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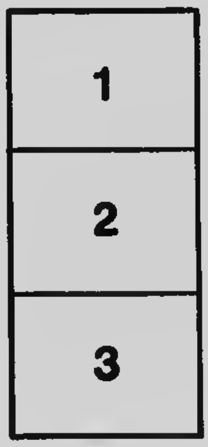
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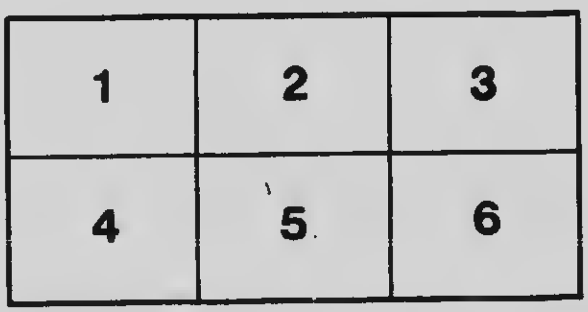
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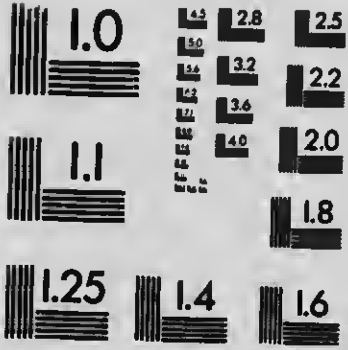

Reprinted From The Journal Of
The Royal Astronomical
Society Of Canada,
February-March, 1908.

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EARTHQUAKES AND THE INTERIOR OF THE EARTH

BY

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no 20679

EARTHQUAKES AND THE INTERIOR OF THE EARTH*

BY OTTO KLOTZ

IN the ninth edition of the *Encyclopaedia Britannica* Professor Archibald Geikie writes: "Though we cannot hope ever to have direct acquaintance with more than the mere outside skin of our planet, we may yet be led to infer the irregular distribution of materials within the crust from the present distribution of land and water, and the observed difference in the amount of deflection of the plumb-line near the sea and near mountain chains. The fact that the southern hemisphere is almost wholly covered with water appears explicable only on the assumption of an excess of density in the mass of that portion of the planet. The existence of such a vast sheet of water as that of the Pacific ocean is to be accounted for, says Archdeacon Pratt, by the presence of some excess of matter in the solid parts of the earth between the Pacific ocean and the earth's centre, which retains the water in its place, otherwise the ocean would flow away to the other parts of the earth. The same writer points out that a deflection of the plumb-line towards the sea, which has in a number of cases been observed, indicates that the density of the

* Address delivered at Ottawa before the Royal Astronomical Society of Canada, February 27, 1908. Illustrated by lantern slides, diagrams and models.

crust beneath the mountains must be less than that below the plains, and still less than that below the ocean-bed."

In passing I may mention that my own observations for gravity in the South Sea show an excess of gravity as indicated by Archdeacon Pratt.

We shall see later what direct acquaintance or information at least we have obtained from the interior of the earth.

Up to 1839 the interior of the earth was considered to be a hot liquid molten mass, and the reasons therefor seemed very plausible:—Did not the temperature increase as we penetrated the earth either in mines or in borings; did not volcanoes give us ocular proof when they transported the flowing lava from the interior; and in connection with these, the analysis of these lavas whether from Vesuvius or Hecla or the Andes or New Zealand or Japan showed that there was a remarkable uniformity in them, leading to the conclusion that they were out of the same cauldron; then there were the hot-springs found all over the world, apparently hot because they came from the heated interior?

These reasons seemed so obviously sufficient, that their very plausibility deadened investigation, as has happened with more than one phenomenon.

Cold, unrelenting, uncompromising, impartial athematics, is not content with plausibility only. In 1839 Hopkins of Cambridge attacked the problem, and endeavoured to calculate how far the planetary motions of precession and nutation would be influenced by the solidity or liquidity of the earth's interior. He found that the precessional and nutational movements could not possibly be as they are if the planet consisted of a central ocean of molten rock surrounded with a crust of 20 or 30 miles in thickness; that the least possible thickness of crust consistent with the existing movements was from 800 to 1000 miles, and that the whole might even be solid to the centre, with the exception of comparatively small vesicular spaces with melted rock.

In treating of the interior of the earth we shall do so under the following headings: Density; Figure of the Earth; Tides; Variation of Latitude; and Earthquakes.

Density or Specific Gravity.—If we compare the weight of a cubic foot of any substance with an equal volume of water we obtain directly the density or specific gravity of the former, as water is the unit of measure. Now this process can be followed for all substances or matter on or near the surface of the earth, but as we cannot penetrate any distance into the earth we cannot directly measure the density for such depths, nor weigh the earth as a whole. However to arrive at the latter several methods are open to us. Here we may first postulate Newton's Law of Gravitation, which declares that "any particle of matter attracts any other particle with a force inversely proportional to the square of the distance between them and directly to the product of their masses."

Our first method is that of the deflection of the plumb-line—or Mountain Method, first applied by Maskelyne in 1774.* Now the direction of the plumb-line is the resultant of all forces acting upon the freely suspended bob or mass. In reality we do not use a plumb-line, but which amounts to the same thing, we use a very sensitive level which owes its position of equilibrium exactly to the same causes as does the direction of the plumb-line. What Maskelyne did was this, he made a topographic survey of Mt. Schehallien and its surroundings, a volumetric survey one may term it, furthermore he determined what the average density of the mountain was, this combined with the volume gave him the mass with which he had to deal outside of the earth itself. Observing, then, zenith distances on the south side of the mountain and again on the north side of it, it is evident that the two would differ by twice the amount that the mountain would deflect the plumb-line from the direction given to it by the attraction of the earth. We have in this case two forces pitted against each other, both forces subject to the same law, *i.e.*, of the inverse squares of the distances and directly as the masses—the unknown quantity being the mass of the earth. From these observations the mean density was found to be 4·5. Now this is an important

* *An Account of the Calculation made from the Survey and Measures taken at Schehallien* by Charles Hutton, F.R.S., 1779.

deduction as will be more fully shown later. Let us state our two facts just found, one is that the density directly measured on the surface was in this case 2·5, and the mean density of the earth 4·5. An interesting inference is made in the above-quoted *Account*, p. 96, viz.: "Consequently $\frac{20}{31}$, or nearly $\frac{2}{3}$ of the distance of the earth, is the central or metalline part." As to the distribution of the density we have by this investigation no knowledge.

The next method briefly to be referred to is that of the pendulum. Now, the pendulum we may consider as an oscillating plumb-line; its action is subject to the same law of gravitation. The greater the pull or force, the more quickly will the pendulum oscillate when disturbed from its position of rest. Hence if we allow a pendulum to swing on top of a mountain whose mass and height are known, and again at the base of the mountain knowing the radius of the earth, in the relation of the equation connecting the observation the only unknown quantity is the mass of the earth, which is thus found. The weak point in this, as in the former method, is the uncertainty of the mass of the mountain, even when numbers of samples of the constituent rock have been weighed.

Another practical application of the pendulum is from observations on the surface of the earth and down in deep mines. This method involves a principle first pointed out by Newton and that is that at any point within a hollow, homogeneous, spherical shell, gravity is zero. Hence in a mine all the matter in a shell the thickness of the depth of the mine has no effect, as the mass in spheres is reduced in the ratio of the cubes of the radii, and the attraction is increased by the square of the radii, the resulting attraction varies directly as the radii. Airy observed by this method, but from the impossibility of obtaining a reliable value for the covering shell the result was not very satisfactory, being 6·56.

The most accurate method is by means of the torsion balance. This is essentially laboratory work, where all the data undergo rigorous determinations and examinations.

From the end of a fine wire, or better still a quartz fibre, is suspended symmetrically a rod having at each end a small metallic ball, each of the same mass. The first determination to be made is the so-called "torsional coefficient," *i.e.*, the resistance that the fibre offers to being twisted. This is done by giving the balls a small rotational motion and observing the time of their swing backward and forward, twisting and untwisting the fibre. The rapidity with which oscillations take place is dependent upon the fibre, the greater its resistence to torsion the shorter will be the period. Having the coefficient determined, the next step is to measure the twist or torsion produced by placing large metallic spheres of known mass on opposite sides of the small balls, and at given distances from them. By the law of gravitation the ball and sphere will approach each other, and the force which is exerted is measured by the amount of torsion of the fibre, and as its coefficient is known the force can be expressed in the ordinary units. Now the force of the earth is known, *i.e.*, we know the acceleration to be 32 feet per second per second, or 978·60 dynes, or we may express the force by saying that the pull of the earth on the small ball is, of course, its weight.

We also know the earth's radius or volume, hence its mass by comparison with the mass of those attracting spheres. As mass is the product of volume into density, we finally obtain the density of the earth, that is, the mean density. Recent determinations by this method give the density as 5·527.

Now what have we learned from these various determinations of the density of the earth? We have found that the mean or average density is about five and a half, *i.e.*, the matter of the earth is volume for volume compared with water between five and six times as heavy as water. Heavy is rather an inaccurate expression, as it implies a force, a pull; better to say, five or six times as dense as water. Mass is independent of force, weight is not.

We have learned something of the earth in its entirety, but we are after details. Although we know so far with a considerable degree of accuracy what its mean density is, yet from it we know nothing definitely about the distribution of the matter. We might surmise or assume as probable that the density increases, perhaps following some law, from the surface to the centre, but as far as the above data are concerned it would only be a surmise. What we can say, however, with certainty is, that if the distribution of mass in the earth is not uniform, then as the density of the earth as a whole is 5·5, some of it must be greater than 5·5 and, of course, some less, as we know to be the case for matter on the surface. Let me say here that the density of iron lies between 7 and 8.

Let us consider briefly another question—the figure of the earth—and see what evidence it can furnish us of its constitution.

Newton applying his law of gravitation and centrifugal force, deduced the flattening for a homogeneous fluid, rotating with a uniform angular velocity to be $\frac{1}{230}$, *i.e.*, the axes in the ratio of 229 to 230.

A few years later Huyghens, on the assumption that the attracting force was concentrated about the centre, found that the ratio of the axes was as 578 to 579, *i.e.*, the flattening $\frac{1}{579}$; this latter assumption is equivalent to considering the bulk of the mass of the earth gathered about the centre. We see then that for a homogeneous earth, *i.e.*, where the density is the same throughout, the flattening is about $2\frac{1}{2}$ times as great as when the density is enormously greater about the centre.

Now from pendulum observations as well as from geodetic measurements the flattening of the earth has been found to be about $\frac{1}{293 \cdot 5}$ (Clarke's value 1880). We see that this value falls between that of Newton and that of Huyghens, obtained under certain and different assumptions. We may infer therefore that the actual conditions in the earth fall somewhere between those assumed by Newton and Huyghens. Hence the conclusion is that the density increases towards the centre. This is an important deduction, and in the sequence of our discussion is the first direct inference of the distribution of the mass within the earth.

In default of knowledge, Laplace assumed, as an hypothesis, the law of compressibility of the matter of which, before its solidification, the earth consisted, to be that the increase of the square of the density is proportional to the increase of pressure. Now the phenomena of precession and nutation are dependent upon the distribution of the mass of the earth, *i.e.*, upon the moments of inertia about the polar and equatorial axes. If we compute the moments of inertia about these two axes we obtain the constant $(C-A)/C$, where C and A are respectively the moments of inertia about the polar and equatorial axes, we find the value to be ·00327, or $\frac{1}{306}$. The moments of inertia of the earth as an ellipsoid about the principal axes are $C = \frac{a^2 + b^2}{5} m$ for the polar axis, and $A = \frac{b^2 + c^2}{5} m$ for the two equatorial axes. Taking the earth as an oblate spheroid $a = b$, hence $\frac{C-A}{C} = \frac{a^2 - c^2}{2a^2} = \frac{e^2}{2}$, where e = eccentricity.

As will be seen from the expression it is equal to the flattening or compression approximately $\left(f = \frac{e^2}{2} + \frac{e^4}{8} + \frac{e^6}{16} + \dots\right)$ or to one half of the square of the eccentricity of the earth, and as this latter quantity is known from the other data we find the two to be fairly accordant, from which it might be inferred that Laplace's hypothesis is verified. But it is necessary not to overlook a very important point, and that is, that the density may only to a degree be dependent upon pressure. The density not only may, but very probably is, dependent largely in the depths of the earth on inherent molecular aggregation; and instead of a homogeneity of material throughout the earth, subject only to the respective pressures at different depths, we probably have to deal with matter inherently of different specific gravity.

There is another phenomenon upon the earth which gives us some clue as to the plasticity or rigidity of the earth, it is the tides. Tidal action through the law of gravitation plays a very important factor in the cosmos, but we can now occupy ourselves, and that but very briefly, only with our own planet. In all or nearly all physical investigations the difficulty of absolute determinations is encoutered. The determinations all pass through the phase of relative measures before the absolute value is arrived at. So it is with the tides.

If we observe the height of the tide at flood and again at ebb, we naturally infer that because water is a fluid, is mobile, it answers or responds to the call or attraction of the Moon and Sun, which the earth as a solid does not. This last statement, however, begs the very question, that of an unyielding solid, which we wish to consider. Let us consider for a moment the earth as a plastic mass. It must be evident then, that although the Moon and Sun would exert their attractive force just as much as before, the phenomenon of tides would practically disappear, for under gravitational stress the land would rise and fall just as the water, and hence their relative position would remain the same. As the land became stiffer, *i.e.*, offered more resistence to being pulled out, tides would appear, until perfect rigidity set in when the maximum rise and fall of the water would occur. We see therefore that the actual tides as we observe them, are a measure of the rigidity or elasticity of the earth. A fluid interior of the earth, as the word fluid is ordinarily understood, seems therefore impossible from the consideration of tides. The gravitational stresses and consequent strains on the interior would continually break up the thin rigid crust of the earth with every revolution of the Moon around the earth. Lord Kelvin found that if the earth had only the rigidity of glass then the tides would be only $^2/_5$ what they would be on a rigid earth, and similarly if the earth had the rigidity of steel then the tides would be $^2/_3$ those of an inelastic earth. As Lord Kelvin says in his closing words on the subject: "On the whole we may fairly conclude that, whilst there is some evidence of a tidal yielding of the earth's mass, that yielding is certainly small, and that the effective rigidity is at least as great as that of steel." *

We will now pass to another consideration involving the nature and distribution of the mass of the earth—it is that of the variation of the pole or poles of the earth.

* *Natural Philosophy*, Vol. II., p. 460.

It is now over a century since Euler established that in any mass-system the axis of free rotation about the centre of gravity can only remain fixed in the system when it is coincident with one of the principal axes of inertia passing through the centre of gravity. Moments of inertia for a solid are generally referred to three principal axes passing through the centre of gravity; for one of them the moment of inertia is a maximum, that is, the summation of the products of every particle of mass by the square of its respective distance from that axis is a maximum; for another, at right angles to the former, the moment of inertia is a minimum. The third axis is at right angles to the plane containing the other two. In the ellipsoid the principal axes would be coincident with its semi-diameters *a*, *b*, *c*. In the oblate spheroid, a figure of revolution, one that is generally assumed in the discussion of the earth, the axes *a* and *b* of the ellipsoid become equal, *i.e.*, the equator is a circle. As stated, Euler showed the stability of the axis of free rotation only then obtains when it coincides with one of the principal axes of inertia. Now in the case of the earth whose shape is due to the very fact of rotation, the principal axis of inertia with which the axis of rotation must coincide to ensure stability must be the polar or shorter one, the one for which the moment of inertia is a maximum.

It may be remarked that for a sphere in which all the diameters are equal, the moments of inertia about any axis through the centre are equal and hence the position of any axis of rotation about the centre may be considered unstable, as the slightest unsymmetrical displacement of mass would produce a permanent change of the position of the rotation axis. Of course the moment a spherical fluid sphere begins to rotate about any axis, the sphere will through the influence of centrifugal force begin to flatten, that is, the axis of rotation will shorten and the axes perpendicular thereto will lengthen. What shape the sphere will take is strictly definable when its period of rotation and the density of the fluid are known.

We see that in the evolution of a spherical liquid or plastic body, when rotation about a diameter is given to it, the axis of rotation will gain stability by the changing form of the body, due to the centrifugal force, and this stability must necessarily continue as long as the mass adjusts itself to the axial rotation, that is, there will be perfect coincidence between the axis of free rotation, and the principal axis of inertia passing through the poles; in short, there will be no variation of the pole. When in the course of time the plastic mass begins to cool and stiffen, it cannot so readily adjust itself to the demands made by the axial rotation. From what we know of the surface and crust of the earth, of faulting; of elevation and sinking of masses; of extrusion and intrusion of lavas, it is obvious that displacements of mass have taken place, and some of them under violence, so that it is reasonable to suppose that at times at least the coincidence between the axis of rotation and the respective axis of inertia would be disturbed. Now according to Euler's theory in this event the axis of rotation will relatively to the solid have a conical movement about the above principal axis of inertia, while pointing to the same fixed point in the heavens, *i.e.*, the declination of the stars is not affected, and its period will be dependent upon the dimensions of the earth and the relation of the principal moments of inertia about the polar and equatorial axes. The period, expressed in terms of the principal moments of inertia, is equal to $\frac{C}{C-A}$. Expressing this numerically we find the period to be about 306 days, say ten months. It is to be borne in mind that this result applies to a perfectly rigid earth, it is obtained simply from a displacement of mass causing a minute divergence between the axis of rotation and the principal axis of inertia. Now the result of this divergence means that the latitude of every place on the earth would go through a cycle of change in 306 days.

Astronomers recognized the validity of Euler's reasoning and examined the records of observations to see if such a period was traceable from latitude observations or meridian circle readings, but they failed. The examination revealed that whatever the fluctuation of latitude, it was confined to a fractional part of a second of arc. The precessional effect upon the axis of the earth, that is, the effect from external forces, the attractions of the Moon and Sun, is to carry the pole around the heavens in about 26,000 years, the axis describing the surface of a cone whose vertical angle is nearly 47°, being twice the inclination of the plane of the equator to the plane of the ecliptic. We shall find that this external influence upon the position of the axis of rotation within the earth is very small, for the precessional effect would be represented on the earth in linear measure by the Arctic circle, and this divided by the number of days in 26,000 years would give the circumference of the circle described by the rotating axis, and this is found to be five and a half feet, which is equivalent for the radius in angular measure of 0″·009, a quantity wholly unrecognizable by observation, so that one may almost strictly say, that the position of the axis of rotation in the earth is not influenced by the change of position in space. However in a quite opposite manner do the changes and distribution of mass within the rotating body act. In this case the change of position of the axis of rotation in the body is predominant, while those in space are secondary and vanishingly small. The following may therefore be almost rigorously stated, that in consequence of the change of distribution of matter of the rotating mass no perceptible change of the position in space of the axis of rotation results from a change in position of the axis of rotation in the body.

Dr. Küstner was the first to show, from his own observations in Berlin, that the latitude had decreased 0″·20 from 1884 to 1885. In 1888 the subject of variation in latitude was taken up by the International Geodetic Commission, and it has actively been prosecuted ever since under the direction of Helmert.

Since 1900 with similar instruments and methods continuous observations have been made at the six international stations—Gaithersburg, Cincinnati, Ukiah, Mizusawa, Tschardjui and Carlo-Forte, all on or very near the parallel of 39° 08′.

A name that will always be most intimately associated with the proof of the change of latitude is that of Chandler, who found that the period was not 306 days, according to Euler's theory, but 427 days. Subsequent to his first announcement in 1891, Chandler examined an enormous amount of material, and as Professor Abbot writes, "From this great array of evidence the fact of the wandering of the pole was not only clearly defined, but also the variation of its period and amplitude came out without question, and an insight was gained, as to the cause of this baffling phenomenon, as follows: The observed variation of latitude is the resultant curve arising from two periodic fluctuations superposed upon each other. The first of these, and in general the more considerable, has a period of about 427 days, and a semi-amplitude of about 0″·12. The second has an annual period with a range variable between 0″·04 and 0″·20 during the last half century . . . . As the resultant of these two motions, the effective variation of latitude is subject to a systematic alternation in a cycle of seven years duration, resulting from the commensurability of the two terms. According as they conspire or interfere, the total range varies between two-thirds of a second, as a maximum, to but a few hundredths of a second, generally speaking, as a minimum."

Now this deviation of 121 days from the theoretical value of 306 days is intimately bound up with the interior of the earth, with its rigidity: as already stated the 306 days pertain to a perfectly rigid earth. The investigation in this respect has led to the result, as stated by Professor Wiechert that the resistance of the earth to deformation is twice as great as that of steel, as we know it. We see then that the variation of latitude tells us something definite about the interior of the earth.

Professor Turner in his "*Astronomical Discovery*" refers to the effects of the wandering of the poles, and says that we should expect to find a swash of the ocean, even if very small, and also that "the little cracks of the earth's skin, which we call earthquakes are more numerous when these unbalanced vibrations are at their maximum; that is to say, about once every seven years,"

—*i.e.*, that earthquakes are in a measure dependent upon the behavior of the axis of rotation. On the other hand a few investigators believe the earthquakes are accountable, to some degree, for the variation of the axis of rotation by the displacement of mass within the earth. This rather extended reference to the wandering of the pole within the earth is introduced to show its connection with the interior of the earth, its rigidity, its elasticity.

We now come to another source of evidence regarding the interior of the earth, it is the principal one that we have for consideration to-day.

EARTHQUAKES AND THE INTERIOR OF THE EARTH.—Let us tarry for a moment with the word wave as understood in physics. A wave is a vibration propagated from particle to particle through a body or elastic medium. We may distinguish different classes or types of waves: gravitational, as in water; longitudinal waves or waves of compression and dilatation, such as manifested in sound; and lastly transverse, as are manifested in the propagation of light. It is certain that the hypocentre or origin of earthquakes is not situate at any great depth compared with the radius of the earth. From deductions based on direct observation within the epicentre, or area within which destruction takes place it appears that probably thirty miles is the very extreme depth at which earthquakes occur. Hence the study of the interior of the earth can not be made from any records within the epicentral region, for the waves received there can not come from or through any greater depth than that of the hypocentre which, as has been said, is within say thirty miles. It is evident we must get farther and farther away to obtain greater and greater depths for the path of those earthquake waves that enable us to study the interior of the earth. Let us consider the first impulse recorded by a number of seismographs or earthquake instruments situate at varying distances of some thousands of miles from the seat of disturbance. Each record would show an abrupt and rapid oscillation. Let it be granted that the origin is known and hence the distance along the surface of the earth and along the chord to each station would be known. Now we can either assume the time of the occurrence of the quake to be known, as is nearly always the case when the epicentre is in inhabited regions, as was the case in San Francisco, Valparaiso, and Kingston, or we may compute it indirectly from the observed times of arrival of the shock at the various stations. The former assumption suits our purpose better. Now see what our problem looks like. It is something like this analogy: Many trains leave Ottawa at the same time in different directions; one arrives at Halifax at a certain time, one in Washington, one at St. Louis and one at Vancouver. If we divide the distance travelled by each, by its respective time consumed, we will get the average speed or rate of propulsion. Granting the same motive power, the road that had the least resistance, the easiest grades would show the highest speed. The distance travelled then combined with the time gives us the average velocity. Now let us return to our earthquake record where we have given the accurate time of transmission, for it is the difference between the time of the actual occurrence of the quake and the time the shock arrives. With the distance our *a priori* knowledge is not so certain for we may say that there are an infinite number of distances between any two points upon the earth, it depends upon the path that the particular wave, which has recorded itself, has taken to reach us from the origin. Torricelli tells us that "nature abhors a vacuum," and similarly nature abhors the roundabout way but follows the line of least resistance at hand. Have you ever followed a mountain stream and seen how it picks out the route of greatest descent, being the easiest and quickest to get down to the valley? Similarly must be the route of our first shock, or preliminary tremors as they are technically called. Now we are safe in assuming that there is some law of increase of density, be it due to pressure or molecular arrangement or both, as we go down in the earth for a considerable depth anyway. This assumption combined with our knowledge of the behavior of different solids of various densities for the propagation of waves leads us to the conclusion that the path of the earthquake wave first to arrive will not be along the geometrically shortest line but along a line concave to the surface, the line along which the pulsations are most quickly transmitted. But even were we to omit the assumption of any particular law for the increase of density as we descend into the earth and treat the medium simply as isotropic we will be able to make the point that we have in view. We will take then that the particular wave travels along the chord, the shortest distance between the two points, *i.e.*, of origin and station, and this distance is accurately known, as is the time. We obtain then an incontrovertible average speed or velocity of propagation of the pulsations. Now let us return to the physical laboratory and see what information we can obtain there to enlighten our path and draw valid conclusions. We find that the speed of propagation through various substances is given, and further that the law of speed is expressed by $v = \sqrt{\frac{E}{d}}$, *i.e.*, the velocity of a wave of compression and dilatation or rarefaction in an isotropic medium is equal to the square root of the elasticity of the medium divided by its density,—or we may say that the velocity varies directly as the square root of the elasticity and inversely as the square root of the density. Increase of temperature also increases the velocity. It is generally accepted that the first preliminary tremors are longitudinal waves, while the second preliminary tremors are transverse, and the waves of the principal portion are surface waves.

When we compare various seismograms of the same quake, having noted on each the various phases, it will be found that the time interval from the occurrence of the shock to the arrival of the long-period waves is directly proportional to the arcual distance from the epicentre. Or inversely, we find for that particular kind of wave that the time interval is proportional only to the respective arcual distances from the centre of disturbance, and as the velocity is dependent upon the density of the medium, the medium, we see, must be more or less uniform, in this respect, which occurs only between two points when the path joining them lies along the surface of the earth. Hence this form of waves must be surface waves. The average speed of these waves is 3·4 km. or 2·1 miles per second. For instance in the San Francisco catastrophe those waves took nearly 17 minutes to reach us here, an arcual distance of 35° 25′ or 3930 kilometres, velocity 3·8 km., hence to complete the circuit of the earth would take a little more than ten times as long, or over two and a half hours.

When, however, we make comparison of the two phases of the preliminary tremors, we note two important facts, the first is, that the time interval is not proportional to the arcual distance, as it is for the above surface waves; now, the natural inference would be that the wave travels along the chord between the hypocentre and the place, and, of course, the chords are not proportional to the arcs which they subtend. On closer examination of the records there will still be a small outstanding difference after making due allowance for the ratio of the chords, that is, the farther place shows the greater velocity, or which comes to the same thing, the time interval for the farther place is relatively shorter than for the nearer place, allowing for difference of distance along the chords. Strictly speaking these chord distances are only applicable in an isotropic medium, in an æolotropic medium we would find the path concave to the surface of the earth, which is really the condition which obtains. This further speed we find attributable to the greater depth, and hence greater density and elasticity of matter through which the waves reaching the farther stations travel. From the relationship which we have shown to exist between velocity, elasticity and density, and from the observed fact that the velocity increases with the depth, to within certain limits, it follows that the elasticity must increase faster with the depth than does the density. This, then, is the first fact that we note with reference to the first preliminary tremors as interpreted from different seismograms. The second is that the interval between the first and second preliminary tremors is not only not constant, but increases with the distance from the hypocentre. This fact immediately differentiates the nature of the waves. It is evident and obvious that one kind of pulsation is gaining on the other, otherwise the two recorded phenomena would not be getting farther and farther apart, and we arrive at the conclusion that we are dealing with two different kinds of waves—with longitudinal and transverse waves. It may be opportune right here to draw a certain inference, after having seen the existence of transverse waves. While longitudinal waves, those of compression and dilatation, may be propagated in a solid or fluid, the transverse waves (those of distortion) can not be propagated in a fluid, taking the term in its ordinary acceptation. We must conclude therefore that in that sense of fluidity we cannot speak of the interior of the earth. The interior of the earth is neither liquid nor gaseous, but solid. It is to be borne in mind, and this point may well be emphasized, that this is not a speculation, as so much hitherto has been about the interior of the earth, but the direct evidence or hand-writing of messengers who have travelled through the earth, and told us their story on the seismogram. The seismograms are the Röntgen rays of the interior of the earth.

Now, as you will see from the diagram which I have constructed from available data for the San Francisco earthquake, the increase of velocity with the depth is fairly well represented by a straight line up to a depth of about one quarter of the earth's radius. The chord of this depth is subtended by an arc of about 83°. It may be remarked that an arc of 83° from Ottawa would pass close to Cairo, Egypt ; Valparaiso, Chile ; and the northern extremity of Japan. Beyond this depth there is no apparent increase in the velocity. Up to this point the elasticity was increasing faster than the density, but henceforth this relationship does not obtain. It would appear as if we encountered different conditions of matter.

It is found that the velocity of the first preliminary tremors increases from 7 km. per second near the surface to nearly 13 km. at great depths, where it is approximately constant. Similarly for the second preliminary tremors we have the velocity increasing from 4 km. to 7 km. per second, depending upon the depth of the path. The surface waves have an average velocity of about 3·4 km. per second.

It may be observed here that the many disturbances in Italy during the past two years must have their origin at very small depths, that is, the hypocentre must be very shallow, for, so far, no record has been obtained here of an Italian volcanic or seismic disturbance, even when the latter has been locally very destructive.

The data at hand are somewhat limited for very distant places, and the conclusions based on the latter might appear based on meagre material. However, they receive ample support from Professor Wiechert, who has paid especial attention to the subject, and who has had at his disposal a vast amount of matter. His conclusions from all the evidence he could gather, and especially from the seismological records, are that the earth is composed, essentially of a stony layer for about a quarter of the diameter, and the interior is a core, most probably of iron. We cannot on this occasion enter into the many other questions connected with our discussion. Volcanoes, which are a phenomenon apart from earthquakes, may be said to be mere pustules in the skin of the earth and are not part of an interior liquid mass or magma, for the latter does not or cannot exist.

I think it must be admitted that what has been presented as evideoce by earthquakes, or rather their seismograms, about the interior of the earth, has been of a most positive and in many respects conclusive character. And we are but at the beginning of this new science of Seismology in unravelling the story of the structure of the earth and of its behavior. Although there is a fairly clear idea of the propagation and nature of the waves issuing from the hypocentre, or more strictly speaking the hypo-area, for the seismic disturbaoce does not issue from a point, but rather an area or volume is involved, yet there remaios much to be learned about these waves. Then, too, the separation on the seismogram of the part due to the motion of the pendulum, which is supposed to be at rest, from the earth movements due to the quake, is a matter of iioport. But for all the difficulties involved, we must oot lose sight of the fact that the seismograms have the data for a complete solution and determinatioo of all the quantities involved in producing the records. The Rosetta stooe is yet to be found for a complete interpretation of the hieroglyphs of the seismogram. When our instruments are made more sensitive, when their time-record is improved, when we can assure ourselves on various seismograms of the identity of the record of one and the same impulse from the hypocentre, say that every seismogram considered shows the impulse from the first wave-front, then, from resulting observation equations, not only will the accurate properties of matter of the interior of the earth at various depths be determined, but eventually also deviations therefrom on particular paths along which the impulses travel, just as our pendulum observations now are mainly utilized for detecting deviations from the theoretical value of gravity; we shall be able to differentiate velocities for the same distance but over different routes, *i.e.*, coming from different hypocentres; for favorably situated stations along a mountain chain, the "roots" of the mountains may reveal their characteristics, that by other methods have been inferred.

Seismology has taken firm root and the outlook for the future is bright, it holds the key to unlock the contents of the treasure vault below us. Earthquakes have already told us much of the interior of the earth and much more is in store.