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by

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"ON THE ORIGIN OF CONTINENTS, ATMOSPHERE AND OCEANS"

by

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Introduction

The title announced for the verbal presentation of this address differed slightly from that given above as it was chosen so that I might include in the talk some kodachrome slides taken during a trip last summer. Although these slides included many pertinent to the study of geophysics and geology, as well as some of general interest, they cannot be reproduced here and so there is no use in referring to them. I will accordingly rearrange this written paper to exclude any reference to personal experiences and give only some modern views upon the possible origin of continents, oceans and atmosphere.

The Early History of the Earth

In 1929 in his great book "The Earth, its origin, history and physical constitution", Harold Jeffreys stated that the origin of continents was unknown but that the earth might well have been formed without an atmosphere and could have produced one since then. Presumably it could have developed an ocean also, although Jeffreys did not indicate very precisely how these processes took place. The answers to these fundamental questions are still somewhat hypothetical and many geologists and geophysicists prefer to leave the problem at about the same stage as Jeffreys. On the other hand, our knowledge of the earth and the physical measurements of its interior and internal processes especially are accumulating rapidly and this paper is an attempt to bring together some of the latest advances; and also contribute one possible explanation of the origin of earth, air and water, three of the four elements of the ancients. It is freely admitted that this view is not universally nor even generally accepted, yet it is an attempt to find an hypothesis which is physically and quantitatively sound and as such is capable of test and closer approximation.

In brief the suggestion which is gradually being pieced together by workers in many fields in several countries is this.

The earth, either when it was formed or at some subsequent period, was hot and liquid and in that state separated into a nickel-iron core and a silicate mantle, primarily perhaps made of magnesium silicate or eclogite. If it formed from a cold dust cloud it could have generated enough heat by its radioactivity to have melted under certain circumstances.

The dust cloud hypothesis does not seem to be a very necessary one, nor does the suggestion that the core of the earth is highly compressed silicate which has undergone a change of state to make it more dense. The theory that the core of the earth is compressed hydrogen seems to be quite untenable; for if the pressure in the interior of a small planet, such as the earth, could compress hydrogen to such an extent, of what material could the large, low density planets like Jupiter possibly be made?

The earth then cooled and solidified from the bottom of the mantle upwards due to the effect of pressure upon the melting point, leaving the core, hot, molten and well insulated until the present time. The probable temperature at all places in the interior below the uppermost layers is close to the original freezing point of the rock mantle.

The original surface was therefore hot, and without continents or much, if any, atmosphere. Arthur Holmes at Edinburgh has devised a radioactive method of estimating that the age of this solidification was about 3.3×10^9 years ago, and other lines of evidence all agree that it was at least between 2 and 4 billion years ago.

The globe then possessed the same deep seated layering as today and no doubt, if one follows the view of Elsasser and Bullard, it possessed convection currents in the molten core which acted and still acts as a self-exciting dynamo and produced the earth's magnetic field. The variations in these currents causes the secular change in the magnetic field with a cyclic period of a few hundred years at any place on the surface.

The outer part of the globe cooled, however, drawing heat both from the interior and from radioactive elements, chiefly uranium, thorium and potassium-40. These had apparently by chemical processes been concentrated towards the surface during the cooling.

The earth was and still is a gigantic heat engine with a present output in the general order of perhaps 10^{10} horsepower.

The surface of the earth quickly cooled to a temperature in equilibrium with the radiation received from the sun and the heat lost from below scarcely affects the surface temperatures today. This heat loss could be brought to the surface either by conduction or by very slow convection currents in a very stiff and essentially solid mantle, or by both actions. It will be realized that although the nickel-iron core may be no more viscous than water, it only occupies an eighth of the volume of the earth and above it the mantle is a rigid solid as far as such brief effects as the tides are concerned. In any case, one can assume that the earth is cooling, if only because it solidified. If it is cooling, it is contracting; the problem is to discover what mechanical process, physically possible in a globe like the earth, could produce the surface irregularities now seen as mountains and continents, and whether this process could also produce the seas and atmosphere.

The present surface and fluid envelopes are therefore the sum total of the results of this process acting over a vastly long period of time. To disentangle this complex result is a very difficult task, although geologists have made remarkably good progress in gaining an understanding of the nature of the surface of continents. The task of understanding the history of continents, oceans and atmosphere would be much easier if the process or processes could be discovered which operate within the earth and give rise to volcanism and mountain building. This would now appear to be possible.

The belts which are active at present

The places where the terrestrial heat engine is showing its working processes most actively today are without doubt along the two great belts upon which are concentrated the great majority of the world's earthquakes, volcanoes and young mountains and island arcs. These belts lie respectively through the Alpine, Persian, Himalayan, Indonesian, Melanesian regions to New Zealand and around the Pacific Ocean from Indonesia, through the East Asian island arcs, the American Cordillera and Andes to Antarctica. These belts are, very roughly, arcs of two orthogonal great circles meeting in a T at Indonesia. Along them, there seem to be occuring exactly those processes required to produce the surface features and elements.

All seismologists now seem to be agreed that earthquakes are due to sliding fracture along ruptures or fault surfaces. These definitely occur under some parts of the active belts of the world to a depth of 700 kilometers. Do not such fractures provide possible channels by which at least some of the gases and liquids trapped within the earth can reach the surface? Gases and liquids are released from volcanoes most of which occur along the same belts as the majority of earthquakes. It is along these same belts that the rocks of the young mountains have been folded. In the latest presidential address to the Geological Society of America, W.W. Rubey has discussed the origin of oceans and atmosphere and suggested that "conceivably the hydrosphere and atmosphere may have come almost entirely from the earth's interior."

Volcanoes today of course give rise to large quantities of water and gases. It would be interesting to know the rate. Some of these products remain in the atmosphere but other gases, especially chlorine and sulphur compounds, seem to enter into combination and thus accumulate as salts in the ocean. Only in this way can the presence of large quantities of sodium chloride in the ocean be accounted for, because the sodium which enters the oceans by the rivers is well known to be chiefly composed of sodium carbonate and sulphate and where else could the chlorine have come from? There have been many papers upon this rate and method of accumulation of salt, but the results are not very satisfactory and the present rate seems to be high.

Argon which forms about 1% of the atmosphere also provides a chance for a possible quantitative measurement of the rate of accumulation of the atmosphere although the details are still under vigorous discussion in the literature.

The other inert gases are all extremely rare in the atmosphere and do not of course enter into chemical combinations from which they might have been released by geological processes. If the earth had no atmosphere to begin with, the scarcity of most of the inert gases is readily understandable: but from where did so much argon come? The clue seems to be that atmospheric argon is almost all argon-40 which is being constantly generated by the rare but active radio-active isotope potassium-40 which forms about 1 part in 9000 of all potassium. The rate at which potassium-40 decays to form argon-40 has been uncertain, and is difficult to determine, but the latest figures suggest that the rate is such that during geological time the atmospheric argon could have been formed from approximately the amount of potassium which there is in the earth's crust. Some mechanism to allow the release of the argon from the rocks would have to be admitted. This has been advanced as an argument that the atmosphere and granitic part of the crust are in some way connected.

Origin of continents

This brings us to the origin of the granitic layer of the crust. This is discontinuous and forms all the continental blocks. It is of the composition of a granite or granodiorite at the surface. It is generally gneissic and appears to get rather more basic at depth before ending abruptly at a depth of about 35 kilometers. This has been determined by seismic work at several places including along the Ottawa valley by Dominion Observatory. Below the granitic layer of the crust the rocks have higher seismic velocities and are presumably ultrabasic rocks, such as dunite or peridotite or eclogite.

In the first place, the idea that continent blocks are part of an original unaltered crust is quite untenable. The outer parts of most continents are young and active mountain ranges like the Cordillera or older, quiescent mountains like the Appalachians. The central parts are Precambrian shields, covered to a greater or less extent, as in the prairies or central United States, by a relatively thin veneer of young and flat rocks. The shields themselves have often been referred to as the root of ancient mountains and they contain abundant traces of altered and folded sedimentary material. The pattern of these ancient ranges does not look at all like that of an original part of the crust.

Another consideration is from the rate of erosion.

The rates of erosion and of deposition

It was estimated by Dole and Stabler that erosion reduces the surface of the United States by one foot in 9,000 years. If this process had continued at the same rate throughout the length of geological time a layer about 17 km. thick would have been removed since the beginning of Palaeozoic time (5×10^8 years) and 110 km. thick since the probable time of origin of the earth (33×10^8 years). For comparison, the thickness of the whole crustal layer above the Mohorovicic discontinuity is only about 30-40 km.

It has been suggested that the present rate is high, so that a better measure is provided by figures recently published by Murray, giving the volumes of sediment deposited on the Gulf Coast in Mesozoic and Cenozoic time.

If we accept from Murray's data from results of drilling and reasonable extrapolation that the emerged and off-shore portions of the Gulf Coastal Plain together contain at least 500,000 cubic miles of Cretaceous and later sediments and also that this was accumulated during 130 million years from a drainage area of 1 1/2 million square miles, then the rate of erosion would have been about 1 foot per 85,000 years. But this takes no account of the sediments swept out to the deep ocean and the floor of the Gulf of Mexico. Kuenen has shown that the volume of deep sea deposits may be three times as great as the corresponding volume of continental shelf sediments.

We need not discuss this in more detail but can safely conclude that the rate of erosion is such that it removes a foot in not more than each few tens of thousands of years off continents in a similar state to North America.

The important point is that if erosion at all comparable to that of Mesozoic and Cenozoic time had taken place in Paleozoic and Precambrian time then there would exist shelves of those earlier ages around North America many times as extensive as those of the Gulf Coast. Of course, there are virtually no shelves at all except in the Arctic where the Coppermine series might be regarded as a very small example. To suggest that the Atlantic and Gulf Coast shelves have only a veneer of young sediments over older rocks is to contradict the evidence from deep wells quoted by Murray. To maintain that no similar Precambrian and Paleozoic shelves ever existed is to deny the existence of an average rate of erosion which was only a fraction of that of today.

It seems quite untenable to suggest that there was so little erosion before Mesozoic time. It is also quite unnecessary because Kay, and Eardley have pointed out that the Appalachian and Cordilleran Mountains were formed out of precisely such shelves as are now forming on the Gulf and Atlantic Coasts. This seems to be an entirely satisfactory explanation. The Jurassic age of the oldest rocks known in these shelves suggest that they only started to form after the Appalachians had been built. Lawson has even suggested that the mountain building process is due soon to be repeated on the Gulf Coast. On the Pacific coast there has not yet been time to form a shelf since the Cordillera was built.

This suggests that the mechanism of growth is already known. Indeed it is widely accepted for recent time, but it is often coupled with the idea that there was throughout Precambrian time a continental block, formed in some other undefined manner. Perhaps this idea is widely held because even after the idea had been accepted that continents are growing it was felt necessary to have a pre-existing block to supply the sediments by which growth proceeds. But is that so? A shelf must be formed only by erosion, but once failure has occurred volcanism supplies abundant lava, ash and intrusive rocks from the interior of the earth to add to the continent.

The shelf along the whole east coast of Asia is bounded by a series of island arcs, all volcanic and all adding abundant material at the margin of the continent. This material is distinguished from the ocean volcanoes by its higher silica content which is precisely the kind of material needed to extend continents.

Rate of volcanic extrusion

The surface of the continental blocks is approximately 50,000,000 square miles and they are about 20 miles thick. If the earth is somewhat over 3 billion years old (Holmes, 1949) then all that is required in order to build the continents is that an average of 1/3 of a cubic mile of new sialic rock should have been extruded each year.

It would be difficult if not impossible to estimate precisely the rate at which such contributions have been made, but it will perhaps suffice to show that the known contributions are such as to make the rate appear to be a reasonable one. There are three kinds of ingneous rock which are known to be quantitatively the most important. These are granites, andesites and basalts. They will be discussed in turn.

The rate and method by which granite is formed cannot be observed in recent rocks as it takes place at depth. Much granite and more granite gneiss has been formed in the past and it is increasingly abundant in the older rocks. But it is doubtful how much of the contributions of granite should be included in this calculation. Admittedly, in areas of young rocks like the United States and central Europe there is evidence of the intrusion of granite magma, but its source is a matter of debate. If it came from the depths as granite the answer to our problem is easy, but erosion should expose more granite in the older rocks, but the old shield areas are not composed of granite, but of well foliated granite gneiss showing abundant evidence of containing great amounts of metamorphosed sediments as has been maintained by geologists in every shield area. The disappearance of the shelves rather than indeterminate petrological arguments force one to believe that the roots of mountains are formed of sediments to which only small additions of materials have been made. These additions have chiefly been water and heat which are supplied during primary mountain building along the great arcuate fractures from the depths. The contributions of new continental material in the granites and gneisses may thus be largely illusory and will not be included, but to take the opposite view would enlarge the source of continental material.

The rocks which are added along the island areas are predominantly andesites, dacites and latites so that they have an average composition similar to granodiorite. At present there are about 500 volcanoes listed as active. To form 1/3 cubic mile of new rock each year each volcano would have to emit a sheet of lava a square mile in area and about 4 feet thick. Probably most volcanoes do not contribute this much each year, but the most active like Paricutin extrude much more. Fenner has estimated that the tuff in the Katmai Valley of Ten Thousand Smokes is more than one cubic mile in volume and represents one principal ash flow. That would equal the contribution necessary from the whole world for three years and it is not the largest single eruption known.

Turning to basalts and pyroxene andesites the quantities known to have been formed are very great. Von Tillo estimated that 2,000,000 square miles on continents and islands were covered by "young" (Tertiary?) volcanic masses. Great volumes have been formed under the oceans, for example, 500,000 cubic miles in the Hawaiian Islands alone. Of course, oceanic eruptions contribute nothing to continents today, but the continents may include rocks poured out in the ocean. Lawson has argued that the action of sea water in breaking down basalt leaves a more siliceous residue which would be of sialic compostion.

These figures do not establish the rate of volcanic out-pouring, and it is not known whether adequate data to establish that rate exist, but they perhaps suffice to show that the formation of continents by extrusion of volcanic rocks and to a greater or less extent by the intrusion of plutonic rocks is a reasonable proposition. Naturally, most of the rocks now exposed have been reworked through succeeding cycles of erosion, deposition and metamorphism so that they are no longer in their original form.

Importance of study of Precambrian rocks

One of the best clues to further work on this problem is to find out more about the Precambrian rocks, for that great period of time before animals had any hard parts which could be preserved as fossils constitutes at least three quarters of geological time, and without a proper understanding of it we can scarcely hope to see the broad picture properly.

Interestingly enough there are few places better situated to study the Precambrian rocks than Toronto 60 miles north of which lies a well exposed and vast area of ancient rocks. Over the past century these have been excellently mapped and a start made by various geologists to divide them into regions of differing structures and rock types. Chemical age determinations made twenty years ago by Ellsworth of the Geological Survey showed that these regions had different ages. It is gradually being recognized that these may be the roots of various ancient mountains, and the pattern which is emerging here and elsewhere suggests that the continents may have grown outwards from nuclei.

In Washington at the American Geophysical Union meetings this month, Ahrens of M.I.T. suggested that the oldest rocks of which the age had been measured occurred in southeast Manitoba, in Southern Rhodesia and in Sweden and that all were somewhat over 2 billion years old. Now the rocks in the first two of these localities at least are predominantly greenstone lavas of Keewatin type, and in two other areas in the interior of Western Australia and around Yellowknife there are regions of similar greenstone rocks whose age has not been measured but which some authors have suggested upon structural evidence to be older than neighboring regions containing rocks of about 1 1/2 billion years old.

The writer has seen four of these greenstone regions and suggests that they are the nuclei of older rocks about which the continents have grown. Other nuclei undoubtedly exist, some of which may be younger, but the main continents may be supposed to have started to form in about the same manner at about the same time. Most of them are probably composed like North America with its two suggested nuclei, or like Eurasia which may have been united along the Urals and later along Alpine-Himalayan belts.

To obtain more age determinations by the method believed to be most reliable a mass-spectrometer of very high resolving power capable of measuring the relative amounts of lead isotopes generated and found in radioactive minerals has been recently completed at the University of Toronto by Collins. The work of making many more age determinations upon Precambrian minerals has been started.

Mechanics of failure in the earth's outer shells

It would be interesting to know the precise method of failure of the outer part of the earth such as is occurring in the present active belts and which can be supposed to have occurred beneath other older mountains when they were active. Very recently Scheidegger has investigated the types of failure to be expected in spherical shells under a variety of conditions that might apply in the outer shells of the earth. The matter is still being investigated but already a possible explanation has been found of the arcuate shape of many mountain and island arcs and a reason why some particular island arcs especially some straight ones in Oceania would not be expected to be arcs of circles. This theory also serves to explain certain differences between shallow and deep focus earthquakes and predicts the directions of first motion of some earthquake movements which have been observed and checked in some instances.

Conclusion

In conclusion this brief account tries to indicate one direction in which the vast amount of geophysical and geological research is pointing. It may be that it will one day be generally recognized that atmosphere, oceans and continents have all grown during geological time; whether this is so or not, it is clear that new ideas and new and more precise and quantitative measurements are combining many parts of geology and geophysics together. Out of this we can soon expect a much clearer physical picture of the earth. As Meteorologists know, geophysics is not just methods of prospecting but includes a wide range of subjects. They have developed rapidly and the solid earth can only be studied adequately by a proper combination of geological and geophysical methods.

Just as it has come to be realized that the atmosphere has structure and can be studied as a dynamic system obeying physical laws, so the same picture is emerging of the earth's interior. In meteorology observations were once confined to the surface and forecasts were largely empirical (although none the less useful). So in the study of the solid earth, observations can now be made accurately of the interior and an attempt made to understand its physical processes in three dimensions throughout the full range of geological time.