THE PLACE OF ORIGIN OF THE MOON—THE VOLCANIC PROBLEM

WILLIAM H. PICKERING

In 1879 Professor George H. Darwin propounded the view that the Moon formerly formed a part of the Earth. That it was originally much nearer to the Earth than it is at present, and is now slowly receding from us, was clearly shown by his equations. After considerable discussion, his conclusions have been accepted by the great majority of astronomers, although many of the geologists do not view them with favor. Assuming the correctness of his hypothesis, it will be of interest to determine, first, if possible, from what part of the Earth the Moon originated, and, second, to follow out our conclusions on this point and see to what results they may lead.

When the separation took place, it has been shown that the combined planet was not very much larger than is the Earth at present. It must therefore have been mostly in the solid or liquid condition. If in the latter state, it is obvious that no indication of the Moon's former place could be found at the present time. Very few astronomers or geologists today, however, believe that the Earth ever was completely liquid. It has probably always been partly solid, partly liquid, and partly gaseous. It is composed of such diverse materials, and these are exposed at different points throughout its volume to such diverse pressures, that, unless we assume it to have condensed from a highly ineandescent nebula, which is unlikely, we should scarcely expect it ever to have presented a uniform liquid surface.

The surface was probably hot, but how hot we have no means of knowing. Beneath the surface, however, where radiation was impossible, much higher temperatures were found, as is still the case and in what follows we shall assume that the interior was practically liquid, or was ready to become actually so where relieved of the pressure due to the gravity of the outer layers; that is, where the centrifugal force became sufficiently high, as in the equatorial regions. Precisely how the Earth came into its present form, whether by planetesimal condensation or otherwise, does not concern us here. We merely assume that in these early days the Earth was in much the same condition that we find it at present, except that it was hotter. We also assume that it was slowly condensing from a more bulky form, rendering fission possible.

These processes of fission and condensation we see going on all around us at the present time in the stellar universe, as indicated by the variable stars of short period and the spectroscopic binaries. It therefore requires no great stretch of the imagination to conceive that it may also have occurred on a smaller scale in the case of our Earth and Moon.

It does not follow, however, that our combined planet was ever incandescent. Indeed, this seems to be unlikely. A cold nebula which is later to condense into a sun must almost necessarily be composed largely of solid matter. The electric disturbances by which we see it, illumine only the gaseous portions, but the metallic elements must be there nevertheless, all the time unseen.

Assuming then a hot, solid, ellipsoidal Earth, with an interior more or less liquid, at least beneath the Equator, revolving on its axis once in about four or five hours, we have a picture of our as yet moonless planet as conceived by the astronomer. As it continued to cool, vast volumes of steam and other gases escaped from its interior, increasing its density and diminishing its volume.

As its volume diminished, its speed of rotation increased, until by centrifugal force, as explained by Darwin, the Moon was born. If the crust was solid, and if the Moon escaped from it, it is almost certain that a scar of some sort would have been left, and it is of interest to see if we can find it.

The specific gravity of the Earth as a whole is 5.6. That of the surface material ranges in general between 2.2 and 3.2, with an average of 2.7. The specific gravity of the Moon is 3.4. This indicates clearly that the Moon is composed of material scraped off from the outer surface of the Earth, rather than of matter obtained from a considerable depth. At the same time, the specific gravity 3.4 indicates that the layer of material removed had an appreciable thickness.

As is well known, the land and water are very irregularly distributed over the surface of our globe. If we erect a perpendicular from a point situated one thousand miles to the northeast of New Zealand and view the Earth from a distance in this direction, we shall find that very little land will be visible, while the outline of the Pacific will approach the form of a circle.

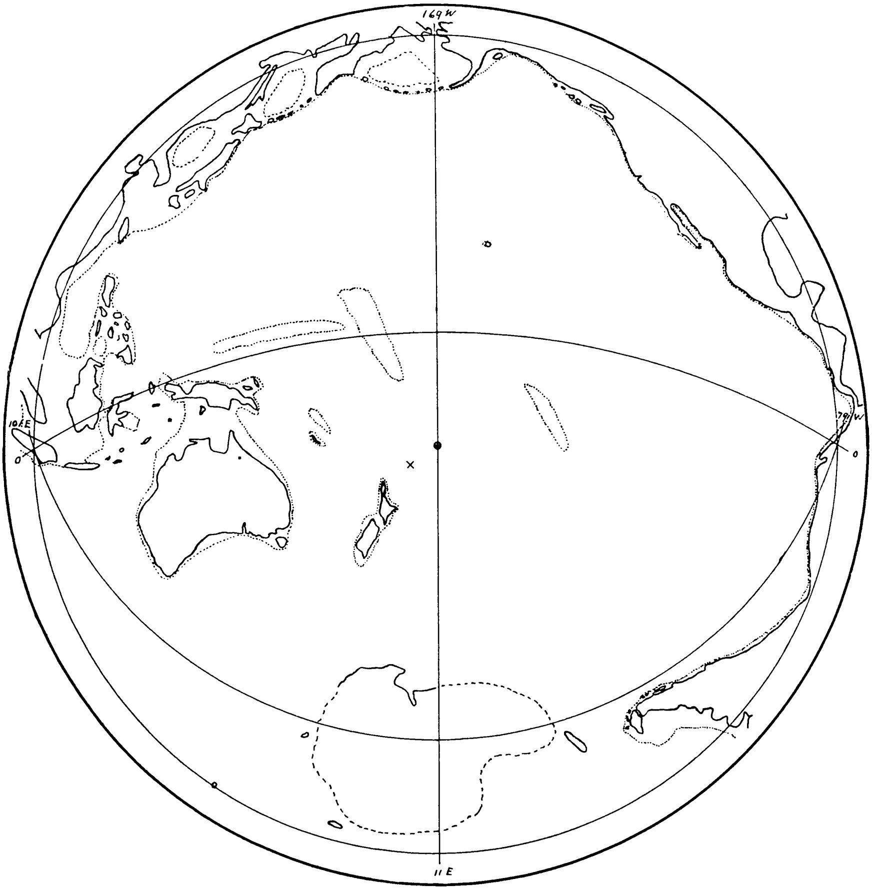

FIG. 1

Figure 1 is a map of the globe on zenithal projection, where the radii are proportional to the actual distances represented. There is no distortion, therefore, in the radial direction, and the exact shape of the Pacific with regard to a great circle is clearly shown. The inner circle represents the circumference of the globe, and is therefore 90° from the central point. The latitude of this point is 25° S. Away from the center the tangential distances necessarily become more and more distorted, the distortion at the circumference making them appear $\frac{\pi}{2}$, or 1.6 times too large.

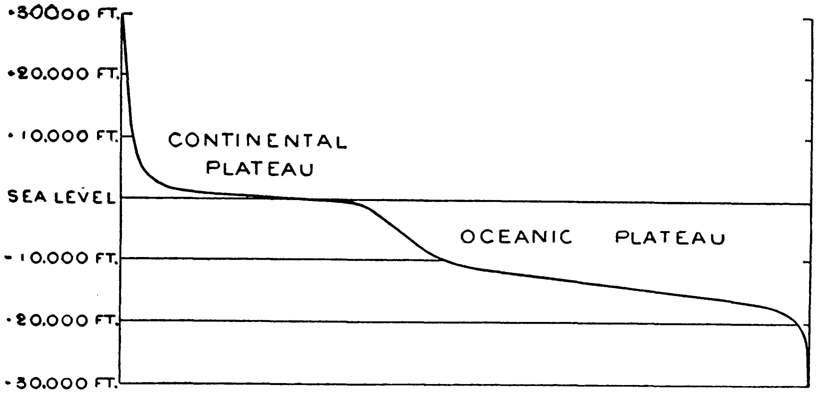

FIG. 2

Figure 2 is taken from Gilbert's *Continental Problems of Geology* (Smithsonian Report, 1892), p. 164, and is founded on the results of the Challenger Expedition as deduced by Murray. In it ordinates represent feet, and abscissas areas, the extreme abscissa representing the total area of the Earth's surface. This area is composed chiefly of two plateaus: one the continental, whose mean altitude is 1,000 feet above sea-level; the other the oceanic, whose mean altitude is −14,000 feet.

It will be noticed that the edge of the continental plateau is below sea-level, but not more than 1,000 feet below it. This contour may be taken, therefore, as the true boundary more properly than the water-line itself. In Fig. 1 it is indicated by a dotted line. Its position near the Antarctic continent is unknown. The location of the latter, excepting where indicated by the full line, has not been determined. The line composed of dashes therefore indicates its maximum possible area.

If we travel north 90° from the central point of Fig. 1, to the immediate vicinity of Bering Strait, and erect another perpendicular, from which we again examine the globe, we shall obtain a view resembling Fig. 3. In this map, which is drawn in orthographic projection, there is no tangential distortion, and the appearance is that which the Earth would have if seen from a great distance. The vertical line is a meridian; the horizontal is a projection of the inner circle shown in Fig. 1. The continents and islands at the edges of the disk have

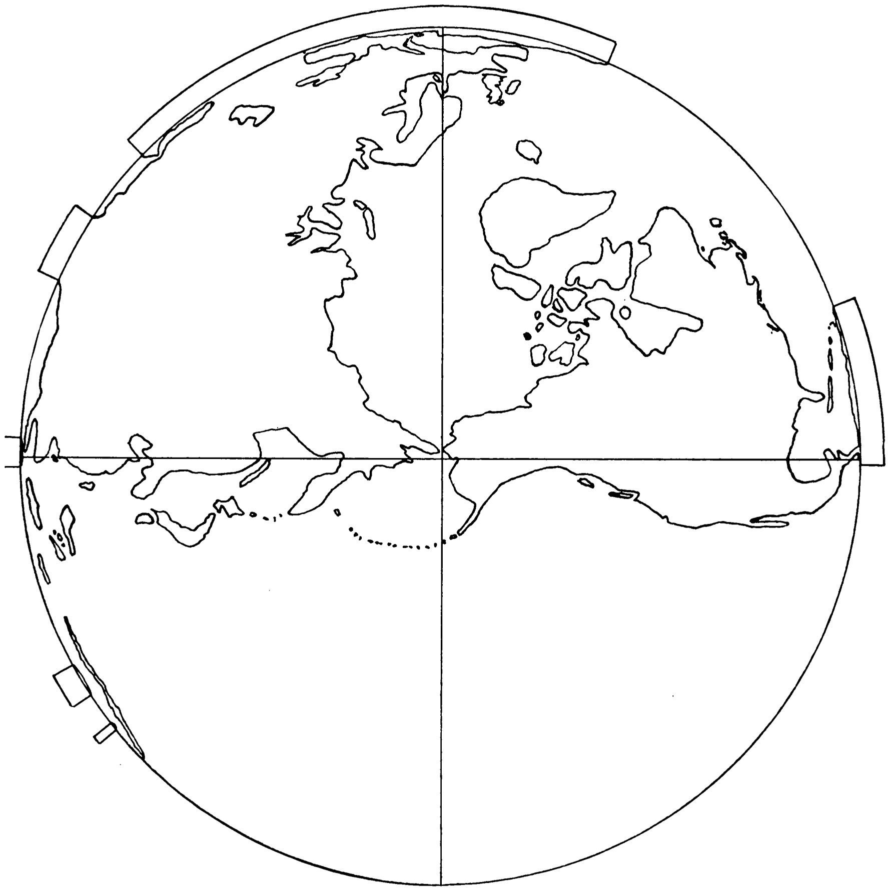

FIG. 3

been allowed to project out beyond the ocean beds in order to make more evident the systematic grouping of the continental masses on one side of the globe. With the exception of Australia, the Antarctic continent, and a small part of South America, all represented in the lower half of Fig. 1, there is no important land on the water side of the globe, not shown in Fig. 3.

An inspection of this figure shows that the Earth's center of gravity, which is the center of the circular arcs, does not coincide with its center of volume, and this deviation would be still more marked were the mobile portions of the surface—i. e., the oceans—drawn off. The center of gravity would then be slightly raised in the figure, and the center of volume still more so. The ocean side of the solid Earth has obviously a higher specific gravity than the continental side.

It is the general opinion among geologists that the continental forms have always existed—that they are indestructible. How, then, could they have originated? We know something of the permanent surface features of three bodies in the universe besides the Earth; namely, the Moon, Mars, and Mercury. None of these shows us anything resembling the irregular terrestrial distribution of the high-and low-level plains, of our continents and oceans.

If we examine more minutely the coasts of our great oceans, we shall find the Pacific bounded by a nearly continuous line of active or extinct volcanoes, and this is true whether in North or South America, Asia, the East Indies, New Zealand, or Antarctica. The only possible break is the east coast of Australia, but even here there is a line of volcanic islands, lying a short distance off the coast, stretching from New Guinea more than half-way to New Zealand. The coasts of the Pacific are generally mountainous and abrupt, and composed of curves convex toward the ocean.

The Atlantic coasts, on the other hand, are generally low, flat, and composed of curves as often concave as convex. As to volcanoes, they are few and scattering. The only conspicuous exception to the general rule is the range of the Lesser Antilles, which both in form and volcanic nature reminds us of the Pacific coast of Asia. The Indian Ocean resembles the Atlantic, except where it approaches the vicinity of the Pacific, and there the characteristic volcanoes again appear.

A curious feature of the Atlantic Ocean is that the two sides have in places a strong similarity. Figure 4 is drawn in globular projection, which is used so frequently for the hemispheres in ordinary atlases, except that in this instance the projection is carried over the Pole onto the other side. This projection gives very little distortion

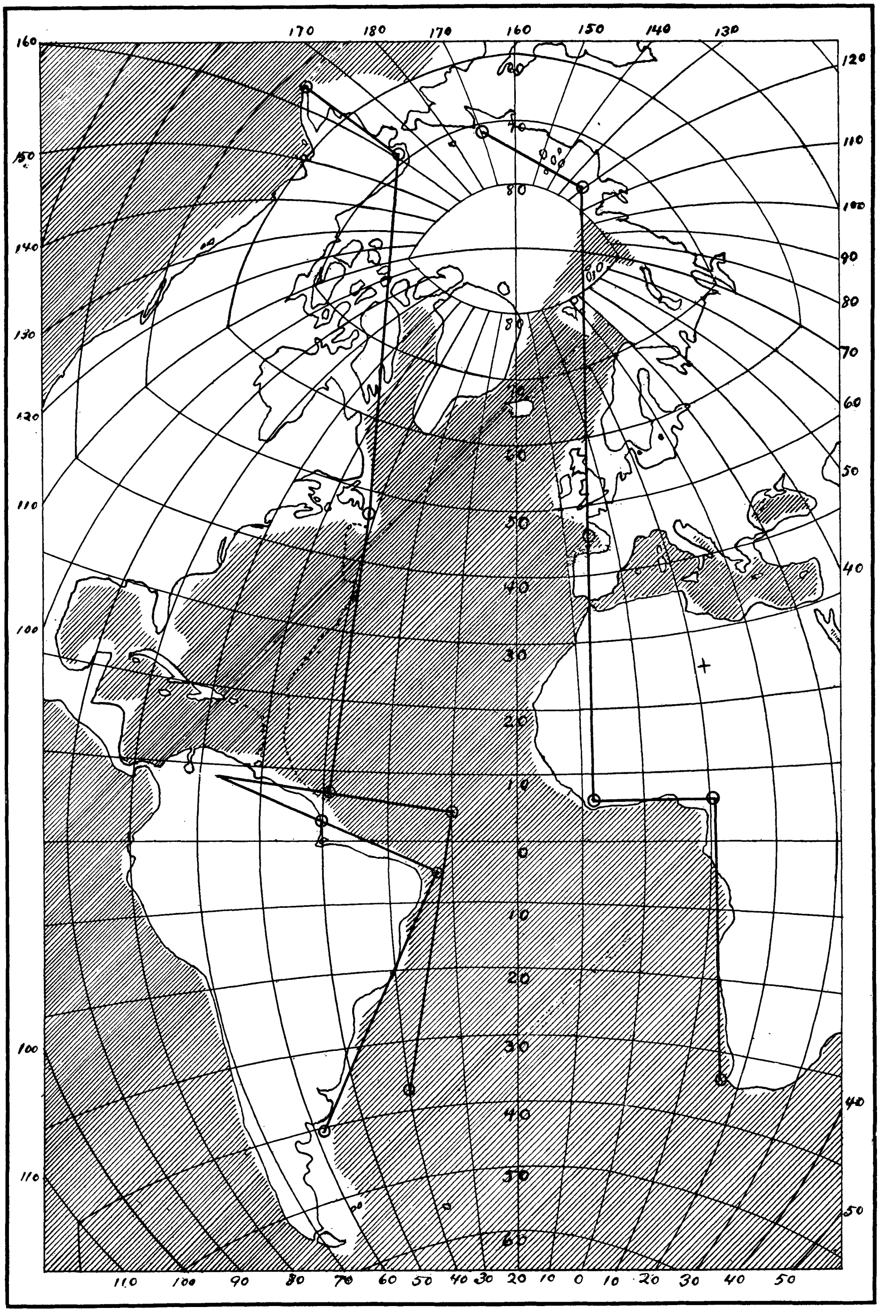
170 180 170 160 150 140 130
160
150
140
130
120
110
100
100
110
120
110
100
90
80
70
60
50
40
40
50
80
70
60
50
40
30
20
10
0
10
20
30
40
50
60
110 100 90 80 70 60 50 40 30 20 10 0 10 20 30 40 50

FIG. 4

in the vicinity of the central meridian, which is the portion of the map to which we shall especially refer. The shaded areas represent those parts of the ocean that are more than 1,000 feet in depth. Regarding the unshaded area between America and Asia we have no information.

When the Earth-Moon planet condensed from the original nebula, its denser materials collected at the lower levels, while the lighter ones were distributed with considerable uniformity over its surface. At the present day we find the lighter materials missing from one hemisphere. The mean surface density of the continents is about 2.7. Their mean density is certainly greater. We find a large mass of material now up in the sky, which it is generally believed by astronomers formerly formed part of our Earth, and the density of this material, after some compression by its own gravity, we find to be 3.4, or not far from that of the missing continents. From this we conclude that this mass of material formerly covered that part of the Earth where the continents are lacking, and which is now occupied by the Pacific Ocean. In fact, there is no other place from which it could have come.

Who it was that first suggested that the Moon originated in the Pacific is unknown. The idea seems to be a very old one. The object of the present paper is to find what support for this hypothesis is afforded by the results of modern science, when examined both qualitatively and quantitatively.

The volume of the Moon is equivalent to a solid whose surface is equal to that of all our terrestrial oceans, and whose depth is thirty-six miles. It seems probable, therefore, that at this time the Earth had a solid crust averaging thirty-six miles in thickness, beneath which the temperature was so high that the materials were in places liquid, and in other places only kept solid by the enormous pressure of the superincumbent material. When the Moon separated from us, three-quarters of this crust was carried away, and it is suggested that the remainder was torn in two to form the eastern and western continents. These then floated on the liquid surface like two large ice-floes.

If their specific gravity was the same as that of the Moon, 3.4, since the continental plateau averages nearly three miles higher than the ocean bed, the specific gravity of the liquid in which they floated must have been 3.7. Later, when this liquid surface cooled, the huge depression thus formed was occupied by our present oceans.

The volcanic islands in the oceans, such as Hawaii, were obviously formed after the withdrawal of the Moon, and are analogous to the small craters scattered over the lunar *maria*. While their surface material presents no extraordinary density, the lava being full of bubbles and small cavities, interesting results have been obtained by the Coast Survey with the pendulum. Observations were made by E. D. Preston near the summit, and on the slopes of Mauna Kea, Hawaii, at altitudes of 13,060, 6,660, and 8 feet. He writes:

> It appears that the lower half of Mauna Kea is of a very much greater density than the upper. The former gives a value of 3.7 and the latter 2.1, the mean density of the whole mountain being 2.9. This is somewhat greater than that found for Haleakala [a neighboring volcano] and is notably larger than the density of the surface rocks. Indeed, this appears to be the highest value yet deduced from pendulum work.[1]

The remark of Major Dutton[2] is interesting in this connection, that a part of the bulk of these mountains is due to accumulation, and a part to uplifting. The upper half is clearly due to matter, chiefly scoria, which has been expelled from the various vents. The lower half is probably due to the slow uplifting of the former ocean bed.

It would seem as if borings carried on in this vicinity to a depth of only a few hundred feet would bring to the surface the same kind of rock material that, beneath the continents, would only be found at a depth of many miles. Presumably this material would turn out to be lava similar to that found on the surface, save that under the great pressure the innumerable little cavities, rendering the material generally so porous, would have practically disappeared. The fact that its density, 3.7, as determined by Preston, coincides with the theoretical value just deduced is of interest.

Turning now to Fig. 4, six points indicated by circles have been marked along the coast-line of the eastern continent. Corresponding to these, six similar points have been marked along the American

[1] *American Journal of Science*, Vol. CXLV (1893), p. 256.

[2] *U. S. Geological Report*, 1882–83, p. 195.

coast. The two broken lines joining these various points are slightly inclined to one another, but the other small differences in relative position and distance are apparent and not real, being due to the necessary slight distortion of the map. The South American continent does not fit well into this arrangement, and does not appear to have remained perfectly parallel to North America during its transit across the fiery ocean, in obedience to the pull of the Moon. Instead, it seems to have rotated slightly, as shown, about a point somewhat to the east of the Isthmus of Panama.

In trying thus to match the continents together, we must take the outline of the continental plateau rather than the coast-line. Five-sixths of the area of the Altantic basin is thus very well accounted for, but there still remains a considerable area east of the United States, together with the Gulf of Mexico, and the Caribbean and Mediterranean Seas, not explained. The eastern outline of the Atlantic area is indicated by the dotted line.

The antipodes of the central spot in the map of the Pacific is indicated by the cross in northern Africa. If the ultimate releasing force which caused the disruption of the Moon was, as has been supposed, the solar tides, we should expect that a certain amount of material might escape from both sides of the Earth. If the Sun were overhead at the central point in the Pacific, then within less than an hour, using Darwin's rate of rotation, it would have been exactly opposite to the area in question in the Atlantic, Gulf, and Caribbean Sea.

The similarity of the Lesser Antilles to the Asiatic islands, already pointed out, corroborates this explanation. It is also to be noted that the greatest depths in the Atlantic, 21,000 feet, are found along the eastern boundary of this region. Similarly, one of the deepest parts of the Pacific, 31,000 feet, is indicated by the × close to the central point on the map, Fig. 1. Around this deep portion on the east, north, and west is a shallower area from 15,000 to 20,000 feet in depth, and then, as we approach the continents, again a deeper area.

All those who have studied the stratification of the Appalachian region have concluded that the sediments came chiefly from the east. Such extensive deposits require a larger land area than now exists;

in fact, one is needed of continental proportions. Whether these deposits are sufficiently ancient to be explained by the lunar hypothesis the writer is not prepared to say.

There are several coincidences relating to the position of the central point of the Pacific which may or may not be accidental. The close coincidence with the very deep area above noted is the first of these. The second relates to its latitude, $-25°$. This is within a degree and a half of the tropic of Capricorn. The tropics are the lines on a uniform sphere where the direct solar tidal pull acts for the greatest length of time on any particular area of rock. Here also the leverage of the tidal pull on the Earth's crust would be greatest in displacing a protuberant equatorial ring. If the Moon were generated from the Earth by centrifugal force, liberated by the tides, we should expect the central point to coincide with one of the tropics of that time. The coincidence with the present tropic would indicate that the axis of the Earth can have changed very little in the meantime. The third and fourth coincidences are more likely to be accidental. The third is that the central point coincides in longitude with Bering Strait, where the two continents are supposed to have slipped past one another. The fourth is that the strait is almost exactly 90°, more accurately 91°, in latitude from the central point.

If the greater continents were split apart, we should by the same analogy conclude that Antarctica and Australia were drawn from the Indian Ocean; the former from the vicinity of the Cape of Good Hope, the latter farther east.

If it is true, as here suggested, that we owe our continents to the Moon, then the human race owes far more to that body than we have ever before placed to its credit. If the Moon had not been formed, or if it had carried away the whole of the terrestrial crust, our Earth would have been completely enveloped by its oceans, as is presumably the case with Venus at present, and our race could hardly have advanced much beyond the intelligence of the present deep sea fish. If the Moon had been of but half its present bulk or had been slightly larger than it is at present, our continents would have been greatly diminished in area, and our numbers decimated, or our lands overpopulated.

Connected intimately with the origin of the continents is the problem as to the cause of volcanoes, and why they are at present always situated near the sea. A point that is of the utmost consequence in its bearing on this question is the fact, noted by Charles Darwin, that active volcanoes are found only where the coast-line is rising. Clearly the same cause produces both effects.

A rising region, as pointed out by Dutton, must evidently be increasing its volume. This increase may occur either with or without an increase of mass. In the latter case the increase must be due to a rise of temperature. It has been shown that, if a part of the Earth's crust fifty miles in thickness were to have its temperature raised 200° F., its surface would be raised to the extent of 1,000 to 1,500 feet.[1] The Bolivian plateau has an elevation of two and a half miles. That of the Himalayas is about a mile higher. It is improbable that these elevations are due to this cause.

The alternative is that in the rising regions we have an increase of mass. If the mass were increased materially, it has been shown by Gilbert[2] that the hot subterranean region should yield to the added pressure, thus neutralizing the elevation. An added column of rock two miles in height could not possibly be supported. Apparently our last resort is to introduce some lighter material, such as water or steam. The pressure on the steam, if its temperature were above the critical point, would be so great that its density would be but little less than the equivalent extrapolated value for water. It might have one-fourth of the weight of an equal column of rock.

Liquid lava is full of water, and as the lava cools the water is expelled from it. The lava at Hilo, Hawaii, contains innumerable bubbles, indicating the presence of steam, which had been retained by it within its structure for many days, ever since it had left the crater of Mauna Loa, fifty miles distant.

Since volcanoes are intermittent in action, the charging process must still be going on at the present time; otherwise there would have been one long discharge in the distant past, which would have rendered all our present volcanoes extinct.

Since volcanoes are active only near the oceans, it has been sug-

[1] Judd, *Volcanoes*, p. 347.

[2] *Continental Problems of Geology*, Smithsonian Report, 1892, p. 165.

gested that the eruption is due to sea water that has entered by cracks in the Earth's crust and is subsequently discharged from the volcano. Volcanoes do discharge salt water, but the solid ingredients of the water do not occur in the same proportions that they do in the sea. Some of the sea salts are often found to be absent, while other salts are often found that do not occur at all in sea water. This fact, together with the inherent improbability that sea water should be sucked in at a low level and pumped out at a high one, renders this explanation improbable.

Another explanation of the universal presence of water in volcanic products is that it is derived from rain water, which has percolated down through the soil. This theory, however, does not account for the fact that volcanoes are always found near the sea. Neither of these theories account for the gradual elevation of the land in volcanic regions.

Since the process of charging volcanoes with steam is still going on, and since it appears that the necessary water is not derived from either the sea or the atmosphere, the only alternative seems to be that it comes from the heavy stony material forming the ocean beds, and does not come in appreciable quantities, at present, from the lighter material forming the continents. It is evident, however, that this lighter material is sometimes cracked, permitting the discharge to take place through it. This was the case with the extinct volcanoes in central Europe, and those near the Yellowstone Park and Arizona in this country. The volcanoes at present active in North and South America seem to rise from what was probably formerly the edge of the continental plateau.

The next question that arises is: From what depth does the lava come? Judged by its temperature at the vent, unless it becomes heated by friction, by compression, or by radio-activity, on its way to the surface, which seems improbable, it must have come from a considerable distance. The rate of increase of temperature with the depth varies in different parts of the world from 20 to 100 feet per degree Fahrenheit. It may fairly be taken near the surface at 100° per mile of depth. From its surface temperature, Bonney estimates[1] that "the lava is generally supplied from a zone situated

[1] *Volcanoes*, p. 284.

at a depth of from 20 to 25, or possibly to 30 miles, in the crust of the Earth." The total thickness of the crust has been estimated by Fisher[1] at 30 miles. These values agree very well with that just computed from the volume of the Moon.

Daubrée has shown[2] that water separated from a chamber filled with steam at a temperature of about 160° C. by a close, fine-grained sandstone, passed through the slab with ease, against the outward pressure of the steam. He also found that the facility with which the water found a passage was increased by heat. There is therefore no difficulty in understanding the transmission of water through hot rocks at considerable depths. Its presence, moreover, would tend to lower the melting-point of the rock, and make it more viscous.

A certain amount of water may even be transmitted in this manner down through the ocean floors; but when we consider that the transmitting medium consists of cold rock several miles in thickness, the water advancing against a constantly increasing pressure, it does not seem that the amount transmitted per year in this manner can be very large.

In our hypothesis explaining the origin of the continents, it was stated that they were composed of the crust which was either originally solid or else had already cooled sufficiently to become so. They had therefore expelled a large part of any water which they may originally have contained. The ocean beds at the time of the great catastrophe were liquid. They therefore absorbed all the water available, if indeed they were not already saturated with it. They had a much higher temperature, having come from a greater depth, and contained much more water at this period, than the continents, and, it is believed, have been giving it out as they cooled ever since.

Doubtless the hot bases of the continents have absorbed some water from the ocean beds as the latter cooled, and the expansion and diminished specific gravity thus caused would tend to elevate them in the vicinity of the oceans. This has occurred notably in the vicinity of the Pacific, the whole of whose coasts are at the present time in a state of elevation. We can understand also that the sys-

[1] Milne, *Seismology*, p. 120.

[1] *Geological Experiments*, Vol. I, p. 237.

tematic difference in material and density, extending over large areas, would render the boundaries of the continents more subject to cracks, with their resulting volcanoes and earthquakes, than other portions of the Earth's surface. A zone of territory subject to earthquakes extends around the Pacific.

As is known from its rigidity, the interior of the Earth as a whole is solid. There cannot even be at present a continuous liquid surface between the center and the crust. Beneath every active volcano, however, there must be an area from which its lava is derived. In some way, without doubt by the contraction of the Earth, this lava is caused to approach the surface, and on the way it gradually changes from a viscous solid to a viscous liquid. There are only two ways in which this change can take place: one is by an increase in temperature, the other by a decrease in pressure. The latter is probably the actual one.

Tangentially considered, the lower portions of what we may for convenience call the Earth's crust are in a state of compression, the upper portions in a state of tension. Radially all are in a state of compression. Between the upper and lower portions is a neutral surface of no tangential strain. When a crack caused by the tangential tension reaches this neutral surface, the viscous rock oozes up through it, becoming more and more liquid as it approaches the surface and the pressure is diminished. As it melts and is relieved of pressure, its density diminishes, and, if it finally reaches the surface, the erupted lava will continue to flow till the pressure at its source is reduced to equality with the hydrostatic pressure at the base of the crack. The larger the opening and the shorter the distance from the surface, the sooner will this equality of pressure occur, and the shorter be the duration of the eruption. The expansion of the bubbles of steam near the top of the crack diminishes the hydrostatic pressure, and their escape obviously causes the explosions usually noticed. The violent manifestations are therefore all generated near the surface, as is the case of a geyser.

The uprush and escape of all this material broaden the crack into a tube several hundred feet in diameter. After the lava has ceased to flow, the steam working its way up to the vent still keeps a somewhat narrowed passage open. It thus continues as a line of weakness; and when the flow of steam and viscous rock from below on all sides toward the area of diminished pressure again increases this pressure beyond the breaking strength of the resisting material, the eruption will be renewed.

Volcanoes frequently lie along arcs of circles, which, if complete, would resemble the lunar *maria* both in size and shape. One of the most complete of these series of arcs has the China Sea for its center, while the volcanoes are found in the Philippines, Celebes, Java, Sumatra, the Malay peninsula, and southern China to the west of Canton. The diameter of this circle is 2,000 miles. The Japan and Bering Seas are similarly partly surrounded by incomplete arcs. The shape of the latter is decidedly elliptical.