Books & arts

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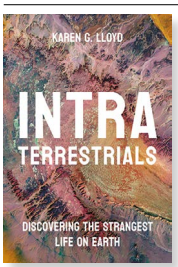
The crater lake at the Poás volcano, Costa Rica, harbours microbial life despite being highly acidic.

The extreme microbes that redefine the limits of life

An adventurous survey of inhospitable habitats unearths extraordinary organisms that pose challenging research questions. **By Andreas Teske**

Is there such a thing as a 'beach read on microbial thermodynamics'? That was how Karen Lloyd, the author of *Intraterrestrials,* informally billed her book when talking to her friends in science (including myself) — and at a beach-bag-friendly 200 pages or so, this lively and compulsively engaging book is an unusual page-turner. Lloyd, a geomicrobiologist, expertly guides readers who have a taste for biological adventures to 'intraterrestrial' life: microorganisms that survive under the most extreme environmental conditions, such as in Earth's deep sediments, deep ocean crust, volcanoes and permafrost soil.

The encounters include microbes that have never been cultured before, or that can live on extremely limited energy supplies, or that persist in states of suspended animation, their biological functions slowed or paused for thousands of years. The intraterrestrials in the title echo the extraterrestrials that might populate other planets and moons. But there's no need to search far for alien-like life: surprising microbes thrive here on Earth.



Intraterrestrials: Discovering the Strangest Life on Earth
Karen G. Lloyd
Princeton University Press (2025)

Lloyd reports on this research frontier and its big-picture implications from a front-row seat, as a seasoned geomicrobiologist who has made major contributions to the unfolding story of intraterrestrials.

Far-flung places

Sampling and studying these microorganisms is difficult — and sometimes dangerous. Dealing with the challenges and keeping reasonably safe requires teamwork, portrayed

here with the right balance of light-hearted banter and ominous foreboding. Lloyd brings the reader along as she collects gas-rich sediments and microbial mats aboard a deep-sea submersible in the Gulf of Mexico; samples sulfurous gas fumaroles in Andean volcanoes; resurrects microbes by drilling Arctic permafrost soil on the Norwegian Arctic archipelago of Svalbard; and experiences hypothermia on a part of the North Carolina coast she thought she knew well.

In one colourful episode, Lloyd and her collaborators descend into the Poás Volcano in Costa Rica to sample microbes in its picturesque turquoise-green crater lake, hoping that the volcano will not erupt there and then (it did so 54 days later, the blink of an eye in geological time). Falling into or even touching the lake 'water' during sampling — while precariously standing on ground at a boot-melting 100 °C and leaning over with a syringe — is not advised: with a pH lower than 1, its concentrated mix of sulfuric and hydrochloric acid is acutely toxic. Lloyd's adventures are briskly paced and set the stage for tackling challenges such as the physiology of acid-adapted microbes and their mode of energy generation, which not only tolerates but often requires high acidity.

Probing the extremes

Largely out of sight, intraterrestrials have, over billions of years, diversified into a veritable forest of microbial evolutionary lineages that are gradually being explored and mapped. The principal tool for this is metagenomic analysis: sequencing DNA extracted from entire microbial communities, then sorting gazillions of gene snippets into reconstructed genomes and finally deciphering their enzymes and biochemical pathways to provide the metabolic blueprint of each organism's capabilities.

Having explained the modern genomic toolbox, Lloyd introduces some important research questions to do with intraterrestrials. For example, what does the extraordinarily slow life of many bacteria and archaea in the deep subsurface mean for their capacity to evolve? They still have to divide and replicate their genomes but they refuse to grow on short timescales, earning them the moniker chronophile (or even hyperchronophile). In contrast to some cultured, slow-growing archaea, populations of which double over weeks and months, and laboratory strains of *Escherichia coli* that can double every 20 minutes, chronophiles would take hundreds or thousands of years to muster enough energy for cell division — making them tricky focal points for PhD projects and research grants.

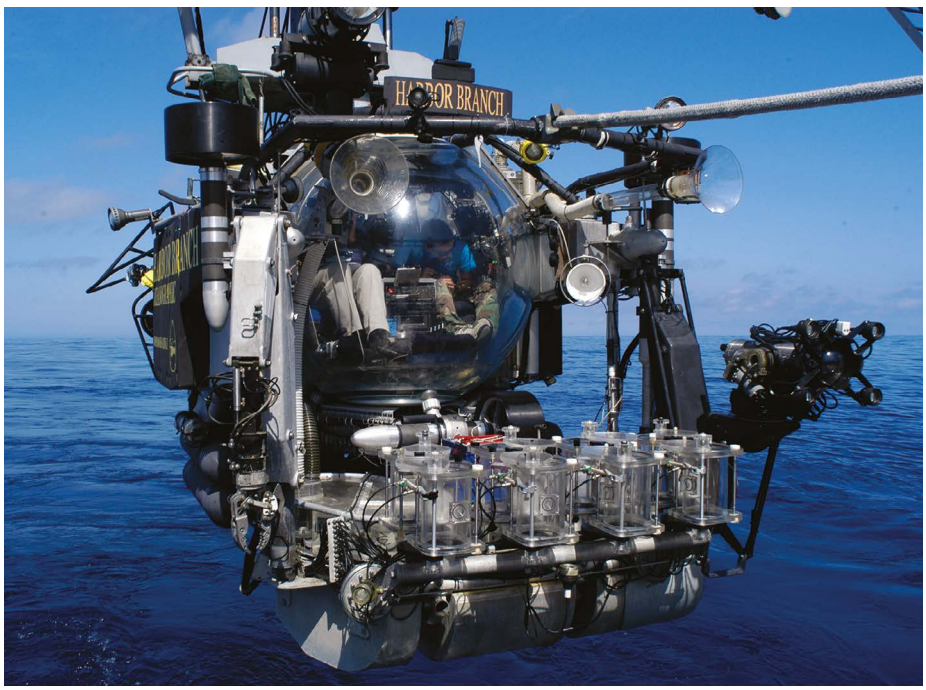
"This expands the range of potential habitats for microbes, perhaps even beyond Earth."

In exploring these questions, the book transports the reader into challenging scientific territory, from the steep canyons of thermodynamics to the labyrinthine pathways of biochemistry. But the tour is sure-footed: the research trails are well marked, signposted in common terms and avoid undue simplification. Particularly interesting is the insight into how microbes survive by using chemical reactions that yield the bare minimum of energy required to support a cell, and how estimates of these minima have been revised downwards, to far below what had been considered possible on the basis of lab studies. Implicitly, this expands the range of potential habitats for microbes, perhaps even beyond Earth. And so the tour concludes by discussing the feasibility of microbial life in space, investigated, for example, by examining mineral signatures in Martian rocks and energy sources in the ice-covered oceans of Jupiter's moon Europa and Saturn's moon Enceladus.

Investigations invigorated

Although intraterrestrials have been studied for more than 30 years, the research detailed in this book stems mostly from three transformative initiatives. One was based at the Center for Dark Energy Biosphere Investigations (2009–19) at the University of Southern California in Los Angeles; and a second at the Research Center for Geomicrobiology (2007–17) at Aarhus University in Denmark. The third, launched in 2009, is the Deep Carbon Life initiative at the Deep Carbon Observatory, a global research programme that brings together geoscientists, chemists and microbiologists to develop an integrated view of the global carbon cycle beyond Earth's surface. Building on long-term efforts in scientific drilling by the International Ocean Discovery Program, these initiatives have brought researchers — and funding — together and made possible deep-sea drilling expeditions that have sparked fresh ideas in extreme microbiology (T. M. Hoehler and B. B. Jørgensen *Nature Rev. Microbiol.* **11**, 83–94; 2013).

Thanks to *Intraterrestrials*, the general reader can now peek into the work of this network of experts and hopefully leave with a changed perspective as regards microbial life on and within this planet, and of its antiquity, evolutionary pace, adaptability and extraordinary tenacity. Lloyd's book is required reading for anyone who is interested in how the microbial world and our home planet have shaped each other. If I could wish for something to make the book even more attractive, it would be illustrations that highlight important concepts and portray microorganisms and their habitats up close. Regardless, I would immediately recommend this eye-opening beach read to students. One must think of the next generation of extreme microbiologists, including those who might not even realize that they will be part of it — until they pick up a copy of *Intraterrestrials*.



Submersibles can sample life on the ocean floor.

DAVID SHALE/NPL

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The author declares competing interests; see go.nature.com/3stikmg for details.