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814TH ORDINARY GENERAL MEETING,

HELD IN COMMITTEE ROOM B, THE CENTRAL HALL, WESTMINSTER, S.W.1, ON MONDAY, JANUARY 24TH, 1938, AT 4.30 P.M.

SIR FRANK DYSON, K.B.E., F.R.S., IN THE CHAIR.

The Minutes of the previous Meeting were read, confirmed and signed and the HON. SECRETARY announced the following elections:—As Associates: The Rev. Chas. T. Cook, James H. Leask, Esq., M.A., F.R.G.S., and the Rev. Stewart M. Robinson, M.A., D.D.

The CHAIRMAN then called on R. Stoneley, Esq., Sc.D., F.R.S., to read his paper entitled "The Interior of the Earth."

THE INTERIOR OF THE EARTH

By R. STONELEY, Esq., Sc.D., F.R.S.

(With Lantern Illustrations.)

UNTIL comparatively recent times the question of the composition and state of the interior of the earth was open for the wild theorisings of philosophers, scientists and theologians alike, and the acceptance of a theory was liable to be settled largely by the eminence of the propounder, a disability from which scientific hypotheses are apt to suffer even to-day. Borings have been made only to relatively short distances, and modern experimental work, such as geophysical prospecting, touches only the outermost few miles of the crust. Our knowledge of the interior, then, is based mainly on indirect evidence, and this has to be drawn from a very wide range of studies. There is the further difficulty that the high temperatures and pressures that appear to be involved require an extrapolation of the laboratory laws of physics, and although astrophysics has accustomed us to a still wider leap, our lack of knowledge of these laws is a serious drawback.

In choosing problems for attack our interest naturally centres on the occurrence and distribution of elements within the earth, their physical states and properties, and the temperature distribution. We may inquire into the past, and seek to know the future of the earth, particularly in its relation to the solar system, but, fascinating as such topics are, they involve for the most part some extrapolation, often risky, of the laws whose validity is established over a limited range of conditions only, and any provisional conclusions must be regarded as speculative. The most important sources of information are the geological, astronomical, geodetic and seismological evidence, and especially the last named ; observations of earth tides and oceanic tides, of thermal conductivity and radioactivity of rocks are likewise important, and all these data must be examined in the light of the laboratory laws of physics, with quantitative tests as far as possible, such as measurements of the thermal and elastic properties of rocks at high temperatures and pressures, or by " exploring " the outer crust of the earth by artificial explosions. It will be more informative to indicate some of the main lines of attack than to give a catalogue of results.

The value of the constant of gravitation, as determined by delicate experiments on the attraction of two bodies, and the value of the acceleration due to gravity, as found from the period of a swinging pendulum, yield in combination with the radius of the earth given by geodetic measurements the value 5·5 as the mean specific gravity of the earth. Now the meteorites that come from outside the earth's atmosphere consist sometimes of stony matter and sometimes of nearly pure iron. If, as has been suggested, these are representative of planetary matter it may well happen that this mean specfic gravity arises from an iron core, of specific gravity 8 or more, surrounded by a rocky shell ; geological evidence suggests that the matter lying beneath the continents and oceans may be ultrabasic rock of specific gravity about 3·4.

The question of whether the earth, apart from its outer layers (perhaps some 30 km. in thickness), consists of a chemically homogeneous substance, condensed centrally under its own gravitational attraction, or whether there are changes in composition, continuous or discontinuous, from point to point is answered by an investigation due to Clairaut. In his monumental treatise, *Théorie de la Figure de la Terre* (1743), he showed that if the earth is an oblate spheroid of ellipticity ε, mass M and radius a, the difference $C\text{–}A$ between the principal moments of inertia is given by the formula $3(C\text{–}A)/Ma^2 = 2\varepsilon\text{–}m$, where m is the ratio of the centrifugal force at the equator to mean gravity and is about 1/288 ; geodetic measures give ε as about

1/297. The value of (C–A)/C is known from the period of the precession of the equinoxes to be about 1/305·6, so that C/Ma^2 is 0·334. Now the moment of inertia about an axis is found by multiplying each constituent mass into the square of its distance from the axis and finding the sum of these contributions; accordingly the moment of inertia is an index of the concentration of matter towards the surface of the earth. For a homogeneous earth the value would be about 0·4, so that the actual earth must be centrally condensed. Further, the data cannot be satisfied by assuming the earth to be chemically homogeneous and compressed under its own attraction.

There is some latitude in choosing laws of density. It has been shown that any law of density giving the correct mean density and satisfying $C/Ma^2 = 0{\cdot}334$ will lead to the correct value of ε and of (C–A)/C, which are, therefore, not independent data. Accordingly, other considerations must be introduced. The so-called "laws" of Laplace and Roche have no geophysical justification, and were introduced illustratively merely to make a certain differential equation integrable; further, they give a value of the density in the upper layers that conflicts with geological evidence. Wiechert's hypothesis that there is a rocky shell of specific gravity 3·2 surrounding a metallic core of density 8·2 and radius 0·78 times that of the earth represented a considerable advance: it was consistent with geological and astronomical evidence, but made no allowance for compressibility.

It is the seismological evidence that is most informative. Earthquakes occur within 20 km. of the earth's surface, and the initial dislocation gives rise to two types of waves, compressional (P) and distortional (S), which are transmitted through the body of the earth and recorded by seismographs at stations all over the earth. In this respect the earth behaves like an elastic solid. By analysing the times of transmission of the pulses to various distances it is possible to find the corresponding velocities at different depths. The direct S waves, however, are not received at angular distances greater than about 103°, and the only explanation seems to be that the central portion behaves like a liquid in not transmitting S waves, a suggestion made by R. D. Oldham, C. G. Knott and B. Gutenberg. The last-named found that the diameter of the liquid central portion must be about half that of the earth; the junction is quite sharp, for waves reflected at the discontinuity can be identified in seismograms.

A further line of evidence is afforded by earth tides, observations on horizontal pendulums, and by determinations of the "variation of latitude." The tides raised in the body of the earth by the sun and moon affect the ocean tides in two ways :—(i) the equilibrium height of the ocean tide is diminished by the tidal rise of the ocean floor and (ii) is increased through the gravitational attraction of this tidal "bulge" in the earth. The effect of the yielding of the earth is thus to alter the height of an oceanic tide in the ratio $1 - h + k$. A similar factor arises when the moon's horizontal attracting force is measured by means of a horizontal pendulum. It was proved by Euler that if the earth is slightly disturbed from a state of steady rotation the axis of rotation will describe a cone in the earth. The actual motion is the same as if a rough cone, fixed in the earth (the "polhode-cone") were rolling on a cone (the "herpolhode-cone") fixed in space. For a completely rigid body the period of movement of the axis of rotation *relative to the earth* should be A/(C–A) days, *i.e.*, about 306 days. This movement of the axis of rotation would give rise to a corresponding fluctuation in the observed latitude of an observatory. The actual observed free period (there is also an annual period, which is ascribed to meteorological causes) was found by S. C. Chandler in 1891 to be about 427 days, and the lengthening is to be attributed (as suggested by Simon Newcomb) to the finite rigidity of the earth ; in fact, the number k, which arises through the yielding of the earth, may be calculated from the observed free period, and is about 0·27. Since $1 - h + k$ is about 0·67, h is nearly 0·6.

Now h and k, the so-called "Love's Numbers," may be calculated directly when the density and elastic properties of the earth are known, and so a comparison is possible. When the density is known the elastic constants at any depth may be found from the corresponding velocities of P and S waves. These calculations have been made on various hypotheses concerning the composition of the interior, but as long as it is assumed that the central part of the earth has a rigidity bearing the relation to the compressibility that the term "solid" implies, the calculated yielding is too small. This suggests, quite apart from the fading-out of S at a distance of 103°, that the interior of the earth is partly liquid, and the discrepancy was cleared up by Dr. Jeffreys, who showed in 1926 that if the Wiechert discontinuity in density is made to coincide with the surface of the Gutenberg liquid core, then when gravitational compression is allowed for the data agree extremely well with the tidal observations. The specific gravity of the solid shell would increase from about 3·5 near the surface to 5·5 about half-way down, with a sudden transition there to a material of very low or zero rigidity and specific gravity about 10. At the centre the specific gravity would be about 12. These values are consistent with the existence of an iron core.

Information about the structure of the surface layers of the earth, just below the sedimentary rocks, is forthcoming from the detailed examination of earthquake records. The pulses recorded at stations within 800 km. of an earthquake focus indicate that below the sedimentary rocks of the continents there is a granitic layer some 17 km. thick, and beneath this a layer of basic rock about 9 km. thick. Below these continental layers the material seems to be ultrabasic rock, with no important change in composition down to the core, except possibly for a discontinuity at a depth of about 480 km., which, if confirmed, may correspond to a transition from a rhombic to a cubic form of olivine under high pressure. There are two types of wave that are propagated over the surface of the earth rather than through the interior; these are respectively called after Rayleigh and Love, by whom they were theoretically predicted. Their times of travel confirm in general the above findings in connection with the continents, and they show that there is a marked difference between the continents and the Pacific floor; owing, however, to the dearth of seismological stations on the islands in the Pacific, precise information about the ocean floor is lacking.

Some inferences concerning the viscosity of the earth are possible from the persistence of the free period of the variation of latitude and from the absorbtion of seismic waves, but these are decidedly precarious, and all that it is wise to say is that for forces of short period (*e.g.*, about a minute) the rocky shell of the earth behaves as an elastic solid, and the core as a liquid, whilst for periods of the order of some thousands of years the earth seems to yield as a whole, after the fashion of pitch, and to behave as a liquid of very high viscosity.

Thermal considerations can only be touched upon briefly. On any reasonable hypothesis concerning the age and thermal conductivity of the earth the " original heat " must have only a small effect on the surface temperature and temperature gradient. The present surface temperature is maintained by solar radiation, and the existing temperature gradient is presumably maintained by the escape of heat generated by radioactive minerals, such as uranium and potassium. The conductivities and radioactive contents of granitic and basic rocks give an estimate of the thickness of the continental layers that is in general agreement with the seismological determinations.

Discussion.

A hearty vote of thanks to the lecturer was proposed by Dr. F. J. W. Whipple. Dr. Whipple called attention to Dr. Stoneley's reference to the evidence provided by meteors as to the likely constitution of the earth. It was almost certain that solid bodies of the size of meteorites could not have been formed directly by the condensation of gaseous material. Meteorites must be the débris of planets or satellites which had met with disaster, either by coming into collision or by approaching some larger body so closely that fracture was produced by the stress set up by gravitation. Saturn's rings were explained by such a fracture. It was likely that any planet which produced metallic meteorites when it broke up had had a core which was solid, not liquid like that of the earth.

Written Communication.

Lt.-Col. L. M. Davies wrote: Since I do not consider myself qualified to discuss the subject of this paper, I would only venture to ask the lecturer a question, which is as follows:

How are the movements of the magnetic pole to be accounted for? These movements seem to be continuous, and the pole itself fairly deep-seated. Would the migrations of that pole not point to something in the nature of convection currents within the earth, thus indicating liquid action of a third kind—*i.e.*, neither very brief nor exceedingly slow, since the location of magnetic north varies materially from year to year?

Author's Reply.

I do not feel qualified to say much about the movement of the magnetic pole. The earth's viscosity is too great for it to be a free precessional motion, and I do not think attempt to explain it as a forced vibration (like the annual period of latitude variation) has been successful.

The reference to meteors was merely that they provide a sample of matter as found in the solar system : whether it is a representative sample is, of course, a matter for conjecture. I agree with Dr. Whipple that matter in the form of meteorites is more likely to be derived from the break-up of a solid planet than from the condensation of a primitive nebula or star, or even a planet with a liquid core. The disrupted body might well be an asteroid small enough to be solid ; accordingly, the *chemical* constitution of meteors may be a guide to the *chemical* constitution of the earth irrespective of the *physical* state of the meteorites, whether before or after their formation.