Few places on Earth’s continents remain to be explored, and it is unlikely that many new natural wonders await discovery in some forgotten corner. But below the ocean surface is a different story. We know more about the facade of Mars than about the 75 percent of our own planet’s surface that lies underwater. Untold surprises await us there.

One such revelation occurred in December 2000. An expedition mapping a submerged mountain known as the Atlantis Massif, midway between Bermuda and the Canary Islands and half a mile under the surface of the North Atlantic, came across a pillar of white rock as tall as a 20-story building rising from the seafloor. Using the remotely operated ArgoII vehicle and the manned submersible Alvin, scientists surveyed and sampled the mysterious formation. Although time constraints limited their investigation to a single Alvin dive, the researchers were able to collect enough information to determine that the white pillar was just one of several such structures in the area that were emitting heated seawater. They had discovered a field of undersea hot springs they named the Lost City Hydrothermal Field. It was unlike anything seen before, including the now famous black smokers.

The initial report describing the discovery, published in the journal Nature in July 2001,
that consume poisonous hydrogen sulfide gas emanating from the vents.

Compared with the savage black smoker environment, the Lost City vents are eerily tranquil. Located about 15 kilometers to the west of the tectonic plate boundary at the Mid-Atlantic Ridge, this vent field atop the Atlantis Massif is too distant for rising magma to heat the fluids to the blistering temperatures found at black smokers. Instead the water is heated by circulation through the merely warm rock below, and the highest measured temperature is only 90 degrees C. Neither are the Lost City fluids acidic. They
are alkaline, with a pH between 9 and 11—similar to milk of magnesia or household ammonia solution. Because these waters cannot readily dissolve high concentrations of metals such as iron and zinc, Lost City does not produce the metal sulfide plumes that characterize black smokers. Rather Lost City vent waters are rich in calcium, which when mixing with seawater produces calcium carbonate (limestone). This limestone forms giant white chimneys, the largest of which towers nearly 60 meters above the seafloor—significantly taller than the loftiest black smoker chimney.

The strange chemistry at Lost City derives from its unique geologic setting, which is rooted in the structure of the planet itself. Picture Earth as a peach. The skin represents the crust, the flesh is equivalent to the underlying solid mantle layer, and the pit stands in for the hot iron core. At the Mid-Atlantic Ridge, the crust is being slowly pulled apart as North America and Africa move away from each other at a sluggish 25 millimeters a year. The separation of the crust has exposed parts of Earth’s mantle at the seafloor, and uplift of this exposed mantle has formed the Atlantis Massif.

The mantle consists mainly of a rock called peridotite, which turns out to be the key to the Lost City’s distinctive chemistry. When peridotite comes into contact with water, it undergoes a chemical reaction called serpentinization. As seawater seeps into the depths of the massif, the peridotite is altered to serpentinite, and the percolating waters become more alkaline as a result of that reaction. By the time the fluids reemerge and mix with the ocean waters, they are loaded with calcium released during serpentinization. Most significant of all, they are now highly reduced, meaning that all the oxygen has been stripped from the water and replaced with energy-rich gases such as hydrogen, methane and sulfide. The concentrations of hydrogen, in particular, are among the highest ever encountered in a natural environment. And that is where things begin to get really interesting.

**In the Beginning**

Hydrogen is full of energy as a consequence of its ability to transfer electrons to other compounds, such as oxygen, releasing energy in the process. Compounds that can readily donate electrons to other compounds are described somewhat confusingly as “chemically reduced.” Scientists have long suspected that reduced gases played an important role in the origin of life on Earth. In the 1920s Russian biochemist Alexander Oparin and British evolutionary biologist J.B.S. Haldane each suggested that the primitive atmosphere of Earth might have been very rich in reduced gases such as methane, ammonia and hydrogen. If the atmosphere had high concentrations of these gases, they proposed, the chemical ingredients required for life might have formed spontaneously.

The idea gained credibility several decades later with the famous 1953 experiment by chemists Stanley Miller and Harold Urey of the University of Chicago. By heating and discharging sparks through a mixture of reduced gases, Miller and Urey were able to create a range of organic compounds (most compounds containing carbon and hydrogen), including amino acids, the building blocks of proteins used by all life-forms on Earth. In the years after the Miller-Urey experiment, however, geologists concluded that the early atmosphere was not nearly as reduced as the duo had assumed. The conditions that formed amino acids and other organic compounds in their experiment, these scientists said, probably never existed in the atmosphere.

But reduced gases abound in the Lost City hydrothermal vents. Could it be that billions of years ago, vents similar to these had the right conditions to produce the building blocks of life? The Lost City vents sit on an underwater peak known as the Atlantis Massif, 15 kilometers west of the tectonic plate boundary at the Mid-Atlantic Ridge. Studies of the vents have revealed how their chimneys formed and suggest that the chemistry there is the sort that could have given rise to the earliest life on Earth.

The massif consists mostly of a rock called peridotite. As seawater filters through fractures in the massif, it reacts with the peridotite, transforming it into serpentinite. This serpentinization drives several processes that are important to the chemistry of Lost City. One, it gives the warm, percolating water an alkaline pH and releases calcium into it. As the water emerges from the vents and mixes with seawater, calcium carbonate forms and precipitates atop the vents, forming white chimneys. Also, the reaction loads the vent fluids with energy-rich gases, including hydrogen, which enable microbes such as methanogens to thrive on and within the chimney walls independent of energy from the sun. Finally, the serpentinization produces chemical conditions that allow the synthesis of organic compounds from inorganic ones—a prerequisite to the evolution of life.

**LOST CITY …**

Both Lost City and black smokers are underwater hot springs. But beyond that, they differ considerably. Below are some of the attributes that characterize Lost City.

- Located 15 kilometers west of the Mid-Atlantic Ridge volcanoes
- Water temperatures up to 90 degrees Celsius
- pH is highly alkaline
- Calcium carbonate forms white chimneys
- Some life-forms operate independent of energy from the sun
... VS. BLACK SMOKERS

The proximity of black smokers to rising magma contributes significantly to the traits that distinguish these vents from the ones at Lost City.

- Located at the Mid-Atlantic Ridge volcanoes
- Water temperatures up to 400 degrees Celsius
- pH is highly acidic
- Sulfide minerals produce black smoke and form chimneys
- Life-forms are indirectly dependent on energy from the sun

ic compounds required for life? Some geochemists investigating this question think so. A number of studies conducted over the past decade have suggested that the chemical reactions that occur during serpentinization are ideal for the production of organic compounds from carbon dioxide. Hydrothermal systems akin to Lost City might have been primitive factories that churned out methane, simple organic acids and perhaps even more complex fatty acids—essential components of the cellular membranes of all organisms. And the vents might have been able to generate these organic compounds without the assistance of living organisms.

Lost City is a natural laboratory for testing these ideas. In 2008 chemist Giora Proskurowski of the Woods Hole Oceanographic Institution and his colleagues published a paper in the journal Science demonstrating that the hydrothermal fluids at Lost City do indeed contain small organic compounds such as methane, ethane and propane. Other work suggests that the reactions at Lost City also produce small organic acids such as formate and acetate. Together these findings confirm that the reduced conditions at the Lost City vents could support the types of chemical reactions necessary to create organic compounds from inorganic compounds—a significant but critical step in prebiotic chemistry.

This new work establishes that some hydrothermal vent environments are able to produce at least simple organic compounds, possible ingredients for life. But Lost City is not a perfect setting for testing such ideas, because the carbonate towers are not sterile chemical reactors. In fact, they teem with microbial life, which raises the possibility that these microbes could be contributing to the formation of organic compounds in the vent fluids. To resolve this puzzle, we must take a closer look at the microbes themselves.

No Sun Needed

Many microorganisms have evolved the ability to consume the abundant energy contained in hydrogen. Methanogens constitute one such group. As their name suggests, methanogens generate methane: the natural gas that many of us use to heat our homes and cook our food. It turns out that up to one third of the microbes at Lost City are methanogens belonging to the family Methanosarcinales. Their presence is not surprising given the abundance of hydrogen in the vent fluids. What is remarkable is that the Lost City methanogens operate independently of the sun.

Virtually all life on Earth depends on solar energy—but it humans, who rely on photosynthetic organisms for food, or plants and algae
that photosynthesize. Even at black smokers, in the darkest depths of the oceans, life depends on the sun. The microbes that support the growth of the giant tube worms, for example, require both sulfide and oxygen. The ultimate source of the oxygen is photosynthetic organisms far above. In contrast, all that the Lost City methanogens need to survive is carbon dioxide, along with liquid water and peridotite, which react to form the raw ingredients they require.

Investigators have found that both geochemical reactions stemming from serpentinization and the activity of biological methanogens contribute methane to the Lost City ecosystem. This simultaneous generation of methane may not be a coincidence. In a series of studies over the past few years, biochemist William Martin of Heinrich-Heine University in Germany and geochemist Michael Russell of the NASA Jet Propulsion Laboratory in Pasadena examined the precise chemical steps required to produce methane abiotically, that is, without living organisms in environments such as that in Lost City. They found that each step is replicable in the biological pathways of organisms that generate methane. From this work, Martin and Russell proposed that on the early Earth, sites like Lost City produced methane geochemically and that primordial life-forms may have simply co-opted each of the chemical steps for themselves, leading to what might have been the origin of the first biochemical pathway.

Martin and Russell are not the first scientists to suggest that life might have arisen at a hydrothermal vent. That idea has been around for a number of years. Support for it comes not only from the advantageous chemistry at hydrothermal systems but also from the evolutionary record found in the genetic material of all living organisms.

The study of ribosomes—biological machines that the cell uses to translate the information encoded in nucleic acids (DNA and RNA) into proteins—has proved especially enlightening in this regard. The ribosomes are themselves built of both RNA and protein. By comparing the sequences of the ribosomal RNA building blocks, or nucleotides, scientists have constructed a family tree that shows the relationships of all life on Earth. Many of the organisms that reside on branches near the root of the tree consume hydrogen and inhabit high-temperature hot springs, either on land or on the seafloor, indicating that the last universal ancestor of all life on Earth may also have inhabited a hot spring, possibly in an environment resembling that of the Lost City Hydrothermal Field.

Geologists have reason to suspect that ecosystems like that of Lost City may have once been relatively common. Peridotite is among the most prevalent types of rock in the solar system. On Earth, it makes up the bulk of the upper mantle. Although newly formed peridotite is rarely found on the terrestrial surface today, it was abundant three billion to four billion years ago. Back then, the planet was much hotter, and increased volcanism transported more of the molten mantle to the surface. In fact, peridotite probably made up most of the rock on the seafloor of the early Earth. This rock would have reacted with water then just as it does now. Warm, alkaline settings akin to Lost City may have thus nurtured the first life-forms. Fiery, acidic conditions similar to those found at black smokers, in contrast, would probably have been too hostile to foster the emergence of life.

The findings from Lost City also bolster hypotheses about where else in our solar system life might exist or have existed in the past. Any planet or moon containing both peridotite and liquid water—the ingredients necessary for serpentsi-
Sourcing Methane

Making that determination may turn out to be harder than scientists had envisioned. Most of the organisms on the tree of life are microbes. Although we can study the DNA and RNA sequences of such organisms, finding a fossil record of small creatures with ambiguous shapes is difficult. To that end, in the past few decades researchers have developed techniques that permit investigation of the evolutionary history of microbes by combing the geologic record not for physical fossils but for chemical ones. Chemical fossils are molecules that can be traced to living organisms and can be preserved as fossils in rocks over millions or even billions of years. Most chemical fossils are derived from the lipids that make up cell membranes. Although lipids do not hold as much information as DNA or a physical fossil does, they are reliable indicators of life and can carry structures diagnostic of the organisms that produced them.

Moreover, the carbon that constitutes the lipids is itself informative, because it contains a marker that reveals how an organism extracted carbon from its environment. That marker is carbon 13, a relatively rare form of the element that does not degrade over time. The carbon in most organisms includes between 1 and 3.5 percent less carbon 13 than does the carbon in the carbon dioxide dissolved in seawater. Scientists have thus assumed that carbon in ancient rocks is depleted by this amount derived from living organisms. And as a corollary to that rule, carbon from ancient rocks that is not depleted comes from abiotic processes.

But Lost City puts the lie to that notion. My work with a team of scientists at the Massachusetts Institute of Technology and at Woods Hole has shown that some of the most abundant lipids found in the carbonates at Lost City are from methanogens. Yet these lipids exhibit no carbon 13 depletion whatsoever. Instead their carbon 13 contents are what one would expect from material that did not derive from living organisms.

How can this be? The use of carbon 13 as a tracer of life rests on the assumption that more carbon dioxide is available in the environment than can be used. As long as there is a surplus of carbon dioxide, organisms can incorporate lighter carbon 12 molecules, which they prefer, and discriminate against the heavier carbon 13. But if carbon dioxide were somehow scarce, organisms would scrounge for every available carbon molecule that they could get, be it the lighter variety or the heavier one. And if that were to occur, the relative abundance of carbon 13 in the organisms would be no different from that in the environment. The chemical tracer of life would be invisible.

This process is exactly what is happening at the Lost City vents. Unlike nearly every other environment on Earth, where carbon dioxide is always available, at Lost City hydrogen predominates and carbon dioxide is scarce, in effect forcing organisms there to extract carbon isotopes indiscriminately.

The invisibility problem applies to methane, too. Usually methane produced by organisms shows an extreme depletion in carbon 13, in contrast to methane from geochemical reactions. But in serpentinizing systems, this difference does not always appear. The methane in the Lost City vent waters lacks the telltale carbon 13 depletion. Researchers know from observation that this methane is a mixture of geologic and biological products. Carbon isotopes alone are incapable of making the distinction, though.

If life has evolved elsewhere in our solar system, the best bet may be that it consists of microbial methanogens living in sites where rock is being serpentinized. We know that methane is somehow being produced on Mars. NASA plans to launch the Mars Science Laboratory in 2011, one of its missions will be to determine the carbon isotope ratio of that methane. A strong depletion in carbon 13 would be an indication that organisms inhabit the Red Planet.

Yet Lost City demonstrates that failure to find that signal can hardly be considered evidence of absence. Indeed, the discovery of microbes thriving in this previously unknown type of ecosystem provides yet more reason to expect that scientists will one day find signs of life beyond Earth.