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Abstract: The article presents a study of mountains' limestone layers and caves, as well as gushing up from deep and ancient aquifers, the pools, or pozas as the locals call them. Whatever their origins, though, the pozas contain a profusion of microbial communities, leaving biologists wondering how so much biodiversity can exist in an area of just 250 square kilometres and with so little phosphate, an essential ingredient of life. The pozas are not exact replicas of the first ecosystems, of course. Back then the atmosphere was very different, and the soup contained only prokaryotes, single-celled microbes without nuclei. But the stromatolites in the pozas might be similar to later microbial mats that lived alongside early eukaryotes. INSET: The dentists who never were.

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Primeval pools

Contents

Welcome to the Earth as it was half a billion years ago, when life took its greatest leap forward. Karen Schmidt takes a trip to the past

• OUR white van bounces along a dusty road, meandering past a grey-striped mountain of twisted rock and acres of brushy creosote and prickly yuccas. A startled burro gallops away. Finally, the shuddering 2-hour ride comes to a halt. We step out into the warm desert silence, soil crunching beneath our feet, and peek through tall grasses at a bright turquoise pool filled with striped fish swimming among what looks like coral. Courtney Turich, a biogeochemist from Pennsylvania State University at University Park, dons her scuba gear and dives to about 12 metres to collect samples. After the dive, she reports, "It looks like brain coral, but it's mushy — it's totally cool! These reefs are like some of the first kinds made on Earth."

A primitive reef in a desert pool? That's just one of many surprises lurking in this arid part of Coahuila state in northern Mexico. Here in the valleys surrounding the town of ***Cuatro*** Ciénegas, which means four marshes, are more than 200 remarkable freshwater oases. Fed by underground waters coursing through the mountains' limestone layers and caves, as well as gushing up from deep and ancient aquifers, the pools — or pozas as the locals call them — have strange chemistries. Phosphorus tends to be in short supply, whereas calcium, magnesium and sulphur are richly available. In essence, the pozas appear to be little versions of the primordial sea, before the dawn of nucleated cells. Primitive microbes flourish here, and even form cooperative communities called stromatolites, the coral-like structures that Turich probed and which reigned supreme on Earth for about 2 billion years.

These rare desert stromatolites are a big draw for this van-load of scientists — a diverse bunch including biologists, biogeochemists, a biogeographer, a biostatistician and an astrophysicist. They have come to ***Cuatro*** Ciénegas this March to investigate a world of "fossil" ecosystems, remnants of the experiments that were brewing on Earth before it erupted in a riot of complex life forms. The ponds are living examples of the processes that led to the first ecosystems, the build-up of our oxygen-rich atmosphere and the evolution of new species. And because life evolves under extreme conditions here, the pozas might offer clues about how to search for signs of life on other planets.

The visitors begin their exploration by poring over a map, reviewing what's known about this part of the desert. Valeria Souza, an ecologist at the National Autonomous University of Mexico in Mexico City, began coming here in 1999 and knows the area best. She points out a fault line where deep springs well up, and wonders aloud how all the underground plumbing interconnects. Geologists think this part of Mexico was once on the coast of the supercontinent Pangaea, bordering a proto-sea. About 150 million years ago, when Pangaea was breaking up amid tectonic upheaval, seawater was trapped deep under ***Cuatro*** Ciénegas. Souza suspects that many microbe species in the pozas originated in these reservoirs and are the descendants of those that lived in the ancient sea.

Whatever their origins, though, the pozas of ***Cuatro*** Ciénegas contain a profusion of microbial communities, leaving biologists wondering how so much biodiversity can exist in an area of just 250 square kilometres and with so little phosphate, an essential ingredient of life. Consider the stark example of two pozas jokingly called the non-identical twins, which are separated by a mere half-metre strip of soil. No one can explain why one is light turquoise in colour and contains little phosphate, while the other is dark brown and rich in phosphate. The team is in the process of examining the microbial communities to see how different they are.

"We've been thinking about this place as the Yellowstone of Mexico, or the next Galapagos Islands," says Brendan Bohannan, an ecologist and biogeographer at Stanford University in California. Or perhaps it could be the next Shark Bay, Australia, the favoured site for studying stromatolites, where a highly salty marine environment has allowed these microbial communities to survive as a modern outpost of the ancient Earth (***New Scientist***, 11 March 2000, p 30).

To see far stranger kinds of stromatolites, we head out to an area on the map called Zona del Silencio, where a wetland called Churince appears like a vast, shimmering mirage, reflecting the steep mountains, cacti and dunes of white gypsum around it. Brad Bebout, a stromatolite specialist at NASA's Ames Research Center in Mountain View, California, wades into a pond to look closely at the golden, fuzzy-looking spheres in the shallows.

These are microbial mats. Under certain conditions, some microbes, such as photosynthetic cyanobacteria, sulphur-reducing bacteria, nitrogen-fixing bacteria and other helpful waste-eaters, glue themselves together into slimy cooperatives that are often layered like a cake. The incorporation of silt and minerals creates a harder structure, a "living rock" called a stromatolite. The cake recipe and final structure vary from place to place, depending on what ingredients are available. Here Bebout finds unlayered, relatively soft stromatolites and collects a sample to analyse at the lab.

It is difficult to separate the components and sort out all the community members of a stromatolite, but Bebout expects at least to find Calothrix, a filamentous cyanobacterium that seems to grow all over the area and which Souza calls "queen of the valley". To get a look at the queen when she's not part of a stromatolite, we need only squat at ground level. The crusty soil here is peppered with sand bubbles: pop the top off a bubble and we can see a green layer that is Calothrix, a modern relative of the ancient cyanobacteria that first put oxygen into Earth's atmosphere about 2.7 billion years ago. "These are the creatures that made life possible," says Souza with affection.

Studying stromatolites provides clues about what life was doing during the greater part of Earth's history — about 3.5 billion years. The pozas are not exact replicas of the first ecosystems, of course. Back then the atmosphere was very different, and the soup contained only prokaryotes, single-celled microbes without nuclei. But the stromatolites in the pozas might be similar to later microbial mats that lived alongside early eukaryotes — organisms with nucleated cells — such as diatoms. What's different today is that many pozas are also home to species that arose later, such as water lilies, endemic fish and snails. Even so, modern stromatolites fix nitrogen and photosynthesise much as their forebears did, and that makes them good examples of highly successful simple ecosystems — and of what to look for on other planets.

That's why astrophysicist Victoria Meadows of the California Institute of Technology's Spitzer Science Center has come on the trip, and is standing at the pond's edge, musing, "What would a planet look like if it were covered with this stuff?" Meadows leads a project called the Virtual Planet Laboratory, the goal of which is to explore the many ways that we might detect simple life on other planets. The measurements that the team makes, of the gases generated by the stromatolites, for example, will be plugged into her computer model. This will help astronomers learn to recognise "biosignatures" — clues that a planet's atmosphere has been influenced by life. In theory, biosignatures should be recognisable from the patterns of radiation given off by distant planets. This is the kind of thing NASA's Terrestrial Planet Finder coronagraph will look for when it is launched in 2014.

Ancient ecosystems

The stromatolites in these pozas might also shed light on one of the key events in our own planet's history: the Cambrian explosion. The fossil record shows that at this time, around 540 million years ago, stromatolites started losing their supremacy, while large-bodied multicellular animals, or metazoans, rose to dominance. Hoping to figure out what triggered this dramatic shift, biogeochemist James Elser and his colleagues at Arizona State University in Tempe found a perfect real-world setting to play with: a spring-fed river here called Rio Mesquites, which contains both stromatolites and a small population of snails that graze on them. "This is a great place to study the early Cambrian food web," says Elser. What's more, phosphate here is limited, just as it was before the big transition.

For the first few billion years of life on Earth, Elser reasons, phosphate was in such short supply that the food chains needed to support complex life could not have arisen. But once oxygen began to accumulate in the atmosphere and oceans, phosphate became more available. Elser thinks that triggered the Cambrian explosion, and soon metazoans were grazing microbial mats out of existence.

If Elser is right, ***Cuatro*** Ciénegas may be the only place in the world where you can still see that transition happening. "We live in a world so dominated by eukaryotes that a chance to see a place where prokaryotes dominate simply cannot be missed," says Antonio Lazcano, president of the International Society for the Study of the Origin of Life and a biochemist at the National Autonomous University of Mexico.

To test his idea, Elser's group first measured the ratio of carbon to phosphorus in the area's stromatolites. This gives an idea of their nutritional quality. They found that the microbial structures, which are hard and riddled with holes, contain so little phosphorus that they serve as empty calories — "junk food" — for the snails, which are therefore unable to thrive in great numbers.

When the researchers added a small amount of phosphate to enclosures in the river, both the stromatolites and the snails flourished. However, higher amounts of phosphate proved detrimental to the snails. This leads Elser to conclude that the first herbivores were probably living on a nutritional knife edge, so focused on coping with low phosphate that they were unable to deal with its abundance. As phosphate levels rose during the Cambrian era, new species must have evolved ways to cope with it. Their studies will appear in Freshwater Biology.

Phosphate availability also has intriguing implications for how organisms spread their genes around. That's because genes not only carry traits, they also carry lots of phosphate in the backbone of their DNA molecules. In a phosphate-poor world, sexual reproduction — which involves giving DNA to a partner — might be too costly, so microbes might have simply scavenged naked DNA lost to the environment by injured or dead organisms of the same or different species. Researchers now think such horizontal gene transfer between microbial species is relatively common. Souza's group, along with Janet Siefert of Rice University in Houston, Texas, and Michael Travisano of the University of Houston, suspect it may even be the dominant way that microbes in the pozas get new genes. "Life is hard here, so horizontal gene transfer is expected to be very important," says Souza. Conversely, when more phosphate is around, sex should become more favourable.

Swapping genes

The three research teams plan to test this idea by studying the rates at which cyanobacteria, bacteria and viruses in the pozas swap genes with one another both in their natural low-phosphate environment and then with added phosphate. They also hope to answer basic questions about how genes flow in a simple, real-world microbial ecosystem. "We don't know yet how often horizontal gene transfer occurs, how often it succeeds or fails, and how important it was in the past," says Siefert. "It's highly possible that we will be able to figure out the rules here." That could lead to new insights about how to contain horizontal transfers that spread antibiotic-resistance genes in pathogenic bacteria and transgenes in engineered hosts. In addition, if horizontal gene transfer among different species looks to be really rampant, that would cast doubt over whether the genomes of modern microbes can reveal anything about their ancestry.

The visiting scientists have many questions and ideas for how to answer them. But as our van travels from poza to poza, in and out of the gated zone of protection established by the Mexican government, it is clear that what they can discover will depend on how well this rare landscape is preserved. Water has been repeatedly diverted — these days to quench thirsty alfalfa crops. "We are at a critical time," says Souza. "Even pumping from wells far away can have an impact here." As we visit, the local environmental organisation Pronatura is gearing up for an onslaught of spring-break revellers, who must be blocked from swimming in the pozas. The wardens must also keep cattle, horses and invasive exotic species from making their way into the reserve.

Still, there is good reason to be optimistic. A few years ago Souza stopped 250 wells from being drilled nearby, and some pozas with falling water levels now appear to be recovering. In 2000 The Nature Conservancy bought a 300-hectare ranch that contains 130 pozas, including many of the most pristine ones, and is now trying to purchase additional water rights in the area.

The most inspiring sign of support for these desert pools comes from the town of ***Cuatro*** Ciénegas itself. Researchers on the trip made several presentations that grandmothers, schoolchildren, teens, farmers, shopkeepers and entrepreneurs came to listen to and take notes. "People here in Mexico crave an understanding of how life began," says Lazcano. The next important step — how early life made the leap to complexity — is another one of those irresistible mysteries, especially once you've seen the pozas of ***Cuatro*** Ciénegas.

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MAP: SNAPSHOT OF THE PRIMORDIAL SEA: In the pools around ***Cuatro*** Ciénegas in Mexico, the microbes that reigned supreme for 2 billion years still flourish

PHOTO (COLOR): The mix of gases emitted by these microbial mats suggests ways to look for life on other planets

PHOTO (COLOR): One of the few places on Earth where microbes still dominate as they did billions of years ago

PHOTO (COLOR): Islands of water in the desert, the pools of ***Cuatro*** Ciénegas have been called Mexico's Galapagos

PHOTO (COLOR): Rock-like microbial mats, or stromatolites, contain so little phosphorus that they are "junk food" for snails

PHOTO (COLOR): Diversion of water for agriculture threatens to dry up the pools and destroy these rare ecosystems

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By Karen Schmidt
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