Studying modern microbial communities to understand life on early Earth

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This planet has never really belonged to us, it has always been a microbial world. Animals and plants originated and evolved in environments dominated by microorganisms, and hence, in close relation to them. To understand how microbial communities behave, their ecology and their metabolism, is to set the basis in understanding life on Earth; why life is the way we know it and see it.

2.5 billion years ago, the Earth was very different from how it is today. Life had already bloomed for around one billion years, but the atmosphere lacked oxygen and ecosystems were very different at the time. Ancient ecosystems were exclusively formed by microorganisms, all anaerobic, and they preferred different metabolic pathways from the ones that dominate today in the biosphere. You may have heard before that photosynthesis was invented by a group of ancient bacteria, the cyanobacteria. They enriched the atmosphere of our planet, bubble by bubble, with oxygen, thanks to their oxygenic photosynthetic activity. So, “forests” existed and dominated the Earth, but they were of microbial nature. What we most often miss to hear is that there is another type of photosynthesis seldom explained in text books. The anoxygenic photosynthesis occurs in several lines of anaerobic bacteria that are able to perceive different wavelengths to harvest light energy and fix carbon using hydrogen sulfide or other reduced compounds as electron donors instead of water, so that no oxygen is released. It was therefore assumed that the anoxygenic photosynthesis is an “ancient” metabolism that preceded the now dominant oxygenic photosynthesis. But is really this way?

Nowadays, there are still some ecosystems that are similar to the ones that once flourished in the Precambrian. These are called microbial mats and they are now restricted mostly to extreme environments, such as geothermal or hypersaline areas. Microbial mats are crowded communities of microorganisms that live tightly packed and organize themselves in layers generating different gradients (of oxygen, sulfur compounds, temperature, etc…). In ecosystems like these, where close interactions are obligatory due to the tight space in which they are confined, metabolic symbioses flourish. Could the first eukaryotic cell, which derived from a symbiotic consortium of bacteria and archaea, have originated in such an environment?

We focused our attention to the microbial mats that inhabit a shallow pond located in the Salar de Llamara (Atacama Desert, Chile). This very small pond harbors conspicuous microbial mats that are arranged along a steep vertical gradient spanning ca. 30 cm depth, with a chemocline at 25 cm, defined by oxygen, salinity and temperature gradients. Using the space-for-time substitution approach that is frequently used by ecologists, it is possible to propose that metabolic changes across the spatial anoxic-oxic gradient may mimic metabolic transitions in early Earth at the time when the great oxidation event happened. Our results suggest that the prevalence of the different carbon fixation pathways that exist have changed across time, supporting the idea that the Wood-Ljungdahl pathway is the more ancient one and dominated early microbial ecosystems before the Calvin cycle took over, making now RuBisCO the most abundant enzyme on this planet. We were also able to draw an early Earth scenario where anoxygenic and oxygenic photosynthesis might have evolved and expanded in parallel, hand in hand with aerobic respiration (Gutiérrez-Preciado *et al.*, 2018)

Microbial mats come in different flavors. In some cases, the cyanobacteria present in these type of communities can biomineralize calcium carbonates extracellularly and generate stromatolites. Fossil stromatolites are the earliest fossil evidence of life in Earth, some are dated back to more than 3 billion years old. Our group has studied the stromatolites from the alkaline lake Alchichica in Puebla, México, and discovered a cyanobacterium, *Gloeomargarita lithophora* that is unique in its ability to precipitate carbonates intracellularly (Couradeau *et al.*, 2012). But this cyanobacterium hid other surprises: reconstructing its phylogeny, thanks to its complete genome sequence, showed that *Gloeomargarita* is the closest known species to the plastids of algae and plants, challenging the accepted view that the endosymbiosis that gave rise to the first photosynthetic eukaryotes occurred in a marine environment (Ponce-Toledo *et al.*, 2017)

Our lab is also focused in understanding the limits of life by studying an ecosystem where many extreme environments converge: extreme acidity, salinity and temperatures can all be found in Dallol in Ethiopia. We know microbial life can thrive in extreme environments, for instance, they have very efficient mechanisms to pump protons out of their cells, keeping inside a neutral pH while swimming in extreme acidic environments. Salty environments pose osmotic problems to all cells and can lead to protein aggregation, so halophiles cope with this by accumulating osmoprotectant compounds in the cytoplasm. Temperature can be extreme in both ends of the range permissive to life. Psychrophilic microbes deal with cold temperatures by producing their own antifreeze proteins and modifying their membrane lipids. On the other hand, thermophiles encode heat-shock chaperones that keep constant care of the correct folding of their proteins as well as modifying certain residues in most of their proteins to synthesize a heat-resistant proteome. But are microbes capable of coping with all these stresses simultaneously?

By studying all these microbial ecosystems in our lab we aim to get clues in understanding how life on early Earth evolved and thrived. Which were the metabolisms present in the microorganisms that lived 2.5 billion years ago? How did they evolve? How did they change our planet? How do modern microbes cope with stresses in extreme environments? What are the strategies they employ for adaptation? How a unique ancestral symbiosis between archaea and bacteria gave rise to eukaryotes? How plastids evolved in eukaryotes, giving them the gift of autotrophy? And so much more questions that remain open…

Further Reading:

Couradeau E, Benzerara K, Gérard E, Moreira D, Bernard S, Gordon EBJ, *et al.* (2012). An Early-Branching Microbialite Cyanobacterium Forms Intracellular Carbonates. *Science (80-)* **336**: 459–463.

Gutiérrez-Preciado A, Saghaï A, Moreira D, Zivanovic Y, Deschamps P, López-García P. (2018). Functional shifts in microbial mats recapitulate early Earth metabolic transitions. *Nat Ecol Evol*. e-pub ahead of print, doi: 10.1038/s41559-018-0683-3.

Ponce-Toledo RI, Deschamps P, Lopez-Garcia P, Zivanovic Y, Benzerara K, Moreira D. (2017). An Early-Branching Freshwater Cyanobacterium at the Origin of Plastids. *Curr Biol* **27**: 386–391.