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ART. I.—*Theory of Earthquakes*; by Professor ALEXIS PERREY,
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EARTHQUAKES are a complex phenomenon. It is difficult to refer them to one cause alone. The shocks or series of shocks in a given region may have a special or local cause. We may distinguish a number of such special causes acting independently of the principal cause whose general action they modify. Moreover, these secondary causes may be modified in their action by the principal cause, the latter manifesting itself only through a differential result.

Among the phenomena, it is difficult to distinguish those which are the effects of the principal cause from those of special or local causes. The first aim of investigation should be to determine that differential result in which the preponderating influence of the principal cause shall become manifest. For this purpose the comparison of a great number of facts is requisite. Before such a comparison, the local or anomalous influences disappear; or, in other words, the influence of the principal cause is brought into strong relief, the differential action making it manifest.

There is a periodicity as to times of occurrence in earthquakes, as in other cosmical and meteorological phenomena. When

¹ Translated for this Journal from a memoir communicated by the author entitled *Propositions sur les Tremblements de terre et les Volcans; formulées par M. ALEXIS PERREY, Professeur à la Faculté des Sciences de Dijon, adressées à M. LAMÉ, Membre de l'Institut*; 36 pp. 8vo. Paris, 1863. Mallet-Bachelier, Quai des Augustins, 55.

Only the part on Earthquakes is here reproduced.

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earthquakes, through a long period, are grouped with reference to the moon's age, two maxima and two minima of frequency may be distinguished in each lunar month, the maxima following immediately the syzygies, and the minima corresponding to the quadratures. When, again, they are grouped with reference to the passage of the moon over the meridian, there are two analogous maxima and two minima, the maxima corresponding to the passage of the superior and inferior meridian, and the minima to the intermediate times.

These laws, based, one on a comparison of more than 6000 days of earthquakes, and the other on a thousand of earthquake shocks, show that there is a relation between the frequency of earthquakes and the rotation of the moon. Is this relation one of cause and effect? I believe so, after a careful study of the subject, and propose to present the evidence.

Suppose the globe to have a fluid nucleus, incandescent, and either liquid or viscous, with a solid crust. Suppose, also, the thickness of the crust to be such that the outer limit of the interior mass be a spheroidal surface, similar to that of the exterior of the sphere. The moon will exert attraction on the central nucleus, and tend to give it an elongated form; and the opposite protuberant parts, formed under the lunar action, will tend to follow the line which connects the centre of the moon with the centre of the earth, as this line changes its position with reference to any fixed point on the earth.

Let us consider, first, the movement of the moon alone, leaving out of view the earth's orbital motion and rotation. The greater axis of the elongated central nucleus would then be directed constantly towards the moon. The two opposite protuberances would exert pressure against the interior surface of the crust, and would tend to change its form; and if the crust had but little thickness and were sufficiently elastic, it would at each instant take the form of the elongated nucleus. These successive changes of form in the solid crust could not take place without causing vibrations which should occur periodically, like their cause, nor without altering, at each place, the direction of the plumb-line which would pass periodically through the same positions. These two periodical phenomena have not yet been shown certainly to occur. Still a series of observation, made through several years by Mr. Airy, give us some reason to believe in their existence.

Suppose now the envelop or crust to have so great thickness and such elasticity that it cannot take at once the form of the central nucleus. Pressure and tension in the crust of a greater or less amount will be the result, which will be a cause of fractures. These fractures will be the starting point of molecular vibrations which may be propagated in the crust to its surface

and have the character of true *earthquakes*. Such is the first or principal cause of the phenomenon.

The two opposite protuberances of the central nucleus together constitute, in their movement of rotation, what we call the great or primary earthquake or seismic wave. The greater the lunar influence, the greater will be the protuberances and the higher the seismic wave.

The sun should produce an analogous effect during the progress of the earth in its orbit. From this, a second seismic wave should result, which, in the case supposed, would also cause, when its crests pass under the points of least resistance, the same kind of subterranean movement.

It is easy to conceive that in their simultaneous progress, these two seismic waves should add to, or diminish, one another, or coalesce in one wave, as with oceanic tidal waves. They will therefore manifest themselves at the surface only by their differential or their resultant effects; and their union will form the great luni-solar wave. Its effect will therefore be the greatest possible at the syzygies; and hence the ruptures of the earth, consequent thereupon, should be most frequent at these two epochs in the lunar period.

Let us now take note of the diurnal motion of the earth. We now have two new seismic waves; a lunar, the crests of which will change place under the meridian with the motion of our satellite, and a solar which will follow the course of the sun. Their effects on the inner surface of the earth's crust will be similar to those of the first two waves mentioned above; and the resulting diurnal wave may be regarded under the same points of view as the luni-solar wave depending solely on the motion of the moon in its orbit.

In their progress, these different waves are similar, or, at least, analogous, to those of the oceanic tides. They may be represented, in their movement, by a periodical function whose maxima and minima correspond to the maxima and minima of pressure on the earth's crust, which, supposing it homogeneous, will experience at these points maxima and minima in change of form, and consequently in frequency of fractures; and therefore maxima and minima in vibrations of the crust, or earthquakes.

Into these periodical functions of the seismic waves (or analytical expressions of the physical laws of the phenomenon) will enter necessarily the distances of the sun and moon from the earth. But the action being in the inverse ratio of the squares of the distances, the effect should be, under this point of view, greater at the perigee than at the apogee. In accordance with this, I have found, that, relatively to the lunar motion, earthquakes are more frequent at the perigee than at the apogee; and

relatively to the earth's orbital motion, they are more frequent at the winter solstice than at the summer, that is, at the perihelion than at the aphelion.

All these waves are, physically, not single waves, but are groups of successive undulations, like the tidal in the ocean. Hence there must be a succession of pressures and tensions in the passage of a seismic wave over a given point. Hence, also, a possible, and probable, succession in the vibrations of the crust. Hence, also, an undulatory character in the earthquake shocks, with alternations of intensity during their passage.

Thus far, we have regarded the crust as having interiorly an ellipsoidal surface, and the central nucleus as liquid or viscous. Let us now suppose the nucleus the same, but the inner surface of the crust as having irregularities like the outer,—that is, mountain elevations projecting inward, and immersed in the fluid mass, and valleys whose depressions are excavated in the crust. Such an internal orographic system would modify the progress of the seismic waves. A wave would rise and increase its velocity and, consequently, its active force, between two mountains or elevations that obstruct its passage; it would spread and lose velocity over a plain or in a valley where it could expand and develop itself; and would beat against the declivities or projections encountered. Hence a new kind of compression, and, therefore, of molecular vibrations, which should propagate themselves to the earth's surface, and appear as earthquakes. Hence also, beyond question, some partial displacements in the walls of the vaulted crust, and ruptures causing vibrations more or less intense. Hence, also, fissures in the vault, of greater or less extent, and more or less abrupt.

An introduction of the incandescent liquid from the earthquake-wave into these fissures could hardly take place without shocks or vibrations more or less apparent. But it is a question whether such vibrations would reach the earth's surface. This would depend on their intensity; and also on the thickness and elasticity of the crust, which would necessarily have an important influence.

These displacements and ruptures could not take place without sound.

Whether the ruptures be a result of the alteration of the form of the crust, under the pressure of a passing seismic wave, or of the shock of a wave against an internal protuberance, or of the contraction of the liquid material on its cooling after it has entered a fissure, or of any other cause, they must always be accompanied by vibrations; and these vibrations would propagate themselves to a greater or less distance, according to the condition and nature of the region.

But are these fractures, as has been said, the only cause of the sounds which so often precede, accompany, or follow, earthquakes? It is difficult to believe it. We acknowledge that we are not ready to explain the sounds that so often precede earthquakes. In the case of earthquake shocks which are continued for a length of time, these sounds are often repeated: And how does the sound-vibration differ from the dynamical vibration which immediately follows it? Moreover, in such earthquake-shocks, continued for a length of time, both aerial and subterranean detonations are frequently repeated without any sensible movement of the ground. Many instances of this kind occurred in the valley of Visp in 1855 and 1856.² The sounds are, in fact, one of the most obscure elements connected with earthquakes.

But to proceed, the ruptures which take place at certain points in the crust shake the neighboring parts, which, in their turn, under the action of successive earthquake waves, lead to other like fractures. Such catastrophes may again and again follow. We thus account for the shocks which are repeated for a greater or less time after every great earthquake.

The fractures opened at any point will become prolonged in the direction of the line of least resistance. Hence comes the change in the centre or focus of principal disturbance, which is often noticed in the course of a long series of shocks.

The introduction of the liquid material of the earth's centre into the fissures is not always effected instantaneously. It may require more or less time; and the vibrations thus caused may take place after the passage of the earthquake-wave. Hence come perturbations in the periodicity of the phenomenon.

It follows from these views, that earthquakes should have their greatest regularity of march and greatest frequency in a certain equatorial zone more or less wide; and outside of this zone, similar effects should be produced, proportioned in intensity to the different earthquake-waves, derived or reflected. But it is seen that the waves that are propagated laterally arrive later, relatively to the passage of the moon over the meridian, at the places where the derivative currents go.

When these derivative or reflected waves, in any case, produce fractures, followed by vibrations which continue for a length of time, we should have a prolonged shaking of a region in which, otherwise, the phenomenon is of rare occurrence. Examples of this kind are the shocks on the Mississippi in 1811; those of Maurienne in 1838; those of Scotland in 1842 and 1843.

² The detonations in the valley of Visp continued to occur at intervals even till May, 1861. The later months of the year do not appear to have been marked by any repetition of the phenomena of 1855.—(Letters and Journal of M. Tscheinen, curate at Grächen.)—Note added August 26th, 1862.

The periodicity of the phenomenon may manifest itself again in the renewal of the shocks. But the maxima and minima of frequency will not correspond with the passage of the principal seismic waves. The order may even be wholly reversed. It is a phenomenon analogous to the "establishment of the port" in the oceanic tides.

The physical law, that earthquakes are more numerous at the syzygies than at the quadratures, is one that is verified by simply counting the days of earthquakes during a sufficiently large number of years. This I have done for a period of 50 years, from 1801 to 1850,³ and also for each half of this period. Again, dividing these 50 years into 10 periods of 5 years each, I have detected two maxima and two minima in nine of these partial periods. In seven, the maxima has occurred at the syzygies and the minima at the quadratures; in two the reverse has taken place. The principal, above pointed out, of the establishment of the port is alone sufficient to explain this apparent anomaly. In these two 5-year periods, there was a series of local shocks in a region where earthquakes are unfrequent.

The quinquennial period from 1810 to 1815 affords no sensible maxima and minima. But the facts on record are few. During the unhappy years of 1814, 1815, the journals took little note of subterranean commotions.

³ Prof. Perrey has made out, from the facts which he has collected, for the first half of the present century (from 1801 to 1850), that there were 5388 lunar days on which earthquakes occurred; or, counting as so many separate days, where 2 or 3 or more earthquakes occur on the same day, but in distant countries and wholly independent, (the most correct method for his calculations,) 6596 lunar days. In order to refer these days to the syzygies and quadratures, he divides the mean lunation of 29.53 days into 8 equal parts, and then groups these into 4, by uniting the 1st and 8th and 4th and 5th, for the new and full moon or syzygies, and the 2nd and 3d and 6th and 7th for the quadratures.

Arranging thus the phenomena, he obtained for the 5388 days,—2761.48 at the syzygies and 2626.52 at the quadratures, leaving a difference in favor of the syzygies of 134.96.

For the 6596 days, he obtained 3434.64 at the syzygies and 3161.36 at the quadratures, leaving 273.28 in favor of the syzygies.

In a similar manner, for the half century preceding, or from 1751 to 1800, he obtained 1901.18 earthquake days at the syzygies, and 1753.82 at the quadratures, the difference in favor of the syzygies being 147.36.

Counting the earthquake days during the years 1761 to 1800, which occur within the period of five days, from the second day before the apogee and perigee to the second day after inclusive, he found 526 earthquake days at the perigee and 465½ at the apogee, leaving a difference of 60½ in favor of the perigee; or leaving off the outer two of the five days, the result was 313½ at the perigee and 278½ at the apogee, or an excess of 35 at the perigee.

Taking the earthquakes of Reggio in Calabria as given for the years 1836 to 1853 (18 years) in a Journal kept by M. S. Arcovito, he finds 437 earthquake shocks at the syzygies and 349 at the quadratures, or an excess of 88 at the syzygies. He also obtains, for the number of shocks when the moon was less than 45° from the meridian 413, when more than 45°, 347, leaving 66 shocks in favor of the former.—See for a fuller statement of these results, and additional facts, *Comptes Rendus*, lii, 146–151, Jan. 28, 1861.

We have above supposed the central nucleus of the earth to be in an incandescent state, either liquid or viscous. But can this be without the existence of intense chemical action proportional to the high temperature of incandescence? Under such circumstances would there not be electro-magnetic currents? May it not be that, through the influence of such currents, which Dr. Ami Boué makes the first cause of earthquakes, and also under that of the various chemical actions going on, gases would be developed so as to form a more or less continuous atmosphere between the central nucleus and the crust? And should not the presence of these gases modify in some way, the dynamic action of the earthquake waves? Is not their sudden explosion, the cause, at times, of transient disturbances in the central mass? And, consequently, are there not thence sensible reactions against the inner surface of the crust, causing strong vibrations that are propagated to the outer surface?

This idea, which I have elsewhere brought forward,⁴ is remarked upon as follows by the learned author of the *Histoire des Progrès de la Géologie*. "As to these immense tempests which the author raises at the surface of the incandescent fluid, whose waves of fire beat against the flanks of the mountains which project downward like gigantic stalactites, they appear to us to be a little remote from the domain of science and to pertain rather to that of the imagination."

But, without taxing too much the imagination, can we not see that these chemical actions, which others have made the sole cause of earthquakes, may produce some perturbations, or modifications, in earthquake movements which shall obscure at times the periodicity?

Formerly, especially during the last century, the existence of numerous vast caverns in the earth, for the propagation of earthquakes, was admitted. We do not deny the existence of such caverns; but, in our view, instead of their favoring earthquake vibrations they would arrest, or at least impede, them. The simplest break will modify the rate and direction of the undulations. But such caverns should also cause, in some cases, molecular vibrations which, on being propagated to the earth's surface, would not differ from ordinary earthquakes. The liquid matter, in entering the cavities, would also cause shocks of a similar kind. Hence may come some of those facts registered in earthquake tables, which interfere with the exhibition of the periodicity.

We pass by other causes to which earthquakes have been attributed. Several, although less general than they have been supposed to be, may be admitted among special or secondary causes.

⁴ Memoir on the earthquakes of the Scandinavian peninsula, *Voyages de la Commission Scientifique du Nord en Scandinavie, en Laponie, etc.*, Paris, 1845.

It cannot be too often repeated, that earthquakes are not of one single kind, identically the same. They are various both in causes and effects; I aim simply to bring out in relief the principal cause. I seek to establish its truth, by the differential influence manifested in its march as regards time.

As to the geographical relations of earthquakes, I say only, that no region is secure from subterranean movements; and that no geological formation is exempt; but that the mountain systems of the surface appear to exercise a great influence at least on their propagation if not on their frequency. The vibrations are usually propagated along the main axis of a chain; as has been observed in the Pyrenees and the Andes. In the great valleys occupied by rivers, the mean direction, as calculated by Lambert, appears to be that of the course of the depression. I have shown this to be the fact with the basins of the Rhone and the Rhine, where the direction is nearly meridional, and the basin of the Danube, which has a transverse course, or from west to east.

In France, the departments most subject to earthquakes appear to be those about the mouths of the large rivers. The department of the Isère, where the depression of the valley of the Rhone forms a kind of node with that of the Saône, is the only one which can compare with the kind just mentioned in number of earthquakes.

It is a question whether or not a double orthogonal curvature in the outer surface indicates an analogous structure through the whole thickness of the crust; and whether or not a structure of this kind presents less resistance to the propagation of shocks.

Whatever may be the cause of the molecular vibration at any given point in the crust, vibrations will be propagated in the form of waves; and in a homogeneous medium, the waves will be spherical and concentric. How will it then be in a medium which is not homogeneous, or is of unequal density? This cannot be decided without investigation.

In the case of the propagation of a series of waves which succeed one another through each point in the sphere of undulation and make successive shocks at the earth's surface, the shocks directly over the centre or focus of the vibrations will be vertical: and the obliquity, or variation from verticality, will be greater the more remote the place of emergence at the surface is from the centre of vibration alluded to; or, the locality being fixed, the nearer this centre is to the surface.

There can be no rotary shocks; the cases of apparent rotation we have explained elsewhere. But does the direction of a shock indicate the point from which it actually comes? I believe not. The difference in the rocks encountered should produce derivative and reflected undulations, as in the case of waves of sound.

Breaks in the rocks, as the caverns referred to, must modify their propagation, vary their direction and weaken their intensity, and may extinguish them; and this may account for the simultaneous shaking of two regions while an intermediate locality is undisturbed—a phenomenon of so frequent occurrence in certain parts of America that the people speak of it under the expression of the earth being *bridged within*, or *suspended*.

Boussingault recognized, as the principal cause of the earthquakes of the Andes, the continual and progressive sliding of the dislocated rocks of which they consist; and he considered the phenomenon as incessant in South America, an earthquake taking place, in his view, somewhere in the Andes at every instant of time.

These views are not at variance with my own. Any slidings due to gravity will be caused, or favored, by the daily vibrations whose effects and causes have been considered.

Calculation demonstrates the existence of two kinds of waves moving with different velocities around a centre of vibration; I admit readily, with Mr. Wertheim, the coëxistence of these two kinds of waves. If then there are several successive sets of vibrations at a given point, each will propagate the double system of waves. It will be the same, also, if there are simultaneous disturbances at a number of neighboring points. The waves of greatest velocity of one set will overtake and pass by those of least velocity in the preceding set, and at an interval of distance depending on the interval of time between the successive vibrations.

The ingenious idea that two species of waves or undulations pertaining to two successive sets of vibrations may produce at the surface of the earth one vibration of combined intensity, has nothing in it to which I can object. It is analogous to the interference of waves of light. We also admit, with Mr. Wertheim, that two such combined waves may occasion greater violence of disturbance than the passage of two successive waves. In this case, the surface of the earth under vibration, if perfectly homogeneous, should present concentric zones in which the disturbance will be alternately more and less great. I would say, however, that I do not believe that such an alternation of effects from earthquakes has ever been observed. For such results, not only would a uniformity in the earth's crust be required, but also the structures on the surface to be upset or damaged should have an identity of construction and of position with reference to the points of compass which cannot be looked for.

At some future time, I propose to consider, from this point of view, the occurrence of the first shock more or less light which precedes often the great shakings, and of the harmless vibrations which separate the disastrous shocks; and also the short interval

of relative repose or simple tremulousness which separates two consecutive shocks of moderate intensity.

As to the velocity of the propagation of shocks, we make no definite statement. Notwithstanding the trials of Dr. Julius Schmidt, we have no confidence in the results derived from his calculations, believing that they are based on too uncertain data.

The methods proposed by Mr. R. Mallet, will we doubt not, if carried out, give an exact determination of this element in the phenomena of earthquakes. We recognize the importance of the problem. But even if the means of noting time should be much better than at present, and in more general use, it may be doubted whether numerical results will be obtained of much value to science.