EARTH TREMORS

BY

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The object of the following paper on Earth Tremors is to bring to the notice of the members of the Seismological Society a study, which has hitherto received but little attention in this country. With the exception of a few brief references to a little work which I have personally undertaken, the paper does not claim any originality it being in the main a compilation of results obtained by observers in Europe.

The discovery of the existence of Earth tremors appears to have been accidental, rather than a result of inductive reasoning. No sooner had philosophers contrived astronomical and other instruments for the purpose of making refined measurements and observations than they at once discovered that they had an enemy to contend against in the form of microscopic earthquakes.

Artificially produced Tremors. Artificially produced Tremors exist in all our towns, and near a railway line they are perceptible with every passing train. Those who use microscopes of high power will readily appreciate how small a disturbance of the ground may be visible by the apparent movements which often take place in the object under examination. Captain Kater found that he could not perform his pendulum experiments in London on account of the vibrations produced by the rolling of carriages. Captain Denman who made some observations on artificially produced tremors found that of a goods train produced an effect 1100 feet distant in marshy ground over sandstone. Vertically however above a tunnel through the sandstone, the effects only extended 100 feet. A remarkable example of the trouble which artificially produced earth vibrations have occasioned those who make astronomical observations, occurred some 20 years ago at the Greenwich Observatory. When determining the collimation error of the transit circle by the reflexion of a star in a tray of mercury, it was found that on certain nights the surface of the mercury was in such of state of trembling that the observers were unable to complete their observations until long after midnight.

After obtaining a series of dates on which these disturbances occurred it was found that they coincided with public and bank holidays on which days crowds of the poorer classes of London flocked to Greenwich park where they amused themselves with running and rolling down the hill on which the Observatory is situated. On these occasions it was found that the disturbance in the Mercury was such that observations could not be made until 2 or 3 hours after the crowds had been turned out of the neighboring Park.

Whether we are to suppose that the hill continued to vibrate for this length of time after the cause of disturbance had been removed or whether it was due to the mercury continuing to oscillate in virtue of its inertia after having once been set in motion it is difficult to say (Palmer. Trans. Seis. Soc. of Japan III p. 148). To obviate this difficulty Sir George Airy suspended his dish of Mercury in a system of india rubber bands, and in this way succeeded in eating the intruders up.

Lieutenant Col H. S. Palmer R. E. when engaged with the transit of Venus expedition in New Zealand in 1874 was troubled with vibrations produced from a neighboring railway. To escape the enemy, he entrenched his instruments by placing them in pits. With pits 3½ feet deep he found himself sufficiently protected. The distance from the line was about 400 yards and the soil through which the disturbances were propagated was a coarse pebbly gravel (Trans. Seis. Soc. of Japan. III 148).

Before the United States Naval Observatory was established at Washington, Professor H. M. Paul was deputed to make a tremor survey to discover stable ground. The results of these experiments were exceedingly interesting. By watching the reflected image of a star in a dish of mercury a passing train would be noticed at the distance of a mile. Its approach could be detected by the trembling of the image before its coming could be heard. At one point of observation the disturbance appeared to be cut off by a ravine. The strata was gravel and clay (Paul. Trans: Seis: Soc: of Japan II p. 41). These few examples of artificially produced tremors, to which many more might be added, have been given because they teach us something respecting the nature of these disturbances.

Hitherto they have only been regarded as intruders which it was necessary to escape from or destroy. From what has been said they appear to be a superficial disturbance which is propagated to an enormous distance. This distance appears to depend upon the propagating medium, upon the intensity of the initial disturbance, and upon its duration. In the observation of these artificial disturbances which are accessible to every one, and which hitherto have been so neglected, we have undoubtedly a fruitful source of study.

Natural Tremors. Next let us turn to those microscopical disturbances of our soil which are due to natural causes. Thus far they seem to have been recorded wherever instruments suitable for there detection have been erected and it is not improbable that they are common to the surface of the whole globe.

Some of the more definite observations which have been made upon earth tremors were those made in connection with experiments on the deviation of the vertical due to the attractive influence of the moon and sun.

Prof. Zöllner who invented the horizontal pendulum which he used in the attempt to measure the change in level due to lunar and solar attraction, found his instrument so sensitive that the readings were always changing.

The most interesting observations which were made upon small disturbances of the soil were those of M. d'Abbadie who carried on his experiments at Abbadia, in Subernoa near Hendage 400 Meters distant from the Atlantic and 62 Meters above sea level. The soil was a loamy rock. Here M.

d'Abbadie constructed a concrete cone 8 meters in height which was pierced down the center by a vertical hole or well which was continued, two meters below the cone into the solid rock. At the bottom of this hole or well, a pool of Mercury was formed, which reflected the image of cross wires placed at the top of the hole. These cross wires and their reflection were observed by means of a microscope. The observations consisted in noting the displacement and azimuth of the reflected image relatively to the real image of the wires. After allowing this structure 5 years to settle M. d'Abbadie commenced his observations. To find the surface of the mercury tranquil was a rare occurrence. Sometimes the mercury appeared to be in violent motion although both the air and neighboring sea were perfectly calm. At times the reflected image would disappear as if the mercury had been disturbed by a microscopic earthquake. The relative position of the images were in part governed by the state of the tide. Altogether the movements were so strange that M. d'Abbadie did not venture any speculations as to their cause but he remarks that the cause of the changes he observed were sometimes neither astronomical nor thermometrical. These observations the principal object of which was to determine changes in level rather than earth vibrations were carried on between the years 1868-1872. (G. H. and H. Darwin: Reports of British Association 1881).

Another instructive set of observations were those which were made in the years 1880-1882 by George and Horace Darwin at the Cavendish Laboratory at Cambridge. The main object in these experiments was to determine the disturbing influence of gravity produced by lunar attraction.

The result which was obtained however shewed that the soil at Cambridge was in such an incessant state of vibration that whatever pull the moon may have exerted upon the instrument which was employed, this was masked by the magnitude of the effects produced by the earth tremors, and the experiments had in consequence to be abandoned. The principle of this instrument was similar to an instrument devised by Sir William Thomson and put up by him in his

Laboratory at Glasgow. As erected by the Darwins at Cambridge it was briefly as follows.

A pendulum which was a massive cylinder of pure copper was hung by a brass wire about a foot long inside a hollow cylindrical support rising from a stone support. A tiny galvanometer mirror was then hung by two fine threads, one of which was fastened to the bob and the other to the stone basement. A ray of light sent from a lamp on to the mirror was refrected to a scale 7 feet distant and by this means any motion of the bob relatively to the stone support was magnified 50,000 times. In several ways the apparatus was insulated from all accidental disturbances. The spot of light was observed from another room by means of a telescope. The instrument was so delicate that even at the distance of 16 feet the shifting of your weight from one foot to the other caused the spot of light to run along the scale. So sensitive was the instrument that notwithstanding its being cut off from the surrounding soil by a trench filled with water and the whole instrument being immersed in liquid to damp out the small vibrations it would seem that the ground was in a constant state of tremor, in fact so persistent and irregular were these movements that it seemed impossible to separate them from the movement due to the attraction of the moon. (Reports of British Association 1881).

As a result of observations like these the world gradually has had forced upon it the fact, that the ground on which we live is probably every where in what is practically an incessant state of vibration. The result of these observations has led those who were interested in the study of earth movements to establish special apparatus for the purpose of recording such motions with the hope that the laws by which they were governed might be discovered.

Instruments specially intented to record Earth Tremors.

The simpler forms of apparatus which have been used may be described as delicate forms of seismoscopes which in addition to being useful as recorders of earth tremors also record the occurrence of small earthquakes. A simple contrivance which may be used for the purpose of recording small earthquakes may be made with a small compass needle. This is deflected so far by the attractive influence of a piece of iron, that on the slightest shake its equilibrium is overcome and it flies to the iron where it remains until reset.

In Japan a large number of small earth disturbances have been recorded with crude apparatus of this description. Another form of apparatus employed in Japan has been a delicately constructed circuit closer. The motions of this instrument it was found might be recorded by means of an electric magnet deflecting a pencil which was tracing a circle on a revolving dial. The revolving dial was a disc of wood covered with paper fixed to the hour hand axle of a common clock.

A third form of apparatus used in Japan consisted of a small piece of sheet lead about the size of a three penny piece suspended by a short loop from a rigid support. Projecting from the lead a fine wire about 2^{in} in length passes freely through a hole in a metallic plate. By the slightest motion of the support the small pendulum of lead is set into a state of tremor and causes its pointer to come in contract with one or other side of the hole in the metal plate, by which it closes an electric circuit.

A more refined kind of apparatus which has been employed in Japan was similar to that used by the Darwins at Cambridge. This was so arranged that any deflection of the mirror was permanent until the instrument was reset and in this way the maximum disturbance which had taken place between each observation was recorded. In addition to these and other contrivances, experiments were made with microphones. Those which were first employed were the ordinary carbon microphones. They were fixed on the head of stakes driven in the ground at the bottom of pits. Another form of microphone which I employed consisted of an aluminium wire standing vertically on a metallic plate, its upper end passing loosely through a hole in an alluminium wire standard. The upper end of the vertical wire was loaded with lead. This contrivances possessed all the sensitiveness of an ordinary microphone whilst if it received a sudden impulse there was a sudden break in the current during the time that the vertical wire was being thrown across the hole in the standard. After many months of tiresome observation with instruments of this description and after eliminating all motions which might have been produced by accidental causes the general result obtained shewed that in Tokio there were microscopic movements of the soil to be detected every day and sometimes many times per day. (For a fuller account of these instruments see "Experiments in Observational Seismology." J. Milne. Trans: Seis. Soc. Vol. III p. 12.)

Work in Italy.

The most satisfactory observations upon microseismic disturbances are those which have been made during the last ten years in Italy.

The father of systematical microseismical research appears to have been Father Timoteo Bertelli of Florence. In 1870 Father Bertelli suspended a pendulum in a cellar which he observed with a microscope. As the result of his observations it was announced to the world that he had perceived the earthquakes which in 1870 shook Romagna although to the ordinary observer in Florence, these shakings had not been perceptible.

In 1873 Bertelli by means of microscopes fixed in several azimuths made 5500 observations on free pendulums. He also made observations on reflections from the surface of mercury.(1)

One result of these observations was to shew that microseismic motions increased with a fall of the barometer. Similar observations were made at Bologna by M. le Conte Malvasia and also by M. de Rossi near Rome. On Jan. 14th 15th and Feb. 25th these three observers at their respective stations, simultaneously observed great disturbances.

Similar investigations were made at Nice by M. le Baron Prost.

Although doubt was cast upon Bertelli's observations they appear to have been the origin of a series microseismical observations, a distinguished leader in which is Prof. M. S. de

(1) Compte Rendus 1875 Jan. to June p. 685.

Rossi of Rome who in 1874 found that large earthquakes were almost always preceeded or accompanied with microseismical storms.

In 1878 Prof. Rossi worked upon these small disturbances with the assistance of the microphone and telephone and his first results were published by Prof. Palmieri. Many of Prof. Rossi's observations were made in the grotto di Roca de Papa, 700 meters above sea level and 18 meters under the soil. Here over 6000 observations were made by means of microscopes, on pendulums of different lengths suspended in tubes cut in the solid rock.

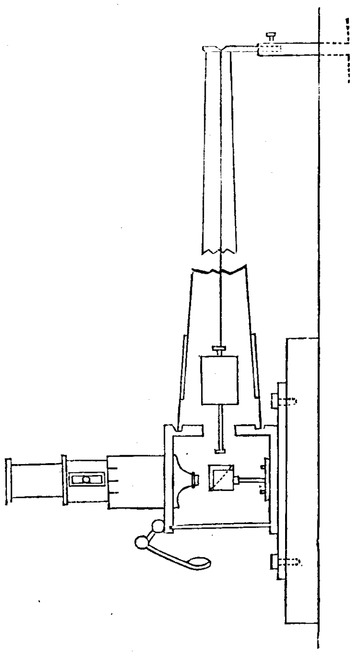

Fig. 1.

It is impossible to describe in detail the various forms of apparatus which have been used by the Italian investigators. A short description of one or two of the more important instruments may not however be out of place insomuch as they will assist the reader to understand the manner in which the various results respecting the laws governing microseismic movements, have been arrived at.

The most important of these instruments is the normal tromometer of Bertelli and Rossi. Fig. 1. This consists of a pendulum 1½ meters long carrying by means of a very fine wire a weight of 100 grammes. To the base of the bob, a vertical stile is attached and the whole is enclosed in a tube terminated at its base by a glass prism of such a form that when looked through horizontally, the motion of the stile can be seen in all azimuths. In front of this prism a microscope is arranged. Inside the microscope there is a scale so arrange that it can be turned to coincide with the apparent direction of oscillation of the point of the stile. In this way not only can the amplitude of the motion of the stile be measured but also its azimuth. The extent of vertical motion is measured by the up and down motion of the stile due to the elasticity of the supporting wire.

Another apparatus is the Microseismograph of Prof. Rossi. This is an arrangement to give automatic records of slight motions. It consists of four pendulums each about 3 ft long suspended so that they form the corners of a square platform. In the center of this platform a fifth but rather longer pendulum is suspended. The four pendulums are each connected just above their bobs to the central pendulum with loose silk threads. Fixed to the center of each of these threads and held vertically by light springs is a needle so adjusted that each thread is depressed to form an obtuse angle of about 155°. These needles form the termination of an electric circuit the other termination of which is a small cup of mercury placed just below the lower end of the needle.

By a horizontal swing of one of the pendulums this arrangement causes the needle to move vertically but with a multiplied amplitude. By this motion the needle comes in contact with the mercury and an electro-magnet with a lever and pencil is caused to make a mark on a band of paper moved by clock work.

The five pendulums being of different lengths allows the apparatus to respond "to seismic waves of different velocites."

Lastly we have Prof. Rossi's Microphone. This consists of a metallic swing arranged like the beam of a balance. By means of a movable weight at one end of the beam this is so adjusted that the other end of the beam falls down until it comes in contact with a metallic stop. This can be so adjusted that a slight tap will cause the beam to slightly jump from the stop. The beam and the stop form two poles of an electric circuit in which there is a telephone. The slightest motion in a *vertical* direction causes a fluctuation in the current passing between the stop and the beam and a consequent noise is

(See Tel Journ: Nov. 15th 1881.)

heard in the telephone.

With instruments similar to these, observations have been made by various observers in all portions of Italy, extending over a period of 10 years.

Every precaution appears to have been taken to avoid accidental disturbances and the experiments have been repeated in a variety of forms. The results which from time to time have been announced are of the greatest interest to those who study the Physics of the Earth's crust and appear to be leading to the establishment of laws of scientific value.

It would seem that the soil of Italy is in incessant movement, there being periods of excessive activity usually lasting about 10 days. Such a period may be called a seismic storm. These storms are separated by periods of relative calms. These storms have their greater regularity in winter. Sharp maximums are to be observed in spring and autumn. In the midst of such a period or at its end, there is usually an earthquake. Usually these storms are closely related to barometric depressions. To distinguish these movements from those which occur under high pressure, they are called *baro-seismic* movements, the latter being called *volcano-seismic* movements. The relation of these storms to barometric fluctuation has been observed to have been very marked during the time of a volcanic eruption.

At the commencement of a storm the motions are usually small and one storm lasting 2 or 3 days may be joined to another storm. In such a case the action may be a local one. It has been observed that a barometrical depression tended to bring a storm to a maximum whilst an increase of pressure would cause it to disappear.

Sometimes these actions are purely local but at other times they may effect a considerable tract of land.

If a number of pendulums of different lengths are observed at the same place, there is a general similarity in their movements, but it is also evident that the free period of the pendulum more or less disturbs the character of the record. The greatest amplitude of motion in a set of pendulums is not reached simultaneously by all the pendulums, and at every disturbance the movement of one will predominate. From this Rossi argues that the character of the microseismical motions is not constant.

Bertelli observed that the direction of oscillation of the pendulums is different at different places but each place will have its particular direction dependent upon the direction of valleys and chains of mountains in the neighborhood. Rossi shews that the directions of movement are perpendicular to the direction of lines of faults, the lips of these fractures rising and falling, and producing two sets of waves one set parallel to the line of fracture and the other perpendicular to such a direction. These movements according to Bertelli have no connection with the wind, rain, change of temperature and atomospheric electricity.

The disturbances as recorded at different towns are not always strictly synchronous but succeed each other at short

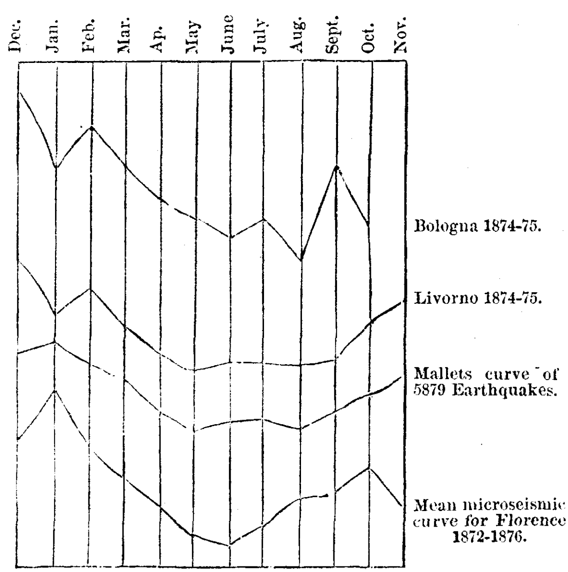

Fig. 2.

intervals. If however we take monthly curves of the disturbances as recorded at different towns in Italy we see that these are similar in character. The maximum disturbances occur about the winter solstice and the minimum about the summer solstice and in this respect they shew a perfect accordance with the curves drawn by Mallet to shew the periodicity of earthquake. The accompanying curves Fig. 2 taken from one of Bertelli's original memoirs, not only shew this general result but also shew the close accord there is between the results obtained at different towns during successive months.

At Florence before a period of earthquakes there is an increase in the amplitude and frequency of vertical movements. The vertical movements do not appear to come in with the horizontal barometrical disturbances but they appear to be connected with the seismic disturbances.

They are usually accompanied with noises in the telephone but as the microphone is so constructed as to be more sensitive to vertical motion than to horizontal motion this is to be expected. This vertical motion would appear to be a local action, insomuch as the accompanying motions of an earthquake which originates at a distance are horizontal.

Storms of microseismic motions appear to travel from point to point. Sometimes a local earthquake is not noticed on the Tromometer whilst one which occurred at a distance, although it may be small, is distinctly observed. To explain this Bertelli suggests the existence of points of interference and the existence of nodes. Similar results were arrived at by Rossi when experimenting at different points on the sides of Vesuvius. Galli noticed an augmentation in microseismic activity when the sun and moon are near the meridian. Grablovitz found from Bertelli's observations a maximum 2 or 3 days before the syzigies and a minimum 3 days after these periods. He also found that the principal large disturbances occurred in the middle of periods separating the quadrature from the syzigies, the apogee from perigee and the *lunistigi.* period from the nodes—whilst the smallest disturbances happened in the middle of periods opposed to these.

P. C. Melzi says that the curves of microseismic motions, earthquakes, lunar and solar motions shew a concordance with each other. With the microphone Rossi hears sounds which he describes as roarings, explosions occurring isolated or in volleys, metallic and bell like sounds, ticking &c. which he says revealed natural telluric phenomena. These are sometimes intolerably loud. At Vesuvius the vertical shocks corresponded with a sound like volleys of musketry whilst the undulating shocks gave the roaring. Some of these sounds could be imitated artificially, by rubbing together the conducting wires in the same manner in which the rocks must rub against each other in an earthquake, by placing the microphone on a vessel of boiling water, or by putting it on a marble slab and scratching and tapping the under side of it.

These then are some of the more important results which have been arrived at by the study of microseismic motions. One point which seems worthy of attention is that they appear to be more law abiding than their violent relations, the earthquakes, and as phenomena in which natural laws are to be traced they are certainly deserving of our attention. As to whether they will ever become the means of forewarning us against earthquakes is yet problematical. Their systematic study however will enable us to trace the progress of a microseismic storm from point to point and it is not impossible that we may yet be enabled to foretell where the storm may reach its climax as an earthquake. These I believe are the views of Prof. de Rossi who is at the present time engaged in the establishment of a system of microseismic observatories throughout Italy.

Before the earthquake of S. Remo on Dec. 6th 1874, Rossi's tronometer was in a state of agitation, and similar disturbances were observed at Livorno, Florence and Bologna. Since February 1883 I have observed a tronometer in Japan, and such results as have been obtained, accord with results obtained in Italy.

The increase in microseismical activity with a fall of the barometer is very marked. The stile of the pendulum does not always oscillate about the same point—there is a deflection of the vertical. In Manila, Father Faura also makes observations with a tromometer, which I am told gives him by its movements very decided indications of approaching typhoons.

As to the cause of tromometric movements we have a field for speculation. Possibly they may be due to slight vibratory motions produced in the soil by the bending and crackling of rocks produced by their rise upon the relief of atmospheric pressure. If this were so we should expect similar movements to be produced at the time of an increase of pressure.

Rossi suggests that they may be the result of an increased escape of vapour from the molten materials beneath the crust of the earth consequent upon a relief of external pressure. The similarity of some of the sounds which are heard with the microphone to those produced by boiling water are suggestive of this, and Rossi quotes instances where underground noises like those which we should expect to hear from a boiling fluid have been heard before earthquakes without the aid of microphones.

One instance was that of Viduare a prisoner in Lima who two days before the shock 1824 repeatedly predicted the same in consequence of the noises he heard.

A possible cause of disturbances of this order may be the sudden fluctuations in barometric pressure which are visible during a storm. During a small typhoon on Sept. 15th in 1881 when in the Kurile Islands I estimated that the needle of an aneroid for several hours worked back and forth with a period of from one to three seconds. At each gush of wind the needle suddenly rose and then immediately fell. At times it trembled. These movements were observed in the open air. The extent of these sudden variations were approximately from .03 to .05 inches. Reckoning an increase of barometric pressure of one hundredth of an inch as equivalent to a load of 20 million pounds on the square mile there must have been the equivalent of loads being continually placed on and removed from every square mile of from 60 to 100 millions of pounds. If the period of application of these stresses approximately coincided with the natural vibrational period of the area affected, it would surely seem, especially when we reflect upon the effect of an ordinary carriage, that tremors of considerable magnitude ought to be produced.

An inspection of the following observations taken from my note book for the same typhoon will suggest that even the larger and slower variations are capable of producing tremulous motions.

Time			Barometer
H.	M.		in.
12—	5	P. M.	29.02
12—	10		29.05
12—	12		29.07
12—	13		29.05
12—	25		29.10
12—	50		29.00
1—	10		29.00
1—	20		29.07

With these atmospheric disturbances not only do tronometers shew movements but the bulbs of delicate levels are in motion. Sometimes they appear to be surging backwards and forwards with an irregular period of from .5 to 2 or 3 seconds and an amplitude of from .25 to .5 of a millimeter. These movements together with those of pendulums apparently indicate a connection between atmospheric and telluric phenomena.