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NUCLEAR GEOPHYSICS

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Subcommittee on Nuclear Geophysics
Committee on Nuclear Science

NUCLEAR GEOPHYSICS

Proceedings of a Conference

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FOREWORD

This conference on nuclear geophysics is the fifth such conference sponsored by the Subcommittee on Nuclear Geophysics. It was held at the National Academy of Sciences Conference Center at Woods Hole, Massachusetts on June 7, 8, and 9, 1962. The conference was attended by about 35 active workers in the field of nuclear geophysics largely from U.S. and Canadian Universities, but including a few foreign guests. This conference represented a return to the type of conference held at the Massachusetts Institute of Technology in 1957 and the preceding conference in that an attempt was made to cover important advances over the whole field of nuclear geophysics rather than choose some specialized area for particular attention.

This written report is largely a product of the reporting skills of two scientists who are themselves contributors to this field of research, G. Faure and C. C. Schnetzler of the Massachusetts Institute of Technology. These reporters tape-recorded the conference, took notes, and obtained copies of the figures presented by speakers. The talks were then reconstructed by the reporters from these data and were sent out to the various authors for correction. In some cases an entirely new manuscript was submitted by the author; in other cases the transcribed manuscript was used, at the author's discretion. We are greatly indebted to P. M. Hurley, also of the Massachusetts Institute of Technology, who undertook the responsibility of serving as editor of these reports.

We are also indebted to the staff of the Division of Physical Sciences of the National Academy of Sciences -- National Research Council, in particular to Lewis Slack and John S. Coleman. Their work in obtaining funds for the conference, obtaining a site, and handling myriad details reduced enormously the burden of work of the Subcommittee. Financial support from the National Science Foundation is gratefully acknowledged.

George W. Wetherill, Chairman
Subcommittee on Nuclear Geophysics

Editorial Committee:
P. M. Hurley, Chairman
Gunther Faure
Charles Schnetzler

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OCEANIC HEAT FLOW DATA

R. P. Von Herzen

During the past decade, about 400 measurements of heat flow through the ocean floor have been made at various localities, largely in the Atlantic and eastern Pacific Oceans and a few in the Indian Ocean. The values range from about 10^{-8} to 8×10^{-6} cal/cm^2/sec. The mean value for the Pacific, with equal weighting for equal areas where measurements exist, is about 1.5×10^{-6} cal/cm^2/sec; for the Atlantic, about 1.7×10^{-6} cal/cm^2/sec; and for the Indian Ocean, also about 1.5×10^{-6} cal/cm^2/sec. The value for the Atlantic may be somewhat higher due to a greater proportion of measurements in regions of anomalously high heat flow. Thus, the mean value for the ocean areas where measurements exist is about 1.5×10^{-6} cal/cm^2/sec. This is approximately the same as the average for the continental regions, although the crustal structure of the two regions is quite different.

The oceanic measurements depend on the constancy of temperature of the deep ocean waters, and the presence of soft muds on the ocean floor which are easily penetrated by measuring apparatus. By the use of either a steel probe (Bullard, 1954; Von Herzen, et al., 1962) or the attachment of small temperature sensors to a coring tube (Gerard, et al., 1962), the vertical temperature gradient in the upper few meters of the sea floor sediments is measured. The product of the temperature gradient by the thermal conductivity of the sediments in which the gradient is measured (Von Herzen and Maxwell, 1959) gives the steady state heat flow through the sea floor. Some evidence of the reliability of this technique is given by the reproducibility of the values at various locations. Of 31 measurements at 13 different localities in the Pacific, 22 of the values are within either 10% of the mean at each station or 10% of the oceanic mean value. Generally, the measurements appear to have a reliability of about 10%.

The values show considerable variation about the mean. The mid-ocean rises, represented as a large topographic uplift in all the major ocean basins (Ewing and Heezen, 1956), show a remarkable correlation with high heat flow values. Values greater than 3×10^{-6} cal/cm^2/sec have been found at 5 localities on the East Pacific Rise between 45° S and 10° N latitude, at 4 localities on the mid-Atlantic Ridge between 10° N and 52° N latitude, and at one locality on the Indian Ocean Rise. The high values appear confined to a strip at the crest of the mid-ocean rises with a width of only a few hundred kilometers. Between 10° and 15° S latitude on the East

Pacific Rise, a detailed series of measurements has shown the very high values, 4 to 8 x 10^{-6} cal/cm^2/sec, nearly always are found within two relatively narrow zones which parallel the trend of the Rise crest and are located approximately symmetrical with respect to each side of the crest. These zones appear to be about 50 to 90 Km. wide, separated by a distance of about 200 to 250 Km. There are no corresponding topographic features of this size in the area.

Two large areas of the Pacific ocean floor appear to show lower-than-average heat flow. These are located to each side of the East Pacific Rise near the equator, and are separated by distances of 3000-4000 km. The average heat flow through both areas is about half the normal oceanic value, over areas approaching 10^6 km^2. These regions do not appear to extend parallel to the East Pacific Rise, but are approximately equidimensional. Outside of these regions, isolated measurements of low heat flow are frequently correlated with a locally very flat sea floor (several miles wide). This also includes the low values measured in the flat floors of trenches (Bullard, et al., 1956; Von Herzen, 1959). The locally flat topography suggests a possible disturbance from the local sea floor environment, such that these low heat flow values may not be representative of the regional geothermal flux.

The regional variations in heat flow may be best explained as a result of a large-scale convection pattern in the mantle. In addition, convection or another mechanism is probably required for more efficient heat transfer than by molecular thermal conduction in rocks, as a consequence of the magnitude of the average oceanic heat flow (Bullard, et al., 1956). A consideration of the possible energy sources for mantle convection favors the decay of radioactive elements dispersed throughout the mantle rocks. However, the regional heat flow differences appear too large to be explained by differences in fixed concentrations of radioactive elements in the rocks beneath such areas.

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CONVECTION AND THERMAL HISTORIES OF EARTH AND MOON

S. K. Runcorn

The thermal history of the earth and moon are radically changed if slow convection currents are occurring within the mantles. Solid-state physics suggests that slow creep with zero long-term strength is possible in these materials at high temperature and pressure, and so the mathematical theory of thermal instability in fluids may be used. It is to be expected that convection will just carry off through the earth's surface the total heat being generated within it. Thus, the good agreement between the mean flow of heat through the ocean bottom (10^{-6} cal/cm^2/sec) and that generated in the earth's mantle, on the assumption that the radioactivity of the mantle is the same as that of chondritic meteorites, (1.60 cal/gm/yr x 4.08 x 10^{27} gm/5.10 x 10^{18} cm^2) is expected. As the seismic evidence seems to indicate chemical homogeneity in the mantle (Birch 1961), there seems no reason to suppose an upward concentration of radioactive elements below the ocean floor. Consequently, the high temperature gradient in the mantle under the ocean (implied by the heat flow measurements), 25° C/km, would cause the melting point of olivine to be exceeded at about 50 - 80 km depth, unless convective flow is providing heat sources, thus decreasing the actual temperature gradient.

On the cold origin of the earth by the accretion process, the possibility that the settling of the iron core would be slow is an idea first put forward by Urey (1952). A convecting earth would assist in the separation of iron towards the center and sialic material at the surface. The theory of thermal convection in spherical shells under a radial gravitational field suggests that when the core was small a single cell convection pattern described by a spherical harmonic of first degree, would form, concentrating much sial in one hemisphere, a relic of which remains in the earth's topography today. When the core radius, as a fraction of the earth's radius, reached the value 0.06, transition in the convection to a second degree harmonic would occur. Further transitions would occur at radii of 0.36, 0.49, and 0.54. Each of these changes of the convection pattern would be expected to set up considerable strains in the earth's crust resulting in orogenesis and metamorphism which might last for a few hundred million years. It is natural to identify these epochs with the 2800 my, 1800 my, 1000 my, and 300 my peaks in the radioactive age histograms. The last transition from 4th - 5th degree convection seems to be identified with the continental drift, inferred, by paleomagnetism and other methods, from the

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geological record since Palaeozoic. A further account of this attempt to explain continental drift by convection in the earth's mantle is given by Runcorn (1962).

Thermal convection, though of 2nd degree, seems required to explain the non-equilibrium shape of the moon, if the process of creep is taken to be effective in this body too, for the non-equilibrium shape cannot be a relic from the early history of the moon. Convection theory then implies the existence of an iron core not more than 4.6 per cent of the moon's volume (c.f. 15 per cent of the earth's).

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CONVECTION IN THE MANTLE

S. K. Runcorn

According to Urey, the amount of heat generated in chondritic meteorites is about 4×10^{-15} cal/cc/sec. If this value is also valid throughout the earth's mantle and the earth is in thermal equilibrium, then the mean heat flow through the earth's surface works out to be 10^{-6} cal/sq.cm/sec. The agreement between this figure and that observed suggests, contrary to early ideas on the subject, that there is a balance between the heat generated within and the heat lost by the earth, so that it is not, as a whole, cooling or heating up. Convection may be postulated as the process for conveying the generated heat, since it is such a self-balancing process.

The author became convinced that convection currents occurred in the earth's mantle because of the palaeomagnetic evidence for continental drift. It is first necessary to note some properties of the type of convection required to cause drift to occur.

The velocity of the convection pattern would have to be in excess of 1 cm/year. This value can be obtained from several considerations of the following type: (I) Present day rates of movement along the San Andreas fault in California. (II) From palaeomagnetic estimates of how much continental drift has occurred in fairly recent times it appears that Europe and America have separated by about 30° longitude since the Permian and that Australia has moved from the pole to 30° S. latitude. These considerations all give about the same values for the required convection velocities.

Convection must be considered as a large scale process which occurs throughout the mantle. Furthermore, it is not a random process but occurs in regular cellular patterns.

Vening Meinesz has advocated convection in the earth's mantle for many years. He believed that the present distribution of the continents and oceans gave a clue to the type of mantle convection. The strongest terms in the spherical harmonic analysis of the departure of the solid surface of the earth from sea level are those of degree 1, 3, 4, and 5 as shown in Figure 1. The presence of the 1st harmonic was consistent with the fact that the continents are on the whole concentrated in one hemisphere and the prominence of the odd harmonics 1,3,5 agrees with the further fact that the continents are, to 5 per cent, antipodal to the oceans. He thus

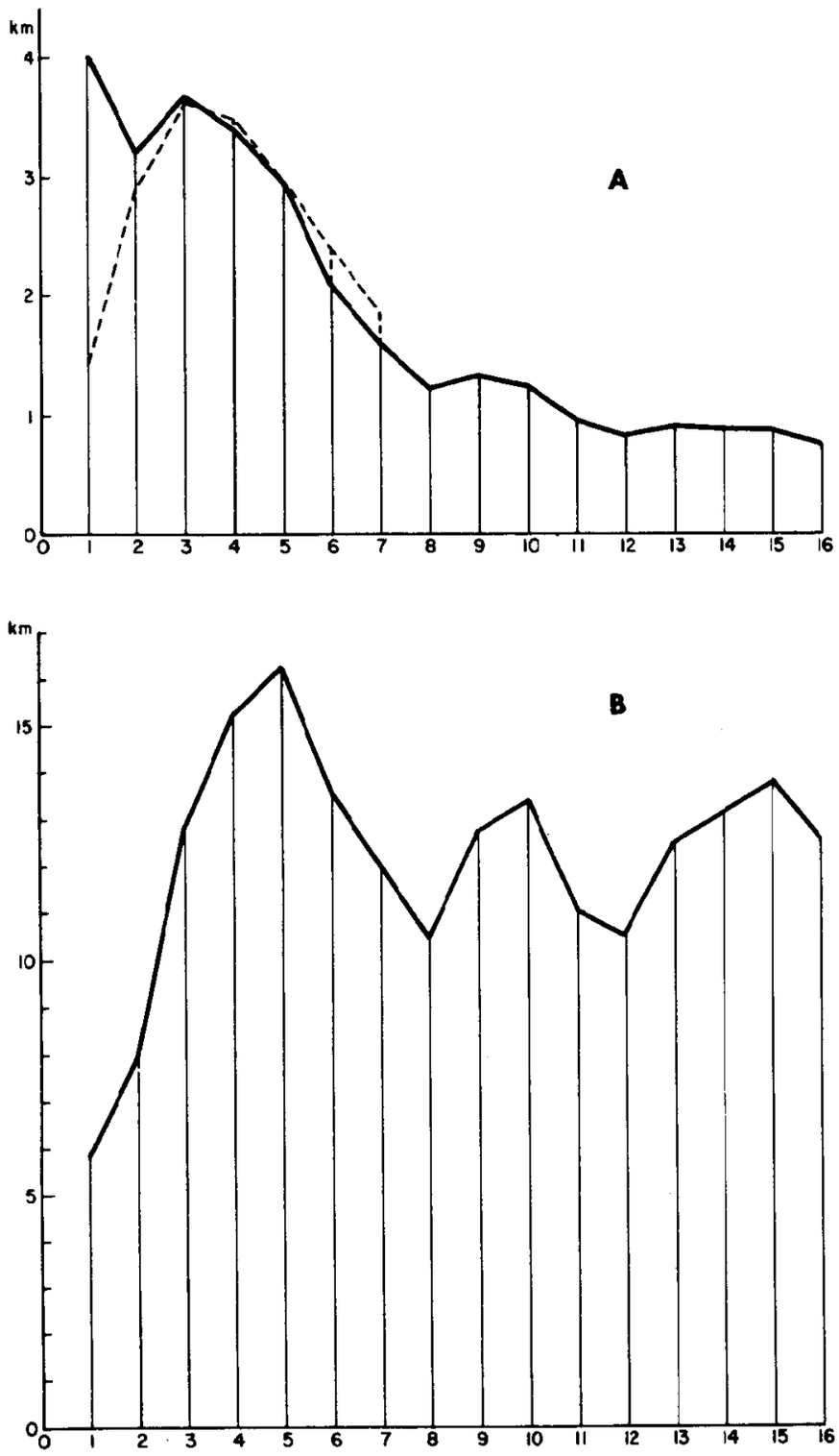


Figure 1

(a) Deviations of Earth's crust's thickness, mean values of spherical harmonic terms of orders 1-16.

(b) Ordinates of (a) multiplied by $\sqrt{n(n+1)}$.

postulated a world-wide mechanism determining the position of the continents. Treating the mantle as a fluid confined between 2 spherical surfaces, Vening Meinesz showed that it is reasonable that convection systems described by spherical harmonics of degrees n = 3,4,5 would develop for the present geometry. Chandrashekar has elaborated on this work and Figure 2 shows the curves he obtained. He plots the degree of the convection pattern against the log of the Rayleigh number and for different ratios (η) of the radius of the inner to the outer spherical surfaces. At marginal stability it is intuitively reasonable that convection pattern is established which has the least Rayleigh number and that in a spherical shell a number of cells are obtained such that their dimensions are comparable with the

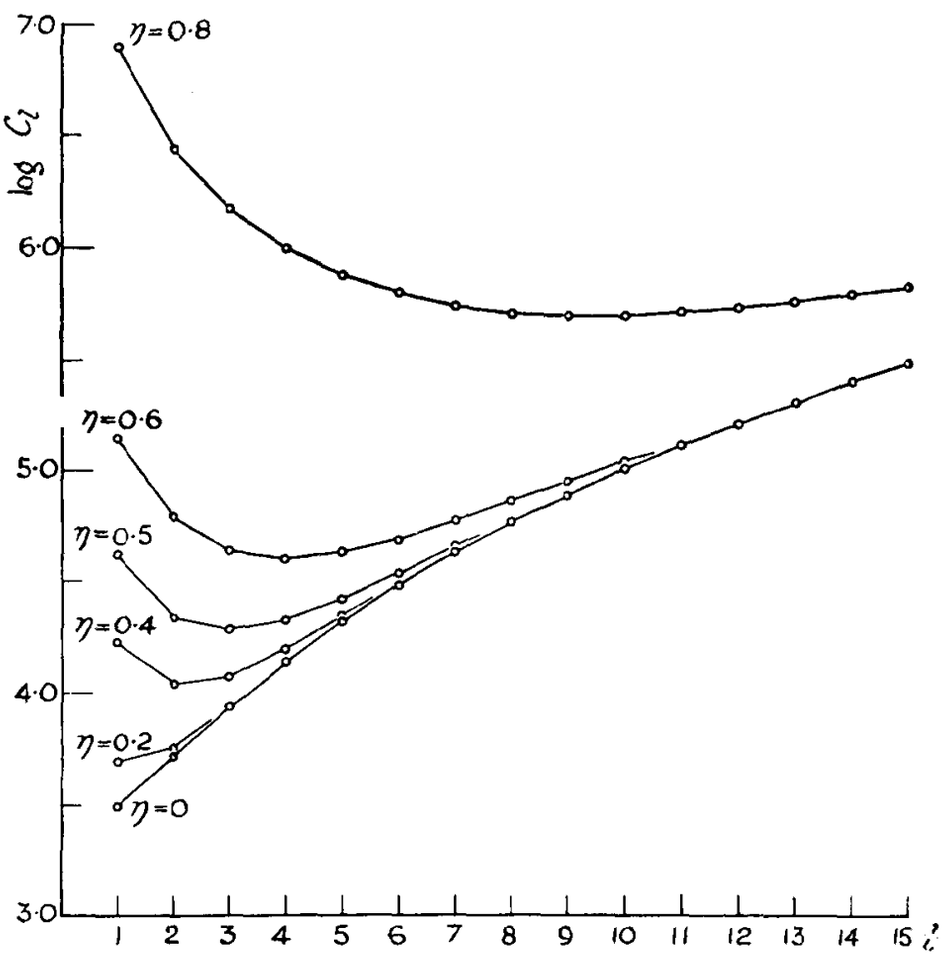


Figure 2. The criterion (C_l) for the onset of convection in the mantle as a spherical harmonic disturbance of order (l) for various thicknesses of the mantle. The different curves are distinguished by the values of the fraction (η) of the radius of the sphere occupied by the inviscid core.

depth of the shell. Thus for a small core, a single doughnut-shaped convection with n = 1 shell results. For the core-radius of 0.4 of the earth's radius the convection pattern with the lowest Rayleigh number will be n = 2. Chandrashekar has shown that at the present core-radius the convection cells excited are those where n = 3, n = 4, n = 5.

Oceanographers have also recently obtained evidence for convection currents different from that of Vening Meinesz, by heat flow measurements in the ocean and by studies of the oceanic ridges. The central rift found in some of the latter imply the existence of tensional forces in the ocean floor; thus positions of these ridges indicate the lines along which the horizontal flow of convection patterns in the mantle vanish. From the oceanographic evidence it appears that the convection pattern in the mantle at present is of the 5th order (n = 5). The arguments of Vening Meinesz regarding the present positions of the continents thus tend to overemphasize the n = 3 and 4 harmonics and this seems to result from the position of the continents reflecting now their position in the past. Although the convection patterns which have put the continents in their present positions have long since vanished it is possible to infer their nature.

Some reconstructions of the past positions of the continents are now summarized.

By averaging the paleomagnetic directions (thus smoothing out the secular variations) for series of Tertiary rocks back to about 60 m.y. old, it is possible to calculate the Tertiary pole positions which, as shown in Figure 3, cluster closely around the present geographical pole. From paleomagnetic data of earlier periods the continents can be put back together in their original positions and Figure 4 gives the results for the Jurassic. Evidently, as one goes back in time the continents are closing together, forming a simpler distribution. In the Permian, these continents form a block around the S. Pole whilst the Northern continents (Europe, N. America) were all at much lower latitudes than at present.

Figure 5 shows the longitudes of pole positions as a function of geologic time, obtained from American and European rocks. The data is least reliable for Precambrian rocks. We must assume that for most of geologic time Europe and N. America were some 30° closer together. Figure 6 shows the top of the present N. hemisphere with America moved closer, as well as the position of the equator, indicating that N. America and Europe were in lower latitudes. Limited palaeoclimatic data indicates that Asia was also at a much lower latitude.

The general situation 200 to 300 m.y. ago therefore was that the continents clustered into two groups, one around the pole and the other at very low latitudes near the equator. Because they were also much closer

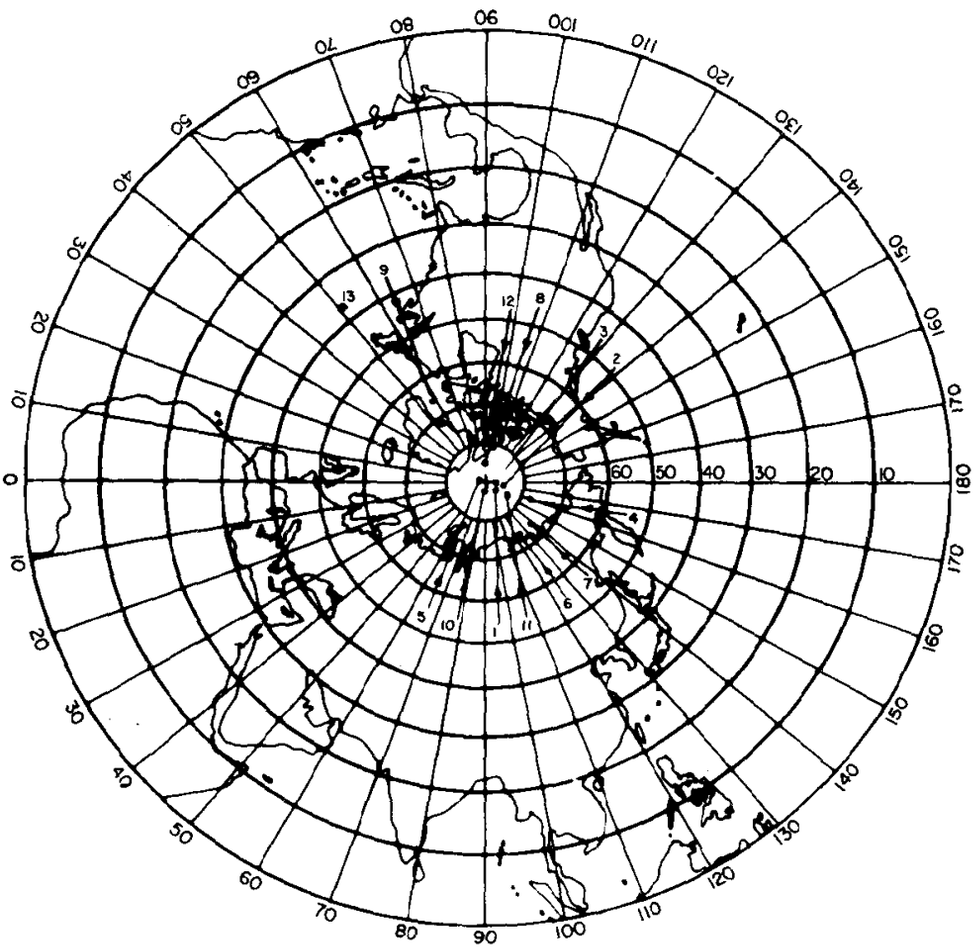


Figure 3. Cainozoic Pole Positions.

together, a spherical harmonic analysis would tend to emphasize the lower harmonics. Figure 7 shows some typical 1st and 3rd and 4th degree convection patterns.

Now for the earth, if the inner spherical surface is considered to be free and the outer one to be rigid, then it can be shown from Chandrashekar's calculations that the present size of the core (i.e., 0.55 x radius of the earth) is only just above the threshold ratio for the production of the 5th order harmonic, which is about 0.54 r. A plausible explanation thus exists of the occurrence of continental drift in the recent history of the earth: the core has slowly been growing, but the radius change need not have been large in the last 200-300 m.y. to start the new convection mode off.

It is relevant at this stage to consider Urey's accretion model for the earth's formation. Urey thought that the segregation of the core might be a very slow process. The present author considers that thermally driven convection might help to form a core. If the earth originated as a mixture of bodies similar in composition to the iron and chondritic

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