Research News

Mantle Geochemistry: Probing the Source of the Earth's Crust

Isotopic analyses of the crust reveal variability in the mantle below

Although overlain by tens of kilometers of rock, the earth's mantle is of great importance to understanding the surface of the earth. The mantle yields magma to form the crust beneath the ocean and to add new rock to the continental crust. It absorbs old ocean floor and sediment after they plunge into ocean trenches. The mantle's slow circulation is intimately connected with the forces that drive the continents around the globe. But only the crust is readily accessible for study.

In order to probe the mantle itself, geochemists have studied basalts, the crustal rocks that are derived directly from the mantle. Relying heavily on isotopic analyses in the last 10 years, they have found that the mantle cannot be a single, chemically uniform layer of rock. Researchers are now trying to relate the chemical heterogeneity of the mantle to the geological processes that have shaped both the mantle and the crust. Many researchers now believe that the formation of the crust over several billion years, rather than some rapid process in the mantle only, played the dominant role in shaping the varied chemical character of the mantle.

Basalts can be used to probe the mantle because the proportions of an element's isotopes in a rock depend directly on their proportions in the mantle rock from which the basalt was derived by melting. The melting process has no effect on the isotopic composition of a basalt. The proportions of strontium-87 and strontium-86, for example, in a basalt are the same as in the mantle rock that melted to produce it. In contrast, the same part of the mantle can produce rock with different chemical characteristics, depending on how and to what extent the mantle is melted.

Until recently, researchers believed that they knew the full range of changes in chemical composition produced by different melting conditions and could make allowance for them. Analyses of rocks recovered by a research submarine from the FAMOUS (French American Mid-Ocean Study) site have shaken this assumption. At the FAMOUS site on the Mid-Atlantic Ridge at 36°N, investigators found lava flows, lying close by each other and formed only a few thousand years apart, whose chemical compositions differ markedly. That there may be separate sources in the mantle for this basaltic rock did not seem reasonable for flows so close together, but no other explanation fit.

Charles Langmuir and Edward Bence of the State University of New York at Stony Brook recently proposed that basalt chemistry may be determined by the combination of many complex melting episodes in the mantle, rather than the single one previously assumed. If so, most any chemical composition could be generated by the right combination of melting episodes. This suggestion has been taken seriously by many geochemists studying the mantle. Interpretations of some data are being reconsidered, especially those chemical differences indicating mantle heterogeneity on a small scale. Thus, isotopic analyses have taken on even greater importance in the effort to identify variations in the composition of the mantle.

The most thorough picture of such variations has been developed for the North Atlantic Ocean (Fig. 1). As was recognized in the 1960's, oceanic islands there differ in isotopic composition from the rocks of the mid-ocean ridge along which they lie. For example, the ratio of strontium-87 to strontium-86 (^{87}Sr/^{86}Sr) is generally higher on Iceland and on the Azores than on the Mid-Atlantic Ridge Such a difference in isotopic ratios is now accepted as a record of chemical differences in separate parts of the mantle. This interpretation is possible because chemical composition can influence isotopic composition. For example, the radioactive decay of rubidium-87 produces strontium-87, but strontium-86 has no radioactive precursor. Thus, the higher ^{87}Sr/^{86}Sr ratios of oceanic islands imply that their sources in the mantle had, when averaged over time, a higher rubidium content relative to strontium than sources for ridges.

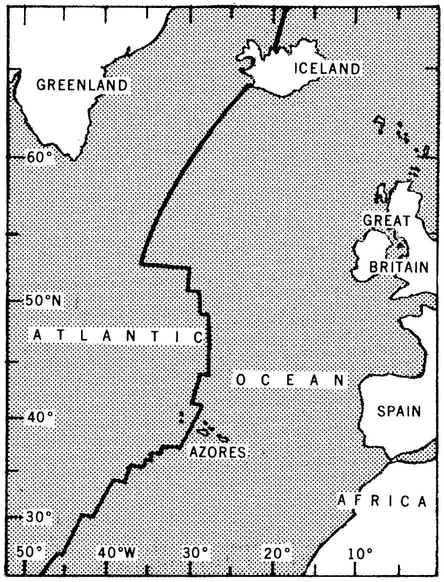

Fig. 1. Mid-Atlantic Ridge (heavy line) between Iceland and the Azores.

Two other isotopic systems studied in oceanic basalts have also revealed chemical differences in the mantle. Lead isotopes provide a record of relative variations in uranium content. The newest system to be studied, the isotopes of the rare-earth element neodymium, indicate variations in samarium, another rare-earth element. The different half-lives of the precursors and the varying chemical properties of the elements involved allow each system to record a unique view of changes in the mantle.

In the last few years, extensive sampling, including dredging, collection from research submarines, and deep-sea drilling, has revealed isotopic variations along the Mid-Atlantic Ridge itself that reflect more complex chemical differences than had been observed previously. William White of the Carnegie Institution of Washington's Department of Terrestrial Magnetism, Jean-Guy Schilling of the University of Rhode Island, and Stanley Hart of the Massachusetts Institute of Technology found that much of the magma extruded at the Mid-Atlantic Ridge does not always have the composition considered normal for ridge basalts. They found that strontium isotope ratios vary widely along the ridge, even equaling those of the Azores, which are considerably higher than those of Iceland (Fig. 2).

Variations in ridge properties may extend further to the south. A number of other investigators have detected seem-

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ingly fundamental chemical differences between the ridge rocks at the FAMOUS site and those recovered by the Deep Sea Drilling Project at 22°N.

Schilling has interpreted this variability as the result of the mixing of two major parts of the mantle. One reservoir would be the asthenosphere, the partially molten layer of mantle rock lying between 75 and 250 kilometers below the surface. Some researchers believe that this layer supplies basaltic magma to the mid-ocean ridges. The other source would be the mantle below the asthenosphere, connected to the surface by rising plumes of partially melted rock. Jason Morgan of Princeton University has suggested that mantle plumes form the roots of volcanically active "hot spots" such as Iceland, the Azores, and Hawaii.

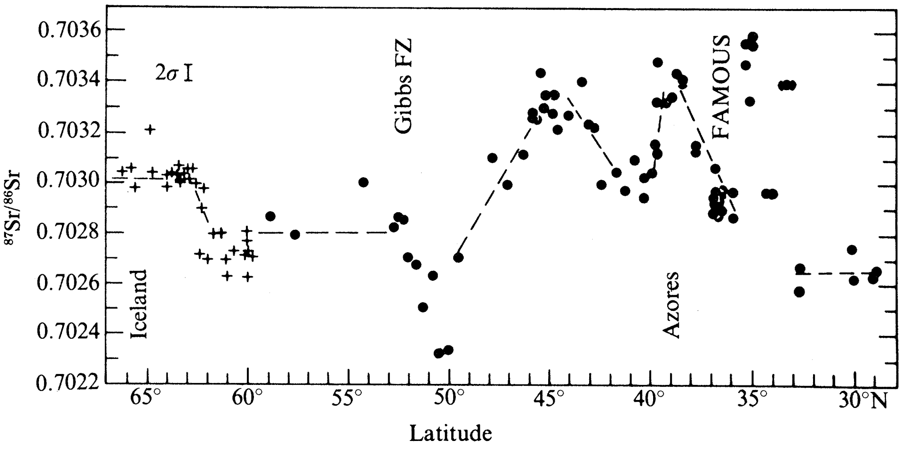

Fig. 2. Variation of the ratio of strontium-87 to strontium-86 with latitude along the Mid-Atlantic Ridge. Relatively higher values were found not only on or near Iceland and the Azores, the locations of hot spots, but also at 45° and 35°N. The latitude marked by "FAMOUS" is the site of the French American Mid-Ocean Study. Precision is indicated by the error bar in the upper left-hand corner. [Source: W. M. White, J.-G. Schilling, and S. R. Hart, in *Nature (London)*]

A number of geochemists are finding the two-source mixing model increasingly difficult to fit to the new data from the North Atlantic. For example, Alan Zindler, Hart, and Frederick Frey of MIT and Sveinn Jakobsson of the Museum of Natural History, Reykjavik, analyzed rocks from the Reykjanes Peninsula, the extension of the Mid-Atlantic Ridge onto Iceland, for strontium and neodymium isotopes and rare earth elements. The mixing of only two sources could account for many of the general trends in composition, but Zindler points out that the variations are more complex than can be completely explained by a simple two-source model. Keith O'Nions and his colleagues at Lamont-Doherty Geological Observatory agree that at least three sources are needed. Rather than citing an exact number, they emphasize that the isotopic variations along the Mid-Atlantic Ridge do not necessarily show that mantle plumes as conceived by Morgan are rising beneath the ridge.

Purely geochemical evidence showing how material from a heterogeneous mantle reaches the surface may not be forthcoming, but seismologists have begun to help out by developing three-dimensional pictures of the upper mantle. H. M. Iyer of the U.S. Geological Survey, Menlo Park, has measured the arrival times of seismic waves that passed beneath Yellowstone National Park, the site of a hot spot and a proposed mantle plume. Iyer found that the seismic waves slowed down as they passed through a giant body of partially melted rock directly beneath Yellowstone extending down to around 250 kilometers. The possibility that this column is the upper part of a deep mantle plume cannot be ruled out, Iyer believes, but recent studies of volcanic activity in the area have caused him to lean toward other theories to explain the excess heat that partially melted the mantle beneath Yellowstone.

In a study of the mantle beneath the island of Hawaii, William Ellsworth of the U.S.G.S., Menlo Park, using similar seismological techniques, did not find a large body of partially melted rock beneath the island, as was found under Yellowstone. Rather, it appears that magma may rise to the active volcanoes from a source at least 100 kilometers deep. Ellsworth believes that he has detected a strong seismic low-velocity zone between 75 and 100 kilometers beneath present-day activity, but the most intense region is deeper and to the east of Hawaii. This is the expected location of a deep, stationary hot-spot source, since it lies directly on the extension of the chain of the Hawaiian Islands. Each of these islands is thought to have been formed sequentially from a single stationary hot spot as the Pacific lithospheric plate slowly slid by.

Isotopic analyses are also being applied in attempts to determine when the mantle separated into the chemically different reservoirs that are now the sources of isotopically different basalts. Initial estimates of an age of about 1.6 billion years for a separation into two distinct layers are now being challenged by theories that the process may have been going on more or less continuously for several billion years.

All three of the isotopic systems studied in basalts (rubidium-strontium, uranium-lead, and samarium-neodymium) can in principle be used to measure how long ago a part of the mantle took on a distinct chemical character, that is, differentiated from the rest of the mantle. The known rate of decay of each isotope's precursor provides a clock to measure this time. But various assumptions are required, and some researchers contend that the simplest interpretation of the data does not give a true age.

Most estimates of the age of mantle differentiation, based on the assumption that it occurred more or less at a single time, range between 1 and 2 billion years, a common figure being about 1.6 billion years. Strontium isotope data supporting this estimate have been gathered from studies of basalts from oceanic islands as well as continental areas by C. Brooks of the University of Montreal and Hart. They correlated the strontium isotope ratio of each sample with the ratio of its rubidium content to its strontium content. A differentiation age of 1.6 billion years is consistent with the correlated data from both the oceanic islands and the continents. Brooks and Hart argue that accidentially calculating the same age for basalts from very different geologic settings is unlikely and cite the closely similar age of 1.8 billion years for oceanic basalts determined from lead isotopic data alone. A similar but lower differentiation age of 1.1 billion years has been derived from samarium-neodymium data by Richard Carlson and Douglas MacDougall of the Scripps Institution of Oceanography and Gunter Lugmair of the University of California, San Diego.

Many investigators have become uneasy with the isotopic dates being calculated for the separation of the mantle into chemically different reservoirs. Mitsunobu Tatsumoto of the U.S.G.S., Denver, notes that the calculated lead isotope age depends to a large extent on how the samples are selected. An age of 1.6 billion years can be derived if a large number of samples around the world are used, but the calculated age varies from

0.8 to 2.5 billion years if only single islands or groups of islands are used, he says. Carlson and his colleagues point out that the difference between the strontium-rubidium age and the samarium-neodymium age might be explained by an erroneous assumption common to both methods. Rather than the assumed single geological event, in which a homogeneous mantle rapidly separated itself into a number of reservoirs, perhaps the mantle has had its chemical composition repeatedly altered over a longer period of time.

O'Nions and colleagues favor such repeated or even continuous mantle differentiation. They argue that repeated differentiation would produce the same distribution of isotopes as is observed. In addition, a single differentiation does not jibe, according to O'Nions, with what is known about the evolution of the mantle and the crust. Dating of continental crust rocks has shown that new crust has been added to the continents several times since 3.8 billion years ago. Because new crust is separated from the mantle during a differentiation process, an isotopic record of many episodes of differentiation during most of the earth's history should be found, not a single one at 1.6 billion years ago, O'Nions says.

His group's evaluation of the available isotopic data from basalts of the North Atlantic supports relatively recent differentiation as well as earlier activity. According to their view, the rubidium-strontium and the neodymium-samarium data suggest that the mantle's composition changed some 200 to 500 million years ago. However, the apparent neodymium isotope ratio at that time still differed from that estimated for the mantle before any differentiation took place. Thus, the composition of the mantle must have been altered by differentiation that took place more than 500 million years ago. Although the lead isotope analyses need not be interpreted as supporting a single differentiation event, they conclude, the lead data do require changes in mantle composition a billion or more years ago.

One improvement in the isotopic data that would help resolve the controversy over mantle structure and evolution, geochemists concede, would be the analysis of more rocks for all three isotopic systems. Heretofore, most labs did not have the capability to use all three methods, and cooperation between labs was limited. As the use of the new neodymium method spreads, geochemists will have the opportunity to compare the behavior of all three systems in the same rock.—Richard A. Kerr

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The Scrapie Agent: Is It a Viroid?

Investigators have known for many years that such degenerative brain diseases as scrapie in sheep and Creutzfeldt-Jakob (CJ) disease, a rare, premature form of senile dementia in humans, are caused by an unusual kind of infectious agent (*Science*, 29 June 1973, p. 1351). Their findings indicate that the diseased brains carry a very small pathogen, such as a virus. But attempts to isolate a causative virus—or a pathogen of any other kind—from the brains have produced more frustration than results. Moreover, some investigators even questioned whether the scrapie and other agents require nucleic acid for their activity, as all conventional viruses do. For example, the infectious brain extracts are not inactivated by ionizing or ultraviolet radiation that normally inactivates nucleic acids. Recently, however, evidence suggesting that the scrapie agent is a very small DNA molecule, possibly the first viroid to be discovered in animals, has appeared.

Viroids are pathogens known to cause a number of diseases in plants. They consist of a small molecule of RNA—one-tenth or less the size of the nucleic acids found in conventional viruses—and lack the protein coat that normally covers viral nucleic acids. Because the behavior of the scrapie agent and that of plant viroids are similar in many ways, Theodore Diener, a plant pathologist with the United States Department of Agriculture, proposed in 1972 that the scrapie agent might be a viroid. (Although the known plant viroids all consist of RNA there is no reason why other viroids could not be DNA. Conventional viruses may contain either DNA or RNA.)

After 6 years of searching, Richard Marsh of the University of Wisconsin and J. S. Semancik of the University of California at Riverside and their colleagues have finally turned up direct evidence that this is the case. They have shown that the scrapie agent has a DNA component that is necessary for infectivity. When they treat extracts of scrapie-infected hamster brains with an enzyme that breaks down DNA, they destroy 90 percent or more of the material's infectivity. Enzymes that break down RNA or protein have no effect. In addition, the molecular weight of the infectious DNA appears to be about 70,000 to 100,000. In other words, it is about the same size as the RNA of plant viroids.

According to Paul Brown, who is studying scrapie at the National Institute of Neurological and Communicative Disorders and Stroke (NINCDS), the suggestion that the scrapie agent contains an essential DNA component is consistent with the properties of the agent with the possible exception of its resistance to radiation. But this may not be an insurmountable problem. Impure preparations of plant viroids are also resistant to radiation; they become sensitive only when purified. A similar phenomenon may occur with the scrapie agent, according to Marsh and Semancik. The material they are studying also becomes more sensitive to radiation as it is purified. The unpurified scrapie agent is closely associated with cellular membranes which may protect it from the harmful effects of the radiation.

The discovery of the chemical nature of the scrapie agent might throw some light on the chemical nature of the agents causing related brain diseases in humans, including CJ disease and kuru, a similar (perhaps identical) condition that was once common among the people in some areas of New Guinea. The symptoms and pathological changes occurring in the human diseases closely resemble those of scrapie. In fact, D. Carleton Gadjusek and Clarence J. Gibbs of NINCDS, who discovered the infectious nature of kuru and CJ disease, have suggested that the agents causing these diseases might actually be variants of the scrapie agent, which could have originally been transmitted to humans who ate scrapie-contaminated sheep brains. Moreover, there are suspicions that similar agents might cause other more common brain diseases, including Parkinson's disease.

Brown sounds a cautionary note, however. He points out that the work of Marsh and Semancik has not yet been reproduced by other investigators, although several now have experiments in progress. If the work cannot be duplicated, the researchers investigating the causes of scrapie and the human brain diseases will have to cope with still more frustration while they try again to corner the elusive agents causing the diseases.—J.L.M.