The genetics of temperature adaptation: How does life thrive in extreme conditions?

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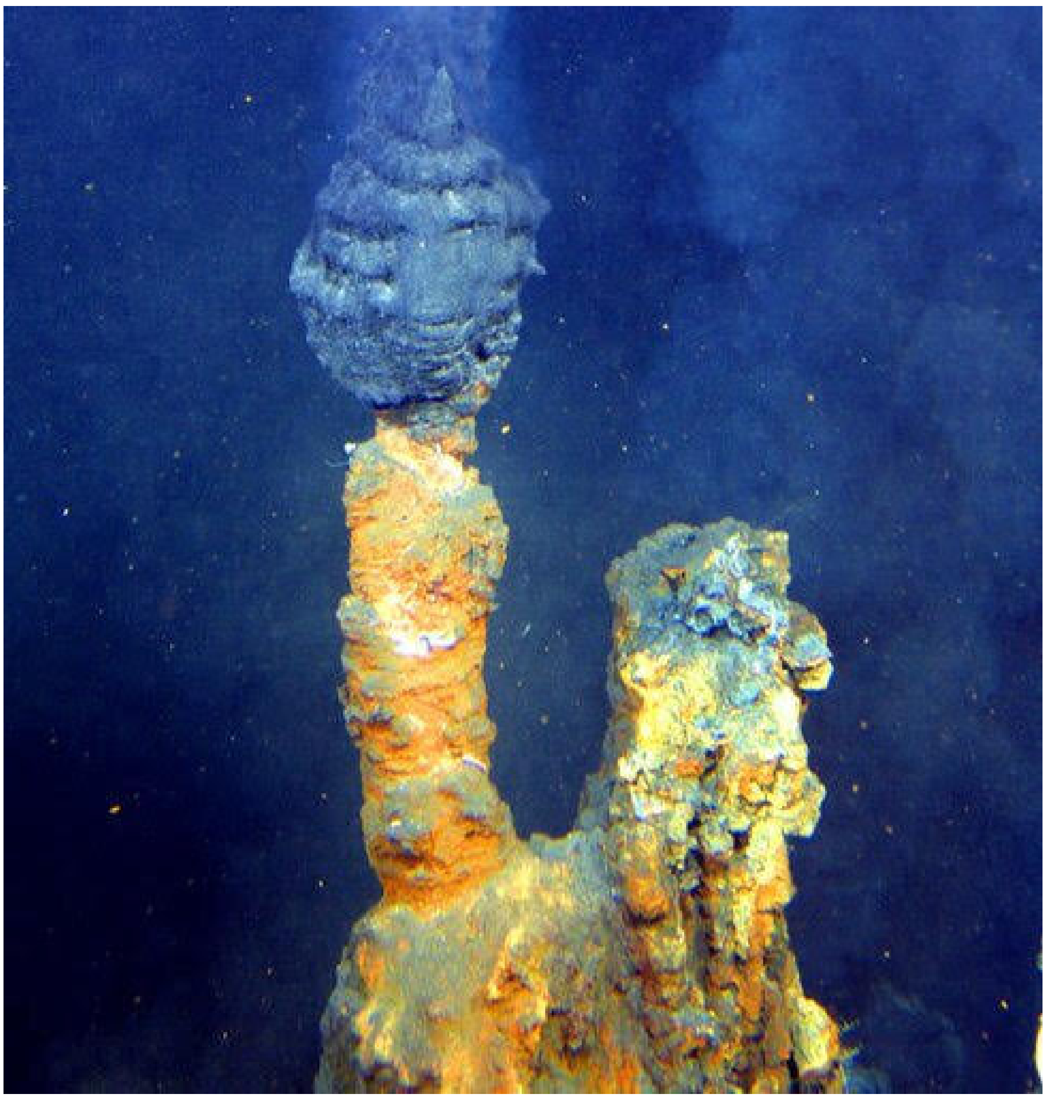


The most heat-tolerant methanogens were found at a deep-sea hydrothermal vent site. Credit: NOAA

The history of the Earth has been one of physical extremes—extreme atmospheric conditions, extreme chemical environments, and extreme temperatures. There was a time when the Earth was so hot all the water was vapor, and the first rain only fell once the planet cooled enough. Soon after, life emerged and through it all, life has found a way.

Today life is found almost everywhere on Earth we have looked; it is difficult to find places where life does not exist. The remarkable ability of life to adapt to variable conditions is one of its defining characteristics. Of its many adaptations, the ability of life to adapt to varying temperatures is one of the most interesting. All of life relies on chemical reactions, which are by nature sensitive to temperature. And yet, life exists across a spectrum of temperatures, from the Antarctic ice shelf to the edges of submarine volcanoes. This begs the question, how does life adapt to different temperatures?

To attempt to unravel this mystery, a research team, led by Paula Prondzinsky and Shawn Erin McGlynn of the Earth-Life Science Institute (ELSI) at Tokyo Institute of Technology, recently investigated a group of organisms called methanogens.

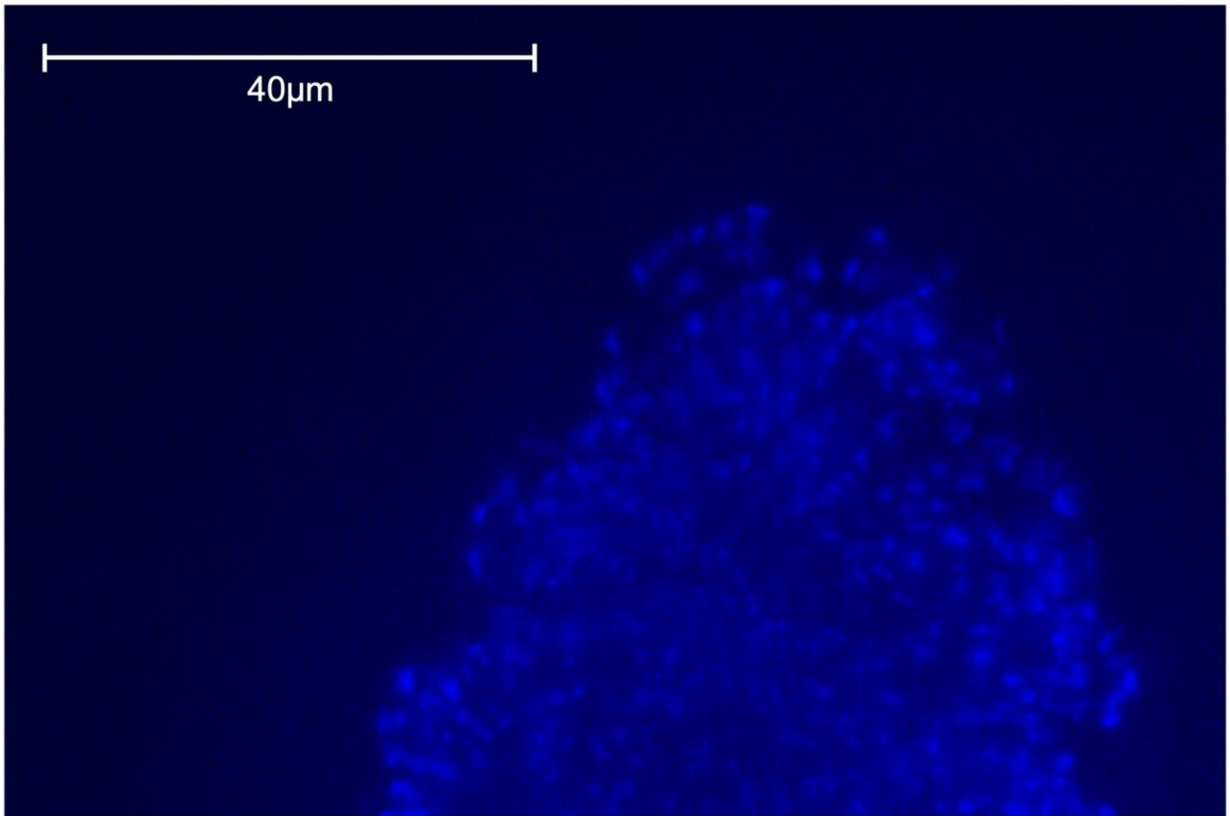
Methanogens are methane-producing, single-celled microorganisms that belong to a larger domain of "Archaea" (ancient, single-celled organisms that do not have cell nuclei and are thought to have been the predecessor to Eukaryotic cells). As a single physiological group, methanogens can thrive across a range of temperature extremes, from -2.5 degrees C to 122 degrees C, making them ideal candidates to study temperature adaptation.

In this work, the researchers analyzed and compared the genomes of different species of methanogens. They divided the methanogens into three groups based on the temperatures they thrived in—thermotolerant (high temperatures), psychrotolerant (low temperatures), and mesophilic (ambient temperatures). They then constructed a database of 255 genomes and protein sequences from a resource called the Genome Taxonomy Database. Next they obtained temperature data for 86 methanogens which are in laboratory collections from the Database of Growth TEMPeratures of Usual and Rare Prokaryotes. The result was a database which linked genome content to growth temperature.

After that, the researchers used a software called OrthoFinder to establish different orthogroups—sets of genes descended from a single gene present in the last common ancestor of the species under consideration. They then segregated these orthogroups into 1) core (present in over 95% of the species), 2) shared (present in at least two species but in less than 95% of the organisms), and 3) unique (present only in a single species). Their analyses revealed that about one third of the methaogenic genome is shared across all species. They also found that the amount of shared genes between species decreases with increasing evolutionary distance.

Interestingly, the researchers found that thermotolerant organisms had smaller genomes and a higher fraction of core genome. These small genomes were also found to be more evolutionarily "ancient" than the genomes of psychrotolerant organisms. Since thermotolerant organisms were found in multiple groups, these findings indicate that the size of the genome is more reliant on temperature than on evolutionary history. They also suggest that as methanogen genomes evolved, they grew rather than shrank, which challenges the idea of thermoreductive genome evolution, i.e., that organisms remove genes from their genomes as they evolve into higher temperature locations.

The researchers' analyses also showed that methanogens grow across this wide range of temperatures without many special proteins. In fact, most of the proteins encoded by their genomes were similar. This led them to consider the possibility of cellular regulation or finer scale compositional adaptations as the root cause of temperature adaptation. To investigate this, they looked into the composition of amino acids—the building blocks of proteins—in the methanogens.



A 100x100 micrometer field of view of an aggregate of methane-producing microorganisms. Credit: Paula Prondzinsky

They found that specific amino acids were enriched in particular temperature groups. They also found compositional differences in the amino acids pertaining to their proteome charge, polarity, and unfolding entropy—all of which affect protein structure, and thereby its ability to function. In general, they found that thermotolerant methanogens have more charged amino acids and functional genes for ion transport, which are not present in psychrotolerants. Whereas psychrotolerants organisms are enriched in uncharged amino acids and proteins related to cellular structure and motility. However, the researchers could not pinpoint specific functions shared by all members of a temperature group, suggesting that temperature adaptation is a gradual process which occurs in fine steps rather than requiring large scale changes.

Altogether, "This indicates that the very first methanogens, which evolved at a time when the conditions on the Earth were hostile to life, may have been similar to the organisms we find on present day Earth," explains Paula Prondzinsky. "Our findings could point toward traits and functions present in the earliest microbes, and even hold clues as to whether microbial life originated in hot or cold environments. We could extend this knowledge to understand how life could adapt to other kinds of extreme conditions, not just temperature, and even unravel how life on other planets could evolve."

More information: Paula Prondzinsky et al, The methanogen core and pangenome: conservation and variability across biology's growth temperature extremes, *DNA Research* (2022). DOI: 10.1093/dnares/dsac048

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