Ophiolites: Windows on Which Ocean Crust?

Researchers now agree that ophiolites are ocean crust shoved onto continents, but what kind of ocean crust are they seeing?

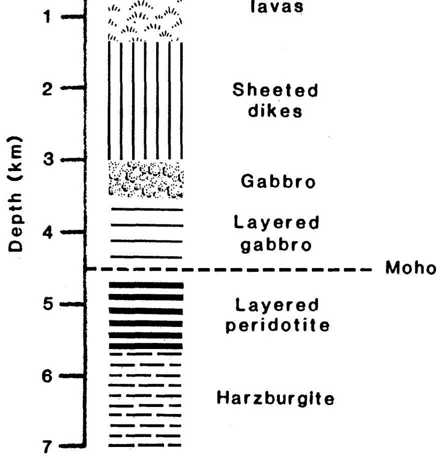
London. About 20 years ago, some continental geologists claimed that they had found great slabs of ocean crust sliced up and laid out on the continents for detailed inspection. The slabs, called ophiolites, do appear to be some sort of ocean crust beached on the edges of continents, but detailed interpretation has been contentious.

Ophiolite specialists and a few oceanographers met recently in London to compare ocean crust and ophiolites.* The claimed family resemblance was still evident, but speakers grappled repeatedly with the diversity of ophiolites. Are any of them at all typical of ocean crust covering the sea floor today? The answer seemed to be that they are typical enough to be useful if care is taken to ascertain what variety of ocean crust formed a particular ophiolite.

To give some idea of the best that oceanographers can do with bona fide ocean crust, the opening speakers reported on the latest, sharpest crustal probings in the eastern Pacific. John Orcutt of Scripps Institution of Oceanography reported on some of the most detailed seismic studies of mid-ocean ridge magma chambers, the source of the ocean crust that covers the major ocean basins. On the East Pacific Rise in 1980, just south of the Gulf of California at 21°N, he and his colleagues listened to small earthquakes through ocean-bottom seismometers placed around "black smokers," the sea-floor vents through which seawater cooling the underlying magma chamber returns to the sea. The 12 locatable microearthquakes clustered at a depth of about 2 kilometers and none was deeper than 3 kilometers, suggesting that the magma chamber reached no higher than that.

The Mexican government refused to let them return to 21°N in 1982, so the Scripps group went to the same rise at 21°50'N. There they listened as seismic waves from more than 4000 submarine detonations passed through the crust and refracted back toward the surface. From the deadening of certain seismic wave paths, it appears that a magma chamber beneath that section of ridge also rises to within 2 to 2.5 kilometers of the sea floor. It is no more than 10 kilometers wide, Orcutt said, and is probably much narrower. Ophiolite geologists had inferred a magma chamber at those kinds of depths as the source of ocean crust, but some of their models of mid-ocean ridges have magma chambers that are too wide to fit the case of the East Pacific Rise, Orcutt said.

The deepest samples ever recovered from within ocean crust confirm the ophiolite-derived model of at least the upper layers of ocean crust, according to José Honnerez of the University of Miami. He described rocks recovered from a hole drilled in 3460 meters of water through 274 meters of overlying sediment and 1075 meters of crustal rock. Although the deepening of one of its earlier holes on the flank of the Costa Rica Ridge was difficult, the Deep Sea Drilling Project's (DSDP) *Glomar Challenger* penetrated almost 500 meters deeper than in any other crustal hole. The January 1983 *Challenger* drilling revealed the same layering of rock types as exposed in ophiolites. In the top 575 meters of crust, volcanic rubble intermingled with lava flows, both thick, massive flows and aptly named pillow lavas that had spilled onto the sea floor. The upper 90 meters of this section was so porous that seawater flowed freely through it.



Ocean crust as seen in ophiolites

At a crustal depth of 440 meters, the drill bit encountered the first dike, a sheet of rock formed by the intrusion of magma into preexisting rock. As the hole deepened, dikes became more frequent until, beginning at 783 meters, there was nothing but dikes intruding dikes. That kind of formation had baffled ophiolite geologists until the theory of plate tectonics showed how dikes could repeatedly intrude between two crustal plates spreading away from a mid-ocean ridge. These crustal layers correspond to the geophysicist's layer 1 (sediment) and layers 2A (aquifer), 2B (lavas), and 2C (dikes). Although DSDP scientists found mineral alteration throughout the hole, the alteration did not demarcate any of the layer boundaries.

Geophysicists' layer 3 still lies beyond the reach of drilling, but geologists can walk across their ophiolites from layer 2, across layer 3, out of the crust, and into the mantle. Geophysicists have presumed that layer 3 is composed of the remnants of magma that crystallized and was left behind in the magma chamber. The expected type of rock, called gabbro, does underlie the dike swarms of ophiolites. The uppermost gabbro plated the chamber roof as circulating seawater cooled it and the lower gabbro formed layers within the chamber.

Below the ophiolite's gabbro at a reconstructed depth of about 5 kilometers is the Moho, the crust-mantle boundary that was the objective of the ill-fated drilling project that preceded DSDP. Below that is the first mantle rock, layered peridotite, which is also derived from rising magma. The lowest ophiolite layer is harzburgite, what researchers believe to be the residue from the melting that produced the magma in the first place. Frozen into the ophiolite's mineralogical layer cake are clues to how it formed— slabs of gabbro falling away from the roof of the magma chamber, blobs of magma percolating through the mantle, and solid mantle rock flowing beneath the crust.

Geologists have not ignored the opportunity to study firsthand a magma system that normally lies kilometers below the

*Ophiolites and Oceanic Lithosphere, a conference held 17 to 19 November 1982 in London, England, by the Geological Society of London, Burlington House, Piccadilly, London, W1.

The Samail ophiolite of Oman

This Earth Resources Technology Satellite image of part of the sultanate of Oman shows the Samail ophiolite south of the city of Muscat (north is up). The once-vertical, layered section of ocean crust and mantle has been laid out on the continent so that the mantle (the darkest terrain, in the center of the image) is to the north of the lighter crustal rock, called gabbro. The boundary between the two, called the Moho, normally lies about 5 kilometers below the sea floor. Just south of the gabbro, along the valley, can be found remnants of the lavas and dikes extruded onto the sea floor from the magma chamber that formed the gabbro.

sea floor. One goal of such studies has been to understand how magma rising out of a long, narrow crack—the boundary between the separating ocean crustal plates at the crest of mid-ocean ridges—can form nearly horizontal layers whose thicknesses range from kilometers to centimeters.

Paul Browning and John Smewing of The Open University in Milton Keynes, England, reported that the layering of gabbros in the Samail (or Semail) ophiolite complex of North Oman reflects changes in chemical composition related to influxes of magma to the chamber. If all of the gabbro in the 600-meter section studied had crystallized and settled from a single batch of magma, Browning and Smewing reasoned, the composition of the gabbro crystals would gradually change from the bottom of the section to the top. Formation of the first crystals would alter the composition of the remaining liquid, which in turn would alter the composition of subsequently formed crystals. Instead, they found layer after layer within which the composition changed gradually across a narrow range, only to jump back suddenly to near the initial values as another cycle and another layer began. Apparently, this layering reflects the expected gradual crystallization of a magma chamber interrupted by the injection of fresh magma from below. Thus, the composition of both the layer 3 gabbros and the layer 2 lavas and dikes, which are extruded from the chamber by the injections from below, would be influenced by the size and frequency of magma injections.

This kind of easy access to the rocks, while convenient for geologists, has hardly eliminated controversy over the interpretation of cyclic variations of mineral composition, as in the case of a 136-meter-thick section of the Bay of Islands ophiolite complex in Newfoundland. Donald Elthon, John F. Casey, and Steve Komor of the University of Houston found 11 chemical cycles in the layered peridotite beneath the gabbro. The usual interpretation would be that these layers formed several kilometers below the sea floor near the bottom of the ridge magma chamber. The Houston group prefers an origin 15 to 30 kilometers down, far below the shallow magma chamber. They say that the types of minerals in the peridotite and their compositions indicate high pressures during their crystallization. In support of a deep, high-pressure origin, they point to laboratory crystallization of mid-ocean ridge basalts, the rock type of crustal layer 2. Many experimental petrologists believe that these laboratory basalts show signs of having left gabbros behind in the shallow magma chamber and of forming crystals earlier at much greater depths as well.

The Houston group resolves their apparent paradox of crystals that formed at great depth being found near the top of an ophiolite by hypothesizing that they formed on the walls of deep conduits feeding the overlying ridge magma chamber. Perhaps 25 to 500 meters wide, a conduit would be plated with a new layer of peridotite each time fresh magma surged toward the magma chamber. The conduit walls themselves would rise toward the surface as the hot, plastic mantle rock surrounding them carried the walls along. As in most models of ocean crust formation, the ascending mantle rock would diverge and peel away to either side as it approached the magma chamber. The once vertical layers of peridotite would thus flop over with the mantle into a nearly horizontal position.

The Houston model of the formation of deep horizontal layering is the latest of a number of explanations of how ophiolites relate to ocean crust. The controversy over these models is being fueled by differences between ophiolites, structural complexities within each ophiolite, and growing concerns about what kind of ocean crust a given ophiolite actually represents.

The Troodos ophiolite on Cyprus is a good example of the problem. The International Crustal Research Drilling Group chose Troodos for a new drilling program because, in the words of Ian Gass of The Open University, it is "the most accessible, least deformed, and best studied analogue" of oceanic crust. Still, there have been some major surprises, according to Gass, Paul Robinson of Dalhousie University in Halifax, and J. G. Malpas of Memorial University of Newfoundland. Instead of a single layer of gabbro beneath the dikes, there are gabbro bodies of differing ages. Dikes intrude into gabbros, and vice versa, quite unlike the idealized ophiolite case.

The biggest surprise came from the first analyses ever made of unaltered Troodos rock samples. The samples fell into two general chemical groupings, each of which resembles the composition of volcanic island arcs, such as the Marianas or the Aleutians, rather than that of mid-ocean spreading centers. But geologists had always considered Troodos to be the classic example of an ophiolite whose rock was formed at a mid-ocean ridge; it has none of the volcanic ash or volcanic erosional debris typical of island arcs. Claude Allegre and his colleagues at the Institute of Physics of the Globe in Paris also emphasized this dual nature of some ophiolites. Allegre reported that, on the basis of the strontium, neodymium, and lead isotope contents of ophiolitic rocks, some resemble crust generated at mid-ocean ridges, as the Bay of Islands ophiolite does, and some resemble island arcs.

An explanation of the Troodos paradox may be that spreading and the creation of new ocean crust did occur but near a subduction zone, where cool, dense ocean crust dives into the mantle, undergoes partial melting, and generates the volcanoes of island arcs. Crust generated at a mid-ocean ridge might become part of an ophiolite through the collision of a ridge with a continent, the edge of the continent lifting part of the thin crust. An increasingly popular view, however, is that many if not most ophiolites originate as ocean crust that forms in a small, marginal basin on the opposite side of the island arc from the subduction zone, or deep-sea trench. The magma generated by the partial melting of wet ocean crust, sediment, and mantle could contaminate the magma source of the spreading center, giving it chemical characteristics of island-arc rock. If the marginal basin closes, the colliding island arc and continent could shove a scrap of ocean crust onto dry land, according to this model.

The catch to this idea is that some typical ophiolites, like Troodos, have subduction-related chemistries but show no sign of an island arc nearby. Casey and John Dewey of the University of Durham suggested one possible explanation. A subduction zone could form suddenly near a spreading center, which for a time continues to form new crust while drawing on subduction-generated magmas. A likely place to make the quick shift, they said, would be at a transform fault, which connects the offset ends of two sections of mid-ocean ridge and allows abutting crustal plates to slide past each other. When the relative motion of the plates changes, their convergence at the now abandoned transform fault could force one of the plates downward, forming a subduction zone and initiating the formation of a young island arc. The new subduction-related magma generation could also feed the adjacent spreading center for a while.

When a continent approaches the young subduction zone, according to this theory, the continent could scrape off the ocean crust that once bounded the active transform fault but later was trapped between the subduction zone and the incipient island arc. The resulting ophiolite would be bounded by transform-related rocks on its inboard side, as both Bay of Islands and Troodos are, and display mid-ocean ridge type chemistry, as at the Bay of Islands, or subduction-related chemistry, as at Troodos. Even ophiolites overlain by island-arc volcanic ash and lava could thus be representative of mid-ocean crust, Casey warned.

One way to deal with the obvious complexities of most ophiolites would be to find one that has not suffered the battering and alteration apparently required to put ocean crust onto continents. R. Varne, B. J. Griffin, and J. A. Jenner of the University of Tasmania think that they have a promising candidate. It forms part of Macquarie Island, the last, lonely outpost south of New Zealand. All of the appropriate crustal layers are there, and the island itself seems to have been simply squeezed toward the surface like toothpaste from a tube. Remoteness, foul weather, and rugged terrain make field studies difficult, but researchers hope that Macquarie will provide an even clearer view of at least one section of mid-ocean crust.

—RICHARD A. KERR

Additional Reading

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2. D. Elthon, J. F. Casey, S. Komor, *J. Geophys. Res.* **87**, 8717 (1982).
3. I. G. Gass, *Sci. Am.* **247**, 122 (August 1982).

New Magnets Enhance Synchrotron Radiation

Most of the wigglers and undulators in future synchrotron radiation centers will be made of samarium-cobalt permanent magnets

Herman Winick of the Stanford Synchrotron Radiation Laboratory facetiously calls it a "death ray" because of its intensity. It is a 2-meter-long array of magnetic dipoles that will be the most powerful source of synchrotron radiation yet produced, when it is installed at Stanford later this summer. Now being tested at the Lawrence Berkeley Laboratory, where it was built under the direction of Klaus Halbach, this dipole array or wiggler is the latest in a series of designs based on the use of samarium-cobalt ($SmCo_5$) permanent magnets. Most of the wigglers and undulators (array of dipoles similar to a wiggler) planned for present and future U.S. synchrotron radiation centers follow Halbach's designs and use the samarium-cobalt compound.

Wigglers and undulators, which are lumped under the term insertion devices, are on the verge of revolutionizing synchrotron radiation research, so the success of samarium-cobalt permanent magnets is far from a technological curiosity. Synchrotron radiation sources up to now have been primarily those portions of electron storage rings where dipole bending magnets keep the circulating electron beam in its curved trajectory. Insertion devices fit in the straight sections between bending magnets. A dipole array forces the electron beam into a sinusoidal wiggle that is superimposed on its circular orbit, thereby shaking out more synchrotron light.

A wiggler generates the same continuous spectrum of light from the infrared to x-rays as a bending magnet does, but the radiation is more intense with the wiggler and extends to even shorter wavelengths. An undulator is designed to maximize the cooperative superposition of light waves emitted by the electrons at each peak of their sinusoidal trajectory. In this way, the smooth wiggler spectrum is broken up into one or more intense bands with a much reduced light output at other wavelengths.

Future synchrotron radiation facilities will rely almost exclusively on the use of insertion devices to generate synchrotron light. The \$62-million Advanced Light Source, centerpiece of the proposed National Center for Advanced Materials at Berkeley (*Science*, 18 February, p. 827), is the first of this new generation of synchrotron radiation sources. A committee of the European Science Foundation has likewise turned in a preliminary plan for a \$142-million synchrotron radiation facility that is only somewhat less devoted to insertion devices, which will service about three-quarters of 90 to 100 experiments.

Existing synchrotron radiation centers are also emphasizing insertion devices as much as possible. For example, expanded experimental areas are being dedicated to beam lines carrying light from insertion devices to researchers' equip-