded the first method of investigation used in his earlier work and employed only the second method i.e. reckoning each ~~district~~ distinct earthquake as an earthquake day. The investigation relates to the period ~~1851~~ 1751 to 1800. He found on this method of reckoning 3655 earthquake days.

He first grouped the earthquakes according to the moon's age, subdividing the lunar month of 29·53 solar days into 8 equal parts. These he grouped in pairs so that the first and eighth correspond to new moon, the second and third to the first quarter, the fourth and fifth to the full moon and the 6th and 7th to the last quarter. For the whole period from 1751 to 1800 he found the frequency to be as follows:-

At the Syzygies ....1901·18 earthquake days
" " Quadratures .....1753·82 " "
Difference 147·36

For the period 1801 to 1845 his results were

At the Syzygies .... 1420·94 earthquake days
" " Quadratures .... 1314·06 " "
Difference 106·88

For the period 1801-1850 he found that for 5388 earthquake dys (using his first method) the distribution was

At the Syzygies .... 2761·48 earthquake days
" " Quadratures........ 2626·52 " "
Difference 134·96

and for the same period (using the second method) he found ~~that~~ for 6596 earthquake days

At the Syzygies ....3434·64
" " Quadratures ...... 3161·36
Difference 273·28

He next subdivided the interval 1751-1800 into two periods of 25 years each and found in each case a preponderance at the syzygies. Carrying the subdivision into 5 periods of 10- ~~there was~~ years he still found that without exception the same preponderance for the syzygies. This encouraged him to try a still further subduvision into 5 yearly periods. At this stage he found the numbers small and irregular but nevertheless in 8 cases out of 10 there was a preponderance at the syzygies.

He next enquired into the earthquake frequency at perigee and apogee for ~~by~~ the earthquakes of the whole period 1751-1800. He found, following his former method, ~~that~~ the following results:—

for the 5 days about perigee 526 earthquake days
..................apogee 465½ " "
Differnce in favour of perigee 60½

and the ratio $\frac{60\frac{1}{2}}{991\frac{1}{2}} = \frac{1}{16 \cdot 3}$

For 3 dys about perigee 313½ earthquake days
.... apogee 278½
Difference in favour of perigee — 35

and the ratio $\frac{35}{592} = \frac{1}{16 \cdot 9}$

These results agree well with those of his earlier memoir for which the corresponding ratios were - for the

5 days about perigee and apogee $\frac{1}{21\cdot2}$
3 .... " $\frac{1}{19\cdot1}$

In addition the records of the earthquakes of Reggio entered in a journal kept by Areovito give 473 shocks at the syzygies and 349 at the quadratures.

He next took up again the relation of earthquake frequency and the moon's meridian passage. For the records 1751-1800 there were but few in which the time of the shock was accurately recorded. The following five lists were the only ones available. It is important to note that in this paper Perrey modified his former method of investigation and merely enquired into the number of shocks when the moon's hour angle was greater and less than 45 degrees. His results I have tabulated as follows:-

District	Period	Number of Earthquake Days Moon less than 45° from meridian	Moon greater than 45° from meridian	Difference
Monteleone	Jan. Oct. 1783 - 1786	475	~~4[illegible]~~ 453	22
Messine	Feb. Jan. 1783 - 1784	84	~~66~~ ~~[illegible]~~ ~~66~~ 60	24
Celanzaro	Feb.-July 1783	102	~~[illegible]~~ 81	21
Scilla	Oct. Nov.	140	~~32~~ ~~[illegible]~~ 120	20
Reggio	1783 - 1785	413	~~348~~ 347	66
Totals		1214	~~[illegible]~~ 1061	153

In a later paper83 published in the American Journal of Science Perrey has reviewed his work, and this review supplemented by a foot note gives an excellent summary ~~to~~ of his research

~~to that date~~. Perrey also mentions that he has subdivided the records from 1801 to 1850 into two equal parts and found the law with regard to the syzygies to hold for each. A further subdivision into 5 yearly periods shows that the law holds in 7 cases, fails in two, while in the remaining case 1810-1815 there is no sensible maximum or minimum. He pointed out however that in the two cases where the law failed there was a series of local shocks in a region where earthquakes are unfrequent; and in the interval 1810-1815 the great wars of Europe diverted the attention of the few journals from subterranean disturbances.

Unfortunately Perrey was never able to complete his investigations owing to the loss of his sight. His final memoir[94] on the subject appeared in 1875 and, feeling that this was to be his finale effort, he gave, in addition to bringing his work up to date, a review of his earlier work. He treated the subject in three divisions corresponding to the three laws which he has enunciated.

In the first place he discussed the relation of frequency with regard to the syzygies and quadratures. After dividing the lunation into eight equal parts of 3.69 days each he found that the earthquake frequency corresponding to these intervals gave two maxima at the syzygies and two minima at the quadratures. He next grouped the eighth parts into four intervals, two of which correspond to the syzygies, and two to the quadratures, and gave the following table:-

Period Studied	Total	Number of Earthquakes.		Difference in favour of Syzygies.
		At Syzygies new & full moon	At Quadratures first & last Quarters	
1843-1847	1604	850·48	753·52	96·96
1848-1852	2049	1053·53	995·47	58·06
1853-1857	3018	1534·13	1483·87	50·26
1858-1862	3140	1602·99	1537·01	65·98
1863-1867	2845	1463·42	1381·58	81·84
1868-1872	4593	2333·48	2259·52	73·96
1843-1872	17249	8838·03	8410·97	427·06
1801-1845	3041	1604·67	1436·33	168·54
1901-1850	6596	3434·64	3161·36	273·28
1751-1800	3655	1904·18	1753·82	147·36

In each case it is seen that there is a preponderance of earthquake days at the syzygies.

In the second place Perrey discussed the earthquake frequency in relation to the times of perigee and apogee. The results of this investigation he tabulated as follows:-

pochs	1843-1872	1801-1845	1801-1850	1751-1801
he five days bout perigee	649	–	242	108
	645	81	244	113
	690	93	256	99
	644	88	234	102
	662	–	247	104
he five days about apogee	582	–	221	90
	594	83	229	100
	618	75	219	90
	627	74	213	88
	594	—	231	97
Total for perigee	3290	262	1223	526
" " apogee	3015	232	1113	465
Difference in favour of perigee	275	30	110	61

Expressing the differences in their ratio to the total numbe of earthquake days these give for the totals of the four columns $\frac{1}{22\cdot9}$, $\frac{1}{16\cdot5}$,, $\frac{1}{21\cdot2}$, $\frac{1}{16\cdot2}$ for the four columns of the above tables respectively, reading from left to right.

By taking into account only the three days about perigee and apogee he obtained the following table:-

	1843-1872	1801-1850	1751-1800
Perigee	1979	734	314
Apogee	1839	661	278
Difference in favour of perigee	140	73	36

The corresponding ratios of the differences to the totals were $\frac{1}{27\cdot3}$, $\frac{1}{19\cdot1}$, $\frac{1}{16\cdot4}$ for the three columns respectively - again reading in order from left to right.

The further investigation of the third law relating to earthquake frequency and the meridian passage of the moon he was unable to undertake. Writing of this he says.

"J'aurais voulu m'occuper encore de la fréquence des tremblements de terre relativement au passage de la lune au méridien, comme je l'ai fait déjà dans ma note du 2 janvier 1854; mais l'état de ma vue ne permet pas aujourd'hui cette nouvelle discussion".

While it is sad to think of the old man being unable to complete the labours of so many years it is, on the other hand, some compensation that it is just this uncompleted aspect of his investigation which is least supported by later evidence; and that he has thus been spared much fruitless labour.

Perrey's closing words are worthy of mention as they clearly indicate both the importance he attached to his work and also its limitations. He says "On a dit que j'attribuais les tremblements de terre à l'action de la lune; on a exagéré ma pensée. Je n'ai pas fait une théorie séismique. Considérant le phenomène complexe, lié intimement a l'activité volcanique et dû, dans son ensemble, à plusiers causes, j'ai seulement en pour but de mettre en évidence l'action prédominante, ou au moins différentielle, de l'une de ces causes. Une théorie rationnelle devra tenir compte des trois lois que j'ai établies relativement à l'influence lunaire sur le tremblement de terre."

The loss to seismology caused by the decline in Perrey's activities was compensated by the budding energies of the greatest English exponent of seismic science - John Milne. After many years of labour in Japan Milne published in 1886 the first edition of his book on earthquakes.[40] In this work he has reviewed Perrey's memoirs, giving the salient results, and pointing out certain anomalies. He showed that Chaplin, at Tokyo had obtained results which did not support Perrey's laws. As, however, Chaplin's results were based on a small number of earthquakes, only 143 in all, this is not surprising. Perrey himself had pointed out that in his five yearly groupings, which on the average contained over 500 earthquakes, anomalies entered into the statistical grouping.

In the same year that Milne's book appeared Knott[R8.] first took up the question of earthquake frequency. He was the first to note in this connection the bearing of the high rigidity of the earth on this problem, and showed that the hypothesis of a fluid earth core could no longer be used to explain earthquake and volcanic phenomena. He does not appear to attach great weight to Perrey's laws, partly because of the small numerical differences on which they are based, and partly because of anomalies such as indicated by Chaplin. Moreover with regard to the short tidal period he says "In all probability the semi-diurnal tidal stresses are too ~~rigid~~ rapid to produce measurabl deformation in the solid earth." It should be remarked, howeve that this view which was later shared by G.H.Darwin, has since been disproved by the experimental researches of Hecker at

Potsdam and Michelson at Chicago and also, in the Southern Hemisphere by Rev. E. Piget S. J. at Cobar (New South Wales).†

About the same time that Miln and Knott became interested in earthquake frequency another great seismologist entered the lists tilting against Perrey's laws. This was Montessus de Ballore who has now for nearly thirty years published ffom time to time short memoirs on this subject. His first paper in 1887 outlines a general plan of correlation between any two kinds if facts and was illustrated by referance to earthquake frequency in relation to the position of the moon. He concluded that there was no evidence of any such relation from an examination of 36,000 earthquake shocks; nut the paper is not convincing as no statistics are given. Some two years later Montessus published more elaborate investigations into the subject. He states that had it not been for semintal reasons Perrey'slaws would have been earlier refuted; and in this memoir attacksthe third law relating to earthquake frequency and the culmination of the moon.It will be recalled that Perrey used two methods of investigation in establishing this law. In the first place he examined the frequency during the lunar day and found two maxima about the times of superior and inferior culmination, and two maxima at the middle times between these epochs. This investigation is based entirely on some 824 shocks at Arequipa. In the second method Perrey enquired into the numbers of earthquakes which occurred when the moon's distance was less and greater than 45° from the meridian. In this case he employed some 2275 earthquakes shocks fsom Southern Italy.

Although Perrey regarded thesecond method as supporting his third law, this is not necessarily the case for the true maxima may have occarred anywhere within a range of 45° and

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† Personal Communication.

not necessarily at culmination.

Montessus in his criticism of this law employed in this paper Perrey's first method of investigation. He rightly assumes that if the law is at all general it should manifest itself in most districts. He employed a large catalogue of some 45,000 earthquakes from 102 different districts. He then divided the lunar day into eight equal parts the middle intervals of the first and fifth of which correspond to the times of superior and inferior culmination, and illustrated graphically his results. The distribution may be read from the graphs and has been quoted by Knott in the following table:-

Eights	I	II	III	IV	V	VI	VII	VIII
Earthquakes	5579	5558	5611	5508	5802	5564	5571	5662

Moreover for 100 of the districts the distribution of the maxima with regard to the particular eights of the lunar day was recorded. It appears that the maximum earthquake frequency occurred

in the first eighth for 14 districts
......second .... 8 "
" third " " 14 "
" fourth " " 11 "
" fifth " " 14 "
" sixth " " 10 "
" seventh " " 14 "
" eighth " " 15 "

If Perrey's law were true there should have been a very great preponderance of the districts having their maxima in the first and fifth periods. Such overwhelming evidence is of course much stronger than that upon which Perrey's law was based an quite refutes the relation claimed for earthquake frequency with the times of superior and inferior culmination.

In 1896 Knott commenced an examination of a possible lunar periodicity in earthquake frequency.[29] He tabulated the earthquakes according to the number of days each had occurred after apogee and after ascending node i.e. according to the anomalistic and nodical lunar months. He then examined the two tables so obtained by the method of harmonic analysis and found that these gave "monthly, fortnightly and weekly periods but the fortnightly period is more marked in the nodical curve than in the anomalistic".

This investigation Knott followed up in greater detail in a paper published early in the following year.[30] The conclusions of this paper very strongly support the two laws of Perrey relating to Perigee and the Syzygies respectively. Knott used as a basis for his work the then recently published earthquake catalogue of Japanese earthquakes prepared by Milne He examined the records both for lunar daily and monthly periodicity, employing in each case the method of harmonic analysis. In the examination for lunar daily periodicity the hourly frequency was tabulated commencing with the time of the Moon's meridian passage. The table of frequency so obtained was prepared for harmonic analysis by taking overlapping means of each successive 5 hours and dividing the sum by the mean of all. The earthquakes were recorded from 15 districts some of which Knott classed together giving 10 groupings in all. Altogether 8331 earthquakes were considered. The harmonic analysis indicated both lunar daily and half lunar daily periods the latter being the more strongly marked. The phase of the periodicity in relation to the time of the moon's meridian passage was different in most groups thus furnishing an argument against Perrey's third law. On the other hand, for the semidiurnal maximum there is a certain amount of regularity in the phase as in four districts the maximum fell within two hours of the half time between the upper and lower meridian passage of the moon; and in the others within two hours of the times of upper and lower meridian passage. Two of the districts, viz. the S.E. corner of Japan and Nagoya are specially important, the former containing about one sixth and the latter nearly one half of the total number of earthquakes recorded. The periodicities in these seem to be more or less complementary and Knott writes, "The curious way in which the comparatively prominent 1st harmonics of these two districts tend to cancel one another, is a warning of the danger of lumping together statistics of different countries or different seismic areas in the search for possible periodicities."

In his investigation of the lunar monthly frequency he point out that there are 5 kinds of months.

1. The anomalistic month (27·545 days) marking the period from perigee to perigee.
2. The tropical month (27·322 days) marking the complete period in declination.
3. The synodic month (29·531 days) from one to the next moon.
4. The sidereal month (27·3228 days) marking a complete cycle with regard to the fixed stars.
5. The nodicalmonth (27·212 days) marking the period from one to the next ascending node.

Since the difference between the tropical and sidereal months is too small to be notable in the period of 8 years over which the earthquake records extend the sidereal month was not considered. In order to prepare the records for harmonic analysis the earthquakes were tabulated in four ways according to the types of months considered. The after shocks of the Mino-Owari earthquake and other obvious after-shocks were omitted so that the total number of earthquakes used for this part of the investigation numbered from 4725 to ~~[illegible]~~ 4741 according to the monthly grouping used. The earthquakes were tabulated according to the number of days reckoned from apogee, from 0°declination, from ascending node and from full moon. The four tables so formed were each prepared by the same process of overlapping means used for the lunar daily frequency, and then subjected to harmonic analysis. The results favour a relation between earthquake frequency and tidal stress as the maximum of the monthly frequency for the anomalistic month is in the vicinity of perigee; and the maximum of the semi-monthly frequency for the synodic month lags one day behind full and new moon.

Knott's results are very important and were summarised by him as follows:-

-"<u>General conclusions</u> - The conclusions are summarised under eight heads

(a) There is evidence that the earthquake frequency in Japan is subject to a periodicity associated with the lunar day.

(b) The lunar half-daily period is particularly in evidenc both by reason of its relative prominence and the regularity with which, in each of the two groups of t several seismic districts, its phase falls in relati the time of meridian passage of the moon.

(c) There is no certain evidence that the loading and unloading due to the flow and ebb of the ocean tides h any effect on seismic frequency.

(d) Hence we must look to the direct tidal stress of the moon, in its daily change as the most probable cause of a range in frequency which does not exceed 6 per cent of the average frequency.

(e) There is distinct evidence, both as regards amplitude and phase, of a fortnightly periodicity associated with the times of conjunction and opposition of the sun and moon.

(f) No definite conclusion can be drawn from the apparent monthly and fortnightly periodicities which seem to be associated with the periodic changes in the moon's distance and declination, for the simple reason that fully as prominent harmonic components exist when the statistics are analysed according to the periodic change in the moon's position relative to the ecliptic, and with this particular period no tidal stresses can be directly associated.

(g) Nevertheless, the value of the phase lends some support to the view that there is a real connection between the change in the moon's distance and earthquake frequency, since the maximum frequency falls near the time of perigee.

(h) These conclusions have, in comparison with previous investigations, a peculiar value, inasmuch as they are based upon accurate statistics of fully 7000 earthquakes occurring within eight ~~hours~~ years in a limited part of the earth's crust, throughout which the seismic conditions may be assumed to be fairly similar from point to point".

These conclusions were challenged by Schuster[87] in the following year. He pointed out that although Knott's investigation suggested the interpretations which he had put upon them the question is after all one of probability. Schuster then calculated the probability of the lunar daily and half-daily periods from Knott's statistics and arrived at the conclusion that ~~of of~~ if the earthquakes had been purely random events there would have been about one chance in four that the lunar ~~day~~ daily period obtained would have occurred and about 2 chances in five for the half-lunar daily period. Hence Schuster concludes that "Until further evidence is brought forward, the lunar day cannot be considered to affect earthquakes".

Schuster also examined Knott's work with regard to the supposed monthly and half-monthly periodicities. He first criticised the results on the ground pointed out by Knott himself that the strongest half-monthly frequency is associate with the period of the nodical month and states that "As there is no conceivable reason why the nodical month should affect earthquakes, the conclusion will reasonably be drawn from this that any period chosen at random would give similar results".

This statement should however not be unreservedly accepted for at the nodes there is a special arrangement of the tidal forces due to the fact that both the tide producing bodies, the sun and moon, are then in the plane of the earth's motion about the sun, and it is not inconceivable that under such circumstances the strains set up may be periodic in character.

Moreover it should be noted that 13 nodical months are nearly the same length as 12 synodic months the former ~~[illegible]~~ containing 353·76 days and the latter 354·37 days. If, therefore, there is also an annual periodicity in earthquake frequency - and this seems accepted by Schuster - it may be that the apparent nodical periodicity of earthquake frequency is due to this relation.

Again as the nodical month nearly coincides with the tropical month, differing only by 12 days in the eight years over which these earthquake records extend, it is not surprising that the periodicity for these two kinds of months should be much the same.

I have examined Knott's statistics with a view of testing the probability with regard to Perrey's laws relating to perigee and the syzygies. It appears that the chances against obtaining the amplitudes indicated for random events is about 19 to 1 in the case of perigee and about 400 to 1 in the case relating to the syzygies.

Schuster admits that the numerical values of the amplitudes appear to favour such relations but ~~the~~ suggests that the high values of the amplitudes may be explained by errors introduced into the calculation of the expectancies due to the tendancy of earthquakes to occur in groups.

It is clearly the case that earthquakes do tend to occur in groups and if the groups were regular, containing the same number of earthquakes per group, this would support Schuster's contention; but the grouping is very irregular and as it cannot be shown that such irregularity would uniformly affect the amplitudes itseems better to accept the figures as they stand. Again the chances that both the laws relating to perigee and the syzygies should be indicated is a series of random earthquakes is very remote, especially when it is considered that the phase also enters into the question. The chances that for random frequencies the maximum of the anomalistic monthly period should fall within 3 days of perige are about 1 in 10 while the chances that the periodic seismic maxima should occur within 1½ days of full and new moon are also only about 1 in 10.

The probability of both the amplitudes and phases favouring a relation with the moon's position is therefore

$$\frac{1}{19} \times \frac{1}{400} \times \frac{1}{10} \times \frac{1}{10}$$ or only 1 in 760,000.

This very high degree of probability very strongly supports the two laws of Perrey relating to perigee and syzygies.

As an example of a limited investigation that of Becke on the earthquakes of Graslitz R. for the month 24th October to 25th November 1897 deserves mention. Becke divided the month into four equal parts grouping them in pairs to cover the syzygies and quadratures. He investigated both the lunar daily and solar daily frequency, arguing that if the earthquakes were affected by tidal strains that similar results should be obtained from both methods of investigation. He plotted ~~fou~~ four curves one pair for the solar and another for the lunar frequency at both the syzygies and quadratures ~~exhibit~~. The solar curves for the syzygies and quadratures exhibit some degree of correspondence but there is little in common between the two lunar curves; nor is there any close correspondence between the solar and lunar curves. Hence Becke concludes that no relation between earthquake frequence and tidal stresses is indicated by his work.

There are however certain features which he has not noted which suggest that, after all, some relation may exist.

It is somewhat remarkable that in the case of three of the four curves a large maximum occurs two hours before, and in the fourth four hours before the lower culminations ~~f~~ of the sun and moon. Again, in each of the four cases there is a pronounced minimum at the times of the lower culminations and in three out of four cases another pronounced minimum at the times of the upper culminations of the sun and moon.

The coincidence of the minima with these meridian passage of the sun and moon is, of course, strongly opposed to Perrey's law relating to the meridian passage of the moon; but it is not necessarily opposed to another conception of the effect of the tidal stresses. The degree of correspondence indicated above appears to me to suggest a rather strong probability of some relation between the earthquake frequency and tidal stresses.

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Oldham has criticised Becke's paper and is not prepared to admit his conclusions. He says "Apart from this, there seems to be a more serious flaw in the argument. Herr Becke appears to have expected that the curve of frequency by lunar time should show maxima about three hours on either side of the time of the lower ~~sun~~ meridian passage of the moon. This again depends on the assumption, tacitly made by every calculator with whose work I am acquainted, that the frequency may be expected to be a function of the hour angle".

Oldham then took up the question of distribution of the tidal forces for a given position of the attracting body - sun or moon. He pointed out that the maximum upward force is exerted at opposite extremities of the earth's diameter with points towards the attracting body; that the maximum dowward force occurs along a great circle perpendicular to this diameter; and that the maximu horizontal force occurs along two small circles whose planes are also perpendicular to the said earth diameter, and lie at 45° from the great circle of maximum downward force. He then applied these criteria to Becke's statistics and concluded that in general the observations do support a relation between the earthquake frequency and the tidal stresses.

In the following year Oldham undertook an investigation on the above lines for the Assam earthquakes[65]. He prefaces his work by the following remark "Ever since earthquakes were first studied there have been repeated and persistent attempts to trace the action of the sun, the moon and the planets in producing them, or at least in influencing their relative frequency". He then briefly reviewed the work of Perrey, Mallet Casani, Montessus de Ballore and Davison, and pointed out that the question was still an open one . The after-shocks of the Assam earthquake he considered specially adapted for use in such an investigation, his views being that "if there was any external cause at work it should be especially easy to trace at a time when, and in a region where, the ~~earthk~~ earth's crust was evidently in an extremely unstable condition".

Another feature in favour of these records was that the shocks were instrumentally observed. His method of attacking the problem was to ascertain when the circles of maximum horizontal and vertical force passed through the earthquake area. In this paper he stated that "the horizontal force attains its maximum along two circles distant about 54°44' from the zenith and nadir respectively". This is, of course, incorrect the distances being 45° instead of 54°44'. The latter angle represents the distance of the small ~~angle~~ circle along which the forces are wholly horizontal.

He pointed out that in latitudes greater than 26°N and S neither the sun nor moon can ever be in the zenith and hence cannot exert their upward maximum force. The circles of maximum downward and maximum horizontal force however can operate in much higher latitudes and will intersect any given meridian at hours equally spaced from the time of the meridian passage of the attracting body. The actual hour, however, will be a function of the body's declination. Hence in searc for any such relation it is necessary to group the earth according to their place of origin, and to have regard to declination of the attracting body.

The Assam earthquakes all lie in about latitude 26°N. Oldham then calculated, for various declinations, the times o. the passage of the circles of maximum downward and horizontal force across the meridian. He summarised his results in the following table:-

Table showing times of passage of circles of maximum horizontal and vertical tide producing force calculated for latitude 26°N.

Declination	Horizontal force Direct	Vertical force Downward.	Horizontal force Indirect.
	Time	Time	Time
	12 hours ±	0 hours ±	0 hours ±
26° N	4 hrs. 15 m.	4 h. 38 m.	—
9° N	3 " 31 "	5 " 31 "	2 h. 14 m.
0°	2 " 59 "	6 " 0 "	2 " 59 "
9° S	2 " 14 "	6 " 26 "	3 " 31 "
26° S	—	7 " 22 "	4 " 15 "

From the above table it would appear that "the effect of the horizontal force must be looked for between 3½ and 4 hours before and after midday, and within two hours an each side of midnight; in the second group the effect is to be looked for betwean ¾ and 3½ hours on either side of midnight and midday; while in the third the condition will be the same as in the first, with the substitution of midnight and midday".

Oldham also recognised that the effect on the production in the amount, than to the actual amount of the force exerted and he also suggested that some lag may occur thus delaying the time of earthquake occurrence.

Another table was also prepared by Oldham showing the times when the effect of the maximum rate of change of the vertical force would be experienced for a place in latitude 26°N. As before he has considered several declinations for the attracting body. His table is as follows:-

"Times of passage of circles of maximum rate of change of the tide-producing forces calculated for Lat. 26° N.

Declination	Direct	Indirect.
	12 hours ±	0 hours ±
26° N	3 h. 22m.	—
9° N	2 " 56"	1 h. 56 m.
0°	2 " 33 "	2 " 33 "
9° S	1 " 56 "	2 " 56 "
26° S	—	3 " 22 "

In the above table the circles of maximum rate of change are taken at 45° from the attracting body.

After this theoretical discussion Oldham proceeded to an examination of the records. These he tabulated for each hour of the day. He found that the graphical representation of the hourly frequency indicated two maxima one from 10 to 11 p.m. and the other from 6 to 7 a.m. For these he has not been able to offer an explanation. But superimposed on this frequency there are other periodicities. When the frequencies were grouped according to the sun's declination there was found to be a fairly close correspondence in the time of the observed and calculated maxima; but as the amplitudes were small it was found desirable to adoptsome method of grouping to cut out diurnal variations which were not connected with tidal stresses. This was effected by grouping the earthquakes so that ~~of~~ ~~at~~ those of noon were taken with those of midnight and those ~~at~~ of each successive hour of the day with those of the corresponding hour of the night. This grouping showed "two very marked maxima, in the distribution of the shocks, one during the fifth hour after, the other during the second hour before, the meridian passage, and these maxima may be taken as being grouped around 4½ hours and 10½ hours of the morning and afternoon. That is to say they both follow by 1½ hours the epoch corresponding to three hours before abd after the ~~mede~~ meridian passage, a time which corresponds more closely to the passage of the maximum rate of change of tidal force, than to that of the circle of maximum Horizontal stress". Oldham recognised that ~~of~~ if the solar stress is really effective that a still more pronounced effect should be shown in connection with the lunar stress. He found, however, that the series of observations was not long enough to eliminate diurnal irregularities and had therefore to abandon this test.

Another important investigation which Oldham has recently taken up was foreshadowed in this paper and will be discussed later. This related to the relation to the seasonal variation in the ratio of the day and night shocks.

Oldham's conclusions may be quoted as follows:-

"It appears then that the tidal stresses have a distinct effect in determining the time of origin of earthquakes, though their influence is small in proportion to other causes, but at the same time it is necessary to enter a caution that, though the facts in this case seem to support the conclusion, they are far from proving it"................................ ....These conclusions must be taken as purely provisions and require verification from a more extended series of observations".

This paper of Oldham's, was by far the most important contribution to the subject of diurnal earthquake frequency in relation to tidal stresses which had appeared up to the date of its publication. It marks not only a distinct break from the line of investigation undertaken by Perrey but offers a rational basis for investigation on the later conception of a rigid earth.

The same subject was discussed in further detail by Oldham in the following year in a memoir of the Geological Survey of India.[66] In this paper he applied the same method of investigation but stressed more fully the significance of the ratio of the day to the night shocks for the sun's north and south declinations. He pointed out that for north latitudes, when the sun is in north declination, both the range in the amount, and the ~~range~~ rate of change in the tidal stress is greater during the day than during the night; and that the contrary relation obtains when the sun is in south declination. This distribution of the tidal forces would tend to increase the ratio of the day and night shocks in summer and to decrease them in winter. An examination of the records shows that this relation holds good. If this relation holds good for the sun it should of course be also manifested for the moon's motion in declination. Oldham consequently examined the records of the Shillong seismograph with this in view, and found that the results indicated the same relation but in a lesser degree. The difference in degree he considered to be due to the number of shocks being insufficient to eliminate the solar effect. His final conclusion reads as follows:-

"From the foregoing considerations it seems probable that the tide-producing stresses are not without effect in determining the time of origin of earthquakes. So far as the Assam records go, it appears that the horizontal tide producing force is more effective than the vertical one, and that any effect produced is due more to a rapid rate of change in amount and direction of the forces that to their actual magnitude. The records obtained in one locality only, especially if limited to a few years in duration, are not, however, sufficient to establish this conclusion as proved - perhaps even insufficien to establish ~~it~~ it as probable."

In the above investigation Oldham assumes that the circles of maximum horizontal force are at 54°14'14" from the attracting body, whereas the true distance is, of course, 45°. This difference ~~is~~ in 9° does not, however, invalidate the argument presented in his memoir.

In view of the foregoing ~~review~~ it is rather surprising to find Dutton[17] in the following year(1904) making the following statement:-

"Since Perrey's announcements the subject has been followed up by several investigators with a rapidly increasing amount of data. The number of recorded earthquakes which have been catalogued is now in the neighbourhood of 140,000, and the records of the newly acquired ones have a much greater scientific value than the old ones of Perrey's time. The results has been that as the number and scientific accuracy of the data have increased, the preponderances which Perrey found at syzygies, at perigee and at lunar culmination have dwindled away to almost nothing, and in many localities have been quite reversed. Moreover, the theory of a molten interior of the earth has in England, America and Italy been definitely abandoned in favour of an earth possessing a high degree of effective rigidity, and the same change of opinion is rapidly gaining ground in Germany. In France the cultivators of earth physics seem to be shaken in their belief in a liquid interior though they are still very conservative in their views. With its fundamental postulate fast vanishing, with support derived from statistical comparisons dissolved away, little remains of the tidal theory of earthquake causation".

While it is true that the conception of a molten interior of the earth had been abandoned and that Perrey's law with ~~res~~ regard to the meridian lunar passage had been refuted by further investigation, it was not correct that Perrey's laws relating to perigee and the syzygies had been disproved.

Dutton seems to have been over influenced in his statement by the fact that Perrey sought to interpret his laws on the postulate of a molten interior of the earth; and the phrase "earthquake causation" suggests that he has misunderstood Perrey's conception of the relation between tidal forces and earthquake frequency.

Two important papers dealing with the lunar periodicity of earthquakes appeared shortly after the publication of Dutton's book. The first of these was that of Omori who investigated the question for the lunar day;[43] and the second by Imamura discussed earthquake ~~ea~~ frequency in relation to the synodic monthly period.[2A]

Omori first briefly reviewed the work of Montessus de Ballore and Knott and then proceeded to examine certain Japanese earthquake records. He pointed out that the after-shocks of ~~gr~~ great earthquakes representing rapid readjustment to equilibrium following the relief of great stresses are particularly suitable for such an investigation. The records examined ~~compose~~ comprise the after-shocks of the Mino-Owari earthquake recorded at Nagoya and of the Hokkaido earthquake felt at Nemuro.

For the sake of comparison he also examined the records of the ordinary shocks felt at Tokyo. At all three centres the shock were instrumentally observed. He divided the lunar day into 24 lunar hours commencing with the moon's upper culmination for Tokyo.

The examination of the earthquakes at Nagoya comprised 1270 shocks extending over eight years (1891-1899). The frequency was plotted as a curve in the usual way and exhibited a very irregular distribution ~~of the frequency~~. When however 3 hourly means were taken the resulting curve became much more regular and showed thwo prominent maxima and minima The maxima occurred about 3½ and 16 hours after culmination; and the minima about 10½ and 21½ hours after culmination.

The records of the earthquakes observed at Nemuro comprised 799 shocks extending over five years (1894-1899). Here again the hourly distribution is very irregular but the 3 hourly measn provide a smooth curve indicating two maxima and two minima. The maxima occur at about 4½ hours and 14 hours after culmination; and the minima at about 8 and 21½ hours after culmination.

The earthquakes of Tokyo comprise a series of 1462 shocks extending over eleven years (1888-1899). The three hourly distribution also indicates for these two maxima and minima. The maxima occur from the 0 to 3rd hours and from the 12th to 15th hours; and the minima from the 9th to 12th Hours and from the 21st tp 24th hours.

Omori concludes that "the occurrence of the two seismic maxima, at a mean interval of 12 hours, and approximately at, or a little after, the meridian passages of the moon, may probably be due to the stress in the earth's crust caused by the direct attraction of the moon."

Omori also considered the indirect affect of the lunar attraction in the loading and unloading of the coastal area by the ocean tides, and concluded that this probably had some effect in determining earthquake frequency? He also studied the barometric variations which also appear to have contribut-ed a factor towards the frequency.

In conclusion Omori remarks "It thus seems that a considerable proportion of earthquakes, from some 50 to 80%, are caused, or accelerated to occur, by the agencies of the atmospheric pressure and the moon's influence or tidal stress

It will be noticed that the times of occurrence of the maxima noted are not closely related to the lunar culmination and so furnish a still further statistical negation of Perrey's law relating to the meridian passage of the moon.

Omori's paper has been discussed by Knott[31] who took exception to the method of 3 hourly grouping which he employed. Knott pointed out that the only satisfactory method, apart from an harmonic analysis by Fourier series, is to take "overlapping sums over suitable intervals". He reexamined Omori's data by this method and arrived at somewhat different results. There is, nevertheless, some measure of agreement in the times of the half lunar daily maxima which according to Omori's results occur from 3 to 4 hours, from 2 to 5 hours, and from 0 to 3 hours after the culminations; and according tp Knott at about 3½ hours 2½ hours and 3½ hours after culminations for Nagoya, Nemuro and Tokyo respectively. In the case of Nagoya and Nemuro the amplitu calculated by Knott considerably exceed the expectancy; but is less than the expectancy for those of Tokyo.

Altogether the evidence points towards a relation between the tidal forces and the earthquake frequency, but is not conclusi

Side by side with Omori's paper appeared the work of Imamura in the same journal.[illegible] The latter undertook an investigation of of Perrey's law relating to the syzygies and quadratures for the earthquakes of Japan. At the outset Imamura stressed the importance of the district grouping of earthquake phenomena. He then briefly discussed the recent work of Omori, Knott and Oldham and indicated the nature of his own conclusions. His method of analysis is based on the fact that a complete synodic month is equal to 29·53 solar days. He has therefore taken the numbers of earthquakes for the first 29 <u>solar</u> days of a month as representing those of lunar days and has increase the number occurring on the 30th solar day in the ratio of 100 to 53 in order to make the value for this day commensurate with that of the other days. This method of analysis is not, of coursem,strictly correct but is sufficiently accurate for the purpose of Imamura's investigation.

The first analysis gave the synodic-daily distribution of 1871 earthquakes recorded in Japan as a whole from 416 to 1860 A.D. The earthquakes were distinguished according to their intensity and in addition to the actual number of earthquakes a weighted sum was calculated in which the values one, two and three were assigned to the small, strong and destructive shocks respectively. The <u>weighted</u> sums for each synodic day were then plotted graphically according to a method previously employed by Omori which practically amounts to the use of overlapping means for any two consecutive days. As stated by Imamura "The curves indicate two distinct pairs of maxima on the 1st and 14t and the 7th and 24th............As regards the causes of the tw pairs of maxima, the first is probably due to the combined tidal effort of the sun and moon, and the second to the resultant of tidal and barometric pressures".

The second analysis gave the corresponding data for the earthquakes recorded at Kyoto for the same interval of time. The results agreed closely with those arrived at for Japan as a whole.

Imamura next grouped the recent earthquakes of Japan from 1873 to 1902 according to the stations at which they were recorded. The great bulk of these observations were instrumentally recorded.

He employed altogether 22 distinct district groupings. In orde to eliminate the influence of the enormous number of shocks which usually follow immediately after a great earthquake he has omitted from the records all earthquake shocks which occurred during the period of one month following such a large earthquake

This adjustment still leaves him with a total of 13,678 ~~shoc~~ shocks, the greatest number occurring in any one of the 22 districts being those of Tokyo which number 2464.

He next analysed the data for each district using the recorded numbers only and employing the <u>weighted</u> sums as in the first two investigations. Tables showing the synodic-daily distribution for each district are given and these are each illustrated graphically by Omori's method. The results of this investigation are discussed by Imamura as follows:-

"Drawing the frequency curves...... we notice firstly, that in most cases there occur two distinct pairs of maxima, one about the times of conjunction and opposition of the sun and moon, and the other at intermediate times; and secondly that the first pair of maxima is pronounced at certain stations , and the second pair at some other stations, while at the remaining stations the two pairs develop equally well. The relation expressed in the second statement may possibly be due to the fact that the observed earthquakes were mostly of inland origin, or of submarine, or of both origins. With this view, I have grouped the different stations into three set different stations into three sets (A),(B) and (C), according as their observations related mostly to inland earthquakes, both inland and submarine, and submarine respectively."

The table given by Imamura is quoted as follows:-

Group	Meteorological Stations	Day of Maximum Seismic Number			
A	Nagoya	2	18	6	26
	Fukuoka	30	18	4	23
	Niigata	30	18	11	23
	Tokyo	30	18	7	23
	Kagoshima	29	~~18~~ 14	4	—
B	Gifu	29	14	–	25
	Osaka	28	12	–	—
	Nagoya	4	15	11	21,25
	Wakayama	28	14	4	20
	Aomori	30	15"	7	20
	Oita	2	18	9	24
	Hikone	29	14	8	—
C	Maebashi	30	15	7	~~25~~ 24
	Mito	30	14	6	26
	Hakodate	28	—	6	21
	Nemuro	—	18	9	26
	Yamagata	1	15	7	23
	Fukushima	2	13	7	24
	Ishinomaki	1	16	10	25
	Utsunomiya	29	12	6	24
	Akita	30	17	6	23
	Miyako	30	17	8	24
	Average	30	15	7	23

The numbers in the above table represent the days of the synodic month commencing with new moon. The numbers underlined represent the days on which the more pronounced of the four maxima occurred.

Imamura then discussed the tabulated results in detail. He pointed out that the two maxima at the times of conjunction and opposition might be attributed to the tidal stresses of the sun and moon. With regard to the other pair of maxima occurring at the 7th and 23rd days he offers an explanation in terms of barometric pressure and oceanic tidal load on the coastal areas. His argument is reproduced as follows:-

"According to Dr.Omori, the barometric pressure has marked influence upon the seismic frequency in Japan; the curves showing the time variations of the two quantities being similar to each other. Now the barometric pressure which reaches in its diurnal variation its maximum at 9 h. and 22 h., will interfere with the tidal force helping or cancellin the latter according as high water or low water occurs at these times. In Tokyo, the synodic days sorresponding to the former case are the 7th and 22nd, the days corresponding to the latter are the 12th and 27th. Allowing an hour or two for time difference of occurrence of maximum tidal and barometric pressures at other localities, the days 6th-9th and 21st-24th are ones in which the resultant of the two influences becomes most effective. Thus we may look for the maximum seismic numbers about the 7th and 22nd which correspond roughly to the actual maxima in question".

The results of Imamura's investigation are very ~~strongly~~ striking and appear to support the view that the corporeal tides, the oceanic tides and the barometric pressure all contribute factors influencing earthquake frequency; and that of these the influence of the corporeal tides is the most prominent.

Imamura's conclusions have, however, been challenged by Knott who wrote as follows:-[31]

"The method of analysis employed by Imamura is identical with that used by Omori, and is purely graphical ....The varieties of graph are nearly as numerous as the places for which they are drawn. In all cases there are from ten to fifteen crests and hollows of varying amplitudes but it cannot be said that there is a tendency for the crest of greatest amplitude to occur at the same time for even the majority of the stations.................................... Imamura considers that he finds evidence of the existence of four principal maxima throughout the lunar month. Two of these he connects with the times of opposition and conjunction of the sun and moon; and the other two he connects in a very ingenious, but in my opinion, very artificial and forced manner with the concurrence of the times of daily barometric maximum and ordinary high tide. It is obvious that with crests occurring on the average every two or three days it is not difficult to find four such coming within a day or two of particular dates; and having regard to the meagreness of the statistics in most instances, and the doubtful accuracy of the method of smoothing, I question if any confidence can be placed on the results indicated".

Although there is a great deal of truth in Knott's cri Imamura's results should not be altogether set aside · seems to be too much uniformity in his results to be acc -ed for by his somewhat doubtful methods alone; but the further examination of his data appears to be desirable. Knott has also reviewed Oldham's work on the Assam earthquake and has regrouped the data and calculated the amplitudes, phases and expectancies for the daily, half-daily and quarter daily lunar periodicities; and also the same elements for the solar periodicity. The results of these calculations Knott has tabulated somewhat as follows:-

Lunar Day Periodicities.

Declination	No. of Eqkes.	Day		Half-day		Quarter Day		Expectancy
		Phase	Ampl.	Phase	Ampl.	Phase	Ampl.	
9° N ±	510	18 h.	·099	4 h.	·099	3·5 h.	·099	·078
9°N to 9°S	333	18 h.	·147	8 h.	·308	5·5 h.	·099	·097
9°S ±	431	24 h.	·202	1 h.	·128	0·5 h.	·113	·085
All	1274	20 h.	·062	8 h.	·05	1·5 h.	·04	·05

Solar Day Periodicities

Declination	No. of Eqkes.	Day		Half-day		Quarter-day		Expectancy
		Phase	Ampl.	Phase	Ampl.	Phase	Ampl.	
9° N ±	436	17 h.	·137	9 h.	·152	4 h.	·137	·083
9°N to 9°S	358	18·5 h.	·132	6 h.	·132	4·5 h.	·255	·094
9° S ±	480	1 h.	·335	5 h.	·118	5·5 h.	·092	·087
All	1274	1 h.	·177	9 h.	·076	4·5 h.	·144	·05

From the above tables Knott drew the following conclusion:-

"Although it must be admitted that the results so far are negative, nevertheless the point of view which led Oldham to discriminate between cases according to the declination is one deserving of more attention. It emphasises the possibility already referred to in other connections, that in the indiscriminate grouping according to probable periodicities there may be a balancing of effects, so that the periodic change looked for may escape notice".

The investigation may however be carried a step further with very interesting results. It does not appear to have occurred to Knott to investigate the probability of obtaining such a series of results as a whole. The following discussion with regard to the solar and lunar daily periodicities will illustrate my meaning.

If earthquake frequency is affected by tidal stresses then for a given range of declination the phase of the maximum frequency should fall at the same period for both the solar and lunar days. An examination of the above tables shows that for the whole daily periodicities there is a striking agreement in this respect.

In the case of declinations greater than 9°N the phase for the lunar day is at the 18th hour and for the solar day at the 17th hour; for delinations between 9°N and 9°S it is at the 18th hour for the moon and at the 18½ hours for the sun;; and for declinations greater than 9°S at 24 hours for the moon and an hour later (1 hour) for the sun. In each case therefore the phase agrees to one hour for the sun and moon. Now the probability that the phase for the sun and moon should agree to witin one hour in the 24 is $\frac{1}{8}$. This will be seen from the fact that ~~of~~ if the lunar phase is fixed the solar phase may fulfil the conditions by falling in the Hour before the hour of ~~ot~~ or the hour following the lunar phase; while the total range of hours is 24 the total range of hours is 24.

The probability that in the phases should agree to an in each of the three groups according to declination is -fore $\frac{1}{8} \times \frac{1}{8} \times \frac{1}{8}$

Again in each of the six cases considered (three each i the sun and moon) the amplitude exceeds the expectancy. The probability of this is clearly $(\frac{1}{2})^6$. Hence the probability that fpr random events the phases and amplitudes should have occurred as found by Knott is not greater than $\frac{1}{8^3} \times \frac{1}{2^6} = \frac{1}{32{,}768}$.

But the probability is actually a far smaller quantity, for the probability of the amplitudes exceeding the expectancies by the given amounts is much greater than ½ for each case.

I have calculated the actual probabilities that the amplitudes should exceed the expectancies for the six cases considered and find them to be as follows:-.

Probabilities for lunar and solar daily periodicities.

Declinations	No. of Eqkes.	Probabilities for lunar day	solar day.
9° N ½	510	·126	·10
9°N to 9°S	333	$\cdot 48 \times 10^{-1}$	·19
9°S ½	431	$\cdot 90 \times 10^{-2}$	$\cdot 17 \times 10^{-6}$

The total probability for the amplitudes only is therefore the product of each of the probabilities given in the above table and = $\cdot 397 \times 10^{-12}$

When the probability for the coincidence of the phase is also taken into account the total probability becomes $\cdot 776 \times 10^{-15}$ or one in 129×10^{13}

Thus the probability that the earthquake frequency considered could exhibit the lunar and solar daily periodicities indicated with an additional agreement in phase for the s and lunar terms is incredibly small; and is sufficient to establish beyond doubt a strong relation between earthquake frequency and the tidal forces of the sun and moon.

Again ~~of~~ if the half daily periodicities he examined in the same way it will be noticed that although the phases of the periods do not agree for the sun and moon the amplitudes in all cases exceed the expectancies, and the probability that this should be the case for the values given is only $.277 \times 10^{-7}$ or one in 44×10^{6}. Hence the semi-daily period is also established beyond reasonable doubt.

In 1913 Montessus de Ballore again took up the question of the validity of Perrey's law with regard to the syzygies[59] For this purpose he made use of megaseisms only taking the period from 1792 to 1899. This period he divided into two parts from 1792 to 1849 and from 1850 to 1899. He adopted a twofold method of investigation. In the first he subdivided the lunar month into 28 equal intervals, and in the second into 12 intervals. He tabulated the frequencies for each method but has not so far published these results, which, he states are being reserved for a special memoir. The number of shocks made use of is 2155, of which 1567 occur in the later period from 1850 to 1899. His plan of investigation was to determine in which of the intervals the absolute maximum and minimum of the earthquake frequency occurred and to compare this interval with the times of each lunar quarter. He states his results in the following table:-

Number of Megaseismes.

Period of Time	Total	Lunation divided into 28 intervals.			12 intervals		
		Max.	Min.	R.	Max.	Min.	R
1792-1849	588	21st	20th	2·72	7th	12th	2·39
1850-1899	1567	16th	4th	2·74	7th	10th	3·38
1792-1899	2155	16th	4th	2·60	7th	2nd	2·85

The figures in the columns for the maximum and minimum are the intervals in which the maximum and minimum number of earthquakes were recorded. The times of new moon, first quarter, full moon and last quarter correspond to the 4th, 11th, 18th and 25th intervals of the first method and to the 2nd, 5th, 8th and 11th intervals in the second grouping. It will be seen that in the 28 intervals grouping the intervals have little or no relation to the phases of the moon. In the case of the 12 interval grouping, however it will be seen that for each of the subdivisions the maximum occurs within one interval of full moon and the minimum within an interval of the last quarter. The quantity R represents the percentage difference between the maximum and minimum frequency. Montessus also assembled his data by giving the weighted values 1, 2 and 3 to the earthquakes according to their intensities. This does not appear to be a method adapted to the problem in hand, and in any case the results which he obtained are similar to those which appear in the table quoted above.

It is difficult to see how from this discussion Montessus arrived at the conclusion that "Il semble donc bien que les mégaséismes ne présentent aucune relation avec les phases de la lune."

The publication of the details promised by Montessus may perhaps make the results of this investigation more clear.

Taber in his investigation of the Charleston earthquakes[91] also enquired into the question of lunar periodicity. He plotted a curve of the earthquake frequency in relation to the times of perigee and apogee; and for the syzygies and quadratures. He also analysed the observations for monthly and semi-monthly periodicities by the methods employed by Knott. He found an excess about 2 to 3 days after perigee and a minimum at apogee but considered that the ratio of the amplitudes to the expectancies were too small to establish such a relation /

Quite recently Oldham has again taken up the ~~same~~ study of earthquake frequency and has published two papers on the subject.[67, 68] In the first of these he has tabulated the ratio of the day shocks to night shocks for Italy, Japan and for the aftershocks of the Assam earthquakes. In all three cases this ratio increases in summer and diminishes in winter. This he explained in his earlier memoirs which have already been discussed in this paper. The investigation he has now however carried a step further by calculating the tidal stresses for each two-hourly period; and has found that there is a close relation with the variation in the vertical tidal stress in th case of the Italian records. The earthquake frequency increase with increase in the ~~tidal~~ total downward tidal stress. In the case of the after-shocks of the Mino-Owari earthquakes the opposite relation appears to hold, as the earthquakes frequency increased with a decrease in the total downward tidal stress.

In his second paper[68.] Oldham has investigated the same question in more detail employing the records of 9066 earthquakes recorded in Italy during the period 1891-1910; and also

8318 earthquakes recorded in Japan betwech 1885 and 1892 These records showed the same seasonal relation for the ratio of the day to night shocks as those previously considered

There can be little doubt that Oldham's results strongly support the relation between tidal stresses and earthquake frequency.

It is clear from this general review on earthquake frequency that some of the most eminent seismologists have little faith in any relation between earthquake frequency and ~~tidal~~ tidal stresses in the lithosphere. Some others are disposed to admit such a relation as probable but there are few who consider the effect to be an important one. Nevertheless the analysis of the various contributions to this subject, particularly of the work of Davison, Knott, Omori and Oldham is, so it seems to me, ~~and~~ sufficient to establish such a relation beyond all reasonable doubt; and at the same time to point to the relation being one of great importance.

The discussion which follows in part II of this paper demonstrates that the relation is not so simple as has commonly been supposed and that it may be strongly marked where least suspected from the older methods of investigating the problem.

Other Periodicities and Earthquake Frequency.

In addition to the periodicities already discussed in this paper there are others which have been suggested from time to time. It is proposed in this section to deal with these somewhat miscellaneous discussions on earthquake frequency.

Perhaps the most important of these periodicities is that which is associated with the 33 years interval; or with some multiple or sub-multiple of that time. 39.

Milne in his "Notes on the Great Earthquakes of Japan" pointed out that the distribution of these shocks indicated the following periodicities:-

In the interval from 666 A.D. to 933 A.D. there appears to be a recurrence of maximum earthquake frequency at intervals of $33\frac{1}{3}$ years.

In the period from 933-1460 A.D. the intervals were generaly 66 years apart, only a few being of 33 years. From 1460-1800 A.D. the intervals were 133 years, 100 years, a few $66\frac{2}{3}$ years, and the rest $33\frac{1}{3}$ years apart.

Naumann has pointed out that the Japanese records indicate a marked cycle of 68 years, and again has noted that there is an approximate coincidence between many of the disturbances and the meteoric showers which occur at intervals of 33 years.

The correlation of earthquake frequency with Bruckner cycles amounts to much the same thing as the search for a 33 year per -iodicity so that whatever evidence supports ~~one~~ one of these periods is also favourable to the other ~~of~~ if the range be taken over a century or two.

Again it has been shown that there is some evidence suggesting a relation between sunspot activity and earthquake frequency and this involves a periodicity of 11·1 years which is, of course, a sub-multiple of the 33$\frac{1}{3}$ year period.

Schuster has analysed the data relating to sunspot activity and has found evidence of other periods[5a] - particularly one of 4·8 years and another of 8·4 years; in addition he recognised one of 11·125 years. Chree states[5a] that "There has been at least one 33 year period during which the mean value of the sun-spot frequency has been exceptionally low".

It has already been mentioned that Delauney[15] believed that he had detected an 11 year period in earthquake frequency corresponding to the periodic time of Jupiter in its orbit.

Montessus de Ballore has on the other hand investigated both sunspot activity and Bruckner cycles[58] in relation to earth-quake frequency and has concluded that there is no evidence of any connection between these phenomena.

Nevertheless the evidence discussed above is not to be lightly set aside and a further investigation into the 33$\frac{1}{3}$ year period with its possible multiples and sub-multiples seems desirable.

Omori has investigated the earthquake frequency at Kyoto[70] and concluded that for the 9th century this exhibited "more or less definitely a period of 6$\frac{1}{2}$ years". The analysis of his results, however, shows that the phrase "more or less" covers a rather wide range in variation. The following times of the maxima and the intervals between them were read from Omori's frequency curve:-

Date of Maximum Earthquake Frequency.	Period elapsed between consecutive maxima.
805·3 A.D.	
811·8	6·5
818·3	6·5
827·8	9·5
832·0	4·2
837·0	5·0
842·0	5·0
851·5	9·5
855·8	4·3
862·0	6·2
867·3	5·3
872·8	5·5
881·0	8·2
886·4	5·4

In order to ascertain the most probable value of the periodicity I have employed the method of least squares, and found for the trial periods of 3½, 4½, 5, 5½ and 6½ years the sums of the squares of the errors to be 18·6, 14·8, 11·0, 18·2 and 36·3 respectively. This method is of course not strictly applicable in this case where varying periods are used as it tends to exaggerate the significance of the smaller periods. The fact that the sums of the errors for the 3½ and 4½ year periods exceeds that for the 5 year period is therefore all the more important, and points to the most probable periodicity as being about, or a little greater than, 5 years. In this case the intervals of 8·2 and 9·5 years might be regarded as somewhat anomalous double periods.

Omori has also suggested a periodicity of 13½ years for t. great earthquakes of Japan dating from 1325 A.D. to 1898 A. The successive intervals between the great earthquakes or groups of earthquakes for the period are, commencing at 1325 A.D. as follows:- 21, 11, 14, 13, 13, 7, 15, 19, 24, 10, 20, 16, 13, 7, 17, 14, 15, 8, 13, 15, 17, 16, 17, 12, 8, 18, 14, 12, 23, 15, 14, 12, 10, 11, 8, 11, 11, 14, 16 and 23 years Omori has taken the mean value of 13½ years as representing the most probable periodicity. I have applied the same test of the sum of the least squares and obtained for periods of 10, 11, 12 and 13½ years the sums of the squares of the error 381, 351, 381 and 467 respectively. This clearly indicates that the most probable periodicity is about or a little more than 11 years and not 13½ years as suggested by Omori.

Although perhaps no great weight can be attached to the 5 and 11 year periodicities indicated above it was thought advisable to state these results for what they may be worth- particularly as Omori's periods of ~~1½~~ 6½ and 13½ years have been quoted as being well founded.

Indeed it seems that the authors who have cited these periodicities hace attached more weight to them than Omori himself appears to have done.

Omori has also found evidence of periodicities having periods of 4½, 9, 12 and 33 days, and of 3 months. These were indicated by the after-shocks of the Kumamoto, Mino-Owari and Kagoshima earthquakes. 69

The Kumamoto earthquake gave periodicities of 4·6, 12 and 33 days and of 3 months. The Mino-Owari earthquake records at Gifu indicated periods of 4½, 12·3 and 33 days.

The Kagoshima after-shocks showed periods of 4·4, 12 and 33 days.

Some thirteen years later, ~~1~~ in 1908, Omori undertook a meteorological study on long period variations in the atmospheric pressure in Japan[77] and found that there was evidence of periodicities having lengths of 4·6, 8·7 and 33 days and also 3 months.

At the same time he found that the after-shocks of the Taito earthquake (Formosa) gave a periodicity of 4·4 days.

Omori therefore concludes that these periodicities are real and are to be correlated with the corresponding variations in atmospheric pressure.

Another periodicity which claims attention is the 452 day cycle suggested by Turner[93.] from his examination of the megaseisms of the period 1350-1889. This period is particularly interesting because its length approximates to that of the Chandler period of precessional mutation, which has a length of 427 days.

Milne who had previously indicated a periodicity of 443 days[45a] for the intervals of rest between the maximum periods of earthquake activity subsequently pointed out[45b] that the records about November 20th, 1910 verified his expectation for that year.

A similar investigation from a different point of view appears to be the correlation of earthquake frequency with the changes in the movement of the earth's axis of rotation.

Any change in the position of the poles causes a corresponding variation in latitude, and it is from such latitude variations that the polar wandering is determined.

Milne in 1893 was the first to point out a relation

42.

between the motion of the pole and earthquake frequency. ~~He subsequently examined the me~~ He drew attention to the fact that the time of the maximum increase in latitude at Berlin corresponded with the maximum of earthquake frequency for Japan. He subsequently examined the movement of the pole for the years 1895 to 1898 inclusive and concluded that megaseismic activity reached its maximum with the maximum polar displacements.

Cacani followed up Milne's investigation for the period 1899 to 1902.⁵ Milne's and Cacani's results have been tabulated by Omori 42 in the following table:-

Year	Total latitude variation	Number of large earthquakes.
1895	0·53"	9
1896	0·91"	18
1897	1·07"	44 or 47
1898	1·03"	30
1899	0·72"	27
1900	0·32"	17
1901	0·53"	22
1902	0·97"	29

In 1903 Milne investigated the question for the period 1892 to 1899. 42a. He divided each year into ten equal parts of 36·5 days and tabulated the number of world shaking earthquakes for each of these periods. He then compared the earthquake frequency for the intervals during which there was a marked deflection ~~displacement~~ in the polar ~~maximum~~ movement with that of the intervals immediately preceding and following the deflection periods. He found that the total numbers of earthquakes before, during and after the deflection periods were respectively 117, 200 and 153.

Milne has interpreted these results as follows:- "One inference from this investigation is not that the molar displacements accompanying large earthquakes result in polar displacements, but rather that changes in direction of these latter movements, particularly when the rate of change has been rapid, have had an influence upon earthquake frequency".

Milne brought this investigation up to date in 1906. 42b. He showed that out of a total of 23 deflection periods there are 18 cases in which the maximum earthquake frequency coincides with a deflection period. The total number of earthquakes occurring before, during, and after comparable deflection periods were found to be 167,287 and 217 respectively.

He also indicated a new method of analysing the data by expressing the deflections between successive periods in angular measure. He found that if small deflections of from 0 to 10° were omitted that "the average number of earthquakes in any period is approximately directly proportional to angular deflections of the pole-path during that period".

In the following year Knott examined the data from a somewhat different point of view. 30a. He considered that the earthquake frequency should not be compared with the actual deflections themselves but with the deviations of these deflections from their mean value. He accordingly analysed the records by this method and found that for small deviations the average number of earthquakes was 11·1, while for the large deviations the average was 18·1. He concluded that this result "lends a certain amount of support to Milne's view that there is some connection between the occurrence of large world-shaking earthquakes and the movements of the earth's pole". Knott however is disposed to interpret this result in a somewhat different manner. He is inclined to attribute the relation to some local change in the earth's rigidity resulting from an earthquake rather than to the direct effect of ~~[illegible]~~ mass. movements. Thus Milne appears to consider the polar movement to be the cause of the earthquake rhythm, while Knott looks upon the polar movement as possibly an indirect result of the earthquake.

Omori has also taken up this question for the earthquakes of Japan.[72] He examined the latitude variations at Tokyo for the period 1895 to 1903, compared it with the ~~[illegible]~~ frequency of the sensible earthquakes at Tokio, and concluded that it bore no relation to the variations in latitude. The case proved quite otherwise however ~~is~~ with regard to the large earthquakes of Japan. Omori found that "the great destructive earthquakes of Japan have a marked tendency to occur in the epochs of the maximum and minimu latitude of Tokyo, a conclusion which is in harmony with the results already obtained by Prof. Milne."

In the same paper Omori points out that Kimura has shown that the latitude variation has exhibited a six years' period for the interval 1890 to 1902; and Omori is disposed to connect this variation with the 6½ years' periodicity which he has indicated for the earthquakes observed at Kyoto during the 9th century.

Conclusion

The search for earthquake frequency has had a fascination for many workers and its numerous aspects have been diligently examined by a number of distinguished seismologists and geologists. The results of these investigations are widely scattered in geological literature and in many cases are at variance one with another. It ~~is~~ has been the object of the author to assemble this literature as completely as possible, and it is hoped that the discussion of the various papers included in this memoir may serve to give a general view of the progress that has so far been made in this direction. Even now there are but few who accept as proved the relationship between earthquake frequency and other natural phenomena, while others, notably Montessus de Ballore, hold the decided view that earthquakes frequency is entirely independent of any such relation. The most recently expressed views of some of the leaders in this field of research will serve to indicate the present trend of thought and criticism. The following brief summary of these is therefore appended as follows:-

Schuster was the first to examine the statistics relating to earthquake frequency from the point of view of probabilitie for random events.[87] After discussing the annual period which Davison had indicated he says "The probability of the accidental nature of so large an amplitude is in the first case only 1 in 300,000 and in the second almost infinitesimally small. The reality of the period would be thereby established beyond reasonable doubt, unless the peculiarity of earthquakes occurring in groups, as discussed in the previous section, can be shown to raise the expectancy sufficiently. The fact, however, that in each hemisphere the phase of the periodicity found is nearly identical in a great number of cases disposes of all doubt which might remain on this point."

Although the amplitudes calculated by Schuster also favour a lunar periodicity he is not disposed to accept this periodicity as real because of certain anomalies, and also on account of the occurrence of earthquakes in groups of two or more.

Omori in 1902 writing the conclusions of his investigations into the "Annual and Diurnal Variations of seismic frequency in Japan"[~~24~~71] says "According to what has been said thus far the seismic frequency seems to have a close relation to the atmospheric pressure."

Oldham in 1903 prefaces his study of diurnal frequency in Assam by the following remarks:-[66]

"Earthquakes are, and are generally acknowledged to be, purely geological phenomena, yet there is a constant tendancy, and have been repeated endeavours, to trace the influence eithe of the sun and the planets, or, in more recent years, of changes in barometric pressure or temperature on the time of occurrence of earthquakes.

Leaving out of account, as unaccountable the purely astrological influence of the planets, it is not inconceivable that, though the cause of an earthquake is terrestrial, the exact time of its occurrence might be decided by some astronomical or meteorological influence. In other words the exact time when a slowly growing strain becomes too great for the resistance opposed to it by the solidity of the rock composing the earth's crust may be determined by the additional stress - small as it is - imposed by a change in the barometric pressure, or by the stresses set up by the attraction of the sun and the moon."

Again, Omori after investigating the lunar day frequency says;[73] "It thus seems that a considerable proportion of earthquakes, from 50 to 80%, are caused, or accelerated to occur, by the agencies of the atmospheric pressure and the moon's influence on tidal stresses"

Hisviews with regard to earthquake frequency and variation in latitude have been previously quoted. In another paper on the "Secondary Causes of Earthquakes"[78] he concludes as follows:-

"The results obtained........which are only fragmentary notes on the secondary seismic causes, show nevertheless that these latter play a very important part in the distribution of earthquakes during the day, the year, the lunar day, etc. As these secondary causes\probably determine the ultimate moment when a long-continued underground stress gives rise to a sudden disturbance their careful study will be, in conjunction with the observation of the fore-shocks........and the investigation on earthquake-zones, of help inapproximately predicting under favourable circumstances the earthquakes likely to happen in a given district."

Imamura after an enquiry into the "synodic-monthly variation of seismic frequency in Japan"[24] concluded that "earthquake occurrences in Japan, when they are distributed in synodic days reach the greatest number at two pairs of times, namely:-

Firstly, at the times of the conjunction and opposition of the sun and moon, the combined effort of the two heavenly bodies being the caude;

Secondly, at the times of quadrature, thecombined effort of the moon and barometric pressure being the cause."

Dutton[17] in his book on earthquakes has expressed his opinion that "with its fundamental postulate fast vanishing, wi support derived from statistical comparisons dissolved away, little remains of the tidal theory of earthquake causation".

Hobbs has discussed Milne's papers on the possible relation of earthquake frequency and the movement of the earth's pole and has written[22] "In itself, Milne's theory is most plausible for the migrations of the pole correspond to changes in latitude, and these must involve migrations within the mobile portions of the earth's crust, consequent upon the distortions of the spheroid. When the direction of pole movement is reversed, sudden and temporary changes in the condition of compression within the zone of fracture (like the loosening of a vise) may precipitate an adjustment of blocks which was before impending".

Knott has written a great deal on earthquake frequency. He studied in particular the question of a lunar frequency for earthquakes and writes as follows:-[31]

"As regards the synodic month, the greatness of the half-monthly amplitude as compared with the monthly amplitude, and the times of occurrence of the maxima and minima, lend some support to the view that we have an indication of tidal effect. The maxima occur at times of new moon and full moon, just about the times, when, in virtue of the combined action of the sun and moon, the ocean tides attain their maxima". He also remarks "The cause of earthquakes is probably to be referred to the earth's heterogeneity of structure or to the inequality of stress due to irregularities of its surface. Rupturing or yielding is not determined by the amount of stress only; it depends in great measure upon how the stress is applied. For rupture to take place the stress must be different in different directions; amd the difference between the greatest and least stresses is an important datum in estimating the tendency to break. So far as can be judged, the only periodic stresses that exist of period long enough to tell upon the earth's substance are the fortnightly, monthly, semi-annual and annual tides, the annual variation of snowfall, and the steady annual and perhaps semi-annual oscillations of barometric pressure over the earth's surface. Inasmuch as the earthquake frequency reaches its maximum in winter whenever there is a marked winter season, we must pass from the annual tidal stress due to the sun as of little account. We seem, however, to find in the accumulation of winter snow, and in the long period oscillations of the atmospheric pressure, two possible determining factors in earthquake frequency".

Gilbert in a paper dealing with the prediction of earthquakes[40] writes "The principal known causes of periodic variation of stress are bodily tides of the earth; oceanic tides, which alternately load and unload the sea bed near the shore; the winter load of snow on parts of the land; annual and diurnal variations of barometric ~~pressure~~;gradient; and the wanderings of the earth's axis of rotation. The relative importance of the several influences can not yet be indicated, but it is known that their absolute importance is not the same inall places. Three belong to the coastal belts, two to the land; and two belong to land and sea, but vary with latitude. Their relative importance in any particular locality may depend also on the direction of the slowly growing tectonic stress of the crust; for in order to be effective the temporary or adventitious stresses must be of such character as to augment the tectonic stresses". Milne has expressed his views in the recent (1913) edition of his book on Earthquakes.[41] He says "speaking generally, as far as I know, neither tidal, barometric, thermometric, solar, lunar or other epigene influences beyond those mentioned, show a relationship to the periodicity or frequency of megaseismic activity.

Their frequency is apparently governed by activities of hypogene origin".

Walker too, appears to hold this view[94] which he has quoted as the most authoritative statement on the subject. He does not however appear to think the search for periodicity a vain one for he writes "..........statistics about earthquakes are rapidly increasing in number and the search for periodicity will again be taken up. It is desirable that the search should proceed on the lines indicated by Schuster".

Drake believes that in the case of China rainfall has been a determining factor in earthquake frequency. He writes[16.] "Some of the most striking evidences of the foregoing data are the following probable rules; first the rapid and strong atmospheric variations, assisted to some extent by rain, are the forces most effective in the final stage of earthquake activity".

Sayles has also investigated this aspect of earthquake frequency and remarks[85] "As far as this work on the earthquakes of the world and rainfall of the United States has gone, I agree with Professor Drake very closely on his earthquake and rainfall discovery.....................The recent work with seismographs has revealed facts which cannot be ignored; movements of the crust felt for some miles from the coast due to the incoming and outgoing of the tides;, sinking and rising of the crust under high and low pressure barometric areas; the transmission of microseisms through the crust caused by the breaking of waves on the coast. The earth is not as rigid as has been thought, but apparently in extremely delicate equilibrium."

Taber in his work on the earthquakes of the Charleston district has discussed the question of tidal frequency. He writes as follows:- [91]

"Many attempts have been made to correlate lunar periodicities with the earthquake frequency of individual districts and of the earth as a whole; but, with the accumulation of accurate statistics, it has been shown that the attraction exerted by the sun and moon on the earth's surface has little if any influence in determining the time of earthquakes. Logically no other conclusion could be expected in the case of tectonic earthquakes, for the attraction of the sun and moon is uniformly distributed over large areas of the earth's surface, and therefor can directly cause very little difference in the stresses on opposite sides of faults. Since the oceanic tides are due to the attraction of the sun and moon, and tidal loading on the surface near the coast line does produce differential stresses, the position of the heavenly bodies relative to the earth may indirectly result in the development, in coastal regions, of stresses sufficient in magnitude to control the time of fault displacements". In his conclusions he also writes "The most important factors affecting the relative pressure on opposite sides of the fault and thus controlling the earthquake frequency are rainfall, height of the water-table and barometric pressure".

The view ~~enumerated~~ enunciated by Taber that any forces affecting earthquake frequency must be such that they operate differentially on opposite sides of the fault plane has also been promulgated independently by Knott. Gilbert too has recognised that the direction of the growing stress must be considered.

Theses aspects of the question together with certain geological considerations with regard to faults are discussed by the author in Part II of this paper dealing with the "Tidal Stresses in the Lithosphere."

Earthquake Frequency with special reference to Tidal Stresses in the Lithosphere.

Part II.

Tidal Stresses in the Lithosphere.

R

~~The Precipitation of Earthquakes by secondary causes.~~

* * *

Part II.

Tidal stresses in the Lithosphere.

In the preceding article (Part I) an enquiry was made into the subject of the secondary causes of earthquakes. Although the evidence is somewhat conflicting there is a strong probability that the small strains set up in the earth's crust as the result of barometric changes, ocean tides along certain coast lines, and tidal stresses in the earth's solid crust are effective in determining the actual time o of occurrence of the earthquake shock. It is clear from the diverse opinions held by eminent seismologists that, as yet, the earth tides are not generall recognised as being competent to precipitate an earthquake. ~~Amongst those who have expressed some belief in a relation between earth tides and earthquakes are the following:-~~

On the contmry certain eminent authorities remain unconvinced of any such relation, as may be seen from the following statements:-

Thus the relation of earthquakes and earth tides stands at present in the realm of controversy. Many of the opinions quoted however were expressed before the recent work of Oldham, Omori and Immamura and others was available for discussion and may not now represent the views of those quoted.

There appears to be, however, at present a disposition to attach rather more importance to barometric changes than to earth tides as possible secondary causes of earthquakes. ~~This is evident from the following statements:-~~

In view of the fact that barometric changes have been more generally accepted as possible secondary causes of earthquakes than earth tides it is interesting to compare the effects of the two sets of forces. This may best be done by comparing the maximum strains effected by each set of forces and G.H.Darwin[67] has in different places calculated the strain due to the tidal forces and ~~here~~ has expressed it as a fraction of the water tides. He concludes that the earth tides are sufficiently large to diminish the apparent height of the water tides to two thirds of their actual value. This is illustrated by fig. 1 From this diagram it is clear that the earth tide must have an amplitude one third of that of the water tide. The double amplitude of the maximum or spring tide for an ideal ocean is calculable from a formula givenby Gray,[21] and amounts to 2·56 feet or ~~·25~~ about 75 cms. On the other hand G.H.Darwin[6] has estimated the effect of parallel barometric waves assumed to have a wave length of 3000 miles and a double amplitude amounting to 50 m.m. of mercury. He concludes that if the earth's crust be as rigid as the most rigid glass that a corresponding earth wave having a double amplitude of 9 cms. would be caused by such a barometric load.

as the amplitude of the earth tide is about one third that of the ocean tide, it should have a double amplitude (from crest to trough) of about 25 c.m.s.

Hence the effect due to the earth tides is seen to be nearly three times that due to maximum barometric changes.

The barometric changes however are not due to a system of parallel waves as calculated by Darwin but to subcircular domes of high pressure and basins of low pressure; ~~and the average distance from the centres of the anticlines is probably les than 5000 miles.~~ In addition it is probable that the rigidity of that part of the earth which us affected is considerably greater than the most rigid glass. These factors would all tend to diminish the value of 9 cms. quoted above. Hence it is probable that the double amplitude of the maximum earth tides is considerably more than three times that set up by the maximum barometric changes.

Note.

There is no omission here, but only an error in numbering the pages.

Thus it appears that the movement of the earth's crust is greater under tidal stresses than under the influence of barometric changes. If therefore barometric changes influence the time of occurrence of earthquakes one might expect to find a still more intimate relation for the earth tides.

Sayles[85.] and others have published data which strongly suggest a relation between railfall and earthquake periodicity.

The barometric range of 50 m.m. of Mercury. chosen by Darwin is equivalent to a pressure of about 26 inches of water; and the only water pressure which is effective is that which soaks into the ground - usually taken as one third of the rainfall. Hence in order to have a strain set up equal to that due to the maximum barometric wave there would require to be 78 inches more water retained in one area than in adjacent one.

Such a condition could only be rarely if ever realised over large areas and hence such a relation as that suggested would be of much less importance than that due to the earth tides.

The search for earthquake periodicity has hitherto proceeded along mathematical and statistical lines without taking into account the geological aspects of the subject. The matter is approached in this paper chiefly from its geological aspects and from these a mathematical theory is developed.

Earthquakes and Faults.

Although Perrey[36] early ventured the hypothesis that earthquakes might be caused by the fracturing of the earth's crust this view was not accepted as th prime cause of earthquakes until a much later period. For example that eminent seismologist J.Milne[40] appears as late as 1886 to have held the view that earthquakes were primarily caused by volcanic activity. This may be seen from the following quotation from his book on earthquakes published in 1886:-

Milne[40] - Earthquakes. pp.295,296.

"*Conclusion*.- Although it would be an easy matter
'to discuss the relationship of earthquakes and
'other phenomena, we must conclude that the
'primary cause of earthquakes is endogenous to
'our earth, and that exogenous phenomena, like
'the attraction of the sun and moon and barometric
'fluctuations, play but a small part in the
'actual production of these phenomena, their
'greatest effect being to cause a slight pre-
'ponderance in the number of earthquakes at
'particular seasons. They may, therefore, some-
'times be regarded as final causes. *The majority*
'of earthquakes are due to the explosive efforts
'at volcanic foci. The greatest number of these
'explosions take place beneath the sea, and are
'probably due to the admission of water through
'fissures to the heated rocks beneath. A smaller
'number of earthquakes originate at actual
'volcanoes.

'*Some earthquakes are produced by the sudden fracture*
'*of rocky strata or the production of faults*. This
'may be attributable to stresses brought about by
'elevatory pressure. Lastly, we have earthquakes due
'to the collapse of underground excavations".
(The italics are mine L A.C.)

The clear recognition of the fundamental relation of faults and earthquakes is due chiefly to the great labours of M. de Montessus de Ballore and the late E. Suess.[90a] M. de Montessus de Ballore[53] has made a most elaborate and thorough study of the distribution of earthquakes and has shown in a most convincing manner their intimate relation to the two great zones of weakness in the earth's crust. This work has revolutionised seismological science and stands as a monument marking the common ground of seismology and geology. The relation of fault zones and earthquakes was first noted by Suess as the result of his studies of the earthquakes of the Murz line.[90b] Great progress has since been made, and as several of the more recent abd severe earthquakes have actually given rise to surface displacements along fault lines these have been made the subject of special study. ~~The principals of such earthquakes are as follows:-~~

This has been particularly the case for the Mino-Owari, the Assam and the San Francisco earthquakes.

32.
The Mino-Owari Earthquake~~s~~ of Japan occurred on the 28th of October 1891. The shock was extremely heavy and shook an area of 243,000 square kilometres or more than 60% of the whole Japanese Empire. The most unique accompaniment of the earthquake was the appearance at the surface of the ground of a great fault trending in a general south east to north west direction and extending along a length of at least 40 miles. Physiographic evidence points to the fault being at least 112 kilometres in length. The surface displacements involved both vertical and horizontal motions. The eastern side of the fault was, in general the downthrow side and was also displaced horizontally, parallel to the fault plane, in a north westerly direction relatively to the other side of the fault. This horizontal movement was on the average from three to six feet. The vertical displacement ~~singularly enough the maximum vertical~~ varied from zero to about 18 feet but singularly enough the maximum vertical movement had the downthrow 6 metres on the western side of the fault; although here as elsewhere the horizontal movement was in the usual direction previously indicated. It is notable that even where no vertical displacement occurred the horizontal movement amounted to several metres.

63 a.
The great Assam Earthquake occurred on the 12th of June 1897. This earthquake shook an area of 1,750,000 square miles and its destructive effects were felt over about one tenth of this area. The earthquake was attended by numerous surface displacements the most important of which is the Chedrang fault. This extended in a general north-north-west direction for a distance of about 12 miles. The chief features of interest with regard to this fault have been summarised by Oldham as follows:-

"Firstly, although the throw of the fault varies from over 35 feet to nothing, yet wherever there is any perceptible throw the upthrow is always on the east and the downthrow on the west Secondly, I was unable to detect any pronounced horizontal movement of one side with reference to the other, in other words the displacement appears to have been simply up or down, so that the fault is a fault pure and simple, and not a heave. Thirdly, wherever the plane of the fault could be seen in rock it was practically vertical, with no pronounced hade in either direction. Fourthly, the displacement appears to have been principally, if not entirely, an elevation of the upthrow side and not a depression of the downthrow side of the fault".

The San Francisco earthquake took place on the 18th of April 1906. Surface displacements also accompanied this earthquake. The "Earthquake crack" as it was called closely followed a direction about north 35° west, and has been traced for a distance of 185 miles. The physiographic evidence shows that this "crack" occurs along a great rift which is known to extend for 400 miles. As in the Assam earthquake the movement occurred along vertical planes, but it also resembled the Mino-Owari fracture inasmuch as both vertical displacements and horizontal movements parallel to the fault were conspicuously developed. In this case the horizontal shift was in the direction opposite to that of the Mino-Owari fracture, so that the area on the west of the fault was moved towards the north-west relatively to that on the east side of the fault. This horizontal displacement varied from a few up to as much as twenty feet. The vertical throw did not exceed four feet and the uplifted area was generally on the western side of the fault. This was not, however, invariably the case as in a few instances the eastern side was uplifted to amounts of about two feet.

In addition to the main fracture numerous minor fissures were formed which ran in many directions

It may be regarded as being now well established that the immediate cause of earthquakes is in most cases a movement along fault fractures. The study of faults enables them to be classified into two main groups - normal and reversed faults. In the case of normal faults the motion is caused by tensional forces while in reversed faults compressive stresses are operative. The different nature of these forces must be taken into account in any attempt to investigate the secondary causes of earthquakes.

Although the motion which gives rise to displacements along fault planes is often approximately in the direction of the dip of the fault, i.e. in the direction in which motion would occur under the action of gravity, this is by no means always the case. This is clearly indicated by the displacement noted in connection with the San Francisco[33] and Mino-Owari[32] earthquakes. Moreover the study of older faults often reveals the presence of slickensides which indicate the direction of the displacement and consequently that of the resultant porces.

The principal elements which are required for the determination of the direction of the stresses along a fault plane are then as follows:-

(a) The direction of the trace of the fault on a horizontal surface, or, in other words, the strike of the fault.

(b) The inclination of the fault plane measured from either the horizontal (the dip) or from the vertical (the hade).

(c) The direction, in azimuth, of the motion as determined by the slickensides or any other method.

The discussion of the magnitude of the tidal stresses and of the positions of the tide producing bodies when they exert their maximum force in the direction of displacement for any given fault is dealt with in the appendix. The general course of the argument, however, may be gathered from the discussion which follows here. This arrangement was considered best as it makes the nature of the argument clearer for those who do not read mathematics.

In the first place we may reproduce the figure published by G.H.Darwin[17] representing the directions and relative magnitudes of the tide producing forces due to a single attracting body.

It will be seen from the diagram Fig. 2. that for any given place the tide generating force will be a maximum when the attracting body is in the zenith and a minimum when it is on the horizon. Moreover, in each of these particular cases the forces are wholly vertical.

It will also be seen that the tide generating force is wholly horizontal when the attracting body is at a zenith distance of about 55° from a given place

The question now arises as to how these forces may operate to assist faulting. We may first consider the case of faults in which the displacement is in a plane perpendicular to the strike of the fault. This may occur in both normal and reversed faults but is, from the nature of the case, because of the force of gravity, more likely to occur in the former than in the latter type.

Normal Faults. Let the strike of the normal fault be represented by the line FF' in fig. 3. The direction of the movement is represented by the arrow which is directed towards the down thrown side of the fault. This is also the direction of the dip of the fault, which is as throughout, here assumed to be a plane surface. The forces operating to produce movement may be represented by two components, one normal to the fault plane and the other lying in the plane of the fault and also in the direction of dip. The first of these components tends to open the fracture, and, hence, by lessening the ~~free~~ frictional resistance, assists movement under the action of gravity. The second component tends to cause movement in the actual direction of the displacement.

The following questions now arise:-

(a) How may the tidal stresses co-operate with the earth's internal forces to assisti in producing movement?

(b) In what positions must the attracting body be to exert its maximum force in the direction of one or other of the components of the internal earth stresses, i.e. parallel and perpendicular to the fault plane?

Question (a).

The tidal force acting on a small part of the earth's crust tends to draw that part away from the earth mass as a whole. If the same force acts on an adjacent and similar part of the earth's crust both parts are drawn away from the main earth mass. but there is no appreciable tendency to separate them. Thus two small areas of rock at A and B fig. 3. are acted on by practically the same force and witout any appreciable tendency to separation along the fault FF'. If, however, strips of some appreciable width such as PQFF' and P'Q'FF' be taken one on each side of the fault, the average forces over each such strip due to the tidal forces will not be the same and the difference between the tidal forces on the opposite zones will constitute a system of forces tending to cause movement along the fault plane. If these forces operate in conjunction with internal forces tending to produce rupture they will cause the earthquake to occur earlier than if they did not exist. ~~Simila~~ Similarly if the tidal forces are opposed to the internal forces they will delay the time of occurrence of the earthquake.

Question (b).

We have seen from fig. 2. that the tidal forces reach a maximum for any given locality with certain positions of the attracting body. In previous investigations of this character it has been assumed that the times of occurrence of the maximum tidal forces are the most likely times for the occurrence of earthquakes. The investigations of Perrey[84] and others on the relation of earthquakes to the passage of the moon across the meridian are based on this hypothesis. Oldham[66] has modified Perrey's hypothesis by suggesting that the time of occurrence of earthquakes may coincide with that of the occurrence of the maximum horizontal component of the tide producing force at the earthquake centre.and he has further modified this theory[67, 68.] by suggesting that the rate of change of the tidal forces may be more effective than the actual magnitude of the forces themselves - an hypothesis which deserves further investigation.

As was shown under question (a) the actual magnitude of the tidal force at any point is not the determining factor in setting up forces which may precipitate earthquakes. The essential factor is the difference in the forces acting on zones of the earth's crust bordering the fault plane. These earthquake precipitating forces do not reach their maxima at the times of the maxima of the tide-producing forces. The analytical proof of this is given in the appendix, but it may be geometrically demonstrated by the following diagrams.

If figs. 4 and 5 are represented the vertical and horizontal components respectively of the tide-producing fores. From fig. 4 we see that when the tide-producing body is in the zenith of a point on an earthquake fracture or fault the vertical tide-producing force~~s~~ V operating on the zone on each side of the fault are the same, so that although the tide-producing forces are at a maximum the differential stress dV between the two zones is zero, or a minimum.

Stet

Let us assume that the distance between the centres of the two zones is say an arc measuring 10° then we may see from fig. 4 that the greatest difference dV in the vertical stresses for the two zones would occur when the zenith distance of the tide-producing body was 45° from a point. Hence the maximum ~~distance~~ difference in the verti components of the tide-producing forces is reached when the tide-producing body lies in a plane perpendicular to the fault plane and at a zenith distance of 45° from the earthquake centre.

Similarly if the curve representing the horizontal component of the tide-producing force

~~demonstrated~~ illustrated in fig. 5 be examined it will be seen that the maximum horizontal force H occurs when the tide-producing body has a zenith distance of 45°. But from fig. 5 it will also be seen that the maximum difference in the horizontal forces dH acting on the zone in question will be reached when the horizontal tide-producing forces are actually zero, that is, when the tide-producing body is either on the horizon or on the zenith. In the former case the forces are tensional and so favour faulting and in the latter case they are compressive and by increasing frictional resistance tend to prevent motion..

Hence the maximum difference in the horizontal components of the tide-producing forces acting on opposite sides of a fault plane is reached when the tide-producing body lies in a plane perpendicular to the fault plane and is either in the zenith or on the horizon of the earthquake centre.

It is only when the tide-producing body is on the horizon, however, that the forces are tensional and favour faulting.

When the tide-producing body is in the zenith the forces are compressive and are most unfavourable to faulting.

In the preceding discussion no account has been taken of the amount or direction of dip of the fault plane. It isnnecessary to consider this factor in order to determine that position of the tide-producing body at which it exerts its maximum force in the direction of assisting the earthquake forces proper. The necessary analytical treatment will be found in the appendix. The result of this investigation may be geometrically illustrated by means of the accompanying diagram. (fig.6)

Let the circle ~~F.L.N.~~ EZE'. represent a section passing through the earth's centre and the earthquake centre E; and let the section be taken perpendicular to the fault plane FF'.

Let the hade of the fault be θ and let ϕ be the zenith distance of the attracting body M. Let the vertical and horizontal components of the tide-producing forces at F be represented by V and H respectively.

It is required to find the value of ϕ.

(a) for a maximum difference in the tidal forces on either side of the fault plane FF' in a direction parallel to FF'

(b) the maximum differance in the tidal forces perpendicular to FF' tending to open the fault fissure.

These conditions have already been shown to be those which are most favourable in assisting faulting.

The conclusions teached (vide appendix) are as follows:-

The forces acting parallel to the fault plane (a) are most favourable to normal faulting when $\phi = 45^\circ + \frac{\theta}{2}$

~~$\phi = (45^\circ + \theta$~~
~~$= (45^\circ + \frac{\theta}{2}$~~) and the fault dips away from the attracting body and are (b) most favourable to reversed faulting when

$\phi = (45^\circ - \frac{\theta}{2})$ and the fault dips towards the attracting body.

The results may be stated in words as follows:-

(1) The tide-producing forces acting parallel to the plane of the fault are most favourable to normal faulting when the attracting body lies at zenith distance from the fault plane of forty-five degrees plus one half the hade of the fault; and the body also lies in a direction opposite to that of the dip of the fault.

And (2) the tide-producing forces acting parallel to the plane of the fault are most favourable to reversed faulting when the attracting body lies at a zenith distance from the fault plane of forty-five degrees minus one half of the hade of of the fault: and the body also lies in the direction of the dip of the fault.

Again it is shown (vide appendix) that the tensional forces perpendicular to the plane of the fault reach a maximum when $\varphi = (90^\circ \pm \frac{\theta}{2})$

and that the compressive forces in the same direction reach a maximum when $\varphi = \pm \frac{\theta}{2}$

These conclusions may be expressed in words as follows:-

(3) The tide producing forces acting perpendicular to the fault plane are most favourable to faulting, both normal and reversed, when the zenith distance of the attracting body from the fault plane is equal to ninety degrees minus one half the angle of hade: and the body also lies in the direction of the dip of the fault plane.

(4) The tide-producing forces are most unfavourable to faulting when the attracting body lies at a zenith distance from the fault plane equal to one half the hade of the fault.

Foot Note.

† the case where $\varphi = 90^\circ + \frac{\theta}{2}$ is identical with that in which $\varphi = 90^\circ - \frac{\theta}{2}$ since the tidal forces are the same both in the direction of the attracting body and in the opposite direction.

Let us now consider the case of faults in which the displacement is not in the direction of the dip. Such a case may be represented by fig. 3

Here LM represents the direction of the displacement. As before the zones PQFF' and F'Q'FF' are those on which the tidal forces act.

The vertical and horizontal tide-producing forces may be resolved as before along the directions LA in the plane of the fault and along the normal to the fault plane.

The condition for the tensional and compressive forces perpendicular to the fault plane is obviously the same as in the preceding discussion so that laws (3) and (4) hold quite generally. The conditions for the maximum effect of the tide-producing forces. lying in the plane of the fault, are however modified but they may be stated by substituting the term "apparent hade" for hade in the preceding laws stated in (1) and (2).

The term "apparent hade" is to be defined as the hadewhich the fault plane would appear to have in a vertical section drawn in the direction of the displacement LM (fig. 3)

Critical Positions of the Tide-producing Body.

From the preceding discussion it will be seen that there are certain critical positions in which the tide-producing body exercises its maximum influence in assisting the earth's internal forces which are primarily reponsible for causing faulting. Sich critical position may be determined when the full geological data regarding the fault plane are known. This may be geometrically shown as follows:-

Let FF' represent the trace of a fault plane making an angle δ with the ~~meridian as~~ direction of the displacement. NN' as illustrated in fig. 7 .

Let E be the earthquake centre.

Let the fault dip in the direction indicated by the arrow and let the amount of dip be $90^\circ-\theta$. The hade is therefore θ.

Let the actual direction of movement be the direction ~~ED.~~ EN

Let ~~EN~~ ED be the direction perpendicular to the fault. First consider the case in which the fault is normal. In this case the tensional forces perpendicular to the fault plane reach a maximum when the tide-producing body is in the direction ED and has a zenith distance of $90^\circ-\frac{\theta}{2}$ from E. Let T represent this position. But since the stress set up by the tide-producing body are approximately the same on opposite side of the earth i.e. at places where zeniths are 180° apart, there is another position T_2 in the direction ED' and at a distance $90^\circ+\frac{\theta}{2}$

which produces the same tensional stresses perpendicular to the fault plane. Hence the positions of T_1 and T_2 are identical. The forces acting parallel to the plane of the fault in the direction NEN' ~~NN'N~~ are most favourable to faulting when the tide producing body acts along the direction FN' and is at a zenith distance from E = $45^\circ + \frac{\theta}{2}$ where θ' is the apparent hade in the direction EN. Let this psoition be represented by T_3.

Normal Faults.

When the direction of the displacement coincides with that of the dip the positions T_1, T_2 and T_3 all lie in a direction perpendicular to the strike of the fault. Moreover since the distance of T_2 from the earthquake centre is $90^\circ + \frac{\theta}{2}$ and that of T_3 is $45^\circ + \frac{\theta}{2}$ the angular distance between T_1 and T_3 is $(90^\circ + \frac{\theta}{2}) - (45^\circ + \frac{\theta}{2}) = 45^\circ$

Hence under the conditions, which are commonly approximately fulfilled in tensional or normal faults, the angle between the two critical positions is 45°. If, therefore, the sun and moon act jointly their effect is a maximum when they are in conjunction near either of the critical positions, T_1 or T_3, or when they are separated by about 45° each being near one of the critical positions T_1 or T_3.

Reversed Faults.

In the case of reversed faults the positions T_1 and T_2 for the tide-producing body again favour movement but the forces acting parallel to the plane of the fault are most favourable to movement when the tide-producing body acts along direction EN and is at a zenith distance from E equal to $45^0-\frac{\theta'}{2}$ where θ is again the apparent hade in the direction EN.

Let T_4 represent this position.

It will thus be seen that for any given position E on a given fault plane FF' there are two critical positions in which the tide-producing body may exercise it maximum influence. These are (T_1 or T_2) and T_3 for normal faults and (T_1 or T_2) and T_4 for reversed faults.

A purely geological examination will, in many cases provide sufficient data to lead to the determination of these two critical positions for a given fault. It is clear that the sun's or moon's influence is not a maximum, except in very special cases, when the tide-producing body is on the meridian; and hence the law which Perrey 83. emmunciated to this effect is here shown to have no physical basis. Moreover M. de Montessus de Ballore has shown 47, 48. by a very comprehensive statistical investigation that the law does not hold even empirically. It must be rembmbered, however, in justice to Perrey that the law of maximum earthquake frequency at the times of the moon's meridian passage was enunciated at a time when the conception of a fluid nucleus for the earth was an accepted postulate of geology; and that moreover the law rested upon the records of one district only - for which, indeed, it may well hold if one of the critical positions abovementioned lie on the meridian..

It might appear at first sight that since the relation of the tidal stresses to earthquake phenomena involve both the direction and amount of the dip of the fault plane and in addition the actual direction of the movement, that the only method of testing the effect of the tidal stresses in accentuating earthquake frequency would be to examine the data for each earthquake separately. This no doubt would prove the most complete and satisfactory line of investigation and may perhaps be possible in some measure in the future. Unfortunately, however, the data does not at this juncture permit of such an investigation. In very few cases indeed has the actual fault causally connected with an earthquake been definitely geologically located. There are two difficulties which stand like lions in the path. The first is that most earthquakes are due to movements which do not actually reach the surface of the earth, and the second is that the great majority of earthquakes are of submarine origin. Nevertheless the general problem is not altogether an insoluble one. The data available have been examined in a general way and furnish a rather startling conclusion.

In undertaking any statistical investigation great care must of course be exercised in the choice of the data to be used. There must be no possibility of a selection which embraces abnormal conditions. In the following discussion the choice was made of the world shaking earthquakes which were recorded for the five years 1899 to 1903 inclusive. These have been tabulated by the Seismological Committee of the British Association for the Advancement of Science and should be thoroughly representative of the phenomena with regard to their distribution both in time and space. They are, moreover, all instrumentally recorded. The published list gives the latitude and longitude for each earthquake and also its time of occurrence.

It was necessary for the purpose of the investigati to calculate the following elements for each earthquake at the time of the shock.

(1) The latitude and longitude of the sun and moon.

(2) The zenith distance of both sun and moon measured from the earthquake centre.

(3) The Azimuthal angle of both sun and moon measured from the meridian.

(4) The angular distance between the sun and mon subtended at the earth's centre.

(5) The angle subtended at the earthquake centre by the aximuthal directions of the sun and moon.

As the list employed embraces 316 earthquakes the labour involved in the necessary calculations has been considerable, and should not have been accomplished but for the kind assistance of my senior students ~~working-in-pairs~~. The calculations were made and checked by thirty students working in pairs and it is believed that the results are reasonably free from errors. Many of the calculations have been again checked by the author and were found satisfactory. The results obtained were tabulated and the results are represented in Tables I and II. These have been further condensed by grouping the results of Tables III, IV, V, and VI. Since the tidal stresses due to an attracting body in a given position are the same (very closely) as those due to the same body when it lies in exactly the opposite or antipodal position with regard to the earth, it was only necessary to take a range from 0° to 90° for the angles obtained in Tables III,IV,V,VI. This range of 90° was subdivided into 9 intervals each having a range of 10° and the number of earthquakes which occurred corresponding to each such interval was then tabulated. These results are given in Tables mentioned.

Table III give the number of earthquakes occurring when the sun's zenith distances from the corresponding earthquakes range from 0 to 10°,11 to 20°,etc.

Table IV gives the corresponding number of earthquake for the moon's zenith distances.

Table V give the number of earthquakes corresponding to angular distances between the sun and moon ranging from 0 to 10°, 11 to 20° etc. and

Table VI gives the number of earthquakes corresponding to the angles subtended by the sun's and moon's azimuthal directions for the same angular intervals of 0° to 10°, 11° to 20°, etc.

A graphical representation of each of the above tables is also given. Fig. 8 corresponds to Table III; Fig. 9 to Table IV; Fig. 10 to Table V, and Fig. 11 to Table VI.

Discussion of the form of the curves representing Tables III, IV, V and VI.

The curve shown in Fig. 8 is so arranged that the vertical distances or ordinates represent the number of earthquakes occurring for each of the intervals 0 to 10°, 11° to 20° etc. which are plotted as abscissae and represent the zenith distances of the sun from the earthquake centre. The curve has several distinctive features.

First there are very few earthquakes occurring when the sun is close to the zenith of the earthquake centre. This is of course directly opposed to Perrey's view that earthquakes are most likely to occur when the attracting body is on the zenith. On the other hand it has been demonstrated in the preceding discussion (vide p. 21) that the maximum compression perpendicular to the fault plane occurs when the sun is near the zenith and the fault is steep. Such compression by increasing frictional resistance opposes the earthquakes forces proper and hence ~~is~~ determines the most unfavourable time for earthquakes. This agrees well with the form of the curve under discussion.

Second. ~~The~~ A large number of earthquakes occur when the sun's zenith ~~position~~ distance is from 81°-90° i.e. when the sun is near the horizon.

This has been shown (vide p. 21) to be the position in which the tensional forces are greatest for steep faults and hence when the tidal forces favour the occurrence of earthquakes.

Third. The curve has a maximum for values 31°to 40° and a minimum for values 41°to 50°. These may represent irregularities in the curve or may perhaps have some significance.

Fourth. The maximum number of earthquakes occur when the sun's zenith distance is from 61°to 70°. It can be shown that such a maximum is in accord with the dynamical theory outlined in this paper, provided that faults having a hade of about 45° are as common as those having other values for the hade. For if a normal fault have a hade of 45° the critical position of the attracting body for the forces parallel to the fault plane is at a zenith distance

$\phi = 45° + \frac{45}{2} = 67\frac{1}{2}°$; and the critical position of the attracting body for forces perpendicular to the fault plane is $\phi = 90° - \frac{45}{2}$ which also $= 67\frac{1}{2}°$. Hence the two critical positions have each a zenith distance of $67\frac{1}{2}°$ and even if faults having a hade of 45° are relatively less common than others one might still expect an exceptionally large number of earthquakes to occur when the attracting body is at a zenith distance of about $67\frac{1}{2}°$ or thereabouts.

If the curve of Fig.   is now examined it will be seen to have the same general form as that of fig. 8 . This would be anticipated since the moon exercises the same kind of influence as the sun.

First. The minimum again occurs when the moon is near the zenith of the earthquake centre,

Second. A large number of earthquakes occur when the moon is near the horizon.

Third. There is a maximum in the interval 41 to 50° and a minimum in the interval 51°to 60° which may be accidental or may have some significance?

Fourth. There is again apparent a maximum for zenith distances of the attracting body ranging from 61 to 70°.

Next, if the curve for Table V, Fig. 10 be now examined it will be seen that the maximum earthquake frequency corresponds to an angular distance between the sun and moon of from 41° to 50°. It has been shown in the preceding discussion (vide p. 24) that such a maximum was to have been expected. Moreover the same argument implies that the earthquake frequency should be greater when the angular distance between the sun and moon is small say from 0 to 30° than when it is large say from 60° to 90°? An inspection of the curve shows that this also is the case.

Finally comes the consideration of Table VI and the corresponding curve shown in Fig. 11 . This curve shows a very high maximu for angular values from 0 to 10° with a rapid falling off in earthquake frequency as the angular values increase to 90°. The significance of this curve is very great. It indicates that when the sun and moon are so situated that they exert their tidal stresses in the same direction there is a great maximu of earthquakse frequency. This curve provides very strong proof indeed of a most intimate relation between earthquake frequency and the tidal stresses set up by the sun and moon. The fact that the sun and moon are jointly related by this curve with earthquake frequency renders it highly probable that the chief relation is directly due to tidal stresses and not to secondary causes such as temperature or barometric changes which are a function of the sun's and not of the moon's position. The conclusion indicated is of such importance that it is desirable to make an estimate of the probability of obtaining such a curve ~~of~~ if the earthquakes were purely random events unconnected with the positions of the sun and moon. It is shown in the appendix (Section II) that the probability of obtaining such a curve from random events is less than 1 in 276 10^{19}. Indeed the probability that the earthquake frequency should be even at least as great as that indicated for that part of the curve renging from 0 to 30° is only 1 in 45×10^{13}. In other words the odds against random events giving rise to such a relation are at least as great as 456, 000,000,000,000 to 1. This enormously high ratio furnishes the clearest proof that earthquakes are very generally precipitated by the tidal stresses due to the attractions of the sun and moon.

The importance of such a conclusion is at once obvious. It provides for each particular earthquake centre criteria for the prediction of the time ~~of~~ to within an hour, of the occurrence of an earthquake if once the approximate period of the earthquake can be determined say to within a month or even a few months. Thus we have, as it were, the fine adjustment to our earthquake prediction apparatus ready to hand; but so far we lack the coarse adjustment.

Considerable progress has however been made in the matter of the approximate prediction of earthquakes* and much may yet be learned from a study of the few shocks and after shocks of earthquakes which will assist in the solution of the problem.

If, in addition, meteorological influences be taken into consideration it may yet be possible to predict the occurrence of earthquakes with sufficient accurracy to provide timely warnings of disastrous shocks. The hope that this investigation might, perhaps, be of value in the future prediction of such earthquakes, has been a constant ~~as~~ inspiration and incentive to the author in his attempt to "follow the gleam".

Acknowledgments.

The author wishes to express here his indebtedness and cordial thanks to those who helped him in this investigation First and foremost to his eminent master and friend Professor David the inspiration of whose teaching first led him along the pleasant paths of geological science; to whose ready counsel and generous help he owes most that may be of value in this work.

To the Rev. Father Pigot S.J. he is indebted for his first active interest in seismology, and through it to the many problems arising from the study of earthquakes.

To his friend Mr.R.J.Lyons the author offers his thanks for his kind help in reading and offering suggestions in connection with the mathematical discussions in the appendix.

Very heartily too does he wish to thank his senior students of 1917 and 1918 for their cooperation in making the necessary calculations. The following are the names of those who have assisted in this part of the work:-

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My thanks are also due to Miss Doris Stilwell for her very kind and able assistance in assembling the literature on the subject.

List of Figures illustrating Part II.

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~~Fig. 5~~
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Fig. 6 Diagram to illustrate the calculation of the tidal stresses set up parallel and perpendicular to the fault plane.

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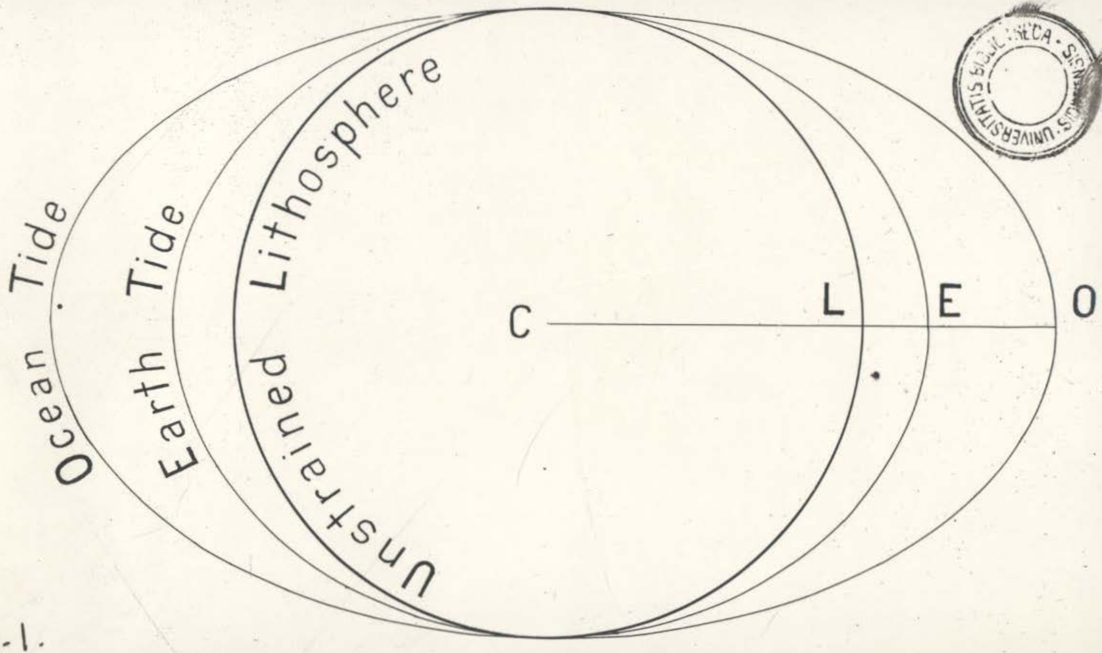
Fig. 11 Showing the number of earthquakes corresponding to the angles subtended by the sun's and Moon's azimuthal directions when the said angles range from 0-10°_ 11-20°, etc..

Text Figures

no. 1 – 11 [in duplicate)



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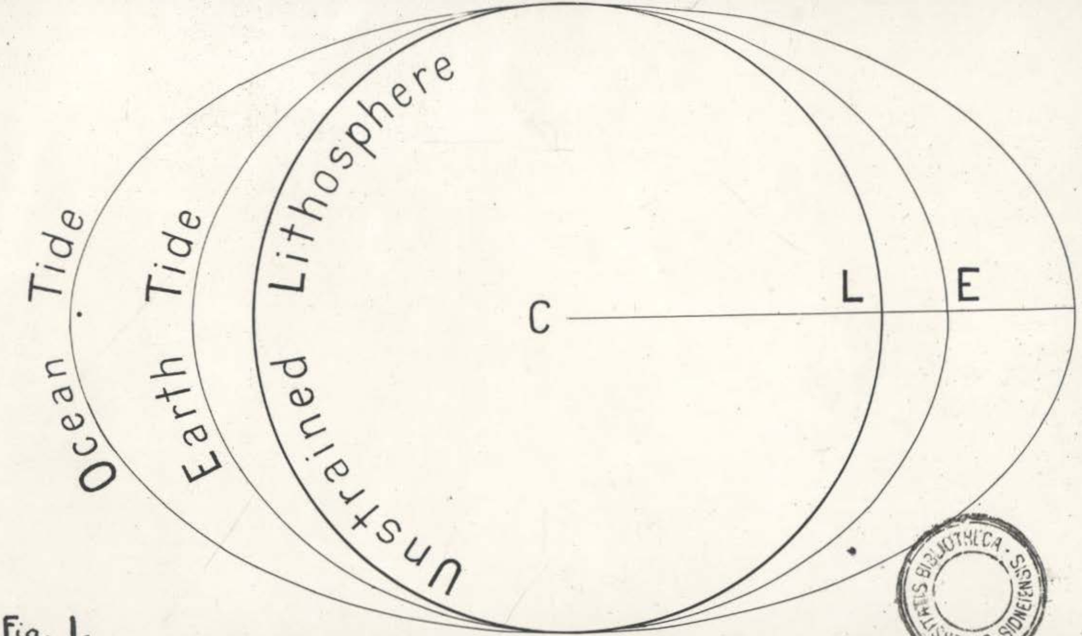

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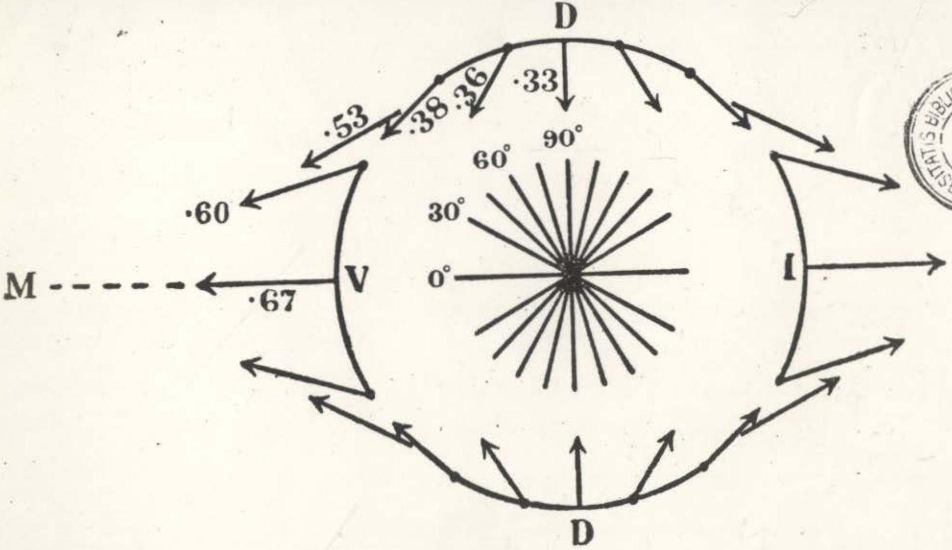
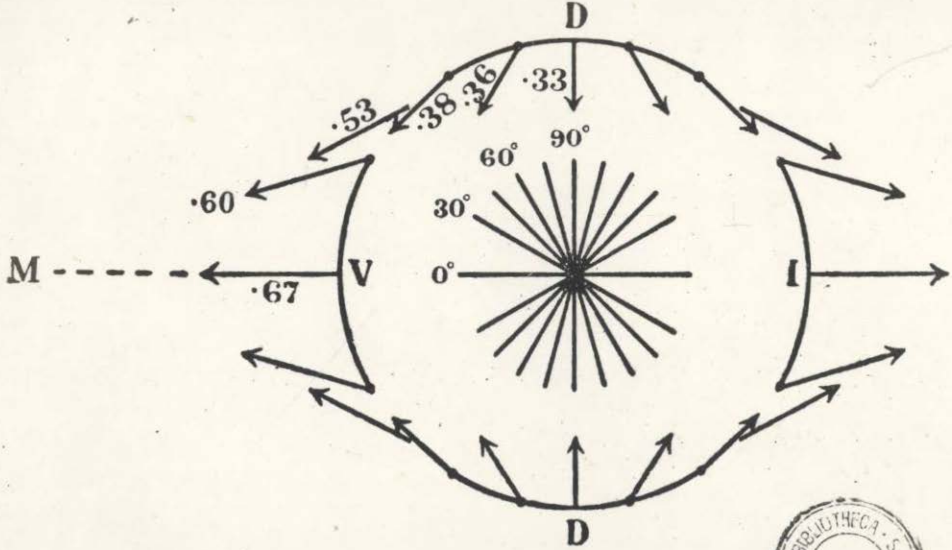


Tide-Generating Force

Fig-2.



TIDE-GENERATING FORCE

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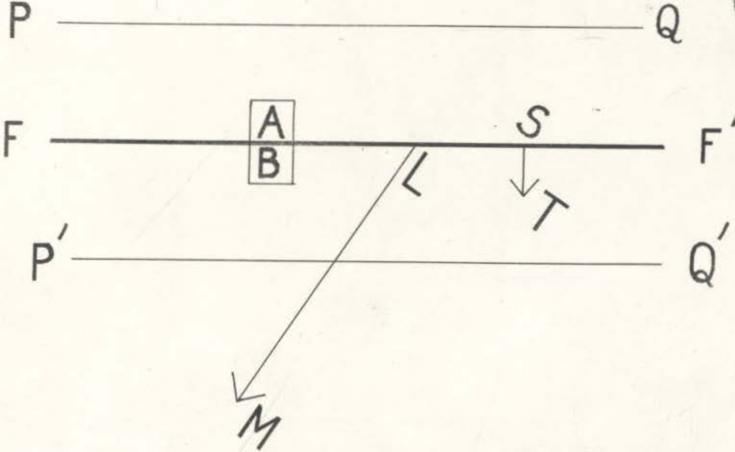

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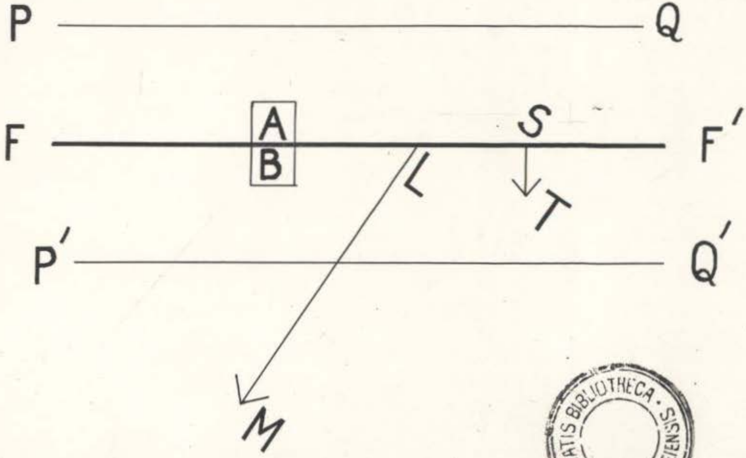
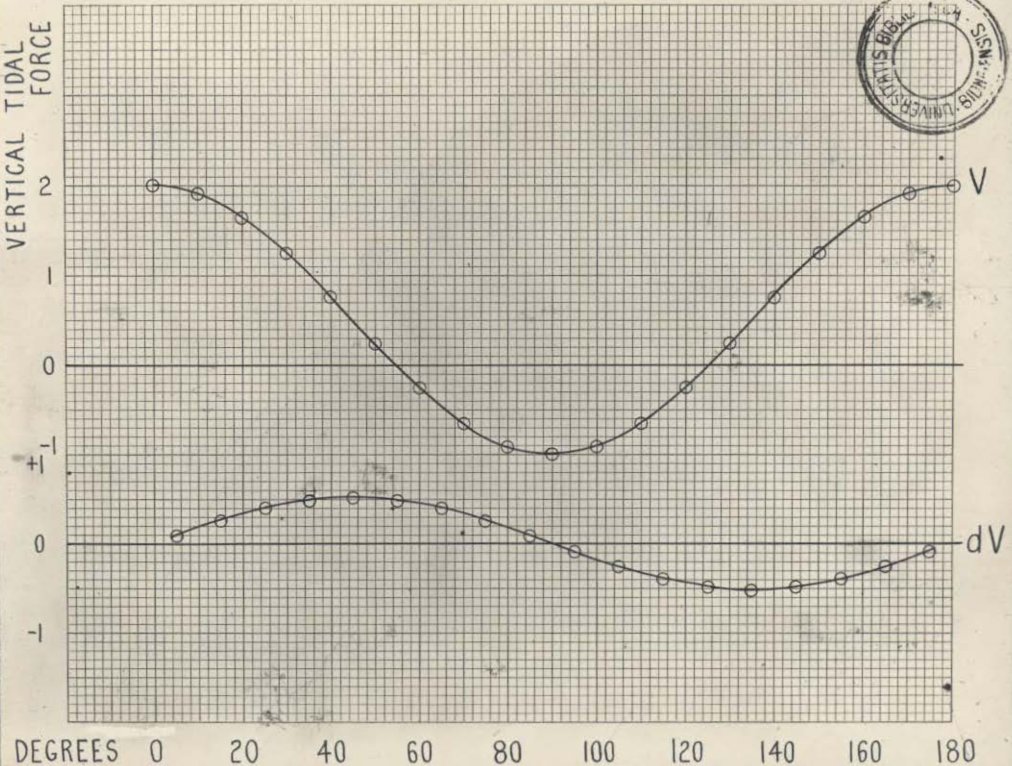


Fig. 3.

Fig. 4.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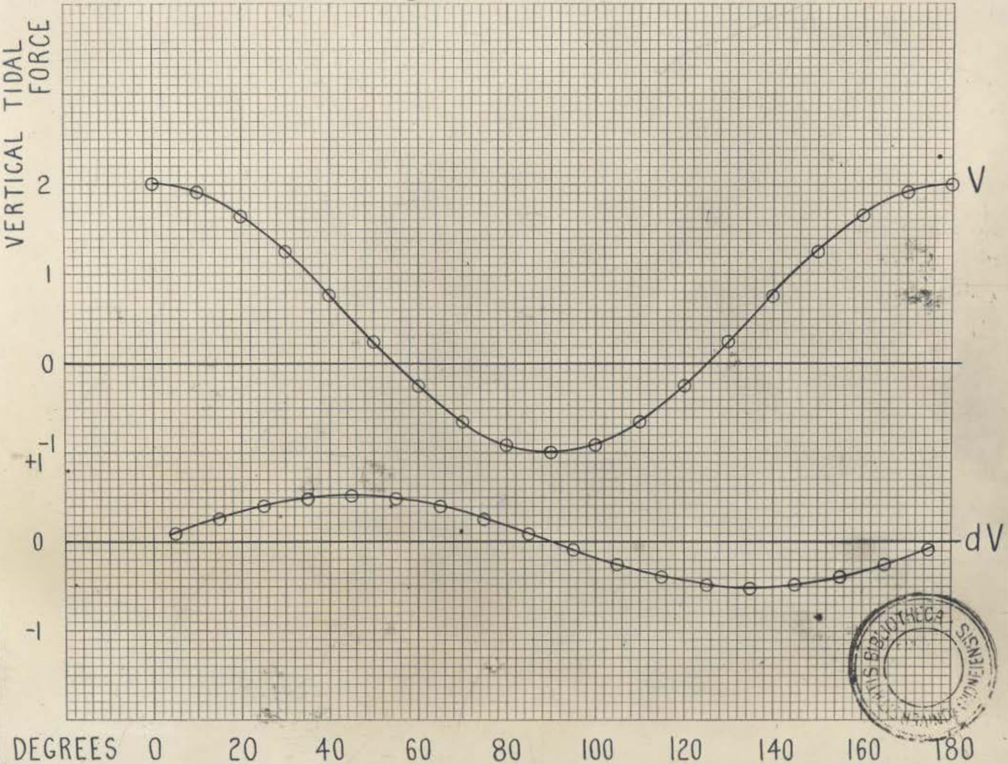
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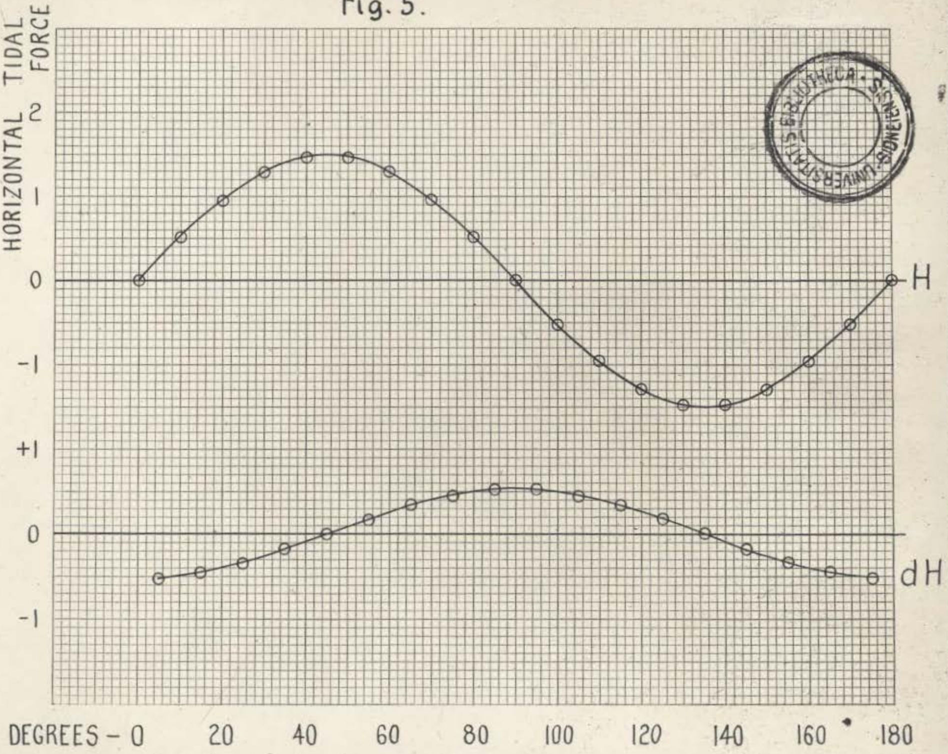
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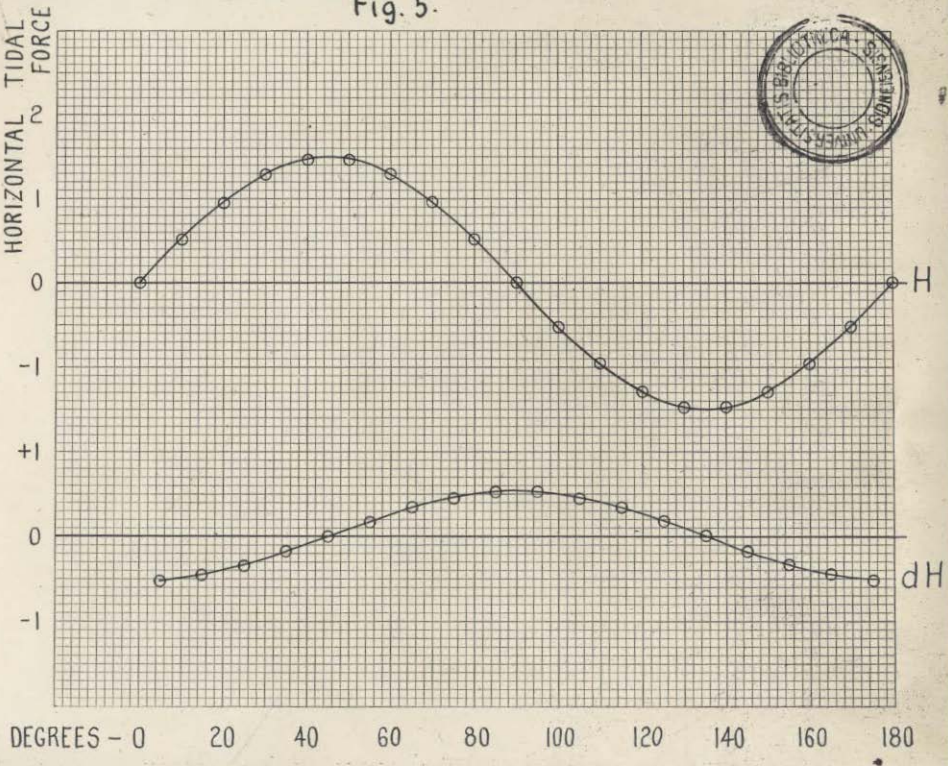
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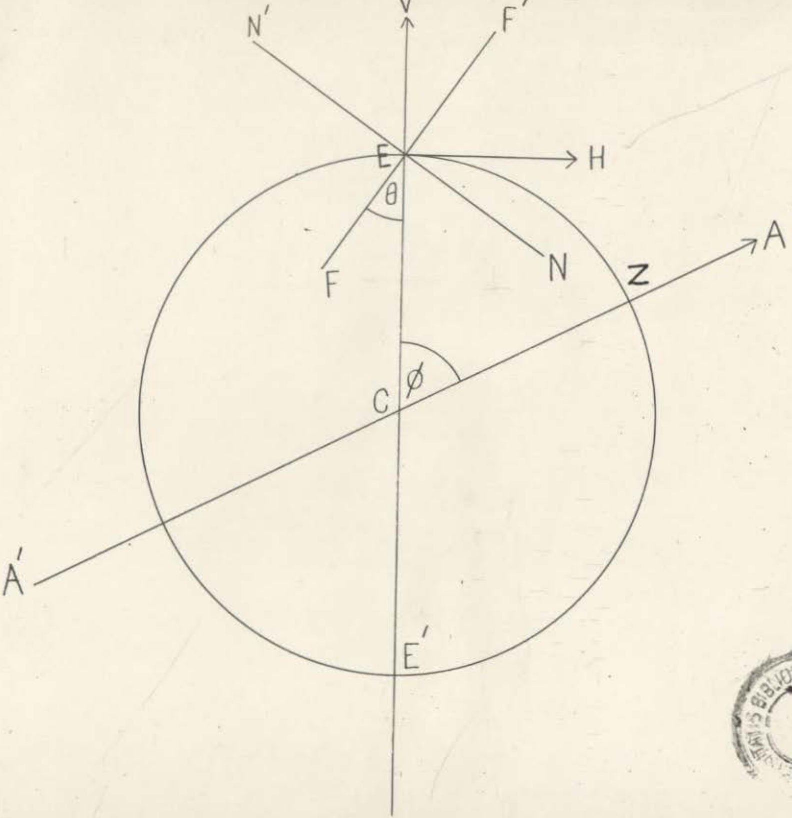

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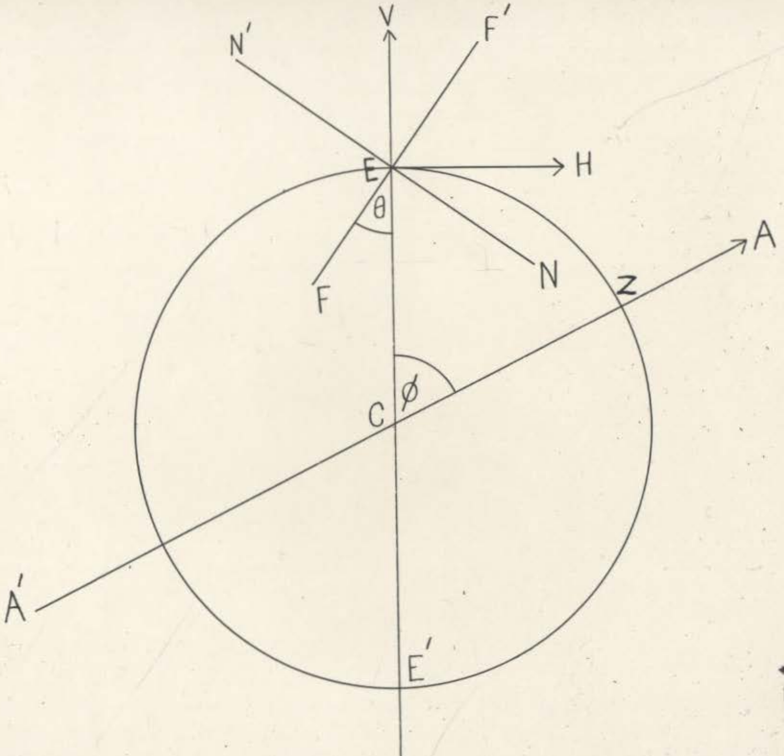

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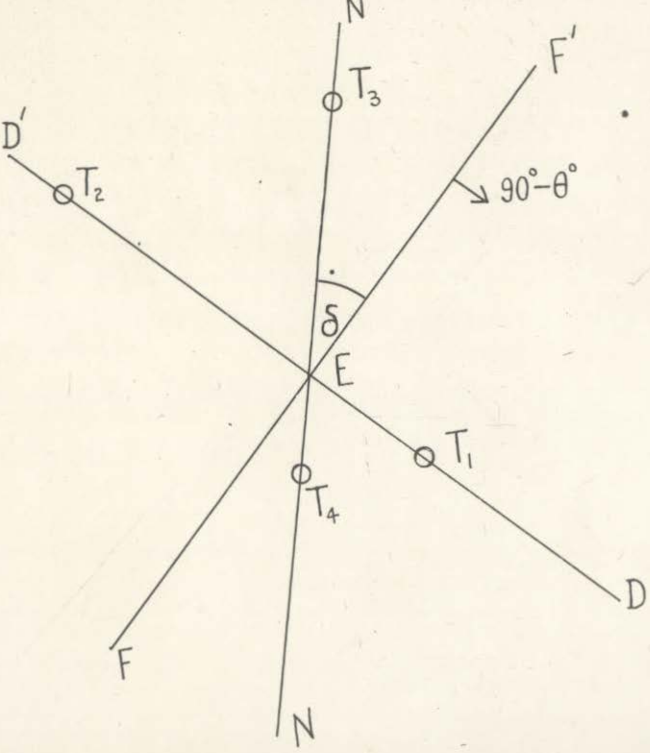

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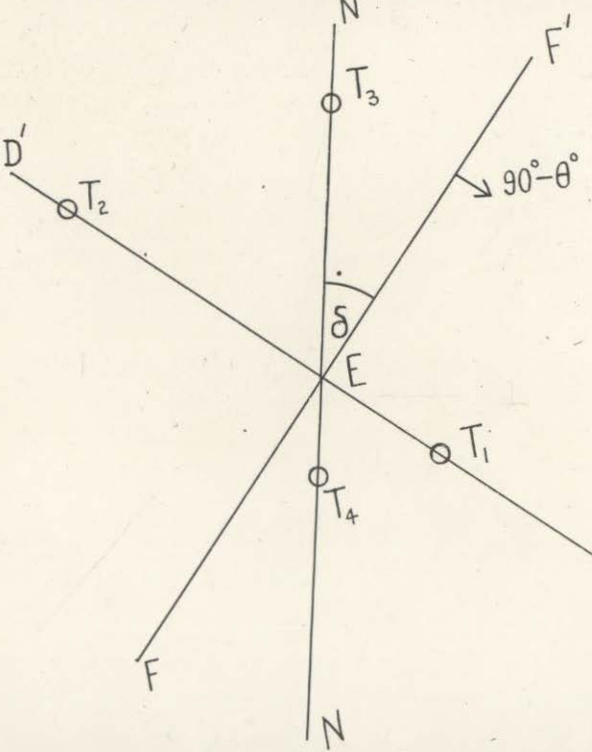

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Fig. 8.

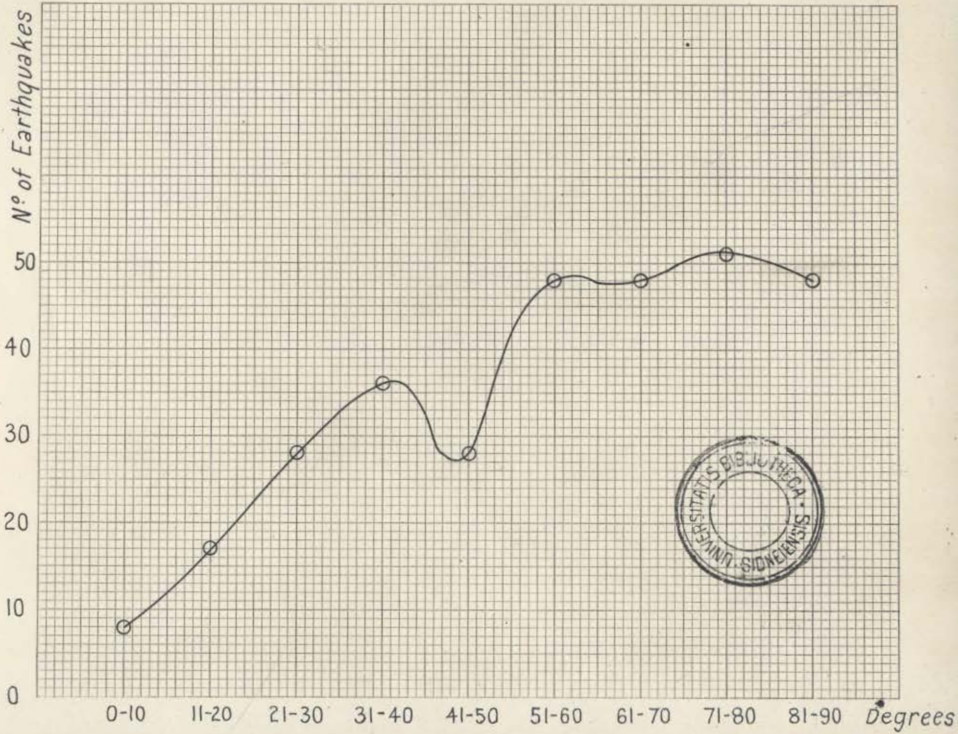

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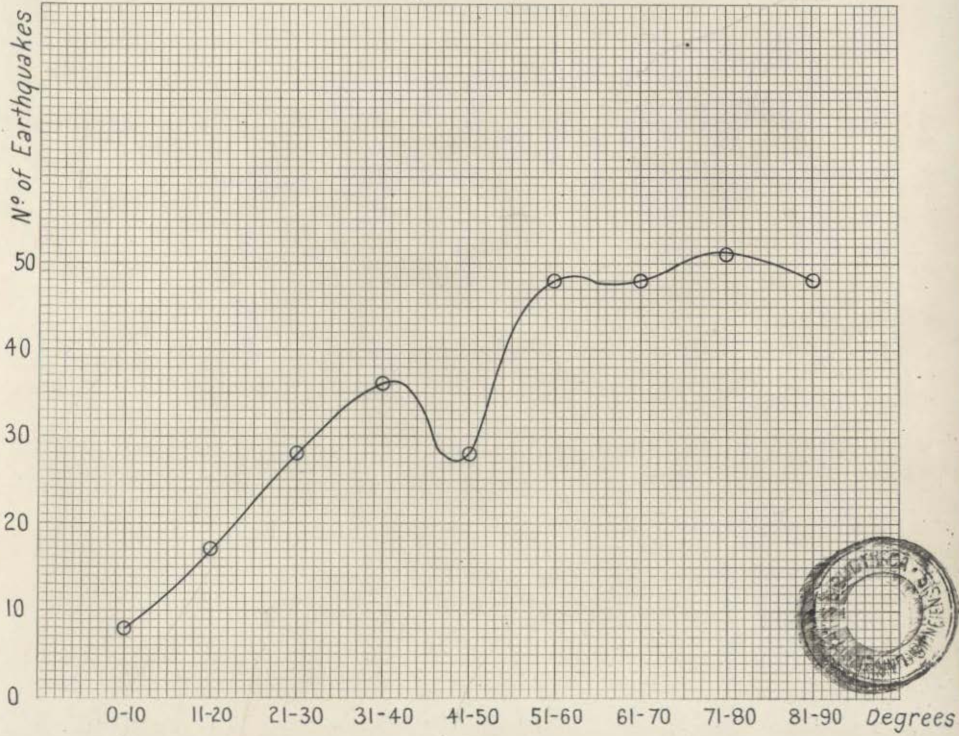
Fig. 8.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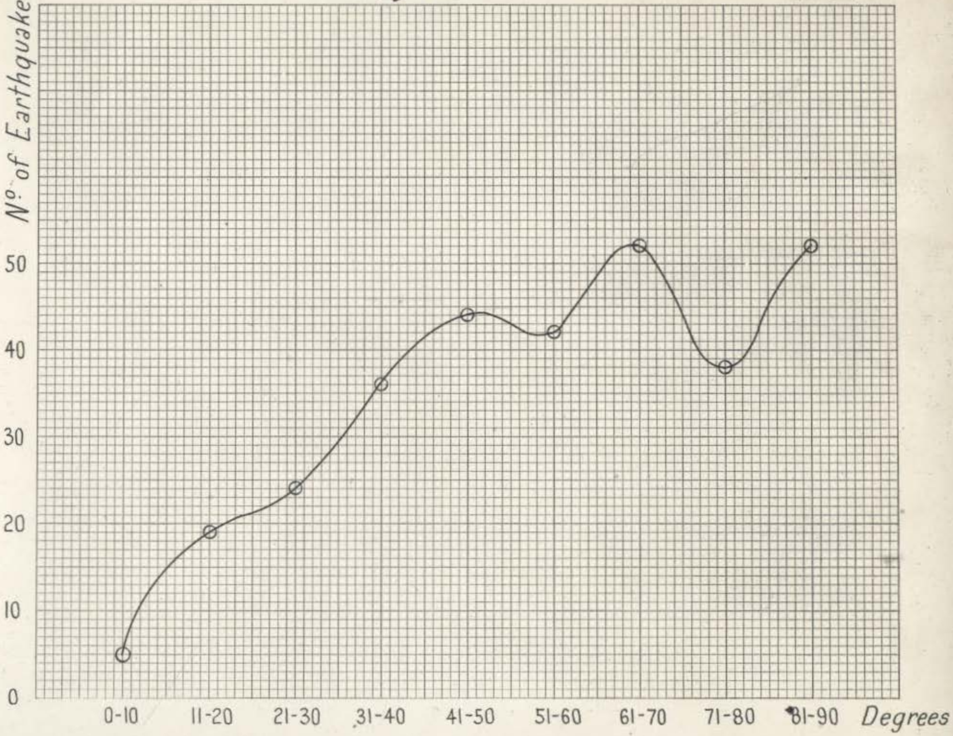
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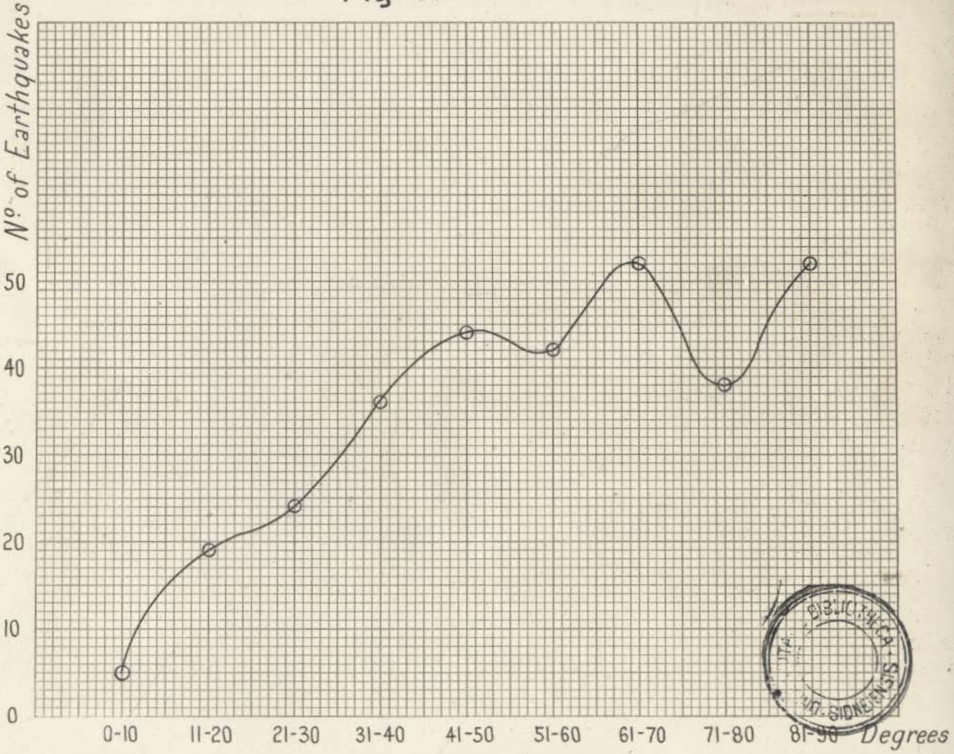
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Fig. 10.

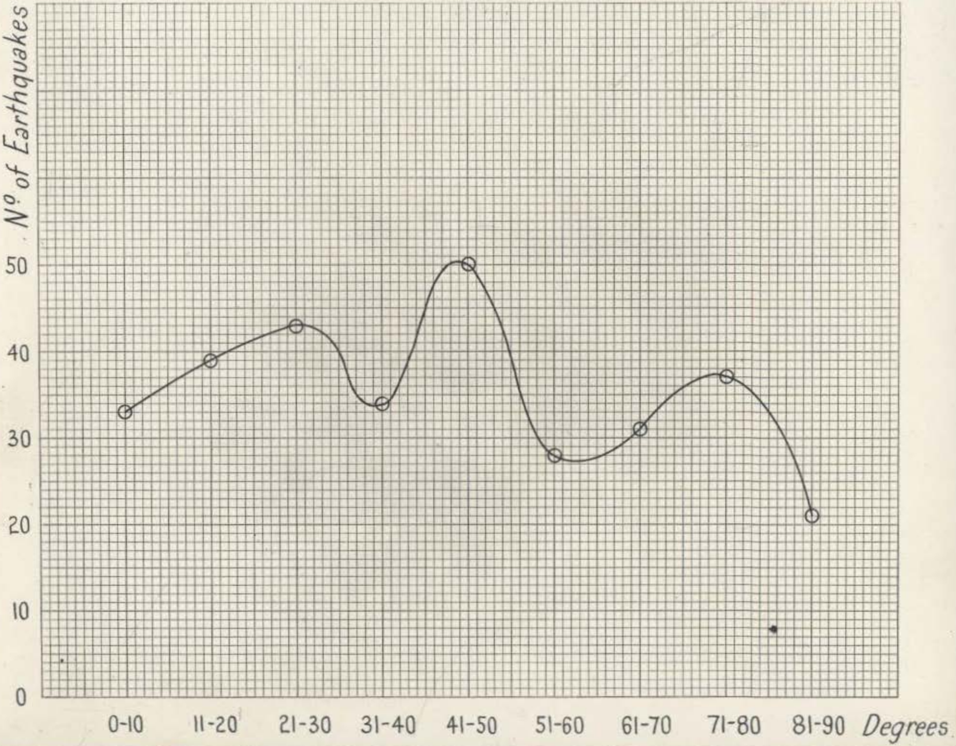

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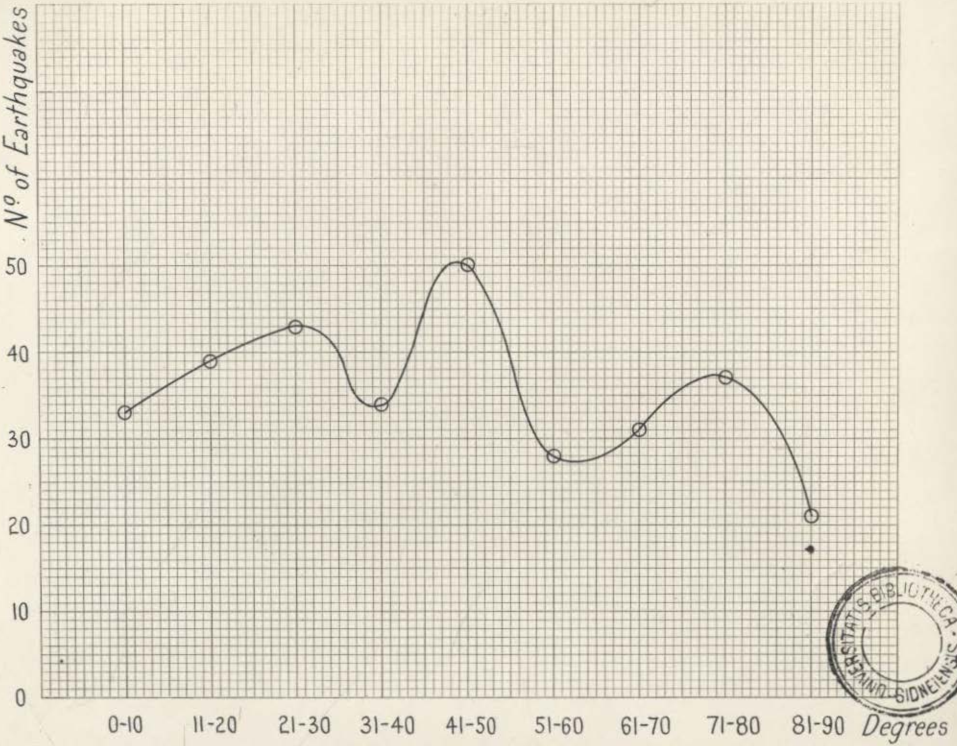
Fig. 10.



Nº of Earthquakes
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Degrees

Fig. 11.

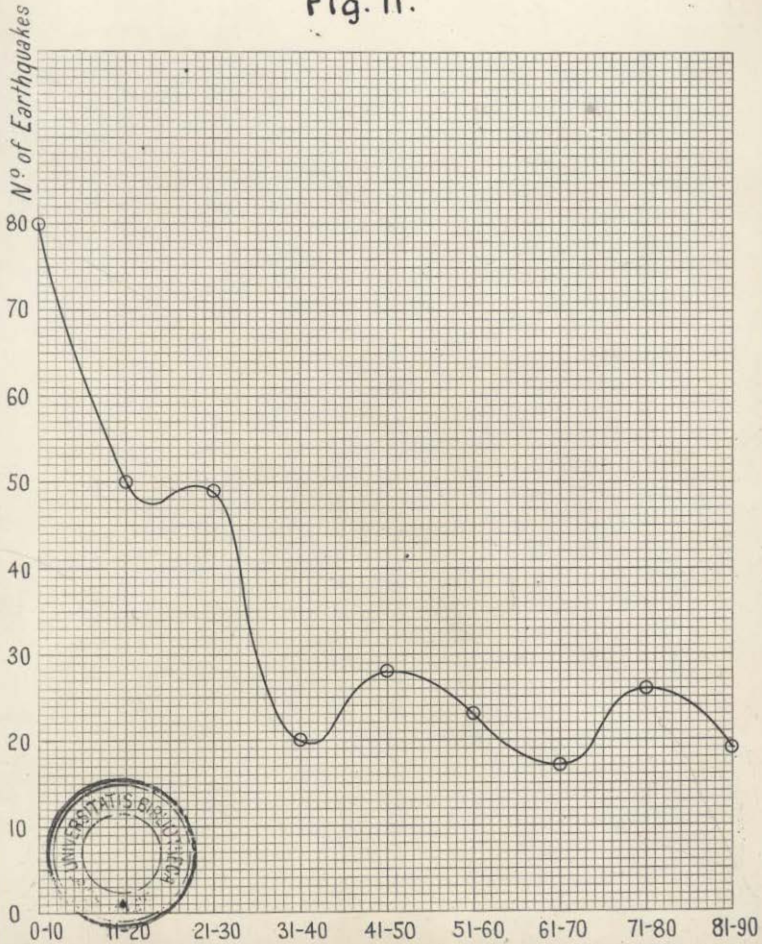
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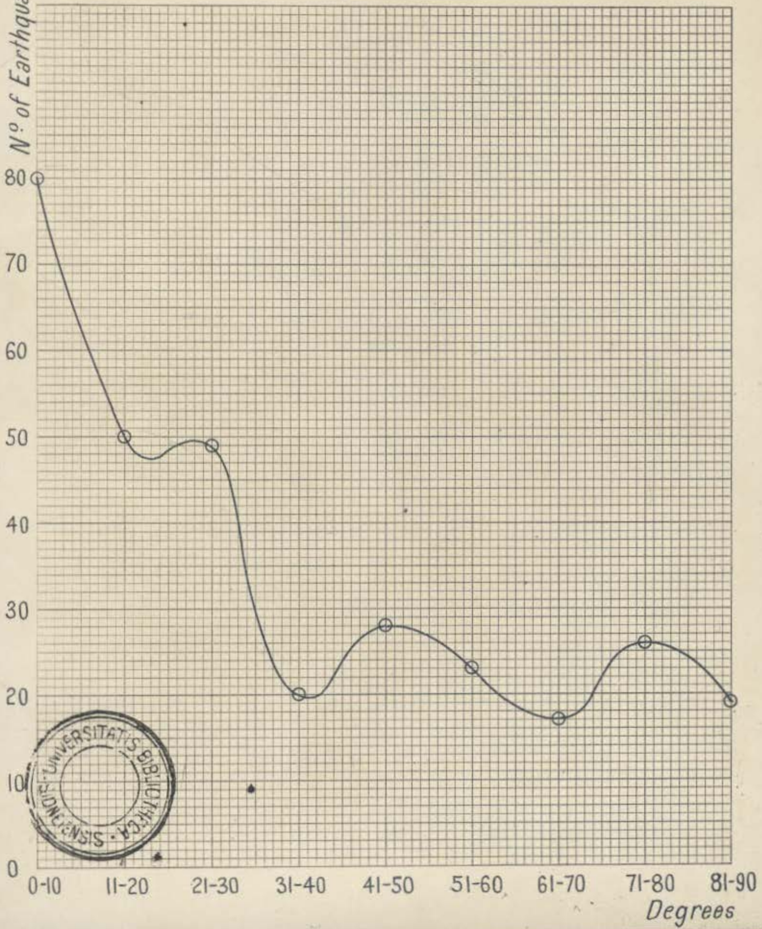
Fig. 11.



No. of Earthquakes
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31-40
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51-60
61-70
71-80
81-90
Degrees

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APPENDIX. A

Mathematical Analysis.

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SECTION I

Tidal stresses and their tendency to produce movement along plane fractures in the outer earth's crust.

The Problem Stated.

Given a plane fracture in the surface zone of the earth's crust, to determine, for a given point on the fracture, the zenith distance of an attracting body in a vertical plane perpendicular to the plane of the fracture such that,

(a) the differences in the components of the tidal forces, taken normal to the plane of the fracture, and acting on adjacent masses on opposites sides of the fracture, are a maximum; and,

(b) the differences in the components of the tidal forces, taken parallel to theplane of the fracture, and acting on adjacent masses on opposites of the fracture, are a maximum

Let EZE' be a central section of the earth, which is assumed to be spherical, taken perpendicular to the given plane fracture FEF'.

Let the trace of the fracture plane FEF' make an angle θ with the vertical E'CE through the point E.

Let the required position of the attracting body lie in the direction CZA making an angle ϕ with EC the vertical at E, and at a distance which is remote as compared with the earth's radius.

Let NN' be the normal to the fracture plane through E.

The attracting body lying in a direction CZA exercises a tide producing force at E, the amount of which may be derived from the potential at E.

It is well known[x] that the tide generating potential P is given by the relation

$$P = \frac{3m}{2r^3} p^2 \left(\cos^2\phi - \tfrac{1}{3}\right) \ldots\ldots\ldots\ldots (1)$$

where m is the mass of the attracting body, r its distance from the earth's centre, p the earth's radius and ϕ the angle between r and p.

This tide generating potential P gives rise to a tide producing force which may be represented by its vertical and horizontal components. Let these be denoted by V and H respectively. Then as can be readily shown[x] by differenting the tide generative potential P

$$V = \frac{m}{r^3} p \left(3\cos^2\varphi - 1\right) \ldots\ldots\ldots\ldots (2)$$

and

$$H = \frac{3m}{r^3} p \sin\varphi \cos\varphi \ldots\ldots\ldots\ldots (3)$$

where V may be taken as positive when directed away from the earth's centre, and H as positive when directed towards the attracting body.

By resolving along the normal NN' we have the forces along NN represented by F_1 where

$$F_1 = H\cos\theta - V\sin\theta \ldots\ldots\ldots\ldots (4)$$

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[x] G.H.Darwin - Article on Tides
Encyclopaedia Brittanica
11th Ed. Vol.XXVI, p.946.

[x] Lamb - Hydrodynamics, p.364.

[x] see also Andrew Gray - A treatise on Physics
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Similarly by resolving parallel to FF' we have the forces along MF' represented by F_2 where

$$F_2 = H \sin\theta + V \cos\theta.$$

Now let the differences in the components of the tidal forces on adjacent masses on opposite sides of the fracture plane be

dF_1 in a direction normal to the fracture plane and dF_2 ....parallel ....

These values will consequently be given by the relations

$$\frac{dF_1}{d\phi} = \frac{d}{d\phi}\left\{3K\sin\phi\cos\phi\cos\theta - K(3\cos^2\phi-1)\sin\theta\right\}$$

and

$$\frac{dF_2}{d} = \frac{d}{d}\left\{3K\sin\phi\cos\phi\sin\theta + K(3\cos^2\ -1)\cos\theta\right\}$$

where $K = \frac{m}{r^3}p$

Hence $\frac{dF_1}{d\phi} = 3K\cos(2\phi-\theta)$ ....(5)

and $\frac{dF_2}{d\phi} = -3K\sin(2\phi-\theta)$ ....(6)

As dF_1 and dF_2 represent the forces tending to produce relative movement of masses on opposite sides of the fracture plane, the most favourable conditions for movement occur when dF_1 and dF_2 reach their maximum numerical values without regard to sign.

From (5) we see that dF_1 has its maximum numerical values when

$$\cos(2\phi-\theta) = \pm 1$$

i.e. when $2\phi - \theta = 0$ or π

or $\phi = \frac{\theta}{2}$ or $\frac{\pi}{2}+\frac{\theta}{2}$ ....(7)

being positive in the former and negative in the latter case.

Similarly from (6) we see that dF_2 has its maximum numerid values when

$$-\sin(2\phi - \theta) = \pm 1$$

or when $2\phi - \theta = \frac{3\pi}{2}$ or $\frac{\pi}{2}$

i.e. when $\phi = \frac{3\pi}{4} + \frac{\theta}{2}$ or $\frac{\pi}{4} + \frac{\theta}{2}$ ....(8)

being positive in the former and negative in the latter case.

From (7) we see that when $\phi = \frac{\theta}{2}$ the forces acting normal to the fracture plane will operate to cause compression tending to close the fracture and that when $\phi = \frac{\pi}{2} + \frac{\theta}{2}$ these forces will operate to cause tension yending to open the fracture.

Again from (8) we see that when $\phi = \frac{\pi}{4} + \frac{\theta}{2}$ the forces acting parallel to the fracture plane will tend to move that part of the earth's crust which lies above the fracture plane downwards towards the earth's interior when the motion is considered relatively to the mass lying under the fracture plane;

and when

$\phi = \frac{3\pi}{4} + \frac{\theta}{2}$ the forces will tend to produce relative motion in the opposite direction.

Now it is known that the tide-producing forces at any part E (fig.~~1~~ 6) are the same whether the attracting body lies in the direction CA or in the opposite direction CA', the direction r being in each case the same.

Hence the disposition of the tidal forces in each of the cases above considered will be the same if the angle $\pi + \phi$ be substituted for ϕ in each case.

SECTION II.

The determination of the probability of certain relations in a certain series of observations.

The Problem Stated.

A certain series of 316 measurements were made comprising angles which ranged from 0 to 90°. These were grouped in 9 sets as shown in the following Table

Range for each group of measurements ~~falling~~	0 -10°	11° 20°	21° 30°	31°- 40°	41° 50°	51° 60°	61° 70°	71° 80°	81° 90°
No. falling in each group	80	50	49	20	28	23	17	26	19

If these represent random measurements what is the probability of obtaining such an arrangement as that indicated in the first three groups?

One ~~Another~~ way of looking at the problem is to enquire what are the probabilities of at least 80 of the measurements falling within the range 0-10°; of 50 of the remainder falling in the range 11°-20°; and of 49 of the remainder falling within the range 21°-30°.

It is shown in text-books dealing with probability [x] that the probability P, that an event happen on at least r out of n occasions where it is in question is given by the relation

$$P = nC_r p^r q^{n-r} + nC_{r+1} p^{r+1} q^{n-r-1} + \dots\dots\dots + nC_{n-1} p^{n-1} q + p^n$$

where the notation ~~relation~~ is the same as that ~~of the preceding discussion~~. adopted by Chrystal.

This formula is readily derived from that giving the probability of the event occurring exactly r times, since it represents the sum of the probabilities that the event occur exactly r, r+1, ... and n times.

Now from the nature of the case when r exceeds the expectancy, the event is less likely to occur r+1 times than r times; r+2 times than r+1 times; and so on. Hence each of the terms in the above expression is less than the

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[x] Chrystal-Algebra Vol.II,p.583.

one which precedes it and therefore the sum of the n-r 1 terms must be less than(n-r 1) times the value of the first term.

Therefore, the probability that at least 80 of the measurements fall within the range 0°-10° is

$$\therefore\ P < (n-r+1)nC_r p^r q^{n-r}$$

$$\text{i.e.} < \frac{1}{47\cdot5\text{x}10^8}$$

Similarly the probability that atleast 50 of the remaining measurements fall in the range 11°-20° is given by

$$\cancel{P'}\ \cancel{187\text{x}}\frac{1}{16\cdot2\text{x}10^3}$$

$$P' < \frac{1}{86\cdot6}$$

And again the probability that at least 49 of the remaining measurements occur in the range 31°-40° is given by

$$P'' < \frac{1}{10\cdot97\text{x}10^2}$$

Hence the total probability that the numbers of measurements reach at least 80,50 and 49 for the respective groups considered is ~~4a~~ less than the product PxP'xP"

$$\text{i.e. is less than } \frac{1}{47\cdot5\text{x}10^3} \text{ x } \frac{1}{86\cdot6} \text{ x } \frac{1}{10\cdot97\text{x}10^2}$$

$$\text{i.e.} < \frac{1}{45\cdot135\text{x}10^{13}}$$

Appendix. B

Part II - Tables 1 to VI.

TABLE I.

Giving particulars of the time and places of 316 world shaking earthquakes and the calculated earth latitudes and longitudes for the sun and moon at the times of the earthquakes.

Earthquake		Nautical Almanac		Earthquakes.		Sun's		Moon's	
No.	District.	Date 1899	Hour.	Lat.	Long.	Lat.	Long.	Lat.	Long.
282	A_1	April 16	2:38	N 58°	W 138°	N 10°	W 39°	N 22°	E 39°
308b	A_1	July 14	1:34	N 60°	W 150°	N 22°	W 22°	S 7°	E 36°
333	A_1	Sept. 3	12:20	N 59°	W 140°	N 7°	E 175°	N 3°	E 172°
334	A_1	Sept. 3	16:53	N 59°	W 140°	N 7°	E 107°	N 7°	E 95°
337	A_1	Sept.10	5:0	N 59°	W 140°	N 5°	W 76°	S 21°	W 16°
337b	A_1	Sept.10	8:43	N 59°	W 140°	N 5°	W 132°	S 21°	W 70°
338	A_1	Sept.10	9:38	N 59°	W 140°	N 5°	W 145°	S 21°	W 83°
341	A_1	Sept.15	17:14	N 59°	W 140°	N 3°	E 101°	S 15°	W 124°
342	A_1	Sept.17	0:51	N 59°	W 140°	N 2°	W 14°	S 9°	W 139°
344	A_1	Sept.22	23:04	N 65°	W 140°	N 0°	E 12°	N 21°	E 116°
345	A_1	Sept.23	1:43	N 55°	W 133°	0°	W 28°	N 21°	W 155°
		1900							
391	A_1	Feb. 25	15:41	N 59°	W 140°	S 9°	E 128°	S 19°	E 78°
442	A_1	Oct. 9	0:27	N 55°	W 132°	S 6°	W 10°	N 14°	W 175°
444	A_1	Oct.16	23:2	N 55°	W 132°	S 9°	E 11°	N 11°	W 64°
		1901							
460	A_1	Jan. 17	16:41	N 60°	W 135°	S 21°	E 113°	S 21°	E 78°
539	A_1	Oct. 15	1:23	N 23°	W 134°	S 8°	W 24°	S 18°	E 11°
560	A_1	Nov.20	11:57	N 50°	W 130°	S 20°	E 177°	S 1°	W 67°
		1902							
643	A_1	Oct. 2	5:48	N 58°	W 145°	S 3°	W 90°	S 9°	W 76°

Earthquake		Nautical Almanac		Earthquakes		Sun's		Moon's	
No.	District	Date	Hour	Lat.	Long.	Lat.	Long.	Lat.	Long.
		1903							
690	A1	March 15	2:13	N 51°	W 128°	S 2°	W 31°	S 8°	E 172
766	A1	Sept.10	1:48	N 58°	W 130°	N 5°	W 28°	N 9°	W 168
		1899							
248	A2	Jan. 13	14:37	N 20°	W 110°	S 21°	E 143°	S 10°	E 173
372	A2	Dec. 25	0:25	N 34°	W 117°	S 23°	W 6°	S 8°	W 95
		1900							
452	A2	Dec. 18	11:15	N 27°	W 120°	S 23°	E 170°	S. 19°	E 132
		1901							
470	A2	March 2	19:45	N 35.30°	W 120°	S 7°	E 67°	N 10°	W 137
472	A2	March 4	22:45	N 23	W 120°	S 6°	E 22°	N 1°	W 159
555b	A2	Nov.13	16:35	N 37°	W 117°	S 18°	E 107°	S 20°	E 140
564	A2	Dec. 8	14:17	N 23°	W 120°	S 23°	E 144°	S 18°	E 121
		1903							
674	A2	Jan.23	17:25	N 27°	W 120°	S 19°	E 112°	S 18°	E 60
		1902							
597	A2B	March 16	23:22	N 30°	W 109°	S 2°	E 12°	N 19°	E 107
661	A2B	Dec.12	11:05	N 23°	W 118°	S 23°	W 168°	N 15°	W 20

Earthquake		Nautical Almanac		Earthquakes		Sun's		Moon's	
No.	District	Date	Hour	Lat.	Long.	Lat.	Long.	Lat.	Long.
		1899							
250	B	Jan. 24	11:45	N 17°	W 99°	S 19°	W 173°	N 22°	W 14°
264	B	March 11	21:37	N 17°	W 103°	S 4°	E 39°	N 4°	E 44°
270	B	March 25	2:27	N 10°	W 87°	N 2°	W 35°	N 1°	E 125°
		1900							
381	B	Jan. 19	18:32	N 19°	W 108°	S 20°	E 85°	0	W 49°
407	B	May 16	8:13	N 20°	W 105°	N 19°	W 124°	S 22°	E 84°
415	B	June 16	2:43	N 3°	W 90°	N 23°	W 41°	S 14°	W 175°
417	B	June 21	8:56	N 15°	W 86°	N 23°	W 134°	N 13°	E 154°
447	B	Nov.9	4:7	N 11°	W 96°	S 17°	W 66°	N 21°	E 152°
		1901							
536	B	Oct.7	14:16	N 7°	W 90°	S 5°	E 143°	N 9°	E 94°
		1902							
576	B	Jan. 16	11:53	N 17°	W 99°	S 21°	W 76°	N 10°	W 94°
578	B	Jan. 18	11:23	N 16°	W 94°	S 21°	W 168°	N 17°	W 61°
606a	B	April 18	14:22	N 15°	W 91.3°	N 11°	E 145°	N 2°	W 75°
642	B	Sept.23	8:16	N 15°	W 90°	N 0	W 36°	N 19°	W 138°
		1903							
671	B	Jan. 13	13:44	N 3°	W 90°	S 22°	E 156°	S 3°	E 28°

Earthquake		Nautical Almanac		Earthquakes		Sun's		Moon's	
No.	District	Date	Hour.	Lat.	Long.	Lat.	Long.	Lat.	Long.
		1899							
291	BD_1	June 4	16:30	N.S 0	W 85°	N 22°	E 112°	N 18°	E 74°
600b	BD_1	1902 March 24	15:26	N 3°	W 87°	N 1°	E 131°	S 8°	W 39°
		1899							
269	C_1	March 23	2:26	N 22°	W 59°	N 1°	W 34°	N 11°	E 106°
292	C_1	June 5	3:2	N 23°	W 73°	N 23°	W 45°	N 20°	W 78°
294	C_1	June 14	23:6	N 18°	W 77°	N 23°	E 14°	N 7°	E 83°
321	C_1	Aug. 2	3:16	N 23°	W 76°	N 18°	W 47°	N 24°	W 92°
322	C_1	Aug. 2	5:57	N 25°	W 90°	N 18°	W 87°	N 23°	W 130°
		1901							
498	C_1	May 27	4:25	N 20°	W 70°	N 21°	W 67°	S 5°	E 50°
		1902							
582	C_1	Jan. 28	6:48	N 20°	W 68°	S 18°	W 91°	S 5°	E 136°
589a	C_1	Feb.16	12:39	N 20°	W 70°	S 12°	E 174°	N 19°	W 80°
600	C_1	March 24	5:58	N 31°	W 80°	N 1°	W 87°	S 6°	E 98°
642	C_1	Sept. 23	16:54	N 31°	W 80°	0	E 105°	N 19°	E 8°
		1903							
672	C_1	Jan. 17	4:12	N 25°	W 88°	S 21°	W 61°	N 1°	E 173°
687	C_1	Feb. 27	21:50	N 20°	W 81°	S 8°	E 36°	S 2°	E 42°
761	C_1	Aug.16	1:35	N 20°	W 72°	N 14°	W 23°	N 16°	W 12°

Earthquake		Nautical	Almanac	Earthquakes		Sun's		Moon's	
No.	District	Date	Hour	Lat.	Long	Lat.	Long.	Lat.	Long.
		1899							
361	C_2	Nov. 18	2:55	N 3°	W 65°	S 19°	W 48°	N 23°	E 147°
		1900							
422	C_2	July 15	6:49	N 12°	W 70°	N 22°	W 101°	S 4°	E 121°
445	C_2	Oct. 28	21:26	N 11°	W 68°	S 13°	E 35°	S 20°	E 104°
		1902							
580	C_2	Jan. 21	9:40	N 3°	W 71°	S 20°	W 142°	N 19°	E 7°
		1899							
303	D_1	July 6	20:38	S 10°	W 90°	N 23°	E 52°	N 22°	E 47°
		1900							
432	D_1	Aug. 31	19:56	N 10°	W 94°	N 9°	E 61°	S 20°	E 136°
		1901							
455	D_1	Jan. 6	12:30	S 2°	W 82°	S 23°	E 174°	N 13°	E 18°
537	D_1	Oct.18	14:56	S 7°	W 85°	S 6°	E 133°	S 4°	E 117
		1903							
675	D_1	Jan. 24	3:37	S 5°	W 86°	S 19°	W 51°	S 19°	W 98°
676b	D_1	Feb.1	21:30	S 15°	W 100°	S 17°	E 17°	N 3°	E 66°
		1899							
268	D_2	March 22	22:23	S 20°	W 67°	N 1°	E 26°	N 12°	E 165°
278	D_2	April 12	5:23	S 28°	W 67°	N 9°	W 81°	N 22°	W 51°
279	D2	April 12	15:36	S 29.5°	W 67°	N 9°	E 126	N 23	E 162

Earthquake		Nautical	Almanac	Earthquakes		Sun's		Moon's	
No.	District	Date	Hour	Lat.	Long.	Lat.	Long.	Lat.	Long.
		1902							
593	D_2	March 5	7:3	S 20°	W 83°	S 6°	W 103°	S 17°	W 157°
605b	D_2	April 11	11:55	S 27°	W 65°	N 8°	W 179°	N 19°	W 131°
		1903							
668	D_2	Jan. 3	16:53	S 15°	W 83°	S 23°	E 107°	S 5°	E 175°
698	D_2?	March 29	4:28			N 3°	W 66°	N 6°	W 59°
793b	D_2	Dec. 7	2:40	S 28°	W 71°	S 23°	W 42°	N 17°	E 179°
		1901							
497	$D_1 D_2$	May 25	19:40	S 15°	W 63°	N 21°	E 64°	N 1°	E 168°
		1899							
295	E	June 16	13:8	N 40°	E 145°	N 23°	E 163°	S 6°	W 101°
		1900							
397	E	March 11	13:32	N 38°	E 142°	S 4°	E 160°	N 16°	W 66°
405	E	May 11	5:21	N 39°	E 144°	N 18°	W 81°	S 11°	E 65°
425	E	Aug. 4	16:18	N 39°	E 144°	N 17°	E 117°	S 21°	W 132°
431	E	Aug. 28	14:32	N 42°	E 145°	N 10°	E 142°	S 11°	W 179°
450	E	Nov. 23	19:54	N 40°	E 148°	S 20°	E 59°	S 21°	E 84°
		1901							
458	E	Jan. 13		N 42°	E 145°	S 22°	E 23°	S 17°	W 55°

Earthquake No.	District	Nautical Almanac Date	Hour.	Earthquakes Lat.	Long.	Sun's Lat.	Long.	Moon's Lat.	Long.
475	E_1	March 18	11:24	N 50°	E 159°	S 1°	W 169°	S 5°	E 168°
475x	E_1	March 19	11:46	N 50°	E 159°	S 1°	W 174°	0	E 170°
483	E_1	April 5	11:32	N 44°	E 149°	N 6°	W 172°	S 15°	E 28°
493	E_1	May 13	18:49	N 42°	E 148°	N 18°	E 77°	N 3°	W 24°
514	E_1	Aug. 8	21:21	N 40°	E 144°	N 16°	E 41°	N 20°	W 25°
516	E_1	Aug. 9	6:32	N 40°	E 144°	N 16°	W 97°	N 20°	W 158°
551	E_1	Nov. 7	18:3	N 40°	E 150°	S 16°	E 85°	S 7°	E 46°
		1902							
584	E_1	Jan. 30	1:59	N 43°	E 145°	S 18°	W 27°	S 12°	W 143°
585	E_1	Jan. 30	13:41	N 43°	E 145°	S 18°	E E 158°	S 13°	E 58°
607	E_1	May 1	23:39	N 39°	E 144°	N 15°	E 4°	S 7°	W 64°
		1903							
760	E_1	Aug. 13	3:46	N 41	E 146°	N 15°	W 55°	N 6°	W 179°
		1899							
267	E_2	March 21	2:31	N 24°	E 129°	0	W 36°	N 19°	E 83°
307	E_2	July 10	19:29	N 15°	E 140°	N 22°	E 69°	N 9°	E 106°
		1900							
446	E_2	Nov. 4	19:39	N 34°	E 139°	S 15°	E 61°	N 11°	W 142°
448	E_2	Nov. 9	5:52	N 34°	E 139°	S 17°	W 92°	N 21°	[illegible]

Earthquake		Nautical Almanac		Earthquakes		Sun's		Moon's	
No.	District	Date	Hour	Lat.	Long.	Lat.	Long.	Lat.	Long.
454	E_2	Dec. 24 1902	17:2	N 27°	E 146°	S 23°	E 105°	S 12°	E 146°
641	E_2	Sept. 21 1903	13:44	N 13°	E 130°	N 1°	E 152°	N 16°	E 25°
681	E_2	Feb. 9 1899	14:48	N 11°	E 142°	S 15°	E 114°	N 17°	W 66°
366	E_3	Nov. 24 1900	6:41	N 43°	E 131°	S 21°	W 103°	N 8°	E 164°
404	E_3	April 24	11:14	N 27°	E 126.5°	N 13°	W 168°	S 5°	E 136°
411	E_3	June 9 1901	0:11	N 30°	E 130°	N 23°	W 3°	S 16°	E 131°
500	E_3	June 6	12:3	N 23°	E 121°	N 23°	E 179°	S 13°	E 68°
505	E_3	June 23	19:3	N 25°	E 135°	N 23°	E 76°	S 6°	E 169°
565	E_3	Dec. 14 1902	10:54	N 14°	E 121°	S 23°	W 164°	S 14°	W 119°
592	E_3	Feb. 28	12:13	N 24°	E 122°	S 8°	E 180°	S 17°	E 70°

Earthquake		Nautical Almanac		Earthquakes		Sun's		Moon's	
No.	District.	Date	Hour	Lat.	Long.	Lat.	Long.	Lat.	Long.
598	E_3	March 19	13:50	N 24°	E 122°	S 1°	E 155°	N 13°	W 74°
606c	W of E_3	April 18	14:36	N 27°	E 113°	N 11°	E 141°	N 2°	W 79°
609	E_3	May 7	14:19	N 30°	E 132°	N 17°	E 144°	N 16°	E 147°
625	E_3	Aug. 20	23:17	N 8°	E 124°	N 13°	E 12°	0	W 144°
655	E_3	Nov. 14	21:30	N 28°	E 128°	S 18°	E 34°	N 15°	E 161
656	E_3	Nov. 16	12:36	N 14°	E 121°	S 19°	E 168°	N 18°	E 8°
658	E_3	Nov. 20	8:32	N 21°	E 121	S 20°	W 132°	N 13°	E 122°
659	E_3	Nov. 20	19:3	N 21°	E 120°	S 20°	E 70°	N 12°	W 28°
		1903							
668b	E_3	Jan. 3	17:17	N 13°	E 120°	S 23°	E 102°	S 4°	E 159°
670	E_3	Jan. 5	9:59	N 34°	E 124°	S 23°	W 149°	N 2°	W 73°
710b	E_3	May 23	10:7	N 7°	E 126°	N 20°	W 153°	N 8°	E 168°
719	E_3	June 6	21:5	N 21°	E 122°	N 23°	E 44°	S 14°	W 167°
748b	E_3	July 23	10:36	N 19°	E 121°	N 20°	W 157°	N 17°	W 166°
764b	E_3	Sept. 6	19:14	N 23°	E 122°	N 7°	E 72°	S 4°	W 106°
773	E_3	Oct. 10	4:41	N 32°	E 132°	S 6°	W 73°	N 17°	E 157°
785	E_3	Nov. 17	8:23	N 9°	E 126°	S 19°	W 130°	S 11°	W 110°
790	E_3	Dec. 1	2:21	N 24°	E 120°	S 22°	W 38°	N 9°	E 101°

Earthquake		Nautical Almanac		Earthquakes		Sun's		Moon's	
No.	District.	Date	Hour	Lat.	Long.	Lat.	Long.	Lat.	Long.
		1899							
263	E_{123}	March 7	12:53	N 33.8	E 136°	S 5°	E 170°	S 19°	E 118°
		1899							
310	F_1	July 16	22:0	N 5	E 130°	N 21°	E 31°	S 19°	E 133°
324	F_1	Aug. 3	16:43	N 8°	E 120°	N 17°	E 111°	N 21°	E 85°
352	F_1	Oct. 13	5:28	S 10°	E 173°	S 8°	W 86°	S 14°	E 26°
354	F_1	Oct. 18	21:16	S 5°	E 148°	S 10°	E 37°	N 16°	W 138°
358	F_1	Nov. 12	11:43	S25°	E 162°	S 18°	W 180°	N 2°	W 57°
365	F_1	Nov. 23	21:56	0	E 128°	S 20°	E 28°	N 10°	W 168°
366	F_1	Nov. 24	6:39	N 5°	E 136°	S 21°	W 103°	N 8°	E 164°
		1900							
377	F_1	Jan. 10	21:5	S 5°	E 148°	S 22°	E 46°	N 22°	E 172°
386b	F_1	Feb. 2	16:15	N 2°	E 126°	S 17°	E 119°	N 4°	E 158°
414	F_1	June 12	8:15	0	E 135°	N 23°	W 124°	S 22°	E 52°
427	F_1	Aug. 13	8:13	N 2°	E 137°	N 15°	W 122°	N 5°	E 95°
438	F_1	Sept. 20	6:57	N 5°	E 136°	N 1°	W 106°	N 9°	W 139°
441	F_1	Oct. 7	9:0	0	E 130°	S 5°	W 139°	N 6°	E 31°
441b	F_1	Oct. 7	20:42	S 12°	E 155°	S 5°	W 47°	N 8°	E 130°

Earthquake		Nautical Almanac		Earthquake's		Sun's		Moon's	
No.	District.	Date	Hour	Lat. L	Long.	Lat.	Lo ng.	Lat.	Long.
448b	F_1	Nov. 11	13:6	N 3°	E 147°	S 7°	E 160°	N 17°	E 90°
		1901							
468a	F_1	Feb. 19	21:36	N 3°	E 152°	S 11°	E 40°	0	E 55°
483b	F_1	April 5	9:53	N 2°	E 130°	N 6°	W 147°	S 15°	E 14°
515	F_1	Aug. 9	1:1	S 20°	E 159°	N 16°	W 14°	N 20°	E 105°
517	F_1	Aug. 9	22:27	S 5°	E 155°	N 16°	E 24°	N 19°	W 28°
530	F_1	Sept. 8	5:42	S 11°	E 170°	N 6°	W 86°	N 16°	W 146°
555	F_1	Nov. 12	22:16	0	E 122°	S 18°	E 22°	S 20°	E 46°
562	F_1	Nov. 24	13:52	N 3°	E 127°	S 20°	E 149°	N 17°	W 45°
		1902							
581	F_1	Jan. 24	13:23	S 8°	E 161°	S 19°	W 160°	N 11°	E 23°
590	F1	Feb. 25	3:35	0	E 127°	S 9°	W 51°	S 7°	E 162°
601e	F_1	March 28	2:43	N 3°	E 130°	N 3°	W 40°	S 18°	W 172°
624	F_1	Aug. 15	20:0	S 15°	E 165°	N 14°	E 61°	S 17°	W 154°
		1903							
673	F_1	Jan. 19	0:36	N 1°	E 140°	S 21°	E 6°	S 7°	W 99°
685	F_1	Feb. 24	5:33	S 8°	E 152°	S 10°	W 80°	S 14°	W 112°
724	F_1	June 10	4:31	0	E 149°	N 23°	W 68°	S 19°	E 119°

Earthquake		Nautical Almanac		Earthquake's		Sun's		Moon's	
No.	District.	Date	Hour	Lat.	Long.	Lat.	Long.	Lat.	Long.
746	F_1	July 11	17:27	S 5°	E 150°	N 22°	E 99°	S 12°	W 54°
775	F_1	Oct. 19	14:47	S 9°	E 168°	S 10°	E 134°	S 6°	E 128°
780	F_1	Oct. 29	2:19	S 20°	E 167°	S 13°	W 39°	S 12°	E 67°
781	F_1	Oct. 29	15:54	S 20°	E 175°	S 13°	E 118°	S 10°	W 129°
784	F_1	Nov. 10	8:46	S 17°	E 167°	S 17°	E 144°	N 15°	E 123°
		1899							
247	F_2	Jan. 11	20:0	N 2°	E 128°	S 22°	E 62°	S 19°	E 68°
347	F_2	Sept. 29	5:1	S 4°	E 129°	S 2°	W 77°	N 14°	W 146°
355	F_2	Oct. 23	15:57	S 9°	E 124°	S 11°	E 117°	N 22°	E 5°
		1901							
471	F_2	March 4	4:12	S 12°	E 113°	S 7°	W 60°	N 3°	E 110°
529	F_2	Sept. 7	10:34	S 5°	E 125°	N 6°	W 158°	N 18°	E 142°
		1902							
621b	F_2	Aug. 6	23:46	S 4°	E 108°	N 17°	E 5°	S 3°	E 49°
655b	F_2	Nov. 14	21:33	S 20°	E 105°	S 18°	E 33°	N 15°	W 135°
		1903							
682	F_2	Feb. 11	4:5	S 8°	E 119°	S 14°	W 57°	N 12°	E 116°
699	F_2	March 29	15:23	S 3°	E 126°	N 3°	E 130°	N 8°	E 143°

Earthquake No.	District	Nautical Almanac Date	Hour	Earthquake's Lat.	Earthquake's Long.	Sun's Lat.	Sun's Long.	Moon's Lat.	Moon's Long.
710a	F_2	May 23	8:7	S 8°	E 110°	N 20°	W 123°	N 8°	W 163°
774	F_2	Oct. 13	15:30ca	S 11°	E 138°	S 7°	E 127°	N 16°	E 44°
		1899							
251	F_3	Jan. 30	5:45	0	E 90°	S 18°	W 83°	S 2°	E 136°
298	F_3	June 23	4:57	N 1°	E 97°	N 23°	W 73°	S 20°	E 123°
299	F_3	June 29	10:52	N 1	E 97°	N 23°	W 162°	N 7°	E 102°
		1900							
376	F_3	Jan. 5	6:56	S 3°	E 102.5°	S 23°	W 103°	S 2°	W 48°
		1901							
456	F_3	Jan. 8	7:38	S 6°	E 92°	S 22°	W 112°	N 6°	E 112°
468	F_3	Feb. 14	20:4	S 8°	E 95°	S 13°	E 61°	S 20°	E 10°
519	F_3	Aug. 17	14:5	S 27°	E 92°	N 14°	E 150°	S 6°	E 171°
532	F_3	Sept. 9	16:26	N 7°	E 90°	N 5°	E 113°	N 13°	E 81°
543	F_3	Oct. 18	21:0 ca	—	—	S 9°	E 41°	S 19°	E 118°
		1902							
574	F_3	Jan. 12	10:24	S 15°	E 100°	S 22°	W 156°	S 7°	W 120°
		1903							
686	F_3	Feb. 26	12:44	S 5°	E 104°	S 9°	E 172°	S 7°	E 156°

Earthquake		Nautical Almanac		Earthquake's		Sun's		Moon's	
No.	District	Date	Hour	Lat.	Long.	Lat.	Long.	Lat.	Long.
774b	F_3	Oct. 18	15:5ca	S 3°	E 98°	S 9°	E 130°	S 2°	E 112°
		1902							
639	F_1E_3	Sept. 15	22:54	N 6°	E 122°	N 3°	E 16°	S 5°	E 180°
		1903							
788	F_1E_3	Nov. 24	1:34	N 3°	E 125°	S 20°	W 26°	S 15°	E 38°
802	F_1E_3	Dec. 27	14:50	N 3°	E 123°	S 23°	E 139°	N 5°	W 121°
		1899							
332	F_1M_1	Aug. 24	3:9	S 27°	E 165°	N 11°	W 47°	N 12°	E 175°
		1899							
305	G_1	July 9	7:8	S 5°	E 65°	N 22°	W 106°	N 15°	W 84°
		1900							
404b	G_1	April 30	8:17	N 12°	E 48°	N 15°	W 125°	N 21°	W 103°
443	G_1	Oct. 9	15:6	N 16°	E 60°	S 6°	E 131°	N 16°	W 28°
		1903							
777	G_1	Oct. 20	21:50	S 33°	E 55°	S 10°	E 29°	S 14°	E 40°
793	G_1	Dec. 6	10:48	S 41°	E 45°	S 22°	W 164°	N 18°	E 47°
		1900							
383	G_2	Jan. 29	10:30	S 10°	E 82°	S 18°	W 154°	S 19°	W 171°

Earthquake		Nautical Almanac		Earthquake's		Sun's		Moon's	
No.	District	Date	Hour	Lat.	Long.	Lat.	Long.	Lat.	Long.
390b	G_2	Feb. 20	9:36	S 19°	E 80°	S 11°	W 141°	S 18°	W 102°
433b	G_2	Sept. 9	10:48	0	E 84°	N 5°	W 163°	N 3°	W 171°
		1901							
492b	G_2	April 26	16:5	N 12°	E 75°	N 13°	E 118°	N 9°	W 131°
		1902							
606d	G_2	April 18	14:34	S 35°	E 60°	N 11°	E 142°	N 2°	W 78°
606d	G_2	April 21	5:26	S 40°	E 68°	N 12°	W 81°	S 9°	E 67°
642b	G_2	Sept. 23	8:29ca.	S 60°	E 77°	S	W 129°	N 19°	E 139°
		1899							
374	G_1G_2	Dec. 31	8:19	S 3°	E 68°	S 23°	W 124°	S ~~2~~23°	W 135°
		1899							
252	H	Jan. 30	23:12	N 35°	W 28°	S 18°	E 130°	S 6°	W 120°
254	H	Feb. 23	1:36	N 45°	W 25°	S 10°	W 21°	N 14°	W 136°
255	H	Feb. 26	1:36	N 45°	W 25°	S 9°	W 21°	S	E 167°
256	H	Feb. 26	23:17	N 52°	W 20°	S 8°	E 14°	S 5°	W 148°
257	H	Feb. 27	3:21	N 50°	W 22°	S - 8°	W 47°	S 5°	E 151°
307b	H	July 10	19:36	N 35°	W 42°	N 22°	E 67°	N 8°	E 105°
308	H	July 11	13:35	N	W 20°	N 22°	E 157°	N 5°	W 158°
346	H	Sept. 26	20:1	N 9°	W 40°	S 1°	E 58°	N 21°	W 23°

Earthquake		Nautical Almanac		Earthquake's		Sun's		Moon's	
No.	District.	Date	Hour	Lat.	Long.	Lat.	Long.	Lat.	Long.
372	H	Dec. 25 1900	12:23	N 30°	W 42°	S 23°	E 174°	S 10°	E 90°
379	H	Jan. 15 1900	7:46	N. 5°	W 40°	S 21°	W 114°	N 18°	E 66°
619	H	July 19 1903	20:49	S 5°	W 25°	N 21°	E 49°	S 17°	W 135°
750	H	July 26	22:34	N 33°	W 57°	N 20°	E 24°	N 4°	E 64°
751	H	July 27	0:32ca	N 33°	W 57°	N 19°	W 6°	N 4°	W 109°
767	H	Sept. 13 1899	3:31ca	N 41°	W 19°	N 4°	W 54°	N 17°	W 157°
259	J	Feb. 28 1900	7:33	N 70°	E 10°	S 8°	W 110°	S 11°	E 121°
430	J	Aug. 27 1901	22:59	N 68°	W 10°	N 10°	E 15°	S 8°	E 47°
486	K_1	April 6 1902	8:55	N 55°	E 132°	N 6°	W 133°	S 17°	E 77°
605a	K_1	April 11	11:41	N 50°	E 110°	N 8°	W 175°	N 19°	W 127°
612	K_1	June 10	18:10	N 53°	E 142°	N 23°	E 88°	N 8°	E 18°
641b	K_1								

Earthquake		Nautical Almanac		Earthquake's		Sun's		Moon's	
No.	District	Date	Hour	Lat.	Long.	Lat.	Long.	Lat.	Long.
641b	K_1	Sept. 21	13:46	N 75°	E 175°	N 1°	E 152°	N 16°	E 26°
666	K_1	Dec? 27	13:41	N 52°	E 88°	S 23°	E 155°	S 19°	E 134°
		1903							
679	K_1	Feb. 5	19:33	N 50°	E 98°	S 16°	E 71°	N 16°	E 169°
689	K_1	March 12	2;19	N 54°	E 87°	S 4°	W 32°	N 5°	E 134°
736	K_1	June 25	10:12	N 51°	E 96°	N 23°	W 152°	N 18°	W 142°
778	K_1	Oct. 22	14:36	N 50°	E 97°	S 11°	E 137°	S 16°	E 169°
789	K_1	Nov. 25	23:46	N 53°	E 110°	S 21°	E 1°	S 10°	E 87°
		1902							
60 610	K_2	May 25	5:20ca.	-	—	N 21°	W 51°	S 18°	E 167°
663	K_2	Dec. 15	17:8	N 42°	E 75°	S 23°	E 102°	N 18°	W 62°
1		1903							
676	K_2	Jan. 31	21:33	N 42°	E 102°	S 18°	E 40°	S 1°	E 79°
683	K_2	Feb. 12	6:42	N 40°	E 87°	S 14°	W 96°	N 7°	E 92°
696	K_2	March 27	19:55	N 40°	E 72°	N 2°	E 62°	0	E 54°
		1901							
542	K_3	Oct.16	17:57	E 70°	N 30°	S 9°	E 116°	S 20°	E 167°
558	K_3	Nov. 17	12:4	E 77°	N 32°	S 19°	E 175°	S 13°	W 107°

Earthquake		Nautical Almanac		Earthquake's		Sun's		Moon's	
No.	District	Date	Hour	Lat.	Long.	Lat.	Long.	Lat.	Long.
		1902							
613b	K_3	June 15	13:36	E 79°	N 29°	N 23°	E 174°	S 11°	W 62°
640	K_3	Sept. 19	18:30	N 37°	E 70°	N 1°	E 81°	N 11°	W 69°
644	K_3	Oct. 5	21:10	E 72°	N 38°	S 4°	E 44°	S 18°	E 98°
662	K_3	Dec. 13	5:8	E 85°	N 30°	S 23°	W 80°	N 17°	E 79°
		1903							
692	K_3	March 22	2:35	E 60°	N 35°	N 0°	W 37°	N 17°	W 110°
709	K_3	May 16	13:0	E 80°	N 23°	N 19°	E 164°	S 16°	E 50°
771	K_3	Sept. 24	13:20	E 58°	N 34°	S 0	E 169°	S 14°	E 142°
791b	K_3	Dec. 3	9:26	E 93°	N 32°	S 15°	W 143°	N 16°	E 22°
		1899							
373	K_4	Dec. 30	22:50	E 42	N 42°	S 23°	E 41°	S 23°	E 25°
		1902							
588	K_4	Feb. 12	21:34.6 or 21:39	E 50°	N 41°	S 14°	E 59°	N 11°	E 116°
		1903							
704	K_4	April 28	11:40	E 43°	N 39°	N 14°	W 175°	N 16°	W 155°
734	K_4	June 24	4:56	E 49°	N 39°	N 23°	W 74°	N 19°	W 82°
		1899							
249	K_5	Jan. 21	20:14	N 37°	E 21.3°	S 20°	E 88°	N 25°	W 144°
343	K_5	Sept. 19	14:11	N 37.5°	E 27.5°	N 1°	E 146°	N 6°	W 29°

Earthquake		Nautical Almanac		Earthquake's		Sun's		Moon's	
No.	District.	Date	Hour	Lat.	Long.	Lat.	Long.	Lat.	Long.
		1902							
618	K_5	July 8	15:38	N 27°	E 56°	N 23°	E 127°	N 6°	E 176°
		1901							
548	K_6	Oct. 28	20:42	N 44°	E 19°	S 13°	E 46°	N 19°	W 109°
		1903							
714	K_6	May 28	21:33	N 39°	E 20°	N 21°	E 36°	N 18°	E 73°
759	K_6	Aug. 10	16:30	N 36.25	E 23°	N 16°	E 114°	S 3°	W 37°
		1901							
479	K_7	March 30	19:11	N 44	E 28.3°	N 4°	E 73°	N 7°	W 197°
		1902							
616	K_7	July 5	2:59	N 40°	E 23°	N 23°	W 44°	N 18°	E 43°
		1902							
626	K_{123}	Aug. 21	15:1	N 40°	E 75°	N 12°	E 136°	N 3°	W 13°
631	K_{123}	Aug. 23	0:58	N 41°	E 79°	N 12°	W 13°	N 9°	W 145°
632	K_{123}	Aug. 23	13:45	N 40°	E 75°	N 12°	E 155°	N 11°	E 30°
635	K_{123}	Aug. 29	3:4	N 40°	E 75°	N 10°	W 46°	N 17°	E 30°
636	K_{123}	Aug. 30	9:47	N 40°	E 76°	N 9°	W 147°	N 14°	W 178°
		1903							

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Earthquake		Nautical Almanac		Earthquake's		Sun's		Moon's	
No.	District	Date	Hour	Lat.	Long.	Lat.	Long.	Lat.	Long.
		1903							
717	K_1A_1	June 2	1:10	N 67°	W 170°	N 22°	W 18°	N 5°	E 74°
792b	K_1A_1	Dec. 4	17:7	N 66°	W 150°	S 22°	E 100°	N 18°	W 73°
		1902							
653	K_{23}	Nov. 3	23:35	N 32°	E 91°	S 15°	E 2°	S 19°	E 51°
		1899							
326	K_5G_1	Aug. 17	8:38	N 16°	E 56°	N 13°	W 128°	S 22°	E 100°
		1901							
513	K_5G_1	Aug. 6	6:39	N 30°	E 55°	N 17°	W 99°	N 15°	E 158°
		1903							
671b	K_5G_1	Jan. 13	14:46	N 24°	E 64°	S 22°	E 141°	N 15°	W 32°
794	K_5G_1	Dec. 9	19:8	N 21°	E 65°	S 23°	E 71°	N 8°	W 32°
		1900							
408	L	May 26	3:59	S 60°	E & W 0°	N 21°	W 61°	N 17°	W 88°
452b	L	Dec. 18	10:4	S 67°	W 125°	S 23°	W 152°	S 19°	E 170°
		1902							
596	L	March 12	3:7	S 60°	W 160°	S 4°	W 44°	N 10°	W 15°
		1903							
765	L	Sept. 7	17:7	S 50°	E 78°	N 6°	E 103°	0	W 66°

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Earthquake		Nautical Almanac		Earthquake's		Sun's		Moon's	
No.	District	Date	Hour	Lat.	Long.	Lat.	Long.	Lat.	Long.
		1899							
283	M_1	April 16	13:36	S 27°	W 167°	N 10°	E 156°	N 21°	W 120°
1		1900							
378	M_1	Jan.12	21:52	S 48°	E 148°	S 22°	E 34°	N 23°	W 175°
		1901							
557	M_1	Nov. 15	8:15	S 43°	E 173°	S 18°	W 128°	S 18°	W 76°
568b	M_1	Dec. 25	21:58	S 58°	E 140°	S 23°	E 31°	N 18°	W 136°
		1902							
586	M_1	Feb. 8	19:43	S 43°	W 171°	S 15°	E 68°	S 7°	E 76°
586b	M_1	Feb. 8	22:12	S 43°	W 171°	S 15°	E 31°	S 7°	E 40°
641c	M_1	Sept. 21	13:56	S 52°	E 152°	N 1°	E 149°	N 16°	E 12°
		1903							
721	M_1	June 7	17:23	S 50°	E 121°	N 23°	E 99°	S 16°	W 103°
738	M_1	July 2	9:22	S 50°	E 150°	N 23°	W 139°	S 8°	W 39°
764a	M_1	Sept. 6	19:10.	S 71°	E 175°	N 7°	E 73°	S 4°	W 105°
769	M_1	Sept. 22	12:14	S 52°	E 160°	N 1°	E 175°	S 7°	W 162°
783	M_1	Nov. 10	5:17	S 50°	E 150°	S 17°	W 83°	N 16°	E 172°
		1899							
286	M_2	May 7	15:11	N 20°	E 170°	N 17°	E 131°	N 15°	E 110°

Earthquake		Nautical Almanac		Earthquake's		Sun's		Moon's	
No.	District.	Date	Hour	Lat.	Long.	Lat.	Long.	Lat.	Long.
351	M_2	Oct. 13	3:13	S 15°	E 178°	S 8°	W 51°	S 15°	E 60°
		1900							
385	M_2	Jan. 31	6:50	0°	E 178°	S 17°	W 189°	S 10°	W 90°
394	M_2	March 8	14:18	S 8°	E 168°	S 5°	E 149°	N 22°	W 133°
424	M_2	July 28	18:59	S 8°	W 178°	N 19°	E 77°	N 4°	E 106°
435	M_2	Sept. 17	9:45	S 5°	E 148°	N 2°	W 147°	N 19°	E 148°
		1901							
496	M_2	May 24	12:32	N 12°	E 165°	N 21°	E 171°	N 6°	W 99°
518	M_2	Aug. 11	2:32	S 23°	E 178°	N 15°	W 37°	N 19°	W 73°
		1902							
619b	M_2	Aug. 2	2:13	0°	E 150°	N 18°	W 31°	N 17°	W 50°
		1903							
678	M_2	Feb. 5	6:26ca	N 8°	W 178°	S 16°	W 92°	N 15	E 3°
798	M_2	Dec. 22	12:53	S 5°	E 170°	S 23°	E 167°	S 13°	W 146°
		1902							
617	M_3	July 6	1:1	S 31°	W 160°	N 23°	W 14°	N 16°	0°
		1903							
705	M_3	April 28	15:59	S 43°	W 143°	N 14°	E 119°	N 16°	E 142°

Earthquake		Nautical Almanac		Earthquake's		Sun's		Moon's	
No.	District	Date	Hour	Lat.	Long.	Lat.	Long.	Lat.	Long.
		1903							
707	M_2E_2	May 12	18:32	N 8°	E 142°	N 18°	E 81°	S 18°	W 77°
708	M_2E_2	May 14	23:41ca	N 12°	E 142°	N 18°	E 4°	S 18°	W 127°
796b	M_2E_2	Dec. 18	0:18	N 5°	E 135°	S 23°	W 5°	S 18°	W 10°
		1899							
309	0	July 14	1:40	N 23°	E 33°	N 22°	W 24°	S 7°	E 45°
		1900							
392	0	March 6	6:0	N 28°	E 33°	N 6°	W 87°	N 21°	W 20°
		1901							
474	0	March 15	23:56	S 10°	E 40°	S 2°	E 3°	S 16°	W 51°
		1903							
694	0	March 25	10:27	N 27°	E 27°	N 1°	W 159°	S 9°	E 170°
718	0	June 4	3:12	N 23°	E 37°	N 22°	W 49°	S 4°	E 67°
		1901							
476	P	March 23	2:10	N 55°	E 170°	N 1°	W 30°	N 17°	E 10°
569	P	Dec. 30	10:34	N 52°	W 160°	S 23°	W 157°	N 1°	E 92°
571	P	Dec. 30	21:0	N 41°	W 173°	S 23°	E 46°	S 5°	W 60°

Earthquake		Nautical Almanac		Earthquake's		Sun's		Moon's	
No.	District	Date	Hour	Lat.	Long.	Lat.	Long.	Lat.	Long.
572	P	~~1902~~ Dec. 31	18:20	N 47°	W 165°	S 23°	E 86°	S 5°	W 11°
700	P	1903 April 2	22:32	N 57°	W 157°	N 5°	E 23°	N 18°	E 93°
502	PE$_1$	1901 June 12	15:19	N 52°	E 160°	N 23°	E 130°	N 15°	E 81°
364	Q	1899 Nov. 22	21:42	N 30°	E 160°	S 20°	E 31°	N 17°	W 75°
534	Q	1901 Sept. 29	22:6	N 30°	E 170°	S 2°	E 27°	N 14°	W 124°
570	Q	Dec. 30	17:51	N 10°	W 130°	S 23°	E 93°	S 1°	W 15°
599	Q	1902 March 22	10:12	N 23°	W 140°	0	W 151°	N 2°	E 14°
789b	Q	1903 Nov. 30	18;43	N 25°	E 165°	S 22°	E 76°	S 19°	W 148°
703	Uncertain	1903 April 11	15:13	–	–	N 8°	E 132°	S 8°	W 167°

TABLE II.

Giving the calculated zenith distances and the azimuthal directions of the sun and moon at the times of ~~earth~~ each earthquake.

TABLE II

Earthquake		Angle	Angle	Angle	Sun's	Moon's	Angle
No.	District	E S	E M	S M	Direction	Direction	E SM
282	A_1	86°	100°	75°	77°	3°	74°
308b	A_1	88°	125°	72°	45°	340°	65°
333	A_1	63°	67°	4°	232°	234	1°
334	A_1	94°	101°	11°	293°	304°	11°
337	A_1	73°	126°	65½°	112°	73°	38°
337b	A_1	55°	108°	66°	349°	118°	51°
338	A_1	55°	93°	66°	187°	130°	57°
341	A_1	102°	74°	134°	297°	162°	45°
342	A_1	106°	69°	125°	56°	180°	56°
344	A_1	111°	76°	103°	32°	291°	79°
345	A_1	98°	37°	124°	75°	215°	40°
391°	A_1	99°	131°	49°	270°	130°	~~40°~~ 42°
442	A_1		53°	17°			
444	A_1	126°		78°	48°		
460	A_1	118°	134°	33°			
539	A_1	108°	136°	35°	58°	51°	27°

Earthquake No.	District	Angle E S	Angle E M	Angle S M	Sun's Direction	Moon's Direction	Angle E SM
560 643	A_1 A_1	84° 80°	106° 87°	66° 10°	229° 117°	293° 111°	64° 16°
690	A_1	96°	102°	25°	85°	63°	~~22°~~ 6°
766	A_1	92°	56°	137°			
248	A_2	68°	97°	30°	75°	77°	2°
371	A_2	60°	133°	86°	281°	331°	50°
452	A_2	96°	66°	35°	60°	81°	21°
470	A_2	29°	29°	24°	166°	218°	52°
472	A_2	39°	44°	5°	250°	254°	4°
555b	A_2	42°	67°	33°	106°	81°	25°
564	A_2	74°	58°	23°	71°	81°	10°
674	A_2	50°	11°	50°	91°	180°	89°
597	A_2B	63°	121°	85°	254°	322°	68°
661	A_2B	112°	90°	30°	51°	75°	24°
250	B	98°	79°	19°	73°	74°	1°
264	B	40°	141°	170°	255°	58°	17°

Earthquake No.	District	Angle E S	Angle E M	Angle S M	Sun's Direction	Moon's Direction	Angle E SM
270	B	53°	147°	160°	94°	285°	11°
381	B	12°	62°	62°	80°	100°	20°
407	B	18°	6°	24°	265°	73°	12°
415	B	46°	91°	45°	71°	80°	9°
417	B	45°	112°	68°	286°	289°	3°
447	B	41°	106°	36°	134°	296°	22°
536	B	53°	164°	51°	89°	346°	77°
576	B	93°	8°	93°	65°	140°	75°
578	B	98°	32°	70°	245°	84°	19°
606a	B	118°	21°	42°	291°	126°	15°
642	B	55°	45°	100°	102°	282°	0°
671	B	67°	61°	122°	64°	272°	28°
600b	BD_1	140°	128°	12°	275°	28°	5°
291	BD_1	152°	152°	36°	271°	89°	2°

Earthquake No.	District	Angle E S	Angle E M	Angle S M	Sun's Direction	Moon's Direction	Angle E SM
269	C_1	32°	144°	139°	128°	28°	80°
292	C_1	26°	6°	31°	85°	249°	16°
294	C_1	82°	148°	68°	68°	42°	26°
321	C_1	28°	14°	42°	276°	276°	0
322	C_1	8°	36°	40°	164°	273°	71°
498	C_1	3°	60°	63°	81°	263°	2°
582	C_1	131°	28°	120°	43°	116°	73°
589a	C_1	62°	9°	71°	92°	266°	6°
600	C_1	30°	25°	6°	193°	187°	6°
642a	C_1	31°	78°	84°	171°	74°	83°
672	C_1	126°	97°	57°	327°	276°	51°
687	C_1	63°	57°	11°	267°	257°	10°
761	C_1	47°	38°	85°	89°	270°	1°
361	C_2	153°	139°	15°	322°	310°	12°
422	C_2	31°	13°	44°	296°	115°	1°
445	C_2	74°	12°	66° ~~28°~~	280°	322°	42°
580	C_2	108°	78°	30°	65°	69°	4°

Earthquake		Angle	Angle	Angle	Sun's	Moon's	Angle
No.	District	E S	E M	S M	Direction	Direction	E SM
303	D_1	39°	43°	4°	66°	71°	5°
432	D_1	150°	50°	100°	51°	73°	22°
455	D_1	102°	81°	24°	248°	77°	9°
537	D_1	140°	157°	17°	252°	249°	3°
675	D_1	37°	18°	43°	112°	218°	74°
676b	D_1	70°	19°	128°	294°	310°	16°
268	D_2	87°	50°	43°	270°	90°	0°
278	D_2	141°	128°	32°	154°	198°	44°
279	D_2	24°	43°	37°	30°	93°	63°
593	D_2	24°	69°	54°	305°	258°	47°
605b	D_2	64°	102°	49°	86°	116°	30°
668	D_2	141°	110°	59°	293°	259°	34°
698	D_2?	-	-	7°	Earthquake position not known.		
793b	D_2	26°	65°	39°	93°	84°	9°
497	D_1	50°	53°	103°	255°	259°	4°

Earthquake No.	District	Angle E S	Angle E M	Angle S M	Sun's Direction	Moon's Direction	Angle E SM
497	D_1D_2	50°	53°	103°	285°	101°	4°
295	E_1	22°	69°	83°	133°	259°	54°
397	E_1	134°	119°	47°	334°	31°	57°
405	E_1	109°	91°	33°	44°	73°	29°
425	E_1	31°	81°	65°	235°	290°	55°
431	E_1	32°	118°	137°	186°	322°	44°
450	E_1	78°	95°	23°	75°	58°	17°
458	E_1	52°	31°	73°	94°	222°	52°
475	E_1	122°	125°	23°	322°	348°	26°
475x	E_1	123°	52°	170°	326°	157°	11°
483	E_1	51°	57°	22°	127°	101°	26°
493	E_1	63°	134°	100°	270°	348°	78°
514	E_1	88°	119°	62°	291°	350°	59°
516	E_1	100°	53°	57°	59°	94°	35°
551	E_1	98°	75°	39°	60°	94°	34°
584	E_1	26	88°	102°	164°	287°	57°

Earthquake No.	District	Angle E S	Angle E M	Angle S M	Sun's Direction	Moon's Direction	Angle E SM
585	E_1	118°	839	95°	348°	80°	88°
607	E_1	115°	41°	109°	318°	226°	88°
760	E_1	121°	147°	121°	25°	130°	75°
267							
267	E_2	155°	60°	118°	12°	278°	86°
307	E_2	66°	34°	38°	290°	266°	24°
446	E_2	93°	75°	24°	70°	86°	16°
448	E_2	45°	15°	37°	259°	2099	50°
454	E_2	117°	141°	41°	41°	180°	41°
641	E_2	26°	100°	126°	117°	298°	7°
681	E_2	154°	140°	28°	180°	46°	46°
366b	E_3	49°	40°	84°	270°	122°	32°
404	E_3	63°	146°	22°	89°	340°	71°
411	E_3	108°	134°	44°	314°	358°	44°
500	E_3	52°	115°	65°	78°	62°	16°
505	E_3	53°	136°	86°	283°	310°	27°

Earthquake No.	District	Angle E S	Angle E M	Angle S M	Sun's Direction	Moon's Direction	Angle E SM
565	E_3	97°	57°	44°	297°	278°	19°
592	E_3	115°	115°	105°	290°	56°	54°
598	E_3	137°	136°	50°	305°	228	77°
606c	W of E_3	31°	151°	144°	112°	21°	89°
609	E_3	16°	22°	5°	138°	134°	4°
625	E_3	107°	87°	154°	290°	268°	22°
655	E_3	78°	35°	49°	78°	106°	28°
656	E_3	124°	108°	19°	304°	295°	9°
658	E_3	68°	9°	71°	281°	180°	79°
659	E_3	116°	134°	78°	54°	314°	80°
668b	E_3	140°	137°	56°	20°	290°	90°
670	E_3	77°	140°	113°	290°	24°	86°
710b	E_3	79°	41°	40°	67°	87°	20°
719	E_3	73°	103°	30°	290°	294°	4°
748b	E_3	76°	69°	10°	75°	80°	5°
764b	E_3	51°	50°	4°	260°	256°	4°
773	E_3	36°	28°	50°	320°	121°	71°
785	E_3	74°	55°	21°	287°	278°	9°

Earthquake No.	District.	Angle E S	Angle E M	Angle S M	Sun's Direction	Moon's Direction	Angle E SM
790	E_3	20°	24°	42°	89°	230°	39°
263	E_{123}	50°	55°	52°	134°	21°	67°
310	F_1	97°	157°	74°	289°	357°	68°
324.	F_1	13°	37°	26°	318°	297°	21°
352	F_1	102°	138°	108°	100°	235°	45°
354	F_1	110°	102°	10°	256°	251°	5°
358	F_1	18°	45°	59°	69°	296°	37°
365	F_1	80°	160°	80°	70°	61°	9°
366	F_1	60°	27°	83°	289°	82°	27°
377	F_1	98°	144°	50°	246°	223°	23°
386b	F_1	159°	31°	135°	30°	85°	55°
414	F_1	100°	96°	40°	65°	65°	0°
427	F_1	99°	43°	138°	72°	276°	24°
438	F_1	117°	85°	32°	84°	82°	2°
441	F_1	87°	97°	10°	273°	278°	5°
441b	F_1	152°	146°	5°	125°	130°	5°
448b	F_1	165°	96°	69°	309°	288°	21°

Earthquake No.	District	Angle E S	Angle E M	Angle S M	Sun's Direction	Moon's Direction	Angle E SM
468 a	F_1	68°	98°	20°	82°	270°	80°
483b	F_1	84°	65°	20°	84°	79°	5°
515	F_1	9°	114°	110°	57°	122°	65°
517	F_1	490°	14°	50°	106°	191°	85°
530	F_1	75°	130°	60°	268°	240°	288
555	F_1	81°	105°	28°	71°	72°	1°
567	F_1	148°	159°	14°	318°	338°	20°
581	F_1	32°	41°	12°	112°	98°	14°
590	F_1	8°	145°	142°	6°	186°	80°
601c	F_1	169°	118°	50°	298°	292°	6°
624	F_1	74°	40°	34°	100°	93°	7°
673	F_1	52°	57°	100°	51°	276°	45°
685	F_1	125°	94°	30°	103°	107°	4°
724	F_1	145°	155°	10°	48°	48°	0
746	F_1	122°	150°	28° ~~122°~~	122° ~~129°~~	129°	7°
775	F_1	33°	40°	6°	267° ~~216~~	273°	6°
780	F_1	136°	95°	102°	141°	256°	65°
781	F_1	55°	55°	110°	266°	87°	1°
784	F_1	57°	124°	74°	101°	122°	21°

Earthquake No.	District	Angle E S	Angle E M	Angle S M	Sun's Direction	Moon's Direction	Angle E SM
247	F_2	69°	61°	8°	241°	248°	7°
347	F_2	153°	94°	109°	101°	256°	25°
355	F_2	9°	60°	67°	244°	117°	53°
471	F_2	160°	163°	11°	196°	170°	26°
529	F_2	102	151°	58°	84°	40°	44°
621b	F_2	75°	59°	144°	290°	266°	24°
655b	F_2	68°	58°	12°	250°	85°	15°
682	F_2	23°	20°	8°	10°	352°	18°
~~682~~	F_2	23°	20°	8°			
699	F_2	7°	20°	14°	40°	58°	18°
710a	F_2	53°	93°	41°	68°	80°	12°
774	F_2	4°	92°	96°	148°	31°	63°
251	F_3	19°	134°	136°	18°	271°	73°
298	F_3	153°	147°	15°	337°	340°	3°
299	F_3	99°	8°	92°	54°	42°	12°
376	F_3	31°	29°	137°	303°	81°	42°

Earthquake		Angle	Angle	Angle	Sun's	Moon's	Angle
No.	District	E S	E M	S M	Direction	Direction	E SM
456	F_3	139°	157°	46°	141°	239°	82°
468	F_3	30°	80°	49°	253°	251°	2°
519	S of F_3	115°	77°	149°	241°	90°	29°
532	F_3	22°	11°	32°	93°	306°	33°
543	F_3	-	-	74°	Earthquake position not known.		
574	F_3	100°	133°	34°	119°	119°	0°
686	F_3	68°	62°	6°	~~89-~~ 988	97°	1°
774b	F_3	33°	15°	17°	100	265°	15°
639	F_1E_3	106°	121°	16°	275°	280°	5°
788	F_1E_3	34°	92°	60°	60°	72°	12°
802	F_1E_3	148°	116°	80°	328°	83°	45°
332	F_1M_1	30°	136°	134°	209°	203°	6°

Earthquake		Angle	Angle	Angle	Sun's	Moon's	Angle
No.	District	E S	E M	S M	Direction	Direction	E SM
305	G_1	20°	32°	21°	154°	106°	48°
404b	G_1	153°	135°	21°	344°	318°	26°
443	G_1	107°	83°	23°	281°	283°	2°
777	G_1	34°	24°	12°	308°	320°	12°
793	G_1	110°	120°	28°	151°	182°	31°
383	G_2	118°	102°	17°	115°	113°	2°
390b	G_2	130°	20°	111°	122°	92°	3°
433b	G_2	113°	106°	8°	89°	90°	1°
492b	G_2	42°	148°	107°	82°	59°	23°
606a	G_2	90°	50°	138°	255°	60°	15°
606d	G_2	39°	34°	16°	54°	27°	27°
642b	G_2	62°	88°	94°	327°	237°	90°
374	G_1G_2	150°	145°	10°	155°	142°	13°
252	H	115°	86°	130°	-	-	52°
254	H	124°	118°	22°	-	-	26°
255	H	126°	46°	168°	-	-	9°

Earthquake No.	District	Angle B S	Angle B M	Angle S M	Sun's Direction	Moon's Direction	Angle B SM
256	H	114°	65°	156°			26°
257	H	119°	45°	156°			33°
307b	H	92°	126°	37°	60°	41°	19°
398	H	158°	136°	46°	178°	~~[illegible]~~ 280°	78°
346	H	~~[illegible]~~ 80°	21°	98°	271°	49°	42°
372	H	33°	48°	80°	90°	257°	13°
379	H	112°	103°	10°	66°	71°	5°
619	H	100°	108°	7°	~~294°~~ 246°	~~291°~~ 249°	3°
750	H	71°	112°	42°	~~79~~ ~~798~~ 79°	67°	12°
751	H	48°	55°	99°	98	250°	28°
767	H	50°	110°	100°	232°	317°	85°
259	J	71°	72°	126°	~~226~~ 116°	254°	42°
430	J	60°	86°	154°	152°	124°	28°
486	K 1	89°	94°	320°	81°	51°	30°
605a	K1	75°	95°	48°	102°	47°	55°

Earthquake		Angle	Angle	Angle	Sun's	Moon's	Angle
No.	District	E S	E M	S M	Direction	Direction	E SM
641b	K_1	74°	89°	125°	348°	148°	20°
666	K_1	85°	98°	20°	301°	317°	16°
679	K_1	109°	65°	79°	28°	95°	67°
689	K_1	70°	53°	15°	113°	125°	12°
736	K_1	84°	94°	11°	56°	54°	2°
778 .	K_1	109°	88°	30°	323°	244°	79°
789	K_1	62°	114°	82°	92°	21°	71°
610	K_2						
663	K_2	110°	108°	17°	334°	316°	18°
676	K_2	90°	16°	42°	63°	44°	19°
683	K_2	26°	34°	9°	184°	187°	3°
696	K_2	44°	42°	9°	198°	209°	11°
542	K_3	121°	74°	51°	56°	77°	21°
558	K_3	73°	18°	74°	77°	167°	90°
613b	K_3	83°	41°	54°	292°	254°	38°
640	K_3	36°	119°	147°	18°	313°	65°
644	K_3	131°	120°	54°	320°	28°	68°

Earthquake No.	District	Angle E S	Angle E M	Angle S M	Sun's Direction	Moon's Direction	Angle E SM
662	K_3	14°	14°	21°	251°	156°	85°
692	K_3	94°	128°	74°	86°	13°	73°
709	K_3	76°	130°	63°	285°	320°	35°
771	K_3	72°	86°	30°	102°	76°	26°
791b	K_3	54°	66°	14°	91°	85°	6°
373	K_4	114°	112°	15°	359°	341°	18°
588	K_4	124°	66°	117°	12°	261°	69°
704	K_4	115°	123°	19°	319°	339°	20°
734	K_4	99°	107°	8°	49°	46°	3°
249	K_5	96°	116°	47°	300°	344°	44°
343	K_5	112°	60°	172°	72°	252°	0°
618	K_5	63°	113°	51°	75°	73°	2°
548	K_6	117°	101°	25°	328°	310°	18°
714	K_6	23°	51°	34°	137°	108°	37°
759	K_6	81°	111°	31°	77°	70°	7°

Earthquake No.	District	Angle E S	Angle E M	Angle S M	Sun's Direction	Moon's Direction	Angle E SM
479	K_7	56°	140°	138°	120°	354°	54°
616	K_7	58°	61°	7°	276°	268°	8°
626	K_{123}	60°	87°	145°	100°	271°	9°
631	K_{123}	84°	116°	128°	280°	51°	49°
632	K_{123}	75°	49°	122°	86°	249°	17°
635	K_{123}	107°	124°	48°	300°	350°	50°
636	K_{123}	117°	94°	30°	49°	69°	20°
717	K_1A_1	88°	96°	90°	29°	299°	90°
792b	K_1A_1	61°	68°	8°	99°	95°	4°
653	K_{23}	82°	116°	48°	77°	42°	35°
326	K_5G_1	149°	122°	44°	3°	311°	52°
513	K_5G_1	133°	95°	99°	322°	70°	72°
671b	K_5G_1	91°	90°	10°	295°	285°	10°
794	K_5G_1	134°	95°	74°	351°	280°	71°

Earthquake No.	District	Angle E S	Angle E M	Angle S M	Sun's Direction	Moon's Direction	Angle E SM
408	L	85°	76°	25°	124°	99°	25°
452b	L	46°	62°	32°	328°	287°	41°
596	L	99°	56°	148°	114°	319°	25°
765	L	119°	122°	12°	208°	223°	15°
283	M_1	52°	66°	80°	310°	48°	82°
378	M_1	88°	78°	28°	238°	35°	23°
557	M_1	56°	88°	50°	83°	298°	35°
568b	M_1	80°	78°	13°	243°	256°	13°
586	M_1	79°	78°	11°	58°	70°	12°
586b	M_1	60°	58°	11°	25°	38°	13°
641e	M_1	54°	48°	45°	357°	56°	59°
721	M_1	75°	76°	22°	338°	315°	23°
738	M_1	97°	58°	78°	62°	350°	72°
764a	M_1	100°	96°	4°	260°	262°	2°
769	M_1	54°	54°	22°	20°	48°	28°
783	M_1	81°	68°	~~310°~~ 72°	~~24°~~ 310°	~~74°~~ 24°	~~50°~~ 74°

Earthquake No.	District	Angle E S	Angle E M	Angle S M	Sun's Direction	Moon's Direction	Angle E SM
286	M_2	38°	57°	20°	270°	276°	6°
352	M_2	127°	110°	108°	109°	247°	42°
385	M_2	98°	88°	12°	246°	256°	10°
394	M_2	20°	97°	80°	280°	256°	34°
424	M_2	78°	105°	30°	104°	96°	8°
435	M_2	114°	154°	65°	264°	157°	89°
496	M_2	12°	94°	88°	29°	86°	57°
518	M_2	32°	67°	34°	278°	259°	19°
619b	M_2	162°	155°	18°	180°	42°	42°
678	M_2	90°	156°	82°	284°	3°	79°
798	M_2	19°	44°	45°	191°	103°	88°
617	M_3	10°	24°	15°	325°	310°	15°
705	M_3	76°	90°	23°	88°	110°	22°
707	$M2E_2$	60°	39°	21°	287°	290°	3°
708	M_2E_2	129°	85°	46°	304°	287°	17°
796b	M_2E_2	43°	37°	7°	59°	63°	4°

Earthquake No.	District	Angle E S	Angle E M	Angle S M	Sun's Direction	Moon's Direction	Angle E SM
309	O	52°	147°	107°	283°	336°	53°
392	O	70°	48°	~~93°~~ 112°	~~273°~~ 93°	273°	0°
474	O	38°	89°	55°	281°	265°	26°
694	O	152°	40°	144°	~~250°~~ 5°	250°	65°
718.	O	78°	140°	65°	289°	309°	20°
476	P	122°	106°	43°	23°	338°	45°
569	P	105°	100°	69°	357°	285°	72°
571	P	37°	70°	102°	107°	259°	28°
572	P	60°	48°	85°	87°	217°	50°
700	P	108°	85°	68°	50°	296°	66°
502	PE_1	36°	71°	46°	232°	271°	39°
364	Q	38°	109°	70°	91°	55°	36°
534	Q	45°	71°	41°	123°	85°	38°
570a	Q	44°	66°	107°	65°	268°	23°
599	Q	25°	144°	14°	30°	49°	19°

Earthquake		Angle	Angle	Angle	Sun's	Moon's	Angle
No.	District	E S	E M	S M	Direction	Direction	E SM
789b	Q	82°	116°	60°	70°	311°	61°
793	Uncertain						

TABLE III.

Angles between the earthquake centres and the sun's zenith positions.

Degrees	0 10	11 20	21 30	31 40	41 50	51 60	61 70	71 80	81 90	Total
Group				Numbers of Earthquakes.						
A_1	-	-	-	-	-	3	4	5	8	20
A_2	-	-	1	1	2	1	1	1	1	8
A_2B	-	-	-	-	-	-	2	-	-	2
B	-	2	-	1	3	4	2	-	2	14
BD_1	-	-	1	1	-	-	-	-	-	2
C_1	2	-	2	3	2	1	2	-	1	13
C_2	-	-	1	1	-	-	-	2	-	4
D_1	-	-	1	3	-	-	1	1	-	6
D_2	-	-	3	2	-	-	1	-	1	7
D_1D_2	-	-	-	-	1	-	-	-	-	1
E_1	-	-	2	2	1	5	3	3	2	18
E_2	-	-	3	-	1	-	2	-	1	7
E_3	-	2	-	3	2	4	4	8	1	24
E_{123}	-	-	-	-	1	-	-	-	-	1
F_1	2	4	2	4	2	6	3	5	6	34
F_2	3	1	2	-	-	1	2	2	-	11
F_3	-	1	3	2	1	-	2	1	1	11
F_1E_3	-	-	-	2	-	-	-	1	-	3
F_1E_1	-	-	1	-	-	-	-	-	-	1
G_1	-	1	1	1	-	-	1	1	-	5
G_2	-	-	-	1	2	-	3	-	1	7
G_1G_2	-	-	1	-	-	-	-	-	-	1
H	-	-	1	1	2	2	4	3	1	14
J	-	-	-	-	-	1	-	1	-	2

Degrees	0 10	11 20	21 30	31 40	41 50	51 60	61 70	71 80	81 90	Total
Group		Numbers of Earthquakes.								
K_1	-	-	-	-	-	1	2	3	4	10
K_2	-	-	1	-	1	—	1	-	1	4
K_3	-	1	-	1	1	2	-	3	2	10
K_4	-	-	-	-	-	1	2	—	1	4
K_5	-	-	-	-	-	-	2	-	1	3
K_6	-	1	-	-	-	-	1	-	1	3
K_7	-	-	-	-	-	2	-	-	-	2
K_{123}	-	-	-	-	-	1	1	2	1	5
K_1A_1	-	-	-	-	-	-	1	-	1	2
K_{23}	-	-	-	-	-	-	-	-	1	1
K_5G_1	-	-	-	1	2	-	-	-	1	4
L	-	-	-	-	1	1	-	-	2	4
M_1	-	-	-	-	-	5	-	4	3	12
M_2	-	4	-	2	-	1	1	1	2	11
M_3	1	-	-	-	-	-	-	1	-	2
M_2E_2	-	-	-	-	1	2	-	-	-	3
O	-	-	1	1	-	1	1	1	-	5
P	-	-	-	1	-	2	-	2	-	5
PE_1	-	-	-	1	-	-	-	-	-	1
Q	-	-	1	1	2	-	-	-	1	5
Totals	8	17	28	36	28	48	48	51	48	312

TABLE IV.

Angles between the earthquake centres and the moon's zenith positions.

Degrees	0 10	11 20	21 30	31 40	41 50	51 60	61 70	71 80	81 90	Total
Groups					Numbers of Earthquakes.					
A_1	-	-	-	1	3	4	4	5	3	20
A_2	-	1	1	-	2	1	2	-	1	8
A_2B	-	-	-	-	-	1	-	-	1	2
B	1	2	1	3	1	-	3	2	1	14
BD_1	-	-	1	-	-	1	-	-	-	2
C_1	2	1	2	4	-	2	-	1	1	13
C_2	-	2	-	-	1	-	-	1	-	4
D_1	-	2	1	-	2	-	-	-	1	6
D_2	-	-	-	-	2	1	3	1	-	7
D_1D_2	-	-	-	-	-	1	-	-	-	1
E_1	-	-	-	1	3	4	4	1	5	18
E_2	-	1	-	3	-	1	-	2	-	7
E_3	1	-	4	4	7	2	3	2	1	24
E_{123}	-	-	-	-	1	-	-	-	-	1
F_1	-	2	5	7	5	3	3	2	7	34
F_2	-	3	1	-	-	3	1	-	3	11
F_3	1	2	2	1	2	-	1	2	-	11
F_1E_3	-	-	-	-	-	1	1	-	1	3
F_1H_1	-	-	-	-	1	-	-	-	-	1
G_1	-	-	1	1	1	1	-	-	1	5
G_2	-	1	-	2	1	-	-	2	1	7
G_1G_2	-	-	-	1	-	-	-	-	-	1
H	-	-	1	-	4	2	4	2	1	14

///

Degree	0 10	11 20	21 30	31 40	41 50	51 60	61 70	71 80	81 90	Total
Group			Numbers of Earthquakes.							
J	-	-	-	-	-	-	-	1	1	2
K_1	-	-	-	-	-	1	2	1	6	10
K_2	-	-	-	1	1	-	1	1	-	4
K_3	-	2	-	-	2	2	2	1	1	10
K_4	-	-	-	-	-	1	2	1	-	4
K_5	-	-	-	-	-	1	2	-	-	3
K_6	-	-	-	-	-	1	1	1	-	3
K_7	-	-	-	1	-	-	1	-	-	2
K_{123}	-	-	-	-	1	1	1	-	2	5
K_1A_1	-	-	-	-	-	-	1	-	1	2
K_{23}	-	-	-	-	-	-	1	-	-	1
K_7G_1	-	-	-	-	-	1	-	-	3	4
L	-	-	-	-	-	2	1	1	-	4
M_1	-	-	-	-	1	3	2	4	2	12
M_2	-	-	3	-	1	1	2	1	3	11
M_3	-	-	1	-	-	-	-	-	1	2
M_2N_2	-	-	-	2	-	-	-	-	1	3
O	-	-	-	3	1	-	-	-	1	5
P	-	-	-	-	1	-	1	1	2	5
PN_1	-	-	-	-	-	-	-	1	-	1
Q	-	-	-	1	-	-	3	1	-	5
Totals	5	19	24	36	44	42	52	38	52	312

TABLE V.

Angles between the sun and moon at the times of occurrence of the earthquakes.

Degrees	0 10	11 20	21 30	31 40	41 50	51 60	61 70	71 80	81 90	Total
Group	Numbers of earthquakes.									
A_1	2	2	1	2	3	2	4	4	-	20
A_2	1	-	3	2	1	-	-	-	1	8
A_2B	-	-	1	-	-	-	-	-	1	2
B	1	2	1	1	2	3	3	-	1	14
BB_1	-	1	-	1	-	-	-	-	-	2
C_1	1	1	-	2	2	2	2	1	2	13
C_2	-	1	1	-	1	-	1	-	-	4
D_1	1	1	1	-	1	1	-	1	-	6
D_2	1	-	-	3	2	2	-	-	-	8
D_1D_2	-	-	-	-	-	-	-	1	-	1
E_1	1	-	3	2	2	2	2	4	2	18
E_2	-	-	2	2	1	1	1	-	-	7
E_3	3	1	4	3	6	1	2	2	2	24
E_{123}	-	-	-	-	-	-	1	-	-	1
F_1	6	4	4	3	5	2	3	6	1	34
F_2	2	3	-	1	1	1	1	1	1	11
F_3	1	2	-	3	4	-	-	1	1	12
F_1E_3	-	1	-	-	-	1	-	1	-	3
F_1E_1	-	-	-	-	1	-	-	-	-	1
G_1	-	1	4	-	-	-	-	-	-	5
G_2	1	2	-	-	1	-	1	1	1	7
G_1G_2	1	-	-	-	-	-	-	-	-	1
H	2	1	3	1	3	-	-	2	2	14

118

Degrees	0 10	11 20	21 30	31 40	41 50	51 60	61 70	71 80	81 90	Total
Group			Numbers of Earthquakes.							
J	-	-	1	-	-	1	-	-	-	2
K_1	-	3	1	1	1	1	1	1	1	10
K_2	2	1	-	1	1	-	-	-	-	5
K_3	-	1	2	1	-	3	1	2	-	10
K_4	1	2	-	-	-	-	1	-	-	4
K_5	1	-	-	-	1	1	-	-	-	3
K_6	-	-	1	2	-	-	-	-	-	3
K_7	1	-	-	-	1	-	-	-	-	2
K_{123}	-	-	1	1	1	2	-	-	-	5
K_{23}	-	-	-	-	1	-	-	-	-	1
K_5G_1	1	-	-	-	1	-	-	1	1	4
K_1A_1	1	-	-	-	-	-	-	-	1	2
L	-	1	2	-	1	-	-	-	-	4
M_1	1	3	4	-	1	-	-	3	-	12
M_2	-	3	1	1	1	-	1	2	2	11
M_3	-	1	1	-	-	-	-	-	-	2
M_2E_2	1	-	1	-	1	-	-	-	-	3
O	-	-	-	1	-	1	2	1	-	5
P	-	-	-	-	1	-	2	1	1	5
PM_1	-	-	-	-	1	-	-	-	-	1
Q	-	1	-	-	1	1	1	1	-	5
Uncertain	-	-	-	-	-	-	1	-	-	1
Totals	33	39	43	34	50	28	31	37	21	316

Degrees	0 10	11 20	21 30	31 40	41 50	51 60	61 70	71 80	81 90	Total
Group				Numbers of Earthquakes.						
J	-	-	1	-	1	-	-	-	-	2
K_1	1	3	1	-	2	1	-	1	1	10
K_2	1	3	-	-	-	-	-	-	-	4
K_3	1	-	2	2	-	-	2	1	2	10
K_4	1	2	-	-	-	-	1	-	-	4
K_5	2	-	-	-	1	-	-	-	-	3
K_6	1	1	-	1	-	-	-	-	-	3
K_7	1	-	-	-	-	1	-	-	-	2
K_{123}	1	2	-	-	2	-	-	-	-	5
K_1A_1	1	-	-	-	-	-	-	-	1	2
K_{23}	-	-	-	1	-	-	-	-	-	1
K_5G_1	1	-	-	-	-	1	-	2	-	4
L	-	1	2	-	1	-	-	-	-	4
M_1	1	3	3	1	-	1	-	2	1	12
M_2	3	1	-	1	2	1	-	1	2	11
M_3	-	1	1	-	-	-	-	-	-	2
M_2B_2	2	1	-	-	-	-	-	-	-	3
O	1	1	1	-	-	1	1	-	-	5
P	-	-	1	-	2	-	1	1	-	5
PB_1	-	-	-	1	-	-	-	-	-	1
Q	-	1	1	2	-	-	1	-	-	5
Totals	80	50	49	20	28	23	17	26	19	312

Degrees	0 10	11 20	21 30	31 40	41 50	51 60	61 70	71 80	81 90	Total.
Group				Numbers of Earthquakes.						
J	-	-	1	-	1	-	-	-	-	2
K_1	1	3	1	-	2	1	-	1	1	10
K_2	1	3	-	-	-	-	-	-	-	4
K_3	1	-	2	2	-	-	2	1	2	10
K_4	1	2	-	-	-	-	1	-	-	4
K_5	2	-	-	-	1	-	-	-	-	3
K_6	1	1	-	1	-	-	-	-	-	3
K_7	1	-	-	-	-	1	-	-	-	2
K_{123}	1	2	-	-	2	-	-	-	-	5
K_1A_1	1	-	-	-	-	-	-	-	1	2
K_{23}	-	-	-	1	-	-	-	-	-	1
K_5a_1	1	-	-	-	-	1	-	2	-	4
L	-	1	2	-	1	-	-	-	-	4
M_1	1	3	3	1	-	1	-	2	1	12
M_2	3	1	-	1	2	1	-	1	2	11
M_3	-	1	1	-	-	-	-	-	-	2
M_2R_2	2	1	-	-	-	-	-	-	-	3
O	1	1	1	-	-	1	1	-	-	5
P	-	-	1	-	2	-	1	1	-	5
PM_1	-	-	-	1	-	-	-	-	-	1
Q	-	1	1	2	-	-	1	-	-	5
Totals	80	50	49	20	28	23	17	26	19	312