Geology

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THE ORIGIN OF CONTINENTS, MOUNTAIN RANGES, AND OCEAN BASINS*

By GEORGE C. KENNEDY

ONE of the unexpected discoveries in earth science in the previous century was that of a fundamental difference between continents and ocean basins. Ocean basins are not merely the low lying parts of the Earth's surface flooded by salt water but are great, relatively steep-sided, structural depressions. In fact, there is too much water for the size of the ocean basins, and parts of the edges of the continents are now flooded and probably have been flooded through a great deal of the geologic past. A typical continental mass with adjacent ocean basins is shown in Figure 1A.

Precise measurements of gravitation attraction in major mountain ranges, continental areas, and over the ocean basins showed an even more unexpected feature. The continents and mountain ranges do not represent extra loads of rock superimposed upon the Earth's crust, but are masses of lighter rock floating in a denser substrate. An iceberg floats above the water much in the same fashion, buoyed up by deep submerged roots. The great mountain ranges of the world and the continental masses similarly have deep roots of light rock penetrating down into the denser crust, and thus the mountain ranges and continents float at elevations appropriate to the depth and size of these submerged light roots. Thus, all the major features of relief of the surface of the Earth show mirror image features within the crust, much as is indicated in Figure 1B. The major mountain ranges float at high elevations because they are buoyed up by light rocks. The continents float at intermediate elevations with roots of intermediate depth, and the deep oceans are underlain by thin layers of light rock.

Seismologists, from the study of earthquake waves, have shown that the Earth's mantle is solid to the depth of the outer core, some 2900 kilometers. The observation that large mountain ranges and continental masses float on the crust of the Earth at elevations appropriate to the size and density of their roots implies that rocks at shallow depths in the Earth's mantle, although solid, have little strength and can flow in response to small stresses given sufficient time. This deduction is strengthened by the observation that rocks in deep, eroded, old mountain chains are intensely contorted and folded, plain evidence that, at high pressures, solid rocks can flow readily and do not have great strength.

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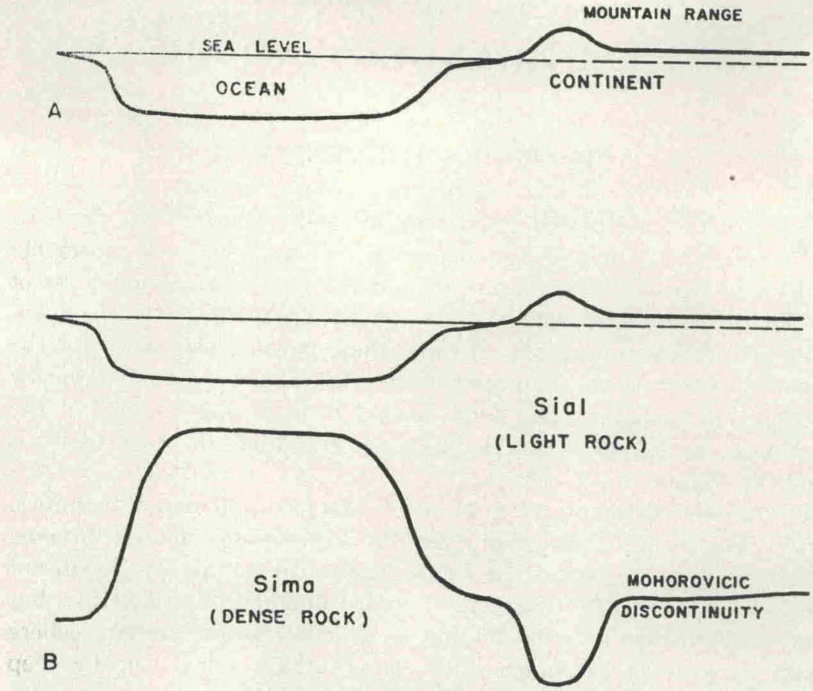

FIG. 1. Profiles through the Earth's crust

Recognition that continental rocks are lighter and more buoyant than oceanic rocks gave rise to the concept that the crust of the Earth is made of two contrasting materials: sialic material, rich in silicon, the alkalies and aluminum, making up the continents; and simatric material, richer in iron and magnesium, making up the denser rocks below the floor of the ocean and lying under the sial of the continents. The sial is assumed to be granite or granodiorite in composition, and the sima is assumed to be basaltic in composition.

Early in this century, the Yugoslav seismologist, Mohorovicic, obtained evidence from seismograms that earthquake waves, traveling a few tens of kilometers below the surface of the Earth, gave records showing sharply higher speeds for both shear and compressional waves than earthquake waves traveling near the surface. This indicated an abrupt change in rock types at a few tens of kilometers under the continents and at a few kilometers under the oceans. In recent years, extensive studies have produced a fairly clear general picture of the nature and depth of this level of change, or discontinuity, under the continents, mountain ranges, and ocean basins. This discontinuity, called the Mohorovicic or M discontinuity, is at a general depth of 30 to 40 kilometers under the continents, but may be as deep as 60 kilometers under the roots of major mountain chains. It is as shallow as 4 to 5 kilometers below the floor of the deeper parts of the ocean. The discovery of the M discontinuity seemed to confirm the notion that the crust is fundamentally made up of two different kinds of rock material. The discontinuity itself appears to be the boundary between these, the sialic rocks above and the simatic rocks below. The rocks below the M discontinuity have seismic velocities and densities which suggest that they may be even richer in magnesium and iron than normal sima of basaltic composition. Consequently, they are, by some, called ultrasima. However, throughout this paper the word sial will be applied to the lower velocity rocks above the M discontinuity, including the range of basalts to granites, and the word sima will be applied to the denser rocks below the M discontinuity.

Prior to and along this general picture, the concept of isostasy developed. This is the notion, previously discussed, that the lighter continental rocks float at an appropriate depth, depending on their mass and mean density, in a denser substratum. As rock is eroded from the tops of continents and mountain ranges they tend to float up higher and higher, renewing their relief, permitting erosion to continue.

Four facts, however, sharply contradict this picture of a sialic crust of varying thickness floating on a simatic substratum of different chemical composition and different density.

1. Large areas of continents, long near sea level, have been uplifted many thousands of feet in the air. Further, this uplift seems to have taken place rather rapidly in terms of geologic time.

2. Sediments of low density, filling troughs along the margins of continents, apparently are able to subside into this higher density substratum.

3. Inasmuch as radioactive, heat-producing elements are associated with sialic rocks, one might expect heat flow through the thicker parts of the Earth's crust to be much greater than through the thinner parts of the Earth's crust. However, as a first approximation, heat flow through the crust of the Earth is approximately the same through continents, mountain ranges, and ocean basins.

4. The lifetime of continents and mountain ranges is vastly greater than rates of erosion would suggest.

Let us examine each of these apparent facts and their consequences on the hypothesis of sialic continents floating on a simatic basin. The problem of the uplift of large plateau areas is one which has puzzled students of the Earth's crust for a very long time. Regions which are at sea level, or near sea level, may, over a relatively short geologic time span, such as a few million years, be uplifted several thousands of feet. The Colorado plateau and adjacent highlands is an example. Here, an area of approximately 250,000 square miles that apparently stood at sea level for several hundreds of millions of years was uplifted approximately one mile vertically some 40,000,000 years ago in early mid-Tertiary time and is still a high plateau. The Grand Canyon of the Colorado has been carved through this great uplifted plateau.

Given an Earth with sialic continents floating in a denser simatic substratum, what mechanism would cause a large volume of low standing continents to rise rapidly a mile in the air? Furthermore, evidence from gravity surveys suggest that the rocks underlying the Colorado plateau are in isostatic balance, that is, this large area is floating at its correct elevation in view of its mass and density. Recent seismic evidence confirms this, in that the depth to the M discontinuity under the Colorado plateau is approximately 10 kilometers greater than over most of continental North America. Thus, appropriate roots of light rock extend into the dense substratum to account for the higher elevation of the Colorado plateau. We have then a double-ended mystery, for the Colorado plateau seems to have grown downward at the same time that its emerged part rose upward. This is just as startling as it would be to see a floating cork suddenly rise and float a half inch higher in a pan of water. To date, the only hypothesis to explain the upward motion of large regions like the Colorado plateau is that of convection currents. Slowly moving convection currents in the solid rock, some 40 to 50 kilometers below the surface of the Earth, are presumed to have swept a great volume of light rock from some unidentified place and to have deposited it underneath the Colorado plateau. A total volume of approximately 2,500,000 cubic miles of sialic rock is necessary to account for the uplift of the Colorado plateau. While it is not hard to visualize rocks as having no great strength at the high pressures and temperatures existing at depths of 40 to 50 kilometers, it is quite another matter to visualize currents in solid rock of sufficient magnitude to bring in and deposit this quantity of light material in a relatively uniform layer underneath the entire Colorado plateau region.

The Tibetan plateaus present a similar problem, but on a vastly larger scale. There, an area of 750,000 square miles has been uplifted from approximately sea level to a mean elevation of roughly three miles, and the Himalayan mountain chain bordering this region has floated upward some five miles, and rather late in geologic time, probably within the last 20,000,000 years. The quantity of light rock which would need to be swept underneath these plateaus by convection currents to produce the effects noted would be an order of magnitude greater than that needed to uplift the Colorado plateau, that is approximately 25,000,000 cubic miles. Even more troublesome than the method of transporting all this light rock at shallow depths below the surface of the Earth is the problem of its source. The region from which the light rock was moved should have experienced spectacular subsidence, but no giant neighboring depressions are known. A lesser but large problem is how such enormous quantities of light rock can be dispersed so uniformly over so large an area.

This evidence of uplift and downsinking of various crustal blocks, with the blocks always remaining in approximate isostatic balance, does not seem to harmonize with the view of a floating sialic continent on a denser substratum where one might expect to find little variation in elevation with time.

The second problem, that of the subsidence of troughs, is of equal difficulty. The rivers of the world carry enormous quantities of sediments seaward. Most of this sedimentary burden is deposited within a few tens or hundreds of kilometers of the shore line and little is transported to the deep ocean basins. Thus, elongate prisms of sediments are built up parallel to the shores of certain regions where great quantities of sediments are transported to the sea. The crust, in response to this added load of sediments, begins to buckle downward. Troughs filled with sediments appear, paralleling the coast line. The chicken and the egg argument enters here, for it is not entirely clear whether deposition of sediments generates the troughs or whether the troughs are formed first and are later filled with sediments. However this may be, one such trough now in the making is along the coast of the Gulf of Mexico on both sides of the mouth of the Mississippi River. Surprisingly enough, this trough deepens at about the rate new sediments are added to it. Thus, the sediments are always deposited in relatively shallow water.

Fundamental laws of physics are violated and on a large scale if this downwarping is produced directly by continued loading of sediments. These deep troughs filled with sediments may contain 50,000 to 100,000 feet of sediments and may be 1000 or more miles long and 100 miles in width. The mean density of the sediments, even compacted under a load of 10,000 feet of other sediments, is approximately 2.4 to 2.5. The rocks displaced in the downwarping trough are known to be denser, with a mean density of 2.8 to 2.9. By what mechanism do light sediments displace denser, crystalline rock? These troughs of sediments, like the plateaus considered earlier, always appear to be in isostatic balance. If the conventional is to be sustained, dense rock must automatically be removed from below the bottoms of these sedimentary troughs at approximately the same rate that they receive sediments from the rivers which feed them so that the troughs balance and float with their upper layers of sediments under a few tens or hundreds of feet of water most of the time.

The problem of the mechanics of the formation of deep troughs of low density sediments is heightened when their full history is considered. Many are known in the geologic record. In most, sediments accumulate for perhaps a hundred million years and reach a total thickness of as much as 100,000 feet. These thick, highly elongate lenses of sediments may then be slowly folded and uplifted to form mountain ranges which may initially stand as much as 20,000 feet high. Surprisingly, the geologic record shows that a large fraction of the mountain ranges of the world have been formed from rocks of these thick, geosynclinal troughs. Extensive volcanic activity may accompany and continue beyond the time of the formation of the mountain ranges. The mystery, then, of the downsinking of the sedimentary troughs, in which low density sediments apparently displace higher density rocks, is heightened when we note that these narrow elongate zones in the Earth's crust, downwarped the most, with the greatest accumulation of rock debris, shed by the higher portions of the continents, become in turn the mountain ranges and the highest portions of the continents.

The third of the major problems connected with the postulated sialic continental area and simatic oceanic region is that pointed out by recent measurements of flow of heat through the crust of the Earth.

A considerable number of recent measurements have been made of temperature gradients and rock conductivities within the outer part of the Earth's crust. Careful temperature profiles have been made within many of the accessible deep mines and in numerous wells and tunnels. From these data, a fairly reliable picture has developed of heat flow within the Earth's outer crust, although measurements are not nearly so detailed or as numerous as is to be desired. The rate of escape of heat through most continental areas appears to be approximately 1.2 microcalories per centimeter per second. It has been known for many years that most of the heat escaping from the Earth is radiogenic heat, generated in the Earth by decay of radioactive isotopes of uranium, thorium, and potassium. Little or none of the heat escaping from the Earth is primary heat, inherited from an initially hot Earth. In fact, there is no compelling evidence that the Earth was molten in its youth or even formed from hot material. We know that the rocks near surface today appear to be in fairly reasonable thermal balance. The rate of heat escaping from them to the surface of the Earth is very close to the rate at which heat is generated in them by radioactive decay of certain elements.

Over the last twenty years, extensive data have been accumulated concerning the distribution of the radioactive elements. Uranium, thorium, and potassium are 10 to 100-fold as abundant in the light silica-rich rocks as they are in denser simatic material, rich in magnesium and iron, and low in silica. Consequently, we might expect that radiogenic heat in the thick sialic continents should be vastly greater than the heat generated in the presumably radioactive-poor simatic material underlying the ocean floors. Further, we would expect heat flow to be greatest in the thickest parts of the continents, that is, in mountainous regions buoyed up by thick roots of sial rich in radioactive elements. A number of studies of heat flow through the continents have been made over the last two decades. These studies have been made by examining the distribution of temperatures and rock conductivities down deep wells and along tunnels. Surprisingly, these studies show almost no correlation between mean elevation of land mass and heat flow through the Earth's crust. This was most unexpected because all the broader regions of higher elevation are presumably underlain by thick zones of light rock which, from all determinations, should be richer in radioactive elements.

Nonetheless, it was confidently expected that heat flow through the floor of the ocean would be a fraction of that observed in the continental land masses. The first measurements of heat flow through the floors of the ocean were reported in 1952 by Sir Edward Bullard. These determinations of heat flow were ingeniously made by inserting probes containing thermisters into the muds on the floors of the oceans. Startlingly, the heat flow determined by these measurements through the floor of the ocean was almost identical with that measured in continental and mountainous areas. Later results by Revelle and Maxwell (1952 and unpublished), although indicating wide ranges of heat flow from place to place in the oceans, have only affirmed the earlier observation that heat flow through the ocean floor is essentially the same as that on the continents.

There seem to be only two possible explanations for this most unexpected discovery: either the concentration of radioactive elements in the rocks below the floor of the ocean is the same as that in rocks which make up the continents or else heat is transferred by some special mechanism from deeper down in the Earth to near-surface sites underneath the oceans. If the concentration of radioactive materials in the few tens of miles below the floor of the ocean is the same as in a few tens of miles below the continents, then our previous view that the floors of the oceans are underlined by radioactive-poor sima and the continents were underlain by radioactive sial certainly cannot be right. The alternative explanation, equally difficult, is that high temperature rocks from deeper down in the Earth are convectively carried up to near-surface environments below the oceans. Thus, heat escape through the floor of radioactive-poor oceans is fortuitously approximately the same as heat escape through the radioactive-rich continents.

The fourth problem, that of the long lifetime of continents and mountain ranges, is perhaps the most difficult of all. The rivers of the world strip tremendous quantities of rock debris off the continents each year and deposit it in the oceans. The Mississippi, for example, contains about one-half weight per cent of solids as it flows into the Gulf of Mexico. Each year, it brings to the Gulf of Mexico approximately 750 million tons of dissolved and solid material. The great rivers are steadily wearing down their basins. Calculations show that the Missouri River lowers its drainage basin about one foot in each eight thousand years, and that the rate of erosion for the entire United States approximates one foot in

10,000 years (Gilluly, Waters, Woodford, 1952). At this rate, all the land masses of the world would be eroded to sea level in something of the order of 10–25 million years. This is particularly surprising in view of the fossil record. Land animals and plants have been known on the surface of the Earth for well over 300 million years, and the sedimentary record indicates high land masses extending back at least two billion years. Much geological evidence indicates that the ancient continents were in approximately the same place as the present continents and that continents have existed more or less as they are today and for a period of at least two billion years. How do we reconcile an erosional lifetime for continents of something like 25 million years with a known lifetime of something of the order of two billion? Why has not all the continental sial been uniformly distributed through the ocean basins?

The mountain ranges bordering the continents and interior to the continents present an even more difficult problem. The rates of erosion along the slopes of steep mountains are many times those of lower lying continental land masses. The lifetime of mountains, therefore, must be far less than the 25 million years estimated for continents. In contrast to this reasoning, however, is the geologic record which strongly suggests that the Appalachian Mountain Range has existed more or less where it is today and, as far as we know, with reasonably similar relief for the last 200 million years, shedding sediments both to interior valleys and coastward. Thus, we see orders of magnitude discrepancy between lifetimes of mountain ranges and continents, estimated on the basis of known rates of erosion, and the lifetimes of the mountains and continents as indicated by the geologic record. Even though we assume that mountain ranges and continents are somewhat analogous to icebergs that float up as their exposed portions are melted away, the presumed depth of roots of the mountain ranges and thicknesses of the light continental rocks permit extension of the estimated lifetime of continents by no more than tenfold that based on present erosion rates and mean elevations.

Thus again, the notion that the rocks which make up the continents are grossly different in composition from those underlying the ocean basin does not seem to hold up, for we would expect that the rain waters washing over the continents would have long ago dispersed the continental rocks into the oceans.

These four major observations then—persistence of continents and mountain ranges in spite of high erosion rates, the relatively uniform values for heat flow in continents and ocean basins, subsidence of marginal troughs in response to loading by low density sediments, and uplift of plateaus once worn to sea level—suggest the inadequacy of the traditional view that continents represent masses of low density silica and alumina-rich rock floating in the denser media of sima, iron, and magnesium-rich rock.

Recent theoretical studies by Gordon J. F. MacDonald and experimental work by Robertson, Birch, and MacDonald (1957) and by the writer, as well as interpretation by J. F. Lovering (1958), suggest a different structure of continents, a structure which simultaneously explains most of the observed phenomena associated with continents, mountain ranges, and ocean basins and accounts for the four major stumbling blocks in existing theory. This new model of the Earth's crust stems from theoretical considerations largely confirmed by recent experimental work in the field of high pressures.

Very many crystalline solids undergo polymorphic inversions to denser phases when subjected to high pressures. The behavior of matter at high pressures has been extensively investigated by P. W. Bridgman (1952) who has demonstrated literally hundreds of polymorphic inversions among common substances in the pressure range 0–100,000 atmospheres. Graphite and diamond form, for example, a familiar polymorphic pair. At sufficiently high pressures and temperatures graphite may be converted to diamond. A temperature of 1500 K and a pressure of 100,000 atmospheres is sufficient for the conversion, and, indeed, many thousands of carats of diamonds are now being made annually by General Electric Company by subjecting carbonaceous material to high temperatures and pressures (Bundy, Hall, Strong, and Wentorf, 1955).

It has long been noted (see, recently, MacDonald, 1959) that basalts and eclogites, rocks with sharply contrasting mineralogy, have essentially identical chemical composition (see Table I).

TABLE I

	Eclogite (MacDonald, 1959)	*Plateau Basalt (Daly, 1933)*
SiO_2	48.12	48.80
TiO_2	.85	2.19
Al_2O_3	10.42	13.98
CaO	9.99	9.38
MgO	14.22	6.70
FeO	13.92	13.60
Na_2O	1.45	2.59
K_2O	.58	.69

Eclogite, however, contains no feldspar; instead, it is made up of jadeitic pyroxene and garnet. The mean density of eclogite is 3.3 gm/cc, that of gabbro is 2.95 gm/cc. As eclogite is the denser of the two phase assemblages, it is the rock which must exist at the higher pressures.

The density contrast, about 10%, between gabbro and eclogite is almost the same density contrast believed from seismic evidence to exist at the M discontinuity, although the contrast at the discontinuity has usually been assumed to be a chemical contrast rather than a phase contrast.

Indeed, Fermor (1914), Holmes (1927), and Goldschmidt (1922) suggested that M discontinuity might be a phase contrast and that the rocks below it are eclogite. Their suggestion received little discussion or acceptance but has been recently revised by G. J. F. McDonald on the basis of calculations of the pressure-temperature conditions controlling the phase change of nepheline plus albite to jade and of albite to jade plus quartz. The calculations of MacDonald (1954) were based on new thermochemical values for heat capacity at low temperatures and heats of solution of nepheline, albite and jade by K. K. Kelley and his colleagues (1953). Similar calculations, Kelley *et al.* (1953) and Adams (1953), have firmly established the slope of the transition in a pressure-temperature plane of the reaction, nepheline plus albite = 2 jade, and that of the reaction, albite = jade plus quartz.

These thermochemical calculations have been confirmed by experimental work of Robertson, Birch, and MacDonald (1957) and by the writer. These two experimental studies, though in disagreement in detail, confirm the calculations based on thermochemical data that, at pressures of 15,000 to 25,000 atmospheres, depending on temperature, the nepheline plus albite undergoes a polymorphic change to jade, and albite undergoes an inversion to jade plus quartz at slightly higher pressures. Further, an experiment made by me on basalt glass showed that, at 500° and pressures below 10,000 bars, basalt glass crystallized as gabbro. The major mineral component is feldspar. At pressures above 10 kilobars and at a temperature of 500°, the amount of feldspar decreases and, finally, basalt glass crystallizes directly to a rock made up dominantly of jadeitic pyroxene. Identification of phases were by X-ray. Significantly, 500° and 10 kilobars are approximately the temperatures and pressures estimated at the M discontinuity underneath the continents. It thus appears that the M discontinuity may reflect a phase change from gabbro to eclogite rather than a change in chemical composition. This phase change will account for the observed change in seismic velocity from approximately 6.5 kilometers per second to 8.1 kilometers per second and a change in density from 2.9 to approximately 3.23. Thus, the older suggestions of Fermore, Holmes, and Goldschmidt are supported by field measurements, theoretical calculations, and recent experimental work.

If the discontinuity caused by a phase change takes place at a depth of 30 kilometers, a depth equivalent to a pressure of approximately 10 kilobars under the continent, how do we account for the much greater depth to the discontinuity under mountain ranges and the much shallower depth to the discontinuity under the oceans? The answer lies in the fact that the change takes place at a different pressure for a different temperature (see Fig. 2). As near as can be told from the computations and from the experimental data, the slope of this phase change is approximately the same as the Earth's pressure-temperature gradient, as indicated in Figure 2.[1] Consequently, if it is assumed that the Earth's temperature increases a little more rapidly per foot of depth under mountain ranges than under continents generally, the transition will take place at a vastly greater depth (Depth C in Fig. 2). If it is assumed that the Earth's temperature increases with depth a little more slowly under the oceans than under the mountains and continents, the transition is at shallow depths (Depth A in Fig. 2). Thus, the single transition explains the varying depths to the M discontinuity under the oceans, mountain ranges, and continents.

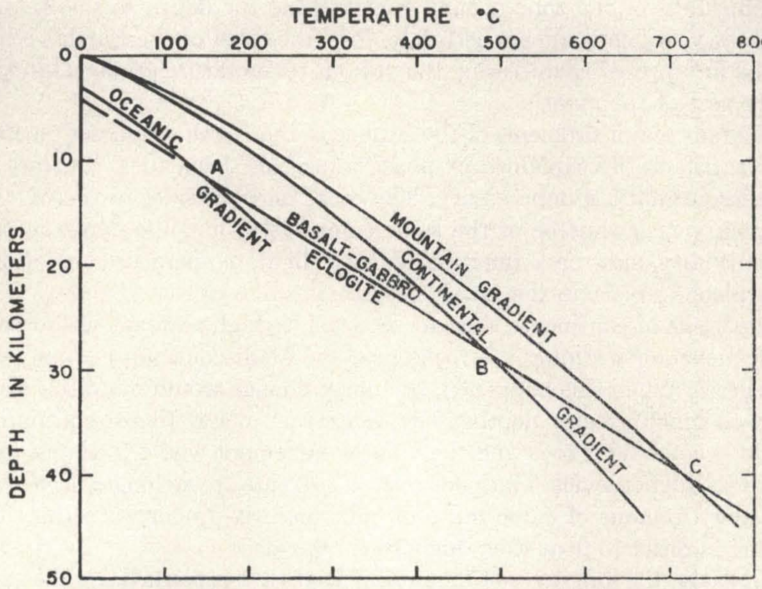

FIG. 2. Postulated temperature gradients under mountain ranges, continental areas, and oceanic regions.

We assume that there are variations in temperature from continents to ocean basins to mountain ranges, and, consequently, we would expect variations in heat flow. However, the necessary variations in heat flow to account for these different depths of intersection are exceedingly small, well within the range of observations and are certainly not the threefold variations in heat flow that we would expect if the continents and mountain ranges were thick zones of radioactive-rich sial and the ocean was underlain by radioactive-poor sima.

It is interesting to note in Figure 2 that, within the assumptions used

[1] The pressure-temperature gradients of Figure 2 are approximately the same as those computed on the assumption that mean heat flow is approximately 1.2 $\times$ 10^{-6} cal/cm/sec and that half the heat is radiogenic heat, generated in the upper 40 kilometers of crust. The remaining half is from below.

in drawing this graph, the Earth's pressure-temperature gradient is almost the same under the oceans as is the slope of the phase change. The intersection here is assumed to be at low pressures and temperatures (Point A in Fig. 2). Because the temperature is very low, reaction rate of the phase change might be expected to be very slow and the response of the discontinuity position under the oceans might be extremely sluggish to small changes in temperature and pressure. Thus, we may not always have thermodynamic equilibrium under the oceans.

Early in this discussion it was noted that the relief of the Earth's crust is a direct function of the thickness of the zone of light rock. If the thickness of the zone of light rock reflects the depth to the M discontinuity, which it almost certainly does, the relief of the Earth's crust can be interpreted as mirroring the various temperature gradients in the upper part of the mantle.

The four major problems of the surface of the Earth, discussed earlier, seem satisfactorily explained by phase transition. A chemical contrast at the discontinuity is unnecessary. The rocks on both sides of the M discontinuity may thus be of the same composition and the depth to the discontinuity may be a function of very slight temperature variations from place to place in the Earth's crust.

The uplift of continents, once at sea level, to high plateaus would be a consequence of warming the rocks near the M discontinuity a few tens of degrees. When this happened, the phase change would migrate downward to much greater depths. The dense rock below the discontinuity would become light rock and the volume increment would float the continents to higher levels. Thus, convection currents are no longer needed to transport millions of cubic miles of light material underneath the continents in order to float them higher into the air.

Similarly, the long lives of mountain ranges are explained. As the tops of mountains are eroded away, pressure at the discontinuity deep below the mountains decreases. Dense rock at the discontinuity would be converted to light rock, so light roots underneath the mountains would be recreated to keep them floated to high elevations.

The downsinking of sediments in troughs is also explained by the phase transition. If sediments from a mountain range were rapidly removed and deposited in troughs, the first effect of loading would be to increase the pressure at the base of the trough with very little change in the temperature. Consequently, the discontinuity would migrate toward the surface. The trough would sink, not only because of the added load of rock at the surface, but because light rock would be converted into dense rock at the discontinuity below the trough with a consequent decrement in volume of material below. Thus, the short-time effect of rapid sedimentation is one of sinking. A most interesting long-time effect appears. The added new sediments filling the trough are of low thermoconductivity and possibly richer in radioactive material than the surrounding rock. Consequently, given sufficient time, the temperature would slowly rise at the bottom of the trough, and, although the discontinuity would first migrate surfaceward under response to loading, it would ultimately migrate downward under response to the rise in temperature owing to the blanket of poorly conducting sediments rich in radioactive elements deposited in the trough. Thus, troughs might sink for considerable time and then be uplifted to form mountain ranges as the roots of the trough deepen with warming of the base.

This implies that mountains are generated largely because of vertical motion and not lateral thrust. A good deal of the faulting and folding of rocks in mountain ranges is assumed to be the result of load. By this thesis, the major folds and faults associated with mountain chains are gravitational in origin, though concomitant lateral thrust of other origin is not excluded.

The problem of the relatively uniform heat flow to the surface of the Earth is readily explained by the phase transition concept. The earlier crustal models assumed continents were made up of silica-rich and radioactive element-rich rocks. Thus, continents should, but do not, show heat flows several times that of oceanic areas. If the bulk composition of continental rocks were not vastly different from the bulk composition of oceanic rocks, we would expect relatively uniform heat flow from place to place in the Earth's crust. This is indeed what we do find. The precision, however, of measuring heat flow is not sufficiently great to exclude the possibility that minor variations in temperature do exist from place to place in the Earth's crust. In fact, it is necessary to appeal to these minor variations to account for the existence of ocean basins, mountain ranges, and continents on the basis of a phase change as discussed here.

If we assume the M discontinuity to be a phase change, many questions are answered, but other questions are also raised. The phase change cannot be a simple solid-solid phase change inasmuch as the major minerals involved are of variable composition. Consequently, the change must take place over a considerable depth interval and should not be a sharp change taking place at a fixed depth. The data of seismology bear on this problem. They permit the interpretation that the discontinuity may take place, instead of at a given depth, over an interval of as much as 10 kilometers under the continents (Frank Press, oral communication). This is within the requirements of the change. However, more difficult problems emerge when oceanic areas are considered. The discontinuity under the oceans is very shallow and apparently takes place over a very narrow depth interval. In fact, the pressure interval seems much too narrow for it to represent the gabbro-eclogite change. However, further experimental work needs to be done to measure precisely the required pressure interval and more refined seismic work will be necessary before we know exactly the distribution of seismic velocities below both the oceans and the continents.

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REFERENCES

1. Adams, L. H., A note on the stability of jadeite, *American Journal of Science, 251*, 299–308 (1953).
2. Birch, F., Flow of heat in the Front Range, Colorado, *Bulletin, Geological Society* of America, *61*, 567–630 (1950).
3. Brigdman, P. W., The physics of high pressure, London (G. Bell and Sons, Ltd.), 1952.
4. Bullard, E. C., Heat flow through the floor of the eastern North Pacific Ocean, *Nature, 170*, 202–203 (1952).
5. Bundy, F. P., Hall, H. T., Strong, H. M., and Wentorf, R. H., Man-made diamonds, *Nature, 176*, 51–55
6. Daly, R. A., Igneous rocks and the depth of the Earth, New York and London (McGraw Hill Book Co.), 1933.
7. Fermor. L. L., The relationship of isostasy, earthquakes, and volcanicity to the Earth's infra-plutonic shell, *Geological Magazine, 51*, 65–67 (1914).
8. Gilluly, James, Waters, A. C., and Woodford, A. O., Principles of Geology, San Francisco (W. H. Freeman & Co.), 1952.
9. Goldschmit, V. M., Uber die massenverteilung im erdinneren, verglichen mit der struktur gewisser meteoriten, *Naturwissenshaften, 10*, 918–920 (1922).
10. Holmes, A., Some problems of physical geology in the Earth's thermal history, *Geological Magazine, 64*, 263–278 (1927).
11. Hubbert, M. K., and Willis, D. G., Mechanics of hydraulic fracturing, *AIME Petroleum Transactions, 210*, 153–168 (1957).
12. Kelley, K. K., Todd, S. S., Orr, R. L., King, E. G., and Bonnickson, K. R., Thermodynamic properties of sodium-aluminum and potassium-aluminum silicates, *U. S. Bureau of Mines Report of Investigations 4955*, (1953).
13. MacDonald, G. J. F., A critical review of geologically important thermochemical data, Doctoral dissertation, Harvard University (1954).
14. MacDonald, G. J. F., Chondrites and the chemical composition of the Earth, *Research in Geochemistry*, New York (P. H. Ableson, J. Wiley), 1959.
15. Nettleton, L. L., Fluid Mechanics of salt domes in Gulf Coast oil fields, *Bulletin, American Association of Petroleum Geologists, 18*, 1175–1204 (1934).
16. Revelle, R., and Maxwell, A. E., Heat flow through the floor of the eastern North Pacific Ocean, *Nature*, 170, 199–202 (1952).
17. Robertson, E. C., Birch, F., and MacDonald, G. J. F., Experimental determination of jadeite stability relations to 25,000 bars, *American Journal of Science, 255*, 115–137 (1957).
18. Yoder, H. S., Jr., The jadeite problem, Part II, *American Journal of Science, 248*, 225–248, 312–334 (1950).