Plate Tectonics: Hot Spot Implicated in Ridge Formation

When the theory of plate tectonics was first widely accepted in the 1960's, most of the major surface features of the ocean floor fit into the general scheme. The theory held that new ocean crust is created as large, thin plates at mid-ocean ridges and that it eventually plunges back into the mantle at the deep trenches, which are paralleled by volcanic mountain chains. But plate tectonics did not explain everything right off. Many geologic features, such as island chains and submarine ridges, did not have an obvious place in the basic theory.

Since the mid-1960's, it has become increasingly evident that volcanic island chains (including completely submerged mountains known as seamounts) and submarine ridges are similar in many ways, but only limited evidence existed showing that they actually formed in the same way. Researchers have believed for several years that the single volcanic chain formed by the Hawaiian Islands and the Emperor Seamounts was built up by magma that welled up through the ocean crust at a hot spot, a spot over a small stationary source of molten rock beneath the moving plates (*Science*, 26 July 1974, p. 340). Now, recent data from the Ninetyeast Ridge in the Indian Ocean has convinced most investigators that it, too, formed at a hot spot.

Previously, island chains and submarine ridges did not fit the generally accepted plate tectonic theory because they are in the middle of plates, not on their edges where 99 percent of volcanic activity occurs. They appeared to experience few if any earthquakes, although the volcanism at plate edges is associated with numerous earthquakes, and their chemical composition was distinct from those of other types of volcanism.

These anomalous aspects and the highly suggestive alignment of features like the Hawaiian-Emperor chain prompted both Jason Morgan of Princeton University and Tuzo Wilson of Toronto University to propose the addition of the hot-spot hypothesis to the basic framework of the plate tectonic theory. At a hot spot, such as that marked by the active volcanoes on the island of Hawaii, magma reaches the surface from an as yet unidentified source beneath the rigid plate. If the plate is moving, a trail of rock is left on the plate as the plate moves over the stationary hot spot, just as smoke is left in the air when the air passes over a chimney. The hot-spot hypothesis was in large degree an intuitive proposition until samples recovered from the Hawaiian-Emperor chain by the Deep Sea Drilling Project (DSDP) confirmed that a hot spot is the only reasonable source for that chain. Although the Ninetyeast Ridge has a much more complex past than the Hawaiian-Emperor chain, analyses of a limited number of DSDP samples from it suggest to most researchers that a hot spot formed it also.

Far higher and longer than the Appalachian Mountains, the Ninetyeast Ridge is like nothing on dry land and is the longest, most striking example of its kind in the sea (Fig. 1). It stretches for 4500 kilometers along the 90-degree east meridian of longitude and is nearly as straight as a meridian. Flat-topped, it rises, on the average, 2 kilometers above the sea floor and is 50 to more than 100 kilometers wide. The ridge disappears to the north under the fan of sediment dropped by the Ganges and Brahmaputra rivers, and to the south it ends a thousand kilometers from the nearest present-day hot spot. Unlike the Hawaiian-Emperor chain, it is largely a continuous ridge with no apparent seamounts and no current volcanic activity.

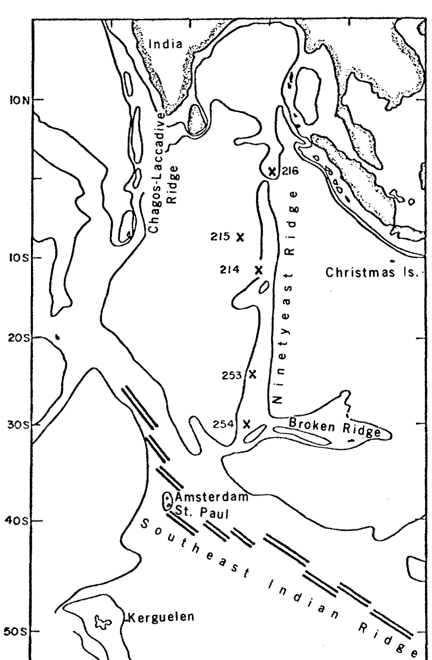

Fig. 1. Eastern Indian Ocean. The crosses indicate Deep Sea Drilling Project sampling sites. The spreading centers of the Southeast Indian Ridge are indicated by the heavy double bars. The ends of the spreading centers are connected by active transform faults. [Source: David Whitford, Carnegie Institution of Washington]

Suggested mechanisms for the formation of Ninetyeast Ridge have been numerous, including plate passage over a hot spot, vertical movement of the ocean floor, the overriding of one plate by another, and the leaking of magma up through a fault between separate plates. In the latter case, magma from the same source supplying a mid-ocean ridge crest, or spreading center, would leak up through an adjoining fault, called a transform fault. Transform faults allow for the movement of newly formed plates past each other where sections of linear spreading center are offset from one another (Fig. 1). In fact, the Ninetyeast Ridge parallels an inactive transform fault.

Arguments favoring particular mechanisms that were based solely on what is known about plate motions in the past had not been convincing to many researchers because of the limited data and the complication of three different plates, the Indian, Australian, and Antarctic, being involved at one time or another. A different approach, successful in the case of the Hawaiian-Emperor chain, is to determine where and when the sampled portions of the ridge were formed. Data now available for Ninetyeast Ridge indicate that it was formed progressively from north to south, but all of the ridge was formed at a point far south of its present location.

Classification of the types and forms of volcanic rocks and their overlying sediments, recovered during DSDP drilling, provided the first support for such a conclusion. Paleontological analyses of the sediments indicated not only that the ridge formed from north to south, but also that the sediment at a particular site on the ridge first collected in shallow water and then moved under warmer and warmer water as it sank to its present depth. Some of the volcanic rocks were even formed on dry land. Researchers tentatively concluded that the ridge grew in length over a period of at least 40 million years, originating well south of the warm tropical waters that it now underlies and then slowly sinking as it moved northward on the Indian plate.

Confirmation of the paleontological ages of the ridge by the radiometric dat-

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ing of the volcanic rocks with the potassium-argon method failed at first, giving an unreasonably fast drift for the ridge. Dating of the same rocks by a modified version of the standard method, which was first developed for the analysis of moon rocks, has recently yielded dates consistent with the paleontological ages. R. A. Duncan of Oregon State University found that the results of the modified method, termed the argon-40/argon-39 incremental heating technique, were not significantly influenced by the rocks' exposure to seawater for up to 80 million years, as the standard method apparently was.

The "clock" for both versions of the method is the slow, unalterable radioactive decay of potassium-40, which is a component of mineral crystals, into the gas argon-40, which is trapped within the minerals. This clock can appear to be speeded up or slowed down if the amount of potassium, argon, or both, is changed by seawater alteration. One of the advantages of argon-40/argon-39 dating is that incremental heating drives off only portions of the argon-40 at a time. With some types of samples, the portions of gas from altered mineral crystals can be distinguished from those derived from unaltered minerals, allowing an accurate date to be determined for the rock as a whole. Duncan's dates give a northward drift of 9.4 ± 0.3 centimeters per year relative to the hot spot, which is generally consistent with drift rates for the Indian plate calculated from continental data.

The actual movement of the Ninetyeast Ridge can be measured relative to the permanent reference framework of the earth's magnetic field. John Peirce, now at Petro Canada Exploration, Calgary, determined the latitude of origin, or paleolatitude, of DSDP samples on and around the ridge by measuring the inclination of the earth's magnetic field that was frozen into the rocks as they solidified. He found that all the samples from the ridge showed similar paleolatitudes, near 50 degrees south, even though its present southern tip is only at 32 degrees south. Such paleolatitudes suggest two hot spots as candidates for the Ninetyeast Ridge source, the one marked by Amsterdam Island and St. Paul Island at about 40 degrees south and the one marked by Kerguelen Island at about 50 degrees south. These results have been used to argue against the ridge's issuing from the junction of a spreading center and a transform fault, because more northern and more variable paleolatitudes would be expected in that case.

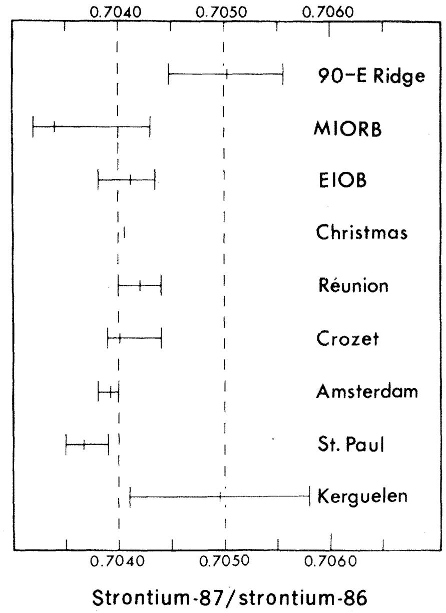


Fig. 2. Comparison of measured strontium-87/strontium-86 ratios in rocks from the Ninetyeast Ridge with those from the mid-Indian Ocean Ridge (*MIORB*), the eastern Indian Ocean (*EIOB*), and various islands in the Indian Ocean. Ranges and average ratios are shown. [Source: David Whitford, Carnegie Institution of Washington]

Another type of evidence, the composition of rocks from the Indian Ocean, also helps resolve the question of the type of source involved. David Whitford, of the Carnegie Institution of Washington's Department of Terrestrial Magnetism, and Duncan have recently found that the geochemical characteristics of the Ninetyeast Ridge, oceanic islands, and spreading centers in the Indian Ocean favor a hot spot rather than a leaky fault junction. In one type of analysis, they measured the concentration of the alkali and alkaline earth elements potassium, rubidium, cesium, barium, and strontium, which are found in trace concentrations in rocks. Different types of magma sources tend to contain characteristic amounts of these trace elements. Their concentrations in rocks from Ninetyeast Ridge are higher than in rocks created at spreading centers in the same area, according to Whitford and Duncan. Since a leaky transform fault would, in their view, probably derive its magma from a spreading center source, they believe that the trace element composition of the ridge argues against the leaky transform fault hypothesis.

The isotopic composition of ridge rocks also favors its origin at a hot spot, in particular the one that formed Kerguelen Island (Fig. 1). Whitford and Duncan measured the ratio of strontium-87 to strontium-86, which depends on the past history of the rock from which the magma was derived. Like the chemical compositions, the strontium isotopic ratios of Ninetyeast Ridge differ significantly from those of Indian Ocean spreading centers, but they are also higher than any of the sampled oceanic islands except Kerguelen Island, whose ratios are identical with those of the ridge (Fig. 2).

Most researchers familiar with the recently acquired evidence support a hot-spot source for the Ninetyeast Ridge, but the details of plate movement during its formation will probably continue to be a matter of some debate. Duncan has proposed the most recent hot-spot scenario, incorporating the Kerguelen source into previous reconstructions. In outline, it begins 105 million years ago with the coast of India over the hot spot, which was just north of the spreading center separating India from Antarctica.

These two continents had recently begun to separate, both having been part of the supercontinent Gondwanaland. During the next 70 million years, the magma of the hot spot poured out near the spreading center as the Indian plate and the ridge moved northward. After 36 million years ago, the Antarctic plate became stationary, allowing the large pile of rock beneath Kerguelen to build.

The gap between the southern end of Ninetyeast Ridge and Kerguelen resulted, according to this scheme, from the migration of the spreading center northward when the Antarctic plate stopped moving relative to the stationary hot spot. New crust continued to form at equal rates in both directions from the spreading center so that the spreading center itself had to move, laying down new crust behind and ahead of it and leaving the hot spot behind beneath Kerguelen. Slight northwestward movement of the Antarctic plate since 27 million years ago would have created the submarine plateau between Kerguelen and nearby Heard Island, beneath which the hot spot now lies.

In contrast to Duncan's scenario, Bruce Luyendyk of the University of California at Santa Barbara has concluded that a Kerguelen source for the ridge requires a 1000-kilometer shift in the location of the hot spot, not just movement of a plate. He inserted a Kerguelen source requirement into a computer reconstruction of Indian Ocean plate movements, which was developed by him and Walter Rennick, then also at Santa Barbara. Based on paleomagnetic data independent of observations on the ridge, their reconstruction requires that the Kerguelen hot spot was once at the location now occupied by Amsterdam Island and St. Paul Island. Such rapid movement conflicts with the immobility or very slow movement generally attributed to hot spots.

Ninetyeast Ridge is only one of many similar ridges that could have been formed by hot spots. But data from other submarine ridges are scarce, so discussions of their origins are liable to remain speculative for some time. The convincing amount of data from the Hawaiian-Emperor chain required 10 years to gather, and then only with much persistence and a little luck. Researchers would like to have more samples gathered along Ninetyeast Ridge, but no major effort there or on any other ridge is anticipated in the forseeable future.

—RICHARD A. KERR

The Fields Medals (II): Solving Geometry Problems with Algebra

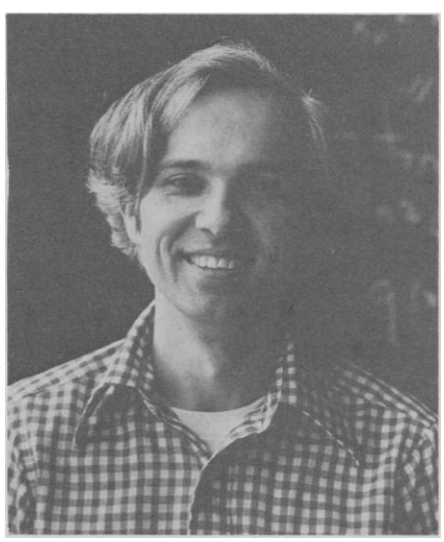
Daniel Quillen was awarded the Fields Medal for his fundamental work in algebra, notably algebraic K-theory, and in topology. Quillen was born on 22 June 1940 in Orange, New Jersey. His father is a high school physics teacher, originally trained as a chemical engineer. Quillen went from the Newark Academy to Harvard, where he earned a B.A. in 1961 and a Ph.D. in 1964. His thesis, on formal aspects of the theory of partial differential equations, was written under the direction of Raoul Bott. Bott, having also been the University of Michigan thesis adviser of 1966 Fields Medalist Stephen Smale, joins his Harvard colleague Oscar Zariski as the second person to count two Fields Medalists among his students.

When Quillen received his Ph.D. at the age of 24, he and his wife Jean, a violist, were already caring for two of their five children. His precocity as a mathematician and as a father perhaps influenced the early graying of his hair, but it has not altered his boyish look or his easy and modest manner. He has a somewhat retiring life-style, appearing rarely in public, and then almost invariably with some extraordinary new theorem or idea in hand. Quillen went from Harvard down the Charles to Massachusetts Institute of Technology, where he has since remained on the faculty. He spent three of the intervening academic years away: 1968 and 1969 as a Sloan Fellow in France; 1969 and 1970 as a visiting member of the Princeton Institute for Advanced Study; and 1973 and 1974 as a Guggenheim Fellow in France.

Quillen's dissertation on partial differential equations was soon absorbed into the working repertoire of that classical field. His interests quickly shifted, however, into mathematical domains of more recent vintage, which are more difficult to describe and motivate to an audience that includes nonmathematicians.

Topology is what underlies the various modern fields of geometry. The geometric objects of its study are called topological spaces. By the middle 1930's an arsenal of rather sophisticated algebraic techniques had evolved for solving the geometric problems of topology. The basic theme was to associate with a topological space X a type of algebraic object $H(X)$, called an Abelian group. The point is that whereas the geometric object is continuous and potentially quite complicated, the Abelian group is discrete and often effectively computable. Finally, the passage $X \rightarrow H(X)$ from the "hard geometry" to the "easy algebra" retains enough significant information to solve important geometric problems.

In order that these algebraic techniques not remain a special craft, the private reserve of a few virtuosos, it was necessary to put them in a broad, coherent, and supple conceptual setting. This was accomplished in the 1940's and 1950's through the efforts of many mathematicians, notably Samuel Eilenberg at Columbia University, Saunders MacLane of the University of Chicago, the late Norman Steenrod, and Henri Cartan of the University of Paris. The result of this enterprise of simplification, unification, and axiomatization was a methodological instrument that could be applied far beyond the setting of its birth; we call it homological algebra. It intruded naturally and fruitfully into every major area of mathematics, and eventually required, in turn, a still more abstract and general conceptualization of its own techniques.



Daniel Quillen [Photo by Margo Woodruff]

This led to what we now call the theory of categories and functors.

Quillen is one of the greatest masters of these homological and categorical techniques. He has used them with stunning originality to treat a variety of problems. He has even invested them with a kind of naïve geometric character which helps remove the shroud of ponderous formalism that had estranged many earlier mathematicians.

One of Quillen's early applications of these methods was to construct a "good" cohomology theory for commutative rings. The latter are algebraic systems in which the familiar kind of addition and multiplication can be performed. The basic examples are number rings, such as the ring of integers, and function rings, which consist of appropriate classes of functions on some geometric space X. In the latter setting Quillen's cohomology, constructed independently by Michel André of the University of Switzerland, is used to study "deformations of structure" on X.

A 1958 Fields Medal was awarded to René Thom for his invention of an extraordinary cohomology theory in topology, called cobordism theory. Quillen showed how the methods of an apparently unrelated field, the theory of formal groups, could be naturally and effectively introduced for cobordism calculations.

A celebrated conjecture in homotopy theory, made by the English mathematician J. F. Adams, had resisted the efforts of numerous mathematicians. Quillen showed how some rather exotic new methods developed by Michael Artin of the Massachusetts Institute of Technology and Barry Mazur of Harvard in the quite distinct field of algebraic geometry could be used to transform the Adams conjecture into a more plausible one in the latter context. The latter conjecture was subsequently proved by Quillen's student Eric Friedlander of the University of Illinois. Meanwhile Quillen developed a totally different but equally original method for proving the Adams conjecture, appealing this time to another remote field, the modular representa-

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