CORRESPONDENCE

"EARTHQUAKES IN THE LIGHT OF THE NEW SEISMOLOGY."

SECRETARY OF THE FRANKLIN INSTITUTE:

Replying to the article by Prof. Oscar C. S. Carter on "Earthquakes in the Light of the New Seismology," I wish to say that there are some points in the argument which appear to me to invite discussion. Before proceeding to analyze the statements with which I disagree, I wish to call attention to a quotation in Professor Carter's article to the effect that "An open-minded hospitality for new facts is essential to intellectual advance."

Passing over the first three theories regarding the condition of the interior of the earth, we come to the fourth, which Professor Carter says is probably the correct one, "and is, that the earth is solid on account of the enormous pressure of the rocks." "It is hot enough to melt rocks, but on account of the enormous pressure the material is pressed solid." There is no mention of the probability that a large portion of the earth ever was or may still be above its critical temperature.

I will introduce a definition of "critical temperature" taken from a standard work on Elementary Physics edited by Aldous, page 326. "For each gas there is a temperature called the "critical temperature," and when the temperature is above this point it is not possible to liquify it by any pressure, however great."

This important principle was discovered by Dr. Andrews. Substantially the same definition is to be found in all works on physics and therefore may be considered as true enough to form the basis of a theory. If there is a critical temperature above which gases cannot be liquified by pressure, then it must follow that any substance above its critical temperature is a gas, even if its density be twice or many times as great as the density of its solid or liquid forms. Modern science teaches that the atom is not the indivisible or incompressible ultimate that it has been supposed to be, and therefore a gas can have a density greater than its solid form.

If we can prove that any portion of the interior of the earth is above the critical temperature of the matter composing it, we will have proved that it is in a gaseous condition. We know that the elements can be rendered gaseous at the temperature of the electric arc, and we find that the temperature of the electric arc has been determined at from 3500 C. to 4000 C. Now if all these elements can be rendered gaseous in the electric arc, it is strong presumptive evidence that the critical temperature of all known matter is near 4000 C.

The next question arises is whether that temperature is reached in the interior of the earth, and if it is, at what depth?

Taking what Professor Carter says on the rate of increase of temperature with depth as representing the known facts in the case, and reducing the Fahrenheit to Centigrade degrees, and allowing for a gradual reduction in the rate of increase, I find that at a depth of 200 miles or less the critical temperature of all known matter is passed, and from that point on the interior of the earth must be in a gaseous condition or all our information about critical temperature is wrong.

Then the question is, how is it possible that a gaseous interior can be rigid?

Rigidity is a property of solids, acquired by a reduction of the amplitude of vibration of its molecules with relation to each other. To test this definition it is only necessary to heat a piece of iron in order to see how rapidly the rigidity decreases as the temperature rises, until when the amplitude of vibration of its molecules becomes too great to be resisted by coherence, the iron melts and becomes a liquid. Therefore, if there is a gaseous interior to the earth in which the pressure has increased the density beyond that of the solid condition of matter, the amplitude of vibration of its molecules with relation to each other must be less than when in the solid condition, and according to the above definition of rigidity it should be more rigid than a solid interior of the same composition. The critical temperature which exists at 200 miles below the surface evidently existed throughout the entire planet at an early state in its development from a nebula, and at that time the whole planet was gaseous, even as the sun is now.

Under such conditions, according to the known laws of diffusion of gases, each gas of which the planet was composed would diffuse throughout the entire planet from centre to circumference. The law referred to says, that in a mixed body of gases each gas diffuses throughout the entire space occupied regardless of density.

The gaseous interior which we have good reason for assuming to exist beyond a depth of 200 miles is but a remnant of a gaseous planet and must have within it some of each of the gases which diffused throughout the planet when in a gaseous condition. Have we any evidence that this is the case? It so happens that we have abundant evidence, but it has heretofore been misapplied and misunderstood.

The gases given off during earthquakes and volcanic explosions have been observed, and in the following selected cases from "Earthquakes and Volcanoes," by Mungo Ponton, F.R.S.E., will show that they play an important part in both phenomena.

"At Palermo in 1726, during a violent earthquake which shook down 1600 houses, the earth opened in one of the streets of the city and threw out burning sulphur with red-hot stones while the atmosphere appeared as if on fire. The flames issuing from the earth kindled the wood-work of the houses in the street and they were all consumed."

In the month of October, 1755, several strange meteorological phenomena occurred in the Spanish peninsula, such as frequent "halos around the sun and moon, numerous luminous meteors, and terrific thunderstorms with much rain. The waters both of wells and rivers became turbid and fetid; rats and reptiles came forth as if frightened, and domestic animals showed much uneasiness. On the first of the following month of November occurred the great earthquake of Lisbon."

An explanation of all of these strange phenomena except the luminous meteors is to be found in the effect of escaping gas, such as sulphuretted hydrogen and sulphurous acid and carbonic acid, from the interior, as a premonitory symptom of the coming shock which, as I shall show, is due to the sudden intrusion of a dike into a fault plane by the extrusive force of magmatic steam. The steam would naturally be condensed to water, and, added to the ground waters would, with its associated gases, render them turbid and fetid.

Under such circumstances the cause of alarm of animals living in burrows or holes is easily explained. The gases immediately reach their smelling organs and alarm them. The same is true of dogs and domestic animals that keep their noses on or near the ground, while man who walks on his hind legs, does not think of the gases as coming from the ground and is not so quickly warned as the lower animals. Where a large amount of such gases ascends through porous soil it might produce an effect on the atmosphere which would be apparent without causing any visible vent or opening in the earth.

"On the tenth of July, 1756, there were two sharp shocks at Lisbon, during which there rose from the ground a cloud of smoke that obscured the sun, and filled the air with a sulphurous smell."

"On the second of April, 1762, the coast of Chittangong in the north-east of the Bay of Bengal, was violently shaken. Many large openings were found in the ground from whence water and mud, smelling strongly of sulphur (H_2S) were ejected. A large river was dried up at a place called Bardavan, while at Bar Charra, near the sea, a tract of land sank down and was submerged, drowning 200 people and their cattle. Sixty square miles of coast permanently subsided, one mountain sank down until only its summit remained visible, while another disappeared altogether.

"Several other hills were rent asunder, and chasms from 30 to 60 feet wide were found. The towns upon the tract which subsided were overflowed and one was submerged upwards of 10 feet. This great subsidence was accompanied by a corresponding elevation of the ground in the island of Romree and Chuduba, lying to the southward."

The foregoing account is interesting as an example of how cracks open in nearly all earthquakes.

Now obviously cracks do *not* open without a competent cause, and I shall refer to this later as showing that they open because of an expansive force from the interior.

"Hungary was the scene of a succession of shocks in 1763, when many houses were overthrown in Comorn. There were formed in the earth large openings from which sulphurous vapors arose. Jets of water the thickness of a man's arm ascended from the Danube to a height of 30 feet, the water being mixed with sand and having a sulphurous smell."

"The coast of Caracas in South America and the adjacent island of Trinidad were violently convulsed in 1766, and the whole city of Cumana was reduced to ruins. The shocks were continued for upwards of a year, and were at first repeated almost hourly. There were frequent eruptions of sulphurous water from fissures in the ground, and an island in the Orinoco disappeared. Four years after, the western coast of St. Domingo was similarly agitated and its chief city, Port au Prince, nearly destroyed. There were found in the earth great clefts whence arose poisonous vapors that caused an epidemic; hot springs also arose in several places, but they proved temporary."

In the above we have again the cracks opening, gases escaping and hot springs resulting from the condensed steam which later disappear.

"The district of Guatamala in Central America was visited by successive shocks in 1773-1775. The city of Iago with all its inhabitants was engulfed in huge chasms which opened in the earth. The earthquakes were connected with volcanic eruptions in the neighborhood. A catastrophe similar to that of St. Iago occurred in 1780 in the island of Candia where, during a violent earthquake, the castle of Eropetre with its garrison of 300 Turkish soldiers and also thirteen small villages in the neighborhood, with their inhabitants, were swallowed up in chasms."

"Toward the end of 1797 the coast of Caracas was again convulsed and those portions of Cumana which had been rebuilt during the last thirty years were once more laid in ruins. On the shores of the bay of Caricao, immediately before the shocks, flames issued from the earth, followed by a noise like the bubbling of gas in water."

"During the summer of the following year, Tuscany was visited by a succession of shocks and the town of Siena was reduced to a heap of rubbish, deep chasms having been found in the principal square."

"In 1806 two severe shocks of earthquake occurred at Krasnojarsk in Siberia, during which a mountain in the neighborhood of that place was engulfed and a lake 300 feet in circumference and 180 feet deep in parts formed in its place. The water of the lake was sulphurous. As the country around was covered with ashes, it is probable that this event was connected with a volcanic eruption."

"A few weeks afterwards a similar lake of sulphurous water was formed near the mountain of Fajola, in the neighborhood of Rome where several severe shocks were felt at the time."

"St. Michaels in the Azores was visited by two severe earthquakes in 1811 and on both occasions they were accompanied by eruptions of a submarine volcano which threw dust, ashes and fragments of lava into the air. The points of eruption on the two occasions, were about two and a half miles apart; but neither of the craters ever appeared above water. These eruptions were attended by loud explosions."

"In December of that year commenced a long series of disturbances in the valley of the Mississippi, in Ohio and in Arkansas. These shocks continued at intervals till 1813 and were more distinguished by their frequency than their violence, which was, nevertheless, on several occasions very considerable. These long-continued earthquakes are the more remarkable from the circumstance that the countries affected by them are situated far from any volcano. The surface of the Mississippi valley was much altered by these convulsions, several new lakes forming while others were drained. New islands raised in the river and during one of the shocks the ground to the south of New Madrid was for a short time so uplifted as to stop the current of the Mississippi and cause it to flow backwards. The ground on which this town is built and the bank of the river for fifteen miles above it subsided permanently about eight feet and the cemetery of the town fell into the river. In the neighboring forest the trees were thrown into inclined positions and many of their trunks and branches were broken. It is affirmed that in some places the ground swelled into great waves which burst at their summits and poured forth jets of water with sand and pieces of coal which were tossed to the height of the trees. On the subsidence of these waves several hundreds of hollow depressions were left from ten to thirty yards in diameter and twenty feet in depth which remained visible many years. Some of the shocks were vertical, others horizontal, the latter being the most destructive. These earthquakes resulted in the general subsidence of a tract of country between seventy and eighty miles in length from north to south and about thirty miles in breadth from east to west."

I shall show how such quakes can be accounted for, and further that they have no direct relation to any volcano except that they have the same ultimate cause, *i.e.*, the gradual separation of the steam and other gases from the gaseous interior by secular cooling. The swelling of the ground into waves and the bursting of these waves at their summits, with the ejection of water and sand, as described, is due to the presence of gases which do not condense as did the steam. The escape of the gases was followed by subsidence and the formation of hundreds of hollow depressions.

"On the nineteenth of February, 1845, an earthquake occurred in New Granada, S. A., attended by peculiar circumstances. The shock was felt chiefly in the plain traversed by the Lagunilla, a small tributary of the river Magdalena, and was accompanied by much noise. Immediately after the shock a great flood of liquid mud was seen to issue from the ravine in which the stream rises. The mud flowed rapidly over the whole plain, carrying everything before it. Tall trees were swept down as if they had been straws, while houses and cottages with their inhabitants were overwhelmed. Only a few of them escaped to the mountains, unfortunately to meet a worse death by perishing with hunger, their place of refuge being unapproachable through the sea of mud. A small number who were near the edge of the torrent escaped over branches of trees. Forty square miles of land was covered by this muddy inundation."

"The north of Italy was much convulsed in March, 1846. The shocks were felt at Genoa and Leghorn where many houses were injured and some overthrown. Several villages throughout Tuscany were nearly destroyed and at Volterra a government prison fell, burying some of the prisoners in the ruins. There was considerable loss of life throughout Tuscany, and Pisa was severely shaken. The leaning tower is said to have rocked in a wonderful manner but was not injured. The vaulted roof, however, of an old church fell. The chief peculiarity in this earthquake was that, in several places jets of muddy boiling water sprang from the earth."

"On October ninth, 1857, in Illinois, there was a smart shock preceded by a remarkable electrical condition of the atmosphere, during which a luminous appearance was observed, described by some as a meteor and by others as a vivid flash of lightning."

This feature of the earthquake phenomena is noted in many cases and of course might simply be a coincidence, but is much more likely to be the effect of gases escaping into the air.

Many more accounts of interesting phenomena connected with earthquakes are contained in Mungo Ponton's book, and enough has been quoted to give the salient features and to show that the opening of fissures, the discharge of mud and sand from small craters, the discharge of sulphurous and other gases as well as the appearance and disappearance of hot springs accompany the more vigorous quakes. We now come to consider how these phenomena can be accounted for by the theory of a gaseous interior, or at least a zone in which matter is above its critical temperature.

Below the zone of solid flowage the zone of critical temperature extends to the centre of the earth. The temperature in this zone determines the

FIG. 1.

A zone in which solids flow under temperature and pressure, in which a fracture is impossible, as it will close immediately, is called the zone of solid flowage and is probably 200 miles thick. Peaks in the zone of solid flowage denote supersaturation with steam and other gases and indicate lava pipes.*

gaseous condition of all of the matter composing it. By the power of diffusion it must remain homogeneous until a portion of it solidifies, when that portion separates from the portion still remaining gaseous.

Owing to the great pressure, the density of the gas is greater than the solid form, and for this reason the solid crust floats on the gaseous core like ice on water. Gases of low critical temperatures diffuse upward through

* The section of Hawaii is intended to convey the idea that there is no connection between Mauna Loa and Kilauea except through the zone of solid flowage at great depth, thus showing how they act independently of each other. The steam escaping through the liquid lava in the craters, causes the lava fountains to play and furnishes the heat to keep the lava fluid. Sea level is shown correctly according to sketch at about three miles below the top of Mauna Loa, Kilauea being 16 miles distant.

The diameter of the lava craters and pipes is exaggerated. It is fitting that this theory of the gaseous interior should be discussed in the Journal of the Franklin Institute, for Benjamin Franklin was the first to suggest it in 1784, as can be seen in the tenth volume of his life and letters in the library of the Institute.

the zone of solid flowage until they reach the bottom of the zone of fracture, where they are stopped until they supersaturate it to such an extent that it has a high elastic force like a compressed spring.

When the tensional strain of the gases becomes great enough to rupture the zone of fracture, a fracture is formed and the supersaturated magma impelled by the steam and other gases rushes into it. The walls of the fracture are colder than the steam, which condenses and causes the fracture to close by reflex action, causing a shock or earthquake. The steam and other gases of low critical temperature which I shall call the magmatic steam, are not held in the zone of solid flowage by the power of diffusion as they were in the zone of critical temperature, but are forced up through this zone by difference of density multiplied by the depth.

For example, suppose that the mean density to a depth of ten miles is three times that of water. The pressure of water increases 0.44 of a pound per foot of depth, and three times that—1.32 pounds pressure per square inch per foot of depth, or 6970 pounds per mile, or 69,700 pounds pressure per square inch at a depth of 10 miles.

According to the formula for calculating the density of a gas which varies directly as the pressure and inversely as the absolute temperature, I find that the mean density of steam at a depth of 10 miles should be 0.65 that of water, assuming the pressure to be 69,700 pounds per square inch,

FIG. 2.

and the temperature to be 803 C. absolute ($530\text{ C.} + 273\text{ C.}$). According to this density, which is probably too high, the weight or pressure of a column of steam at a depth of 10 miles should be 15,100 pounds per square inch. Deducting this from 69,700 we get 54,600 pounds per square inch, or say 27 tons per square inch as the differential pressure acting on the steam at that depth to drive it up through the zone of solid flowage. The differential pressure at 100 miles would be ten times as great as at 10 miles and therefore it appears that at the bottom of the zone of solid flowage there is over 500 tons per square inch differential pressure.

Were it not for the high temperature and pressure and the fact that steam enters into the composition of silicates as a hydrous fusion at high temperatures, it is doubtful if even these high differential pressures could force it through. But by constant addition from below and relief from above the steam passes through the zone of solid flowage as through a porous diaphragm, and carries with it the heat necessary to make local fusions of the zone of fracture and discharge it as lava. The reason for calling the zone of solid flowage "solid," instead of "liquid," is, that the zone of critical temperature or gas zone is denser than the matter above it, or they would change places. If the gas expands on changing its state after cooling below the critical temperature, it would have to expand more to become a liquid than to become a solid, and the pressure is sufficient to prevent this, and therefore it takes a short cut and becomes a solid without becoming liquid. This expansion of the material in the zone of solid flowage is

evidently less than the contraction of the zone of critical temperature, or otherwise the earth would expand as a whole instead of contracting, as we know it does. The local expansion immediately below an earthquake that causes fractures to open is the tearing of the zone of fracture by the tensional pressure of the magmatic steam which has been accumulating for a long time under the differential pressure which drives it up through the zone of solid flowage. The quakes and tremors are not so much the result of the rupture as the result of the opening and closing of the fractures due to the intrusion and condensation of the steam. The non-condensing gases associated with the steam, pass on through to the surface and cause the peculiar atmospheric effects noted and alarm animals living in burrows, and cause sand and mud to be ejected, as in the New Madrid quake. When Professor Carter stated that 95 per cent. of all quakes were caused by faulting and slipping of the rocks, he stated only a part of the truth. The next question which would naturally follow would be what causes the faults and slips? Professor Carter would probably say, contraction and folding. But contraction and folding would cause overthrust and compression, and most certainly not cause cracks to open. The only cause competent to produce a crack or spread apart its walls is a local expansion immediately below the cracks. Now if we imagine that the zone of solid flowage has peaks and ridges on it,

FIG. 3.

just as the outer surface has, and that the magmatic steam collects in these peaks and ridges beneath the zone of fracture until it has sufficient expansive force to rip the zone of fracture, we can see why a fault plane once established will continue to act as an earthquake centrum for a long time without showing much displacement. The accumulation of magmatic steam throughout the thickness of the zone of solid flowage would have the effect of reducing its density, and if it should accumulate faster than it escaped through the zone of fracture then the surface must rise, and—on the contrary—if it escaped through the zone of fracture faster than it accumulated, then the density would increase and the surface must come down. Now that is just what happens in regions of rising such as the Andes, the density is less than it is under the ocean to the west where subsidence is taking place. It is no argument to say that the "earth's crust is in an unstable equilibrium," for it has had plenty of time to get into equilibrium. The question is, what disturbs the equilibrium?

A difference of 2 per cent. in density between two regions, if applied through the thickness of the zone of solid flowage (200 miles), would cause a difference of elevation of four miles, or 21,000 feet, and if by escape of the steam in one case and accumulation in the other the densities become reversed, the elevations will change with them. Professor Carter after having said that it is solid, speaks of the earth's crust breaking and caving in, as cause of earthquakes. This appears highly improbable, as on account of the great pressure, cavities could not exist.

The different kinds of vibrations which are found to occur in earthquakes can be explained by supposing that in case the fault plane is vertical, the opening and closing causes a horizontal movement, while if a sill of lava is being introduced horizontally between bedded rocks, the intrusion and condensation of the magmatic steam causes a vertical movement.

Figures 2 and 3 illustrate apparatus for producing shocks of both kinds. In the first experiment, boil the water in the wash-bottle and force the steam into the rubber bag which is held tightly between the cakes of ice by the rubber band around the two cakes. When the steam enters suddenly the rubber bag will be distended, the cakes forced apart and the band stretched. The steam will be condensed by the cold walls of the bag and the walls will come together with a shock. Turn the ice cakes so that the bag is horizontal and the shock will be vertical.

In the second experiment, boil the water and force steam into the inverted bell jar filled with water. The steam on entering will be condensed and cause a shock to the sheet-rubber cover to the top of the bell jar. Small objects placed on this sheet-rubber may be tossed about in a manner similar in earthquake shocks.

All the complicated phenomena of volcanic action—hot springs, geysers, mud volcanoes and ore deposition—can be explained by the theory herein set forth, but as Professor Carter treated on the subject of earthquakes only, which is but one of the many effects produced by magmatic steam, I will merely refer to other papers on the subject which I have written: "Relation of Magmatic Waters to Volcanic Action," JOURNAL OF THE FRANKLIN INSTITUTE, October, 1908; "A Theory of Volcanic Action and Ore Deposition," Institute of Mining and Metallurgy, London; "Magmatic Waters," Canadian Mining Institute, 1906.

HIRAM W. HIXON.

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