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Earth, heat flow in

Observations of heat flow through the ocean floor are being successfully interpreted in terms of the cooling of aging lithosphere, and continental heat flow can be interpreted as the additive effect of heat from the mantle and heat generated at a high level from crustal concentrations of radiogenic elements. Most of the high heat flow areas of the world that are being expressed as active volcanoes are associated with extremes of topography and are concentrated close to active plate margins. *See* EARTH, INTERIOR OF; OCEANIC ISLANDS.

Hot spots are a group of volcanic features that occur in both continents and oceans. They possess characteristics that cannot be explained in the above three ways. Hot spots can be defined as topographically high areas of volcanic activity distinct from those commonly developed at plate margins. Interest in hot spots has developed because they might help to show how lithospheric plates are driven across the surface of the Earth and because of a hope, since shown to be unfounded, that they might provide a fixed frame to which plate motions could be referred. Studies of hot

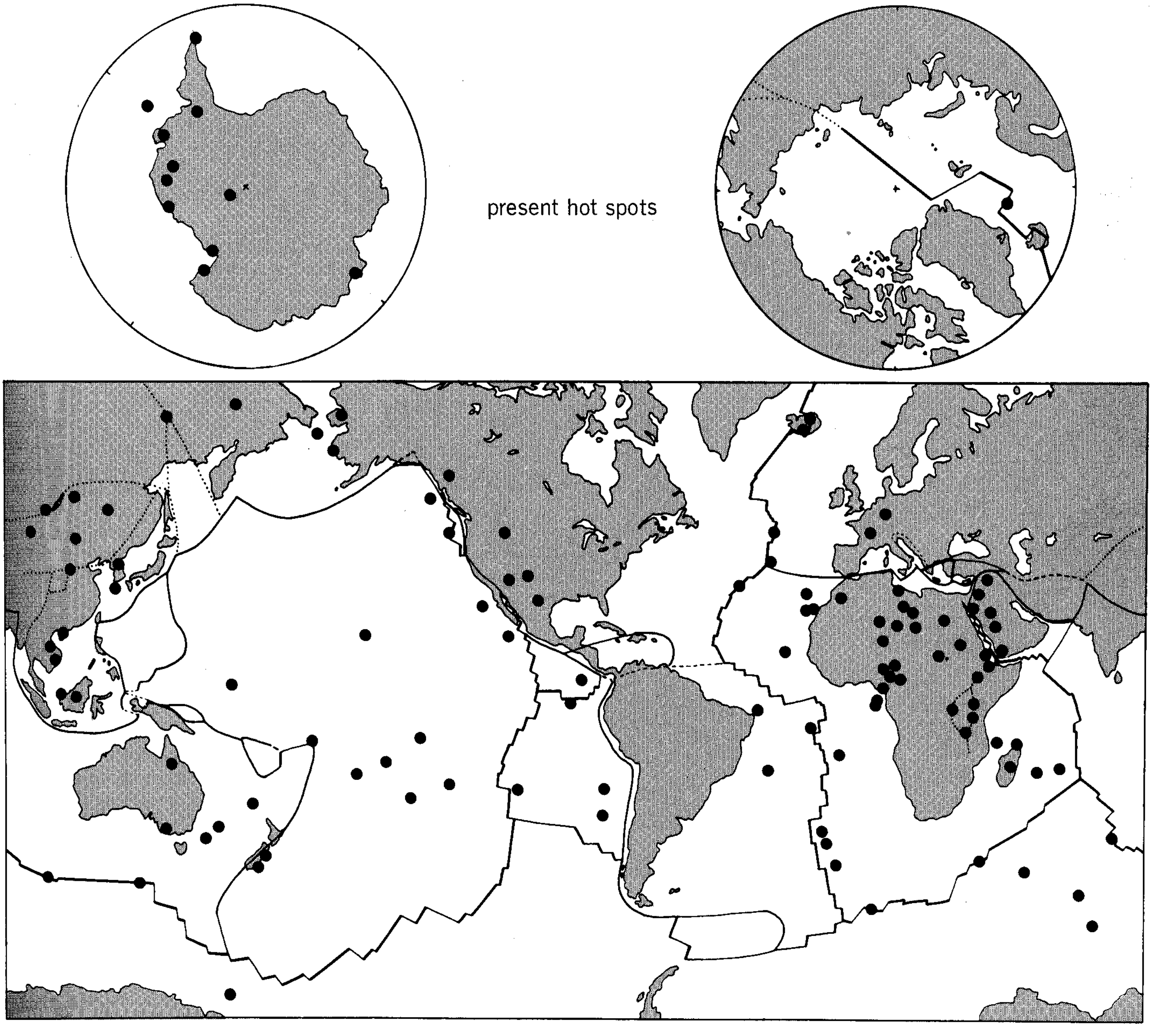

Fig. 1. World distribution of 120 hot spots where volcanic activity has occurred within the last 10,000,000 years.

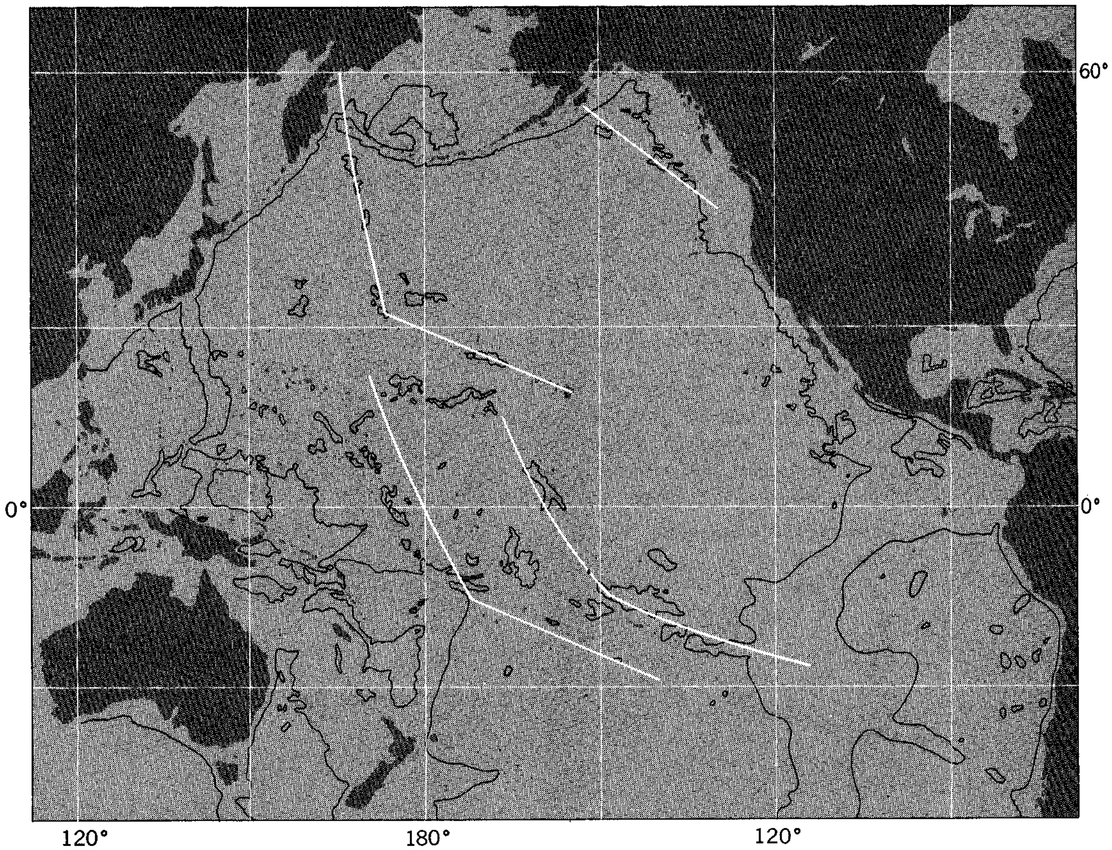

Fig. 2. Hot spot trajectories constructed by rotating the Pacific plate 34° about a pole at 67°N73°W and then 45° about a pole at 23°N110°W. *(From W. J. Morgan, in R. Shagam, ed., Studies in Earth and Space Sciences, Geol. Soc. Amer. Mem. 132, pp. 7–22, 1972)*

spots formed during the last 2,000,000,000 years are providing evidence of how continents rupture and of how long the rigid lithosphere has been breaking up and moving about in the complex interwoven cycles of ocean opening and closing that result in continental drift.

Present hot spots. A striking feature of hot spots of the world is their uneven distribution (see Fig. 1). This inhomogeneity is partly, but cannot be entirely, due to the difficulty of successfully recognizing all hot spots, especially in extensive oceanic areas such as the Pacific. Hot spots like Iceland are concentrated along the axes of spreading oceanic ridges, where they are readily recognized by their anomalously high topography as well as by the distinctive chemistry of the lavas they erupt. W. J. Morgan pointed out that a majority of this group of hot spots lie close to triple junctions, places where three plate boundaries meet (for example, the Azores and Bouvet Islands in the central and South Atlantic). Concentrations of hot spots within plates are very uneven. A major concentration lies in the northern half of the African plate. Volcanism within this plate started roughly simultaneously in a number of widely separated areas about 25,000,000 years ago and coincided with the beginning of an episode of rifting that has led to the separation of Arabia from Africa along the Red Sea and the Gulf of Aden and to the development of the East African Rift Valley. A similar episode of rifting and volcanism in Africa marked the breakup of Gondwanaland between 100,000,000 and 200,000,000 years ago.

More than 10 years ago, J. T. Wilson showed that aseismic ridges and lines of islands in oceans could be explained as products of the passage of rigid oceanic lithosphere over underlying hot spots. Morgan produced supporting evidence for this hypothesis by showing that three L-shaped ridges in the Pacific (Fig. 2) could be described by two successive rotations of the rigid Pacific plate over three hot spots which had been fixed with respect to each other during the last 70,000,000 years. Deep-sea drilling close to the Line Islands (the upper arm of the middle of the three L-shaped ridges of Fig. 2) during 1973–1974 has shown that more complicated relations between hot spots and plate motions are needed to account for the aseismic ridges of the Pacific. In this respect, Pacific Ocean hot spots are being shown to resemble those of the Atlantic and Indian oceans, which are known to erupt intermittently and to move with respect to each other in complex and irregular ways at velocities at times as high as 6 cm/yr.

Atlantic hot spots have also been shown to have lives ranging from 200,000,000 to 20,000,000 years, although some may be even shorter-lived. The spectacular development of hot spots on the African plate during the last 25,000,000 years, and during the breakup of Gondwanaland, has shown (Fig. 4) a characteristic sequence of development from uplift and volcanism through the develop-

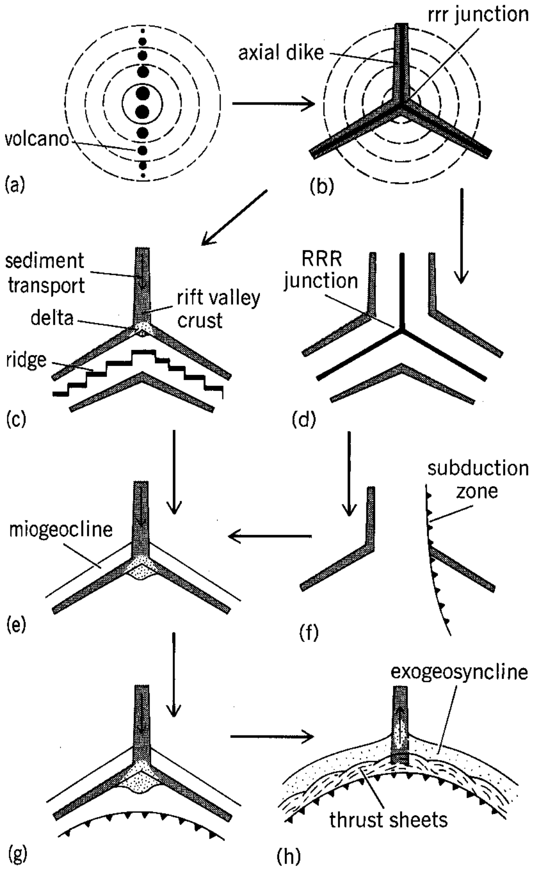

Fig. 3. Schematic origin and evolution of plume-generated triple junctions: *(a)* uplift develops over plume with crestal alkaline volcanoes; *(b)* three rift valleys develop, meeting at an rrr (rift-rift-rift) junction; *(c)* two rift arms develop into a single accreting plate margin (ridge), and continental separation ensues; *(d)* three rift arms develop into accreting plate margins that meet at an RRR junction, where three spreading ridges meet; *(e)* Atlantic-type continental margin evolves with growth of delta at mouth of a failed arm and miogeoclines; *(f)* one arm of RRR system of *d* begins to close by marginal subduction; *(g)* Atlantic-type continental margin with miogeoclines and failed rift arms approaches a subduction zone; *(h)* continental margin collides with subduction zone, collisional orogeny ensues, sediment transport in the failed arm reverses polarity, and failed arm is preserved as an aulacogen striking at a high angle into an orogenic belt. *(From K. Burke and J. F. Dewey, Plume generated triple junctions: Key indicators in applying plate tectonics to old rocks, J. Geol., 81:406–433, 1973)*

ment of crestal rifts on uplifts and three-armed rift junctions to continental rupture (Figs. 3*a*–*d* and 5). The most common sequence of events (Fig. 3*c*) is for two rift arms at a triple-rift junction to spread, and thus create a new ocean, and for the third to survive as a failed rift arm striking at a high angle into the continent. The characteristic irregular shapes of continental margins (Fig. 5) are thus seen as a normal consequence of rupture along lines joining triple-rift junctions over hot spots. The major deltas, such as those of the Niger and the Mississippi, which lie at the mouths of failed rift arms, are places where exceptional accumulations of petroleum are commonly found.

Aulacogen patterns. One of the main results of the application of the principles of plate tectonics

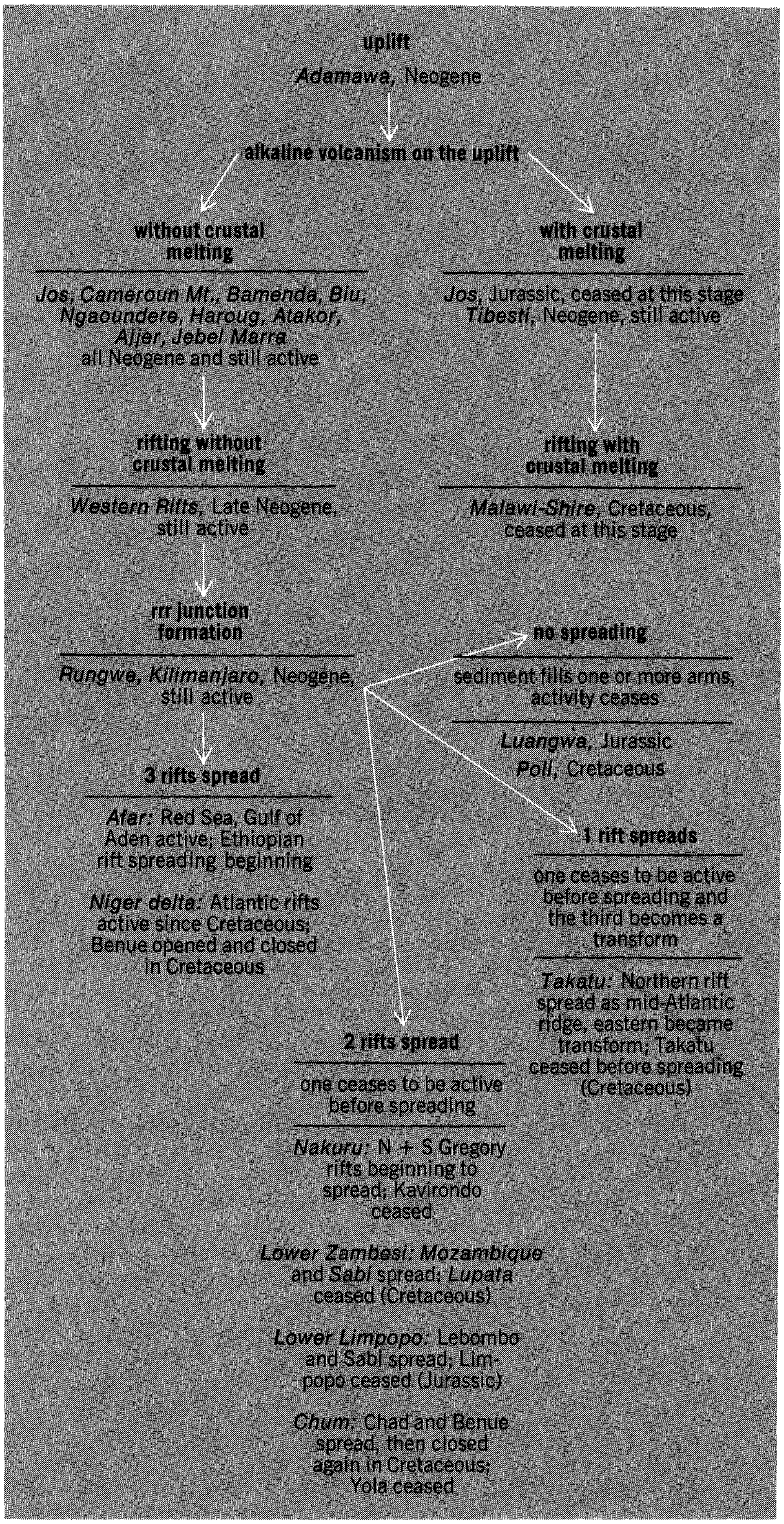

Fig. 4. Sequences of African structural development, *(From K. Burke and A. J. Whiteman, Uplift, rifting and the break-up of Africa, in D. H. Tarling and S. K. Runcorn, eds., Implications of Continental Drift to the Earth Sciences, Academic Press, vol. 2, pp. 735–755, 1973)*

to the interpretation of continental geology has been the recognition that orogenic belts mark places where oceans have first opened and then closed (the so-called Wilson cycle, after J. T. Wil-

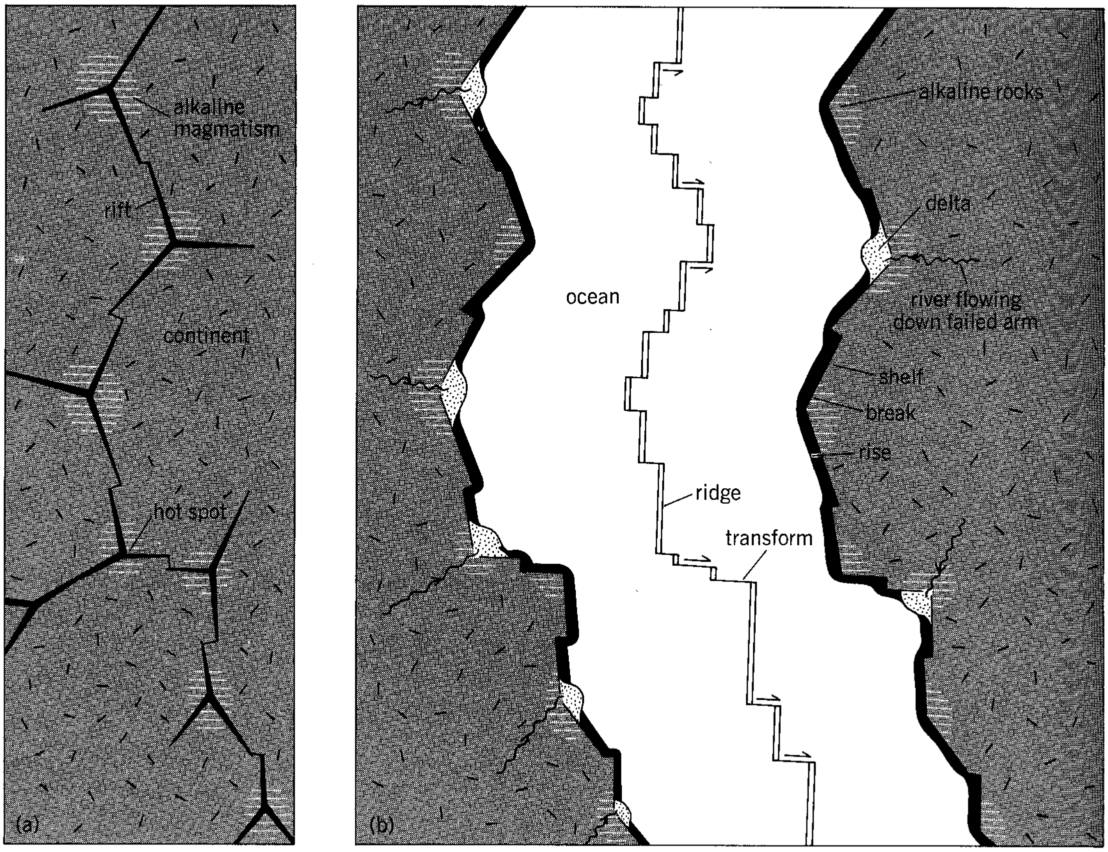

Fig. 5. Sketch maps representing early stages of Wilson cycle. (*a*) Continental crust starting to rupture along rifts that meet at rrr junctions over hot spots characterized by alkaline magmatism. Major irregularities in continental margins mark sites of former rrr triple junctions; minor irregularities mark misfit connections between propagating rifts. (*b*) Ocean in advanced Atlantic stage. Rivers flow down failed arms to feed deltas at reentrants on continental margins. Shapes of continental margins retain pattern of continental rupture. Alkaline rocks with ages dating rupture are concentrated at projections and embayments. Shapes of deltas and interdelta miogeoclinal sediment wedges are more variable than shown and are controlled by such factors as wind direction, transform strike, salt tectonics, and currents both at surface and at oceanic depths. *(From J. F. Dewey and K. Burke, Hot spots and continental break-up: Implications for collisional orogeny, Geology, 2:57–60, 1974)*

son). The irregular continental margins formed by ruptures that linked lines of hot spots during ocean opening can be recognized where the oceans have later closed as bends in mountain belts, some having failed arms leading away at high angles into cratonic areas (Fig. 3*h*). This relationship between failed rift arms and mountain belts was first recognized more than 25 years ago by N. Shatsky in the Soviet Union. Shatsky coined the word aulacogen for the failed rifts. It was not recognized that the junction of an aulacogen with a mountain belt marks the site of a former hot spot until mountain building was interpreted in terms of ocean opening and closing.

Because the pattern formed by an aulacogen and its junction with a mountain belt is so distinctive (as in Fig. 3*h*), the sites of old hot spots have proved readily recognizable, and during 1974 it was shown that hot spots have formed a distinctive feature of the Wilson cycle throughout the last 2,000,000,000 years. Prior to that time, more complex patterns prevailed, and it has been inferred that, because of greater rates of radiogenic heat generation, the thick rigid lithosphere that characterizes the plate tectonic regime had not developed.

Source of volcanic materials. Although much has been learned in recent years about hot spot distribution in space and time, no correspondingly clear picture has emerged of the source of the volcanic materials in the hot spots. There is some geochemical evidence that indicates a source at a depth greater than the 100 km or so that is sufficient to produce most hot spot volcanic material. Among the hypotheses of hot spot origin currently under consideration are: production of hot spots along propagating fractures in the lithosphere; origin by partial melting at the abraded base of the lithosphere, leaving a dense root in the mantle that serves as an anchor to keep the hot spot fixed; and an origin from deep-mantle plumes. Seismic evidence has revealed the existence of an area of anomalous density just above the core-mantle boundary beneath the Hawaiian Islands. This anomalous mantle is compatible with the last two hypotheses.

For background information *see* Earth, heat flow in; Earth, interior of; Rift valley; Volcanology in the McGraw-Hill Encyclopedia of Science and Technology.

[Kevin Burke; W. S. F. Kidd]

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Earth, interior of

The acceptance of the concept of continental drift has revolutionized the earth sciences. Although the mantle of the Earth is a solid, on geological time scales it must behave like a fluid. One of the most important unanswered questions concerns the mechanism that causes continental drift.

Energy and motion in surface plates. The surface of the Earth is broken up into a number of plates that move with respect to one another. Plates apparently are created from mantle rock at ocean ridges and descend into the mantle at trenches. Lateral motion between plates results in great faults such as the San Andreas in California.

Relative motion between plates is responsible for most mountain building, earthquakes, and volcanism. The energy source for plate motions is also the energy source for these secondary phenomena. The only energy source of sufficient magnitude is the heat generated by the decay of radioactive elements within the Earth. Principal sources of heat are uranium-235, uranium-238, thorium-232, and potassium-40. The concentration of these elements within the Earth can be estimated from the measured heat flow to the Earth's surface and the relative concentrations of these elements in surface rocks.

Once the energy source is found, it is necessary to determine the mechanism that converts heat into motion in order to explain the relative motion of the surface plates. This can be done if the solid mantle of the Earth behaves like a fluid on geological time scales. Such behavior is in accord with present understanding of the physics of mantle rocks. At high temperatures crystalline solids under low stresses deform because of diffusion of atoms and dislocations within the crystals. This deformation is strongly temperature-dependent; only at temperatures near the melting temperature does significant deformation occur. Studies of the subsidence due to glaciation and the subsequent uplift have supplied quantitative values for the fluidlike properties of the solid mantle.

Mantle convection. A fluid that is heated from within and cooled on the upper surface is subject to thermal convection. The interior of the Earth is hot, and the uncompressed density of the interior rocks is less than that of the cool, near-surface rocks. In the gravitational field of the Earth, the cool near-surface rocks tend to sink, and the hot interior rocks rise. Numerical calculations of the resultant flows have been made by D. L. Turcotte, K. E. Torrance, and A. T. Hsui. A typical flow pattern is shown in Fig. 1.

The near-surface rocks are cold and brittle and form the rigid surface plates of plate tectonics. Deformations of the surface rocks cause fractures that result in earthquakes. The surface plates are created from hot ascending mantle rocks at ocean ridges. During the ascent of the mantle rocks, partial melting of the basalt component occurs owing to the reduction of pressure. The liquid basalt is light and mobile and rises to the surface, causing volcanism at ocean ridges and forming the ocean crust above the Moho.

As the near-surface rocks convect away from the ridge, they cool by conduction of heat to the surface. It is deduced from the topography of the ocean ridges that the thickness of the surface plates increases as the square root of their age. This is the expected relation for a cooling plate, and it is concluded that the lower boundary of the plate is defined by the temperature at which the plate significantly deforms under stress (about 1000°C).

Because of thermal contraction the uncompressed density of the cool surface plate is greater than that of the underlying hot mantle. As the plate thickens, it becomes gravitationally unstable and plunges into the mantle at an ocean trench. The gravitational body force on the dense plate pulls it down like a stone in water, and the surface plate is pulled with it; this is a primary mechanism causing continental drift.

It has been deduced from seismic observations

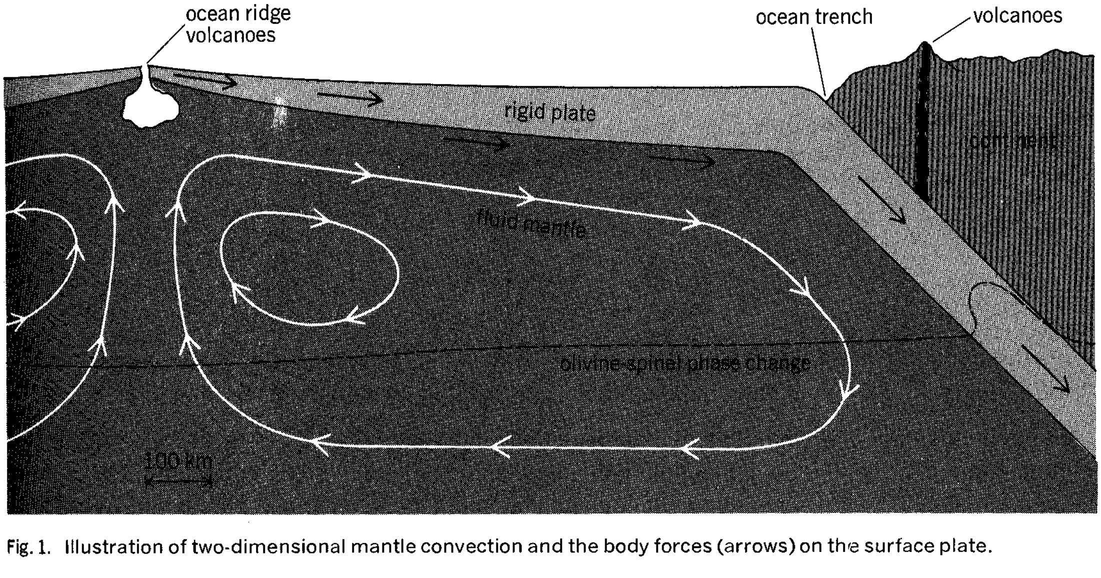

Fig. 1. Illustration of two-dimensional mantle convection and the body forces (arrows) on the surface plate.

On preceding pages:

Left. Scanning electron micrograph of the tongue of a housefly; magnification 90X.

Right. Scanning electron micrograph of a daisy pistil fertilized with two pieces of pollen; magnification 105X.

Both specimens were photographed in the natural state without use of fixatives, preservatives, or stains. (Courtesy David Scharf)

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