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Mystery of the Hidden Cosmos

Dark matter may be much weirder than physicists thought

BIOLOGY

Life at Hell's Gate

An astonishing discovery is forcing scientists to reconsider whether life can exist in the most extreme places on Earth and in space

By Douglas Fox

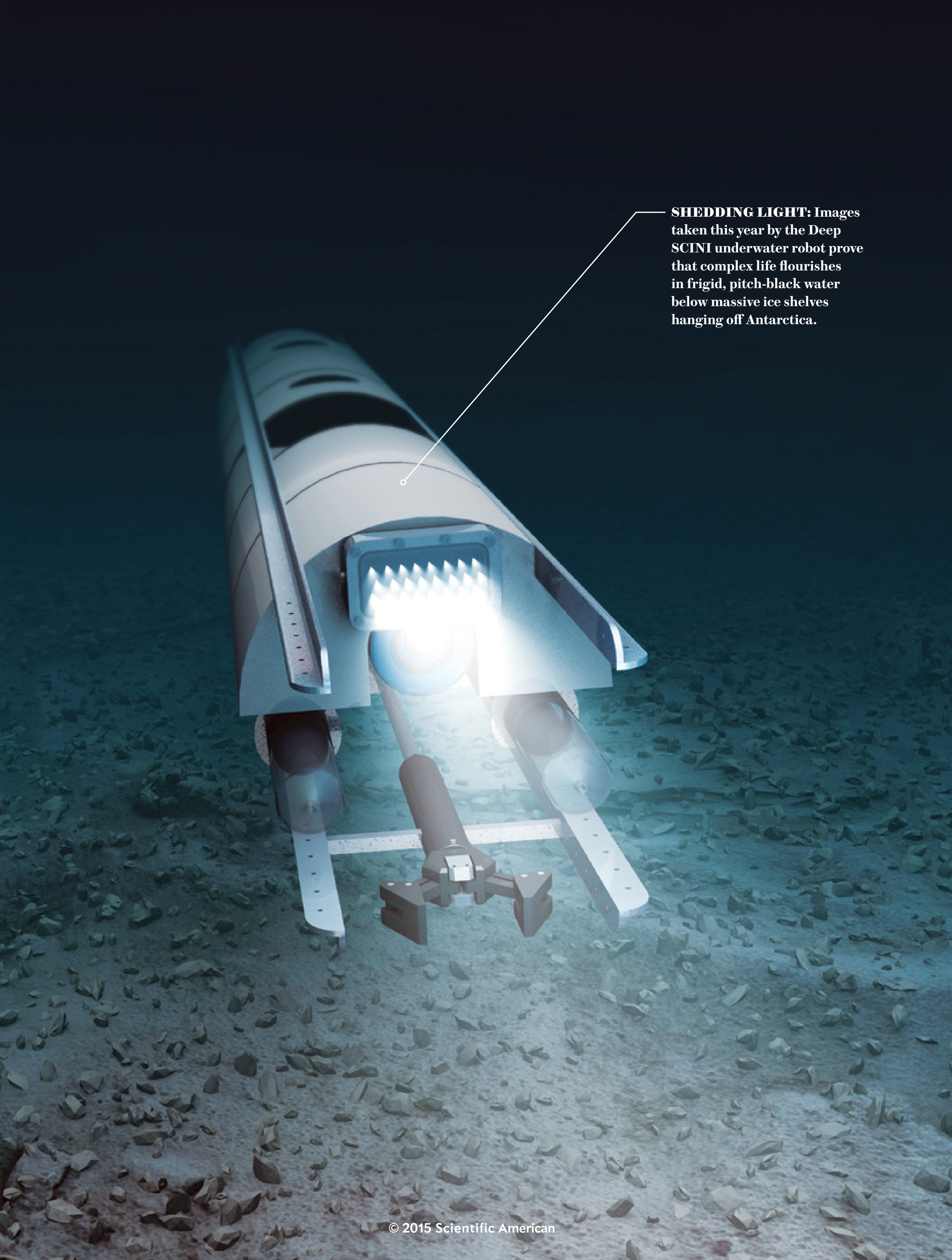
IN BRIEF

In January glaciologists drilled down through 740 meters of ice where the Antarctic continent meets the sea. A robot sent down the hole discovered fish and other animals living in just 10 meters of seawater, 850 kilometers from the open ocean and sunlight. Conventional wisdom held that this remote spot would be almost lifeless.

Fish eat tiny amphipods that in turn eat microbes. Microbes at this isolated place may be fed by debris falling from the underside of the ice as it slides into the water. Without sunlight and photosynthesis, the microbes obtain energy from that debris in unusual ways.

The discovery opens the possibility of life in places on Earth thought to be uninhabitable and on planets and moons such as Europa.

Illustration by Bryan Christie



SHEDDING LIGHT: Images taken this year by the Deep SCINI underwater robot prove that complex life flourishes in frigid, pitch-black water below massive ice shelves hanging off Antarctica.

The coast of the West Antarctic

landmass is one of the most desolate places on the planet. For 1,000 kilometers, it is buried under the West Antarctic Ice Sheet, a series of interconnected glaciers the size of western Europe that slowly slides off the continent into the sea. As the ice crosses the end of the buried land, it becomes a flat shelf hundreds of meters thick that extends hundreds of kilometers farther out to sea, floating on the water. The shelf is the size of Spain, so vast that it could take three to 10 years for an ocean current far below to carry a speck of plankton from the open sea, where sunlight and food are abundant, to the forbidding darkness way back at the submerged shoreline.

Douglas Fox is a science journalist whose work has also appeared in *Discover, Esquire, National Geographic* and *Nature*. Research for his stories has taken him to Antarctica four times since 2007.

COLD START: Researchers camping on the Ross Ice Shelf in January drilled through 740 meters of ice to see what existed at the grounding zone far below.

RACHEL MURRAY

Ocean life was the last thing Robert Zook and a dozen or so scientists expected to see this past January when they undertook a glaciological mission to the grounding zone, where the ice sheet transitions to the Ross Ice Shelf. They had traveled to this remote place to figure out how the underbelly of the slowly creeping West Antarctic Ice Sheet was responding to climate change. They brought several biologists who studied rudimentary microbes but no one who studied anything larger.

On January 16 the group crowded around video monitors in a darkened room on top of the ice—an improvised control center built inside a metal shipping container. For days tractors had dragged the cramped box, mounted on four giant skis, along with half a million kilograms of equipment and supplies, to this spot, 850 kilometers back from the shelf's front edge on the sea. They had used a hot-water drill to bore a hole slightly wider than a basketball hoop down through 740 meters of ice to reach a tiny wedge of water below, along the buried shoreline. They had then hung a robot, called Deep SCINI, on a cable and had begun to painstakingly lower it down the borehole, as a tether unfurled to keep it electronically connected to the control room.

Zook had scrambled to quickly design and build Deep SCINI to withstand the severe cold and high pressure of the depths. But he had only had time to test the remotely operated vehicle, or ROV, in a swimming pool. The crew watched nervously for 40 minutes as the narrow, two-meter-long robot descended deeper and deeper into the void. A light on the robot's nose reflected brightly off each white ripple in the icy walls of the shaft, giving the impression of a cosmic wormhole leading to another world.

The researchers in the crowded room collectively exhaled as the walls of the hole suddenly fell away into empty blackness. Deep SCINI had passed through the bottom of the ice and entered the 10-meter sliver of saltwater below. A barren seafloor rose into view, rocky and lifeless—a dark, frigid seabed humans had never seen. Water samples the crew had hoisted up the hole a few days earlier were crystal clear, lacking any obvious sign of life. Ross Powell, a glacial geologist at Northern Illinois Universi-

DISCOVERIES

Surprise: Life under the Ice

This past January researchers were flabbergasted to find numerous fish and amphipods (tiny, shelled animals) living at the Ross Ice Shelf grounding zone, 850 kilometers back from the open sea and under 740 meters of ice above. Other creatures (*noted below*) had been found in the past under the front edges of ice shelves, much closer to sunlit waters, often hanging from the underside of the ice in an upside-down world.

Map by XNR Productions

ty who co-led the expedition, described the grounding zone as "pretty inhospitable" when we spoke by satellite phone after the samples had been retrieved.

The robot's pilot, Justin Burnett, slid his fingers across a touch pad to guide Deep SCINI up to the underside of the floating shelf. The ROV's lights exposed a dark, bumpy roof of ice embedded with silt. Here and there a mote of sand dislodged from the ceiling—glinting in the light as it streamed down, like a falling star. Sometimes one of these falling stars acted strangely—it appeared to dart sideways. No one could be sure, but it seemed in the video as if something had *moved*.

Burnett began to nose Deep SCINI back toward the seafloor when suddenly the video froze. The robot had shut down to avoid becoming overheated—ironic in this water, which at –2 degrees Celsius was kept liquid only by salinity and extreme pressure from the ice above. Zook called on the radio to the winch operator outside and asked him to lower the robot to the bottom while the researchers rebooted it.

When the video cameras came back on, someone inside the cold shipping container yelled, "Look, look, look. Holy sh—t!" All eyes swung left, to the monitor for the downward-looking camera.

A graceful shape glided across the screen—tapered front to back like an exclamation point, its translucent body bluish, brownish, pinkish. It was a fish, as long as a butter knife. The room erupted in gasps. This team, here to investigate glaciers, had just found complex life in one of the supposedly most uninhabitable places on Earth.

The ROV stayed down six hours that day, encountering three different types of fish—20 or 30 in all. Shrimplike amphipods flitted about. The crew saw a maroon-colored jellyfish and an iridescent body swimming overhead that might have been a comb jelly. "You got a sense that they were a community living there," Powell told me shortly afterward. "It wasn't just a chance event." The barren depths, it turned out, held plenty of life.

The entire scope of the mission changed in an instant: the imperative now was to capture some of the animals, if possible, so researchers could later analyze them. Over the next several days Zook fashioned a makeshift trap on Deep SCINI with a piece of window screen and baited it with fish meat. When the robot was again lowered to the seafloor, its camera watched for four hours as dozens of amphipods crawled about the trap, like flies on a trash can. When the winch operators hoisted it back up, the trap contained more than 50 amphipods. The crew froze the tiny crustaceans and flew them back to McMurdo Station, the main U.S. logistics hub in Antarctica, as Zook and the scientists prepared to depart.

Discovering complex life in such abundance came as a complete shock. The findings are still reverberating through the scientific community, upsetting long-held assumptions about life on our planet and the potential for finding life on other worlds.

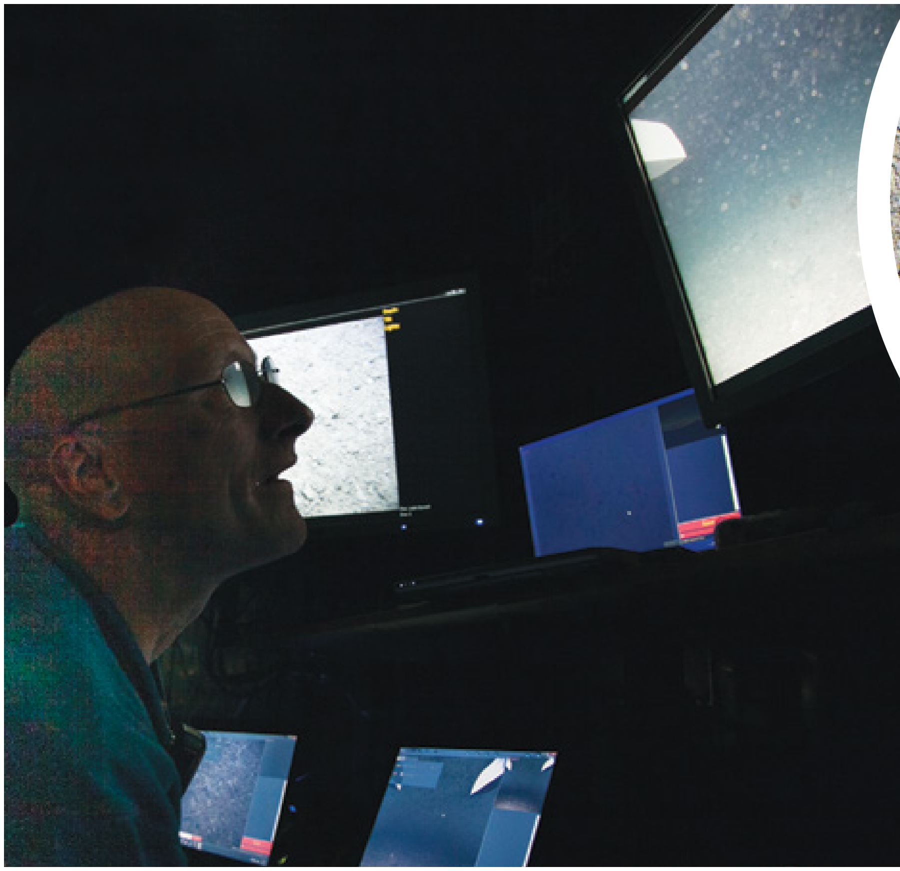
Evidence of life under Antarctica's ice has come slowly. The climate is forbidding, and expeditions are expensive, especially if they require drilling through hundreds of meters of ice. For these reasons, what little information scientists have gathered has come from the front edges of ice shelves near open water.

In the 1960s glaciologists stumbled on a colony of seals that had somehow survived despite being permanently stranded on the McMurdo Ice Shelf, 25 kilometers in from the shelf's edge—too far in for them to shimmy back to the sea. The seals congregated near a deep crack where the ice shelf buckled. They dived into the crack to hunt for food in the seawater below. The biologists wondered what the seals could possibly be eating in the dark, desolate waters—especially because they appeared to be even fatter than seals living on the open ocean—but the scientists had no way to find answers.

A clue came by chance in 1975, when low clouds forced John

Oliver's helicopter to land by a nearby crack in the ice. Oliver, then an oceanographer at the Scripps Institution of Oceanography in La Jolla, Calif., and his partner decided to dive into the crack. They descended an underwater ice wall, and 40 meters down they saw something alien: hundreds of green-glowing anemones rooted in the ice. They returned a year later to harvest some anemones but found the water swirling with ice crystals, forcing them to abandon the planned dive without collecting or even photographing the animals. All that came of their finding was a single sentence buried deep in a scientific paper on glaciers.

In 2003 Yuuki Watanabe, a biologist then at the University of Tokyo, was camped on the thin, seasonal sea ice near the Riiser-Larsen Ice Shelf 3,000 kilometers away. The ice, which forms on water off the front edge of ice shelves in winter, allowed him to stay in a hut and study the feeding habits of seals. Instruments he had attached to the animals revealed that they frequently dove 150 meters into the water; he assumed fish were congregating there. But when he attached a camera to one seal, the photographs revealed tentacle-waving animals hanging upside down from the underside of the shelf—a big surprise. Watanabe reasoned that the seals were diving under the lip of the shelf to eat whatever hung there.



FISH! **Bob Zook (*left*) peers at live video sent by his robot, submerged in a pocket of water at the grounding zone. Expecting no visible life, he was shocked to find three species of fish, some of them translucent and the size of a butter knife (*right*).**

RACHEL MURRAY

Few people were even aware of the glimpses Oliver and Watanabe had gained when Zook was hired in 2010 to bring an ROV to help engineers test a hot-water drill on the Ross Ice Shelf at Coulman High, a site 10 kilometers back from the shelf's front edge, where the ice was 250 meters thick. The team melted a hole through the ice, and Zook sent his robot down. As he drove it along the underside of the ice, something strange came into view on the video monitor: tentacles—phantom and ghostlike—the arms of thousands of sea anemones, which normally live rooted on the seafloor. Here they hung upside down, their stalks burrowed into the ice. Worms inhabited other ice burrows. Shrimpy amphipods and krill flitted through the water. And fish meandered about; one of them swam upside down, its belly skimming the icy ceiling. The accidental sighting was "so out of context," Zook said. "There was zero expectation that this would happen."

Marymegan Daly, an anemone specialist at Ohio State University, was stunned when she saw the first photographs. "It blew my mind. They looked like bats hanging off a cave ceiling," she says. "It never occurred to me that anemones would be living there."

No one had imagined an upside-down ecosystem on the underside of an ice shelf. But scientists could at least rationalize its existence through conventional wisdom at the time. Complex life under the front of the ice could be fed by ocean water wafting in from the sunlit sea nearby, biologists reasoned. But life would quickly dwindle farther back under the shelf—more distant from sunlight. Smaller and smaller organisms would eat the disappearing bits of food until none remained, marking the beginning of an enormous region inhabited only by microbes, reaching hundreds of kilometers back under the country-sized ice shelves toward land and ending at the grounding zone.

The isolation from sunlight and photosynthesis at the grounding zone is profound. The most barren stretches of ocean bottom that humans had previously found are dark, abyssal seafloors, out in the middle of vast oceans under 6,000 meters of water. Life at these depths depends on bits of dead plankton filtering down from the sunlit waters far above. At the grounding zone, there is no sea surface above. Stacy Kim, an Antarctic benthic ecologist at Moss Landing Marine Laboratories in California, had expected the zone to be many times more isolated than the abyss.

In 2013 the ANDRILL Science Office at the University of Nebraska–Lincoln, which funded the 2010 trip, hired Zook to build a more advanced ROV—the one that became Deep SCINI. He built its camera windows, made of sapphire, and its body, made of millions of tiny, hollow glass spheres, to withstand water pressures down to 1,000 meters so it could explore under thicker, more remote parts of the ice shelf. Zook was then invited to bring Deep SCINI on the expedition led by Powell—an unparalleled effort to drill into the grounding zone.

The 53-year-old Zook hardly fits the profile of a scientific ex-

plorer. He never graduated high school. He spent a few years designing early wireless phone systems before taking a job in 1997 maintaining radio repeater towers and air-navigation beacons at McMurdo Station. Zook and Burnett, a robotics graduate student at the university, rushed for six months to finish Deep SCINI, pulling 15-hour days in a sweaty brick hanger in Lincoln. Deep SCINI had been funded only as a prototype, not for real exploration. When they arrived at the drill camp on January 2, 2015, the robot still lacked a navigation system and a system to manage power consumption, making it prone to overheating.

After Deep SCINI was hoisted out of the hole following the fish discovery, the team lowered a package of oceanographic instruments belonging to Powell and parked it on the sea bottom for 20 hours. There it measured ocean currents and salinity—data that might give clues to how quickly the ice was melting. And it tracked the levels of oxygen and other chemicals in the water—suddenly crucial, given the discovery. All the while, fish and amphipods visited the package's camera.

People at the camp wracked their brains during late dinners, trying to make sense of the animals. "We have to ask what they're eating," said Brent Christner, a microbiologist at Louisiana State University who has studied Antarctic microbes for 15 years. Sunlight was way too far away, and any water from the shelf's front edge that did drift back here would have been picked clean of food during years of slow migration.

The mystery was heightened by the extravagant energy needs of animals compared with microbes. Fish require a multilevel food pyramid. At the bottom, microbes use energy from sunlight or chemicals to pluck molecules of carbon dioxide out of the water and grow. Amphipods eat the microbes and recycle their carbon. Fish, at the top, eat the amphipods. This transfer of carbon, or energy, up the food pyramid is inefficient, said John Priscu, a microbial ecologist at Montana State University who co-led this year's expedition. About 100 kilograms of microbes are needed to support one kilogram of fish.

Mystery also surrounds the million square kilometers of land hidden under the West Antarctic Ice Sheet. Glaciologists have drilled a few holes through the ice into the mud below. It is rich in the microscopic shells of diatoms that lived 20 million to five million years ago—evidence that a shallow sea covered the area in warmer times. Remote seismic mapping shows ancient sediment layers hundreds of meters thick, containing billions of tons of decomposing marine organisms that died and settled to the bottom.

In early 2013 the same team of scientists who in January drilled to the grounding zone drilled through the ice sheet 100 kilometers inland, hitting a subglacial reservoir called Lake Whillans. (I was with them for that expedition.) Organic carbon from the ancient marine layers made up 0.3 percent of the lake's mud—a striking amount similar to that in the soil that nourishes desert grassland across the U.S. The team discovered microbes in the lake, too. Without sunlight and photosynthesis, the microbes obtained energy by using oxygen in the lake to "burn" chemicals such as ammonium and methane seeping up from the decomposing layers below.

Could it be that the fish at the grounding zone were being fed by a similar source?

As Deep SCINI went down the hole, the glassy ice walls briefly turned opaque and brown just before the robot emerged into the water cavity. The bottom 20 meters of ice was cluttered with the same kind of carbon-rich debris seen in Lake Whillans—material that froze onto the underside of the glacier as it dragged across land thousands of years ago.

Bits of that sediment dropped from the ice ceiling as Deep SCINI explored the ocean cavity—those glinting specks of dirt that descended like falling stars. About a millimeter of the ice's underside melts every day, releasing the nutrient-rich crumbs. Priscu noticed that amphipods swarmed greedily about the clouds of debris that billowed from the bottom of the hole after the walls there were disturbed by the robot. He wondered if the ice that cut this place off from sunlight might also feed it by supplying organic detritus that sustains microbes at the bottom of the food pyramid. The fish "are getting their food from above," he said. "I am almost 100 percent sure."

In Priscu's mind, glaciers flowing from land to sea over the grounding zone provide a slow conveyor belt of debris-rich ice that begins to melt as it contacts seawater, sprinkling out its detritus. The dirty ice melts quickly enough that it drops its entire load by the time it moves 40 kilometers out over the sea. This local rain of sediment "can help fertilize the seawater, which helps to create [a] habitable zone" at the very back of the ice shelf, said Slawek Tulaczyk, a glaciologist at the University of California, Santa Cruz, who co-led this year's expedition with Powell and Priscu.

These isolated habitats could be widespread. More than 20,000 kilometers of grounding zones, hidden under floating ice, encircle Antarctica's coast. Imagine looking down on Antarctica from space and peering through the ice to find a ring of fish and other animals 40 kilometers wide around the entire coastline—a vast, thriving ecosystem, not a lifeless hell.

The vast stretches of dark ocean under the ice between this oasis and the open water may also contain at least some animals. In 1977 a single hole was drilled through the Ross Ice Shelf, 475 kilometers back from the open sea, into a water column that was 240 meters deep. A camera lowered through the hole shot several hundred photographs of the seafloor, and two appeared to show fish. Amphipods were also seen. "People didn't pay a lot of attention," Kim says. But that old observation seems more noteworthy now that fish have been found in the far more isolated environment of the grounding zone.

This vision of life spread under ice shelves becomes even more enthralling. Recent images taken by ice-penetrating radar from planes, which can map the three-dimensional structure of the ice sheets, show that water melted from the ice, which is lighter than the seawater because it has less salt, flows out from the grounding zone along the underside of the shelf in well-defined plumes for hundreds of kilometers. "You're talking about an upside-down river," says David Holland, an oceanographer at New York University. The inverted rivers melt channels into the ice that can be 500 to 3,000 meters wide and 200 meters up into the ice itself. If the rivers carry debris that has melted free from the ice, they may feed organisms along those channels.

UPSIDE-DOWN WORLD: **Surprising creatures had also been found under the front edge of the Ross Ice Shelf (*top*) in 2010. Instead of being rooted in the seafloor, anemones (*right*) were rooted in the underside of the ice, growing downward; other animals flitted about, including an unknown creature nicknamed "egg roll" (*left*).**

BEN CRANKE *Getty Images (ice shelf)*; COURTESY OF ANDRILL SCIENCE MANAGEMENT OFFICE, UNIVERSITY OF NEBRASKA–LINCOLN *(egg roll and sea anemones)*

The sense of intrigue about how remote life can be on Earth has only deepened as biologists examine the photographs and specimens that Zook caught, as well as the upside-down anemones collected in 2010 at Coulman High (the data were released only in 2013 after a long delay). A striking realization is emerging: these species, living in places so extreme, are surprisingly unremarkable. "The habitat is so bizarre," Daly says. "But the animals are really vanilla."

The anemones, for example, belong to a well-known family that lives worldwide. "There's nothing unexpected about them, anatomically," Daly says—no novel gland or other organ to explain how they burrow into the ice while avoiding freezing. They might survive by concentrating salt around their bodies, which can act as antifreeze. Daly did notice one adaptation: their eggs are extremely fatty, so they float to the ice ceiling above rather than sinking to the seafloor below.

The red, shrimpy amphipods discovered in January appear to belong to a well-known group that inhabits the world's deep ocean floors—"voracious scavengers," according to Kathleen Conlan, a marine biologist at the Canadian Museum of Nature in Ottawa. In Antarctica, she says, "if there's an organic source coming from that debris [in the ice above] and stimulating the growth of microbes, then the amphipods could be picking that off."

The blue-brown-pink fish were also recognized in photographs. Arthur DeVries, an ichthyologist at the University of Illinois at Urbana-Champaign who has studied Antarctic fish for almost 50 years, identified them as Antarctic silverfish, one of the most abundant species around the continent's coastal waters. Ironically, the fish are vulnerable to death by freezing.

Finding such humdrum creatures in strange places suggests a profound truth: that Earth's most remote, unexplored environments may not be as extreme as we thought. "We always think we've got a good handle on this planet," observes Britney Schmidt, a planetary scientist at the Georgia Institute of Technology. The January discovery "tells us how naive we are," she says. "For me, that's where the real lesson is."

Indeed, complex life might exist in all kinds of places we have dismissed as uninhabitable. We often define habitability in terms of liquid water, both on Earth and on other planets and moons. Schmidt sees it differently: "I'm looking for geologic sources of energy," where plate tectonics or sliding glaciers, for example, can bring long-buried carbon back up to where it can be eaten once again. "These cycles can feed life," she says.

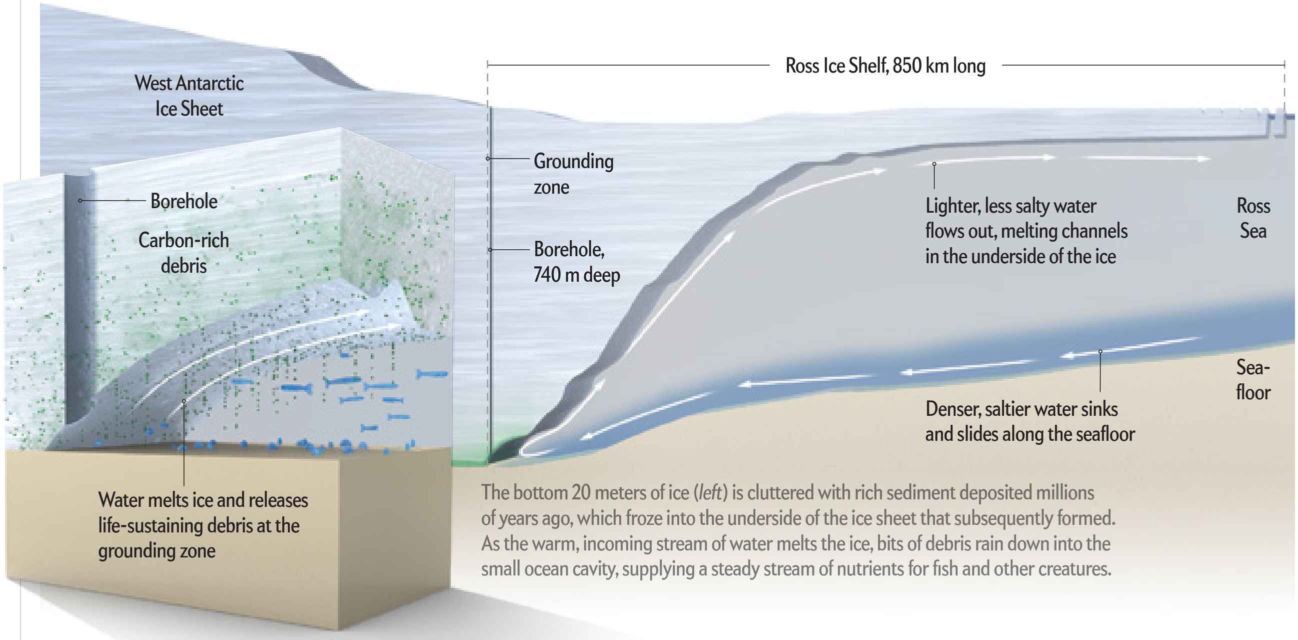
Other recent discoveries bolster this way of thinking. Swarms of worms were found on the Gulf of Mexico seafloor, in upwelling patches of methane ice—an exotic, solid form of natural gas that develops at high pressure. Despite inhabiting such a weird place, the worms eat a typical diet: bacteria, which in turn consume the methane ice. Different worms have been found in water gurgling through bedrock fractures three kilometers below Earth's surface, feeding on microbes that eat minerals in the bedrock. Some deep-living microbes are even nuclear-powered, in a sense, consuming hydrogen that is produced by the decay of uranium and other radioactive elements.

Then there is subglacial Lake Vostok, located in East Antarctica, 1,500 kilometers inland from the January drill site. Vostok sits under 3,700 meters of ice, cut off from air and sunlight for 15 million years. In the 1990s Russian scientists drilled down

SCIENTIFIC AMERICAN ONLINE For more on the landmark discovery at the Ross Ice Shelf grounding zone, see ScientificAmerican.com/jul2015/fox

Fish Feed on Million-Year-Old Debris

The massive West Antarctic Ice Sheet (*left*) slowly oozes off land to the sea, where it becomes a floating ice shelf (*right*). The transition point is called the grounding zone. Dense saltwater slides back to the grounding zone, where it melts the ice, creating a small cavity of water that stays liquid at –2 degrees Celsius because of enormous pressure from 740 meters of ice above. Scientists assumed the pitch-black cavity would be virtually lifeless because it is 850 kilometers from sunlight, needed by microorganisms to sustain a food web. But in January researchers found fish and other complex life there, which seemed to feed on sediment falling from the ice (*inset, bottom left*).



The bottom 20 meters of ice (*left*) is cluttered with rich sediment deposited millions of years ago, which froze into the underside of the ice sheet that subsequently formed. As the warm, incoming stream of water melts the ice, bits of debris rain down into the small ocean cavity, supplying a steady stream of nutrients for fish and other creatures.

and, without puncturing the lake itself, retrieved ice that had frozen along the upper edge of the water in the lake. Well-respected polar biologists reacted with skepticism and ridicule in 2013, when Scott Rogers, a biologist at Bowling Green State University, analyzed the DNA trapped in this ice. He reported finding DNA evidence of aquatic animals that might inhabit the lake, including anemones and crustaceans.

"I think it's good to keep an open mind" about Rogers's analysis, Tulaczyk says. Despite being so deeply buried, Vostok probably contains substantial amounts of oxygen, injected into the lake as ancient air bubbles melt out of the ice above.

A similar process could exist on Europa—an ice-covered moon orbiting Jupiter, thought to harbor an internal ocean of liquid water underneath 10 to 20 kilometers of ice. Schmidt and others have found evidence of strong ocean currents inside Europa, powered by the gravitational tides and frictional heating from Jupiter. If those currents warm and melt the underside of the ice, that could fuel an ecosystem similar to the one found in subglacial Lake Whillans or at the grounding zone. The warm currents could drive a kind of plate tectonics, in which ice on Europa's surface is recycled to the interior ocean, bringing with it a steady flow of oxygen and other compounds.

The discovery of animals at the grounding zone poses plenty of questions. Powell will estimate the ocean currents and heat reaching this place, which will reveal the rate at which melting ice can sprinkle out new food. A string of instruments that Tulaczyk lowered into the ice hole as it froze shut will provide further information on currents by monitoring the changing tilt of the ice shelf that occurs with daily tides, beaming this information back weekly via satellite link. Priscu and Christner will dissect amphipods and DNA-fingerprint the contents of their guts to see what the animals eat. They will also analyze DNA from microbes in the water and mud to determine what energy source powers this food web—ammonium, sulfur or other chemicals.

Powell hopes to return to the grounding zone with a larger ROV that can explore farther under the ice, capture video and measure chemicals in the water. Zook hopes to harvest some live fish and other animals. But right now he feels lucky with how Deep SCINI performed. "The rule of thumb [in Antarctica] is that any new, major technological project doesn't work on its first year," he told me while packing up in January. Deep SCINI's success "was a minor miracle." SA

MORE TO EXPLORE

A Microbial Ecosystem Beneath the West Antarctic Ice Sheet. Brent C. Christner et al. in *Nature,* Vol. 512, pages 310–313; August 21, 2014.

Ongoing findings about life under the Antarctic ice can be found at the Whillans Ice Stream Subglacial Access Research Drilling program site: www.wissard.org

FROM OUR ARCHIVES

Witness to an Antarctic Meltdown. Douglas Fox; July 2012.

scientificamerican.com/magazine/sa

Illustration by Bryan Christie