NATURE OF THE EARTH'S INTERIOR.*

ITS RELATION TO THE QUESTION OF DEEP MINING.

BY PROF. E. H. L. SCHWARZ, A.R.C.S., F.G.S.

GEOLOGY has inherited many beliefs from mediæval times, which still remain part of the creed of those who profess to base their ideas on solid fact. One of the most ingrained of these beliefs is that of a hot, liquid interior of our earth. It was proved to the satisfaction of the Mediterranean nations by the flows of lava from the chimneys of Etna and Vesuvius, and it was the civilization of these nations which spread and was taken up by the rest of the world so that ideas started in Italy became the heritage of all thinking men. Then Kant and Laplace, with their nebular hypothesis, put this liquid globe theory on a basis which satisfied every condition then known or imaginable. If, however, we examine the premises of the Laplacian theory; if we put ourselves outside our hereditary tendencies and dispassionately review the whole question, we shall find that all the so-called proofs and reasons for the earth's interior being hot and liquid rest on arguments which will not hold water. The lava of Etna, for instance, cannot come from any profound depths. The gaseous sphere with which Laplace commences his history of the solar system could not have existed, as the kinetic energy of gaseous molecules would have prevented their being whirled round in a coherent globe; the solar system, in fact, at the present day, instead of affording testimony in favor of the nebular hypothesis, contains so many contradictory evidences that a new theory of its origin has become imperatively necessary.

Not only is the philosophy of modern geology destructive of the old idols of theory and hypothesis, but it is constructive, perhaps merely to set up a new idol, but nevertheless the new hypothesis of the nature of the earth's interior rests on a basis of probable fact and stands four-square to modern knowledge. I refer to Prof. T. C. Chamberlin's Planetismal hypothesis. I cannot here explain the hypothesis as a whole; it is available to all in the Text Book of Geology published by Profs. Chamberlin and Salisbury; suffice it here to state that the theory necessitates the gradual growth of the earth from a small, solid nucleus by the infalling of meteorites and that it is still growing. My purpose in the present paper is to examine some of the results of the physical investigation of the surface of the earth which prove by undeniable evidence the existence of a solid interior of the earth, which we postulate from theoretical considerations if we accept the planetismal hypothesis; and as none of the processes of earth building explained by this hypothesis require a hot interior, we are left with presumptive evidence that it is cold.

In the first place we are now enabled to actually test the physical condition of the interior of the earth by means of vibrations which travel through it. When an earthquake originates at any one place there is sent forth a vibration which affects the outer siliceous surface only; the latter heaves as an ice-floe would upon the surface of an agitated ocean. Besides this surface quake there are vibrations which travel by the brachistochronic or the shortest possible paths right through substance of the earth's interior to a spot on the other side, where the vibration can be recorded. Now, when a shock is communicated to a body, there are two kinds of waves that are set up; there is the normal or compressional vibration, which can be propagated in any medium, solid, liquid or gas; but if the medium is solid, there is a further transverse wave, which, on account of its being distortional, cannot be propagated in a liquid or gas. The velocities of these two waves are very different, and when we find on the recording seismograph two distinct vibrations separated by a definite time interval, which is proportional to the distance traversed in the earth's interior, then we can state that the earth's interior is solid throughout. Indeed, we can say more than that. The difference in the rates of the two waves is such as would be experienced in a medium twice as rigid as steel. Arrhenius has maintained that a gas might be so compressed that it becomes as compact as a solid, but then it could not transmit distortional waves, which can only be propagated in rigid substances, and Arrhenius's theory of the gaseous interior of the earth must fall to the ground on that fact.

There is another curious fact connected with earthquakes which bears on our subject. For direct paths between two points in the earth's crust less than 1,000 miles apart, the one being that at which the earthquake occurs and the other being that at which it is recorded, the speed of transmission is such as is found in waves propagated through ordinary rocky material; but if this straight path penetrates more than 30 miles below the surface, the waves are accelerated. There is, as it were, a globe of high elasticity, twice as rigid as steel, immediately below 30 miles in the earth's crust, whereas all above is not materially different in physical condition from the rocks exposed on the surface. If the earth's interior were molten, let alone gaseous, it would be impossible from the laws of diffusion for this sharp demarcation between crust and interior to remain in existence.

Having established the fact that the earth's interior is a solid, let us now examine the temperatures observed in the earth's crust.

As we go downward in the earth's crust there is a distinct increase of temperature below the variable zone affected by the climatic and seasonal conditions. This increment is on an average about 1 deg. F. for every 60 feet. But what is this average calculated upon? It is obtained by massing all the figures from various rock systems and dividing through. If now we take the older and younger rock systems we shall find that the former, nearer the earth's centro-sphere, have a temperature increment of only 1 deg. F. in every 200 feet, whereas the latter may have as rapid an increment as 1 deg. F. in every 28.1 feet (Anzin, near Valenciennes). In the British Isles we may obtain in this confined area alone differences ranging from an increment of 1 deg. F. for every 34 feet to 1 deg. F. for every 130 feet.

To explain the earth's temperature we have no reason to postulate an internal molten sphere of rock; in fact, were there any heat at all in the center of the earth, life on the surface would be impossible from the enormous additional heat received by the crust by radiation. The source of this earth temperature lies firstly in the chemical changes which go on in the rocks themselves and secondly in the fact that all siliceous rocks contain radium, and lastly in the movements in the earth's crust, which produce frictional heat.

To take the first case first. The earth's crust is a veritable chemical laboratory, in which reactions are always going on. The simplest process is the oxidation of pyritic carbonaceous shale rock, such as we find abundantly in the Lias of Europe and above the Dwyka Conglomerate in South Africa. When water containing oxygen gains access to this rock through cracks, there is immediately a reaction which sets up so much heat that not infrequently steam and sulphurous vapors are given off and escape at the surface as in solfataras near volcanoes. In the Kimberley mines, which pierce the carbonaceous shale of the Dwyka series near the surface, this action has happened in many instances, and the reef has burnt for years. It must be remembered, however, that the reaction is reversible. An oxidized sediment deeply buried may become pyritized and hence heat will be absorbed and locked up so that pyritic shales will show abnormally high temperature increments near the surface and abnormally low ones below the range of surface waters.

The following figures are given by Sir A. Geikie for the Rose Bridge Colliery Shaft at Wigan, and will show at a glance how dependent on the rock encountered is the temperature increment.

Depth, in Yards.	Increment, in Feet.	Increase, in Feet, for 1 Deg. F.	Temperature, Fahr.	Increase.
558	...	....	78.0	...
605	141	70.5	80.0	2.0
630	75	28.0	83.0	3.0
663	99	48.5	85.0	2.0
671	24	24.0	86.0	1.0
679	24	24.0	87.0	1.0
734	165	110.0	88.5	1.5
745	33	66.0	89.0	0.5
761	48	32.0	90.5	1.5
775	42	28.0	91.5	1.0
783	24	48.0	92.0	0.5
800	51	51.0	93.0	1.0
806	18	36.0	93.5	0.5
815	27	54.0	94.0	0.5

In one place, therefore, the rate of increase may vary from 1 deg. F. to every 24 feet to 1 deg. F. for every 110 feet.

In the deeper-seated portions of the earth's crust, where the pressure is so enormous that solids become potential liquids and the molecules of which they consist have the mobility of those liquids, silicic acid or silica becomes active. The heat of combination is equal to that of nitric acid, and wherever this silicic acid comes in contact with a carbonate it replaces the carbonic acid, forming first the various lime silicates, wollastonite, garnet, epidote and so forth, but later, if the process is continued, sending the bases out in solution and entirely replacing the original compound. The heat-equivalent of all these reactions can be worked out, and in the near future it will be possible, if the history of a piece of metamorphic rock is known, to say that it has given out or absorbed so many calories.

The important fact to observe is that chemical reactions may add to or subtract from the heat of the earth's crust. Generally it may be stated that at great depths the reactions cause diminution of temperature, whereas nearer the surface they are of such a nature that they cause rise of temperature. Every reaction has its own heat equivalent, but it may be safely stated that the majority of heat producing reactions stop at five miles depth in the earth's crust, and that the nearer the surface the greater the number of such reactions. From which it follows that rocks once deeply buried, but now uncovered, are rocks such as have been formed under conditions of heat absorption, and we arrive at the apparent paradox that the fundamental granite and gneiss was melted under conditions of great cold. It is impossible in a paper of this nature to go over all the reasons which make such a fact extremely probable; suffice it here to call to mind that the liquid condition of a substance means that the mass offers no resistance to distortion; hence under enormous pressures it is quite possible to liquefy a solid, such as granite, in much the same way as one can cause lead to flow under pressure†, and in that case, the molecules having the mobility of that of a liquid, will cause the granite to have all the features of a rock crystallized from igneous fusion. From field evidence of the contact of granite and slate, for instance, it is abundantly clear that the rock cannot have been at the temperature necessary to cause it to melt under atmospheric pressure; in the classical examples at Huelgoat in the department of Finisterre, in Brittany, the Silurian slates on the west of the granite are entirely unaltered, though on the east side they have suffered extreme metamorphism, proving that it is not the heat of the granite that has to do with the metamorphism, but rather the pressure which happened to be concentrated on only one side of the granite.

Turning now to the heating effect of radium, we have the work of Joly in the Simplon and St. Gothard rocks to guide us.

In the St. Gothard tunnel, Stapff observed in the central portions temperatures which worked out at a gradient of 46.6 meters (152.8 feet), for 1 deg. C. (33.8 deg. F.), with small irregularities, which he attributed to cold springs and the decomposition of the rock. At the north end, where the tunnel pierces the granite of the Finsteraarhorn massif, there is a rise of temperature sufficient to make the gradient 20.9 meters (68.6 feet) for every 1 deg. C. Stapff explained the last rapid increase by imagining that the granite retained some of the original heat of its molten condition, but Prestwich, on the other hand, preferred to look upon it as the result of mechanical actions which had comparatively recently been in progress, and to which the upheaval of the Alps was due. In the more recently bored Simplon tunnel, Stapff, basing his estimates on the experience obtained in the St. Gothard, predicted a maximum temperature of 47 deg. C. (116.6 deg. F.), while others predicted much lower ones. The actual temperatures observed, however, rose to the north end to 55 deg. C. (131 deg. F.), and caused immense difficulties in ventilation and working. This unexpected high temperature was believed by Fox to be due to proximity to volcanic rocks, but nothing of the sort has been noticed on the surface. This fact nevertheless shows how impossible it is to estimate increase of temperature in the earth's crust; in the Simplon case the excess of heat almost stopped the working, whereas the deep levels of the Witwatersrand, which should be almost unbearably hot if the established temperature gradients existed in nature, are comparatively cool.

Joly investigated the Simplon and St. Gothard rocks with a view to ascertaining their radium contents, and found that the amount of radium contained in the various types encountered corresponded in a remarkable way with the temperature gradients, so that in the high gradient region of the St. Gothard the amount

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† The parallel of granite and lead under pressure is not strictly a true one, since the granite becomes molten through the solvent action of water, which, under high pressures, dissolves silicates.

was 14.1 billionths of a gramme per gramme of rock, whereas in the low gradient region it fell to 3.3 billionths. In regard to the temperatures of the two tunnels, the following tables show the same correspondence:—

Simplon Tunnel, amount of radium per gramme of rock substance in billionths of a gramme:

Jurassic and Triassic altered sediments	6.4
Crystalline schists, partly Jurassic and Triassic and partly Archæan	7.3
Monte Leone gneiss and primitive gneiss	6.3
Schistose gneiss	6.5
Antigorio gneiss	6.8
Mean for all rocks	7.1

St. Gothard Tunnel, amount of radium per gramme of rock substance in billionths of a gramme:

Granite of Finsteraarhorn	7.7
Maximum	14.1
Usernmulde	4.9
St. Gothard massif	3.9
Tessin mulde	3.4
Mean in Central Section	3.3

From Joly's figures there can be no doubt left in one's mind that radium has at any rate a very great influence on the temperature observed in rocks, if it is not entirely responsible for all the heat in the earth's crust. But the work of Strutt, who initiated this line of research, is still more positive. The following table is taken from his work on the distribution of radium in the earth's crust and on the earth's internal heat:

Rock.	Locality.	Radium in Billionths of a Gramme per Gramme of Rock Substance.
Granite	Rhodesia	9.56
Granite	Cape of Good Hope	7.15
Granite	Shap Fell	6.65
Granite	Isle of Rum	6.76
Olivine basalt	Skye	1.32
Basalt	Victoria Falls	1.26
Basalt	Ovifak, Greenland	0.613
Dolerite	Isle of Canna	1.24
Dunite	Loch Scaivig	0.664
Stony meteorite	Dhurmsala	1.12
Iron meteorite	Three specimens	....
Native iron	Disco, Greenland	0.424

The general result of the analysis of the 33 specimens tested is that the radium content is higher in silicious than in basic rocks and that meteoric iron is free of radium. Assuming that the rate of increase observed in the crust of the earth is 1 deg. F. for every 42.4 feet, according to Prestwich's mean, then if all the heat were solely produced by radium contained in the earth, the amount would be .175 billionths of a gramme per gramme of earth substance, taking it all through. All igneous rocks, however, contain far more than this; the poorest of all, the Greenland basalt, contains 10 times as much and an average rock 50 to 60 times as much.

If then the earth cannot contain on an average more than .175 billionths of a gramme per gramme of earth substance and that 5 billionths is a representative value for rocks in the crust of the earth, then not more than 1/30 of the earth's volume can consist of material similar to that encountered on the surface. This would give a depth of rock crust of about 45 miles, assuming a total absence of radio-active material within.

Suppose, further, that all the heat in the earth's crust is produced by radium, then the temperature at the base of the 45 miles will be 1530 deg. C. (2786 deg. F.). Radium has been tested up to a temperature of 1200 deg. C. (2192 deg. F.), at which point no diminution of its properties was observed, so that there is no reason to suppose that the temperature at the base of the rocky crust would interfere with the emanation of heat. Remembering, however, that the fundamental rock of the earth's crust is granite, the radium content 5 is probably far too low; considering also the contributory effects of the chemical reactions, the depth of the radium-containing crust can be halved or at any rate reduced to Milne's estimate of 30 miles. There is a further consideration not contemplated by Strutt, namely; the probability that the radium is concentrated near the surface of the earth and the heating effects therefore would be confined to a zone near the surface.

These researches then lead us to the conclusion that the earth consists of a self-heating crust resting upon a solid nucleus. Is there any reason to believe that this central nucleus is hot or cold? Until very good evidence is adduced to the contrary, the earth centrosphere must be regarded as having the temperature of outer space, that is—273 deg. C. (—459.4 deg. F.), plus any heat that may have radiated out into it from the surface layer. For consider how this earth's center has been formed. Meteorites large and small have come together and have been consolidated by mutual gravitation; heat by impact of new meteorites has been generated and the whole has swung round for immeasurable time in an extremely cold medium. When the earth was small, or even as large as the moon, the radiation of heat into space would have been rapid enough to cool down the whole to the temperature of outer space. Only later, when water became abundant on the surface and the outer rocks became disintegrated, changed by chemical processes, enriched by the concentration of radio-active substances through solution and deposition and distorted by earth folds and quakes, could the internal generation of heat keep pace with the radiation of heat into space and the crust of the earth could thus become habitable. If we accept Prof. Chamberlin's planetismal hypothesis, then it seems inevitable that we must regard the earth's center as a cold body like that of the moon. In a small body, a cold nucleus surrounded by a hot surface would gradually assume the temperature of the surface, but in a vast body like the earth the penetration of the heat into the interior is stopped by absorption in chemical and physical changes near the base of the crust, and at most the temperature cannot be in excess of that existing in the surface layer i. e., 1530 deg. C. (2786 deg. F.).

The production of molten lava in volcanoes is to be attributed to local causes in the outer 10 or 12 miles of the crust; where movement and consequent frictional heat is being developed; as this heat is brought in lava streams and hot springs to the surface and there dissipated into space, the melting of the rock under these circumstances does not add to the general body heat of the earth. Or to look at the question in another way; since the heating effects in the earth's crust in the end can be traced to the agency of water, so we can state roughly that the limit of warmth in the earth is determined by the percolation of water; as granite has been formed with the help of water we can define this limit of heat at that depth to which the earth's substance has the elasticity of normal rocky substances, namely: 30 miles.

In other words, the temperature increment in the earth's crust will increase as we go downward till a limit is reached, and beyond that, there will be a decrease. Is there good evidence for this theoretical deduction in actual fact? South Africa is peculiarly well situated to answer this question. From the recent work of Jean's, it is found that the earth is pear-shaped with the stalk end in Africa and the blunt end in the Pacific. The reason for this shape is that nowhere else in the globe are sedimentary rocks of post-Archæan age so thinly developed; for immense periods the Continent of Africa has been practically uncovered by the sea, and as a consequence, where the rest of the crust has been burdened by thicknesses of strata representing billions of tons, Africa has stood free. Hence, whereas the rest of the globe has been depressed, Africa has been bulged out beyond the limits of the sphere.

In piercing the rocks in Africa we therefore penetrate deeper into the earth's interior than in any other part of the globe, and we find that the temperature increment, instead of being anything like the average of 1 deg. F. for every 60 feet, is 1 deg. F. for every 225 feet on the Rand.

There are of course other areas of low temperature increment in the globe, such as the granite area of Minas Geraes in Brazil, also a region of granite and gneiss thinly covered with sediments, but nowhere else than in Africa is such a vast area of low temperature increment to be reckoned on. If the height of the bulge of Africa above the spherical surface be taken at five miles this would mean that in five miles the temperature increment has fallen from 1 deg. F. for every 60 feet to 1 deg. F. in 225 feet.

It is, however, impossible to reduce the observations to scale in this way; a contemplation of the rates of increase at various places given in any of the lists makes is quite obvious that no prediction of temperature increase at one place can be made from observations at another, as we have seen was done with unfortunate consequences in the case of the Simplon tunnel; in the British Isles alone the temperature increment varies from 1 deg. F. for every 34 feet to 1 deg. F. for every 130 feet; but, taking all the variations into account, there is sufficient evidence from the observations to bear out the contention that the nearer the interior of the globe the less is the temperature increase for equal distances. This has been long recognized and regarded as an insoluble enigma, but in the light of modern geological thought it is not only not an enigma but a necessary consequence.

The belief in a hot interior of the globe has so possessed the minds of people, that when deep level mining is proposed, the public still cling to the belief that it must be impossible because their geological text books say that at such depths the temperature would be prohibitive to working. I venture to trust, therefore, that a more widespread knowledge of Chamberlin's planetismal hypothesis and the developments that have appeared since its publication are not only of academic interest, but have an important bearing on the economic welfare of this country. I have, I am afraid, outlined a number of contentious arguments, but the intention of this paper is more to call attention to the trend of modern investigation in geology than to prove each step, and I have elsewhere dealt with the whole subject *in extenso*.

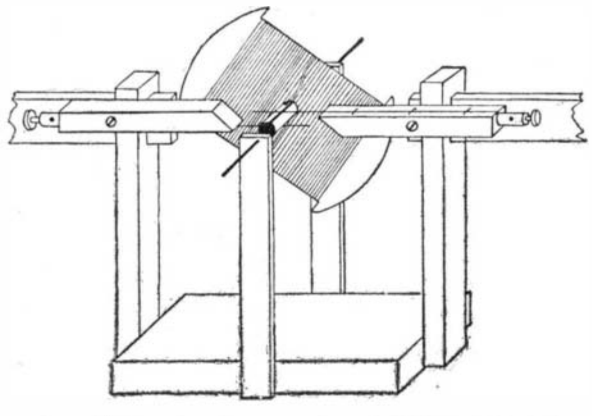
APPARATUS TO ILLUSTRATE EARTH-INDUCTION, AND THE PRINCIPLE OF THE SIMPLE DYNAMO AND MOTOR.*

By Henry S. Curtis.

The apparatus consists of an armature shaped as shown in the figure, about three inches long and one and one-half inches wide. It is fixed to a four-inch length of steel knitting needle, which serves as an axle. This axle rests in two holes bored in metal uprights, so that the axle is about four inches above the base of the apparatus. The armature is made of soft sheet iron, and is wound with about six layers of No. 22 insulated copper wire, and the terminals of the wire are soldered to the two sections of a one-inch long brass tube, slit on both sides, and insulated, so as to serve as a commutator. The brass tube is mounted on a cylinder of cork, through which the axle passes, the diameter of the tube being one-fourth inch. It is bound to the cork cylinder with waxed thread. The armature and uprights are mounted on a wooden base, about six inches square, and at the two sides, so that the armature may revolve between, with a leeway of about an inch, are two wooden uprights with slots cut facing the armature, so that magnets may be inserted, and act as field magnets to the revolving armature. On these uprights are set small wooden cross pieces pointing in toward the commutator, and carrying straight pieces of copper wire. These wooden cross pieces are pivoted each on a single screw, so that the copper wire may be brought in contact with the commutator, and act as brushes. The outer ends of these wires lead to binding posts screwed into the outer ends of the cross pieces. The apparatus is very simple, and the cost of the material is slight.

* School Science and Mathematics.

In the original apparatus the core of the armature



ARRANGEMENT OF ARMATURE PARTS.

was made of a single thickness of soft sheet iron, cut out with shears, but I believe several layers would give a better effect. The diagram will make clear the general arrangement of parts.

USE OF THE APPARATUS.

The apparatus may be made to show the following phenomena very nicely:

First. Earth-induction. If the apparatus be connected to a galvanometer (an ordinary laboratory astatic galvanometer is sufficiently sensitive) the current induced when the armature is spun around by hand in the earth's field may be plainly shown. A difference of deflection also may be noted, if the apparatus is shifted, so that the plane of the rotating armature is at different angles to the earth's lines of force.

Second. The principle of the dynamo may be shown by inserting the two bar magnets in the slots, with opposite poles facing the armature. The galvanometer will show currents opposite in direction, when the armature is rotating first in one direction and then in the other, or when the polarity of the field is reversed. Indeed, by holding one magnet in the hand, at a distance of several inches from the apparatus, a marked deflection of the galvanometer may be obtained.

Third. The apparatus illustrates very well the principle of the motor by connecting several dry cells in place of the galvanometer. The motor may be reversed by reversing the polarity of the field or the direction of the current.

To blacken light woods, make a preparation of an ounce of borax, dissolved in a quart of water, with two ounces of shellac. The liquid is then to be boiled until a perfect solution is obtained, then stir in two teaspoonfuls of glycerine, and complete by adding a sufficiency of soluble aniline black to completely darken the liquid, which will now be ready for use.