Searching for Life Where the Sun Don't Shine:
Explorations to the Seafloors of Earth and Europa



by

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## ABSTRACT

Hydrothermal vents on Earth's seafloor host entire ecosystems that live off energy from chemosynthesis rather than photosynthesis. This energy process uses chemical reactions between metals and hot gases from inside Earth's mantle to fuel thriving communities of exotic organisms. Some researchers think life originated at these vents and if they're right, that means there's a chance life could have also originated near similar hydrothermal vents on other planets or moons. One of the most promising places to search is the suspected sub-ice ocean on Jupiter's moon, Europa.

This is the story of humankind's efforts to understand the origins of life by looking for it in extreme environments where life thrives without relying on the sun as an energy source. It follows an oceanographic expedition to the Mid-Cayman Rise, led by Chris German of the Woods Hole Oceanographic Institution and NASA's efforts to plan a future mission to Europa. By understanding how life can live without the sun, we may discover how life began on our planet and whether or not Earth is the only place in the universe capable of supporting a biosphere.

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On February 17, 1977, Tjeerd van Andel of Stanford University and Jack Corliss of Oregon State took a few last breaths of the South Pacific air before closing the basketball hoop-sized hatch of the research submersible, *Alvin*. Their pilot, Jack Donnelly, then guided the 23-foot long craft down 9,000 feet towards the seafloor, away from the team's research vessel *Knorr* and mother ship, *Lulu*. Ninety minutes later, the trio reached the bottom.

Six hours and forty-seven minutes later, they were back at the surface. When the science team extracted the first water samples taken from the seafloor, the entire lab on the *Knorr* was filled with a horrible stench: rotten eggs.

It was a watershed moment in humankind's understanding of the origins of life.

Six months later, on August 20, 1977, the *Voyager 2* probe launched into space aboard a Titan IIIE/Centaur rocket from Cape Canaveral, Florida. The spacecraft sent back its first photos of Jupiter after twenty months in transit to the gas giant and after another two and a half months, it flew to within about 125,000 miles of Europa—one of Jupiter's 64 moons. As raw images beamed back to Earth at a rate of one every 90 seconds, scientists, engineers, students and journalists sat glued to their seats staring at stunning images that revealed a white, icy world, criss-crossed with dark lines and a surface seemingly as smooth as anything thus far seen in our solar system.

Images and data received from *Voyager 2* suggested that beneath that layer of water ice lies a liquid water ocean bigger than all of Earth's oceans combined covering the entire moon—itself about the same size as our own moon.

Soon researchers began to wonder if, beneath that layer of ice at the bottom of thousands of feet of water and methane liquid, the seafloor there smelled like rotten eggs, too.

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At first glance, space and sea might seem like opposite ends of a spectrum that defines extremely hazardous environments to life—or hazardous to *our kind of life*, at least. In space, there's no air to breathe and thus, no air pressure to hold our skin and organs in place, maintain water in our bodies as a liquid versus a vapor, and keep oxygen circulating in our blood. A human can die within several seconds of exposure to the vacuum of space. In the oceans, an equally deadly environment exists, though at pressures up to several thousand times higher than what we're used to—pressures that would crush us without the protection of a submarine or deep diving suit.

But both space and oceans share a lot in common. They're both vast, almost entirely unexplored regions, compared to tiny us. And both have a lot to tell us about life.

The fact that life exists in the first place is rather incredible. Life could have very easily not existed. We haven't yet found evidence for past or current life on any of the planets and moons in our solar system. We haven't begun to scratch the surface on whether life exists outside our solar system, but we haven't found it anywhere out there yet. And still, it's *everywhere* here. We find life under highly acidic rocks, within massive glaciers, in the darkest chasms of the ocean. Try to find the most desolate, barren, inhospitable hell on Earth, and you'll find life there, too.

Chris German is in the business of exploring some of Earth's more hellish environments. A geophysicist at Woods Hole Oceanographic Institution in Massachusetts, German leads research expeditions aimed at understanding the complex plate tectonics and chemical reactions taking place on Earth's seafloors. By discovering the history of the planet's shifting seafloor, he's uncovering knowledge of the nature of extreme environments—the kind where life probably shouldn't exist, but does.

At 8:00 a.m. Friday, January 6, 2012, German began perhaps the most promising research expedition of his 28-year career. He watched from the deck of the research vessel *Atlantis* as his team and crew totaling nearly fifty people embarked from Port Everglades, Florida. The last shipment of equipment had only narrowly arrived with half an hour to spare before the ship's departure, culminating years of preparations for this expedition. *Atlantis* headed south, passed the Florida Keys in the late afternoon, and turned west, following a backwards S route that would take the team around the western end of Cuba to a stretch of ocean above a 70-mile long ridge in the seafloor called the Mid-Cayman Rise (MCR). Their target: three hydrothermal vent sites along the ridge that German and colleagues had discovered and mapped during two previous expeditions in 2009 and 2011. Dubbed "OASES 2012: Return to the Cayman Rise," this research expedition was chronicled by Julia DeMarines, a research assistant of the astrobiology curator at the Denver Museum of Nature and Science.

Hydrothermal vents happen where near-freezing water at the bottom of the ocean meets scalding hot magma. The magma is produced by a heat source that comes from energy released from the decay of radioactive materials deep inside the planet and also leftover heat from the Earth's formation. When water and magma meet, the now superheated water shoots up through cracks in the seafloor, creating plumes of hot gases and chemicals that can reach several hundred feet in height. The plumes are often black and bubbly—the ocean version of a diesel train engine belching a steady stream of black smoke into the sky. This gives rise to the nickname *black smoker*. Miraculously, this mix of hot gases, chemicals and cold water creates conditions that form the ocean equivalent of a desert oasis.

These sites host communities of living matter that can be denser than any patch of life on land in the known biosphere and 10,000 to 100,000 times greater than the rest of the seafloor. Here, exotic tendril-like organisms called tubeworms grow eight feet tall and clams can be a foot across. Normally, clams a third of an inch across are a century old. Yet, at these plumes, clams nine inches across are just ten years old. That means their growth rates are 300 times faster than those of clams anywhere else on the seafloor.

This is remarkable given that the pace of life on the bottom of most of the ocean is *slooooow*. Once, in 1968, the *Alvin* submersible sank to a depth of 5,000 feet after a cable attaching it to its mother ship snapped as the vessel was being lowered into the water. The three-person crew was able to scramble to safety, but they forgot to grab their bag lunches: three apples and three bologna sandwiches. These sat on the ocean floor for 10 months before a rescue crew was able to recover *Alvin*. Upon finding the lunches, the crew was amazed at how little they had changed—some even tasted the sandwiches. Salty, but fine, they said. It was as if the biological process of degradation had simply stood still.

Yet, life thrives at hydrothermal vents. The 2011 cruise had been especially productive in proving the amazing diversity of life near these extraordinary sites. German had personally witnessed the discovery of the first live tubeworm found near a hydrothermal vent in the Atlantic Ocean. Bigger still, that team had found chemosynthetic shrimp (which live off energy from chemical reactions from the vents instead of photosynthetic processes involving the sun) and tubeworms occupying the same site—perhaps the landlubber equivalent of finding a lion and a polar bear chewing on the same antelope in the middle of the Sahara.

Now the team was heading back to the MCR to collect the first physical samples from what some consider the most interesting collection of hydrothermal vents on our planet.

The MCR is home to the deepest known underwater volcano in the world and is unique among the world's 42,000 miles of ocean ridges for its geologic diversity. "In a nutshell, it displays perhaps the broadest range of mid-ocean ridge geologic processes all active in the same place," says German. The ridge is considered an "ultraslow" spreading ocean ridge, meaning it moves at a rate of less than an inch a year, as compared to the relatively speedy "slow" spreading ridges which move at just under two inches a year or "fast" spreading ridges which have been clocked at a blazing eight inches a year. The site is the home of three different types of vents, which are classified by their temperature and the chemical composition of the rocks that give life its fuel.

The first, Type 1, is common throughout the world's mid-ocean ridge system and is characterized by high temperatures (sometimes more than 400 degrees Celsius) and "mafic" rocks from the Earth's crust, meaning they are rich in magnesium and iron. Type 2 vents have similar high temperatures, but these vents are the result of reactions between seawater and far deeper rocks from the Earth's mantle with even higher concentrations of magnesium and iron. These are classified as "ultramafic." Type 3 vents, too, are ultramafic but have much lower temperatures. Since they're formed by older lavas comparable to material that erupted on the early Earth, ultramafic vent sites are among the most exotic and captivating of hydrothermal environments to marine geologists.

Chief Scientist German had found evidence for these three vent sites during his first trip to the MCR in 2009. Past experience in the southern Indian and Arctic Oceans had tempered expectations for discovery of new vents sites to roughly one site for every 100 miles of mid-ocean ridge explored. Since the MCR was only 70 miles long, that first voyage was "probably the highest-risk expedition I have ever undertaken," says German. The probability of finding even one vent site there was fairly low to begin with.

Thus, finding three vents of three different types on the same relatively small stretch of mid-ocean ridge was astounding, a bit like looking for a coffee shop and finding a Starbuck's, a Dunkin Donuts and a Caribou Coffee on three corners of an intersection of a two-road town in the middle of a Nebraska cornfield. That's why, in the world of hydrothermal vents, there's more than one reason why this specific stretch of seafloor real estate is considered a "hot spot."

Unfortunately, his discovery was followed closely by setback. The 2009 expedition was cut short by Tropical Storm Ida before the team could get up close to any of the prospective sites with its Remotely Operated Vehicle (ROV), *Nereus*. German had to wait until the 2011 opportunity to get a closer look, but this 10-day expedition was only intended to photograph and map the vent sites. No samples were collected. Both expeditions paved the way for the 2012 expedition, which would be the first to study each site in depth and to obtain actual samples of the rocks, water, tubeworms, and other critters in the vent communities.

German hopes that the samples from these wildly diverse vents, all within a small patch of mid-ocean ridge, will reveal secrets to the formation of the early Earth, and maybe while they're at it, the origin of life itself. By studying how a living ecosystem can sustain itself in the deep, black ocean, far below the reach of the sun's rays, German isn't just classifying exotic worms and clams in a quirky Twilight Zone setting—he's looking through time.

"Just like the Hubble Telescope, pointed at the most distant points of the Universe, hydrothermal sites like these may become a sort of lens that allows us to view back into Earth's distant past and explain how life originated on Earth," says German.

And just like the Hubble Space Telescope, his expedition is funded primarily by the agency largely responsible for directing our eyes skyward: the National Aeronautics and Space Administration.

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Just as it helps Chris German answer riddles about the origin of life on Earth, life's surprising hardiness gives astrobiologists cause for hope in finding life on seemingly inhospitable hells *off* Earth, too. Among researchers on the search for those hells is Steve Vance, a member of the Science Definition Team for NASA's Europa missions. As Chris German and the crew of *Atlantis* set out to scoop up evidence of life on the bottom of Earth's seafloor, Vance met with a team of engineers and planetary scientists at NASA's Jet Propulsion Laboratory (JPL) to plan a mission with a similar objective yet radically different destination. Their goal: to find out if there's hydrothermal vent-like life on Jupiter's moon, Europa.

Vance and his colleagues are busy planning a mission to send a robotic spacecraft to gather more data on the icy moon to determine whether life once existed (or still exists today) in an ocean below the surface-covering layer of ice there. Based on data from *Voyager* and, later, the *Galileo* robotic flyby missions, scientists think there could be similar geologic processes on Europa's seafloor as we find on our own seafloor. If so, there's reason to believe life could be thriving today in the cold, dark depths there, huddled around oases of hydrothermal vents just like on Earth. That's why, to people like Vance, it's at the intersection of life where space and ocean exploration come together.

Traditionally, the search for life beyond Earth has been focused on a region surrounding the sun (or in the case of other solar systems, another star) where a planet or moon with sufficient atmospheric pressure can maintain liquid water on its surface. This is based on the assumption that life elsewhere beyond Earth would be a lot like life found on our planet—particularly, that liquid water would be essential to its survival. The search for the right conditions for life involves finding a planet or moon in a location that isn't too close to its host star to boil off any liquid water or too far from the star to keep all water in its solid ice phase. This is what astrobiologists and astronomers refer to as a "Goldilocks planet"—one that's not too big, not too small, not too hot, and not too cold—but just right.

Except, Europa isn't a Goldilocks planet. It lies well outside the supposed habitable zone of our solar system (which conveniently only includes a region of space containing Earth and our moon). So how could life possibly survive on Europa?

The answer lies in how life gets its energy. More than 99% of life on Earth gets its energy from the sun. Plants get their energy from photosynthesis, which produces oxygen. Animals breathe this oxygen and eat the plants. Other animals eat those animals. Then animals die and become nutrients in the soil for plants, thus completing the extraordinary, miraculous circle of life as we know it.

But hydrothermal vents demonstrate that not all life needs the sun to serve as the stork. The remaining less than 1% of life just needs a little bit of superheated water from melted rocks deep within the earth mixed with the right blend of rotten egg-smelling rocky sediments combined with near freezing seawater at bone-crushing depths to survive.

Simple enough, right?

The process of obtaining energy from chemical reactions between water and compounds in the rocky sediments rather than sunlight is called chemosynthesis. In the case of hydrothermal vents, the primary compound is hydrogen sulfide. This chemical process is the reason why NASA's interested in hydrothermal vents on Earth's seafloor. And if chemosynthetic life exists anywhere outside of Earth, Europa would be a good place to start looking for it. The sixth closest of Jupiter's moons, Europa may be one of the few places in our solar system where chemosynthetic life not only could have lived in the past, but might still be thriving today. If there's water and the moon is as thermally active as scientists think, the conditions might be just right to sustain an alien ecosystem.

Vance and his colleagues at JPL are hoping to be the first to find that alien ecosystem. They're currently working on a proposal to launch a mission to Europa in 2020, which could reach the icy moon by 2026. It's a long time to wait, but such is the reality of conducting research on a subject 500 million miles away.

This is where the explorations of the very high meet those of the very low. And there may be no greater connection—or common purpose—between exploration of the heavens and the depths of our seas than in the search for life and its mysterious origins.

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Before 1977, biology textbooks claimed that to sustain a living ecosystem, you needed energy from the sun. That was before Donnelly, van Andel, and Corliss dove to the bottom of the sea in *Alvin* as part of the Galapagos Hydrothermal Vent Expedition.

Their mission didn't have anything to do with rewriting biology textbooks. Van Andel, a geo-archaeologist, and Corliss, a geologist, were more interested in the seafloor itself. Scientists had speculated the existence of hydrothermal vent systems, but no one had ever proven they were there and certainly no one had seen them in person. Their speculation stemmed from heat-flow calculations along the 42,000-mile global mid-ocean ridge system—a planet-wide mountain range that forms the largest geographic feature on Earth and snakes around the seafloor like the seams on a baseball. This underwater mountain range marks the line where Earth's tectonic plates are spreading apart from each other—the same phenomenon behind the suspiciously similar coastlines of South America and Africa that make the jigsaw-like continents appear to have fit snugly together at one time. Well, they *did.* That is, before seafloor spreading pushed them apart over millions of years at a rate about as fast as your fingernails grow, creating gaps in the ocean's bottom along the ridge where new crust from the planet's mantle oozed upwards, cooled, and formed brand new seafloor.

Scientists made heat-flow calculations to characterize what this new crust should look like. Clive Lister, a geophysicist at the University of Washington, argued that since the young crust coming up from the mantle was being cooled by the near-freezing ocean water, it should cool and contract the farther it got from the ridge. That meant the hottest spots should be near the ridge. Yet, when actual heat-flow measurements were made at portions of the seafloor up to several hundred miles out from the ridge, everything looked right *except* for those spots nearest the ridge. They weren't as hot as they should have been. Where was the missing heat?

Lister speculated that the ridge was essentially a giant heat blister. Molten rock chambers at temperatures of 1,200-1,400 degrees Celsius lay below the ridges and cracks in the seafloor allowed cold water to seep into the crust. Where cold water met hot magma, the water expanded, became superheated and shot back up to the surface in the form of underwater hot springs, or hydrothermal vents. This is where he thought the missing heat might be going.

At least that was the going theory as Donnelly steered *Alvin* down into the darkness. He, van Andel, and Corliss were on the search for missing heat.

Enclosed in an almost seven-foot diameter titanium pressure sphere, the three men huddled together behind walls less than two inches thick. At a depth of 9,000 feet, they had long since passed the point where the suns rays penetrate the sea (roughly 3,300 feet). The water pressure at this depth is nearly 300 times higher than at sea level, which meant that every square inch of the hull felt about the same as your big toe would feel with the weight of an entire Jeep Wrangler pressing down on it. "If seawater with that much pressure behind it ever finds a way to break inside, it explodes through the hole with laser-like intensity," wrote legendary oceanographer Bob Ballard in *The Eternal Darkness*. Ballard was the co-chief scientist of the Galapagos Hydrothermal Expedition (along with Richard von Herzen) and was onboard the support ship, *Knorr,* while Donnelly patrolled the seafloor in *Alvin*. "A human body would be sliced in two by a sheet of invading water, or drilled clean through by a narrow (even a pinhole) stream, or crushed to a shapeless blob by a total implosion," wrote Ballard.

The crew relied completely on *Alvin's* quartz iodide and metal halide lights to illuminate their path through the darkness. To navigate, Donnelly used three transponders—which the team named Sleepy, Dopey, and Bashful—that had been dropped five days earlier in a triangular pattern at various points in the area. Unlike airplanes, which use light and radio waves to navigate, submersibles need to rely on sound waves (just like dolphins) to figure out where they are and where they're headed. Light and radio waves can't travel very far in water. *Alvin's* navigation computer sent out sound waves toward the transponders, which in turn, sent back sound waves of their own. Based on the data from the transponders, Donnelly was able to steer *Alvin* toward the team's target location on the seafloor.

Their intended target had been identified two days earlier, when the *Knorr* had located a spike in water temperature near the seafloor. The research vessel had been dragging a camera sled called ANGUS (Acoustic Navigated Geological Undersea

Surveyor) outfitted with a sensitive thermistor capable of picking up tiny temperature changes in the water. Operators on *Knorr* needed to keep ANGUS 15 feet above the seafloor—a difficult task given the varied landscape of the rugged, volcanic terrain.

Good thing ANGUS's toughness matched the motto on its side: "Takes a Lickin' But Keeps on Clickin." Despite occasional collisions, operators were able to maneuver the 2-ton steel sled over seven miles of seafloor real estate in a 12-hour span. Only one three-minute period of trolling had yielded anything significant.

When the team reviewed the photos the next day, they were shocked at what they saw. Thirteen photos taken during that three-minute interval revealed an incredible accumulation of life—mostly in the form of white clams and brown mussel shells—that no one had expected to see. Living communities this deep had never been seen before. The deep ocean floor was supposed to be devoid of life.

Van Andel and Corliss sat with eyes peeled out the sub's 4.5-inch circular viewports. Not only were they looking for heat in a cold, barren abyss; they were now on the search for life.

As Donnelly zeroed *Alvin* in on their target, formations of long-cooled, hardened lava "pillows" were all they could see. These had been formed as cracks emerged in the crust, caused by the seafloor spreading. The cracks allowed magma to spew from the Earth, cool, and form mounds as if the planet had squeezed hundreds of tubes of toothpaste from its belly and failed to utilize any of it.

*Alvin* inched closer and the team noticed the lava patterns began to change—appearing smoother and shinier as they approached the target. These lava flows were sinewy and suggestive of faster, fresher flows. They were getting closer.

When at last they reached the coordinates of the temperature spike, the crew entered an alien world. The dark water shimmered blue from manganese and other minerals carried up through the crust by superheated water. Clams measured a foot or more in length piled high surrounded by shrimp, crabs, fish, and small lobster-like creatures. Strange plants grew from the rocks, almost like dandelions, and bizarre, wormy tendrils reached out from clumpy harbors.

"Isn't the deep ocean supposed to be like a desert?" Corliss asked a graduate student on the support ship *Lulu* by acoustic telephone.

It was. Until now.

Not only had the team found their missing heat by discovering the first hydrothermal vent, but they'd also stumbled upon something else, something potentially even more profound. "A suspicion dawned on us," reported Ballard. "These unexpected life forms might actually be a bigger discovery than the expected warm water."

When Donnelly brought *Alvin* back to the surface, the research team struggled to figure out what to do with their unexpected biological samples. They hadn't prepared for living samples. They thought they'd be dealing with rocks. They didn't even have a single biologist onboard (only geologists, geophysicists, chemists, geochemists, physicists, and one lucky science writer).

A small amount of formaldehyde and some Russian vodka the team had picked up in Panama were the only preserving liquids they could come up with. Over the next several days, the team found four more vent sites, each unique from the previous one. They came up with names for each site—Clambake I, Clambake II, Oyster Bed, Dandelion Patch, and, finally, the Garden of Eden.

The discovery of these sites was applauded throughout the scientific community. Biologists were eager to find out just what sort of life could live in darkness on the bottom of the ocean. Hydrothermal vents and the ecosystems they generated would come to redefine the making of the planet and our theories about how life began here. But first, there was the issue of the rotten eggs smell.

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Hydrogen sulfide is a poison gas that's lethal for humans even in very low concentrations. Yet, this compound—two parts hydrogen, one part sulfur—turned out to be the food source for bacteria that were driving an entirely new ecosystem. (New to *us* at least. Some scientists suspect this type of ecosystem might, in fact, be the oldest type of ecosystem on our planet.)

For more than a century, biologists have known that bacterial life can exist based on chemosynthesis, but before the 1977 Galapagos Hydrothermal Expedition, no one had imagined an entire ecosystem could be generated from chemosynthetic processes alone.

Chemosynthesis is the biological conversion of carbon molecules and nutrients into organic matter—the stuff of life. Whereas photosynthesis uses energy from sunlight to convert carbon dioxide into that organic matter, giving off oxygen as a byproduct, chemosynthesis uses inorganic molecules (such as hydrogen sulfide) or methane and combines them with an oxygen source (in this case seawater) to create simple sugars. Those sugars are the fuel that bacteria live off and the bacteria are the fuel that larger organisms need to survive. Chemosynthesis that uses hydrogen sulfide produces sulfur as a byproduct—and it's the sulfur that smells like rotten eggs.

Hydrogen sulfide is one of many compounds that hitch a ride in the superheated water as they rocket back up to the surface of the seafloor after sneaking down through fissures to meet pockets of magma from the Earth's mantle. These substances get dissolved by the hot water from the rocks lining the fissure, creating a chemically-enriched water mixture. This mixture then gets buoyant as it's heated, eventually escaping back into the frigid ocean water.

But how could such an alien process—fundamentally different from the basis for the vast majority of all life on Earth—exist *here*?

Enter Günter Wächtershäuser. A German chemist turned patent lawyer who specializes in chemical and biochemical inventions, Wächtershäuser (pronounced VEK-terz-hoi-zer) first proposed in 1988 that a similar chemosynthetic process to the one observed on the Galapagos Hydrothermal Vent Expedition had been around on Earth for a very long time. Not only was it common to the planet Earth throughout its history, he argues, this process was fundamental to all living ecosystems going back to the very first genesis of life around four billion years ago.

If we could travel back to that time, we'd see a wholly different Earth than we see today. We'd see a planet emerging from the cataclysm of an impact with a rogue planet that created the Moon and is thought to have tilted the Earth's axis to about 23.5 degrees. The planet would have only recently cooled down enough to bear a solid crust, though intense volcanism and geological upheaval would have created a toxic atmosphere almost completely devoid of oxygen. With no ozone layer, the planet would be drenched with massive doses of ultraviolet light and radiation from the sun. We'd see comets, meteorites and asteroids raining down across the landscape in a period of heavy bombardment, leaving behind condensed water that would form clouds and eventually, combined with volcanic outgassing, oceans. Photosynthesis wouldn't take place on Earth for perhaps another two billion years. Yet, it would have been in this literal hell on Earth where we would have seen (if we'd remembered to take a microscope with us) the first life forms start to appear.

Wächtershäuser, who's also an honorary professor for evolutionary biochemistry at the University of Regensburg in Germany, points to Earth's early oceans and period of high volcanic activity as the perfect environment for the birth of Earth Life Form #1, or the "pioneer organism", an acellular (containing no cells) entity that likely passed through the loneliest life in the history of the planet in a manner of minutes. His origin of life premise is called the Iron-Sulfur World Theory. It says that hot, pressurized water mixed with dissolved gases (including hydrogen sulfide, carbon monoxide, carbon dioxide, hydrogen cyanide and ammonia) passed out of prehistoric vents and over various minerals containing iron, nickel and other metals within the rocks around the vents. These metals served as catalysts for a chain reaction that synthesized organic compounds and coupled some of them with other metals to form new compounds with greater ability to yield new chemical reactions.

This coupling between the catalyst and the product of an organic reaction is the key first step of Wächtershäuser's theory.

What comes next is the miracle of evolution. Starting with these metals and gases reacting together as life emerged, Wächtershäuser says evolution starts with the beginning of a primitive metabolism that created increasingly complex chemical reactions, eventually leading over time to the formation of DNA—life's blueprints for making more living cells today. Before living cells were around, these metals and gases reacted together in a purely chemical sense, according to predetermined "pathways." There were only so many compounds around back then and only so many ways these could react together. "Hydrogen sulfide, sulfur dioxide. Hydrogen cyanide, carbon monoxide, carbon dioxide, hydrogen, nitrogen, ammonia," says Wächtershäuser, pausing before adding "Oh, phosphor oxide, $P_4O_{10}$. That's it." Aside from a few other trace molecules, these were the gases belched from the belly of the planet that formed the first chemical reactions that served as the precursor to life.

When these gases come up from deep within the Earth, they move from a state of high pressure, high temperature to one of low pressure, low temperature. This happens rapidly, causing a non-equilibrium condition called *quenching*—where the ratio of gases at a high temperature gets frozen in the same concentration upon transferring into a low temperature environment. "Let's say at high temperatures you have an equilibrium ratio of carbon dioxide to carbon monoxide, 1:1," says Wächtershäuser. "And at low temperatures, you may have an equilibrium ratio of 10,000:1. So if you quench, then you may have a low temperature mixture still having a high concentration of carbon monoxide."

The quenching is important because it creates a chemical potential. The chemical potential drives the reactions between gases and metals at hydrothermal vents. Here, because of the unique combination of the right gases and the right metals at the right temperatures, reactions start to build off each other, creating "a synthetic reaction whereby the organic products that are synthesized promote in turn the rate of another reaction," says Wächtershäuser.

In other words, certain reactions create byproducts that then are used to speed up other reactions, leading to longer, more complex strings of organic molecules.

According to his theory, all evolution happens using this method of "feed forward" reactions, where organic products promote other reactions yielding new organic products of increasing complexity. This is what gave rise to amino acids, peptides, sugars, proteins, nucleotides, and nucleic acids, like DNA and RNA. After that, as the theory goes, life evolved higher levels of complexity and ventured beyond vent communities. It isn't clear when photosynthesis first arose, but most estimates range from 2.5 to 3 billion years ago. The rest, as they say, is history.

Since we can't go back in time, we'll never know if Günter's theory of life rising from the depths of the Earth's molten innards is true or not. And his is only one of several competing origin of life theories, which generally fall into two camps. Metabolism-first theories (like the Iron-Sulfur World Theory) start with simple molecules that build increasing levels of complexity. Replicator-first theories, on the other hand, suggest that simple organic molecules occur naturally and are able to self-replicate right from the start.

Chemist Stanley Miller is in the replicator-first camp. Miller, who is sometimes referred to as the "Father of origin of life chemistry," earned early fame for a classic experiment he conducted in 1952 as a graduate student with Harold Urey demonstrating how amino acids could be generated in a lab environment from simple compounds subjected to electrical discharges in the early Earth atmosphere. The spontaneous creation of amino acids doesn't by itself explain life's origins, since it's still a huge jump to go from simple amino acids to complex, self-replicating chains of genetic instructions contained within DNA and RNA. But his findings did lay the cornerstone for origin of life research and sparked many curious minds to test all sorts of combinations of conditions that could have been around on the early Earth. Still, sixty years later, none of these efforts have been able to replicate life from scratch in a lab.

One of the leading variants of the replicator-first camp is the "RNA World Theory," which suggests that RNA molecules arose before the first proteins since before them, there would have been no molecule of heredity, or "blueprint" molecule to manufacture other molecules consistently. Advocates of this theory say there was a time when RNA alone handled all maintenance activities of a cell, acting as both genetic material and a catalyst for metabolism reactions. The evolution of DNA then reallocated labor for replication and genetic storage to the more stable DNA molecule.

But Wächtershäuser thinks it's too much of a jump to assume life began with the ability to self-replicate. "The beginning of the genetic machinery is not replication. Replication has no purpose in itself," says Wächtershäuser. To him, the beginning of the genetic machinery of replication begins with something akin to the chemistry that goes on in the core of the ribosome, which is a bit like the manufacturing plant of all cells. That chemistry boils down to peptide formation—basically, simple amino acids linked together. It's a crucial step and it's something his experiments have been able to produce in the lab under high temperature conditions—the same conditions that are thought to have been around in the early Earth around hydrothermal vent systems. It isn't conclusive proof his theory's right, but he's getting closer.

Unfortunately for Wachtershauser, maybe the best proof to his theory lies about 500 million miles away from his lab in Germany, beneath the icy shell of a moon discovered more than 400 years ago by a man named Galileo Galilei.

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Nineteen seventy-seven was the kind of a year that only comes around once every 176 years. That's how often the outer planets of our solar system (Jupiter, Saturn, Uranus, Neptune... sorry Pluto) line up just right in their orbits around the sun to allow for a spacecraft to slingshot past all four of them. Rather than wait until 2153, NASA decided to take advantage of the opportunity of '77. The space agency launched the twin, 1-ton space probe emissaries, *Voyager 1* and *Voyager 2,* from Cape Canaveral in September and August of that year, respectively.

Their mission was only supposed to last for four years, and technically, both spacecraft were only heading to Jupiter and Saturn. Mission designers had planned *Voyager 2*'s trajectory so it could continue on toward Uranus and Neptune only if *Voyager 1* (which launched second but took a faster route) succeeded at Jupiter and Saturn. Fifty-two worlds and 12 years later, the Volkswagen Beetle-sized probes brought new meaning to success in planetary science.

Their journeys to the outer planets gave humanity a premier front row seat to see half the solar system up close in great detail for the first time (the *Pioneer 10* and *11* spacecraft had zipped past Jupiter in 1973 and 1974, though they were far less capable and yielded significantly less data). The *Voyager* craft sent back stunning images of the Great Red Spot on Jupiter that revealed it to be a raging storm the size of two full earths. Saturn's rings—thought to be smooth and ordered—were actually oddly intertwining and kinked. Uranus was orbiting sideways. Neptune owned the fastest winds in the solar system. And that was just the planets. The forty-eight moons captured by the *Voyager* craft were arguably even more striking than their parent planets.

The largest of Jupiter's moons are the four Galilean moons—Io, Ganymede, Callisto, and Europa—so named for their discoverer, Italian astronomer Galileo Galilee. Galileo made the discovery in 1610 after tweaking his telescope to reach a magnifying capability of 20x (20 times better than the naked eye). These four worlds were the first moons discovered orbiting a planet other than Earth (since our own moon is awfully hard to miss, we'll probably never know which of the first humans looked up and said, "what's *that*?" Thus, it's probably safe to credit Galileo with discovering moons).

The Galilean moons proved to be full of surprises at close range. An active volcano was spotted on the innermost of the Galilean moons, Io, spouting ash and gases a whopping 174 miles in height—the first evidence of active volcanism beyond Earth. The team would find half a dozen more erupting volcanoes on Io over the course of the mission. Team leader Brad Smith said this made Io look like a pizza. Later, astronomers would identify more than 400 active volcanoes there, making Io the most geologically active world in our solar system.

You'd think such a world might be a hot one, but you'd be wrong. Most of Io's surface is -150 degrees Celsius. Colossal eruptions of gases condense and fall back to the surface as pastel yellow, orange and bluish white sulfur dioxide snow. This makes Io a surrealist's dream: fiery hell plus winter wonderland with an everything-on-it sulfuric pizza (remember the egg smell?) surface and the churning clouds of Jupiter looming above hazy skies.

Finding Io's volcanoes was like finding a smoking gun at a crime scene as far as astronomers were concerned—they disclosed a great deal of the moons' mysteries right off the bat. The volcanoes determined Io's swirling color palette—reds, yellows, browns, greens and gray-white sulfur dioxide frost. They also tipped scientists off to the phenomenon of tidal heating, which is the cause of Io's agitation and the source of hope for testing Wächtershäuser's hydrothermal vent theory beyond our home planet.

As previously mentioned, volcanic activity on Earth is produced by a heat source that comes from energy released from the decay of radioactive materials deep inside the planet and also leftover heat from its formation. But Io is too small for leftover heat and too active to explain its volcanoes by radioactive decay alone. Instead, the strong gravitational force from Jupiter pulls Io inward, while the weaker gravitational forces of its neighboring Galilean moons, Europa and Ganymede, pull Io outward. These three moons actually fall into an elegant, stabilizing dance coined *orbital resonance*, where Io travels around Jupiter exactly twice as fast as Europa, which travels twice as fast as Ganymede. This makes the distance between Io and Jupiter vary along its orbit as the moon fights with the competing forces (or *tidal* forces). These tremendous tidal forces alternate between squeezing and stretching its core, causing Io's surface to rise and fall by the length of a football field every time it completes an orbit, which it does every 42.5 hours. This squeezing and stretching causes friction. Friction causes heat and pressure. Heat and pressure cause molten material and gases to explode from the surface. Hence, volcanoes.

Io's smoking gun was pointing straight at its neighbor, the next closest Galilean moon to Jupiter: Europa. At the time of *Voyager 1*'s flyby of Io on March 5, 1979, scientists had just begun to re-think the internal makeup of the Galilean moons. If there was tidal heating on Io, partially caused by gravitational forces of Europa and Ganymede, wouldn't there be similar forces acting on Europa and Ganymede, too?

A month after the Io flyby, *Voyager 1* came within several hundred thousand miles of Europa, though its trajectory was planned to take it back around Jupiter and away from the moon. Scientists had to wait another four months for *Voyager 2* to get up close to Europa.

By the time *Voyager 2* reached Europa, the team's hopes were soaring. They knew Europa was rich with water in its icy outer layer. If there was tidal heating on Europa, could it be enough to melt the bottom of the moon's ice crust, perhaps enough—*gasp*—to sustain a liquid water ocean?

Some even imagined they'd see several miles-long geysers bursting from the icy shell. But when the first photos came in, the team found no geysers. Instead, they were confronted with a giant white eyeball staring back at the camera, striped with wide brown veins slicing across the entire surface.

If you were to walk across that surface, Europa's stripes would appear almost painted on. There's almost no elevation change across most of the moon. Some scientists think the stripes may be cracks in the ice that spread pieces of the crust apart—not unlike seafloor spreading on Earth—allowing for liquid water to well up from the ocean beneath and freeze again, forming a younger swath of icy surface.

Despite the absence of geysers or volcanoes on its surface, Europa does feel strong tidal forces. On Earth, the tidal force from the moon controls our ocean tides, which influence when ships leave for a day of fishing or whether a sand castle on the beach will meet its demise an hour after its construction. But on Europa, the effects of its host planet are a bit steeper. Jupiter is so much bigger than our moon—30,000 times more massive—and so close to Europa that its tide stretches the 2,000-mile wide moon by more than 100 feet. This also makes the moon's orbit ever-so-slightly non-circular, giving the orbit a tiny eccentricity, but one with enormous implications. Huge tidal forces are the crucial factors that suggest Europa's ocean is able to remain in its liquid water phase instead of freezing completely into the layer of ice above it. According to planetary scientists, everything interesting about Europa follows from this subtle eccentricity.

Further evidence for liquid water on Europa came from the *Galileo* mission, launched in 1989, which brought far greater scientific firepower to bear on Jupiter and its moons. In particular, *Galileo* measured Europa's magnetic field and found that it flips direction every five and a half hours—another byproduct of the domineering influence of its host planet.

If an electrical conductor is placed in a varying magnetic field, electrical currents will be induced in it. Those currents will then induce a magnetic field oriented in the opposite direction to the original magnetic field that generated the current, partly cancelling it out. Since Jupiter has a powerful magnetic field and its axis of rotation doesn't exactly line up with its magnetic axis, Europa crosses from the north side to the south side of Jupiter's magnetic field—or vice versa—every five and a half hours. Imagine you are Jupiter and Europa is orbiting around your belt. Now, imagine trying to learn to hoola hoop for the first time. The wobbly hoop is the orbit of Jupiter's magnetic field—and every time it touches your belt, it's wobbling in a different direction. Up, down, up, down, up down. This causes the orientation of the magnetic field in Europa's orbit to vary as Jupiter rotates.

In Europa's case, a magnetic field oriented in the opposite direction to Jupiter's would indicate the moon has a massive electrical conductor somewhere inside it. And it just so happens that a moon-swallowing subsurface saltwater ocean matches the prediction for this electrical conductor quite nicely.

Along with its two compatriots Io and Ganymede, Europa dances a violent, synchronized tango around its host, causing friction and inducing a magnetic field—enough, some scientists hope, to indicate the presence of a sloshing ocean somewhere beneath miles of occasionally shearing ice.

Below that potentially 100-mile deep ocean, there may be a similar seafloor to one not so different from ours.

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As he watched Florida recede in the distance, thoughts of the journey behind and the one lying before Chris German filled a hopeful mind. "Deep joy," describes German, reflecting on his outlook at the start of the expedition. "The mystery (of the existence of the vent sites) had already been removed by the 2009 & 2011 expeditions so we knew exactly where to go, I had the best kit on the planet to sample with in ROV *Jason* and in my NASA/NSF team I had assembled some of the best experts in the world, who have also become my friends along the way, to take out and sample the site with," says German. "It couldn't get much better."

This voyage to the MCR was planned to last 22 days. In 28 years of exploring since he began his PhD studies at the University of Cambridge, German has spent around a thousand days at sea, about on par for a modern day oceanographer. It's a life of discovery and adventure but it also demands sacrifices—while at sea he's missed his wife's birthday (twice), his son Martin's 18th birthday, and his daughter Helen's 16th birthday (while in the Antarctic).

Now on *Atlantis*, bearing down on potentially the most significant sampling of hydrothermal vent sites on the planet, German hoped real discoveries would be waiting for the team somewhere about 400 miles south of Havana.

In addition to grabbing temperature readings, biological samples and close-up shots of the vents, German wanted to study the MCR for what it can tell us about Earth's history. Since the MCR is an ultraslow spreading ridge, it acts differently than its faster counterparts. Usually rocks get older the farther you go from the spreading center of a mid-ocean ridge. That's because new seafloor is being created by magma erupting and then cooling and molding together with the older surrounding seafloor. But at ultraslow spreading ridges, one side of a tectonic plate is older and heavier than another and ends up sinking—or subducting—under another plate. As it sinks, it pulls the other side of the plate out from underneath the next plate over—a bit like pulling one book out of a stack of books that have tilted over on their sides on a bookshelf. The side that gets pulled out is even older crust—old enough, potentially, to have been around during the brief but legendary lifetime of our good friend, Earth Life Form #1.

At 9:45 p.m. on January 8, *Atlantis* reached her destination above a hydrothermal vent site called Von Damm—named after the late geochemist Karen Von Damm. After two and a half days in transit, the ship rocked in the calm waves, keeping relatively stationary by use of one bow thruster and the stern propellers since her anchors couldn't reach the seafloor, 7,500 feet below.

On the deck beneath two 42,000-pound capacity cranes sat the Remotely Operated Vehicle (ROV) *Jason*, named after an ancient Greek mythological hero famous for leading a group of adventurers called the Argonauts. *Jason* is the most capable U.S. academic research vessel roaming the seas today, able to reach 99% of the world's seafloor at depths down to 21,000 feet.

The vehicle is also nearly indefatigable. It can work 24 hours a day with the help of a pilot, navigator, engineer, and three scientists. That means teams of six rotate through four-hour shifts, allowing *Jason* to remain submerged for many days at a time for continuous imaging, observation and sampling.

Tethered to *Jason* is it's partner vehicle *Medea*, which serves as something of a shock absorber for the Greek hero. Any yanks on the line from *Atlantis* are transferred down to *Medea*, which maintains enough slack in the fiberoptic cable to allow *Jason* to roam around within 115 feet of *Medea*.

In Greek mythology, Medea was Jason's wife.

Chris German is thankful for his robotic helpers and their human watchmen. He relies heavily on the engineering team for real-time adjustments to the dive plan and troubleshooting the *Jason*/*Medea* vehicles. Without the team's constant attention on the robots, there are no photos of vents, samples of tubeworms, or up-close sonar mapping of the seafloor. He recalls a saying from Captain Dale of his 2009 expedition, who said, "Robots are like dogs: they'll do their best, but neither one is any better than the person who trained them."

The next day, the engineering team had *Jason* ready to go by noon, but a few technical difficulties pushed the inaugural dive back a few hours. By 4:30 p.m., *Jason* was on the ocean bottom with all systems running. Its first photos from the deep were of weathered rock outcrops, a few fish and shrimp, mussels and tubeworms. Data were displayed in an operations van—a mobile boxcar of screens and instrument displays for monitoring *Jason's* progress that shared the deck of *Atlantis* with a host of equipment. Using its manipulator arms, *Jason* collected five tubeworms, a clam, and a sea cucumber.

The science teams started working their round-the-clock shifts. Twenty-three people from nine institutions in three countries made up seven science teams. There was the Carbon Team made of Max Coleman and Sarah Bennett from NASA's JPL. They wanted to track the state of carbon as it exits from the vent sites and how it gets altered through the food chain. "We're looking at the whole carbon cycle, from abiotic carbon production deep within the crust, to biotic carbon production through chemosynthesis," says Bennett. "If hydrothermal systems were to exist on Europa, it's studies like this that may help us to calculate the biomass that may exist."

Just about everything seems to revolve around carbon. It's an organic element, so the biologists study it because it tells you something about how life has evolved there. It's preserved in rocks, so the geologists want to measure it to figure out the ages of their samples. It gets spouted from superheated gases, so the chemists want to know what it mixes with.

That's why Coleman and Bennett are part of each of the other teams as well—the Plume, Biology, Geology, Fluids and Microbiology Teams—in order to get at the bigger picture of all things carbon in and around the vent systems.

After *Jason's* first dive was declared a success, the crew of *Atlantis* brought the ROV back up to the surface. Securing *Jason* and *Medea* to the deck and distributing samples among eager science teams, *Atlantis* made for the second target, named the Piccard vent site (named after late undersea explorer Jacques Piccard), merely an hour's drive away.

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Meanwhile, Steve Vance is still in the middle of planning discussions at JPL for a potential Europa mission that could launch in 2020. The team he's on has just finished developing three different mission designs with three different vehicles—an orbiter, a flyby (like *Voyager* and *Galileo*) or a lander mission—that they plan to pitch in a report to NASA agency brass in late May.

Collecting samples on Europa and actually sending them back to Earth for laboratory analysis like German's team does on *Atlantis* is probably many decades away from becoming a reality. Vance says a lander could collect samples, but it would be confined to collecting and analyzing only what it could reach at its landing spot. An orbiter or flyby mission, on the other hand, might be able to bounce radar waves off the icy surface to send back data about the moon's mysterious ocean.

"If we had a mission with radar on it, you can construct a radar observation that could possibly see through more than ten kilometers of ice. Depending on how pure the ice is, radar propagates pretty well through ice," says Vance. "There's a possibility if (Europa has) a thin ice shell, you could see all the way to the ocean. At least to the extent that you could say, 'here's an ocean layer.' You couldn't see a whale... " Vance paused for a second, then clarified. "Not that we're expecting to see a whale, per se."

The mere thought that alien fishes, sharks and squids could be chasing each other around in the pitch black waters of Jupiter's moon *right now* has astrobiologists like Vance itching to get a look below the ice. If there's life on Europa, it's much more likely to be microscopic bacteria—somewhat akin to what early Earth life was like for the vast majority of our planet's biological history, some four billion years—but that doesn't mean we can't speculate.

Rock star communicator of astrophysics and space exploration, Neil de Grasse Tyson, agrees. "I want to go ice-fishing on Europa, cut a hole, put a submersible, look around, see if anything swims up to the camera lens and looks at the camera," says Tyson.

One future mission to the Galilean moon that isn't a part of NASA's current plans yet could do just that. This concept is the cryobot: a robotic probe that could land on the surface of the ice, drill down through to the ocean by melting the ice using heat from its nuclear power source and then release a hydrobot (fancy term for robotic submarine) into the potential ocean below. The hydrobot would then begin collecting chemical measurements and start hunting for sea creatures.

Problem is, without detailed radar data of its surface, no one knows exactly how thick the ice layer is. Just as pizza aficionados debate the merits of New York thin versus Chicago-style deep-dish crust, so do planetary geologists argue over the thickness of Europa's ice. According to Vance, there's at least a mile and a half of ice at some points in Europa's shell. "Some of the craters have raised central peaks," says Vance, a bit like if you imagine watching a commercial where a drop of milk falls in slow motion into a bowl, making a momentous splash, and you pause it right at the height of the upward splash. "In the case of these craters, the mechanics lead to the central peak freezing in place. And the central peak needs a certain amount of material underneath to support it."

But that doesn't necessarily mean you'd have to drill through all that ice to reach the ocean. Richard Greenberg is a Professor of Planetary Sciences at the University of Arizona and an outspoken advocate for the New York-style thin crust ice layer. He thinks evidence from *Voyager* and *Galileo* show that Europa's geology cycles water up through the ice repeatedly, potentially bringing fresh seawater up to the surface and eliminating the need to drill through miles of ice to figure out if there's life in Europa's oceans.

"Everything on Europa's surface came up from the ocean not long ago. If we were to land at a random place, we could hardly go wrong," writes Greenberg in his book, *Unmasking Europa*. "If there is life on Europa, it may be hard to miss it."

Ultimately, whether life can be found at the surface, below the surface, or not at all could depend on whether Europa's geology supports a similar type of volcanic gases mixing with transition metals and cold salt water, like the ROV *Jason* witnessed up close at the MCR hydrothermal vents. And even though we can get real-time photos and samples of vents on Earth, we still can't observe anything about the mantle below the seafloor crust on our own planet, let alone a moon 500 million miles away. "It's an interesting parallel with the things that we don't know very well on Earth," says Vance. "Mantle convection on Earth is a big, difficult topic because we have to infer things indirectly from seismic data. We have to infer the structure and composition of the mantle from seismic observations."

Planetary scientists apply similar inference techniques in determining the structure and composition of other planets and moons. To reconstruct the composition of Europa, Vance says "you apply the same physics that you'd apply to mantle geology to ice geology." Observations to date have been able to give scientists a good idea of the rough magnitude of tidal energy that should be on Europa. But no one knows whether that energy gets dissipated in the ice shelf, the ocean or the rocky interior of the moon. "So there's a partitioning problem which then relates to whether you can have underwater volcanoes," says Vance. "It's not as obvious."

Tyson may have to wait awhile before packing up his ice fishing pole. Unfortunately for Vance and his colleagues at JPL, the agency's planetary science budget just got hosed, to put it lightly, to the tune of a cool $300 million. These cuts to NASA's proposed 2013 budget have forced the agency to renege on an agreement for joint U.S.-European robotic missions to Mars in 2016 and 2018, forcing the European Space Agency to scramble for another partner, probably Russia. It's also forced NASA to scale back ambitious missions to other planets and moons.

Such is the stark reality of planetary science in the 21st century with a limited national budget in the middle of an economic recession.

That's one reason Vance is part of the NASA team tasked with slimming down a previous proposed mission to Europa that would have placed an orbiter around the moon in 2026. With a planned launch in 2020, the very originally named Jupiter Europa Orbiter (JEO) would have spent 30 months touring the Jupiter system. The mission would have included four flybys of Io, nine of Callisto, six of Ganymede, and another six of Europa before entering a circular orbit around Europa for nine months, then ultimately meeting a fiery death in a controlled crash landing into the icy moon. The team had just finished its proposal when the planetary science decadal survey—a roadmap for figuring out priorities among thousands of planetary science mission proposals—came out. The survey brought mixed news. The good: Europa was deemed the second highest priority (behind Mars) for finding life in the solar system. The bad: the JEO mission was far too expensive at $4.7 billion to fund as it was originally designed.

Today, the jury's out on whether NASA's next robotic emissary to Europa will be an orbiter, flyby or lander. Other space agencies are already moving forward on their plans—the European Space Agency recently announced its next large space science mission will be the Jupiter Icy Moons Explorer—JUICE—to be launched in 2022. JUICE will arrive at the Jupiter system in 2030 and will focus on Europa's neighbor Ganymede but will also include two flybys of Europa.

Personally, Vance is torn between the flyby and the lander concepts. Both have tradeoffs. He says Europa's extremely high radiation levels are actually an advantage in the lander case. "It turns out you'd save a lot of money on operations for a lander mission," said Vance. "The lander doesn't live that long on the surface, because of the radiation environment. So it's short and sweet. A lot of money that you spend on a mission is to keep a standing team of 100 people working on it for a long period of time. So a lander has [brevity] going for it." That saves money.

Despite savings in operational cost, higher initial up-front costs may mean the lander mission will have to wait for future funding opportunities. According to a May 2012 report from the Outer Planets Assessment Group (a NASA-sponsored forum for scientists and engineers to discuss plans for exploration of the outer solar system), the planetary science community favors either the flyby or orbiter mission options, given NASA's current budget outlook. In particular, the group says that the flyby concept, with more than 30 close-range flybys of the moon, "offers the greatest science return per dollar, greatest public engagement, and greatest flow through to future Europa exploration."

In addition, a flyby mission could yield a priceless result that could serve the whole scientific community for a long time: data.

"If you're going to do this thing once every fifteen years, you want to get a whole, huge chunk of data that will keep you busy after your mission is over. And I can picture having detailed global mapping for geological and compositional interpretations as being that big chunk of data that you would want," says Vance. These data could then be used to figure out an ideal landing spot for a future lander—or cryobot—mission.

Only getting one shot every fifteen years means the pressure's on for Steve and his colleagues at JPL. He's been studying Europa for about seven years. He's 34 now. If a Europa mission—whatever it is—is launched during the proposed window for JEO, he'll be 41. By the time that spacecraft makes it to the moon, he'll be 47.

Last year before the decadal survey came out, he used to joke to friends and colleagues that if he was to father a child now, that child would have been born, taken a first step, learned to read, passed through adolescence, scared Steve to death at being behind the wheel for the first time, and well on his or her way to preparing for college all before the potential spacecraft made it to the Galilean moons.

This is on the chance such a mission gets funded, launches successfully (on-time and on-budget), travels several billion miles through space using the gravity well of Venus as a slingshot, then lands (if they pick the lander) on the icy terrain of a radiation-soaked world that flexes by a hundred feet every 85 hours.

No wonder planetary scientists often think of their spacecraft as children: alive, young, naïve, full of potential, in need of protection, nourishment, guidance, and ultimately, deliverance.

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*Jason* submerged for its tenth and final dive of the expedition. The team had returned to the Von Damm site for a final look at the rocks surrounding the hydrothermal system.

In the operations van aboard *Atlantis*, the Geology Team looked on—Guy Evans and Frieder Klein from Woods Hole and Matt Hodgkinson from the University of Southampton in the U.K. Unless you have the right rocks yielding the right chemistry, you won't get the right conditions for life, regardless of what planet you're on. At least as far as life as we know it goes. We've been wrong before.

"There are some conditions you need to understand when thinking about the origin of life," says Klein. "The key components are pH, hydrogen concentration, methane, $CO_2$, and temperature, which we try to constrain using the rock record."

A particularly interesting rocky outcrop north of the vent site appeared on the screens at around 9:00 p.m. The ROV pilot reached out with *Jason's* robotic arms to grab hold of the rock and pull. The rock didn't budge. He tried again, maneuvering *Jason's* arms to try a different angle. Still, nothing moved. After an hour-long struggle and with more biology and fluid samples to collect, Chris German called off the assault. The team dubbed the outcropping 'kryptonite.'

By 4:00 a.m., *Jason* and *Medea* were still at work and Evans, Klein, and Hodgkinson came back to the operations van to resume the rock hunt after a brief rest. At 6:00 a.m. *Jason* returned to the area where it had wrestled with the kryptonite. A near-identical outcrop once again filled the screens and the team resumed the attack. Thirty minutes later, *Jason's* strength was still no match for the rock. With another thirty minutes left of the team's final dive, the Geology Team decided to move on to look for a more pliable sample.

Thus far, samples of mantle rocks—the ancient seafloor thought to be dragged up by the sliding-book-on-the-bookshelf tectonic plate at this ultraslow spreading ridge—had not been collected. If found, these rocks would help tell the story of the early ocean seafloor and, potentially, the environment surrounding the original genesis of life. The Geology Team wondered if *Jason* was wrestling with a primordial clue.

Fifteen minutes before the end of the dive, the team found a third outcropping—similar in composition but slightly more weathered than the previous two. They decided to let their robotic friend engage in one final boulder brawl.

With three minutes left on the clock, *Jason,* leader of the Argonauts, broke free a chunk of kryptonite the size of a Thanksgiving turkey-serving platter.

It didn't turn out to be kryptonite. Only basalt. Tough, tough, layered basalt—a common form of volcanic deposit on the seafloor. Interesting, but not the clue they were looking for.

Maybe the sought-after mantle rocks were covered in sediment, maybe they weren't there after all. That, along with a continuous stream of unresolved questions reflecting the eternal curiosity and resiliency of the human spirit, will be up to future explorers to battle.

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Eight days after German and his crew reached the sunny Florida Keys, a team of Russian scientists finally reached the surface of Lake Vostok—a sub-glacial lake in Antarctica buried under 12,362 feet of ice. It took the team more than 15 years of stop and go drilling to reach the surface of the lake in the same spot that happens to hold the record for coldest temperature ever recorded on Earth: -89 degrees Celsius.

The lake is roughly 14 million years old and has been completely untouched by humans for all of our history. It's average temperature is calculated to be about -3 degrees Celsius and the only reason it remains in liquid form is because of the extremely high pressure caused by the weight of the ice above it. It has oxygen levels fifty times higher than most other freshwater lakes on Earth. It's one of the largest lakes on the planet. It's also completely cut off from the sun.

But what could be most intriguing about this isolated lake is that it represents a bridge: a terrestrial environment that's perhaps as close as we can get to studying an extraterrestrial one without leaving Earth. In other words, Lake Vostok is a bit like a mini-Europa ocean right here in our own backyard.

That the lake has been isolated for millions of years draws interesting questions about life, its origins and evolution. Is there life in the lake? If so, did it venture off on a completely different evolutionary branch than every other place on Earth? Could there be a heat source sustaining a chemosynthetic ecosystem like we find near hydrothermal vents in the oceans?

Just what's *down* there?

By studying extraordinary environments like Lake Vostok, we're building answers to these and other questions that help define life's place in the universe. And that place is hardly defined yet. When confronted with the intricacies of life's processes and the string of events that were required to create it, some speculate the origin of life is so improbable even on the scale of the entire universe that the only way it could have possibly arisen is if there exists an infinite number of universes, or a *multiverse*—ensuring the one we're in had to have developed, eventually.

Others, like Günter Wächtershäuser, argue that life's not only likely to arise given the right starting conditions, but probably inevitable to emerge throughout the universe. "If this theory is in principle correct," he says, "then life starts the same way everywhere—on Earth, or anywhere else in the universe. It starts with the same elements, with the same chemical properties of these elements and they will do the same reactions, with the same feedback and so forth."

To Wächtershäuser, there is elegance in this predictability. "One day we will know how life starts and we will know that there is a chemical law for life's beginning. It's a chemical *law*. And we will know that as well as we know (that) the summation formula for water is $H_2O$."

As for Lake Vostok, the Russian team can't actually retrieve samples of the lake until January 2013 because their drill can only bring back ice samples, not liquid, so they have to wait for the lake to freeze again over the Antarctic winter. By then, Chris German will be off on another expedition—this time to a promising hydrothermal vent site off the coast of Chile. And Steve Vance will be busy preparing the instruments that will be used, hopefully, to tell humanity whether or not we're really alone in our own solar system.

And maybe, somewhere, a tubeworm will grow a little bit longer.

Waiting.

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