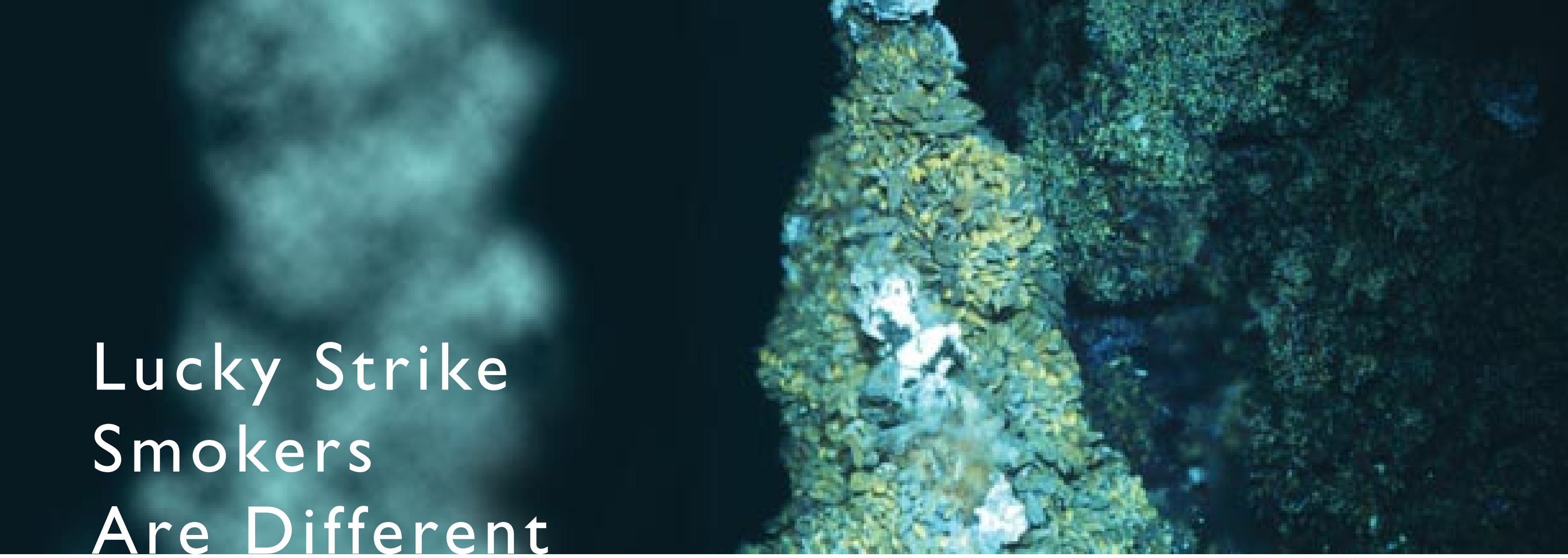


Lucky Strike Smokers Are Different

by Paul Asimow

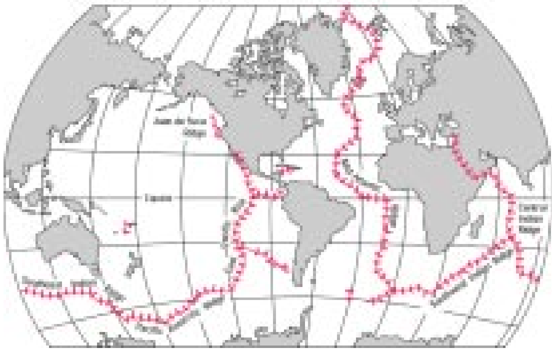
In the dredging bucket of *Atlantis II* was a new species of mussel, right, clinging to lumps of fool's gold (iron sulfide) and glassy lava.

Left: A forest fire in an overflowing ashtray? Not exactly. The "cigarette butts" are tubeworms, which live near volcanic vents below the Pacific Ocean. Called smokers, these vents belch out superheated water and assorted minerals. Smokers have been found along midocean ridges all over the world, but those at Lucky Strike (*not* named after a cigarette brand) are unique, with a different geology, vast numbers of mussels (top right), and not a tubeworm in sight.

On a pleasant September day in 1992, after the winter storms and before the hurricane season, a French-American science party aboard the research vessel *Atlantis II* was cruising up and down the Mid-Atlantic Ridge near the Azores looking for hot water vents at the bottom of the ocean. Navigating by real-time multibeam sonar, the ship arrived at a promising volcanic construction along the ridge. Instead of doing the vent search first, the scientists decided to lower a dredging basket for a rock sample. The dredge returned from 1,600 meters under the sea filled with live mussels and fresh sulfide minerals (above). This was quite unexpected: they didn't think they were near a possible vent site, and they'd never found these mussels before. In honor of its remarkably random discovery, the vent field was christened Lucky Strike. It's unusual in many more ways than mussels, and I'm trying to find out why.

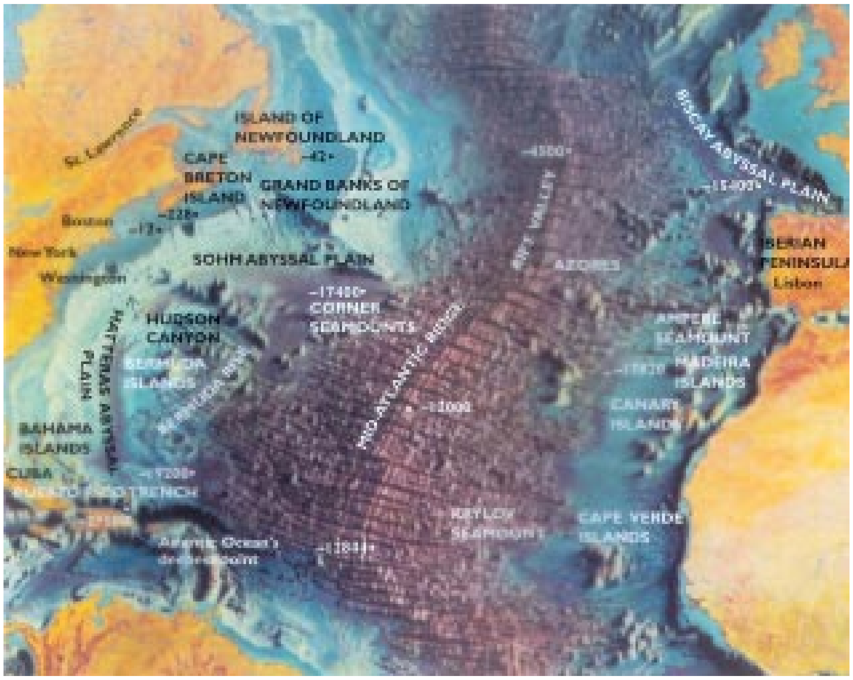
Anyone who studied geology more than 20 to 30 years ago probably learned only about the continents. They're very easy to study, because you can walk around on them. And they have a lot of history—many parts of the continents are billions of years old. But nowadays, all the interesting action is under the ocean, especially along the midocean ridges. These ridges are a global system of volcanoes about 40,000 kilometers long. They include the Mid-Atlantic Ridge, which runs right down the middle of the Atlantic Ocean; the East Pacific Rise (which spreads much faster than the Mid-Atlantic Ridge, adding about 10 centimeters of new crust a year, compared with two centimeters of new crust a year at the Mid-Atlantic Ridge); and the Southeast, Southwest, and Central Indian Ridges. Despite the faster spreading rate in the Pacific, the Atlantic Ocean is growing at the expense of the Pacific, because its margins are still attached to the continents rather than subducting (sliding) underneath them and returning to the mantle below. (I probably won't be able to say that any more in 100 million years or so.)

The artist's impression of the seafloor of the Atlantic on the next page shows the Mid-Atlantic Ridge to be quite a respectable mountain range, rising 2,000 meters above the abyssal plain (the flat ocean floor), which is generally about 5,000 meters deep. The depth of the crest of the Mid-Atlantic Ridge varies along its length: it's mostly around 2,500 meters deep, but as you go up toward the Arctic, it gets shallower, and even rises



The midocean ridges wind around the globe like the seams of a baseball. The ocean crust really is coming apart at the seams at these ridges.

From *Understanding Earth,* Frank Press and Raymond Siever, 1994, 1998, 2001, by W. H. Freeman & Co. Used with permission.



Map of the Atlantic Ocean floor showing the Mid-Atlantic Ridge as a sizeable mountain range, broken up into numerous segments by fracture zones called transform faults.

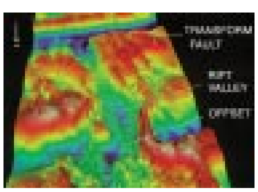
Right: The Thingvellir plains are part of the rift valley of the Mid-Atlantic Ridge, which runs above water across Iceland. The cliffs on the left side of the valley are on a tectonic plate moving toward America, while those in the upper far right distance are on a plate moving east. Volcanoes and geysers are active all along the valley floor.

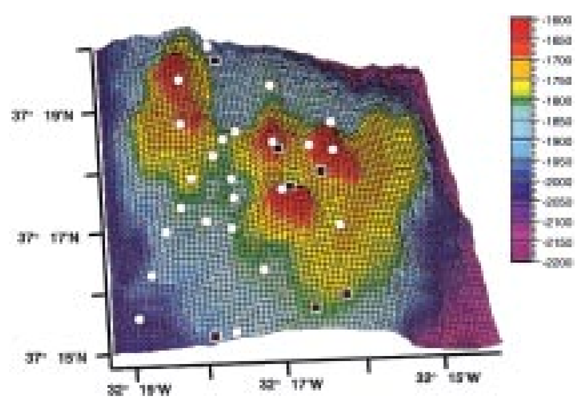
above sea level across Iceland. Iceland is the only place where you can walk around on the ridge without getting wet.

Looking more closely at the Mid-Atlantic Ridge, you can see in the model lower left that there's a 20-kilometer-wide rift valley running down the center of the mountain range, and that the ridge is broken into segments separated by deep cracks in the crust called transform faults, or fracture zones. All the midocean ridges are divided into these segments, and we don't really know how they form—it's an interesting puzzle. Are they just a geometric constraint of the way the earth is spreading? Are they due to preexisting weaknesses in the lithosphere (the cold and therefore brittle layer of rocks near the earth's surface), perhaps left over from the way the continents broke apart? Or are they generated by instabilities in the upwelling of the mantle underneath? Eventually, I would like to get at which of these possible causes are the most important.

If we zoom into the rift valley, we often find that there's a volcano sitting in the center. The Lucky Strike seamount (literally, mountain under the sea), below, is about 600 meters high, not tall enough to stick up out of the valley, but still a pretty big feature. And sitting on top of it are three active volcanic cones. They're very anomalous in composition, which is part of the story. The hydrothermal site I'm going to talk about is on the side of one of them.

The seafloor of the rift valley is covered with what are called pillow basalts, formed when basaltic lava erupts from below into cold water. As it emerges into the water, it tends to separate into blobs. The outside quenches into glass, while the interior crystallizes more slowly, and then these blobs pile up. You can find them on land in some places, and they're clear evidence that you're looking at something that used to be under water,

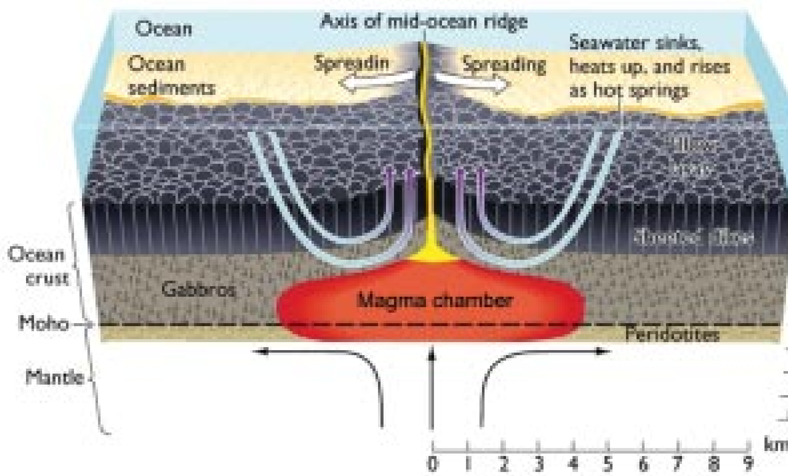




Above: Part of the Mid-Atlantic Ridge, with blue areas the deepest. A segment of the rift valley runs down the center, bounded by a transform fault at the upper end and a short offset at the lower. Right: The Lucky Strike seamount, a large volcano in the rift valley, is topped by three volcanic cones, the red peaks in the center, between which are the hydrothermal vent fields. (Black boxes: dredge sites; white circles: rock core sites).

Earth and Planetary Science Letters, 148, Langmuir et al., Hydrothermal vents near a mantle hot spot: the Lucky Strike vent field at 37°N on the Mid-Atlantic Ridge, 69-91. ©1997, with permission from Elsevier Science.

Right: All ocean crust—70 percent of the earth's surface—forms at the midocean ridges. Lava rises to the surface from the magma chamber at the ridge axis and becomes pillow basalt. It's very porous, so that sea water sinks through, heats up as it comes close to the magma chamber, and shoots back out onto the ocean floor as a hot spring, or hydrothermal vent.



A black smoker, above, and pillow basalt, below. Most of the seabed around the ridge areas looks as though it's covered with these pillows, formed when hot lava erupts into the cold seawater.

because we know of no way to make pillow basalts on land. There are also hydrothermal vents dotted around, where hot water comes out of the seafloor—imagine an underwater version of a geyser field in Yellowstone National Park. The one at left is called a black smoker: It's black because there are minerals dissolved in the water, mostly manganese oxides, and as soon as the water emerges from the seafloor, they precipitate out, so that you get clouds of black sediment shooting up looking just like dirty smoke pouring out of a chimney.

Now why would you want to study midocean ridges? I can give you a lot of good reasons. In the first place, that's where the entire ocean crust forms. While the active spreading centers themselves are very narrow (new ocean crust reaches its full thickness within a couple of kilometers of the ridge axis), a staggering 70 percent of the earth's surface is oceanic crust, and all of it has formed at a midocean ridge within the last 200 million years or so. The processes of crust formation at the ridges are relatively simple and reproducible, and this imparts a very characteristic structure to the entire oceanic crust.

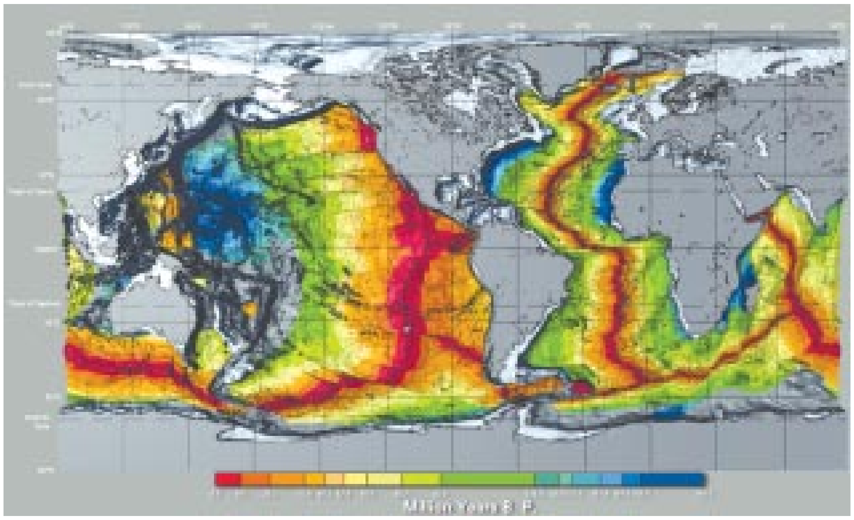
A cross section of a midocean ridge, such as the one in the diagram above, shows this characteristic structure: a sequence, from bottom to top, of mantle rocks such as peridotites, intrusive gabbros (granular igneous rocks that crystallize at depth), sheeted dikes (lava crystallized in the crack that was bringing it to the seafloor), pillow basalts, and sediments. This sequence was known from on-land geology since the beginning of the 20th century, in places where a midocean ridge has been pushed up on land, and it's called an ophiolite complex, which, incidentally, is a really bad two-language play on words: this type of rock when it gets altered forms serpentinite, and *ophios* is Greek for snake.

The tectonic plates carrying the continents are spreading apart at the ridges because of gravitational forces distributed across the plates and at all their edges. Locally, beneath the spreading ridge, the earth's mantle (the layer between the crust and the core, 2,900 kilometers deep) has to well up to fill the space. It's a popular misconception that the mantle is liquid. In fact, it's rock solid due to the high pressure of the rocks above pressing down on it. When the mantle is drawn upward by spreading at the ridge, the pressure drops, and it partially melts at depths between about 30 and (at most) 200 kilometers. The molten fraction can then separate and rise buoyantly up into the crust. It usually "ponds" at a shallow depth (a few kilometers), and sits there in what's termed a magma chamber, slowly cooling and crystallizing into igneous rocks.

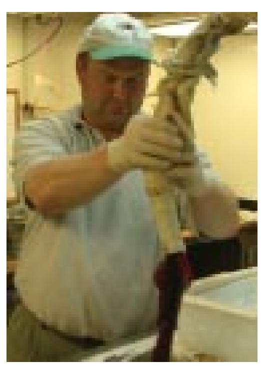
Occasionally, the ocean crust cracks all the way to the top, and lava (which is what we call magma once it reaches the surface) erupts onto the seafloor, spreading all around as pillow basalts. In the conduit where the crust cracked, the magma crystallizes and forms a dike. The plates continue to spread apart, the crust cracks again, another eruption of lava occurs, and another dike forms. Eventually, you get sheet after sheet of dikes transitioning upward into pillow basalts. Because the pillow basalts are very porous, seawater makes its way down into the holes, gets close to the magma chamber, heats up, and reacts chemically with the basaltic rocks, altering their composition. This water can't get into the magma chamber itself, so it's pushed up again to come out at a place of least resistance, near the axis of the midocean ridge where the crust is being pulled apart. The places where it boils out most vigorously are the hot springs, or hydrothermal vents.

A second reason for studying the midocean ridges is that the volcanoes here are grossly dominant over all other types of volcanoes on earth. If you're interested in volcanic rocks, this is the place to go: 20 cubic kilometers of new igneous rock are formed at the ridges every year. The continents average between one and two

Müller, R. D. et al. Digital Isochrons of the Ocean Floor, http://gdcinfo.agg.emr.ca/app/agemap_e.html



This digital map of ocean-floor age reveals how young the rocks around the midocean ridges are. Red areas are rocks formed less than 10 million years before the present (B.P.), and blue areas are rocks that formed in Jurassic times, 200 million years B.P. Because the East Pacific Rise is spreading particularly fast, the age bands on either side are quite wide.



Courtesy Galapagos Rift 2002 Expedition, funded by NOAA, NSF and WHOI.

Above, a colony of tubeworms at the East Pacific Rise and right, Woods Hole Oceanographic Institution biologist Tim Shank extracting a young specimen from its white chitin tube. Fully grown, tubeworms can reach eight feet.

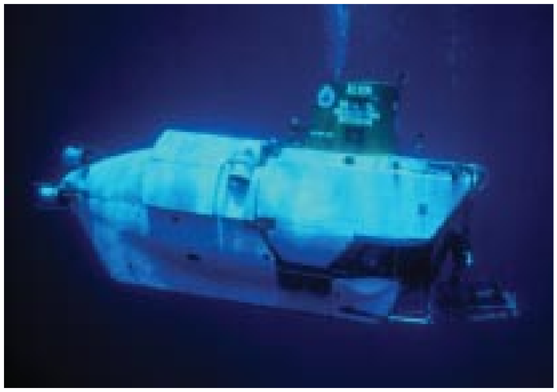
billion years old, but the seafloor is nowhere older than Jurassic, a mere 200 million years.

A significant fraction of the earth below sea level has been resurfaced within the last 10 million years, especially on the fast-spreading East Pacific Rise. So there's a lot of action going on down there—a lot of new rock being made, a lot of heat getting out of the interior of the earth, a lot of chemical differentiation going on, and a lot of interesting events to study.

Third, and my best reason, is that as volcanic systems go, it's the simplest. A classic problem in petrology is to separate the effects of the process of melting from the effects of the source composition (what was in the rocks that were melted to make the magma that cooled to make the rocks we're studying). At the ridge, this is a fairly tractable problem because there's no preexisting overlying crust to alter or contaminate what's coming out of the upper mantle, which appears to have a reasonably homogeneous source composition. Moreover, because the ridges are under a few thousand meters of water, and therefore under a few hundred bars of pressure, the volatile chemicals that come out of volcanoes—things like water, carbon dioxide, noble gases, methane, hydrogen, and hydrogen sulfide—actually stay dissolved in the glass that forms the rims of the basalt pillows. It's much easier than studying volcanoes on land, where all these chemicals are spewed into the air when the water coming out flashes over into steam, often explosively. Which brings me to a fourth excuse for studying undersea volcanoes: it's relatively safe!

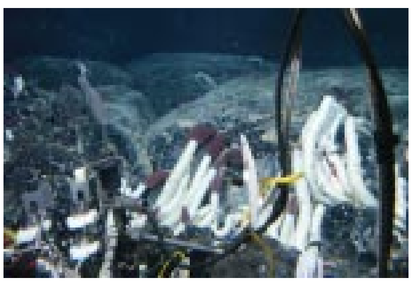
A fifth, and very important, reason for studying midocean ridges is that they control the chemistry of the ocean water itself to a significant extent. For example, ocean water usually has a magnesium concentration of 53 millimoles per liter, but there's no magnesium at all in the hydrothermal fluids coming out the vents. And that's because the ridges are the major sink for magnesium in the

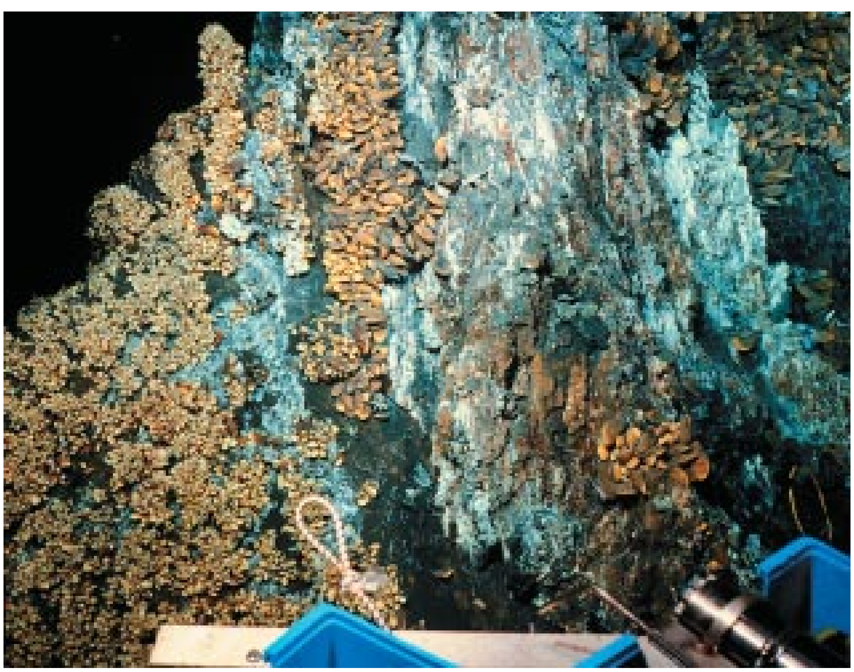
Right: ***Alvin,*** **the deep-submergence vehicle operated by WHOI, can take two scientists and a pilot to a depth of 14,700 feet and is packed with robotic arms, sensors, sampling baskets, cameras, and 12 powerful lights for illuminating the seafloor.**



When *Alvin* revisited the tubeworm-rich vent site "Rose Garden" in the Galapagos Rift earlier this year, the tubeworms were gone, and the area was coated with fresh lava, as in the scene on the left. But a very young tubeworm colony was starting up at a nearby site, named "Rosebud," lower left. Below: *Alvin* approaching a vent at Lucky Strike. Tubeworms are absent, and mussels coat almost every surface. Their shells are white, but a coating of iron hydroxides makes them look rusty.

Courtesy Galapagos Rift 2002 Expedition, funded by NOAA, NSF and WHOI.

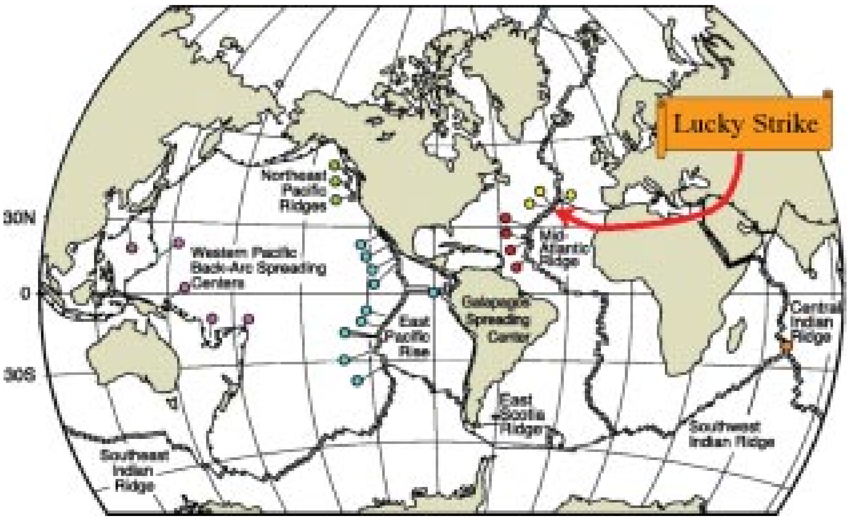


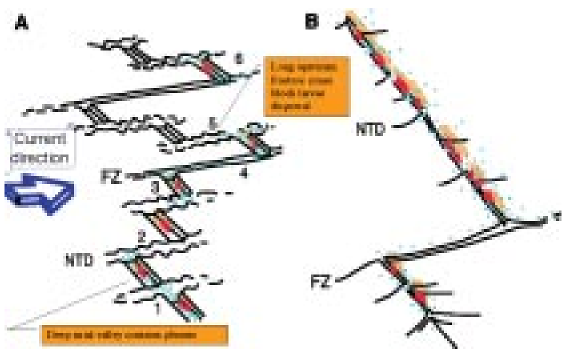


oceans. It weathers off the continents, gets into the oceans via the rivers, sinks through the porous pillow basalts into the crust, and stays there. It's true of a number of other elements as well, but clearest for magnesium.

Finally, but perhaps most surprisingly, there's life down there. In the total absence of sunlight, there are biological communities that live on these volcanic systems. One of the most amazing discoveries of the last 50 years was made in 1977 by Robert Ballard in the Woods Hole Oceanographic Institution (WHOI) deep-submergence vehicle *Alvin*. When he dived down to a hydrothermal vent near the Galapagos Islands, he found a whole ecosystem down there, including bacteria, tubeworms, shrimp, crabs, mussels, clams, octopuses, and fish—everything but plants. Until this find, no one knew that it was possible to have biological communities that were not based on photosynthesis. The animals are feeding on bacteria that get their energy from reactive chemicals in the hot water coming out of the vents. Heat coming out of the earth can provide energy to support life, just like heat from the sun can. It's life, but it's a hard life. It requires some pretty fancy biological tricks to exploit these chemical reactions for metabolism, and most organisms can tolerate only a limited range in temperature. Each species needs to find the right distance from a high-temperature vent, and when the vent position shifts, they're likely to get cooked (there's a spot on the ridge known as the tubeworm barbecue), frozen out, or covered in lava. It's now become a popular belief that these deep-sea vents may have been where life originated—as hostile as they seem to us, they would have been a much less hostile environment than the earth's surface four billion years ago. And, by the way, evidence for a liquid water ocean beneath the ice on Jupiter's moon Europa has excited a great deal of speculation, because hydrothermal energy sources could make that world one of the only other places in the solar system able to support life.

Being a geologist and not a biologist, what I want to know is this: At what level of detail do the physical and chemical variations among the midocean ridges control where the hydrothermal sites are, what kind of vents develop, and what sort of biological communities live on them? How does the physical shape of the ridge system, and the frequency of the volcanic events there, control the opportunities for life to survive? The animals can exist only in a habitat having a stable heat source that goes on for a long time. Does the structure of the ridge also control the opportunity for life to move from one place to another? If you can only live along the rift valley, your opportunities to migrate from one active vent field to another may be limited by the geography. As shown on the map on the next page, the East Pacific Rise has a lot of vent sites and is one entire





Above: Colored lollipops mark known hydrothermal vent sites along the major midocean ridges, with a different color for each biogeographic province, areas where the same animals are found at each site. Right: It's much easier for the larvae of vent animals to spread along the East Pacific Rise ridge zone (B) than along the Mid-Atlantic Ridge (A), which has more fracture zones (FZ) and offsets (nontransform discontinuities, NTD) as well as steeper cliffs edging the rift valley, which trap the vent plumes. Blue dots identify vent animal larvae distribution; red triangles, active vents; orange areas, hydrothermal plumes.

biogeographic province—you find the same organisms wherever you go—but the Mid-Atlantic Ridge has two distinct biogeographic provinces right next to each other, with essentially unrelated organisms and different biological communities. Why is this? One possibility is that, because the fast-spreading East Pacific Rise has relatively few fracture zones—called transform faults—and they're relatively short, it's quite easy for organisms to move up and down it. Moreover, because the rift valley of this ridge is very shallow, the hydrothermal plumes carrying live bacteria and animal larvae can get out of the valley and spread in the general ocean currents. The Mid-Atlantic Ridge, in contrast, has a 1,500-meter-deep rift valley, which the plumes can't rise out of. And there are lots of long fracture zones, which the bacteria and larvae can't get past. Because of this physical isolation, the next ridge segment could have a completely different biological community.

A second possibility, and one that I favor, is that different biological communities, if they can get to a particular ridge segment at all, are responding to chemical differences between midocean-ridge rocks when they decide where to set up camp, and when the different organisms begin fighting over resources. The rock chemistry affects the chemistry of the hydrothermal fluids that come out through the vents, which controls the mineralogy of the deposits at the vents, and hence the elements available to the bacteria as a source of energy. Different elements are used by different species of bacteria, and different populations of animals feed on them.

How do we find these vents? It's actually quite hard. To study the surface of the earth you can fly around in an airplane, and see very large areas very clearly, or you can fly a satellite overhead, and see the whole world. The reason the bottom of the ocean is the last frontier is that it can't be viewed from the air or from a surface ship, because sea-water absorbs any sort of electromagnetic radiation such as light, radio, and radar. Sonar is too coarse a tool to find these little vents until you're already close, while the area you can observe out of a small submersible is so tiny that using one to look for vents would be like exploring a map of the world with an electron microscope. But we have our ways.

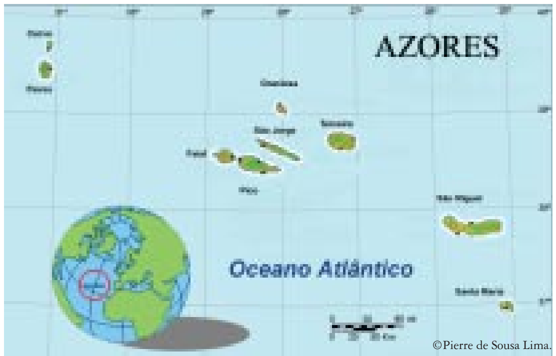
The first is to look at the water chemistry. Water is sampled by dropping a long cable off the side of a ship; attached to the cable is a series of buckets triggered to close at different depths, a method called hydrocasting. Because hydrothermal water is rich in certain metals, like manganese, an increase in the concentration in a sample can point to a vent. It's also very cloudy, something you can measure with a nephelometer, a tool that transmits light across a few centimeters of seawater and measures how much is absorbed

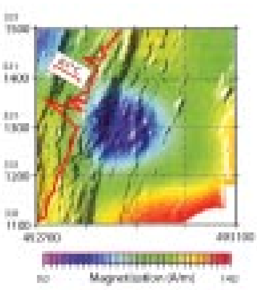
Another way is by doing a seafloor magnetic survey. Fresh igneous rock is magnetized, but at a vent site the hot water flowing through the rock destroys the magnetic minerals, so that a bull's-eye of low magnetization indicates hydrothermal activity—although it can't tell you whether or not the vent is active.

There's also acoustic scintillation tomography, a catchy phrase for something similar to what bats do when they use echolocation. If a bat sends out two clicks and notices a difference between the echoes, it knows a tasty bug is moving nearby. If we send two sonar pings out from a fixed buoy or stationary submarine,

The striking Eiffel Tower smoker vent at Lucky Strike is 20 meters tall. Almost every part is encrusted with mussels.

The Azores are an archipelago of volcanic islands formed by a hot spot. The active hot spot is east of the Mid-Atlantic Ridge, but a couple of older islands on the west side of the ridge have been separated from the others by continued seafloor spreading at the ridge axis. Below: One way to find hydrothermal vents is to tow a magnetometer along the ocean floor. Hot water demagnetizes the rocks, so that a blue bull's-eye of low magnetization can reveal a vent site—though it could be a dead one.





Johnson, H. P. et al., *EOS*, 83, 73-79 (2002)

and they travel through even a small area where hot and cold water are mixing vigorously, they come back decorrelated. This can pinpoint the possible location of a vent to within meters in an area of one square kilometer.

And then there's the dumb-luck method, which is how the Lucky Strike segment was found. The FAZAR expedition on *Atlantis II* (FAZAR stands for French American ZAPS and Rocks, and if that still doesn't mean much, ZAPS stands for Zero-Angle Photon Spectrometer, an instrument to measure manganese in seawater), was supposed to find the hydrothermal sites with ZAPS, and also to explore how the geochemistry of rocks along the ridge was affected by the proximity of the Azores archipelago. When the ship got to Lucky Strike (no one had ever been there before, because every previous cruise had picked a parallel extinct rift, thinking it was the axis of the ridge), the scientists took one dredge before taking water samples, and pulled up the live mussels and fresh sulfides shown on page 9. It's the least efficient way possible to find a hydrothermal site, yet in this case it worked. A return cruise was organized with *Alvin* to explore this little postage stamp of an area, and they found a field of vents. Some of the cooler-looking ones were named Eiffel Tower, Statue of Liberty, and Sintra (a beautiful part of Portugal, whose national waters surround the Azores).

The water coming out of these vents is at 330 degrees Celsius. On the seafloor this isn't boiling, because of the high pressure, but it's still very hot. And the black smoker chimneys here, unlike most others in the world, are not built of sulfide minerals but of barium sulfate, aka barite. The animal community is dominated by mussels, whereas many other vent sites are dominated by large tubeworms. It's an entirely new biogeographic province.

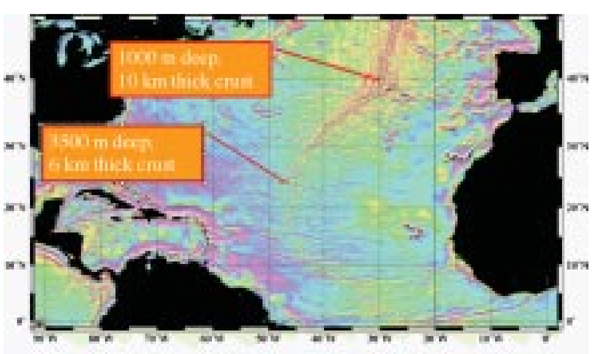
Why is this hydrothermal vent different from all the others? This is where I come in: I'm a specialist in igneous rocks, and I think that geochemistry can explain a lot about why there's a different community of life forms at Lucky Strike.

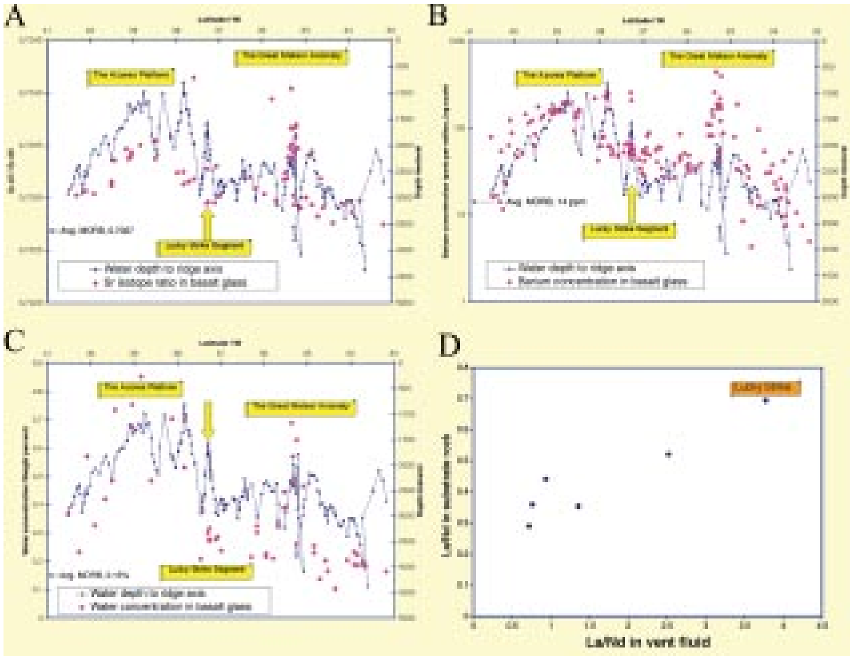
Although most midocean ridge rocks are about the same, because the mantle source is rather homogeneous and the spreading process is everywhere similar, exceptions occur near hot spots—volcanic sources that are fixed in one place while the earth's plates move over them. The most famous hot spot is the Hawaiian Islands, which get progressively older the further away they are from the current vent of the volcano, on the edge of the Big Island. Some hot spots are near ridges and interact with them, and one of these is the Azores, a cluster of nine islands belonging to Portugal that straddle the Mid-Atlantic Ridge.

Hot spots affect ridges in several ways. The first is obvious in the map of seafloor depth shown below. The axis of the Mid-Atlantic Ridge is normally about 3,500 meters deep, with an igneous crust about six kilometers thick, but going up toward the Azores, the ridge is only 1,000 meters below sea level, and the crust is 10 kilometers thick. Crustal thickness is just a reflection of how much basalt has been made, so that there must be more mantle melting near the Azores. The depth to the ridge axis, in turn, reflects the density of the underlying rock column—since crust is less dense than mantle, areas of thick crust stand higher, a principle called isostasy, which is just Archimedes' principle applied to the earth's rigid upper layers floating on the ductile interior.

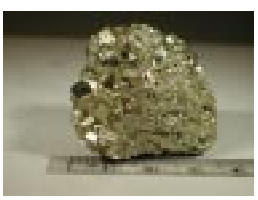
The second effect is that the chemistry is anomalous in several ways. The first anomaly is in the radiogenic isotope ratios, which are the ratios of different isotopes of things like lead, formed by the radioactive decay of things like uranium. These are some of geochemists' favorite and absolutely most obscure tools (*E&S*, 1997, No. 1, p. 20). In graph A on the next page, you can see that the strontium 87/86 isotope ratios at Lucky Strike and the Azores are higher than for ordinary midocean ridge basalt (MORB). It's a sign that we're looking at old, recycled crust: rocks that were enriched in rubidium relative to strontium (^{87}rubidium decays to ^{87}strontium with a half-life of 48 billion years) by melting a long

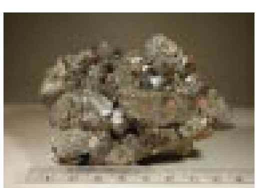
Around the Azores, the Mid-Atlantic Ridge comes much closer to the surface of the ocean, as this marine gravity map of the depth of the seafloor shows.





The strange chemistry of sites along the Mid-Atlantic Ridge near the Azores: A, strontium 87/86 ratios; B, barium levels in the rocks; C, water dissolved in the basalt glass; D, ratio of lanthanum (La) and neodymium (Nd) in the substrate rock compared with that in the vent fluid. The blue lines in graphs A through C are bathymetric depth, and Avg. MORB is the average value for ordinary midocean-ridge basalt.





Lucky Strike smokers are made of barium sulfate (barite), top, whereas other smokers are mainly sulfides such as iron sulfide (iron pyrites or fool's gold), center, or zinc sulfide (sphalerite), bottom.

time ago, subducted back into the mantle, mixed around, and brought back up by the Azores.

In addition to strange isotope ratios, the rocks near the Azores have very strange trace-element concentrations, enriched in some cases by factors of hundreds. The concentration of barium in the rocks, for instance, changes from 14 parts per million (ppm) in average basalt to 50 or 60 ppm in the Lucky Strike segment, and up to 200 or 300 ppm near the Azores (graph B).

Moreover, the rocks themselves are very rich in dissolved water as you approach the Azores (graph C): ordinary basalt is about 0.15 percent water by weight, but in the vicinity of the Azores it gets up to one percent water, which has all kinds of wonderful effects on the way the mantle melts and the chemistry evolves.

The unusual composition of the lava is reflected in the chemistry of the water coming through the hydrothermal vents. Remember, this is seawater that soaked through the porous crust, got close to the magma chamber, heated up, interacted with the rocks down there, and flowed back up again. It inherits the chemistry from the rock that it interacts with, and we can see evidence of this inheritance by looking at the ratio of two rare-earth elements in vent fluids and the volcanic rocks dredged nearby. You can see from graph D, above, that Lucky Strike is definitely wacky, both the rocks and the vent fluid.

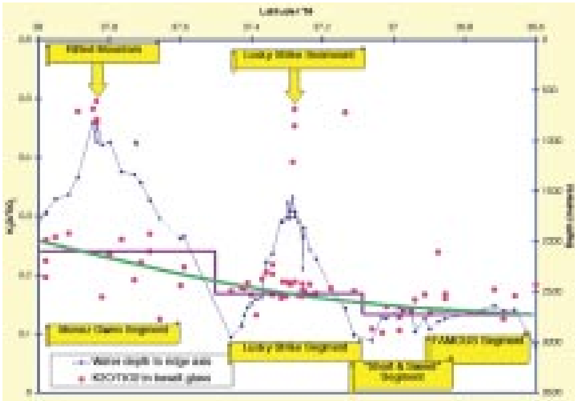
The rocks are weird, the water is weird, and the minerals that precipitate out of the water are weird. Nearly all the black smokers in the world are made of sulfides, mainly of iron, zinc, and copper. (Iron sulfide smokers are just big piles of fool's gold). They can accumulate into massive sulfide deposits, which can be very important economically if by some chance the seafloor ends up on land. A huge black-smoker-related sulfide deposit in Oman drove the entire Mesopotamian Bronze Age until the copper ran out. Lucky Strike smokers are different: they're made from sulfates, mostly barite, the mineralogist's name for barium sulfate.

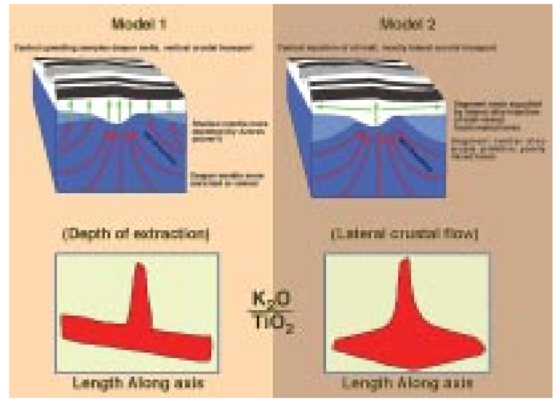
The mineral substrate and water chemistry in turn affect the microbial ecology of the smoker columns. As I explained earlier, there are bacteria down there that get their energy by oxidizing sulfides into sulfates, and others that get their energy by reducing sulfates to sulfides. In the absence of plants, which can't grow down there because there's no sunlight, these bacteria form the basis of the entire food web. Sulfate-reducing bacteria and sulfide-oxidizing bacteria use different metabolic pathways to provide organic carbon to their hosts, and function well in symbiosis with different animals. At Lucky Strike, the bacteria are living on barite, a big source of sulfate, which may be the reason that mussels are so dominant in this place.

Finally, I want to close with the question I raised earlier—why is the Mid-Atlantic Ridge segmented? Is the segmentation imposed from above by the crust, or from below by the mantle? The Lucky Strike segment is a really good place to look at this because there are chemical signals associated with the structure of the segment and the proximity to the Azores that I think will allow us to tell the difference.

Let's zoom out a bit from the Lucky Strike segment and look at the water depth and potassium/titanium ratio in basalt glass (another obscure geochemist's ratio that shows the influence of the hot spot) for four adjacent segments increasingly distant from the peak of the Azores platform at a latitude of 39.5 degrees north: Menez Gwen, Lucky Strike, "Short and Sweet," and FAMOUS. You can see from the graph on the opposite page that there's a regional gradient

Right: With the Azores to the left, and moving south along the Mid-Atlantic Ridge, the potassium/titanium ratios have been plotted at four ridge segments. The ratio spikes in the middle of some segments. Far right: Model 1 would produce a gradient in the potassium/titanium ratio, with a spike in the middle of each segment, and a smooth downward gradient along the segments as they get farther away from the Azores. Model 2 would give segments that all have a constant composition (but also with a spike), and the potassium/titanium ratio would look like a staircase. Are the values in the graph best joined by the green gradient or the purple staircase? It could be either: the data aren't good enough. We need better measurements.





of decreasing potassium/titanium ratio with increasing distance from the Azores, and you can also see, superimposed on the gradient, that the ratio spikes in the middle of some segments. We've come up with two models to explain this.

In Model 1, the mantle flows up more in the middle of a segment, where the crust is thicker, and comes up from further down in the earth. This deeper part of the mantle might be more enriched in potassium than the shallower parts, which may have been depleted by the Azores hot spot, hence the spikes. If this is what's going on, then the north side of each segment, closer to the Azores than the south side, should have more of the "Azores signature," and we should expect to see a regional gradient (except for the spike) expressed within each segment. We should also see a smooth downward gradient along the four segments as they get farther away from the Azores, the green line in the graph.

The alternative hypothesis, Model 2, is that essentially *all* the magma is added to the crust in the middle part of each segment, where it can either erupt as lava onto the seafloor, showing its full range of compositional diversity (as reflected by the potassium/titanium ratio), or the lavas can get mixed up in magma chambers and then be forcibly injected sideways along lateral dikes in the crust. We know this happens because we've actually been able to see it with sonar: during a dike injection event, the sonar and seismic signals propagate along the seafloor for several kilometers. If this is what is happening, each segment would have a relatively even composition, except for a spike in the middle where the near-primary mantle melts can emerge unmixed. In this model, the potassium/titanium ratio would be a staircase, the purple line on the graph.

Is there a gradient or a staircase? Unfortunately, it could be either—the data are too noisy. This research was done 10 years ago based on a cruise that was focusing their sample collection on different issues, and we really need to go back and get more measurements, particularly at the ends of the segments.

To sum up, the Lucky Strike segment shows how many of the earth's systems are linked. An anomalous mantle chemistry caused by the nearby Azores hot spot leads to an anomalous crustal thickness, ridge axis depth, and rock chemistry, which in turn causes an unusual hydrothermal flow with an odd water composition, which produces strange vent chimneys. And all of this leads to a unique biogeographic province. A lucky strike indeed. □

Assistant professor of geology and geochemistry Paul Asimow grew up in Los Angeles, but earned his bachelor's degree on the East Coast, completing an AB at Harvard in 1991. The Southland must have lured him back, because he came to Caltech for his graduate studies, gaining an MS in 1993 and a PhD in 1997, as well as the Richard H. Jahns Teaching Prize in 1995. After two years as a postdoctoral research fellow at the Lamont-Doherty Earth Observatory of Columbia University he returned to Caltech in 1999 to take up his present position. A keen piccolo, flute, and tuba player as well as a music arranger and conductor, he may be most visible on campus as the associate conductor of the Caltech-Occidental Concert Band. But for many people around the world, he is best known for his inexplicable Web page of snowy owl photos. This article is adapted from a talk given on the 65th Annual Seminar Day in May.

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