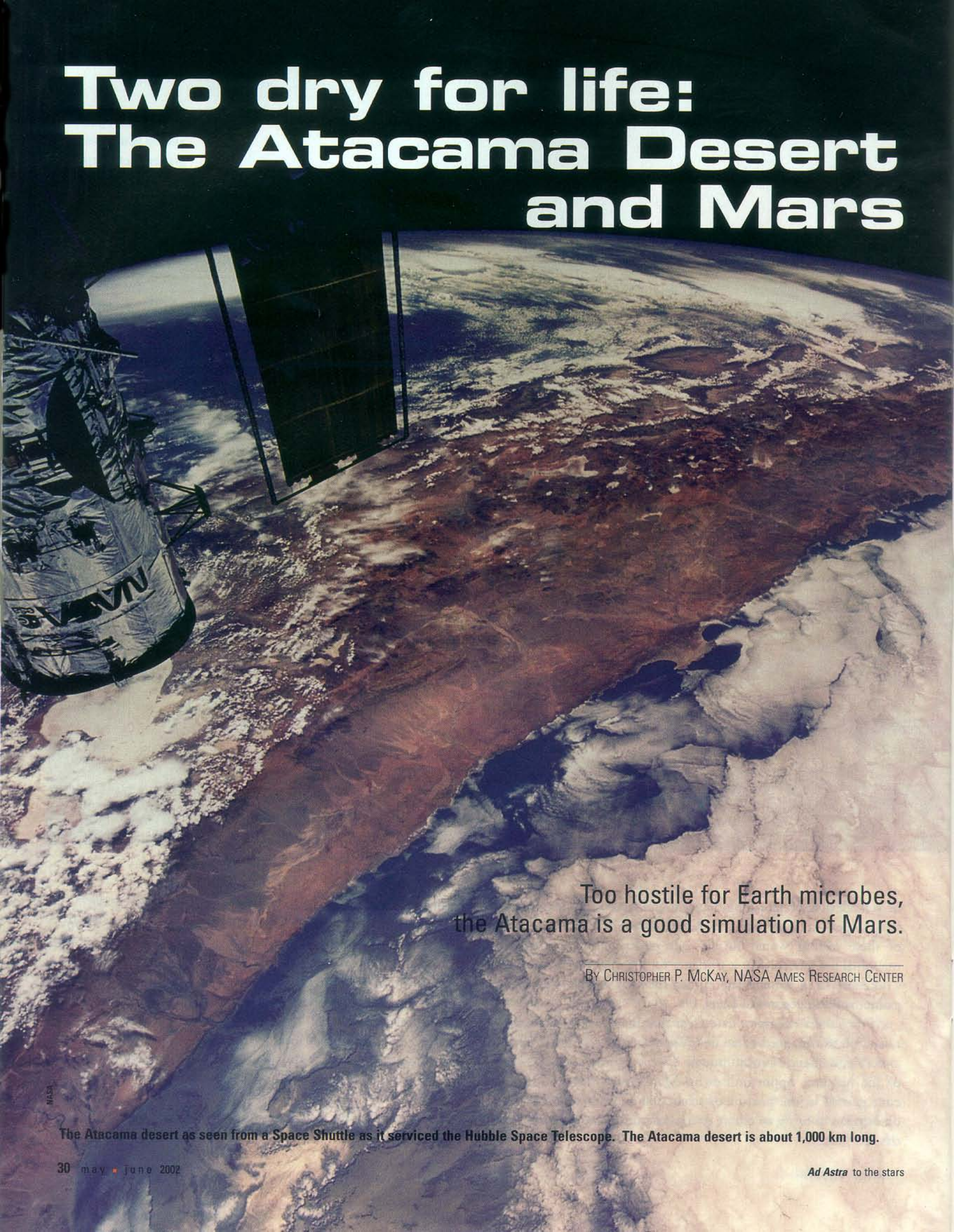
Two dry for life: The Atacama Desert and Mars



Too hostile for Earth microbes, the Atacama is a good simulation of Mars.

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The Atacama desert as seen from a Space Shuttle as it serviced the Hubble Space Telescope. The Atacama desert is about 1,000 km long.

There are stories of children living in the Atacama Desert reaching adulthood before ever seeing rain. Our measurements performed in this desert support these stories.

Over 5 years ago we installed an automatic environmental station in the extreme arid core of the Atacama, near an abandoned nitrate mine. In those five years we recorded only one rain. It was a miniscule 2 millimeters that fell near midnight. The rain was so slight that a standard weather station a few blocks from our instruments did not even record it. We recorded it because our station had several sensitive devices specifically designed to record low levels of moisture in deserts. Indeed our team has spent almost two decades studying life in deserts, both hot and cold.

Of all the deserts we have worked in, the Atacama is the driest. It is the only desert that we found to be too dry even for microbial life. It is, in microbiological terms, the most Mars-like environment on Earth.

The Dry Coast

The Atacama Desert is about 1000 km long extending from 30°S to 20°S along the Pacific coast of South America, but is only a few hundred kilometers wide. It sits between the towering Andes Mountains and the coast. The Atacama Desert owes its extreme aridity to a persistent climate pattern that is formed by the presence of the strong high-pressure center in the atmosphere over the Pacific Coast of South America and by a constant temperature inversion due to the cool north-flowing Humboldt ocean current.

The position of the Pacific high-pressure center is generally stable with a small shift of a few degrees south in the summer. The high-pressure center creates easterly trade winds (winds blowing from the east) which push ocean storms west, out to sea, and away from the South American coast. The high Andes to the east cut off any moisture that would come across from the Amazon basin.

Even though it is located in the tropics, the Atacama does not get extremely hot due to its proximity to the cool Pacific Ocean. The maximum temperature we recorded was 37°C. The Atacama is known as a temperate desert. Even though it is not extremely hot, it is probably the driest desert in the world.

The driest parts of the Atacama desert are located between approximately 22°S to 26°S in the broad valley formed by the coastal range and the medial range. Our main study site is located in this broad valley within the University of Antofagasta desert experimental station (24° 04' 50" S, 69° 55' 11" W, elev. 900 - 1000 m) near the abandoned nitrate mine of Yungay.

The surface is characterized by a dried soil surface with little moving sand and few stones. Drill cores show that the soil vertical profile is composed of broad alternate layers of sandy soil and impervious clay which inhibits vertical water diffusion. There is virtually no vegetation except at rare sites where the water table reaches the surface. Throughout the region the water table is typically at a depth of 25 meters or more. There are no permanent human settlements in the central desert near Yungay.

As Old as Dirt

Geological and soil mineralogical evidence suggests that extreme arid conditions have persisted in the southern Atacama for over 10 million years making it one of the oldest, if not the oldest desert on Earth.

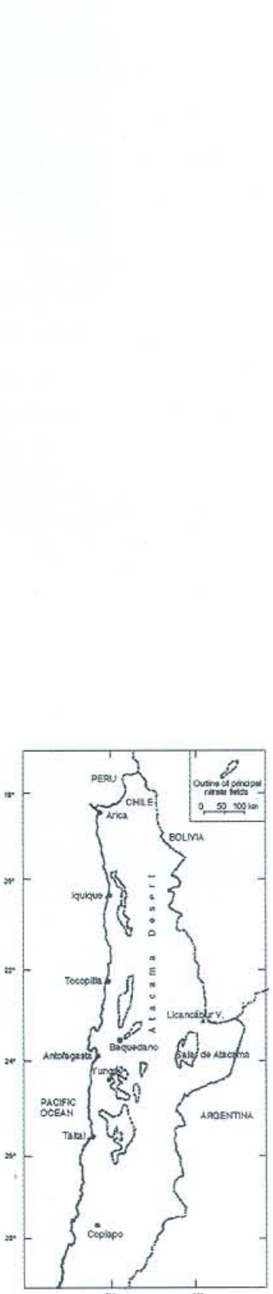
Life in the Dry

Any past or present life on Mars was probably microbial and it therefore makes sense to search for microbial ecosystems in Mars-like places on Earth. The basis of any ecosystem must be primary productivity. That is, some organisms must be capable of producing organic material from inorganic material. On Earth the dominant form of primary productivity is photosynthesis. For this reason our team has spent decades studying microbial photosynthesis in desert environments, by single-celled organisms known as cyanobacteria (also known as blue-green algae).

We have found that in many of the extremely arid deserts on Earth microbial photosynthesis occurs only under or within translucent stones. Porous sandstone is an example of a type of stone within which cyanobacteria can live. Light can penetrate into the sandstone and water can be held in the pores. Quartzite is the most common type of desert stone under which cyanobacteria can live. Light levels beneath the stones are sufficient to allow for photosynthesis and the stone apparently traps soil moisture. Both in the sandstone and under the quartzite the organisms find a habitable micro-environment—it is as if they are living in a little rock greenhouse.

We have not found any suitable sandstone in the Atacama but there are quartzite stones on the desert surface. In all the other deserts we have studied the underside of these quartzite stones are green with algae.

However, algae are not observed under the translucent stones that are present near our study site



Chris McKay

Location of study site near Yungay, Chile, an abandoned nitrate mine, in the extremely arid region of the Atacama desert.

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in the core of the Atacama. We have observed these algae under quartzite stones along the coast at the same latitude, and at sites inland but further south in the wetter regions. Presumably, the extreme arid regions of the Atacama desert are too dry an environment to provide for such microorganisms.

Thus, the Atacama crosses the dryness threshold for life. Along the coast where fog is common—or in the south below the arid core—algae are present under stones. The desert in these regions still looks barren and lifeless, but closer examination shows that the algae are there. However, as one moves in toward the core of the desert and rain levels drop to a few millimeters a decade, the algae are no longer present: the limit of life has been reached and crossed. Without enough water there is no life, and we can see in the Atacama that not enough water is available.

The surface of the Atacama is characterized by a dried soil surface with little moving sand and few stones.

Unfortunately for those with thoughts of life on Mars, the arid core of the Atacama desert is much wetter than Mars today. As such, we conclude that the surface of Mars today is most likely as barren of microbial primary production as is the arid core of the Atacama. Mars would need to have water levels comparable to the coastal or southern parts of the Atacama for microbial photosynthesis to occur.

Sterile soils?

Without photosynthesis a true microbial ecosystem cannot be maintained. However, there might still be organisms in the soil. We expect that in the Atacama, like locations elsewhere on Earth, bacteria are falling down from the sky. Bacteria are so small that they can be carried by winds essentially everywhere across Earth. They are even landing on Earth's South Pole. As such, it might be possible that some sort of meager existence in the arid core of the Atacama is possible for a few hardy bacteria due to bacteria being carried in by the wind. Thus, we expected that we would see low levels of organic material and some soil bacteria in the desert soil. In most of the desert this is what we did see. However, in the most arid region (in the very core of the Atacama desert) we were surprised to find extremely low organic content—and virtually no bacteria in the soil samples.

We think this is another Mars-like threshold. To understand this, imagine moving east, in from the coast. The first threshold or challenge that life faces is the one in which the level of available water becomes too low to support microbial photosynthesis. The second threshold that is reached is (we think) a chemical one. At this point, the level of water activity is so low that photochemical oxidants produced by ultraviolet light can build up in the soil. These oxidants actively destroy bacteria. They literally sterilize the soil.

Everywhere on Earth these oxidants are being produced. But in all other locations water deactivates them and the production of organic matter by life overwhelms them. This is not the case in the driest place on Earth. Here, the conditions are finally lifeless—and dry enough that the oxidants can build up. Interestingly, this is exactly what we think has happened on Mars. And the buildup of oxidants on Mars is what is thought to have caused the activity seen in the Viking biology experiments.

Radiation resistant superbugs

The few bacteria that are found in the Atacama soils are subjected to dry conditions. To survive they must be able to recover from the stress produced by dehydration. Dehydration is known to cause damage to DNA. Interestingly, bacteria that can survive damage to their DNA due to dehydration can also survive damage to their DNA due to high levels of radiation. The ability of some organisms to survive high radiation and live, for example, inside nuclear reactors is a puzzle since there is no known natural environment on Earth that would select for organisms capable of enduring such high levels of radiation resistance. The correlation between dehydration resistance and radiation resistance has led to the suggestion that organisms have "learned" to survive dehydration in nature and that their resistance to radiation is a byproduct of an evolutionary adaptation to dehydration.

If radiation resistance does arise from dehydration resistance, then one might expect to find the most radiation resistant bacteria on Earth in the driest desert. With this in mind we have begun a program of characterizing the radiation resistance of the soil bacteria throughout the Atacama. Perhaps there we will find a superbug able to survive high levels of dryness and high levels of radiation: a candidate for the first Mars micro-astronaut.

Dry—even in El Niño

The climate throughout South America is affected by changes in rainfall due to El Niño. El Niño events can bring heavy rainfall to the deserts of Peru and stronger events can penetrate further inland and southward. Previous studies have shown that mud-flows and heavy rains during the 20th century at Antofagasta on the coast in Northern Chile are related to the occurrence of El Niño events. Thus, the effects of a strong El Niño event on the coast of South America do reach as far south as Antofagasta. We wondered if a strong El Niño could bring rain to the core region of the Atacama and we were fortunate to have our data include the period of the strongest recent El Niño, which spanned from April 1997 to mid-May 1998. Our results show that this El Niño did not cause rain at our study site even as its effects were being felt in the coast at the same latitude.

Nitrates on Earth and Mars

One of the most interesting features of the Atacama desert are the large accumulations of nitrate that are found there. In some locations the desert surface is composed of several meters of virtually pure nitrates. The Atacama is the only place on Earth that has such deposits. Accumulations of nitrates are unusual for two reasons. First nitrate is very soluble and is carried away by water. Secondly, microorganisms consume nitrate. Nitrate is second only to oxygen as a desirable compound for microorganisms to use to react with organic material.

There was enough nitrate in the Aatacama that in the early 1900s nitrate mining operations were conducted. Throughout the desert the top few meters of surface were literally stripped away. As the near surface supplies were exhausted and with the invention of the Haber-Bosch process for industrial production of ammonia, the Chilean nitrate mines were abandoned. Only one or two mines still operate in the northern Atacama today.

The age and aridity of the Atacama are probably directly responsible for the large nitrate accumulations that are present there. The nitrates are likely to be of atmospheric origin, being produced by natural electrical events such as lightning and aurora. The nitrates are not biologically decomposed or carried away by water flow—for the simple reason that there is so little water available to do so. As such, the Atacama's nitrate deposits have accumulated into significant concentrations over the long age of the desert.

Frost on Mars. There is water on Mars as shown by this Viking Lander 2 image taken at Utopia Planitia on May 18, 1979.

Three factors seem to be responsible for the nitrate deposits in the Atacama: extreme age, lack of water, and lack of microbial activity. All three were present on Mars. Thus, is it probable that early in Mars' history, as atmospheric processes such as lightning produced nitrate, nitrate sediments accumulated on the surface. As is the case the Atacama, the surface of Mars may be richly layered with nitrates. Confirming this supposition would be important for understanding the total planetary inventory and fate of nitrogen on Mars. If Mars does have large nitrate deposits this could be a useful resource for human exploration and for the re-creation of a biosphere on that planet via terraforming.

Nitrogen is a key element for life. Mars does not have enough of it in its atmosphere.

From here to Mars

Our studies in the Atacama are just in the beginning stages. In the years to come we will collect a more complete environmental dataset. We will conduct further biological studies, not only in the extreme arid core of the Atacama, but also along a line to the south where conditions become wetter—and then further along a line to the coast where fog becomes an important source of moisture.

As we move along these moisture gradients in the Atacama we move from conditions like Mars today to conditions that might have prevailed on Mars during a wetter, more hospitable, but still dry, phase.

In so doing, we cross the border from sterility to life. Studying this border here on Earth may help us to recognize this boundary when we cross it on Mars.

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