Hydrothermal Vents

Mummy is boiling our water to make it safe, but weren't we told that microbes can live in boiling water?

Photo by Yan Krukau: https://www.pexels.com/photo/woman-stirring-dumplings-in-pan-6617530/

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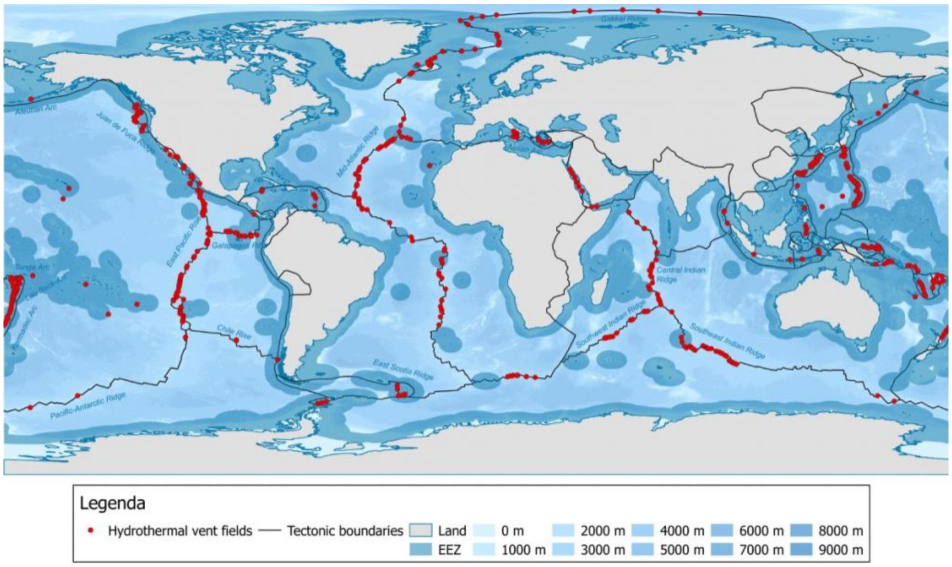
Storyline

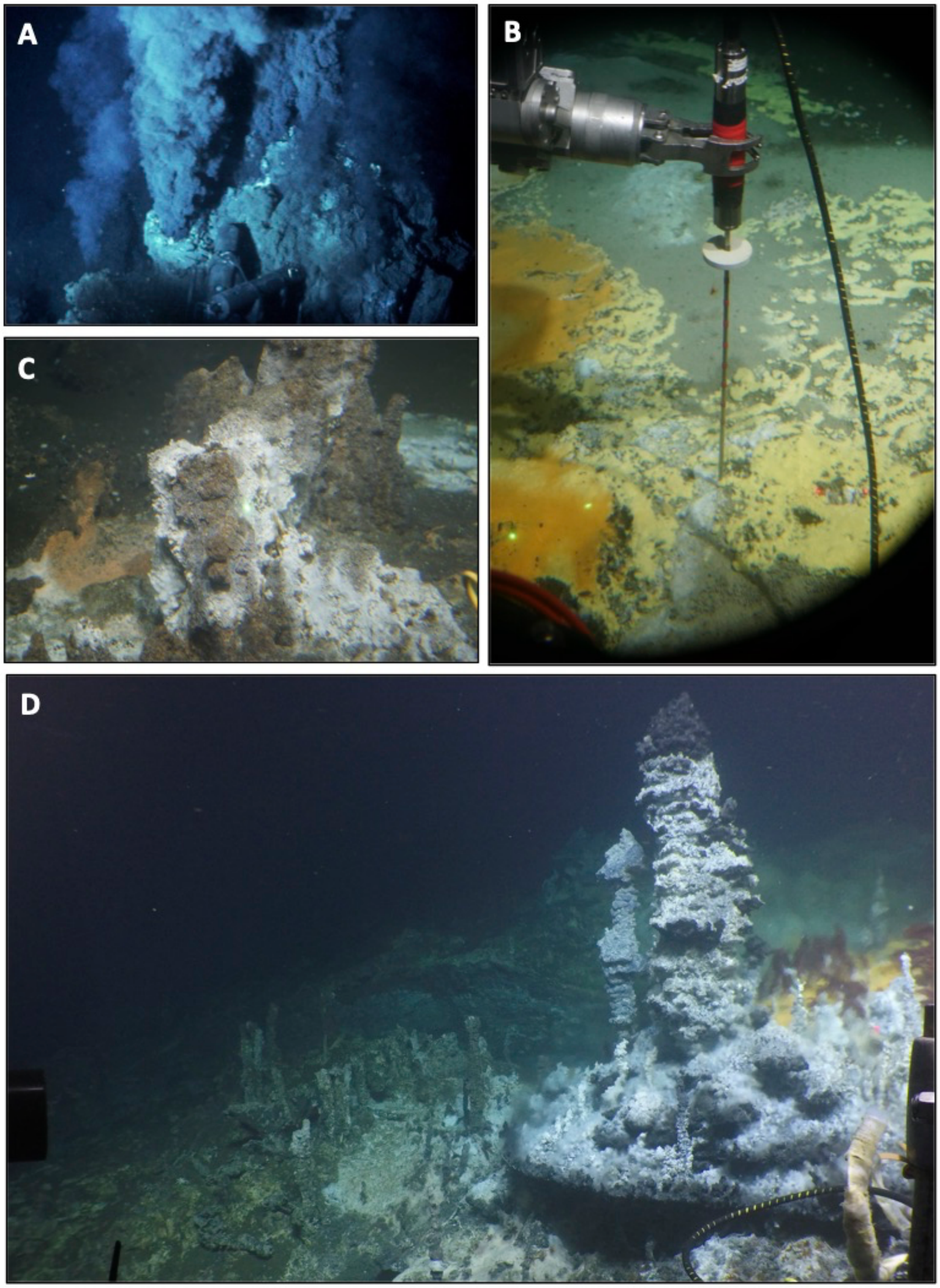
Yes, microbes can live in water that is near the boiling point at 100°C, or even hotter, in places called hydrothermal vents, which are essentially deep-sea hot springs. At deep-sea pressure, water heats up above 100°C and does not turn into vapor. Since the living conditions close to hydrothermal vents are extreme, the microorganisms that require or tolerate these conditions are also called extremophiles, or extreme-lovers. Some of the most extremophilic microorganisms on Earth have been found at hydrothermal vents, including new types of archaea that grow at temperatures up to 120°C. Hydrothermal vents also provide unusual chemical conditions that sustain microbial life, and many chemical compounds in hydrothermal vent fluids can sustain microbial life even in the absence of organic substrates. Hydrothermal vent ecosystems are based on microbes that utilize the chemical energy of hydrothermal vent fluids (chemosynthesis), not light energy that sustains plant life in the surface biosphere (photosynthesis).

Hydrothermal Vents: The Microbiology

1. What are hydrothermal vents? Through the middle of the Atlantic, Indian and Pacific Oceans runs a volcanic underwater mountain chain where the earth's ocean crust is splitting and hot magma from the Earth's interior rises towards the seafloor, fills the gap and creates new ocean crust. At many spreading center locations, seawater moves through deep cracks in ocean crust, is heated under high pressure, takes up numerous chemicals from the surrounding rock, and returns back to the seafloor forming deep-sea hot springs, called hydrothermal vents.



Global distribution of hydrothermal vent fields (red dots) at mid-ocean spreading centers where two oceanic plates separate in a tectonic boundary (black lines). From: https://opengeology.org/ textbook /4-igneous-processes-and-volcanoes/04-16_distribution_of_hydrothermal_vent_fields/



Hydrothermal vent landscapes. A) "black smoker" hydrothermal chimney emitting extremely hot, sulfide- and metal-rich vent fluid, at 9°N East Pacific Rise. B) Thermal measurement at microbial mat growing on hydrothermal sediments. C) Oil-soaked hydrothermal mound, and D) delicate hydrothermal mineral formations, all Guaymas Basin, Mexico. Photos by Alvin group, Woods Hole Oceanographic Institution.

Hydrothermal vent fluids are very hot (up to 400°C) and contain high concentrations of sulfide, heavy metals, and methane. While these chemicals are poisonous for people and most animals and microorganisms, special kinds of microorganisms are attracted to them and use them for chemical reactions that release energy and allow these microorganisms to thrive. In this way, chemical energy drives the microbial ecosystem and sustains chemosynthetic life at hydrothermal vents in the dark deep sea, in contrast to photosynthetic life in the surface biosphere that is ultimately sustained by light energy.

Many extremophilic and chemosynthetic microbes at hydrothermal vents are not bacteria, but belong to the archaea, a deeply rooted evolutionary branch of microscopic life that has evolved separately from the bacteria. Archaea share the small size and simple cell structure of bacteria, but based on the structure of basic genes and cell molecules they are more closely related to the eukaryotes, complex life forms with a nucleus and with intracellular organelles.

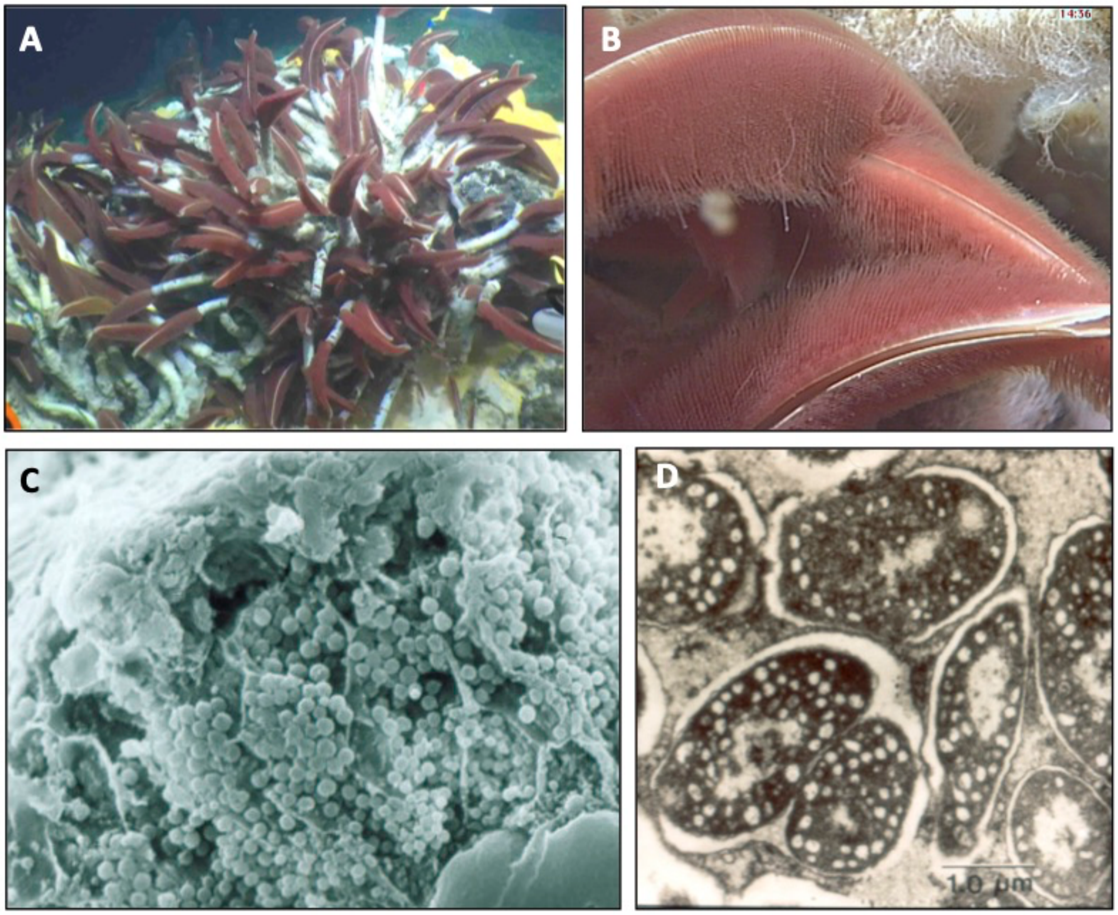
2. How do we access hydrothermal vents? Using a very small, tough submersible like *Alvin* that can carry passengers, or remotely controlled deep-sea robots with cameras. These vehicles must be able to withstand the enormous pressures of the deep sea, while recording environmental data and collecting samples. Due to the vastness and remoteness of the deep ocean, new hydrothermal vents are waiting to be discovered even today.

Deep-sea submersible Alvin. Top image, *Alvin* during recovery after a dive by its Mother ship *Atlantis*. Bottom, inside *Alvin*, with the pilot at the front porthole.

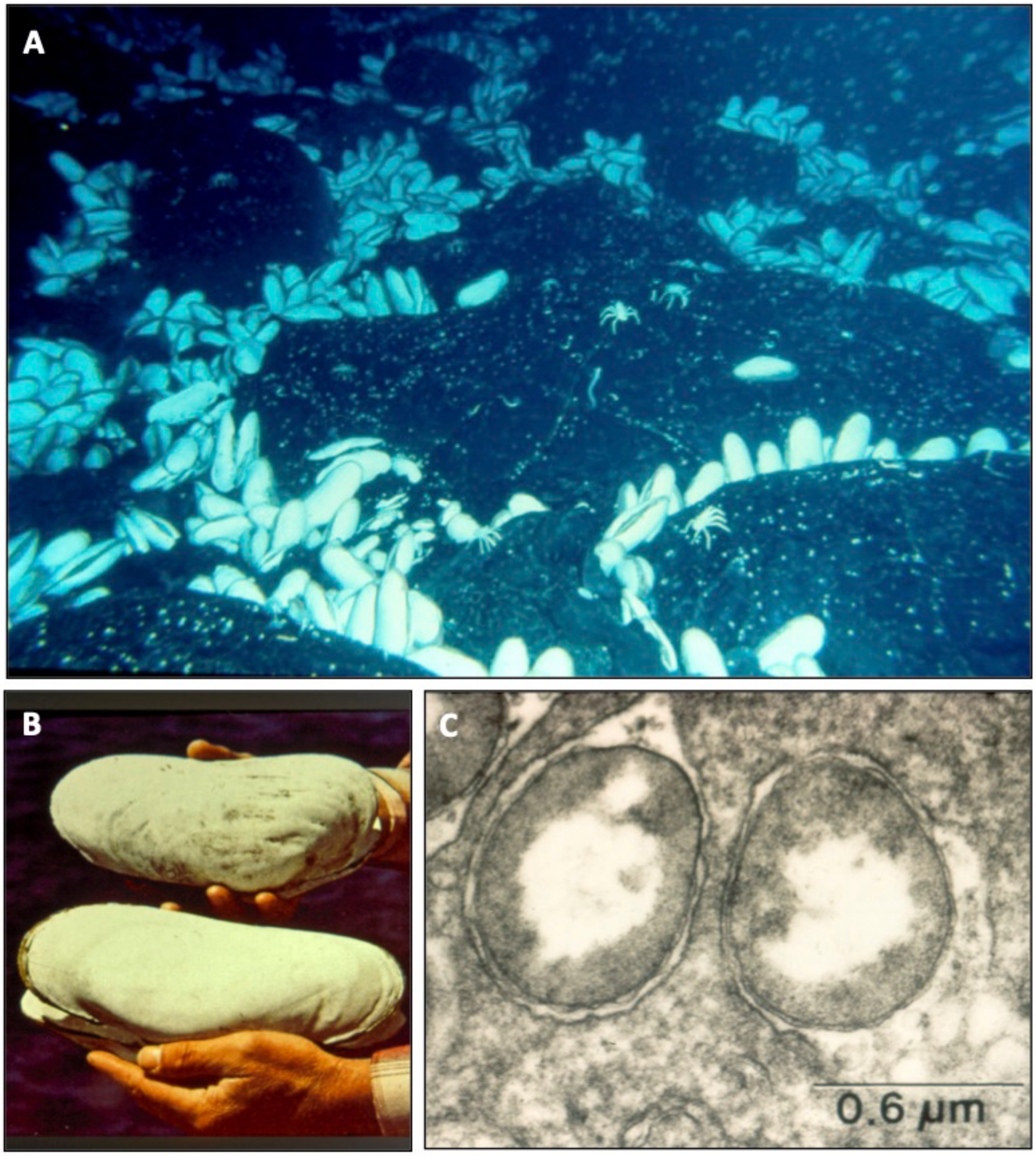
3. ***How do hydrothermal microbes grow?*** Many hydrothermal vent bacteria and archaea do not require common food sources, such as carbohydrates, proteins or fat, but they build up their cell biomass from carbon that occurs as CO_2, the gas carbon dioxide that is dissolved in seawater and in hydrothermal vent fluids. They share this capability with plants that perform photosynthesis and use light energy to turn CO_2 into biomass. There is no natural light at deep-sea hydrothermal vents, and therefore the bacteria and archaea that can turn CO_2 into biomass are driving this process by using the energy derived from chemical reactions with vent fluids, which contain energy-rich minerals, in a process called chemosynthesis. The detailed biochemical processes are very diverse, but the outcome is that hydrothermal vent ecosystems are sustained by microbial chemosynthesis, in contrast to the surface biosphere that is sustained by photosynthetic plants and algae that harness the energy of light to assimilate CO_2 from the atmosphere and to turn it into biological building blocks for cell growth and metabolism.

Since deep-sea hydrothermal vents and their life-supporting chemicals occur only in distinct and separate spots on mid-ocean ridges, abundant microbial and animal life at hydrothermal vents forms island ecosystems, which contrast with the sparse desert-like conditions of the deep sea that surrounds them. Interestingly, hydrothermal vent microbes are swept away and distributed by deep-sea ocean currents, so that newly emerging hydrothermal vents get quickly settled by newly arriving microbes, soon followed by drifting eggs and larvae of hydrothermal vent animals.

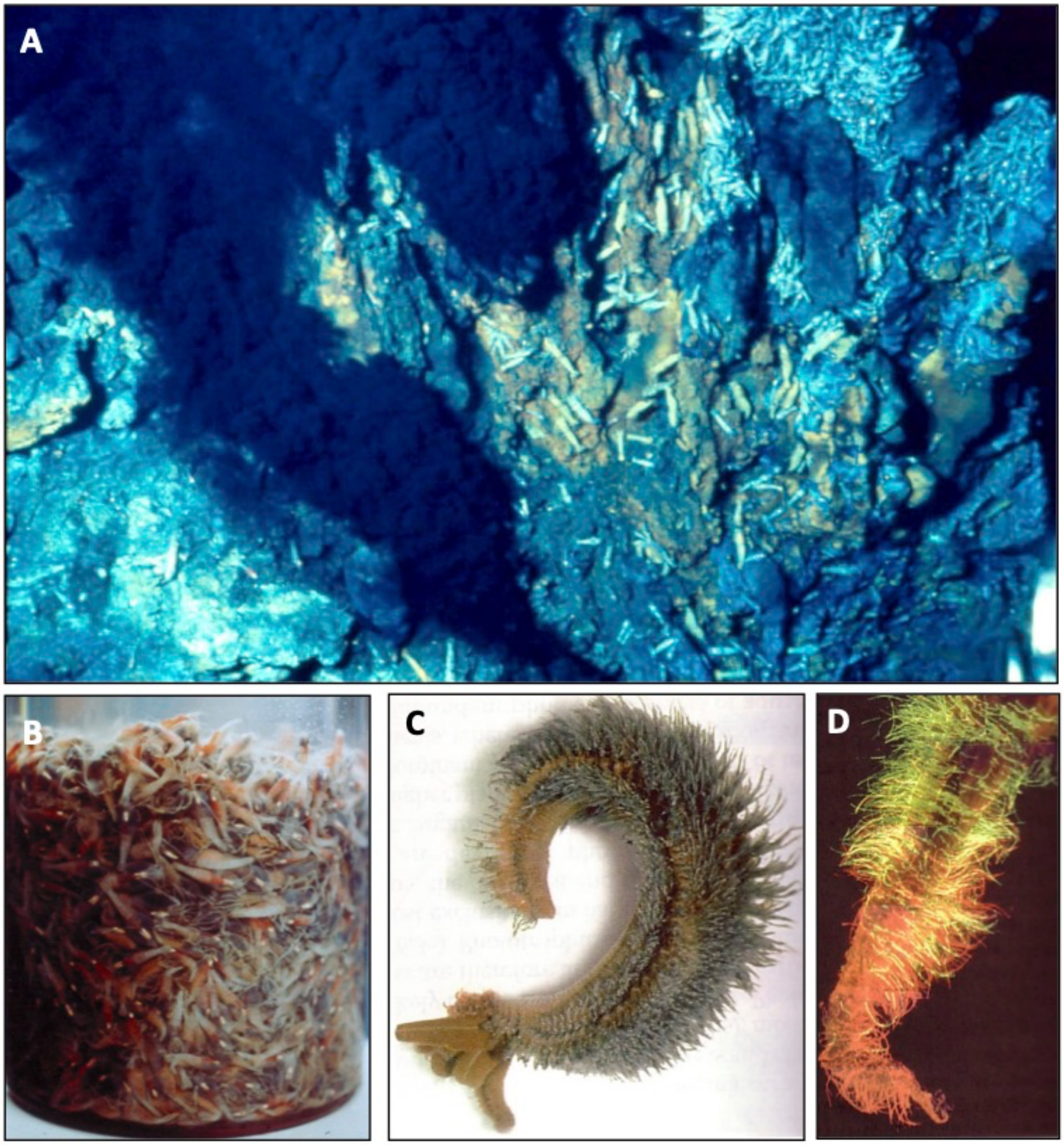
4. ***What does the hydrothermal vent ecosystem and microbial food web look like?*** Hydrothermal vents harbor not only unusual microbes but also unusual and abundant animal life, for example unique worms and mussels that live in symbiosis with bacteria inside their own bodies that obtain energy from toxic hydrothermal vent chemicals and grow enough bacterial biomass to sustain their host animals. (Symbiosis means two different animals or microbes living together and obtaining a mutual benefit that they would not have otherwise). Many hydrothermal vent animals, for example the tube worm *Riftia pachyptila* or the giant vent clam *Calyptogena magnifica* are so dependent on their internal symbiotic bacteria that they no longer have their own mouth or gut, and they would not survive without their symbionts that feed them. The symbiotic bacteria live only inside their hosts, and are inherited by the next generation through eggs or larvae, or acquired from small populations in the hydrothermal vent environment.



Riftia pachyptila, a large hydrothermal vent tube worm with chemosynthetic symbiotic bacteria. A) Colony of *Riftia pachyptila* tubeworms at the hydrothermal vents of Guaymas Basin, Mexico. B) The red gills of *Riftia* in closeup, where the worm is taking up hydrogen sulfide, oxygen and CO_2 (carbon dioxide). C) The bacteria-growing tissue in the body of *Riftia*, the trophosome with its fine network of blood vessels that supply hydrogen sulfide, oxygen and CO_2 to the symbionts. D) Bacterial cells surrounded by trophosome tissue. The white pearls are stored carbohydrates, synthesized by the chemosynthetic bacteria. Photos A and B by Alvin group, Woods Hole Oceanographic Institution; C and D, Holger Jannasch, Woods Hole Oceanographic Institution.



Calyptogena magnifica, a large hydrothermal vent clam with chemosynthetic bacterial symbionts. A) Clam field at hydrothermal vents of 21N East Pacific Rise; here the clams occupy fissures in seafloor lava where diluted vent fluid, mixed with seawater, emerges. B). Freshly collected *Calyptogena* clams in hand to show size. C) Sulfide-oxidizing bacterial symbionts growing in the gill tissue of *Calyptogena*. Photos by Holger Jannasch, Woods Hole Oceanographic Institution.



Hydrothermal fauna with external chemosynthetic bacterial symbionts. Many vent animals harbor chemosynthetic bacteria that grow on their body surfaces (epibionts), and provide a food source that supplements their nutrition as they graze on free-living bacterial biomass. A) The hydrothermal shrimp *Rimicaris exoculata* swarming around hot hydrothermal vents on the MID-Atlantic Ridge. B) Harvested vent shrimp in glass beaker. The chemosynthetic bacteria grow in the inside of the carapace and on the feeding appendages (mandibles). C) The vent worm *Alvinella pompeiana*, living on hydrothermal chimneys and burrowing into cracks in the hot hydrothermal rock. D) Each bristle on the worm's back is overgrown with filamentous bacteria, stained yellow and red. Photos A and B, by Holger Jannasch, Woods Hole Oceanographic Institution. Photos C and D, by Craig Cary, Waikato University, New Zealand.

5. ***Archaeal symbioses?*** New types of hydrothermal vent symbioses are still being discovered, and it seems very hard to find a hydrothermal vent animal that does NOT harbor some kind of bacterial symbionts. Since you are probably asking whether this is also true for archaea: hydrothermal vent archaea are not found living as symbionts. Their environmental preferences might be too extreme, to the point where animal life can no longer exist, neither with nor without symbionts.

6. ***Summary.*** The exploration of hydrothermal vents has greatly advanced knowledge on extremophilic microbial life and on unusual animal life that is uniquely adapted to the hydrothermal habitat and relies on microbial symbiosis to survive and to thrive. Since their discovery in 1977, hydrothermal vents are recognized as one of the most memorable sights on Earth, but since they are remotely located in the deep sea, they can only be visited by a deep-sea submersible. For this reason, only a small proportion of all globally existing hydrothermal vents have been explored in any detail, and new types of hydrothermal vents with new fauna and new microbial communities are waiting to be discovered (perhaps by you!).

The Evidence Base, Further Reading and Teaching Aids

Concise video on hydrothermal vents, covers all the essentials, and provides good visuals (even red-hot lava flashing as it emerges in the deep-sea):
https://oceantoday.noaa.gov/underwatervolcanoes/

"The Adventures of Zach and Molly", by Jim Toomey, award winning cartoonist of 'Sherman's Lagoon', an educational cartoon series that promotes ocean education and ocean literacy. Best for grade school. https://ecogig.org/zackandmolly

The frame grabber system of deep-sea submersible *Alvin*, accessible for everyone, provides a clickable photo tour of *Alvin* dives since 1988, with one photo every 30 seconds. The image recordings are not edited or filtered and therefore provide authentic *Alvin* geek fare, but you have to search for the gems among humdrum footage of underwater experiments and laborious sample collections. Image quality improves in recent *Alvin* dives, especially since 2014.
http://4dgeo.whoi.edu/alvin

Oceanographer and vent researcher Susan Humphris introduces hydrothermal vents for a general audience: https://www.whoi.edu/multimedia/hydrothermal-vents/

Schmidt Ocean Institute provides high-resolution curated deep-sea images from ROV expeditions around the world, has themed expedition records archived, and provides real-time links to ongoing expeditions on R/V *Falkor*. https://schmidtocean.org

The Ocean Exploration Trust provides high-resolution curated deep-sea footage from ROV expeditions around the world, has an archive of themed video collections (in my opinion, by far the best in existence), and provides real-time links to ongoing expeditions on R/V

Nautilus. (https://nautiluslive.org/expedition). Excellent vent footage can be found (for example) in the 2017 Gulf of California and Pescadero Basin expeditions, or the 2019 Gorda Ridge expedition.
Pick expeditions of interest on the index site: https://nautiluslive.org/expedition-index

The online resource library of the National Geographic Society has a vent online module: https://www.nationalgeographic.org/activity/hydrothermal-vent-chemistry-life/?utm_source=BibblioRCM_Row

Cavanaugh, C.M., S.L. Gardiner, M.L. Jones, H.W. Jannasch, J.B. Waterbury. 1981. Prokaryotic Cells in the Hydrothermal Vent Tube Worm Riftia pachyptila Jones: Possible Chemoautotrophic Symbionts. Science. 213:340-342. doi: 10.1126/science.213.4505.340. (*the discovery of hydrothermal vent symbiosis between bacteria and invertebrate*)

Corliss, J.B., J. Dymond, L.I. Gordon, J.M. Edmond, R.P. Von Herzen, R.D. Ballard, K. Green, D. Williams, A. Bainbridge, K. Crane, and T. Van Andel. 1979. Submarine Thermal Springs on the Galapagos Rift. Science 203:1073-1083. Doi: 10.1126/science.203.4385.1073 (*the discovery of hydrothermal vents*)

Devey, C.W., C. F. Fisher, and S. Scott. 2007. Responsible science at hydrothermal vents. Oceanography 20, 162-171. (*excellent general discussion of the environmental impacts of hydrothermal vent research*)

Dick, G.J. 2019. The microbiomes of deep-sea hydrothermal vents: distributed globally, shaped locally. Nature Reviews Microbiology **17**,271–283. https://doi.org/10.1038/s41579-019-0160-2 (*comprehensive up-to-date microbiology review*)

Dombrowski, N, A. Teske, and B.J. Baker. 2018. Expansive microbial metabolic versatility and biodiversity in dynamic Guaymas Basin hydrothermal sediments. Nature Communications 9: 4999. https://doi.org/10.1038/s41467-018-07418-0 PMID (*metagenomic analysis of microbially rich hydrothermal sediments*)

Dubilier, N., C. Bergin, and C. Lott. 2008. Symbiotic diversity in marine animals: the art of harnessing chemosynthesis. Nature Reviews Microbiology 6:725-740. (*Everything about microbial symbiosis in hydrothermal vents, cold hydrocarbon seeps, and many other ecosystems*)

Fisher, C., K. Takai, and N. Le Bris. 2007. Hydrothermal vent ecosystems. Oceanography 20, 14-23. (*good general introduction*)

Martin, W., J. Baross, D. Kelley, and M. Russell. 2008. Hydrothermal vents and the origin of life. Nature Reviews Microbiology **6**, 805–814. https://doi.org/10.1038/nrmicro1991 (*vent biochemistry and its potential for the origin of life*)

Glossary

Archaea. An evolutionary branch of microbial life that has evolved separately from the bacteria billions of years ago. Archaea have different cell membrane lipids, different ways to organize, store, copy and read their genomic DNA, distinct intracellular signaling pathways, and distinctly different ribosomes, the multienzyme complexes that translate genomic information into protein biosynthesis. Although Bacteria and Archaea have similar cell size (typically around 1 micrometer, 1/1000 of a millimeter) and cell structure (no nucleus, no organelles), Archaea are genetically and biochemically as different from bacteria as eukaryotes, the evolutionary branch of complex cells and multicellular life forms. Archaea contain many extremophiles which are adapted to extreme environmental conditions, for example extreme heat, pressure and toxic chemicals at hydrothermal vents.

Chemosynthesis. A microbial process where microorganisms use the chemical energy derived from the oxidation of hydrothermal vent gases (hydrogen sulfide, methane, hydrogen) to take up carbon dioxide (CO2) and to transform it into building blocks for producing biomass. In contrast to photosynthesis, chemosynthesis does not require light to provide the energy for carbon assimilation, and therefore provides the basis for ecosystems in dark environments, such as hydrothermal vents (at depths of typically 2500 m, light only reaches 100 or 200 m deep into the ocean).

Mid-ocean Spreading Center. The area where two oceanic plates split apart and magma moves up, filling the gap and slowly adding new ocean floor at a rate of a few centimeters per year. Hydrothermal vents occur specifically at spreading centers, as seawater percolates through the cracked rock, is heated to high temperature at the subsurface magmatic heat source, and rises back to the seafloor as hydrothermal fluid, highly enriched in minerals and gases leached from the subsurface rock and formed by high-pressure reactions with seawater salts. Mid-ocean spreading centers with hydrothermal vents extend around the globe and run through the central Atlantic, Indian, Pacific and Arctic Oceans. Starting from mid-ocean ridges, the spreading ocean crust ultimately collides with lighter continental crust, dives underneath (is subducted) and returns into the Earth's interior, which completes the plate tectonic cycle.

Smoker, or black smoker. A hydrothermal mineral formation, reminiscent of a chimney that emits dark smoke, formed by minerals that settle (technical term, precipitate) from hot hydrothermal fluids (up to 400°C hot) as these fluids emerge at the seafloor and encounter cold (2-3C) deep-sea water. The highly concentrated dissolved compounds, mostly metals and sulfide, cannot stay in solution when the temperature drops rapidly, and turn into solids instantly, forming and extending a metal sulfide chimney where hydrothermal fluids continues to rise within its central internal channel.

Sulfide, or more accurately hydrogen sulfide. Dominant sulfur compound (dissolved as S^{2-}, HS^-, or as the gas H_2S) in cold seep fluids, very toxic when inhaled but a favored energy source for many microorganisms, produced from elemental sulfur or seawater sulfate either geothermally or by microbial activity of sulfur- and sulfate-respiring microbes. The gas hydrogen sulfide (H_2S) has an unmistakable odor of rotten eggs or very ripe saltmarsh sediments; while it is certainly not suitable for classroom experiments, marine microbiologists regard it positively as an indicator for a thriving microbial ecosystem.

Symbiosis. The association of two different species for mutual benefit. In cold seeps, symbiosis appears in some of its most extreme and interesting forms, when a marine invertebrate (clams, mussels, diverse worms) harbors hydrocarbon-degrading bacteria in its own body tissues; for example, mussels and clams harbor these bacteria in the epithelial cells of their gills. The bacteria produce biomass that provide nutrition of the host animal, and the host provides a stable environment for the microbes, since it can adjust the supply of their carbon substrate (in most cases, methane) and oxygen.

Thermophiles. Microbes that are adapted to high temperatures, and metabolize and grow preferentially at high temperatures. Moderate thermophiles prefer 40-60°C, classic thermophiles 60-80°C, and extreme thermophiles above 80°C. The maximum temperature range of microbial life is 110-120°C, reached in laboratory tests by a few hydrothermal vent archaea. Physiologically, many thermophiles do not require oxygen and are averse to oxygen exposure, since oxygen does not stay dissolved in hot fluids. At room temperature (20-25°C) or under cold conditions, for example in deep sea water (2-4°C), thermophiles shut down their metabolism and, analogous to hibernation, are able to wait for days and weeks before they resume activity when the temperature increases. Note that the inverse does not work for cold-adapted microorganisms (called psychrophiles) since heat damages them irreversibly.