CONTINENTAL DRIFT

Thermal convection within the earth's crystalline mantle provides a mechanism for large-scale surface displacements. Oceanic ridges occur where the flow of convection cells comes up to the surface; trenches occur where it descends again.

DONALD L. TURCOTTE and E. RONALD OXBURGH

TODAY MOST EARTH SCIENTISTS accept continental drift as a geological fact. Relative movements between continents on a time scale of 10^8 years are necessary to explain many geological observations. The remarkable similarity in shape between the west coast of Africa and the east coast of South America has been recognized for nearly as long as accurate maps of the Atlantic have been available; many have assumed that these continents once were connected. It is also accepted that the continents float on the mantle much like blocks of wood on water.

Paleomagnetism and measurements of magnetic anomalies have provided quantitative evidence supporting the drift hypothesis. Diffusion creep offers an explanation for the fluid-like behavior of the crystalline mantle. Thermal convection cells within the upper mantle provide a mechanism for large-scale surface displacements. The ascending flows of the convection cells are associated with oceanic ridges and the descending flows with oceanic trenches at the edges of continents.

Francis Bacon (1561–1626) was one of the first to note the similarity in shape of Africa and South America. Subsequent work has matched rock type and age, mountain ranges, ancient fault zones, mineral deposits and faunas as well as shape. Some aspects of the fit[1] are illustrated in figure 1.

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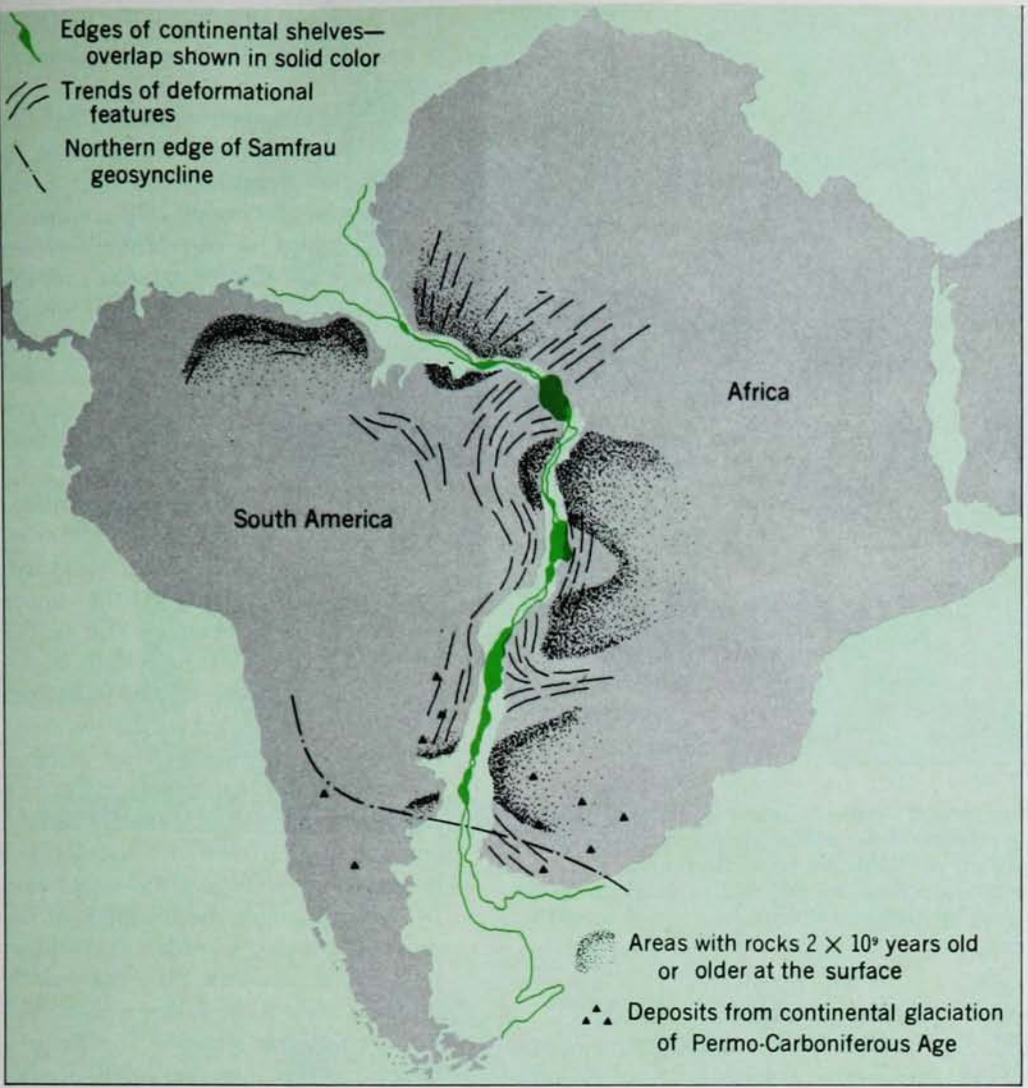
Controversial idea

Alfred Wegener[2] and Alexander L. du Toit,[3] both leading advocates in the earlier part of this century, provided much of the qualitative evidence favoring continental drift. Wegener proposed that continental movements were driven by gravitational forces. Sir Harold Jeffreys[4] showed, however, that gravitational forces are many orders of magnitude too small to provide the required relative motion. Continental drift fell into disrepute during the 1930's and 1940's because of Jeffreys's strong arguments, the specious nature of some of the geological reasoning advanced by its supporters and the failure to find an alternative driving mechanism.

During this time the only widely accepted large-scale dynamic phenomena were differential vertical movements of the continents, mountain building and relative motion along fault zones. These generally were attributed to the traditional



ONCE CONNECTED? South America and Africa are matched at the edges of the continental shelves (after E. Bullard et al[1]). Geological features that appear to match across the coastlines are shown (after Patrick M. Hurley[1] and Alexander du Toit[3]). —FIG. 1

mechanism of thermal expansion or contraction of the earth (see, for example, Elie de Beaumont[5]).

Paleomagnetism

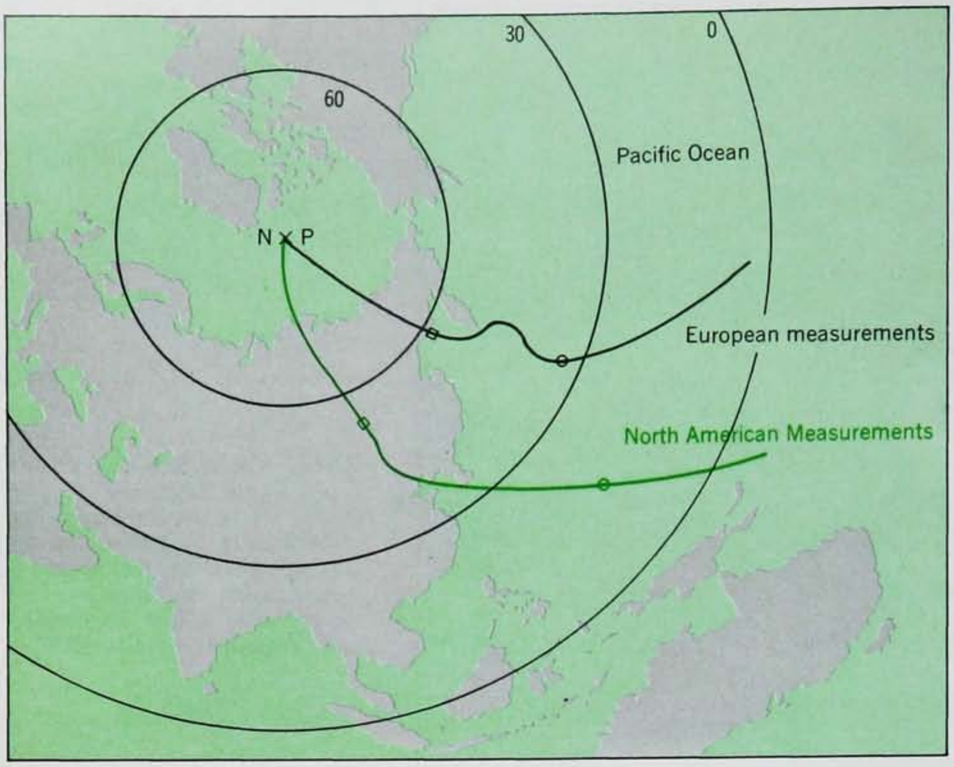
In the last 20 years, the work of Patrick M.S. Blackett, Takesi T. Nagata, Keith Runcorn and others[6] on the magnetic properties of rocks has provided substantiation of continental drift. At the time of their formation some rocks acquire permanent magnetic properties that relate to the orientation and intensity of the ambient magnetic field. For example if a rock forms by the crystallization of a high-temperature silicate liquid (such as basalt) and contains a few per cent of a ferromagnetic compound such as magnetite (Fe_3O_4), it acquires a strong remanent magnetism on cooling to some temperature below its Curie point. The orientation of the remanent magnetic vector is a function of the magnetic latitude at which the cooling occurs.

Systematic measurements made in relatively undisturbed rock sequences give two principal results: The polarity of the earth's magnetic field has undergone periodic reversals in the past and the apparent magnetic latitude of a given area has varied continuously with time. From measurements made on a rock unit of known age one can derive an apparent pole position with respect to that area at a specific time; measurements on rocks of different ages allow the derivation of a polar-wandering path.

Of particular interest was the discovery[6] that contemporaneous positions of the earth's magnetic pole, as determined from measurements on different continents, do not coincide. The systematic difference between the pole positions as measured in North America and Europe is shown in figure 2. Note that the difference between the pole positions diminishes as we approach the present. Relative movement between the continents can explain these observations.

The required rate of divergence is consistent with other qualitative evidence that North America and Europe were connected 300 million years ago. This rate corresponds to an average of several cm per year. We note that the paleomagnetic method depends upon the assumption that the earth's magnetic field has, on the average, remained close to that of an axial dipole during the last 10^9 years. This assumption has been questioned, but there is no strong case for an alternative.

The evidence of latitude changes provided by paleomagnetism is consistent with that from other latitude-dependent characteristics of rocks. For example, modern living coral reefs are virtually restricted to latitudes within 30 deg of the equator (figure 3a). Fossil reefs, however, which appear to have been built by coral polyps with environmental tolerances similar to those of modern corals, are found at almost every latitude (figure 3b). We find that if fossil reefs are restored to an original latitude of growth as derived from local paleomagnetic measurements, the distribution shown in figure 3c results. This distribution is very similar to that observed today. Evidence of this



POLAR WANDERING PATHS for Europe and North America. Black line on top is defined by the succession of pole positions derived from paleomagnetic measurements on rocks from Europe; color line below is based on North America. Rectangles and circles indicate the apparent pole positions about 200 million and 300 million years ago respectively. The discrepancy may be explained by continental drift. —FIG. 2

kind is derived from a wide variety of rock types, desert sandstones, salt deposits, continental glaciation deposits and coals.

Radius of the earth

In any quantitative discussion of continental drift one must prescribe the boundary conditions as closely as possible. We shall assume here that the earth has not changed in radius or mass by a significant amount (say, more than 1%) during the last 10^9 years. Clearly, if large changes in radius were permissible a new class of continental-drift models would be available. The continents at some time in the past could have covered, or nearly covered, an entire earth of smaller radius. Subsequent expansion of the interior could have separated the continents and carried them apart, in much the same way that a brittle wax coating on a balloon would be split and carried apart by inflation of the balloon.

One of the earliest to suggest changes in radius of the earth as an explanation of continental drift was O. C. Hilgenberg,[7] but in recent years S. Warren Carey[8] has been its most vigorous advocate. If the temperature of the earth is increasing because of heating from radioactive decay, expansion is expected. Gordon J. F. MacDonald[9] has attributed mountain building on the edges of continents to the resulting thermal stresses.

Another possible cause for change in the earth's radius is change in the gravitational constant. Several authors[10] have considered the effect on the earth's radius of the time dependence of the gravitational constant proposed by P.A.M. Dirac.[11] However, Francis Birch[12] has shown that changes in the earth's radius resulting from either thermal effects or changes in the gravitational constant are limited to about 100 km and therefore cannot explain large-scale continental movements. Paleomagnetic evidence[13] also indicates that large changes in the earth's radius in the last 300 million years are implausible.

A viscous mantle

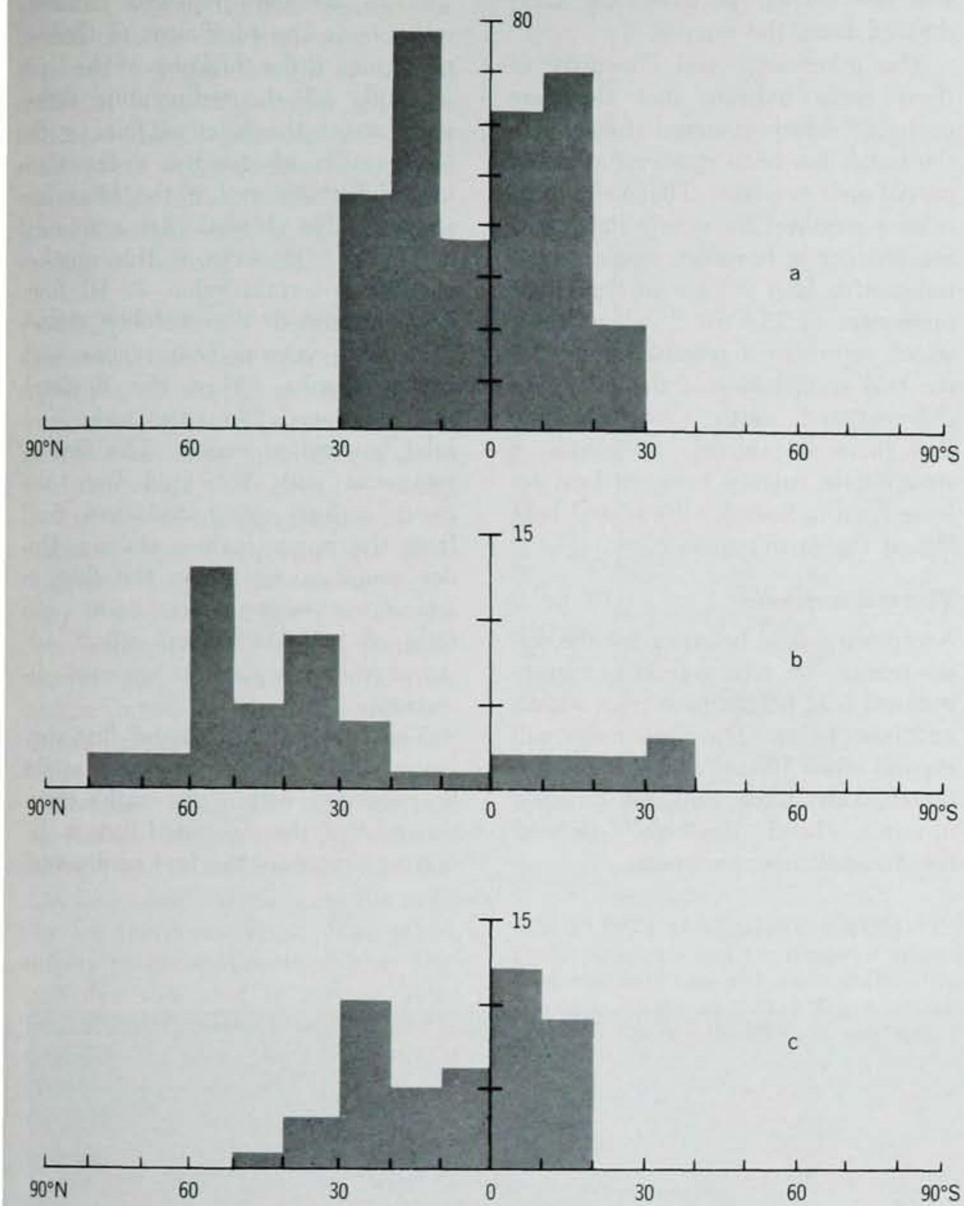
Observations of the travel times of seismic waves show that the upper 3000 km of the earth is essentially a solid, crystalline aggregate. For this reason many geophysicists rejected the possibility of large-scale horizontal movements of the crust. Today, however, there is considerable evidence that over long periods of time the earth's mantle behaves like a viscous fluid and that its elastic behavior is restricted to short-period phenomena.

Seismic observations show that the earth's crust is about 35 km thick in continental areas and about 5 km thick under the oceans. On continents there is a positive correlation between the height of the topography and the thickness of the crust; under the highest mountains the crust is up to 60 km thick. The crust has a mean density of about 2.85 gm/cm^3 and the upper mantle beneath the crust has a density of about 3.4 gm/cm.^{3}

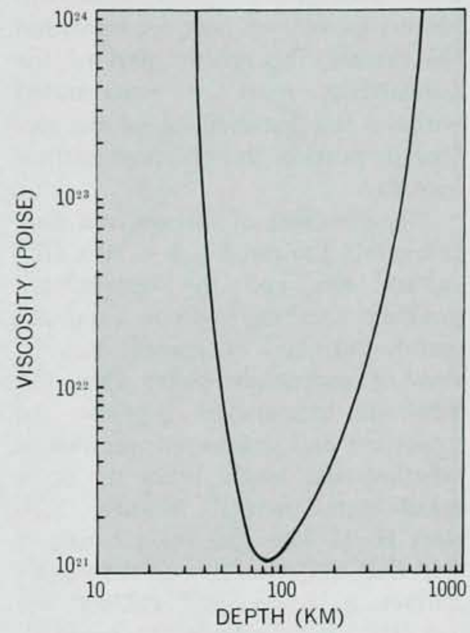
These and other considerations have led to the concept of *isostasy*, that the crust is floating in hydrostatic equilibrium upon the upper mantle. Measurements of the earth's gravitational field substantiate isostasy. The uniformity of the measured gravitational field shows that, with local exceptions, the total mass within a narrow column lying along any earth's radius is nearly constant. This is the condition for hydrostatic equilibrium. A variety of geological processes continuously changes the thickness of the crust; therefore, in order to maintain isostasy, it appears that the mantle must be able to flow like a fluid. Uplift phenomena provide further evidence for this fluid behavior. Studies of shorelines in Scandinavia show that this land-mass has risen by about one cm per year during the last 100 years. This continental uplift is attributed to the melting of the ice cover approximately 11 000 years ago. Elastic rebound is not capable of explaining this phenomenon; Norman A. Haskell and others[14] have shown, however, that the uplift can be explained if the mantle is taken to be a viscous fluid with a viscosity of about 10^{21} poise. Max D. Crittenden[15] has studied the uplift of Lake Bonneville following removal of the water load by evaporation, and he can also explain the measured rate of uplift with a viscous model. Similarly land areas subject to large loads are depressed. Central Greenland is depressed well below sea level by an iceload several km thick.

Diffusion creep

Although there is gross evidence that the silicate rocks of the upper mantle behave like a viscous fluid, a physical explanation for this type of behavior is required. It is well known that solids are subject to plastic deformation; however, under some conditions



CORAL-REEF DISTRIBUTION as a function of latitude: a, present distribution; b, distribution of fossil reefs; c, distribution of fossil reefs when restored to original latitude using paleomagnetic measurements (after Edward Irving[6]). The ordinate shows the number of reefs for each 10 degrees of latitude. —FIG. 3



DEPTH DEPENDENCE of viscosity, based on diffusion creep in the upper mantle, possibly follows this curve. —FIG. 4

solids may behave as Newtonian fluids.[16] A possible explanation for the fluid-like behavior of the upper mantle is diffusion creep (Herring–Nabarro creep). When a crystal is subjected to anisotropic stress, field atoms tend to diffuse away from the regions of high normal stress and there is a complementary migration of lattice vacancies towards these regions. This process tends to relieve the stress difference, a strain results, and there is "flow." Diffusion creep produces a linear relation between stress and rate of strain. Grain-boundary slip also results in viscous behavior.

Robert Gordon[17] has used an analytic expression that determines the viscosity due to diffusion creep to show that viscosities in the range 10^{20}–10^{25} poise are reasonable for the earth's mantle. The diffusion-creep viscosity is exponentially dependent on both the temperature and pressure; thus for reasonable temperature gradients the viscosity is expected to increase rapidly at depths greater than about 200 km because of the pressure dependence. This result is consistent with the calculations of a rotational figure of the earth, made by MacDonald,[18] which show that the average viscosity for the entire mantle should be near 10^{26} poise. A possible dependence of viscosity on depth is given in figure 4.

Even if diffusion creep is not the applicable mechanism, values of the viscosity obtained from diffusion creep give a maximum that other creep mechanisms may reduce. Thus known solid-state phenomena can explain the fluid behavior of the earth's mantle. Laboratory measurements of creep behavior at high temperatures and pressures are of great importance, but measurements at sufficiently low rates of strain (for example 10^{-14} sec^{-1}) are difficult.

Heat sources, thermal gradients

Very little is known about the temperature of the earth as a function of depth. Although many measurements of surface heat flux have been made, uncertainties in the process of heat transfer and in the variation of the physical parameters such as thermal conductivity with depth introduce uncertainties of hundreds of degrees at a depth of a few tens of kilometers. In addition, we are not sure what the heat sources are. Regardless of the energies associated with the formation of the earth, it is likely that the release of gravitational potential energy associated with the separation of the dense metallic core was sufficient to melt, or nearly melt, the entire earth between 3 and 4.5 x 10^9 years ago. Since that time the main source of heat has been radioactive decay of unstable isotopes of uranium, thorium and potassium. Although the amount and distribution of radioactivity within the earth's mantle are not known independently, we do know that, unless some kind of convective transfer of heat occurs within the mantle, the greater part of the radioactivity must be concentrated within a few hundred km of the surface to provide the observed surface heat flow.

Measurements of surface heat flow fall within the range $0.2 - 10 \times 10^{-6}$ cal/cm^2 sec, and the temperature gradient near the surface (approximately 20K/km) is typically two orders of magnitude larger than the adiabatic temperature gradient. An important and unresolved question is whether the earth today is in a steady-state thermal balance. William H. K. Lee and Seiya Uyeda [19] find that the mean flux to the earth's surface is 1.5×10^{-6} cal/cm^2 sec ($\pm$ 10%). For a steady-state heat balance the mean heat release from radioactive decay in the rocks of the mantle must be 1.8×10^{-15} cal/gm sec. This value is an order of magnitude smaller than the heat generated by radioactivity in basaltic rocks and an order of magnitude larger than the heat release in the ultramafic rocks that are carried as blocks by lavas derived from the mantle.

The mineralogy and chemistry of these rocks indicate that they are probably mantle material from which the basalt has been removed as a first partial-melt fraction. The mean heat release required for steady-state thermal balance is, however, similar to the radioactive heat release in chondritic meteorites (1.25×10^{-15} cal/gm sec), which represent a possible model for the bulk composition of the early, undifferentiated earth. We conclude that there is probably at present a steady-state balance between heat release from radioactive decay and heat loss at the earth's surface.

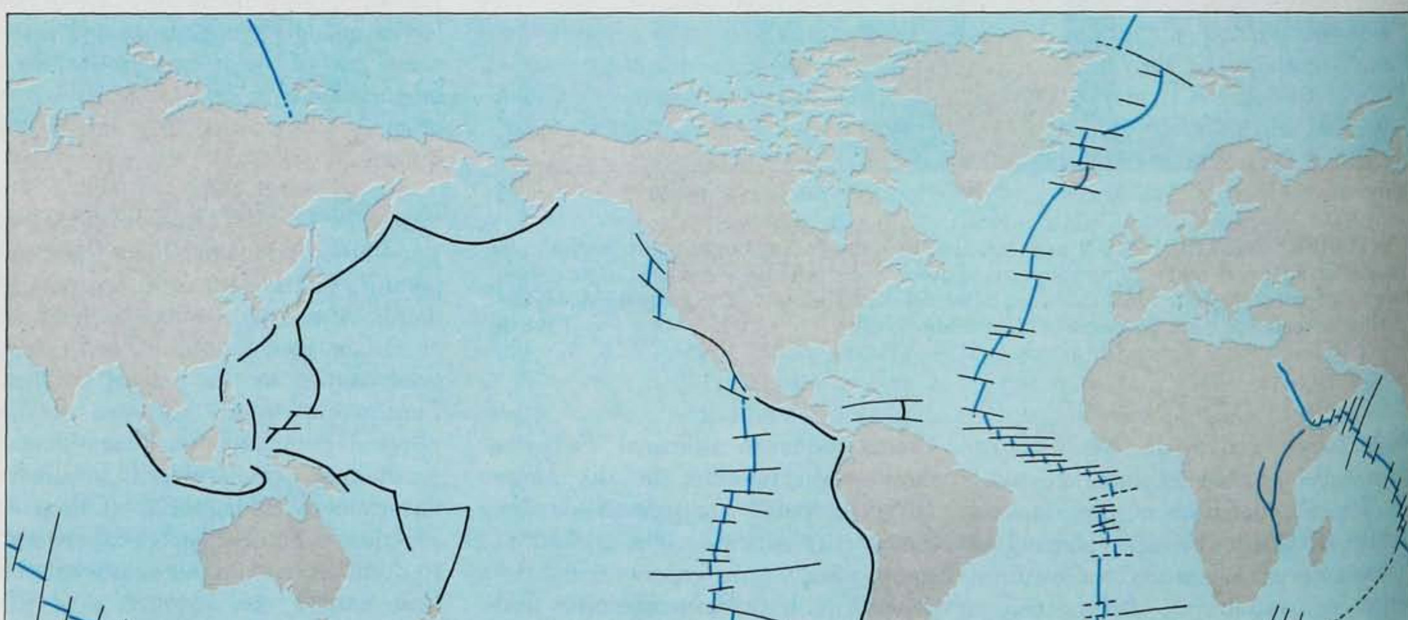
Thermal instability

Accepting a fluid behavior for the upper mantle, we have a fluid in a gravitational field heated both from within and from below. The deep rocks will expand when heated and the gravitational body force will be directed upwards. Lord Rayleigh[20] defined the dimensionless parameter

$$R = \alpha \triangle T d^3 g / \kappa \nu$$

(known as the Rayleigh number) where α is the coefficient of thermal expansion, d the thickness of the layer of fluid, $\triangle T$ the temperature difference across the layer of fluid, g the acceleration of gravity, κ the thermal diffusivity and ν the kinematic viscosity. He showed that a thermal instability will occur if this number exceeds a certain value. P. H. Roberts[20] extended the stability theory to include volume heat release with similar results. When the Rayleigh number exceeds the critical value, cellular convection occurs. The flow is rotational with hot fluid from the lower surface rising and cool fluid from the upper surface sinking. Under some circumstances the flow in laboratory experiments takes the form of two-dimensional rolls.[21] Adjacent rolls circulate in opposite directions.

The late Arthur Holmes[22] first suggested that cellular convection might be occurring within the earth's mantle and that the associated flow is the driving mechanism for continental



RIDGES AND TRENCHES around the world. Ridges are regarded as loci of ascending flow and trenches as loci of descending flow. Both trenches and ridges are offset by faults. Note that although the general character of the ridge-trench system is well known, there still are areas of uncertainty, particularly where the system meets continental areas. —FIG. 5

drift and other dynamic crustal phenomena. Several authors[23] have concluded that the Rayleigh number for the earth's upper mantle is several orders of magnitude larger than the critical Rayleigh number and have shown that the velocities associated with cellular convection in the mantle are of the right order of magnitude to explain continental drift.

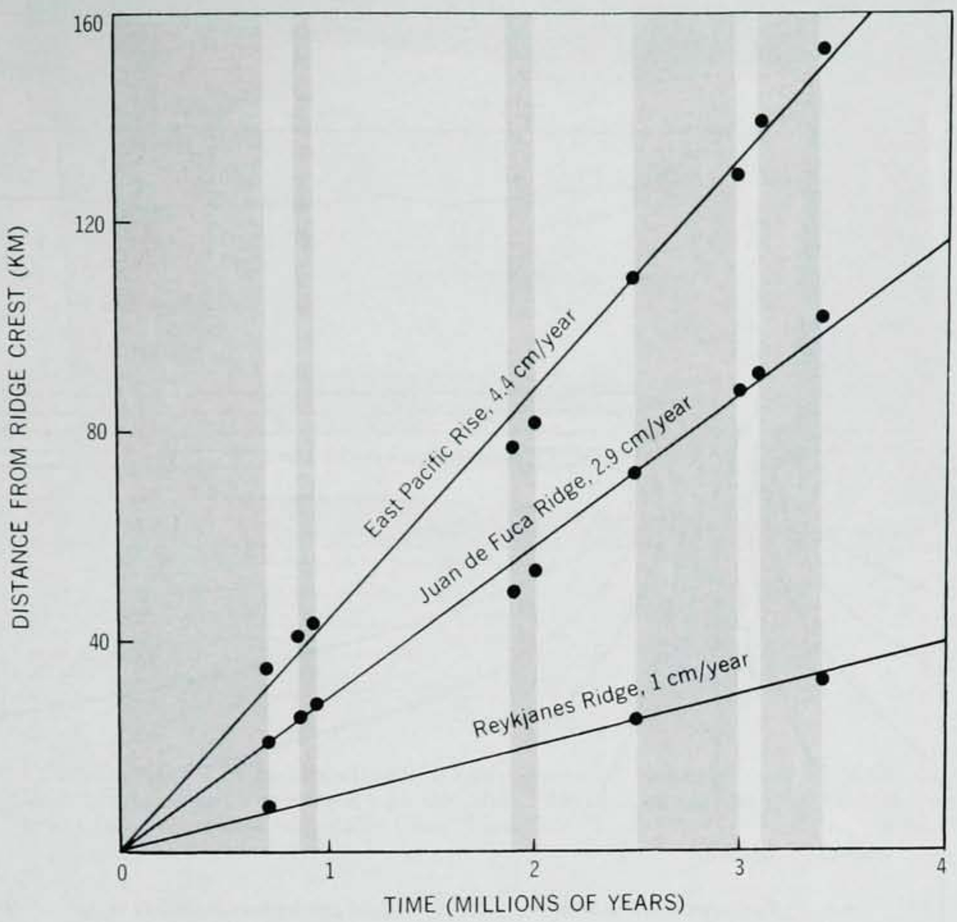
Ridges and sea-floor spreading

Convective cells now operating in the upper mantle are thought to have the form of elongated rolls, tens of thousands of km long and several thousand km wide.[24] Regions of rising, diverging flow are associated with the oceanic ridges. Oceanic ridges comprise wide belts of submarine mountains that rise 3–4 km above the sea floor, and appear to form a semicontinuous and branching world-wide system (figure 5). Note that the mid-Atlantic ridge nearly bisects the Atlantic Ocean.

Oceanic ridges are characterized by shallow seismic activity, volcanic activity, and a surface heat flux that may be as much as six times the average for the ocean floors. The ridges display extensional features that suggest that the crust is moving away from them on both sides. The ocean floor is regarded as the upper surface of the convection cells. Mantle material rises at the ridge to form new oceanic crust, which is then convected laterally. This general process is known as "ocean-floor spreading" and was first proposed by Harry H. Hess.[25] As hot mantle material rises under the ridges it partially melts due to the reduction in pressure. The liquid produced by this process is basaltic magma, which rises rapidly to the surface through the slowly convecting mantle, giving rise to volcanic activity along oceanic ridges. The basalt generated in this way forms the thin oceanic crust that caps the mantle in oceanic areas.

Linear magnetic anomalies

Fred J. Vine and Drummond Matthews[26] have given striking evidence supporting sea-floor spreading. A striped pattern of magnetic anomalies lies parallel to much of the world-wide oceanic ridge system,[27] and in many cases the anomaly patterns are strikingly symmetric about the ridge crest. Vine and Matthews proposed that these linear anomalies represent a fossilized history of the earth's magnetic field. As the oceanic crust is formed in the vicinity of the oceanic ridge, the mantle material cools through its sub-Curie blocking temperature and the rock is magnetized with the polarity of the earth's magnetic field. As the oceanic crust is convected away from the ridge the magnetic anomaly produced by the magnetized crust is a record of the earth's field at the time the crust was formed.



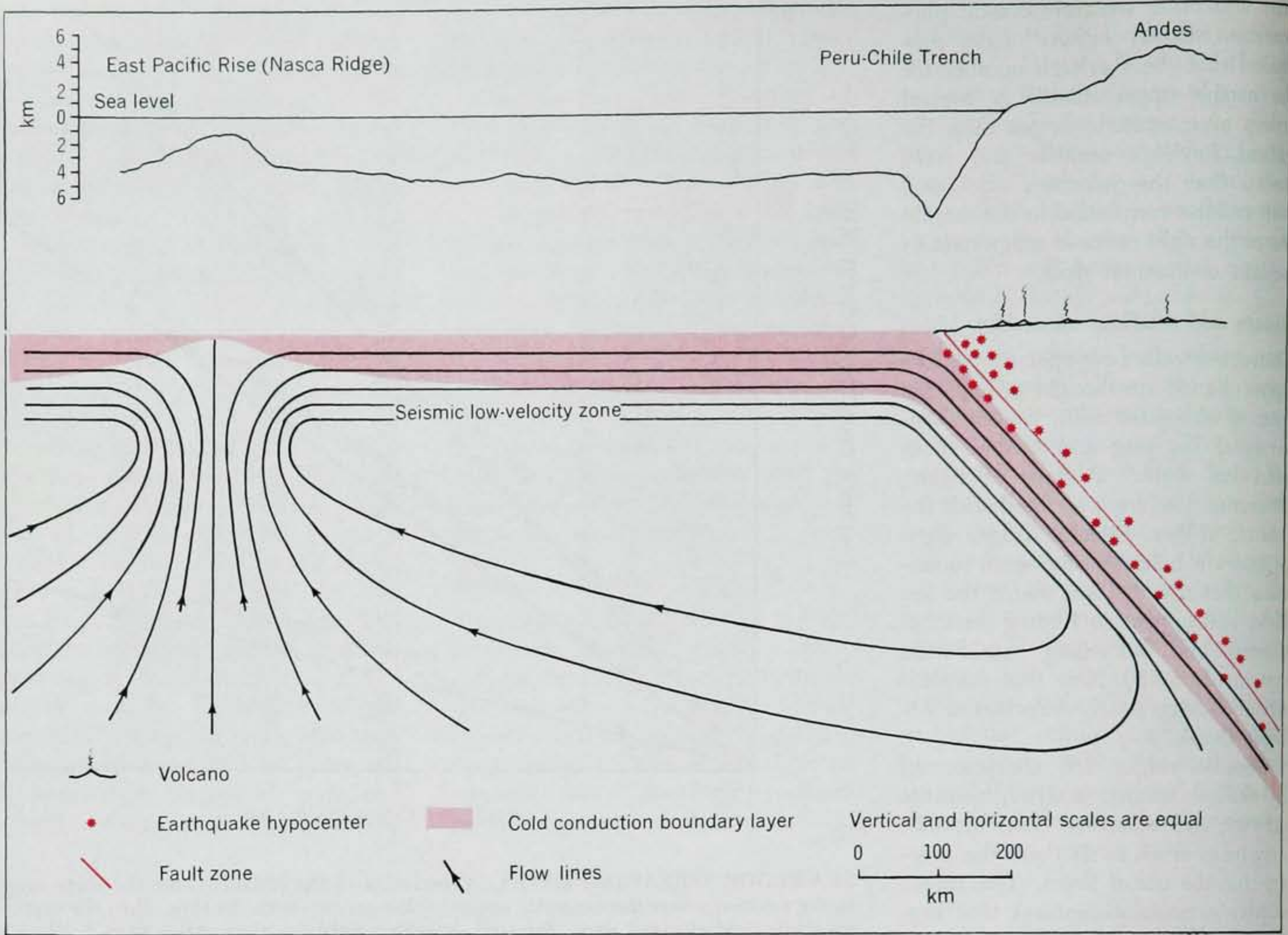
SEA-FLOOR SPREADING RATES. Correlation of the distance from the ridge crest to the position where the magnetic anomaly changes sign with the time when the earth's magnetic field changed sign. Inferred spreading rates are given (after Fred J. Vine[29]). Intervals shown in gray indicate periods of normal (same as today's) polarity of the magnetic field; open intervals are times of reversed polarity. —FIG. 6

Since independent evidence[28] implies that the earth's magnetic field is subject to polarity reversals on a time scale of $10^4 - 10^7$ years, the striped pattern of anomalies is explained and the rate of movement of the crust can be deduced from the spacing of the stripes. Several of these space–time correlations are shown in figure 6. The data points correlate the distance from the ridge crest to the position where the magnetic anomaly changes sign with the time when the earth's magnetic field is known from independent evidence to have reversed. The spreading rate is the slope of this space–time curve. The data points lie close to straight lines; the spreading rate for the mid-Atlantic ridge is near 1 cm/year and the rate for the East Pacific Rise is near 4 cm/year. Many authors[29] have obtained similar correlations.

Since sea-floor spreading is a symmetric process, the actual rate of opening of an ocean is twice the spreading rate measured on one flank of a ridge. The measured spreading rates of 1–5 cm/year are of the correct magnitude to explain continental drift. It should also be noted that the mean rates of slip on major fault zones such as the San Andreas fault are also in the range of 1–5 cm/year.[30]

Oceanic trenches

If we accept oceanic ridges as sources of new oceanic crust, complementary zones of converging descending flow must exist if surface area (and thus volume) is to be conserved. Oceanic trenches (figure 5) are identified as such regions of descending flow. They



POSSIBLE CELL STRUCTURE for the East Pacific Rise–Andean region (looking north). The rapid, low-viscosity, hot ascending flow is situated under the rise; cooling by conduction to the ocean establishes a cold, brittle thermal boundary layer at the upper surface; gravitational instability of the cold boundary layer and interference of the continental margin causes descending flow along a steeply inclined fault characterized by seismic activity. Frictional dissipation along the fault gradually destroys the cold boundary layer by conductive heating and gives partial melting along the fault zone with consequent volcanic activity at the surface. Profile at top shows the topography from ridge to trench with the vertical scale exaggerated 20 times. –FIG. 7

are narrow, elongate, perioceanic depressions that are about twice the depth of the adjacent oceans; arcuate strings of volcanic islands commonly lie on the continental side of the trenches, for example the Aleutians with the Aleutian Trench. Oceanic trenches are characterized by large negative gravity anomalies. Zones of earthquake activity extending from near the bottom of the trench to depths of 700 km lie close to a plane inclined at 45 deg towards the island arcs.

An analysis of the first motions of these earthquakes as recorded at different observatories[31] shows the motion on such a fault to be predominantly downwards. The ocean floor appears to be sliding down an inclined fault under a relatively static block. This model has been used to explain[32] an extensive zone of high Q (low attenuation of seismic energy and therefore presumably low temperature) that dips beneath the fault zone. The associated island arcs are largely built of volcanic material and are commonly the site of current andesitic and basaltic volcanic activity.

Heat flow on the island-arc side of the trench is more than twice the heat flow on the ocean side.[33] Both the high heat flow and the volcanic activity can be explained quantitatively by frictional heating of the fault zone.[34] The andesitic lavas are attributed to melting of the descending oceanic crust, and the basaltic lavas to melting of mantle material; in contrast, beneath oceanic ridges only the mantle can be melted and only basaltic magmas are observed.

Figure 7 shows the topography off the west coast of South America at 22 deg S. A possible convection cell operating between the Nasca Ridge, part of the East Pacific Rise, and the Peru–Chile Trench is illustrated. The fault zone shown is well documented and was the source of the 1960 Chilean earthquake; taking the place of the island arc in this case are the Andean mountains on the continental side of the trench.

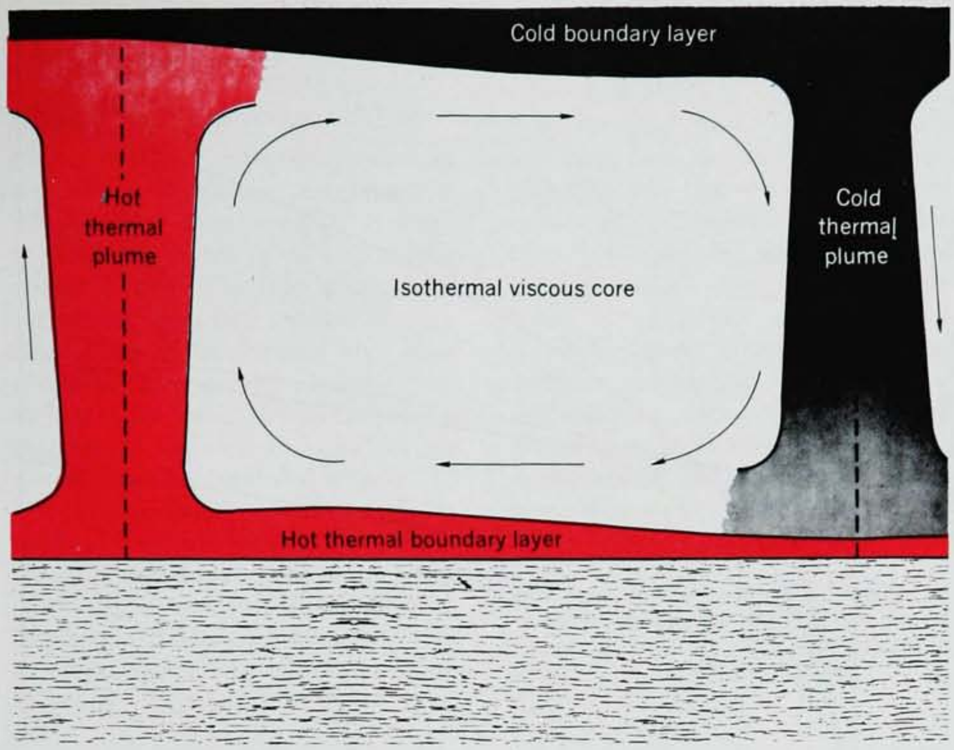
Boundary-layer convection

So far our discussion of cellular convection within the earth's upper mantle has been qualitative; to make quantitative predictions we need a theory for the structure of the convection cells. While a considerable literature exists on the linear stability problem,[35] the nonlinear theory for the structure of steady thermal convection has received little attention.[36] A theory for the structure of convection cells applicable to the earth's mantle has been given by the authors.[37] For a fluid with large Prandtl and Rayleigh numbers it is appropriate to use a boundary-layer theory. A fluid is confined between two horizontal boundaries and is divided into two-dimensional rolls with rectangular cross sections; alternate rolls rotate clockwise and anticlockwise. For constant fluid properties an analytic solution for the flow field and temperature distribution is easily obtained. The entire flow field is highly viscous and the inertia of the fluid may be neglected.

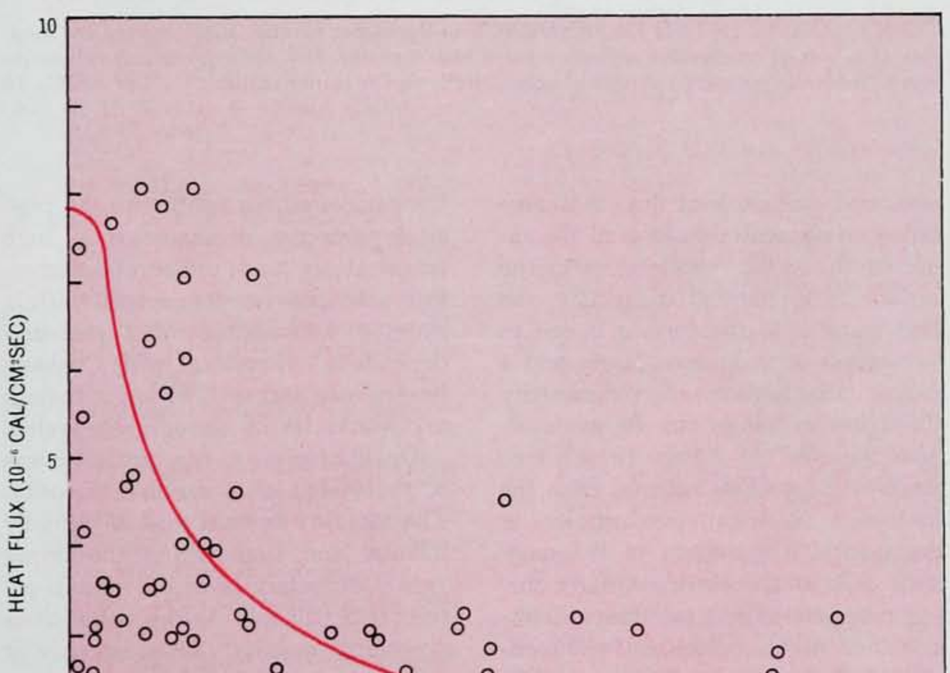
With the viscosity much larger than the thermal diffusivity (large Prandtl number), thermal gradients are restricted to thin thermal boundary layers on the boundaries of each cell. When the two hot thermal boundary layers formed on the lower surface of adjacent cells meet, the flow separates from the lower boundary and forms a hot thermal plume that rises to the upper surface. Similarly when two cold boundary layers formed on the upper surface in adjacent cells meet, the flow separates from the upper boundary and forms a cold plume that descends to the lower surface. The buoyancy forces in the plumes drive the viscous flow. The flow structure is illustrated in figure 8.

We have applied the constant-property, boundary-layer theory for cellular convection to mantle convection.[38] Predicted velocities are in good agreement with those associated with continental drift, and the theory predicts the pattern of heat flux to the ocean floors. This prediction is compared with measurements made on the ocean floor[19] in figure 9. Although there is a large scatter in the observational data, reasonable agreement between theory and measurement is obtained. Similar correlations based on convective heat transfer have been given by Marcus G. Langseth et al[39] and by Dan P. McKenzie.[40]

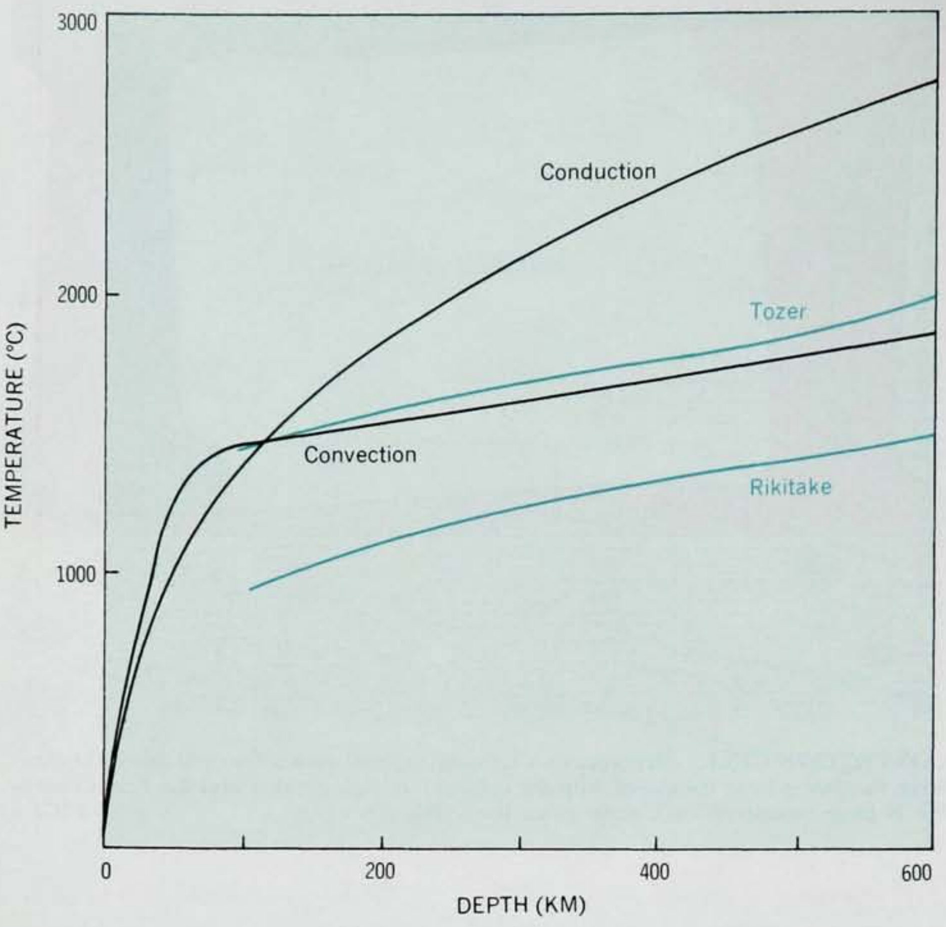
If thermal gradients are restricted to thin thermal boundary layers, it is expected that the thermal gradient in the mantle below the thermal boundary layer will be close to the adiabatic gradient. Such a convection temperature profile is shown in figure 10. Included for comparison is a typical conduction profile with volume heat release due to radioactivity.[41] A conduction profile can be valid only if thermal convection is not occurring. For a conduction solution to give the



CONVECTION CELL. Structure of a two-dimensional convection cell when the Rayleigh number is large compared with the critical Rayleigh number and the Prandtl number is large compared with unity (after the authors[37]). —FIG. 8



OCEAN-FLOOR HEAT FLUX as a function of distance from an oceanic ridge. Open circles are measurements for the East Pacific Rise compiled by William H. K. Lee and Seiya Uyeda[19] and the solid curve is the boundary-layer theory as compiled by the authors.[38] The wide scatter of the measurements is in part because of experimental difficulties but probably also reflects true heat-flow variations resulting from near-surface irregularities in both topography and conductivity. —FIG. 9



TEMPERATURE-DEPTH DEPENDENCE in the upper mantle. Black curves are theoretical values of conductive and convective heat transfer. Colored curves are values inferred from the measured electrical conductivity in the upper mantle.[42] —FIG. 10

measured surface heat flux, it is necessary to concentrate much of the radioactivity in the mantle close to the surface; with thermal convection, the heat transfer to the surface is one to two orders of magnitude larger and a deeper distribution of radioactivity through the mantle can be assumed. Also included in figure 10 are two temperature profiles inferred from the measured electrical conductivity in the mantle.[42] Variations in the magnetic field at the earth's surface during magnetic storms provide a determination of the electrical conductivity of the mantle to depths of 1500 km. These measurements seem to favor the boundary-layer distribution of temperature over the conduction profile.

Variable properties

The present generation of physical models for the upper mantle has many deficiencies; those that are relatively complete are qualitative and, except in the most general way, incapable of being tested. Those that are quantitative and rigorous are necessarily oversimplified and suffer from uncertainties relating to the physical properties of materials at high temperatures and pressures. Numerical solutions for convection with a strongly temperature- and pressure-dependent viscosity, with volume heat release and with no lower boundary would be of considerable value.

Qualitatively we can predict some of the effects of a variable viscosity. The viscosity of cold rock is virtually infinite, and thus within the upper (cold) boundary layer the viscous assumption will fail. As the hot viscous upwelling material flows laterally it will cool rapidly and become a near-rigid plate that rides passively on the viscous hot mantle beneath. We should also expect the hot ascending flow to be driven by a relatively small temperature excess, to have high flow rates and to be localized, while the cold descending flow requires a large body force and therefore a large temperature difference. Similarly the upper horizontal flow that is derived from the hot ascending flow should move more rapidly and occur within a shallower depth interval than the deeper counterflow.

The base of the upper horizontal flow probably occurs about 150 km deep in the seismic low-velocity zone (figure 7). Within this zone seismic waves are strongly attenuated and the melting point is closely approached or exceeded; as a result the mantle has little strength. It is expected that this zone decouples the upper horizontal flow that carries the crust from the sluggish, more viscous counterflow beneath.

These considerations have led some to adopt an ocean-floor spreading model with a deep structure different from that outlined above. The model suggests that below the seismic low-velocity zone the thermal gradient is controlled by conduction processes and that at the low-velocity zone the conduction gradient intersects the melting curve. Ocean-floor spreading is assumed to occur by injection of magmas along the oceanic ridge. These magmas are derived from the low-velocity zone that decouples the moving upper layer from a relatively static zone beneath. A satisfactory match to the surface heat flow observations can be given by this model; the most important difference is that ridge structure does not extend deeper than the low-velocity zone. Otherwise the general character of the descending flow is common to both models.

World-wide seismicity

Further confirmation of the ocean-floor spreading hypothesis and the concept of thin, brittle surface plates that slide with respect to each other has come from earthquake studies. Following the recognition by J. Tuzo Wilson[43] of the character of the transverse faults that appear to offset midocean ridges (figure 5), W. Jason Morgan[44] has shown that the whole surface of the earth may be divided into a series of internally rigid blocks that are in motion with respect to each other. Earthquakes occur along the margins of these blocks. Because the motion takes place on the closed surface of a sphere of constant volume, only three kinds of motion are possible between adjacent blocks; they may move past each other along edges that are sectors of great or small circles parallel to the relative motion, they may move away from each other with a new surface created between them (at ridges) or they may move together, in which case surface must be destroyed (at trenches).

Clearly there must be a balance between the creation and destruction of crust. The type of motion associated with any particular earthquake may, under favorable circumstances, be identified, and the motions observed make consistent patterns around the margins of all blocks that have been investigated in detail.

The thick crust of the continents is carried about passively as if riding on a conveyor belt. Its mean density is too low and its thickness too great for it to participate to any significant extent in the descending flow. It appears that a continental mass will ride its conveyor belt as far as the zone of descending flow; once there the continent either decouples from the flow beneath, or it stops the flow. In contrast it appears that the thin, cold oceanic crust can readily be carried down into the mantle.

Implications of a flowing earth

In the last five years verification of ocean-floor spreading has changed the status of continental drift from speculative conjecture to a generally accepted fact. The ramifications of ocean-floor spreading for almost every field of the earth sciences have been enormous. Large-scale motions of the surface have been shown to involve complementary mass transport in the mantle down to depths of at least 700 km. Mass motions on this scale at rates of centimeters per year must certainly control the thermal structure of the upper mantle. Similarly, when geochemical balances are made, account must now be taken of the large-scale mass motions that not only bring new material to the surface but remove it as well.

Earthquake seismologists for the first time have found a coherent explanation for the world-wide distribution of earthquakes and their motions.[45] Within the field of classical geology a host of long-standing problems, for example sedimentary-basin subsidence, regional differential vertical movements, igneous and metamorphic activity and orogenic phenomena, must all be reconsidered in the light of this revolution in fundamental concepts.

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