Long before the plate-tectonic revolution began in the 1960s, scientists envisioned drilling into the ocean crust to investigate Earth's evolution. As early as 1881, Darwin suggested drilling Pacific atolls for scientific purposes. From the end of the nineteenth into the first half of the twentieth century, drilling was used to penetrate the reef and uppermost volcanic foundation of several oceanic islands, and these glimpses of oceanic geology whetted the scientific community's appetite for deeper and more complete data.

The idea of ocean drilling gained momentum in the 1950s and resulted in the “Mohole project,” whose objective was to sample the material beneath the Mohorovicic discontinuity, or “Moho,” the boundary between Earth’s crust and mantle. The Mohole project proved to be ahead of its time, but the program’s test drilling in the deep eastern Pacific Ocean proved that ocean crust could be successfully drilled and cored from a dynamically positioned ship in several thousand meters of water. Mohole was succeeded beginning in the late 1960s by the hugely successful Deep Sea Drilling Project, the International Phase of Ocean Drilling, and the current Ocean Drilling Program. (For “An Abridged History of Deep Ocean Drilling” by Arthur E. Maxwell, see Oceanus Vol. 36, No. 4.)

A major scientific goal of all these efforts has been to recover a complete section of normal ocean crust and uppermost mantle. The lithology, properties, and geological relations of these rocks are key to understanding such varied phenomena as convection in the earth's mantle, melting and transport mechanisms in the upwelling asthenosphere beneath mid-ocean ridges, rock deformation and alteration, the sources of magnetic anomalies in ocean basins, and hydrothermal circulation and formation of ore deposits.

**Poking at the Oceanic Lithosphere**

The outstanding obstacle to drilling through the entire ocean crust is that normal crustal thickness is on the order of 6 to 7 kilometers. Penetrating it beneath several thousand meters of water is presently at the limits of drilling technology as well as beyond the financial boundaries of scientific funding. Currently, drilling to depths of 1.5 to 2 kilometers has yielded upper ocean crust samples, as well as sections of deeper crust and upper mantle where these rocks are exposed by natural tectonic processes. Pieced together, these sections are in many ways similar to our conception of what ocean crust should look like, based on studies of ophiolites, old seafloor parcels that have been exposed above sea level by various tectonic mechanisms. (See map on page 24.)

At its base, the “standard ophiolite model” (see figure at left) includes an “ultramafic” layer (made up of dense rock rich in iron and magnesium) that represents the oceanic mantle. The overlying crust is formed from melt that rose buoyantly into the upper mantle, which is dominated by layered gabbros and ultramafics. This section, known as Layer 3, is typically 1.5 to 2 kilometers thick.

The crust above Layer 3 is known as Layer 2, and it is typically 3 to 4 kilometers thick. Layer 2 is composed of sheeted dikes and extrusive basalts, which are formed when magma erupts onto the seafloor and solidifies quickly, forming pillow basalts. These basalts are typically 1 to 2 kilometers thick.

The seafloor itself, which is typically covered by a layer of silt and clay called the seafloor sediments, is only a few meters thick. The lithosphere, which is the outer layer of the Earth, extends downward to the base of the crust, which is typically 6 to 7 kilometers deep.

**Schematic section through oceanic crust, based on study of subaerially exposed ophiolites and drilling results in the ocean basins. Boundaries between lithologic units are usually transitional and complex, and units may be thin or missing where magma input is episodic, notably on slow-spreading ridges.**
stantly at a mid-ocean ridge from the hot, upwelling mantle. From bottom to top, the crust consists of layers formed by crystallization in presumed magma chambers or zones of hot crystal mush, a shallower section of vertically oriented, intrusive dikes,* and a volcanic surface layer of pillow basalts extruded onto the seafloor and capped by sediments. Laboratory analyses show that each of these sequences transmits sound waves with characteristic velocities, and seismologists studying sound propagation in the deep ocean basins have roughly equated observed crustal velocity layering with rock type in the standard ophiolite model. From mapping of seismic velocities, the subseaﬂoor depth of the top of the mantle (the Moho), and thus the apparent thickness of normal ocean crust, appears to be remarkably uniform at about 6 to 7 kilometers.

However, there are several problems with relying too heavily on the ophiolite and velocity models. First, while ophiolites offer the convenience of being able to walk the outcrop and directly study geological relationships, there is considerable debate as to their value for interpreting the structure of normal ocean crust. Many ophiolites are known to have originated in unusual tectonic settings such as behind island arcs or above subduction zones, and it is uncertain how representative they are of crust beneath most large ocean basins. Second, it is likely that the standard ophiolite model is overly simplistic. Spreading rates and the associated levels and constancy of magma production vary dramatically among mid-ocean ridges, so the magmatic and tectonic structure of deep ocean crust probably seldom approaches the ideal model, particularly where magma supply is limited. Finally, our suppositions about the relative uniformity of crustal thickness and composition, as inferred from velocity-lithology correlations, could be seriously in error. In particular, normally high-velocity ultramafics of the upper mantle may become altered by seawater that penetrates deeply along faults and fractures. Such alteration can dramatically reduce sound velocity in these rocks, making them appear seismically to be part of the ocean crust and thus causing us to overestimate true crustal thickness.

To resolve such uncertainties, we are still faced with the need systematically to sample the entire crustal and uppermost mantle sequence within the ocean basins. To date, the best path to this goal has been to sample local tectonic exposures, but because of the intermittency and incompleteness of outcrops, this has been considered a piecemeal solution at best. Recent discoveries, however, indicate that complete, naturally occurring crust-mantle cross sections may be exposed on the seafloor by unusually long-lived faults. These sections have the potential to yield long-sought answers to questions about the structure and origin of oceanic crust.

*Diﬀers from when vertical fissures allow molten material to rise through preexisting structures.
expressed in the form of large normal faults, is much more profound at slow-spreading ridges, particularly at segment ends. These faults cut deeply into and sometimes through the ocean crust. If extension occurs for a long enough period on a fault, then a significant portion of the ocean crustal section, and possibly even upper-mantle rocks, could be exhumed along the fault plane. Do these geological cross sections actually exist on the seafloor, and, if so, under what conditions are they formed?

Recent discoveries suggest an affirmative answer to the first question. In 1996, both British and US expeditions to the slow-spreading Mid-Atlantic Ridge found remarkable seafloor edifices, each of which appears to have originated by long-lived slip on an individual normal fault. These features, which we term “megamullions,” have two distinctive characteristics: first, a domelike or turtleback shape extending over a diameter of some 15 to 30 kilometers, and second, conspicuous grooves or corrugations (mullions) that formed as part of the faulting process and that parallel the direction of fault slip. A steep, west-facing normal fault formed as the megamullion developed, and it cuts the mullions at right angles. The image was generated from multibeam sonar data that give complete bathymetric coverage of the seafloor.

Interpreted development of a megamullion near the end of a spreading segment during a period of amagmatic extension. Development begins when a detachment fault first forms following a magmatic episode of seafloor spreading, and it ends with abandonment of the detachment when a new fault breaks through rift-axis crust that is weakened by renewed magmatism.
between about 21° N and 31° N on the Mid-Atlantic Ridge, and a number of other megamullions have been recognized where strong tectonic extension occurs on slow- to intermediate-spreading mid-ocean ridges in the Indian Ocean.

Each detachment fault that forms a megamullion has three notable features: a breakaway zone where the fault began, the exposed fault surface that rides over the megamullion dome, and a termination, which usually is marked by a valley and adjacent ridge. By identifying breakaway and termination ages from dated seafloor magnetic anomalies, we can establish that the faults forming the North Atlantic megamullions accommodated slip for periods between 1.0 and 2.6 million years, with an average period of 1.5 million years. The original dip of the faults is uncertain, but they probably dipped at up to about 45°, much like most seismically active normal faults presently observed at the axes of mid-ocean ridges. With this dip, the faults would have exhumed a full 6-kilometer-thick crust and even exposed the underlying mantle within less than a million years. As these rocks are drawn out from beneath the fault, the footwall “rolls over,” laying out the geological cross-section across the surface of the megamullion. The rollover also flexes the brittle footwall much like bending a wooden ruler—the upper part of the footwall block is under tension and new normal faults break through the detachment surface.

Under what conditions do these long-lived faults develop? In terms of their position on the seafloor, all megamullions identified thus far appear near segment ends at inside-corner (IC) locations (that is, within the bights between the actively slipping sections of ridge-axis discontinuities and the spreading axis). Geophysical data and recovered rock samples show that ocean crust at inside corners of slow-spreading ridges is intermittently thin or missing compared to relatively normal thickness, outside-corner (OC) crust on the opposite side of the spreading axis. This seems to be best explained by consistent orientation of faults dipping from inside corners toward outside corners; in this way the upper crust (hanging wall) is frequently stripped from the inside-corner footwall. However, this process cannot be continuously occurring on a single fault. If it were, all inside corners would exhibit megamullions (but only a small percentage do), and they would almost exclusively expose mantle rocks (which they do not). Rather, it appears that a single fault is normally active for only a short period of time (a few tens to hundreds of thousand of years) before it is abandoned and replaced by a new fault closer to the spreading axis.

What, then, promotes slip on a single fault for periods of up to 2 million years or more? And what eventually causes the fault to be abandoned? Clearly, for a fault to remain active it must be weak in comparison to the overlying mantle crust where another fault might otherwise nucleate. Recent laboratory studies have demonstrated changes in deformation mechanism at sub-seafloor depths where faults in the brittle lithosphere flatten out into zones of plastic deformation in hotter, deeper rocks. These changes weaken the rock by a factor of ten or more compared to surrounding, unfractured rocks, and thus promote slip in the shear zone. Slip probably is also enhanced by the occurrence of weak serpentinites along faults at shallower levels within the brittle lithosphere. Serpentinites form as seawater percolates down fractures and reacts with ultramafic rocks in the lower crust and upper mantle at temperatures ranging from about 100° to 500°C.

These kinds of weakening, however, are not the entire answer to the question of fault longevity because they probably occur on many (if not most) faults in slow-spreading crust, whereas truly long-lived faults are few and far between. A more complete explanation can be devised if we consider the temporal variability of magmatism at the spreading axis. Episodes of magmatism are known to occur at time scales of tens to hundreds of thousands of years at slow-spreading ridges, and recent analysis of gravity data over ridge flanks also indicates a predominant cycle at a period of two to three million years. Megamullions consistently correlate with the parts of these longer cycles where the gravity data indicate the presence of thin crust and predominantly amagmatic extension. Thus, it appears that persistent slip on a fault occurs while the spreading axis is relatively cold, but that when magmatism is renewed, it heats and weakens the lithosphere, new faults form, and the long-lived fault is abandoned. The relative rarity and the locations of megamullions...
suggest that completely amagmatic extension is not common even in slow-spreading crust, and when it occurs it is restricted mostly to segment ends near ridge-axis discontinuities.

Windows of Opportunity

The cross sections through the crust and into the upper mantle that appear to be laid out across the surface of megamullions offer exciting new windows of opportunity finally to sample the oceanic lithosphere in detail. Marine geologists are now proposing to drill a series of half- to one-kilometer-deep holes, aligned in the direction of fault slip across the surfaces of megamullions. From these cores, we should be able to construct a composite, but relatively complete, picture of the entire crust-mantle section, without ever having to drill the 6 kilometers or more that would be required to reach the mantle beneath normal-thickness ocean crust.

There is, however, much to be done before the drilling occurs. A few samples have been obtained from megamullions, and as expected they include lower-crustal and upper-mantle rocks. Nonetheless, most of our interpretations are based on remotely sensed data such as gravity and bathymetry, together with models of the faulting process. Detailed surveys and sampling with deep-towed instruments and submersibles like Alvin are needed fully to document the geology of the outcrops and to select optimum locations for drilling. This mapping and sampling will also provide critical information for correlating data between drill holes and to understand the three-dimensional internal structure of the crust and mantle.

In addition to providing lithospheric cross sections, megamullions have the potential to yield significant insights into other outstanding geological problems. For example, it has long been thought that the primary source of marine magnetic anomalies lies in the upper, extrusive section of the oceanic crust. Yet, at megamullions, where this layer is thought to be missing, perfectly normal magnetic anomalies usually are developed. Either we are grossly mistaken in our interpretation of these features, or else the lower part of the ocean crust contains a substantial magnetic signature. Near-seafloor magnetic studies and laboratory analyses of magnetization in recovered rock samples will resolve this question.

Although the focus here has been on oceanic lithosphere, we also can benefit from and contribute to the study of tectonics in continental crust (see photos on these two pages). Megamullions have dimensions, shape, and an apparent mode of origin via long-lived detachment faulting that are very similar to those of “metamorphic core complexes” exposed in extensional mountain belts such as those found in the southwestern United States. In these areas, domed core complexes have exhumed rocks from some 15 kilometers deep in the continental crust, and their structure and deformation history have been studied extensively for more than two decades. Cross-pollination of insights gained from both the continental and oceanic realms will allow us to develop a much more comprehensive understanding of extensional tectonism and the intriguing exposures of deep lithosphere both on land and in the ocean basins.

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Born and raised in the natural geological laboratory known as the Black Hills of South Dakota, Brian Tucholke has been a geologist from the time he first crawled off his baby blanket and grabbed a fistful of dirt. As one of the Ph.D. students entering the MIT/WHOI Joint Program in its inaugural year, he (mostly) gave up the bedrock stability of the western mountains for the rolling sea, and he has since been on more than 25 oceanographic research cruises to investigate the flow of abyssal currents, seafloor sedimentation patterns, the paleoceanographic history of ocean basins, the structure and evolution of continental margins, and the tectonics of mid-ocean ridges. The mark of his passage can often be seen in the imprint of his cowboy boots, several decrepit pairs of which he has buried at sea in oceans ranging from the North Atlantic to the Bellinghausen Sea off Antarctica.