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Speculations on the Earth's Thermal History

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Abstract: The gross structure of the Earth's interior—mantle and core with their subdivisions—affords evidence of the thermal evolution. The principal event was the formation of a liquid iron core from an initially cool unsorted conglomerate after about 500 m.y. of heating by radioactivity and tidal friction. Core formation was accompanied by conversion of gravitational energy to heat, the deep interior reaching temperatures of 4000°–5000°; this process was completed about 4500 m.y. ago. Fractional melting of the mantle concentrated radioactive and "lithophile" elements in the upper mantle and transition zone, leaving the lower mantle devoid of radioactivity. Formation of stable continental crust became possible after this upward concentration and decay of radioactivity, beginning about 3500 m.y. ago. Further concentration of the radioactive elements in the continental crust has left the subcontinental mantle impoverished by comparison with the suboceanic mantle. Present temperatures are consequently higher in the suboceanic mantle than at the same depths beneath continents, approaching or reaching melting temperatures beneath the oceans while cooling continues beneath continents. The required concentrations of radioactive elements appear to be in reasonable agreement with existing measurements if the primitive undifferentiated Earth resembled the meteorite Orgueil in its radioactive content.

The kindest words regarding these entertainments are those of H. H. Read, quoted by L. R. Wager (1958) in his address at the 1958 meeting of the British Association for the Advancement of Science: ". . . just as things too absurd to be said can yet with perfect propriety be sung, so views too tenuous, unsubstantial and generalized for ordinary scientific papers can yet appear with some measure of dignity in presidential addresses." This is then an appropriate occasion to review some speculations, by no means original, on the large-scale evolution of the Earth. Views on the early history of the Earth and on happenings in the deep interior can hardly fail to be tenuous and generalized, so I think they may qualify under Read's dictum. Nevertheless, we cannot hope to account for the development of the surface film which naturally engages most of our attention without considering the enormously larger interior from which this film was derived and which continues to determine its evolution.

A classical method of approaching the thermal history of the Earth is by way of calculations based on the theory of heat conduction. If one knows (1) the internal temperature at some past time, (2) the distribution of heat sources and sinks in space and time, (3) the coefficient of thermal transport, and (4) the surface temperature, one can determine the temperature, and perhaps more important for comparison with present conditions, the flow of heat to the surface, for all later times. Of these, only the surface temperature is fairly well known. The geological record suggests that average surface temperatures have not strayed widely from the present ones; astrophysical theory suggests only a moderate increase of solar luminosity during the last few billion years, equivalent to an increase of the mean surface temperature of the Earth by some 30°C (Schwarzschild, 1958, p. 206). As for the other required data, a great many different assumptions have been used for calculations, with, naturally enough, a great variety of results. Qualitatively, the conclusions often follow directly from the assumptions; for example, if we postulate heat sources deep in a poorly conducting Earth, we are fairly certain to discover that this region is heating up, and so on. I do not intend to add new calculations of this kind to the many existing examples, which now include a wide range of increasingly realistic and complex assumptions (*see* for example Lubimova, 1958; 1961; Levin and Majeva, 1961; MacDonald, 1959; 1961; 1964a;

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Clark, 1956; 1957; 1961); the best estimates of present temperatures are probably to be obtained from the analysis of various temperature-dependent physical properties, and I shall return to this later. Rather I should like to consider the following questions: To what extent can we narrow the range of assumption by considering the large structural features of the Earth's interior? Can we deduce the trend of thermal history from the present internal arrangements? It is my thesis that the present internal structure, determined by the methods of geophysics and geochemistry, may be interpreted in much the same spirit that we bring to the interpretation of visual geological evidence, where we can frequently detect the general sequence of events despite much obscurity of detail.

The major divisions of the internal structure are mantle and core, whose dimensions and properties are known with remarkable precision (Figs. 1, 2). The core constitutes about one third, the mantle two thirds, of the whole mass. Both are further divided by seismologists: like any proper geological unit, the mantle is subdivided into lower, middle, and upper mantle. Similarly, we distinguish an inner and outer core, with a somewhat complex transition region between. We are so used to this structure that its implications tend to be ignored. A classical geological conception, the chemical difference between mantle and core, has been confirmed in recent years by experiments with explosively generated shock pressures equal to those of the core. The hypothesis of iron core versus silicate mantle depended originally upon

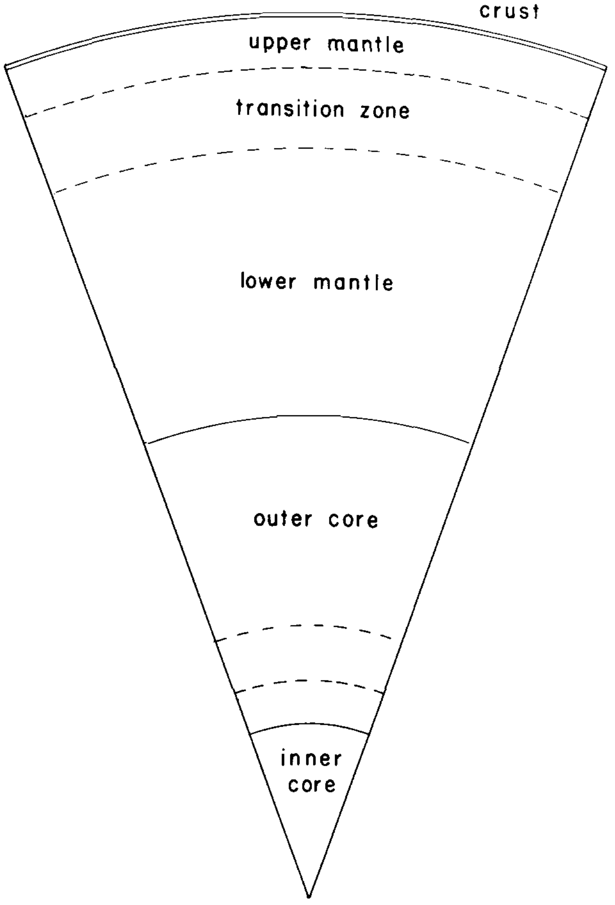

Figure 1. Major divisions of the Earth's interior, true scale; the crust corresponds to a 40-km continental crust.

the recognition that meteorites—irons and stones—furnished samples of an early stage of the chemical history of the inner planets; it became the cornerstone of Goldschmidt's geochemistry. This hypothesis has now, I think, advanced to the status of fact: the most convincing proof can be condensed into a single figure (Fig. 3; *see also* McQueen and others, 1964; Birch, 1964). Here a number related to the seismic velocities is plotted against density for the metals through the transition group; the solid curves are experimental, and the broken curves show the same quantities for the mantle and core. No allowable adjustment of the date permits us to make a satisfactory core of light metals or their oxygen compounds, nor can the mantle be made of heavy metals. Transformation of light compounds to a metallic state may take place in the Earth, but the density of the core demands a metal of the transition group, and only iron is sufficiently abundant. The properties of iron are close to those required and can be adjusted with small amounts of light alloying elements. We have here the most complete demonstration that core and mantle are chemically distinct. This is the most significant single fact concerning the Earth's large-scale evolution.

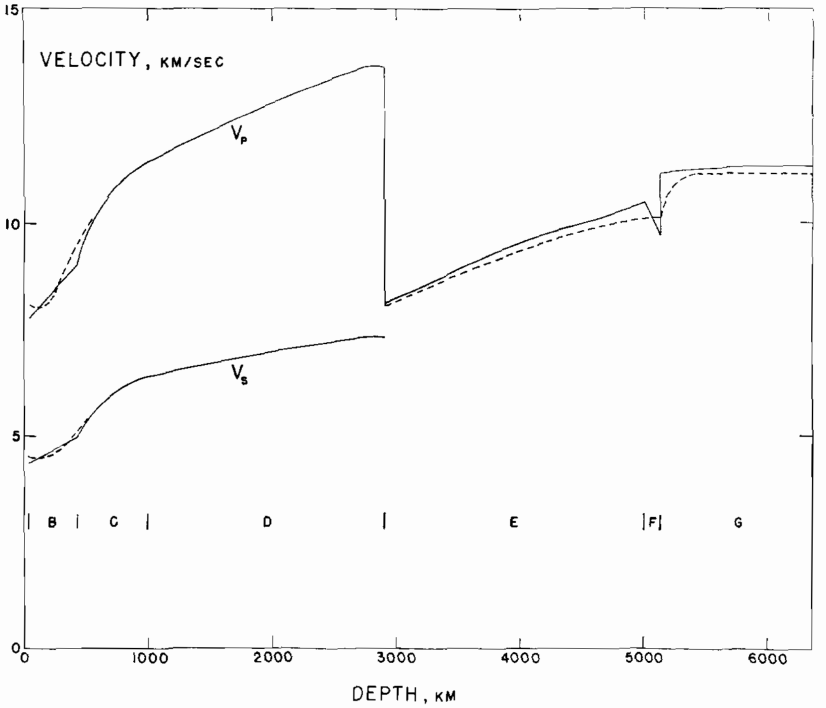

Figure 2. The seismic evidence for the internal structure of the earth: velocities as function of depth, after Jeffreys (1959, solid curves) and Gutenberg (1959, dashed curves). See later references for fine structure of transition from outer to inner core.

With the iron-core hypothesis at least a century old, it is remarkable that the process of core formation has received so little analysis. In recent years, however, it has become an important element in the theories of Urey, Ringwood, Elsasser, and others, and we may look for more adequate attention.

We speak of core *formation*, since a chemical fractionation of this kind is, I think, unacceptable as a primary feature; the primordial ingredients may not have been thoroughly mixed, but a grossly homogeneous beginning seems plausible. I have not seen a very satisfactory treatment of the stage of accretion; the factual basis is slender, the role of assumption too great. The amount of kinetic energy brought by the infalling matter was extremely large; on the other hand, radiation according to T^4 is efficient in dissipating energy and preventing the development of high steady temperatures. Unless accretion was very fast, or unless an appreciable fraction of the radiated energy was reflected back, the temperature of the primitive accumulation was probably nowhere greater than 1000° or so, warm rather than hot. A similar conclusion was reached by Urey (1952; 1957; Safronov, 1959, gives references to earlier work), and by others who have considered this problem.

heating, mainly by radioactivity, and we must now consider the radioactive composition of the primitive Earth. This is one of the major uncertainties for thermal theory. Even the proportions of U, Th, and K, the important long-lived heat-producing elements, are uncertain for the Earth as a whole. Several models have been suggested, which fairly well limit the range of possibilities. Probably the most

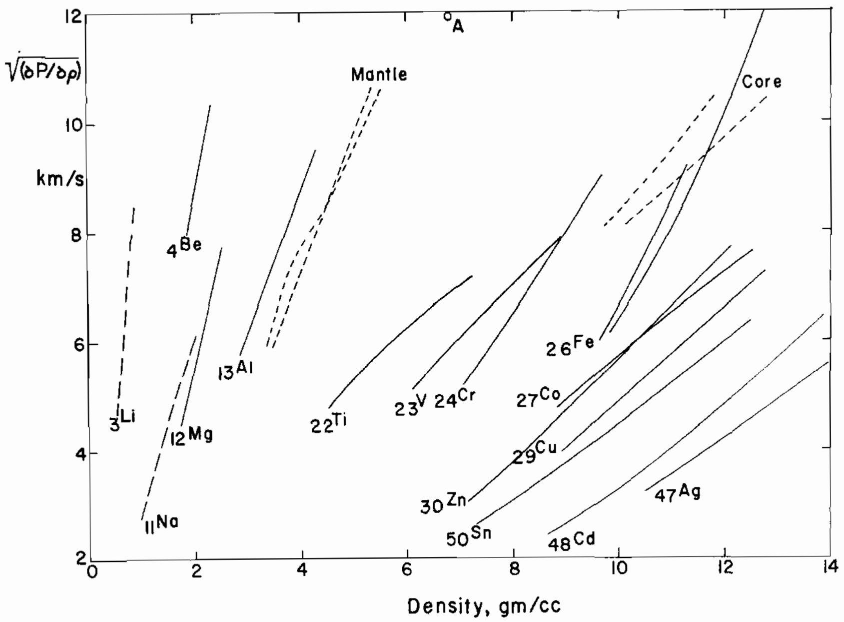

Figure 3. Hydrodynamical velocity, $(\partial P/\partial \rho)^{\frac{1}{2}}$, versus density. The solid curves are shock data for metals; the dashed lines are from static compressions. The dashed curves for mantle and core are obtained from seismic velocities combined with representative density distributions. The circle labeled "A" is for dunite at 2.4 megabars. (For references, *see* Birch, 1963.)

The date of accumulation is uncertain. The most precise early date is the 4550 million years found by Patterson (1956) for the time when certain stony meteorites were enriched in and certain iron meteorites were depleted of uranium and thorium. It is not clear what terrestrial event, if any, corresponds to this date, but the organization of the planets must have been well on its way, since the parent or parents of the meteorites had evolved to a first stage of chemical fractionation. The stage of accretion was thus earlier, by perhaps 500 million years as we shall see, or in round numbers, at 5000 million years.

The next stage after accumulation was one of thoroughly investigated model is based on the radioactivity of the chondritic meteorites. This model has the virtue of providing a good account of the Earth's present rate of heat generation, if we suppose, as most of the calculations bear out, that the rate of heat loss is nearly equal to the rate of heat generation. Until a few years ago, there was no known material of which this could be said. With the neutron-activation method of analysis for uranium and thorium, the minute amounts in chondrites and other meteorites have become measurable—amounts a hundred times smaller than those of average basaltic rocks (Hamaguchi and others, 1957; Bate and others, 1957). Complaints about "black boxes" are sometimes heard among geologists, but in the face of this and many similar feats I feel that we ought rather to rejoice that modern techniques are now fulfilling so many of the dreams of earlier geologists, who complained more reasonably about the limitations of the classical methods.

The average chondrite seems in many ways a suitable sample of the undifferentiated Earth, but for the average chondrite this ratio is 75,000 g/g. If uranium is preferentially removed from mantle to crust, as compared with potassium, then the K/U ratio for mantle rocks should be still higher. There is little reliable evidence as yet concerning mantle rocks, but various geochemical trends seem inconsistent with this conclusion.

Another kind of difficulty has been pointed

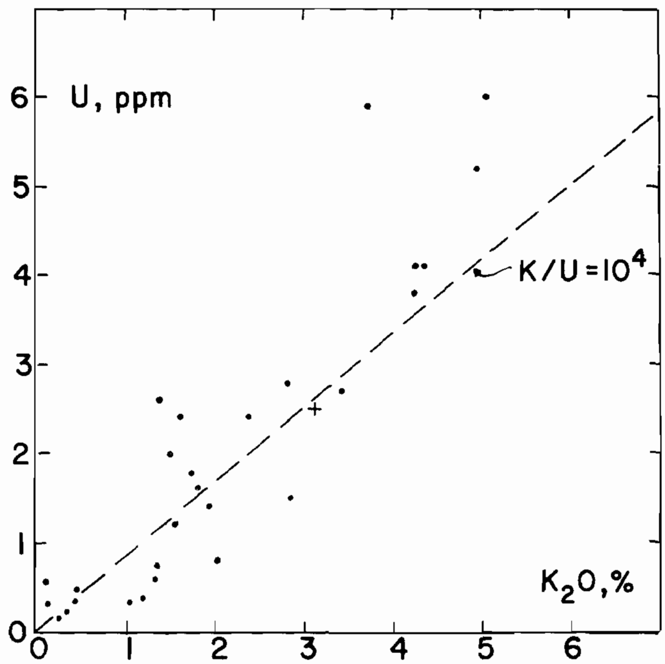

Figure 4. Uranium and potassium in rocks of the batholith of southern California (Larsen and Gottfried, 1961). The dashed line corresponds to the ratio, K/U = 10,000 g/g. The cross marks the average values for the Idaho batholith.

but there are several troublesome implications. Unless we are far wrong about the average composition of the continental crust, the primitive Earth of chondritic composition barely supplies enough uranium and thorium for this crust alone. On the other hand, the crust requires only about one sixth of the total potassium, the rest remaining in the mantle. But in the accessible rocks, potassium and uranium tend to occur together, although with fairly large fluctuations: Figure 4 shows typical data for rocks of the Southern California batholith (Larsen and Gottfried, 1961). A ratio of potassium to uranium (K/U) of about 10,000 g/g is found for many groups of rocks, out by Gast (1960): the strontium isotope ratio, Sr^{86}/Sr^{87}, is higher for chondrites than for basaltic rocks, a fact which excludes the derivation of basalt from a chondritic parent. We must not, of course, confuse these particular meteorites with the primitive Earth; they are samples of an unsuccessful planet, with its own complex and obviously different history. At most, the meteorites provide a kind of fossilized chemistry suggesting early stages of chemical and mineralogical differentiation for the Earth, of which we have found as yet no authentic terrestrial samples.

A different model, based on the thorium-uranium and potassium-uranium ratios of crustal rocks, has been proposed by Wasserburg and others (1964); the adopted ratios are Th/U = 3.7, K/U = 10^4. The uranium content referred to the mass of the mantle required to produce the current heat loss is $3 \cdot 3 \cdot 10^{-8}$. These ratios, if valid for the primitive Earth and for the crustal rocks, should also hold for the mantle.

At least one meteorite comes close to meeting these specifications. The carbonaceous chondrite, Orgeuil, according to Lovering and Morgan (1964), has a K/U ratio close to that of crustal rocks and a uranium concentration of about $3 \cdot 10^{-8}$. The Th-U ratio determined by Lovering and Morgan is anomalously low, and their value for potassium is appreciably lower than that of Edwards (1955; Edwards and Urey, 1955) for another sample of this meteorite, so further verification is probably needed. With the values of Lovering and Morgan, Orgueil can be fitted into a conceivable evolutionary sequence for the crustal rocks and other meteorites (Fig. 5).

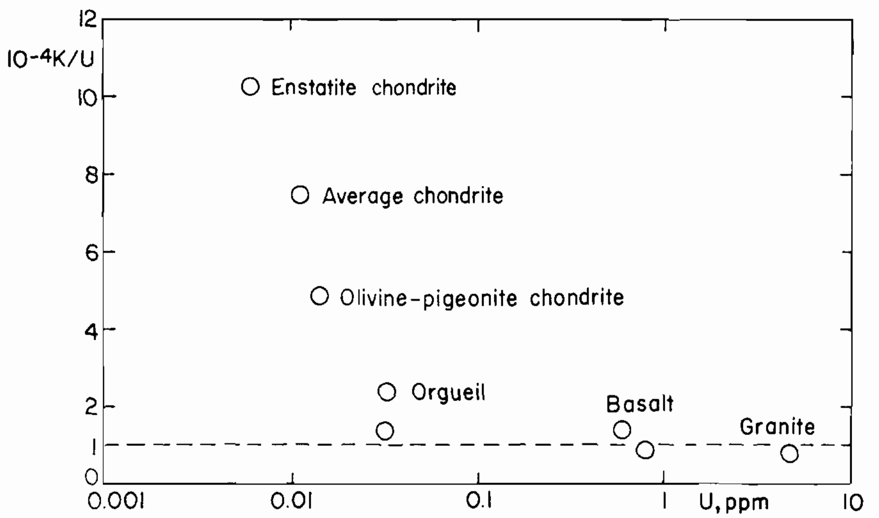

Figure 5. Potassium-uranium ratio versus uranium for several chondrites and rocks (Tilton and Reed, 1963; Lovering and Morgan, 1964; Wasserburg and others, 1964)

Because of the different mixtures of radioactive elements, these models have significantly different rates of heat generation in the past (Fig. 6); the larger fraction of potassium^{40} in the chondritic model accounts for the higher rate of heat generation, relative to the present rate. The absolute values of the present rates are shown in Figure 7 for a few materials; two values are indicated for comparison—the rate of heat loss to the surface of the Earth divided by the masses of mantle and whole Earth, respectively. It seems improbable that the original value deviated widely from the range of 40 to 50 cal/g By, as of the present. It would be virtually impossible to account for the present surface heat flow with a mantle made of peridotite, for example. On the other hand, Orgueil shows one of the highest values found for relatively undifferentiated material.

Although these uncertainties about the ratios of the radioactive elements affect the determination of the rate of heating, the heating of the roughly homogeneous undifferentiated Earth is the stage most satisfactorily treated by thermal calculations. With the chondritic values, the temperatures increase as shown in Figure 8, from a series of calculations by MacDonald (1959; *see also* Lubimova, 1958); here the origin time is taken as 4500 million years ago. With these assumptions, the melting temperature of iron is reached in about 600 million years at a depth of a few hundred kilometers; at this point, a change of regime sets in, and the curves for later times are not realized. The interval of heating required to reach these temperatures would be longer with the Wasserburg mixture, but again shortened if the beginning is put at 5000 million years.

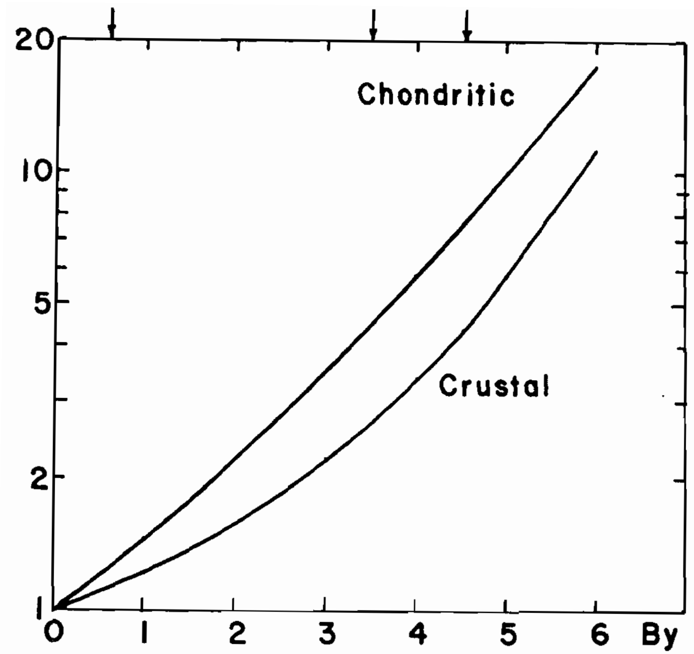

Figure 6. Rates of radioactive heat generation in the past, relative to present rate, for average chondrite (K/U = 75,000 g/g, Th/U = 3.7 g/g) and for crustal rocks (K/U = 10,000 g/g, Th/U = 3.7 g/g)

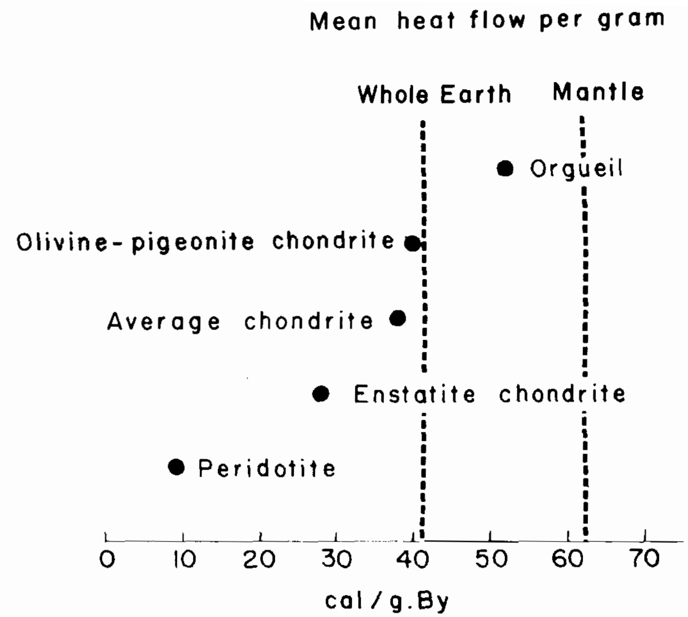

Figure 7. Present rates of radioactive heat generation in several materials, and present mean rate of heat loss of the Earth divided by the mass of the whole Earth and of the mantle, respectively. (References as for Figure 5.)

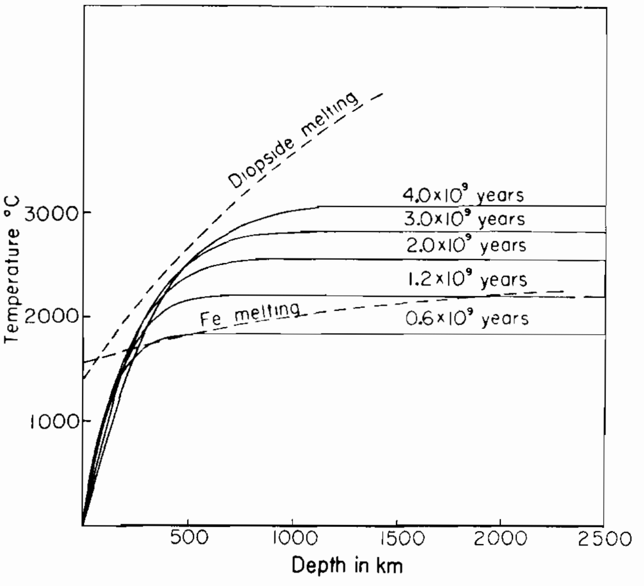

Figure 8. Temperatures in a homogeneous Earth heated by the radioactivity of the average chondrite (MacDonald, 1959, Fig. 4).

Other sources of heat in these early times are probable, but not easily evaluated: short-lived radioactive elements may have made an appreciable contribution, and tidal dissipation must have been important when the Moon was only a few Earth radii away. Current theories seem to favor the formation of the Moon by consolidation of a swarm of small bodies, but neither the date nor the distance away are very definitely established. However, as the history of the Earth-Moon system is traced backward in time, the distance diminishes and tidal dissipation in both terrestrial and lunar tides increases (Ruskol, 1963; MacDonald, 1964b). It is tempting to associate the formation of the Earth's core with this period of strong interaction with the newly formed Moon, or even to find in the process of core formation the possibility of the Moon's having been generated from the Earth itself—an appealing theory which has invariably encountered apparently fatal difficulties. None of this is necessary for core formation; it can be energized by the long-lived radioactive elements alone, but the time required is reduced if supplementary heat sources are available.

The mechanics of separation of the iron has been examined recently by Elsasser (1963). In his theory, a layer of molten iron forms and becomes unstable with the development of a large "drop," which sinks to the center, displacing the lighter silicates (Fig. 9). It is essentially the mechanism of the salt dome or igneous intrusion, on a giant scale and in the reverse direction. It is evidently a highly unsymmetrical process, somewhat reminiscent of the parlor trick of removing the vest without the coat, and it cannot well be followed in

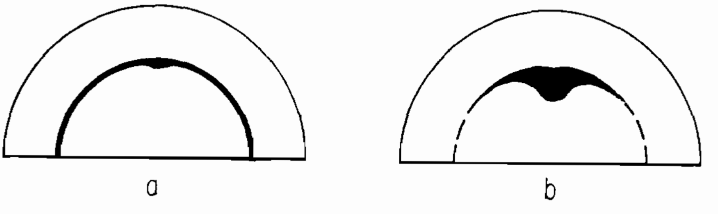

Figure 9. Stages of drop formation from a heavy liquid layer (Elsasser, 1963)

detail. In moving toward a configuration of lower potential energy, gravitational energy is transformed to thermal energy, to the amount of about 600 cal/g as an average value for the whole mass. This is equivalent to an average rise of temperature of some 2000°; for comparison, the heat content of liquid iron at 1600°C and 1 atmosphere is about 350 cal/g. Thus the process was strongly exothermic and self-accelerating; I believe, with Elsasser, that it must have reached completion in a geologically short time.[1] The temperature distribution then probably approximated to the melting curve of iron, possibly with traces of the unsymmetrical descent of the iron. It is this temperature, or something close to it, which became the "initial" temperature for the subsequent thermal evolution. If the time of 4500 million years can be given a definite significance for terrestrial events, it may well correspond to the completion of the core-mantle separation. The date of the original accumulation is then earlier than this by the time needed for heating to the point where the iron began its descent, which I take as roughly another 500 million years.

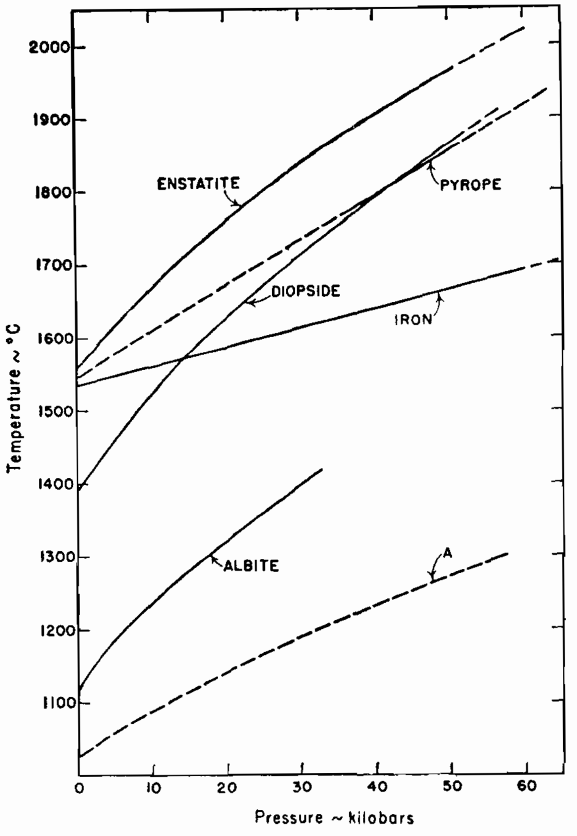

Figure 10. Melting temperatures versus pressure (Boyd, 1964)

With the movement of one third of the whole mass toward the center, the whole Earth was profoundly reorganized. While the iron was unsymmetrically sinking, the lighter portions were unsymmetrically rising, undergoing partial fusion, mixing, and unmixing. The original surface was engulfed and digested, although a thin solid skin must have existed over most of the surface most of the time. The development of thick, stable crustal areas had to await the decay of radioactivity and the

[1] For a different view *see*, for example, Urey, 1951; Runcorn, 1962.

solidification of most of the mantle. Except in the outer parts, the temperature has not changed greatly since this time; thus we must now consider briefly some estimates of present temperatures.

Correlation with temperature-dependent physical properties seems to be the most reliable approach to present temperatures; Verhoogen's survey (1956) still includes most of the possibilities. Tozer (1959) has examined the electrical conductivity of the mantle, finding a temperature of 4500°K for the lower mantle. Seismology contributes the important fact that the outer core is liquid, the mantle solid. With the identification of the core as mainly iron, and of the lower mantle as high-pressure phases of light-element silicates and oxides, it is reassuring to find that the melting curves have the right relationships at high pressures, iron melting at lower temperatures than the more refractory silicates as shown by Figure 10, after Boyd (1964). A melting curve for the lower mantle has been calculated by Clark (1963) and lies well above those of the figure. Estimates of the melting point of iron at the pressure of the core-mantle boundary fall between 4000° and 5000°, in fair agreement with the deductions from electrical conductivity (Birch, 1963, p. 161).

Another kind of information concerning mechanical properties is derived from the damping of free oscillations. Far from responding to shocks after the fashion of a "mudball," sometimes suggested as a mechanical model, the globe rings like a fairly good bell. Free oscillations and long-period surface waves excited by large earthquakes continue for remarkably long times. The mechanical absorption in the lower mantle is much smaller than in the upper mantle. This may be expressed by a number called "Q," a measure of the "quality" of resonant systems. According to Anderson and Archambeau (1964), Q ranges from about 100 in the upper mantle to about 2000 in the lower mantle. The theory of this absorption is far from complete, but it may reasonably be concluded that the lower mantle is farther from its melting temperature than is the upper mantle; this fits well with the high calculated melting temperatures for the lower mantle, and with estimates of temperature.

Calculations of the rate of temperature change needed to produce a "low-velocity" layer have been used by Clark and Ringwood

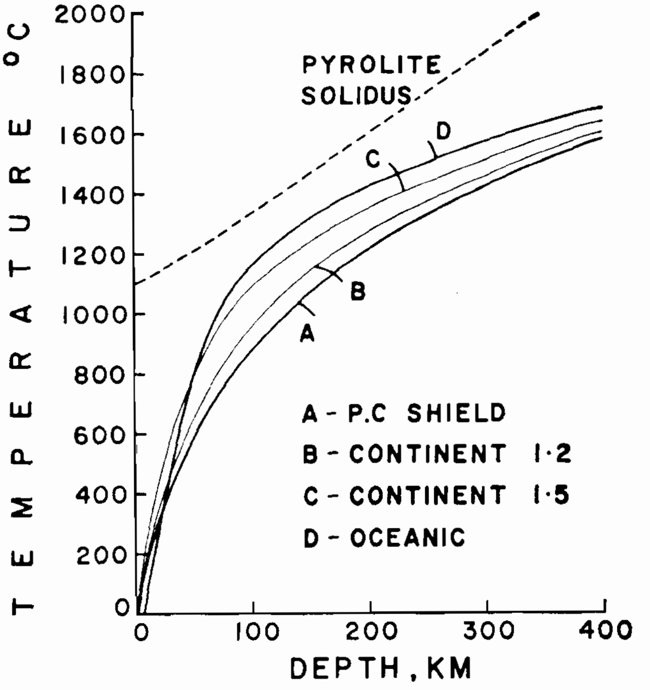

Figure 11. Temperatures in the upper mantle (Clark and Ringwood, 1964)

(1964) along with other geophysical and petrological arguments to fix the temperatures in the upper mantle (Fig. 11). All these methods lead to relatively consistent estimates, and to a fairly reliable picture of the present temperature distribution without reference to past or future evolution. For the direction of change, let us go back to the review of constitution.

The lower mantle consists of close-packed, high-pressure phases, oxygen compounds of magnesium, silicon, and iron, of extremely high melting temperature (Birch, 1952; 1964; Clark, 1963). Most of the Earth has existed at the pressures necessary for the stability of these phases ever since it reached its present size, and thus complete melting has never taken place. During the heating associated with core

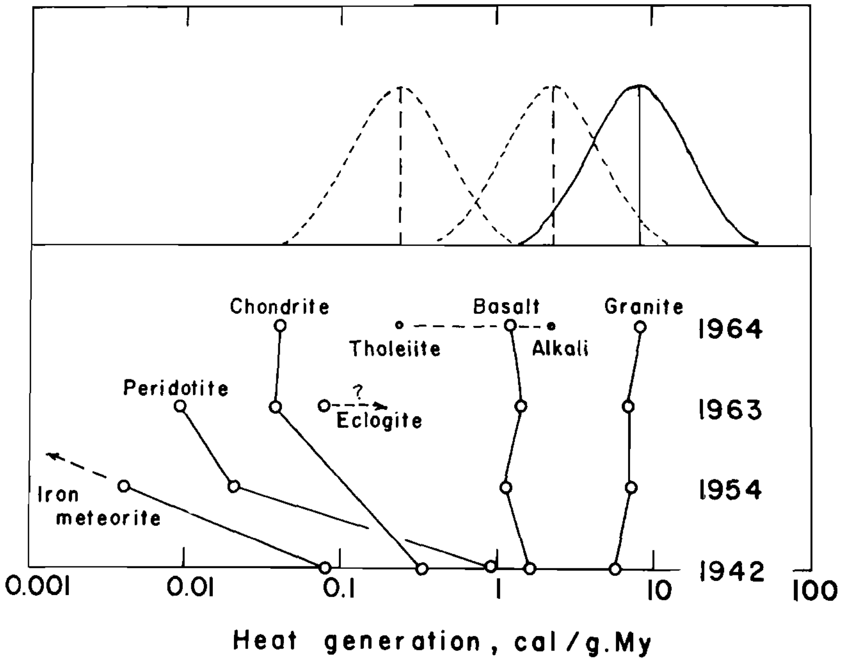

Figure 12. Radioactive heat generation in groups of rocks and meteorites. The dates at the right refer to compilations by the following: Evans and others (1942); Birch (1954); Tilton and Reed (1963); Wasserburg and others (1964). The values for tholeiitic and alkali basalts are estimated from the potassium analyses by Engel and Engel (1964a; 1964b). Hypothetical lognormal distribution functions at top.

A significant detail is provided by the existence of the inner core. This is best interpreted as a solid phase, predominantly iron. It cannot be a primitive feature, but must have solidified after the core had formed. Thus the existence of this solid center means that the core has cooled, if only a little.[2]

[2] The transition from outer to inner core, known only in terms of seismic velocity, becomes increasingly complex (Bolt, 1964; Hai, Nguyens, 1963, thesis, Propagation des ondes longitudinales dans le noyeau terrestre, Univ. Paris; Adams and Randall, 1964), and a multicomponent system appears to be indicated, but a solid "innermost" region mainly of iron is still the most plausible interpretation.

formation, however, the low-melting fraction of the original material melted and accumulated at the upper levels, forming the upper mantle and some fraction of the middle mantle or transition zone. The lower mantle seems to be seismically inert—the deepest earthquakes occurring at a depth of about 700 km, in the transition zone. Particularly important for the thermal history, during the fractionation accompanying core formation, the radioactive elements were, I believe, eliminated from the lower mantle and concentrated in the upper mantle. As this conclusion is not generally adopted by writers on the thermal evolution, let us examine some geochemical evidence.

The accessible rocks show an enormous range of radioactive content; even now we face analytical difficulties with the extremely depleted ultramafic rocks. Average values of heat production for various materials are shown in Figure 12, where I have also suggested frequency distributions for several categories on the assumption of lognormal distributions (Ahrens, 1954; for much new information, the recently published book, *The Natural Radiation Environment*, edited by Adams and Lowder, may be consulted; *see particularly* Chapters 1–5) with standard deviations corresponding to a factor of 2. The values for granites and basalts have not changed much in the last 20 years, but those for ultramafic rocks and meteorites have decreased greatly as more reliable methods have been introduced. Granites have typically about 10 times as much uranium as basalts, several hundred times as much as chondrites, at least a thousand times as much as peridotites; iron meteorites have gone clear off scale (Reed and others, 1958; Bate and others, 1958). Qualitatively, the relationships are what we might expect if granite and basalt, on the one hand, and peridotite on the other, evolved from a common ancestor resembling Orgueil, or, again, if granite and peridotite represent extreme fractions of a basaltic parent. Evidently extreme fractionation of the radioactive elements does take place under terrestrial conditions.

The explanation is familiar to crystal chemists and can be summarized as follows: the radioactive elements, U, Th, and K, exist as ions which are too large to be accepted in the close-packed lattices of the high-melting silicates such as olivines, pyroxenes, or even calcic plagioclase. In the crystallization of a melt, they are concentrated in the last liquid fraction and are finally found in the feldspars, micas, accessory minerals, and intercrystalline films. Potassium becomes a major component in the feldspar of granitic rocks, the lowest-melting rocks with the highest proportion of the radioactive elements. If ordinary peridotites reject these elements so completely, even greater depletion may be inferred for the high-pressure phases of the lower mantle.[3]

We come to the same conclusion by considering total quantities in present crust and original mantle. Whether we start with the chondritic composition or the Wasserburg mixture, a high degree of concentration is required to form a lithosphere or continental crust having the uranium or thorium concentration of the common rocks. By complete vertical segregation, we obtain only about 0.9 ppm of uranium for a 35-km continental crust from a mantle having the chondritic average of $1.1 \cdot 10^{-8}$, or about 2.6 ppm with the Wasserburg mixture and $3.3 \cdot 10^{-8}$. As these numbers are comparable with estimates for the actual uranium content of the continental crust, this crust cannot have been formed from *upper* mantle alone if this had only the original average composition. The upper mantle contains only about 20 per cent of the mass of the whole mantle, and the continental crust can be formed from the upper mantle only if the upper mantle in turn has been enriched with virtually all the uranium originally in the whole mantle. With the fixed proportions of the Wasserburg mixture, the same conclusion holds for thorium and potassium. Fractionation must have affected a large proportion of the lower mantle.

These considerations point to an intermediate stage between core formation and crust formation, a stage in which the upper mantle is enriched in the radioactive elements and, by inference, the other elements with similar chemical behavior—Goldschmidt's "lithophile" elements. Recent investigations by Patterson and Tatsumoto (1964) also lead to the concept of a two-stage evolution of the crust-mantle system based on the development of lead isotope ratios.

Rock ages seem to have an upper limit of about 3500 million years, leaving an interval of 1000 million years between completion of the core and the appearance of stable continental crust. Possibly the reason for the absence of older rocks was the greater rate of heat generation, 3–5 times higher than at present, and the proportionally greater rise of temperature within a crust; if present thermal gradients were multiplied by 3, very little continental crust would remain. The segregation of the low-melting portion of the mantle into upper and middle mantle was accomplished in this interval. From this time on, the continental crust developed by the processes of intrusions, flows, explosions, all of which bring rocks which are much more radioactive than the average upper mantle toward the surface.

The rates of continent formation are still

[3] As an interesting speculation, one might consider how different would have been the Earth's thermal development if a large fraction of the radioactive heat were produced by a long-lived isotope of magnesium.

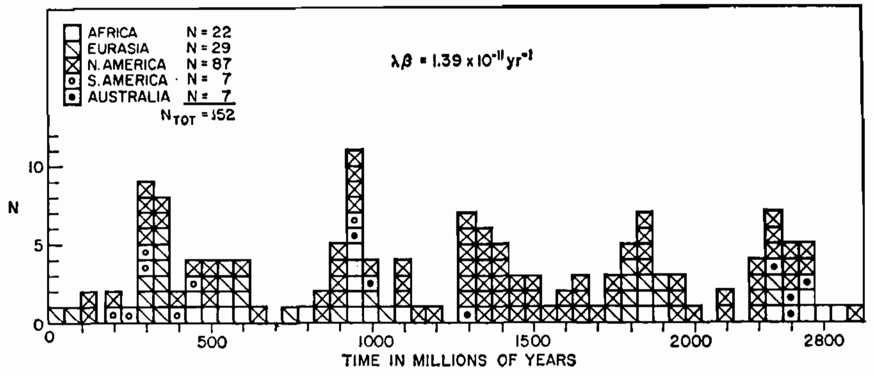

Figure 13. Rb/Sr ages after Aldrich and others (1960). The age scale doubles beyond 2000 million years.

poorly known. The distribution of ages has been interpreted by some as indicating cycles of high activity; others, however, assume a roughly uniform rate of growth. A histogram of Rb/Sr ages compiled by Aldrich and others (1960) (Fig. 13) may be taken to support a thesis of periodicity, but the statistics need examination. If we pick out the 88 ages of North American rocks, North America being being best represented by these determinations, we obtain the distribution of Figure 14. Except for the heavy concentration of ages between 1300 and 1500 million years, which may only mean excessive sampling of rocks of this interval, the distribution is reasonably consistent with a hypothesis of uniformity for periods of 300 million years or so. The geographical and geological origins of samples can evidently greatly influence such distributions, and require careful scrutiny before we can reach conclusions about periodicity. Estimates of average rates have been given for North America by Engel (1963) and by Hurley and others (1962). Engel's estimates are shown in Figure 15, together with the relative rates of radioactive heat generation in the past. Patterson and Tatsumoto (1964) believe that most of the growth took place between 2500 and and 3500 million years ago; my interpretation of this is shown by the dashed lines. Possibly the evidence, such as it is, is compatible with a declining rate of growth comparable to the decline of radioactive heating. For the present discussion, the essential point is that the growth of continents means concentration of the radioactive elements into a surface layer and depletion of the subcontinental upper mantle. This rearrangement of heat sources leads to lower temperatures beneath the continental plates than at equivalent depths in the less differentiated upper mantle beneath the oceans.

The foregoing conclusion depends upon a remarkable discovery of the last 10 years, the

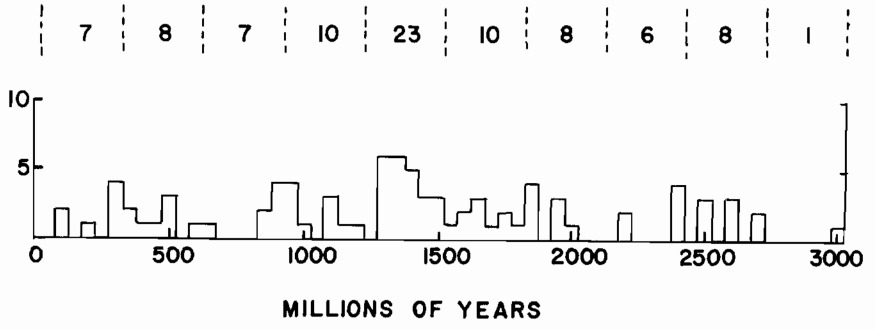

Figure 14. Rb/Sr ages of Figure 13 for North America only, uniform age scale. The numbers above the histogram are the numbers of age determinations in the indicated 300-million year subdivisions.

rough equality of heat flow for oceanic and continental areas. A method for finding the heat flow beneath the oceans was introduced by Bullard in 1949, and has been rapidly developed and exploited, so that there are now nearly 10 times as many individual determinations of heat flow at sea as on land. The detection of high values of heat flow on the oceanic rises is perhaps the most spectacular result of this work, but even more significant is the finding that the average oceanic heat flow is nearly the same as the average continental heat flow. The distribution of values, averaged for 5-degree–by 5-degree-compartments, is shown in Figure 16 (*see also* Lee, 1963; Lee and MacDonald, 1963). The simplest interpretation, and the only one which does not demand a high degree of coincidence, was suggested by Bullard (1952): The amount of radioactive heat generation per square kilometer (more probably, per 1000 km^2) of surface is about the same whether the surface is oceanic or continental. The mean value of heat flow is about 1.4 microcalories per cm^2 second; most of the observations, disregarding the very high values around hot springs and volcanoes, fall between 0.7 and 3.0. This explanation also implies that the heat sources producing this flow are concentrated within a few hundred kilometers of the surface.

Now a large fraction of the continental heat flow is accounted for by the radioactivity of the continental rocks, but the oceanic crust is thin, probably less radioactive, and incapable of providing more than 5 or 10 per cent of the oceanic heat flow. The oceanic heat flow must come mainly from the mantle, whereas the continental heat flow comes mainly from the crust. Thus the suboceanic and subcontinental upper mantles must be chemically different, if only with respect to minor elements; other differences, of a seismological nature, may be partly accounted for by temperature differences. These considerations raise much doubt regarding supposed horizontal displacements of continents. If the radioactivity of a continent were somehow added to the radioactivity of an oceanic mantle, the heat flow should be approximately doubled; on the other hand, a region from which a continent was

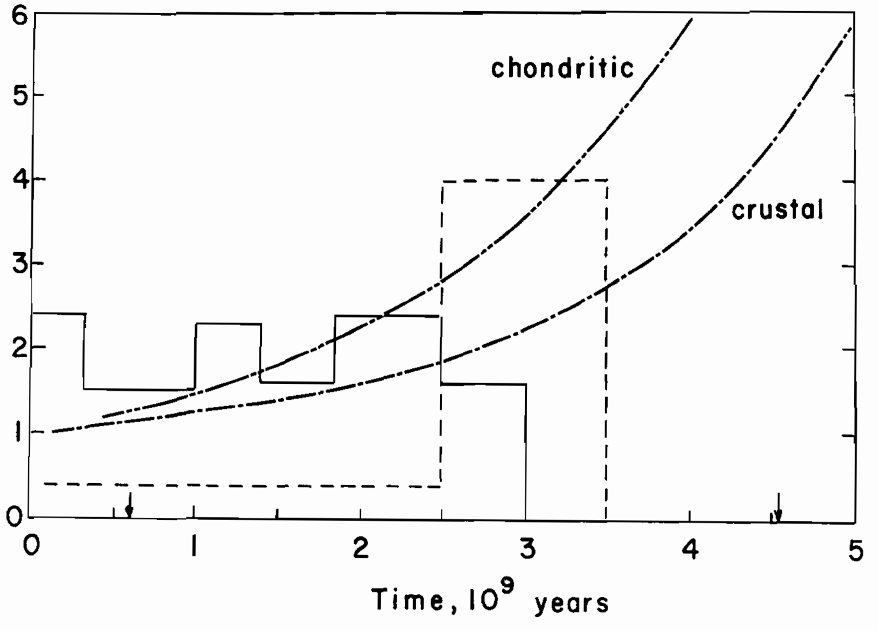

Figure 15. Relative rates of growth of North America (solid line, Engel, 1963; dashed line after Patterson and Tatsumoto, 1964) and relative rates of radioactive heat generation for the average chondrite and average crustal rock. The times of core formation (4550 million years) and of the beginning of the Cambrian Period (600 million years) are marked by arrows on the time scale.

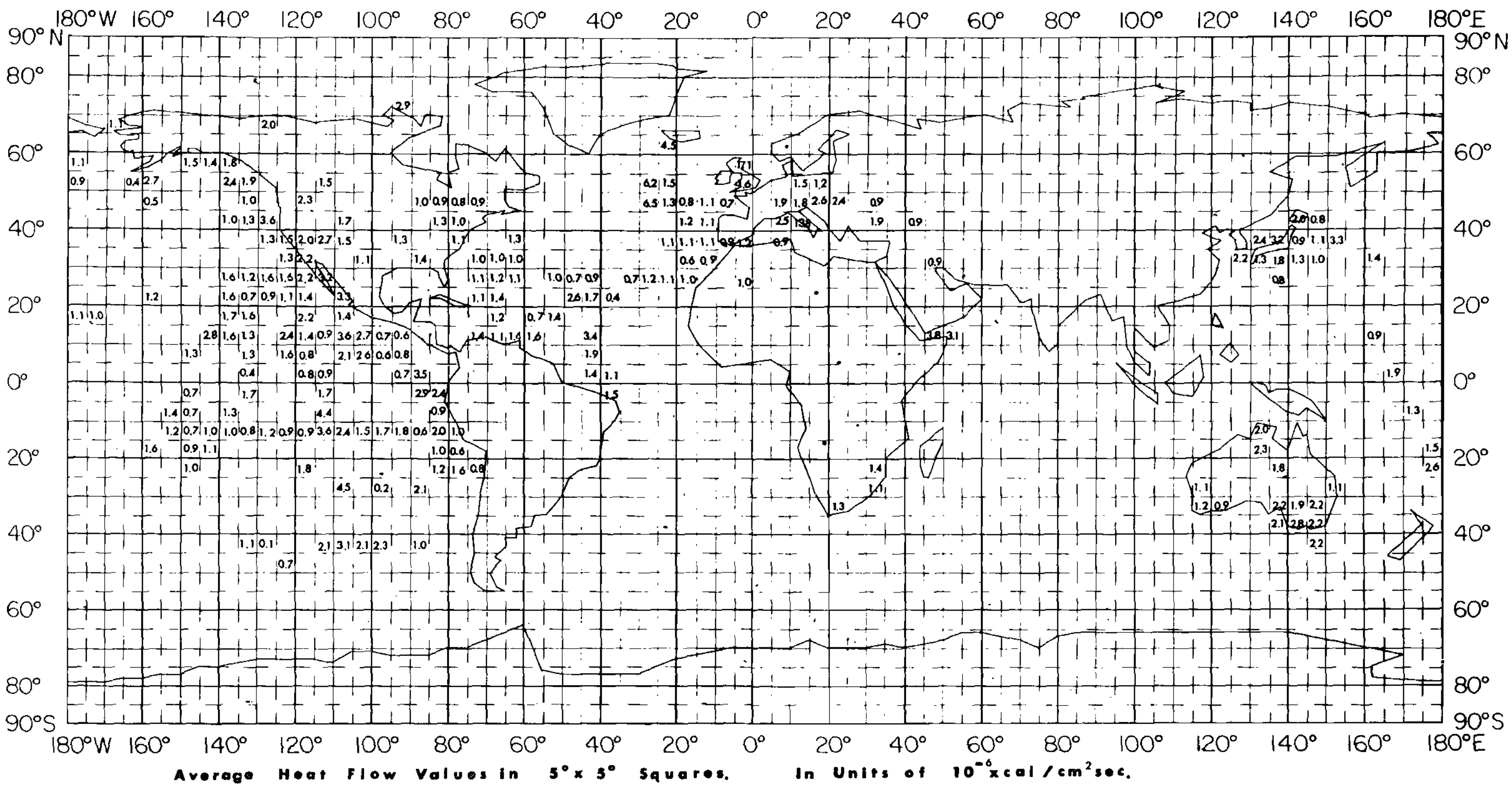

Figure 16. The distribution of heat flow, as averages for 5-degree- by 5-degree-compartments. Heat flow in 10^{-6} calories/cm² sec. A value is given for each compartment having one or more determinations (Chi-yuen Wang, unpub.).

removed should show abnormally low heat flow over an area of continental dimensions. The distribution of heat flow, as we know it at present, although showing much fluctuation, does not seem to be compatible with either of these conclusions. This and other evidence, (Benioff, 1954; MacDonald, 1963) suggests that continental plates are strongly coupled with the underlying upper mantle, and that basalts are derived by partial or complete melting, the source rocks must also be low in radioactivity, since partial melting increases the radioactivity of the melt. The Wasserburg mixture gives a reasonable figure for the average radioactive composition of the suboceanic mantle on the hypothesis of complete vertical concentration in the upper mantle or upper mantle plus some fraction of the transition

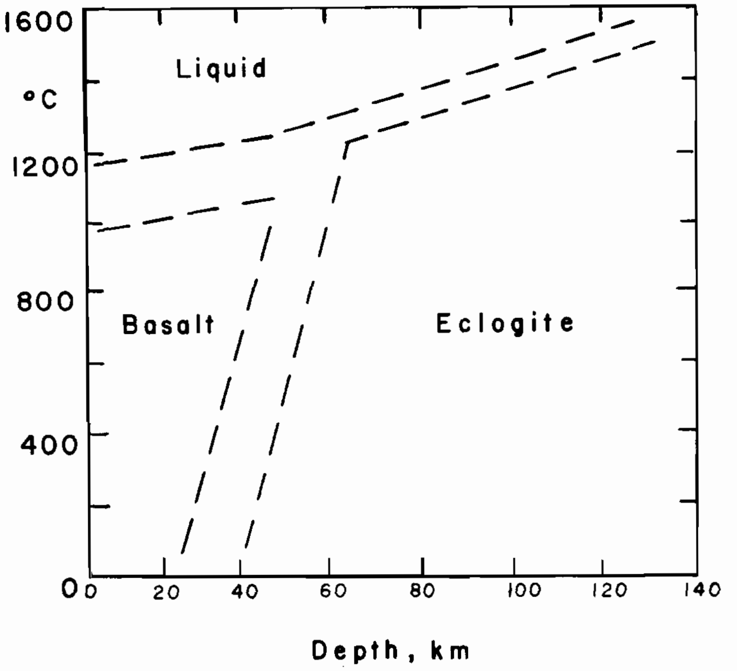

Figure 17. Phase relations of basalt and eclogite (after Yoder and Tilley, 1962).

this mantle differs in essential respects from the upper mantle beneath the oceans. If continents are to drift, some 400 km or so of mantle must go along with them.

With the Wasserburg mixture, the typical continental crust contains 70 per cent of all the radioactivity initially below it; with my assumption, the other 30 per cent is now distributed through the underlying upper mantle, which then turns out to have, on the average, 0.05 ppm U and 0.05 per cent K. The upward concentration beneath the oceans must be much less pronounced, although small quantities of potassium-rich rocks are found on islands and ridges. Engel and Engel (1964a; 1964b) give evidence that the common basalts of the ocean floor are tholeiitic, with low potassium and, inferentially, low uranium. Whether these zone. The upper mantle alone, to a depth of about 400 km, includes about 16 per cent of the mass of the mantle; the upper mantle plus half the transition zone includes about 30 per cent. Thus the original concentrations in the mantle are multiplied by 6 or by 3, depending upon the choice. The results are 0.2–0.1 ppm U, 0.2–0.1 per cent K. According to Engel and Engel, the average tholeiite contains 0.16 per cent K_2O, or 0.13 per cent K. These numbers are fairly self-consistent; they also imply an average composition for the upper mantle close to that of tholeiite, or eclogite, its high-pressure form, at least with respect to U and K.

As we know from the work of Yoder and Tilley (1962), eclogite melts to a liquid of very nearly the same composition, with a small melting interval (Fig. 17). With 0.2 per cent K, and other elements in the Wasserburg ratios, about 300 million years are required, at present rates, for the generation of the latent heat of melting (100 cal/g). The actual time for melting may be considerably increased by conductive losses, or movement of the melt toward the surface may begin when only a fraction has been melted. The redistribution of radioactivity the patterns of continental growth suggest, however, that growth proceeds outward around the perimeter of the early nuclei (Fig. 18, after Engel), with marginal sedimentation, metamorphism, and granite formation as important processes. Evidently lateral transport of sediments containing heat sources and their deposition in thick layers must in due course in-

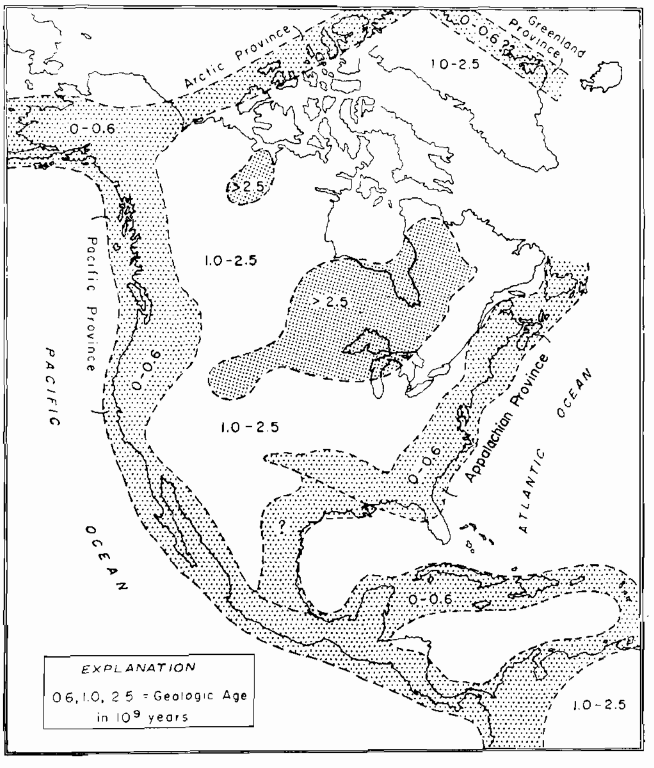

Figure 18. Evolution of North America (after Engel, 1963).

will be such as to lower the temperatures, and the convective transport, small in the total, prevents the development of a completely molten layer. The temperature is probably close to that of melting throughout much of the suboceanic upper mantle. This is just the reverse of the thermal situation envisioned by Jeffreys, for example (1952; 1959), before the exploration of the oceanic heat flow, although in other respects the views which I am presenting are very similar to those of Jeffreys.

There is no obvious reason why continental growth should not continue in the areas of the present oceans; perhaps the oceanic rises exemplify an early stage. The reconstruction of fluence the deep temperatures around the continental margins, and there is evidence of lower than average heat flow in the old shield areas from which large thicknesses of crustal rock have been removed (Kraskowski, 1961; Ringwood, 1962; Howard and Sass, 1964; Clark and Ringwood, 1964). Even without this, the temperatures will be higher beneath the oceanic side than beneath the continental side, as indicated by MacDonald's calculations for a distribution of radioactivity resembling the one postulated here (Fig. 19). The temperature distribution is highly unsymmetrical, with cooling beneath the continents, incipient melting beneath much of the ocean. I cannot follow up these speculations here, as there must be limits even for a presidential address.[4]

To summarize: the present large-scale structure of the Earth suggests the following historical outline:

(1) accretion of material resembling stone and iron meteorites to form an unsorted conglomerate 5000 million years ago;

(2) heating by radioactivity and tidal friction, with melting of iron beginning at a shallow level in about 500 million years;

(3) descent of iron to form the core with release of some 600 cal/g, melting of a fusible portion of the silicate phase and its rise to form an upper mantle containing all the Earth's radioactive elements, between 4500 and 3500 million years ago;

(4) continental crust formation, attaining stability in some areas 3500 million years ago and continuing, with further upward concentration of radioactivity at the expense of the underlying upper mantle, redistribution by erosion and lateral transport, remobilization of sediments; cooling of subcontinental mantle, temperatures at or near melting in the suboceanic upper mantle. The continental margins are indicated as sites of special activity.

With radioactivity as the principal present source of energy, the ultimate history must be one of cooling toward the surface temperature; thus the long-range outlook is determined by the evolution of the Sun. Astrophysics tells us that the sun must eventually consume the hydrogen of its core and begin to burn helium, with an increase of luminosity and consequently of the Earth's surface temperature. At some point in the Sun's progress toward the red giant stage, heat will begin to flow from the surface to the interior of the Earth, melting will proceed inward, and finally the materials will be dispersed, to confound the cosmochemists of 10 billion years hence.

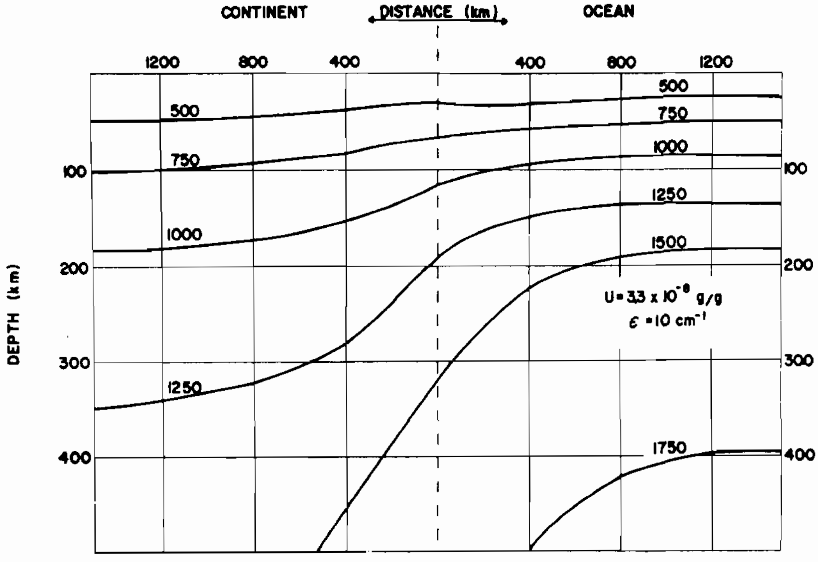

Figure 19. Temperatures beneath oceanic-continental boundary (MacDonald, 1964a, Fig. 12; this is but one of a number of solutions corresponding to different numerical assumptions)

[4] A further theme for speculation may be noted: if the continental area grows, accompanied by a growth of the oceanic volume (Rubey, 1951), it would appear that oceanic depth must increase. What is the future for such a process?

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