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History of Ocean Basins

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ABSTRACT

For purposes of discussion certain simplifying assumptions are made as to initial conditions on the Earth soon after its formation. It is postulated that it had little in the way of an atmosphere or oceans and that the constituents for these were derived by leakage from the interior of the Earth in the course of geologic time. Heating by short-lived radio nuclides caused partial melting and a single-cell convective overturn within the Earth which segregated an iron core, produced the primordial continents, and gave the Earth its bilateral asymmetry.

Mid-ocean ridges have high heat flow, and many of them have median rifts and show lower seismic velocities than do the common oceanic areas. They are interpreted as representing the rising limbs of mantle-convection cells. The topographic elevation is related to thermal expansion, and the lower seismic velocities both to higher than normal temperatures and microfracturing. Convective flow comes right through to the surface, and the oceanic crust is formed by hydration of mantle material starting at a level 5 km below the sea floor. The water to produce serpentine of the oceanic crust comes from the mantle at a rate consistent with a gradual evolution of ocean water over 4 aeons.

Ocean ridges are ephemeral features as are the convection cells that produce them. An ancient trans-Pacific ridge from the Marianas Islands to Chile started to disappear 100 million years ago. Its trace is now evident only in a belt of atolls and guyots which have subsided 1–2 km. No indications of older generations of oceanic ridges are found. This, coupled with the small thickness of sediments on the ocean floor and comparatively small number of volcanic seamounts, suggests an age for all the ocean floor of not more than several times 10^8 years.

The Mid-Atlantic Ridge is truly median because each side of the convecting cell is moving away from the crest at the same velocity, *ca.* 1 cm/yr. A more acceptable mechanism is derived for continental drift whereby continents ride passively on convecting mantle instead of having to plow through oceanic crust.

Finally, the depth of the M discontinuity under continents is related to the depth of the oceans. Early in the Earth's history, when it is assumed there was much less sea water, the continental plates must have been much thinner.

INTRODUCTION

The birth of the oceans is a matter of conjecture, the subsequent history is obscure, and the present structure is just beginning to be understood. Fascinating speculation on these subjects has been plentiful, but not much of it predating the last decade holds water. Little of Umbgrove's (1947) brilliant summary remains pertinent when confronted by the relatively small but crucial amount of factual information collected in the intervening years. Like Umbgrove, I shall consider this paper an essay in geopoetry. In order not to travel any further into the realm of fantasy than is absolutely necessary I shall hold as closely as possible to a uniformitarian approach; even so, at least one great catastrophe will be required early in the Earth's history.

PREMISES ON INITIAL CONDITIONS

Assuming that the ages obtained from radioactive disintegrations in samples of meteorites approximate the age of the solar system, then the age of the Earth is close to 4.5 aeons.[1] The Earth, it is further assumed, was formed by accumulation of particles (of here unspecified character) which initially had solar composition. If this is true, then before condensation to a solid planet the Earth lost, during a great evaporation, a hundred times as much matter as it now contains. Most of this loss was hydrogen. An unknown but much smaller amount of heavier elements was lost to space as well. The deficiency of the atmosphere in the inert gases points clearly to their loss. Urey (1957) suggests loss of nitrogen, carbon, and water, and perhaps a considerable proportion of original silicate material. He also points out that the lack of concentration of certain very volatile substances at the Earth's surface indicates that it never had a high surface temperature. This low temperature more or less precluded escape of large amounts of material after the Earth condensed and suggests that the loss occurred when the material forming the Earth was very much more dispersed so that the escape velocity from its outer portion was comparatively low. The condensation was rapid, and some light elements and volatile compounds were trapped within the accumulated solid material of the primordial Earth. I will assume for convenience and without too much justification that at this stage the Earth had no oceans and perhaps very little atmosphere. It is postulated that volatile constituents trapped within its interior have during the past and are today leaking to the surface, and that by such means the present oceans and atmosphere have evolved.

THE GREAT CATASTROPHE

Immediately after formation of the solid Earth, it may have contained within it many short-lived radioactive elements; how many and how much depends on the time interval between nuclear genesis and condensation. The bricketted particles from which it was made might be expected to have a low thermal conductivity at least near its surface as suggested by Kuiper (1954). The temperature rose, lowering the strength and perhaps starting partial fusion. The stage was thus set for the *great catastrophe* which it is assumed happened forthwith. A single-cell (toroidal) convective overturn took place (Fig. 1) (Vening Meinesz, 1952), resulting in the formation of a nickel-iron core, and at the same time the low-melting silicates were extruded over the rising limbs of the current to form the primordial single continent (Fig. 1). The single-cell overturn also converted gravitational energy into thermal energy (Urey, 1953). It is postulated that this heat and a probably much larger amount of heat resulting from the energy involved in the accumulation of the Earth were not sufficient to produce a molten Earth. The great quantitative uncertainties in this assumption can be gauged from MacDonald's analysis (1959).

[1] Aeon = 10^9 years (H. C. Urey).

The proposed single-cell overturn brought about the bilateral asymmetry of the Earth, now possibly much modified but still evident in its land and water hemispheres. After this event, which segregated the core from the mantle, single-cell convection was no longer possible in the Earth as a whole (Chandrasekhar, 1953).

The critical question now facing us is what percentage of the continental crustal material and of the water of the oceans reached the surface in the *great catastrophe*. On the basis that continental material is still coming to the surface of the Earth from the mantle at the rate of 1 km^3/year*, accepting Sapper's (1927, p. 424) figure on the contribution of volcanoes over the past 4 centuries, and assuming uniformitarianism, this means 4×10^9 km^3 in 4 aeons or approximately 50 per cent of the continents. So we shall assume that the other half was extruded during the catastrophe. The percentage of water is much harder to estimate. Rapid convective overturn might be much less efficient in freeing the water as compared to the low-melting silicates. The water might be expected to be present as a monomolecular film on grain surfaces. The low-melting silicate droplets could coagulate into sizable masses as a result of strong shearing during the overturn. On the other hand, shearing that would break down solid crystals to smaller size might increase their surface areas and actually inhibit freeing of water films. The best guess that I can make is that up to one-third of the oceans appeared on the surface at this time.

It may be noted that a molten Earth hypothesis would tend toward the initial formation of a thin continental or sialic layer uniformly over the Earth with a very thin uniform world-encircling water layer above it. Later it would require breaking up of this continental layer to form the observed bilateral asymmetry. With the present set of postulates this seems to be a superfluous step. Bilateral asymmetry was attained at the start, and it would be impossible ever to attain it once a core had formed, unless George H. Darwin's hypothesis that the moon came out of the Earth were accepted.

We have now set the stage to proceed with the subject at hand. Dozens of assumptions and hypotheses have been introduced in the paragraphs above to establish a framework for consideration of the problem. I have attempted to chose reasonably among a myriad of possible alternatives, but no competent reader with an ounce of imagination is likely to be willing to accept all of the choices made. Unless some such set of confining assumptions is made, however, speculation spreads out into limitless variations, and the resulting geopoetry has neither rhyme nor reason.

TOPOGRAPHY AND CRUSTAL COLUMNS

If the water were removed from the Earth, two distinct topographic levels would be apparent: (1) the deep-sea floor about 5 km below sea level, and (2) the continental surface a few hundred meters above sea level. In other words, the continents stand up abruptly as plateaus or mesas above the general level of the sea floor. Seismic evidence shows that the so-called crustal thickness—depth to

* This figure includes felsic volcanic material probably derived from partial melting within the continental crust but does not include magmas that formed intrusions which did not reach the surface.

the M discontinuity—is 6 km under oceans and 34 km under continents on the average. Gravity data prove that these two types of crustal columns have the same mass—the pressure at some arbitrary level beneath them, such as 40 km, would be the same. They are in hydrostatic equilibrium. It is evident that one cannot consider the gross features of ocean basins independent of the continental plateaus; the two are truly complementary.

Whereas 29 per cent of the Earth's surface is land, it would be more appropriate here to include the continental shelves and the slopes to the 1000-m isobath with the continents, leaving the remainder as oceanic. This results in 40 per cent continental and 60 per cent oceanic crust. In 1955 I discussed the nature of the two crustal columns, which is here modified slightly to adjust the layer thicknesses to the more recent seismic work at sea (Raitt, 1956; Ewing and Ewing 1959) (Fig. 2). A drastic change, however, has been made in layer 3 of the oceanic column, substituting partially serpentinized peridotite for the basalt of the main crustal layer under the oceans as proposed elsewhere (Hess, 1959a). Let us look briefly into the facts that seemed to necessitate this change.

That the mantle material is peridotitic is a fairly common assumption (Harris and Rowell, 1960; Ross, Foster, and Myers, 1954; Hess, 1955). In looking at the now-numerous seismic profiles at sea the uniformity in thickness of layer 3 is striking. More than 80 per cent of the profiles show it to be 4.7 ± 0.7 km thick.

Considering the probable error in the seismic data to be about $\pm$ 0.5 km, the uniformity may be even greater than the figures indicate. It is inconceivable

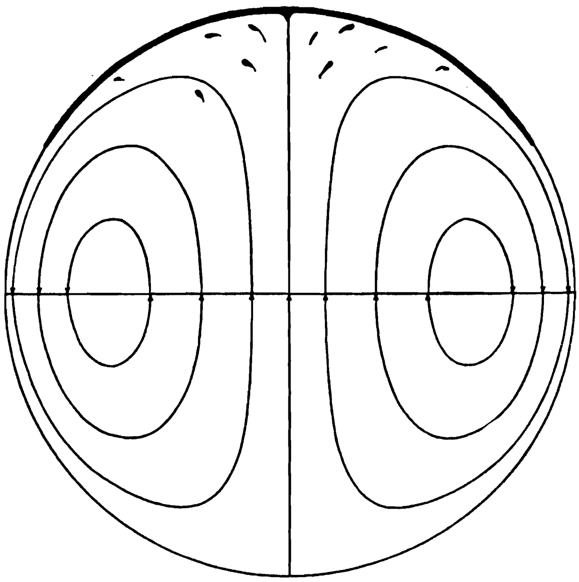

Figure 1. Single-cell (toroidal) convective overturn of Earth's interior. After Vening Meinesz. Continental material extruded over rising limb but would divide and move to descending limb if convection continued beyond a half cycle

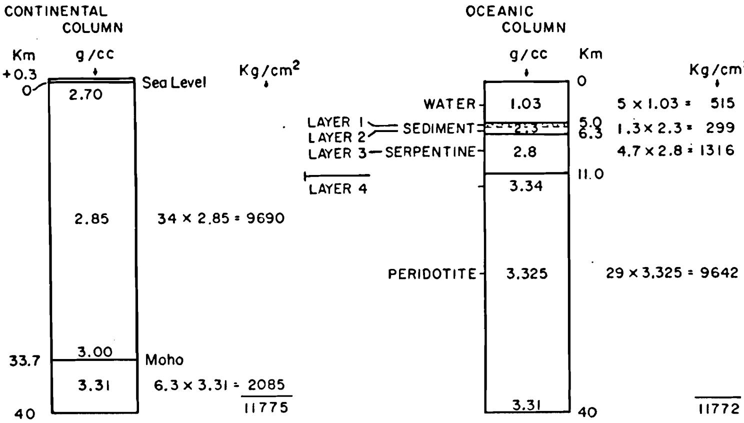

Figure 2. Balance of oceanic and continental crustal columns

that basalt flows poured out on the ocean floor could be so uniform in thickness. Rather, one would expect them to be thick near the fissures or vents from which they were erupted and thin or absent at great distance from the vents. The only likely manner in which a layer of uniform thickness could be formed would be if its bottom represented a present or past isotherm, at which temperature and pressure a reaction occurred. Two such reactions can be suggested: (1) the basalt to eclogite inversion (Sumner, 1954; Kennedy, 1959), and (2) the hydration of olivine to serpentine at about 500°C (Hess, 1954). The common occurrence of peridotitic inclusions in oceanic basaltic volcanic rocks (Ross, Foster, and Myers, 1954) and absence of eclogite inclusions lead the writer to accept postulate (2). Furthermore, the dredging of serpentinized peridotites from fault scarps in the oceans (Shand, 1949)[2], where the displacement on the faults may have been sufficient to expose layer 3, adds credence to this supposition. This choice of postulates is made here and will control much of the subsequent reasoning. The seismic velocity of layer 3 is highly variable; it ranges from 6.0 to 6.9 km/sec and averages near 6.7 km/sec, which would represent peridotite 70 per cent serpentinized (Fig. 3).

MID-OCEAN RIDGES

The Mid-Ocean Ridges are the largest topographic features on the surface of the Earth. Menard (1958) has shown that their crests closely correspond to median lines in the oceans and suggests (1959) that they may be ephemeral features. Bullard, Maxwell, and Revelle (1956) and Von Herzen (1959) show that they have unusually high heat flow along their crests. Heezen (1960) has demonstrated that a median graben exists along the crests of the Atlantic, Arctic, and Indian Ocean ridges and that shallow-depth earthquake foci are concentrated under the graben. This leads him to postulate extension of the crust at right angles to the trend of the ridges. Hess (1959b) also emphasizes the ephemeral

[2] J. B. Hersey reports dredging serpentinized peridotite from the northern slope of the Puerto Rico Trench (Personal communication, 1961)

character of the ridges and points to a trans-Pacific ridge that has almost disappeared since middle Cretaceous time, leaving a belt of atolls and guyots that has subsided 1–2 km. Its width is 3000 km and its length about 14,000 km (Fig. 4). The present active mid-ocean ridges have an average width of 1300 km, crest height of about 2½ km, and total length of perhaps 25,000 km.

The most significant information on the structural and petrologic character of the ridges comes from refraction seismic information of Ewing and Ewing (1959) (Fig. 5) on the Mid-Atlantic Ridge, and Raitt's (1956) refraction profiles on the East Pacific Rise. The sediment cover on the Mid-Atlantic Ridge appears to be thin and perhaps restricted to material ponded in depressions of the topog-

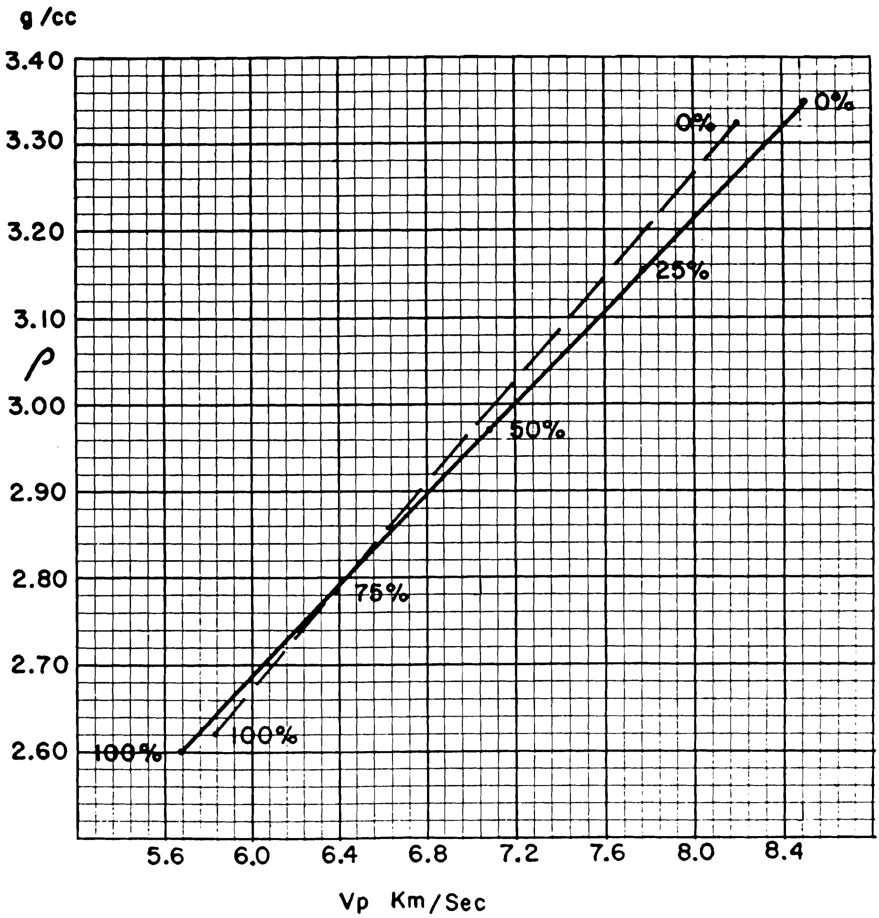

Figure 3. Relationship between seismic velocity, density, and per cent serpentinization. Solid curve for room temperature and pressure. Dashed curve estimated for T and P at 15 km depth. Curves based on measurements in laboratory by J. Green at the California Research Laboratory, La Habra, with variable temperatures up to 200° C and pressures up to 1 kilobar. The 100 per cent serpentinized sample measured by F. Birch at Harvard at pressures from 0 to 10 kilobars at room temperature (Hess, 1959a).

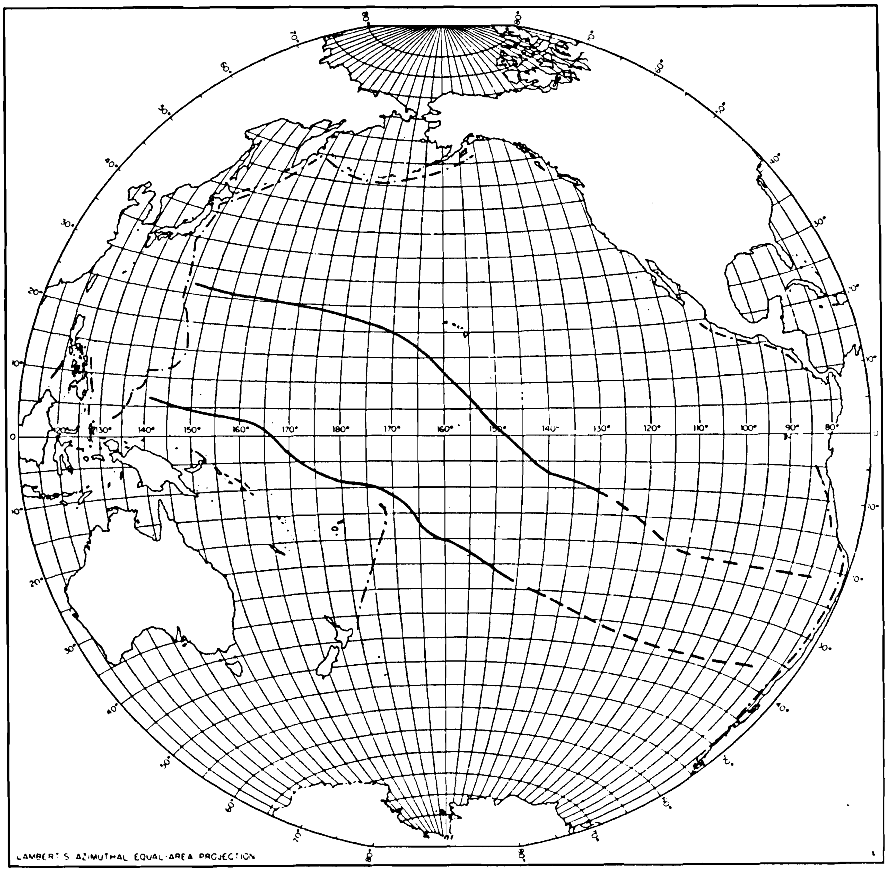

Figure 4. Former location of a Mid-Pacific Mesozoic ridge

raphy. On the ridge crest, layer 3 has a seismic velocity of from 4 to 5.5 km/sec instead of the normal 6 to 6.9 km/sec. The M discontinuity is not found or is represented by a transition from layer 3 to velocities near 7.4 km/sec. Normal velocities and layer thicknesses, however, appear on the flanks of ridges.

Earlier I (1955, 1959b) attributed the lower velocities (*ca.* 7.4 km/sec) in what should be mantle material to serpentinization, caused by olivine reacting with water released from below. The elevation of the ridge itself was thought to result from the change in density (olivine 3.3 g/cc to serpentine 2.6 g/cc). A 2-km rise of the ridge would require 8 km of complete serpentinization below, but a velocity of 7.4 km/sec is equivalent to only 40 per cent of the rock serpentinized. This serpentinization would have to extend to 20-km depth to produce the required elevation of the ridge. This reaction, however, cannot take place at a temperature much above 500° C, which, considering the heat flow, probably exists at the bottom of layer 3, about 5 km below the sea floor, and cannot reasonably be 20 km deep. Layer 3 is thought to be peridotite 70 per cent serpentinized. It would appear that the highest elevation that the 500° C isotherm can reach is approxi-

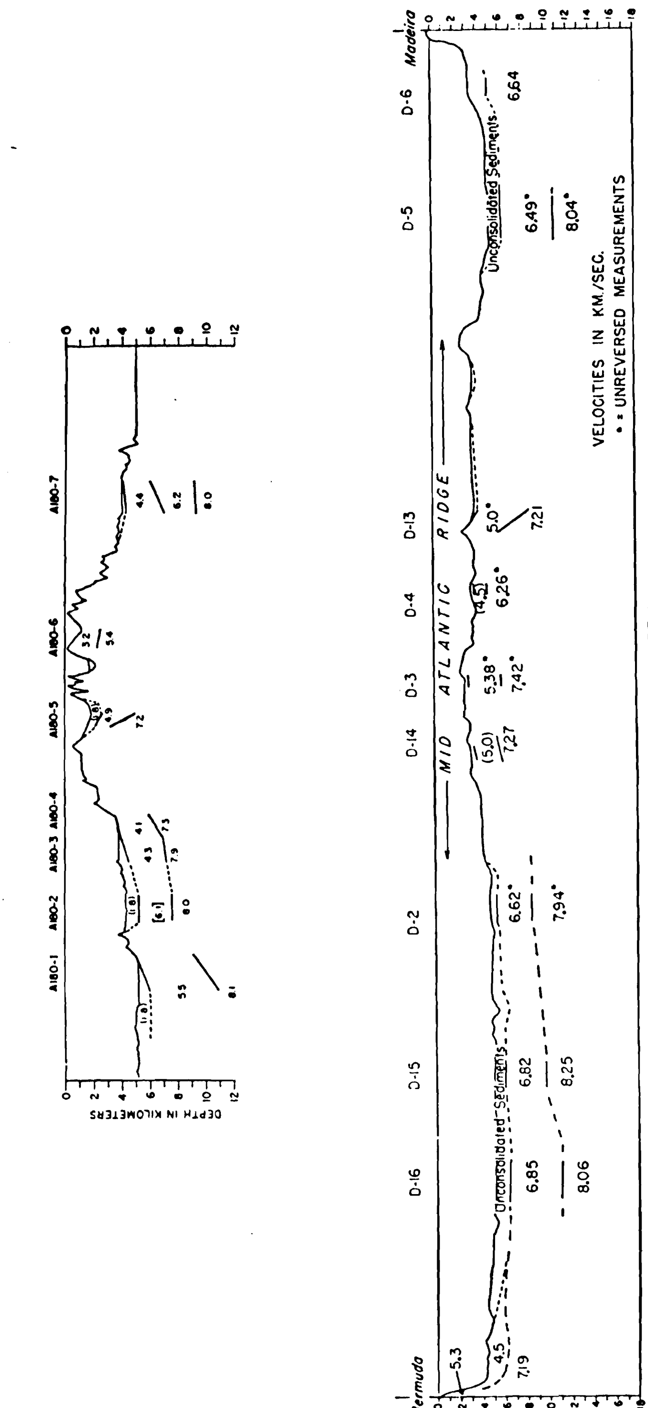

Figure 5. Seismic profiles on the Mid-Atlantic Ridge, by Ewing and Ewing (1959)

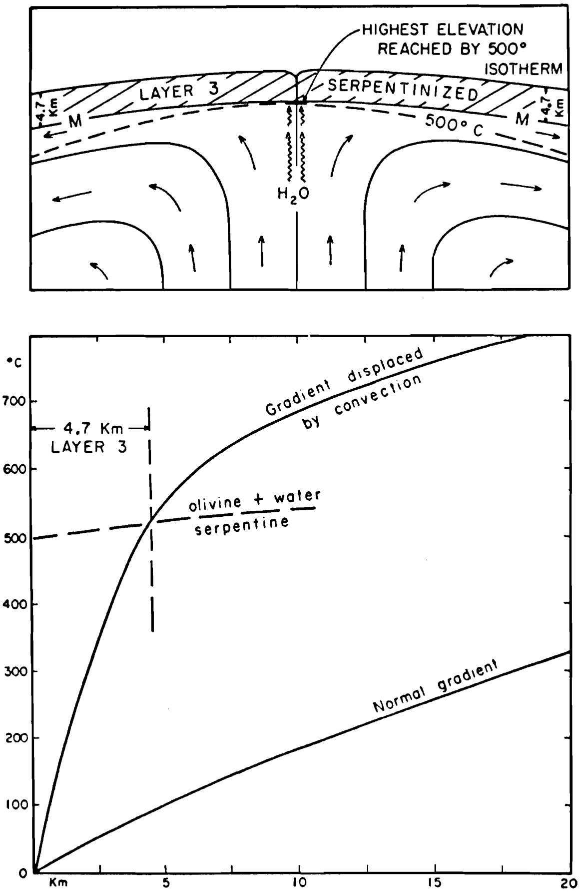

Figure 6. Diagram to portray highest elevation that 500° C isotherm can reach over the rising limb of a mantle convection cell, and expulsion of water from mantle which produces serpentinization above the 500° C isotherm

mately 5 km below the sea floor, and this supplies the reason for uniform thickness of layer 3 (Fig. 6).

CONVECTION CURRENTS IN THE MANTLE AND MID-OCEAN RIDGES

Long ago Holmes suggested convection currents in the mantle to account for deformation of the Earth's crust (Vening Meinesz, 1952; Griggs, 1939; 1954; Verhoogen, 1954; and many others). Nevertheless, mantle convection is considered a radical hypothesis not widely accepted by geologists and geophysicists. If it were accepted, a rather reasonable story could be constructed to describe the evolution of ocean basins and the waters within them. Whole realms of previously unrelated facts fall into a regular pattern, which suggests that close approach to satisfactory theory is being attained.

As mentioned earlier a single-cell convective overturn of the material within the Earth could have produced its bilateral asymmetry, segregating the iron core and primordial continents in the process. Since this event only multicell convection in the mantle has been possible. Vening Meinesz (1959) analyzed the spherical harmonics of the Earth's topography up to the thirty-first order. The peak shown in the values from the third to fifth harmonic would correlate very nicely with mantle-size convection currents; cells would have the approximate diameter of 3000 to 6000 km in cross section (the other horizontal dimension might be 10,000–20,000 km, giving them a banana-like shape).

The lower-order spherical harmonics of the topography show quite unexpected regularities. This means that the topography of a size smaller than continents and ocean basins has a greater regularity in distribution than previously recognized.

Paleomagnetic data presented by Runcorn (1959), Irving (1959), and others strongly suggest that the continents have moved by large amounts in geologically comparatively recent times. One may quibble over the details, but the general picture on paleomagnetism is sufficiently compelling that it is much more reasonable to accept it than to disregard it. The reasoning is that the Earth has always had a dipole magnetic field and that the magnetic poles have always been close to the axis of the Earth's rotation, which necessarily must remain fixed in space. Remanent magnetism of old rocks shows that position of the magnetic poles has changed in a rather regular manner with time, but this migration of the poles as measured in Europe, North America, Australia, India, etc., has not been the same for each of these land masses. This strongly indicates independent movement in direction and amount of large portions of the Earth's surface with respect to the rotational axis. This could be most easily accomplished by a convecting mantle system which involves actual movement of the Earth's surface passively riding on the upper part of the convecting cell. In this case at any given time continents over one cell would not move in the same direction as continents on another cell. The rate of motion suggested by paleomagnetic measurements lies between a fraction of a cm/yr to as much as 10 cm/yr. If one were to accept the old evidence, which was the strongest argument for continental drift, namely the separation of South America from Africa since the end of the Paleozoic, and apply uniformitarianism, a rate of 1 cm/yr results. This rate will be accepted in subsequent discussion. Heezen (1960) mentions a fracture zone crossing Iceland on the extension of the Mid-Atlantic rift zone which has been widening at a rate of 3.5 m/1000 yrs/km of width.

The unexpected regularities in the spherical harmonics of the Earth's topography might be attributed to a dynamic situation in the present Earth whereby the continents move to positions dictated by a fairly regular system of convection cells in the mantle. Menard's theorem that mid-ocean ridge crests correspond to median lines now takes on new meaning. The mid-ocean ridges could represent the traces of the rising limbs of convection cells, while the circum-Pacific belt of deformation and volcanism represents descending limbs. The Mid-Atlantic Ridge is median because the continental areas on each side of it have moved away from it at the same rate—1 cm/yr. This is not exactly the same as continental drift. The continents do not plow through oceanic crust impelled by unknown forces; rather they ride passively on mantle material as it comes to the surface at the crest of the ridge and then moves laterally away from it. On this basis the crest of the ridge should have only recent sediments on it, and recent and Tertiary sediments on its flanks; the whole Atlantic Ocean and possibly all of the oceans should have little sediment older than Mesozoic (Fig. 7). Let us look a bit further at the picture with regard to oceanic sediments.

Looking over the reported data on rates of sedimentation in the deep sea, rates somewhere between 2 cm and 5 mm/1000 yrs seem to be indicated. Writers in the last few years have tried hard to accept the lowest possible rate consistent with the data in order to make the thickness jibe with the comparatively thin cover of sediment on the ocean floor indicated by Seismic data. Schott's figures for the Atlantic and Indian oceans as corrected by Kuenen (1946) and further corrected by decreasing the number of years since the Pleistocene from 20,000 years to 11,000 years indicate a rate of 2 cm/1000 yrs. Hamilton's (1960) figures suggest 5 mm/1000 yrs. A rate of 1 cm/1000 yrs would yield 40 km in 4 aeons or 17 km after compaction, using Hamilton's compaction figures. A 5-mm rate would still give 8.5 km compacted thickness instead of 1.3 km as derived from seismic data. This 1 order of magnitude discrepancy had led some to suggest that the water of the oceans may be very young, that oceans came into existence largely since the Paleozoic. This violates uniformitarianism to which the writer is dedicated and also can hardly be reconciled with Rubey's (1951) analysis of the origin of sea water. On the system here suggested any sediment upon the sea floor ultimately gets incorporated in the continents. New mantle material with no sedimentary cover on it rises and moves outward from the ridge. The cover of young sediments it acquires in the course of time will move to the axis of a downward-moving limb of a convection current, be metamorphosed, and probably eventually be welded onto a continent.

Assuming a rate of 1 cm/1000 yrs one might ask how long, on the average, the present sea floor has been exposed to deposition if the present thickness of sediment is 1.3 km. The upper 0.2 km would not yet have been compacted and would represent 20 million years of deposition. The remaining 1.1 km now compacted would represent 240 million years of accumulation or in total an average age of the sea floor of 260 million years. Note that a clear distinction must be made between the age of the ocean floor and the age of the water in the oceans.

In order to explain the discrepancy between present rate of sedimentation in the deep sea and the relatively small thickness of sediment on the floor of the oceans, many have suggested that Pleistocene glaciation has greatly increased the rate of sedimentation. The writer is skeptical of this interpretation, as was Kuenen in his analysis (1946)[3]. Another discrepancy of the same type, the small number of volcanoes on the sea floor, also indicates the apparent youth of the floor. Menard estimates there are in all 10,000 volcanic seamounts in the oceans. If this represented 4 aeons of volcanism, and volcanoes appeared at a uniform

[3] The Mohole test drilling off Guadalupe Island in 1961 suggests a rate of sedimentation in the Miocene of 1 cm/1000 yrs or a little more.

rate, this would mean only one new volcano on the sea floor per 400,000 years. One new volcano in 10,000 years or less would seem like a better figure. This would suggest an average age of the floor of the ocean of perhaps 100 to 200 million years. It would account also for the fact that nothing older than late Cretaceous has ever been obtained from the deep sea or from oceanic islands.

Still another line of evidence pointing to the same conclusion relates to the ephemeral character of mid-ocean ridges and to the fact that evidence of only one old major ridge still remains on the ocean floor. The crest of this one began to subside about 100 million years ago. The question may be asked: Where are the Paleozoic and Precambrian mid-ocean ridges, or did the development of such features begin rather recently in the Earth's history?

Egyed (1957) introduced the concept of a great expansion in size of the Earth to account for apparent facts of continental drift. More recently Heezen (1960) tentatively advanced the same idea to explain paleomagnetic results coupled with an extension hypothesis for mid-ocean ridges. S. W. Carey (1958) developed an expansion hypothesis to account for many of the observed relationships of the Earth's topography and coupled this with an overall theory of the tectonics of the Earth's crust. Both Heezen and Carey require an expansion of the Earth since late Paleozoic time (*ca.* 2×10^8 years) such that the surface area has doubled. Both postulate that this expansion is largely confined to the ocean floor rather than to the continents. This means that the ocean basins have increased in area by more than 6 times and that the continents until the late Paleozoic occupied almost 80 per cent of the Earth's surface. With this greatly expanded ocean floor one could account for the present apparent deficiency of sediments, volcanoes, and old mid-ocean ridges upon it. While this would remove three of my most serious difficulties in dealing with the evolution of ocean basins, I hesitate to accept this easy way out. First of all, it is philosophically rather unsatisfying, in much the same way as were the older hypotheses of continental drift, in that there is no apparent mechanism within the Earth to cause a sudden (and exponential according to Carey) increase in the radius of the Earth. Second, it requires the addition of an enormous amount of water to the sea in just the right amount to maintain the axiomatic relationship between sea level-land surface and depth to the M discontinuity under continents, which is discussed later.

MESOZOIC MID-PACIFIC RIDGE

In the area between Hawaii, the Marshall Islands, and the Marianas scores of guyots were found during World War II. It was supposed that large numbers of them would be found elsewhere in the oceans. This was not the case. The Emperor seamounts running north-northwest from the west end of the Hawaiian chain are guyots, a single linear group of very large ones. An area of small guyots is known in the Gulf of Alaska (Gibson, 1960). There are a limited number in the Atlantic Ocean north of Bermuda on a line between Cape Cod and the Azores, and a few east of the Mid-Atlantic Ridge; other than these only rare isolated occurrences have been reported.

Excluding the areas of erratic uplift and depression represented by the island arcs, lines can be drawn in the mid-Pacific bounding the area of abundant guyots and atolls (Fig. 4), marking a broad band of subsidence 3000 km wide crossing the Pacific from the Marianas to Chile. The eastern end is poorly charted and complicated by the younger East Pacific Rise. The western end terminates with striking abruptness against the eastern margin of the island-arc structures. Not a single guyot is found in the Philippine Sea west of the Marianas trench and its extensions, although to the east they are abundant right up to the trenches.

Fossils are available to date the beginning of the subsidence, but only near the axis of the old ridge. Hamilton (1956) found middle Cretaceous shallow-water fossils on guyots of the Mid-Pacific mountains, and Ladd and Schlanger (1960) reported Eocene sediments above basalt at the bottom of the Eniwetok bore hole. It should also be noted that atolls of the Caroline, Marshall, Gilbert, and Ellice islands predominate on the southern side of the old ridge, whereas guyots greatly predominate on the northern side. Hess (1946) had difficulty in explaining why the guyots of the mid-Pacific mountain area did not become atolls as they subsided. He postulated a Precambrian age for their upper flat surfaces, moving the time back to an era before lime-secreting organisms appeared in the oceans. This became untenable after Hamilton found shallow-water Cretaceous fossils on them. Looking at the same problem today and considering that the North Pole in early Mesozoic time, as determined from paleomagnetic data from North America and Europe, was situated in southeastern Siberia, it seems likely that the Mid-Pacific mountain area was too far north for reef growth when it was subsiding. The boundary between reef growth and nonreef growth in late Mesozoic time is perhaps represented by the northern margins of the Marshall and Caroline islands, now a little north of 10° N, then perhaps 35° N. Paleomagnetic measurements from Mesozoic rocks, if they could be found within or close to this area, are needed to substantiate such a hypothesis.

The old Mesozoic band of subsidence is more than twice as wide as the topographic rise of present-day oceanic ridges. This has interesting implications regarding evolution of ridges which are worth considering here. Originally I attributed the rise of ridges to release of water above the upward-moving limb of a mantle convection cell and serpentinization of olivine when the water crossed the 500-degree C isotherm. As mentioned above, this hypothesis is no longer tenable because the high heat flow requires that the 500-degree C isotherm be at very shallow depth. The topographic rise of the ridge must be attributed to the fact that a rising column of a mantle convection cell is warmed and hence less dense than normal or descending columns. The geometry of a mantle convection cell (Fig. 8) fits rather nicely a 1300-km width assuming that the above effect causes the rise.

Looking now at the old Mesozoic Mid-Pacific Ridge with the above situation in mind, volcanoes truncated on the ridge crest move away from the ridge axis at a rate of 1 cm/yr. Eventually they move down the ridge flank and become guyots or atolls rising from the deep-sea floor. Those 1000 km from the axis, however, were truncated 100 million years before those now near the center of the

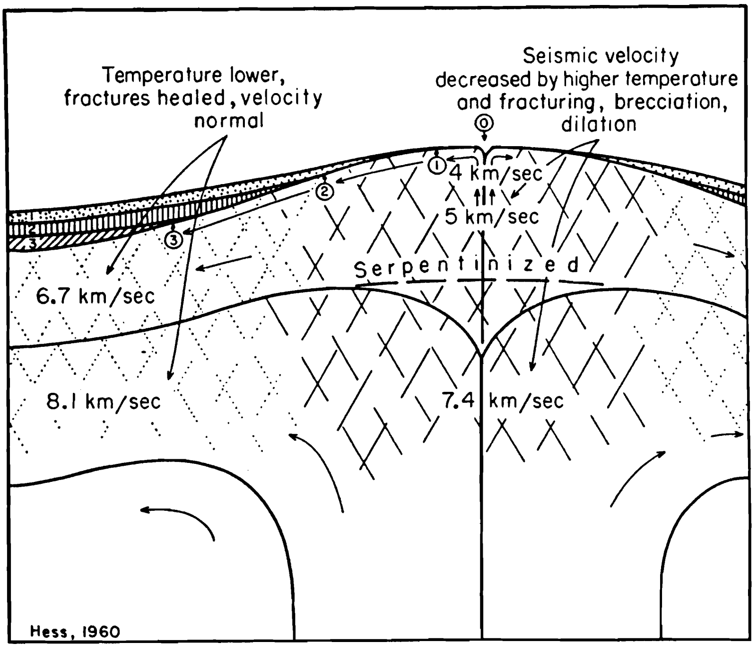

Figure 7. Diagram to represent (1) apparent progressive overlap of ocean sediments on a mid-ocean ridge which would actually be the effect of the mantle moving laterally away from ridge crest, and (2) the postulated fracturing where convective flow changes direction from vertical to horizontal. Fracturing and higher temperature could account for the lower seismic velocities on ridge crests, and cooling and healing of the fractures with time, the return to normal velocities on the flanks.

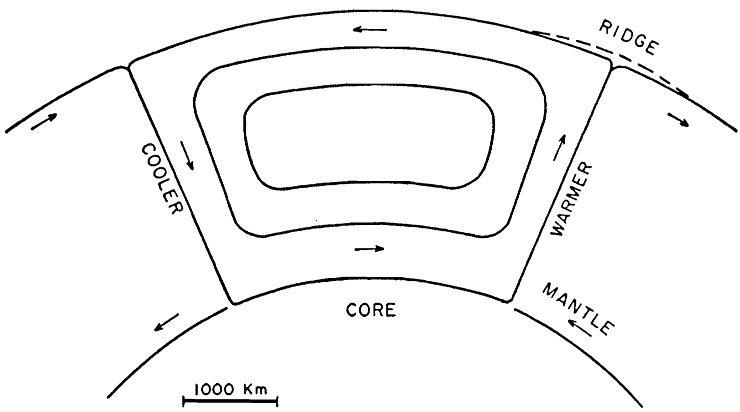

Figure 8. Possible geometry of a mantle convection cell

old ridge (Fig. 9). On this basis it would be very interesting to examine the fauna on guyots near the northern margin of the old ridge or to drill atolls near the southern margin to see if the truncated surfaces or bases have a Triassic or even Permian age. At any rate the greater width of the old ridge and its belt of sub-

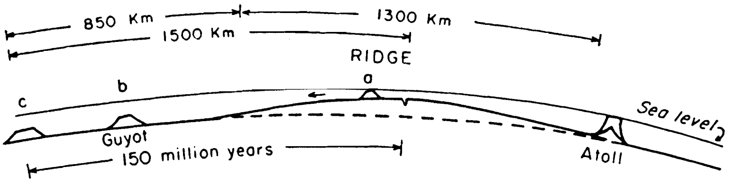

Figure 9. Diagram to show progressive migration of volcanic peaks, guyots, and atolls, from a ridge crest to the flanks, suggesting that the wave-cut surfaces of guyots or the bases of atolls may become older laterally away from the crest

sidence compared to present topographic ridges could be explained by the above reasoning.

Turning to a reconsideration of the Mid-Atlantic Ridge it appears that layer 3, with a thin and probably discontinuous cover of sediments, forms the sea floor. The dredging of serpentinized peridotite from fault scarps at three places on the ridge (Shand, 1949) points to such a conclusion. The abnormally low seismic velocity, if this is layer 3, might be attributed to intense fracturing and dilation where the convective flow changes direction from vertical to horizontal. The underlying material, which ordinarily would have a velocity of 8 km/sec or more, has a velocity approximately 7.4 km/sec partly for the same reason but also because of its abnormally high temperature (Fig. 7). The interface between layer 3 and the 7.4 km/sec material below is thus the M discontinuity. The increase in velocity of layer 3 to about 6.7 km/sec and of the sub-Moho material to 8 km/sec as one proceeds away from the ridge crest may be attributed to cooling and healing of the fractures by slight recrystallization or by deposition from solution in an interval of tens of millions of years.

DEVELOPMENT OF THE OCEANIC CRUST (LAYER 3) AND THE EVOLUTION OF SEA WATER

Assuming that layer 3 is serpentinized peridotite, that the water necessary to serpentinize it is derived by degassing of the rising column of a mantle convection cell, and that its uniform thickness (4.7 ± 0.5 km) is controlled by the highest level the 500° C isotherm can reach under these conditions, we have a set of reasonable hypotheses which can account for the observed facts (Fig. 6).

The present active ridge system in the oceans is about 25,000 km long. If the mantle is convecting with a velocity of 1 cm/yr a vertical layer 1 cm thick of layer 3 on each side of the ridge axis is being formed each year. The material formed is 70 per cent serpentinized, based on an average seismic velocity of 6.7 km/sec, and this serpentine contains 25 per cent water by volume. If we multiply these various quantities, the volume of water leaving the mantle each year can be estimated at 0.4 km^3. Had this process operated at this rate for 4 aeons, 1.6×10^9 km^3 of water would have been extracted from the mantle, and this less 0.3×10^9 km^3 of water now in layer 3 equals 1.3×10^9 km^3 or approximately the present volume of water in the oceans.[4]

[4] The estimate of how much of the present Mid-Ocean Ridge system is active is uncertain. That fraction of the sytem with a median rift was used in this estimate. The whole system is approximately 75,000 km long. The velocity of 1 cm/yr is also uncertain. If it were 0.35 cm/yr, as Heezen mentions for widening of the Iceland rift, this coupled with a 75,000 km ength of the ridge system would give the required amount of water for the sea in 4 aeons.

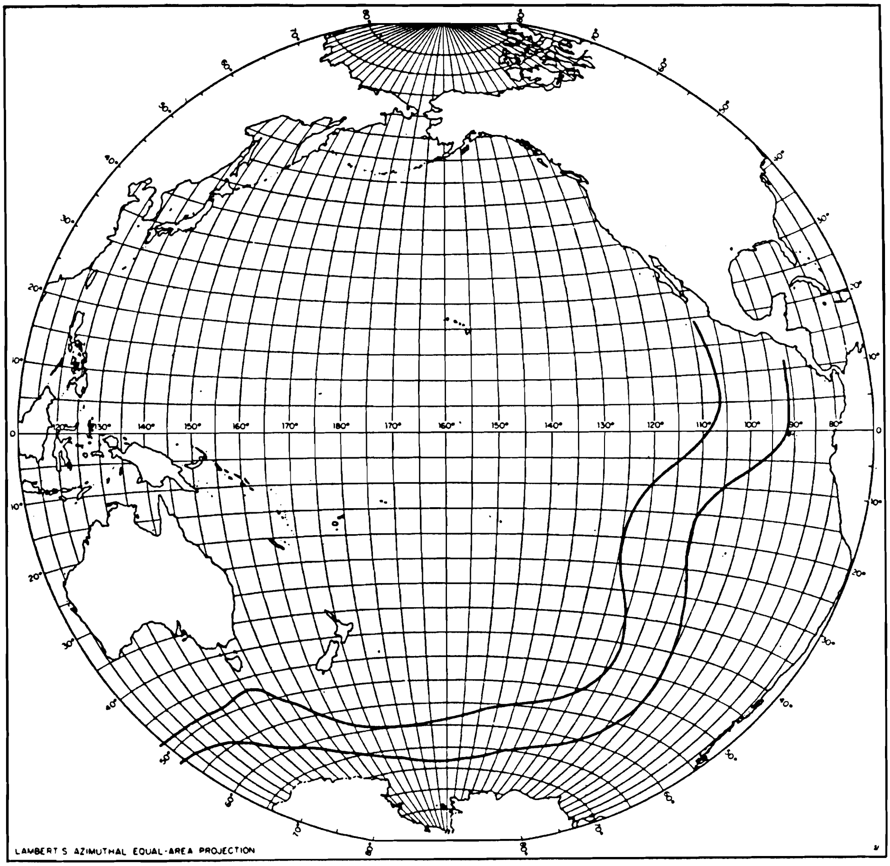

Figure 10. Approximate outline of East Pacific Rise, which possibly represents an oceanic ridge so young that it has not yet developed a median rift zone and pre-Rise sediments still cap most of its crest

The production of layer 3 by a convective system and serpentinization must be reversed over the downward limbs of convection cells. That is, as layer 3 is depressed into the downward limb it will deserpentinize at 500° C and release its water upward to the sea. Thus the rate of entry of juvenile water into the ocean will equal the rate of acquisition of water from the mantle to form layer 3 over the rising limbs of convection cells.

It is not at present possible to check against the record the assumption that the process outlined went far back to the beginning of geologic history at a uniform rate. If Africa and South America moved away from each other at the rate of 2 cm a year they would have been adjacent to each other about 200 million years ago. Presumably this was the beginning of the convection cells under the present ridge. The assumption of a rate of movement for convection of 1 cm/yr was based on the above situation because the geologic record suggests splitting apart near the end of the Paleozoic Era. The convection cells under the Mesozoic Mid-

Pacific Ridge ceased to function about 100 million ago inasmuch as the crest is known to have begun to subside at this time. It must have taken at least 150 million years at 1 cm/yr for the flanks of the ridge to spread to a width of 3000 km, and possibly the convection cells were in operation here for several times this long. The East Pacific Rise crosses the Mesozoic ridge at right angles and presumably did not come into existence until recent times, but certainly less than 100 million years ago. No evidence of older ridges is found in the oceans, suggesting that convection is effective in wiping the slate clean every 200 or 300 million years. This long and devious route leads to the conclusion that the present shapes and floors of ocean basins are comparatively young features.

RELATIONSHIP OF THICKNESS OF CONTINENTS TO DEPTH OF THE SEA

In Figure 2 the balance of oceanic and continental columns is portrayed. The layer thicknesses are derived from seismic profiles, and the densities are extrapolated from seismic velocities and petrologic deduction (Hess, 1955). Gravity measurements during the past half century have shown that the concept of isostasy is valid—in other words that a balance does exist. The oceanic column is simpler than the continental column and less subject to conjecture with regard to layer thicknesses or densities. The main uncertainty in the continental column is its mean density. Given the thickness of the crust, this value was derived by assuming that the pressure at 40 km below sea level under the continents equalled that for the same depth under the oceans, or 11,775 kg/cm^2. The mean density of the continental crust then becomes 2.85 g/cc. The latitude that one has for changing the numerical values in either of the two columns is small. The error in the pressure assumed for 40 km depth is probably less than 1 per cent.

The upper surface of the continent is adjusting to equilibrium with sea level by erosion. But as material is removed from its upper surface, ultimately to be deposited along its margins in the sea, the continent rises isostatically. If undisturbed by tectonic forces or thermal changes it will approach equilibrium at a rate estimated by Gilluly (1954) as 3.3×10^7 yrs half life. It is thus evident that, if the oceans were half as deep, the continents would be eroded to come to equilibrium with the new sea level, they would rise isostatically, and a new and much shallower depth to the M discontinuity under continents would gradually be established. A thinner continent but one of greater lateral extent would be formed inasmuch as volume would not be changed in this hypothetical procedure. The relationship between depth of the oceans, sea level, and the depth to the M discontinuity under continents is an axiomatic one and is a potent tool in reasoning about the past history of the Earth's surface and crust.

The oft-repeated statement that amount of water in the sea could not have changed appreciably since the beginning of the Paleozoic Era (or even much further back) because the sea has repeatedly lapped over and retreated from almost all continental areas during this time interval is invalid because the axiomatic relationship stated in the last paragraph would automatically require that this be so regardless of the amount of water in the sea.

One can compute the pressure at 40 km depth for an ocean with 1, 2, 3, or 4

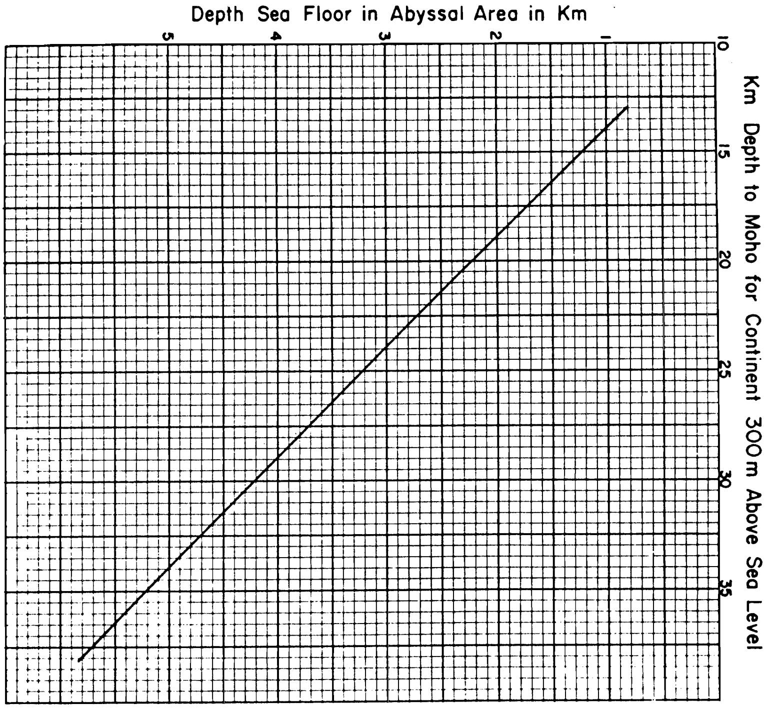

Figure 11. Graph portraying depth to the M discontinuity under continents *vs.* depth of abyssal areas in oceans, computed from balance of crustal columns

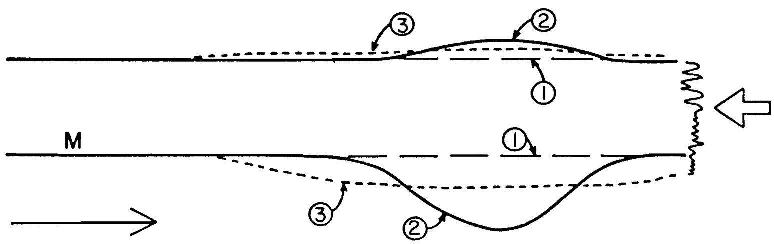

Figure 12. Diagram to illustrate thickening of a continent by deformation. Initially a mountain system and much larger root are formed, but both spread laterally with time and isostatic adjustment

km of water and equate this to continental columns for the same pressure at 40 km, distributing the amount of crustal material (density 2.85 g/cc) and mantle material (density 3.31 g/cc) in such proportion that balance is established. This computation is shown graphically in Figure 11. Assuming, as has been done in this chapter, that the oceans have grown gradually with time, one must suppose that the continents were much thinner in the early Precambrian. This could possibly be recognizable in the difference of tectonic pattern in very old terrains as compared to present continental structure.

If there is gradual increase of water in the sea one may ask why continents are not eventually flooded and why are there not continental-type areas now a kilometer or more below sea level. No extensive areas of this sort are found. Part of the answer might lie in the generation of new continental material at a rate equivalent to eruption of new water. An increase of depth of the sea by 1 km allows thickening of the continents by about 5 times this amount, which would be several times in excess of the estimated 1 km^3 per year extraction of magma from the mantle. Even if this were an underestimate there is no reason why continents might not extend laterally rather than grow thicker. The answer seems to be that there is more than enough energy in the crustal regime of the Earth to thicken the continents to an extent that they are maintained somewhat above the equilibrium level (Fig. 12). A continent will ride on convecting mantle until it reaches the downward-plunging limb of the cell. Because of its much lower density it cannot be forced down, so that its leading edge is strongly deformed and thickened when this occurs. It might override the downward-flowing mantle current for a short distance, but thickening would be the result as before.

The Atlantic, Indian, and Arctic oceans are surrounded by the trailing edges of continents moving away from them, whereas the Pacific Ocean is faced by the leading edges of continents moving toward the island arcs and representing downward-flowing limbs of mantle convection cells or, as in the the case of the eastern Pacific margin, they have plunged into and in part overridden the zone of strong deformation over the downward-flowing limbs.

RECAPITULATION

The following assumptions were made, and the following conclusions reached:

(1) The mantle is convecting at a rate of 1 cm/yr.

(2) The convecting cells have rising limbs under the mid-ocean ridges.

(3) The convecting cells account for the observed high heat flow and topographic rise.

(4) Mantle material comes to the surface on the crest of these ridges.

(5) The oceanic crust is serpentinized peridotite, hydrated by release of water from the mantle over the rising limb of a current. In other words it is hydrated mantle material.

(6) The uniform thickness of the oceanic crust results from the maximum height that the 500° C isotherm can reach under the mid-ocean ridge.

(7) Seismic velocities under the crests of ridges are 10–20 per cent lower than normal for the various layers including the mantle, but become normal again on ridge flanks. This is attributed to higher temperature and intense fracturing with cooling and healing of the fractures away from the crest.

(8) Mid-ocean ridges are ephemeral features having a life of 200 to 300 million years (the life of the convecting cell).

(9) The Mid-Pacific Mesozoic Ridge is the only trace of a ridge of the last cycle of convecting cells.

(10) The whole ocean is virtually swept clean (replaced by new mantle material) every 300 to 400 million years.

(11) This accounts for the relatively thin veneer of sediments on the ocean

floor, the relatively small number of volcanic seamounts, and the present absence of evidence of rocks older than Cretaceous in the oceans.

(12) The oceanic column is in isostatic equilibrium with the continental column. The upper surface of continents approaches equilibrium with sea level by erosion. It is thus axiomatic that the thickness of continents is dependent on the depth of the oceans.

(13) Rising limbs coming up under continental areas move the fragmented parts away from one another at a uniform rate so a truly median ridge forms as in the Atlantic Ocean.

(14) The continents are carried passively on the mantle with convection and do not plow through oceanic crust.

(15) Their leading edges are strongly deformed when they impinge upon the downward moving limbs of convecting mantle.

(16) The oceanic crust, buckling down into the descending limb, is heated and loses its water to the ocean.

(17) The cover of oceanic sediments and the volcanic seamounts also ride down into the jaw crusher of the descending limb, are metamorphosed, and eventually probably are welded onto continents.

(18) The ocean basins are impermanent features, and the continents are permanent although they may be torn apart or welded together and their margins deformed.

(19) The Earth is a dynamic body with its surface constantly changing. The spherical harmonics of its topography show unexpected regularities, a reflection of the regularities of its mantle convection systems and their secondary effects.

In this chapter the writer has attempted to invent an evolution for ocean basins. It is hardly likely that all of the numerous assumptions made are correct. Nevertheless it appears to be a useful framework for testing various and sundry groups of hypotheses relating to the oceans. It is hoped that the framework with necessary patching and repair may eventually form the basis for a new and sounder structure.

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