

The ORIGIN of the Land UNDER the Sea

The deep basins under the oceans are carpeted with lava that spewed from submarine volcanoes and solidified. Scientists have solved the mystery of how, precisely, all that lava reaches the seafloor

By Peter B. Kelemen

KEY CONCEPTS

- Eighty-five percent of the earth's volcanic eruptions occur deep underwater along mid-ocean ridges.
- Lava ejected from those narrow chains of seafloor volcanoes produce the rocky underpinnings of all oceans.
- Until recently, no one understood much about how the molten lava rises up into the ridges.
- Scientists now think they have deciphered the process, beginning with the formation of microscopic droplets of liquid rock in regions up to 150 kilometers deep.

—The Editors

At the dark bottom of our cool oceans, 85 percent of the earth's volcanic eruptions proceed virtually unnoticed. Though unseen, they are hardly insignificant. Submarine volcanoes generate the solid underpinnings of all the world's oceans—massive slabs of rock seven kilometers thick.

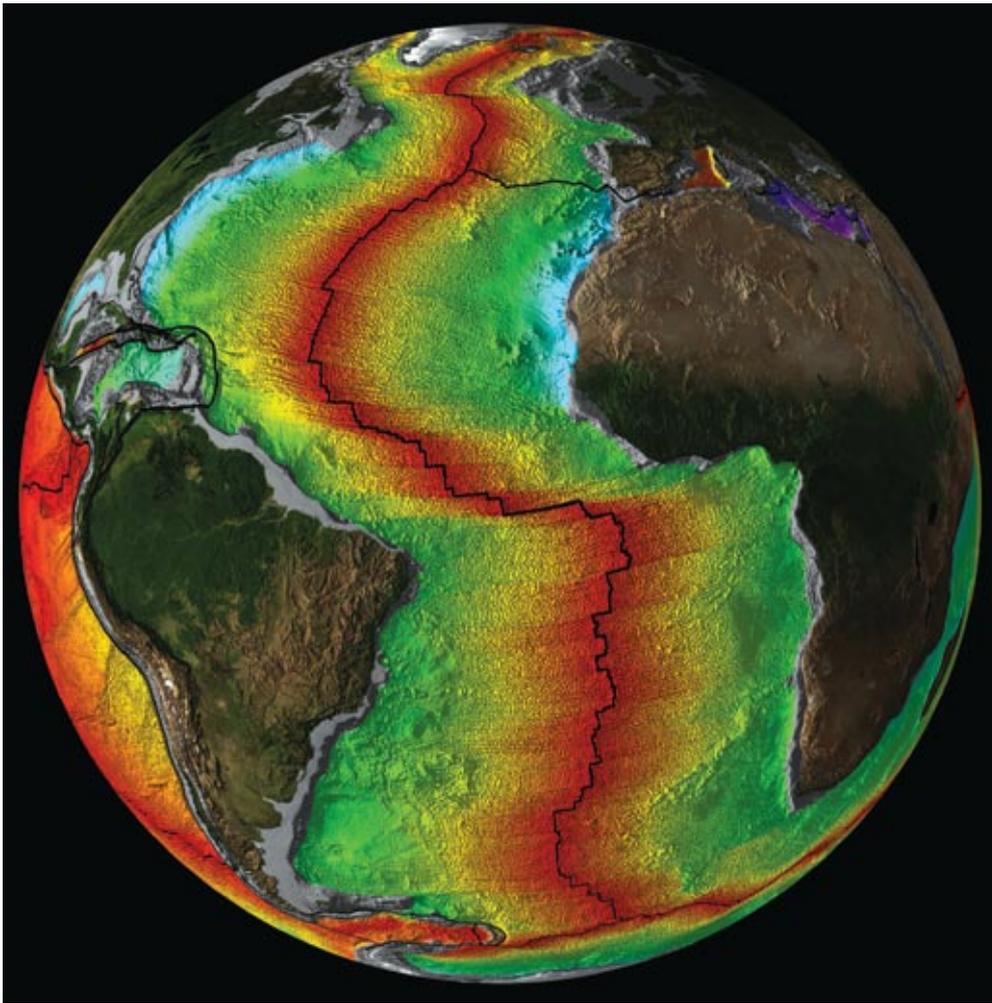
Geophysicists first began to appreciate the smoldering origins of the land under the sea, known formally as ocean crust, in the early 1960s. Sonar surveys revealed that volcanoes form nearly continuous ridges that wind around the globe like seams on a baseball. Later, the same scientists strove to explain what fuels these erupting mountain ranges, called mid-ocean ridges. Basic theories suggest that because ocean crust pulls apart along the ridges, hot material deep within the earth's rocky interior must rise to fill the gap. But details of exactly where the lava originates and how it travels to the surface long remained a mystery.

In recent years mathematical models of the interaction between molten and solid rock have provided some answers, as have examinations of blocks of old seafloor now exposed on the continents. These insights made it possible to devel-

op a detailed theory describing the birth of ocean crust. The process turns out to be quite different from the typical layperson's idea, in which fiery magma fills an enormous chamber underneath a volcano, then rages upward along a jagged crack. Instead the process begins dozens of kilometers under the seafloor, where tiny droplets of melted rock ooze through microscopic pores at a rate of about 10 centimeters a year, about as fast as fingernails grow. Closer to the surface, the process speeds up, culminating with massive streams of lava pouring over the seafloor with the velocity of a speeding truck. Deciphering how liquid moves through solid rock deep underground not only explains how ocean crust emerges but also may elucidate the behavior of other fluid-transport networks, including the river systems that dissect the planet's surface.

Digging Deep

Far below the mid-ocean ridge volcanoes and their countless layers of crust-forming lava is the mantle, a 3,200-kilometer-thick layer of scorching hot rock that forms the earth's midsection and surrounds its metallic core. At the planet's cool surface, upthrust mantle rocks are dark



MID-ATLANTIC RIDGE (*black "stitching"*), a 10,000-kilometer-long string of volcanoes at the bottom of the Atlantic Ocean, is the longest mountain range in the world. The colors indicate the ages of the rocky crust under the ocean, which is youngest (*red*) near the ridge and gets progressively older as it nears the continents.

GEOLOGIC GLOSSARY

DUNITE: A rock that is made up almost entirely of the mineral olivine and typically forms a network of light-colored veins in the upper mantle.

FOCUSED POROUS FLOW: The process by which melt often travels through the solid rocks of the earth's interior; the melt flows through elongated pores between single microscopic crystals, somewhat like water flowing through sand.

LAVA: Molten rock expelled during a volcanic eruption at the earth's surface.

MELT: The name for molten rock before it erupts.

MID-OCEAN RIDGES: Underwater mountain ranges that generate new ocean crust through volcanic eruptions.

MINERALS: The building blocks of rocks, which can be made up of single elements, such as gold, or multiple elements; olivine, for instance, comprises magnesium, silicon and oxygen.

OPHOLITE: A section of ocean crust and underlying mantle rocks that has been uplifted onto the continents during the collision of tectonic plates.

green, but if you could see them in their rightful home, they would be glowing red- or even white-hot. The top of the mantle is about 1,300 degrees Celsius, and it gets about one degree hotter with each kilometer of depth. The weight of overlying rock means the pressure also increases with depth—about 1,000 atmospheres for every three kilometers.

Knowledge of the intense heat and pressure in the mantle led researchers to hypothesize in the late 1960s that ocean crust originates as tiny amounts of liquid rock known as melt—almost as though the solid rocks were “sweating.” Even a minuscule release of pressure (because of material rising from its original position) causes melt to form in microscopic pores deep within the mantle rock.

Explaining how the rock sweat gets to the surface was more difficult. Melt is less dense than the mantle rocks in which it forms, so it will constantly try to migrate upward, toward regions of lower pressure. But what laboratory experiments revealed about the chemical composition of melt did not seem to match up with the composition of rock samples collected from the mid-ocean ridges, where erupted melt hardens.

Using specialized equipment to heat and squeeze crystals from mantle rocks in the laboratory, investigators learned that the chemical composition of melt in the mantle varies depending on the depth at which it forms; the composition is controlled by an exchange of atoms between the melt and the minerals that make up the solid rock it passes through. The experiments revealed that as melt rises, it dissolves one kind of mineral, orthopyroxene, and precipitates, or leaves behind, another mineral, olivine. Researchers could thus infer that the higher in the mantle melt formed, the more orthopyroxene it would dissolve, and the more olivine it would leave behind. Comparing these experimental findings with lava samples from the mid-ocean ridges revealed that almost all of them have the composition of melts that formed at depths greater than 45 kilometers.

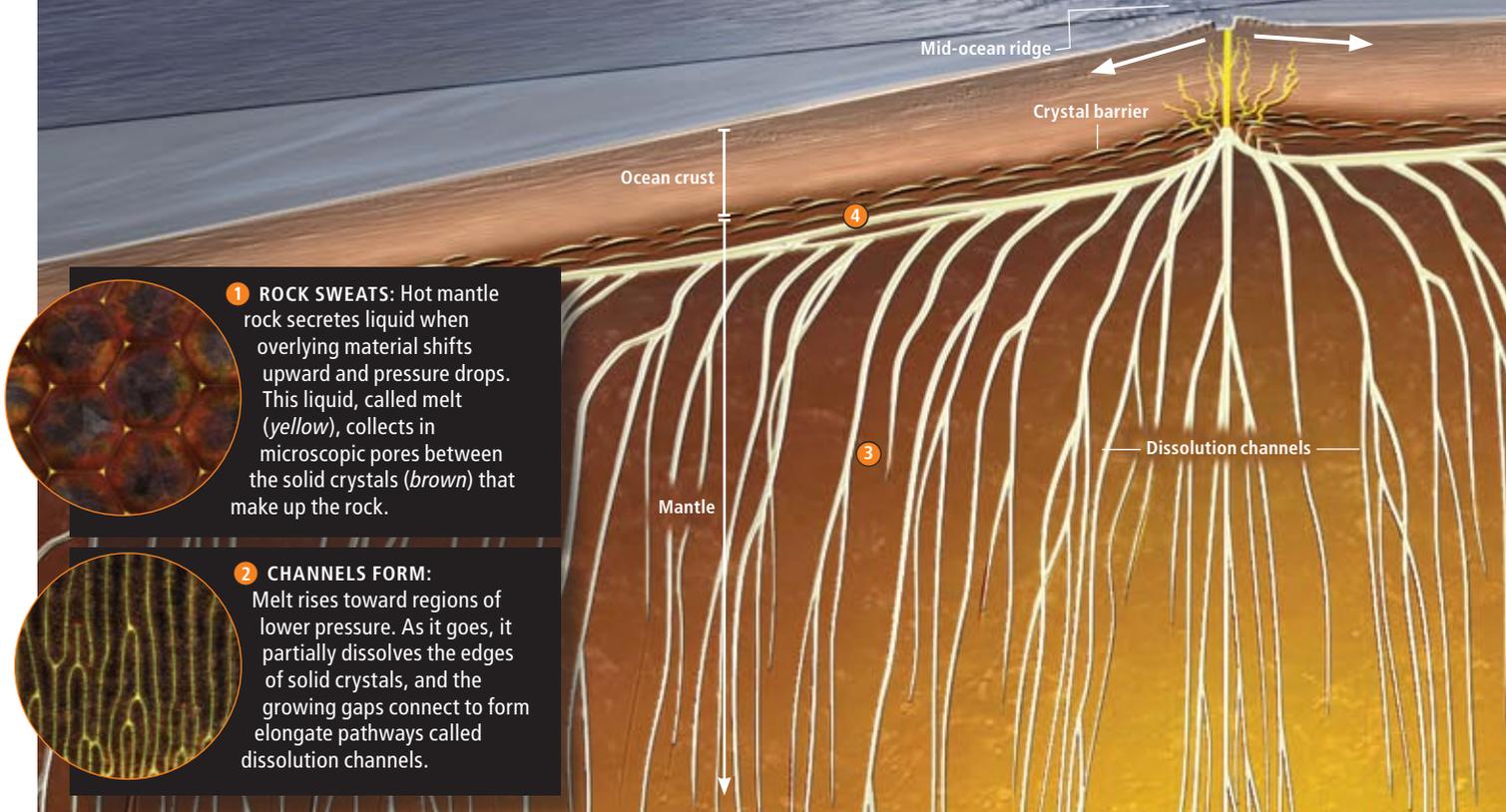
This conclusion spurred a lively debate about how melt is able to rise through tens of kilometers of overlying rock while preserving the composition appropriate for a greater depth. If melt rose slowly in small pores in the rock, as researchers suspected, it would be logical to assume that all melts would reflect the composition of the

ELLIOT LUM AND JESSE WARNER CIRES, *University of Colorado at Boulder*, and NOAA/National Geophysical Data Center (www.ngdc.noaa.gov/mgg); SOURCE FOR DATA: “AGE, SPREADING RATES AND SPREADING SYMMETRY OF THE WORLD’S OCEAN CRUST,” BY R. DIETMAR MÜLLER ET AL., IN *GEOCHEMISTRY, GEOPHYSICS, GEOSYSTEMS*, VOL. 9, 004006, 2008 (DOI:10.1029/2007GC001743)

SWEATING THE SEAFLOOR

The solid foundation of the earth's ocean basins consists of massive slabs of volcanic rock seven kilometers thick. This rock, known as ocean crust, originates as tiny droplets that form across broad regions of the planet's solid interior, or man-

tle, almost as though the rocks were sweating. Yet through a process known as focused porous flow, those countless droplets all emerge along mid-ocean ridges. As this new material rises up, older crust moves away from the ridges (*arrows*).



1 ROCK SWEATS: Hot mantle rock secretes liquid when overlying material shifts upward and pressure drops. This liquid, called melt (*yellow*), collects in microscopic pores between the solid crystals (*brown*) that make up the rock.

2 CHANNELS FORM: Melt rises toward regions of lower pressure. As it goes, it partially dissolves the edges of solid crystals, and the growing gaps connect to form elongate pathways called dissolution channels.

3 MELT OOZES SLOWLY: Melt rises only a few centimeters a year because dissolution channels are congested with rock grains that the melt cannot dissolve. Gradually, millions of threads of melt coalesce into larger conduits.

4 BARRIERS BLOCK FLOW: In the cool upper mantle, some rising melt loses enough heat to crystallize, forming solid barriers. These crystal barriers arise deeper far away from the ridge, so they guide the remaining melt toward the ridge.

5 CRACKS OPEN: Underneath the mid-ocean ridge, crystallized melt blocks upward flow completely. Melt accumulates in lens-shaped pockets until the pressure inside rises enough to fracture the colder rocks above.

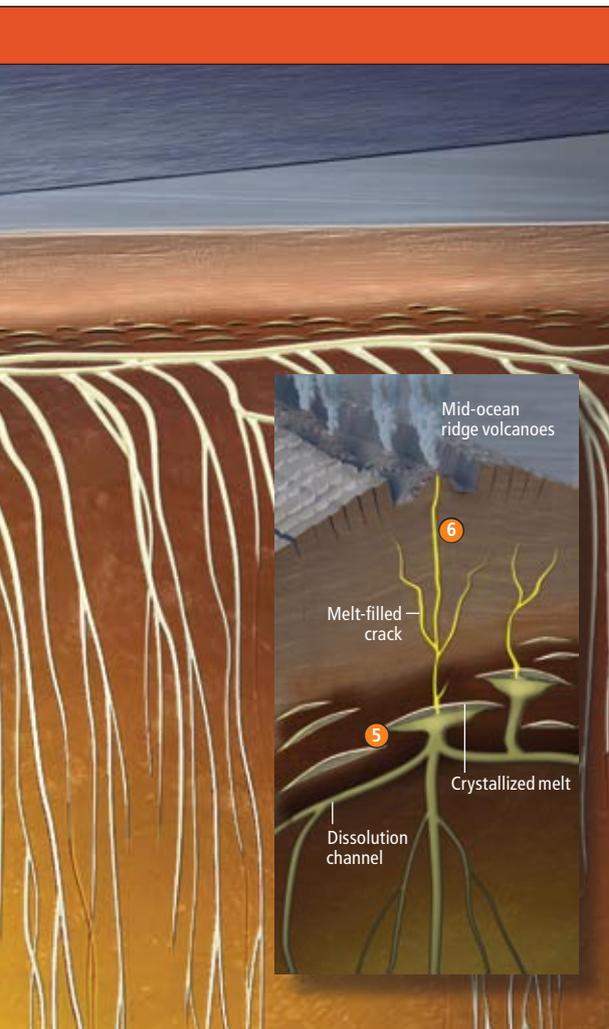
shallowest part of the mantle, at 10 kilometers or less. Yet the composition of most mid-ocean ridge lava samples suggests their source melt migrated through the uppermost 45 kilometers of the mantle without dissolving any orthopyroxene from the surrounding rock. But how?

Cracking under Pressure?

In the early 1970s scientists proposed an answer that was not unlike the typical layperson's view: the melt must make the last leg of its upward journey along enormous cracks. Open cracks would allow the melt to rise so rapidly that it would not have time to interact with the surrounding rock, nor would melt in the core of the crack ever touch the sides. Although open cracks are not a natural feature of the upper mantle—

the pressure is simply too great—some investigators suggested that the buoyant force of migrating melt might sometimes be enough to fracture the solid rock above, like an icebreaker ship forcing its way through polar pack ice.

Adolphe Nicolas of the University of Montpellier in France and his colleagues discovered tantalizing evidence for such cracks while examining unusual rock formations called ophiolites. Typically, when oceanic crust gets old and cold, it becomes so dense that it sinks back into the mantle along deep trenches known as subduction zones, such as those that encircle the Pacific Ocean. Ophiolites, on the other hand, are thick sections of old seafloor and adjacent, underlying mantle that are thrust up onto continents when two of the planet's tectonic plates collide. A fa-



6 MELT FLOWS QUICKLY: Open cracks allow melt to escape rapidly upward, completely draining the pocket below. Some melt erupts as lava atop the mid-ocean ridge volcanoes, but most of it crystallizes within the crust below.

amous example, located in the Sultanate of Oman, was exposed during the ongoing collision of the Arabian and Eurasian plates. In this and other ophiolites, Nicolas's team found unusual, light-colored veins called dikes, which they interpreted as cracks in which melt had crystallized before reaching the seafloor.

The problem with this interpretation was that the dikes are filled with rock that crystallized from a melt that formed in the uppermost reaches of the mantle, not below 45 kilometers, where most mid-ocean ridge lavas originate. In addition, the icebreaker scenario may not work well for the melting region under mid-ocean ridges: below about 10 kilometers, the hot mantle tends to flow like caramel left too long in the sun, rather than cracking easily.

A Porous River

To explain the ongoing mystery, I began working on an alternative hypothesis for lava transport in the melting region. In my dissertation in the late 1980s, I developed a chemical theory proposing that as rising melt dissolves orthopyroxene crystals, it precipitates a smaller amount of olivine, so that the net result is a greater volume of melt. In the 1990s my colleagues—Jack Whitehead of the Woods Hole Oceanographic Institution; Einat Aharonov, now at the Weizmann Institute of Science in Rehovot, Israel; and Marc Spiegelman of Columbia University's Lamont-Doherty Earth Observatory—and I created a mathematical model of this process. Our calculations revealed how this dissolution process gradually enlarges the open spaces at the edges of solid crystals, creating larger pores and carving a more favorable pathway through which melt can flow.

As the pores grow, they connect to form elongate channels. In turn, similar feedbacks drive the coalescence of several small tributaries to form larger channels. Indeed, our numerical models suggested that more than 90 percent of the melt is concentrated into less than 10 percent of the available area. That means millions of microscopic threads of flowing melt may eventually feed into only a few dozen, high-porosity channels 100 meters or more wide.

Even in the widest channels, many crystals of the original mantle rock remain intact, congesting the channels and inhibiting movement of the fluid. That is why melt flows slowly, at only a few centimeters a year. Over time, however, so much melt passes through the channels that all the soluble orthopyroxene crystals dissolve away, leaving only crystals of olivine and other minerals that the melt is unable to dissolve. As a result, the composition of the melt within such channels can no longer adjust to decreasing pressure and instead records the depth at which it last "saw" an orthopyroxene crystal.

One of the most important implications of this process, called focused porous flow, is that only the melt at the edges of channels dissolves orthopyroxene from the surrounding rock; melt within the inner part of the conduit can rise unadulterated. Numerical models thus provided key evidence that melt forming deep within the mantle could forge its own upward path—not by cracking the rock but by dissolving some of it. These modeling results were complemented by our ongoing fieldwork, which yielded more direct evidence for porous flow in ophiolites.

FAST FACTS

- It takes an average of 100 years to generate a new swath of oceanic crust six meters wide and seven kilometers thick.
- The hot rock of the earth's mantle is composed of solid crystals, but like a glacier made of solid crystals of ice, mantle rock can flow up to 10 centimeters a year—about as fast as fingernails grow.
- Eruptions of lava at mid-ocean ridges billow across the seafloor at velocities that may at times surpass 100 kilometers per hour.

HOW MID-OCEAN RIDGES FORM

Sometimes new oceans are born on dry land, where tectonic forces pull the land apart in a process called continental rifting. A rising plume of hot mantle rock breaks up and thins the continent from below. This thinning segment of continental crust constitutes a so-called rift valley in which eruptions of basaltic lava—the same kind of lava that makes up ocean crust—become common. As the two sides of the rift diverge, the valley eventually falls below sea level and floods. Once underwater, the volcanoes of the former rift valley become a mid-ocean ridge, where new ocean crust is generated between the two pieces of the old continent.

[INTRIGUING SIMILARITIES]

Water on Land Flows Like Melt in the Mantle

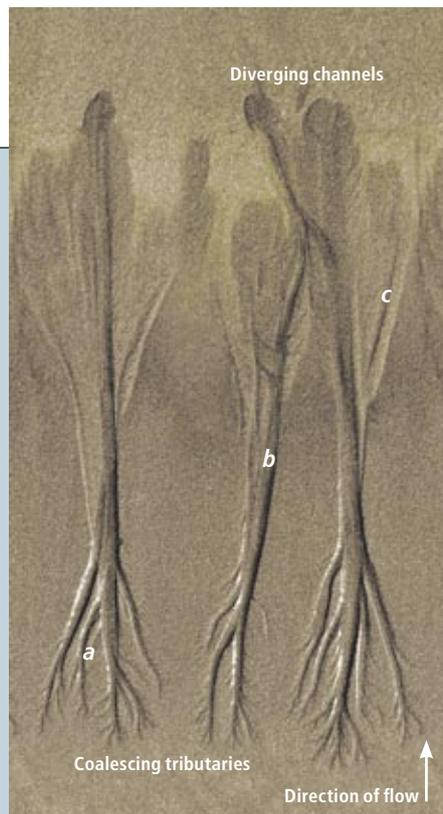
Water flowing over a beach carves a network of channels, much like those that molten rock, or melt, forms as it rises through the earth's solid interior. Although these channel patterns develop by different means—water on the beach physically lifts sand grains and moves them, whereas melt dissolves some of the surrounding rock—their likeness suggests that similar physical laws govern each.

In both cases, regular patterns arise from random starting conditions. On the beach, groundwater that emerges on the surface at low tide flows quickly toward any low spots. This water picks up sand grains, and as it flows, it carves increasingly deep channels that in turn redirect any additional water that enters them along the way (a). As a result of this feedback mechanism, regularly spaced channels arise and coalesce downstream (b)—even though their point of origin is random. Like creeks and streams feeding a large river, this erosion pattern emerges because it is the best way for the system to conserve energy: the deeper and wider a channel is, the less energy is lost because of friction between the moving water and underlying sand.

Conservation of energy is also a key factor controlling chemical erosion in the earth's mantle. As melt dissolves the surrounding rock, it gradually enlarges the tiny open spaces, or pores, it travels through. These so-called dissolution channels grow and coalesce as the melt migrates higher because the viscous drag, which is analogous to friction, diminishes as pores grow larger [see box on preceding two pages]. As on the beach, many small, active channels supply a few large ones—a pattern that partially explains why undersea eruptions are generally confined to mid-ocean ridges rather than scattered randomly across the seafloor.

Changing conditions can force coalescing channels to diverge. On the beach, water drops its load of sand as the slope flattens out, forming barriers that divert water away from the main channel (c). As in a delta where a river meets the sea, water accumulates behind the obstructions, then periodically overflows and erodes new pathways, which in turn become clogged and abandoned. A similar divergence occurs in the uppermost mantle, which is cooler than the rock deeper down. There the melt cannot remain entirely molten, and parts of it crystallize. Periodically, though, melt bursts through the solid crystal barriers—sometimes forging a new conduit to the seafloor.

—P.B.K.



Focused Effort

The only way to fully appreciate the Oman ophiolite is from the air. This massive formation constitutes a nearly continuous band of rock 500 kilometers long and up to 100 kilometers wide. Like all ophiolites, the mantle part of the Oman ophiolite is generally weathered to a rusty brown color and conspicuously laced with thousands of veins of tan-colored rock. Geologists had long ago identified these veins as a rock called dunite but had not carefully measured the compositions of the minerals within either the dunite or the surrounding rock.

As scientists would expect for rocks once part of the upper mantle, the surrounding rock is rich in both olivine and orthopyroxene. The dunite, on the other hand, is more than 95 percent olivine—the mineral left behind as melt rises through the mantle. Dunite also completely lacks orthopyroxene, which is consistent with the chemical theory predicting that all the orthopyroxene would have been dissolved away by the time the melt reached the uppermost mantle. From this and other evidence, it seemed clear that the dunite veins were conduits that

transported deep melts up through the shallow mantle beneath a mid-ocean ridge. We were seeing dissolution channels frozen in time.

As exciting as these discoveries were, they did not fully explain a second mystery that long perplexed geophysicists. The massive lava flows at mid-ocean ridges emerge from a zone only about five kilometers wide. Yet seismic surveys, which can distinguish between solid and partially molten rock, show that melt exists to a depth of at least 100 kilometers in a region several hundred kilometers across. How, then, does rising lava get channeled into such a narrow region of volcanism on the seafloor?

In 1991 David Sparks and Mark Parmentier, both then at Brown University, proposed an answer rooted in the variable temperature of ocean crust and the uppermost mantle. Newly erupting lava constantly adds material to the slabs of ocean crust on either side of a mid-ocean ridge. As older parts of the slabs move away from the ridge, making way for new, hot lava, they gradually cool. The cooler the crust, the denser it becomes, and so the farther into the warm mantle it sinks. This cooling trend means that in the

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PETERB. KELEVEN

open ocean far from the crest of a mid-ocean ridge, the seafloor and base of the ocean crust below it are an average of about two kilometers deeper than the seafloor and the base of the crust directly underneath the ridge. In addition, the cold crust cools the top of the mantle, so that the cooled part of the uppermost mantle gets thicker, and its base deeper, farther from the ridge.

Based on this relation, Sparks and Parmentier created a computer model of porous flow within the mantle. In their simulations, they could see that some of the rising melt loses enough heat to crystallize in the uppermost mantle—effectively forming a dam or roof. These barriers form deeper the farther from the hot, mid-ocean ridges they are, so as the remaining melt migrates upward, it is forced to do so at an angle, following this inclined roof toward the ridge.

Ultimate Eruptions

Field observations and theoretical models thus provided good explanations for two major mysteries. Ascending melt does not take on the chemical composition in equilibrium with the surrounding mantle rocks because it is chemically isolated within wide dunite conduits. And these conduits are directed toward the mid-ocean ridges as some of the melt cools and crystallizes in the uppermost mantle. But a new question soon arose: If the rise of melt is a continuous, gradual process, as we predict, what unleashes the periodic bursts of molten rock that constitute volcanic eruptions on the seafloor?

Again, field geology guided our theorizing. In the Oman ophiolite, Nicolas and his colleague

Françoise Boudier at Montpellier showed in the mid-1990s that melt accumulates in lens-shaped pockets—a few meters to tens of meters high and tens to hundreds of meters wide—within the shallowest part of the mantle, just below the base of the ocean crust. To explain the physical processes involved, my colleagues and I had to consider how differently mantle rocks behave just below the base of the crust than they do at greater depth.

Underneath an active spreading ridge such as the East Pacific Rise or the ridge that formed the Oman ophiolite, the rocks of the uppermost mantle (that is, the part of the mantle within 2,000 meters of the base of the crust) lose heat to the cool, overlying seafloor. Consequently, some melt cools and crystallizes. With the constant influx of melt from below blocked from continuing upward, melt begins accumulating in lens-shaped pockets below the crystallized material. As more melt enters, the pressure inside the lens rises. Deeper down, the rocks would be hot enough to flow in response, thereby relieving this pressure surge, but here heat loss to the overlying seafloor makes the rocks too stiff. As a result of the increasing pressure, the rocks above the melt pockets periodically crack, forming conduits that lead into the young ocean crust above. Some of the melt collects and freezes near the base of the crust, building up new rocks without ever erupting. But at times the melt surges all the way up and out the neck of a volcano, forming a lava flow up to 10 meters thick and 10 kilometers long, incrementally paving the seafloor with volcanic rock.

Branching Out

These detailed insights into melt-transport networks deep underneath the seafloor bear many similarities to what scientists know about river networks on the earth's surface.

Like the force of small streams joining to form rivers, chemical erosion in the deeper mantle forms a coalescing network in which many small, active tributaries feed fewer, larger channels. Melt that crystallizes in the upper mantle forms “levees” that redirect its flow much like a muddy river that deposits sediment and creates natural levees as it flows into the sea. In both situations, the levees are breached periodically, allowing large, transient outbursts to pass through a single conduit. Research on the underlying physical processes that govern river- and melt-transport networks may ultimately yield a single fundamental theory that explains the behavior of both. ■

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Peter B. Kelemen is Arthur D. Storke Memorial Professor at Columbia University's Lamont-Doherty Earth Observatory. Kelemen first began contemplating how magma migrates through the earth's rocky interior in 1980 while he was in the Indian Himalaya mapping ophiolites. Since then, he has investigated the interaction between solid and molten rock using a combination of fieldwork, mathematical chemical modeling and fluid dynamics research.

➔ MORE TO EXPLORE

Extraction of Mid-Ocean Ridge Basalt from Upwelling Mantle by Focused Flow of Melt in Dunite Channels. Peter B. Kelemen, Nobumichi Shimizu and Vincent J. M. Salters in *Nature*, Vol. 375, pages 747–753; June 29, 1995.

Causes and Consequences of Flow Organization during Melt Transport: The Reaction Infiltration Instability. Marc W. Spiegelman, Peter B. Kelemen and Einat Aharonov in *Journal of Geophysical Research*, Vol. 106, No. B2, pages 2061–2077; 2001.

Dunite Distribution in the Oman Ophiolite: Implications for Melt Flux through Porous Dunite Conduits. Michael G. Braun and Peter B. Kelemen in *Geochemistry, Geophysics, Geosystems*, Vol. 3, No. 11; November 6, 2002.

See movies of mathematical models of seafloor spreading at www.ideo.columbia.edu/~mspieg/ReactiveFlow



FORMER OCEAN CRUST and part of the underlying mantle are exposed on dry land in the Sultanate of Oman. Called an ophiolite, this massive brown rock formation, now weathered into rugged hills, was thrust up onto the continent during the ongoing collision of two tectonic plates.

BRADLEY R. HACKER