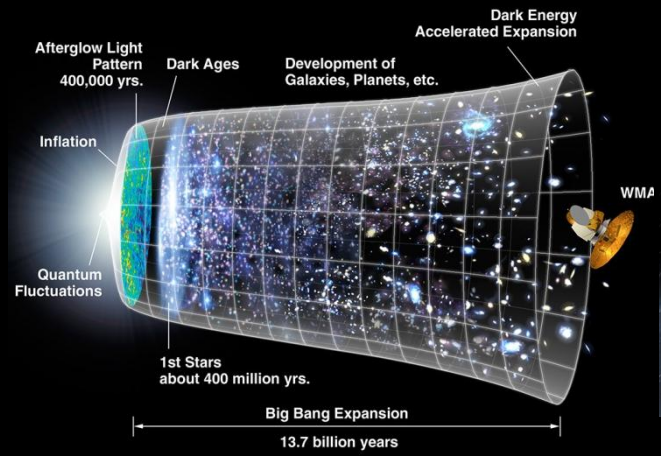
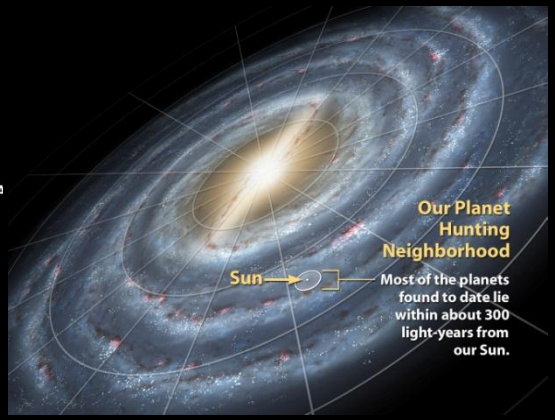
Life in Extreme Environments Applied to the Habitability of the Universe

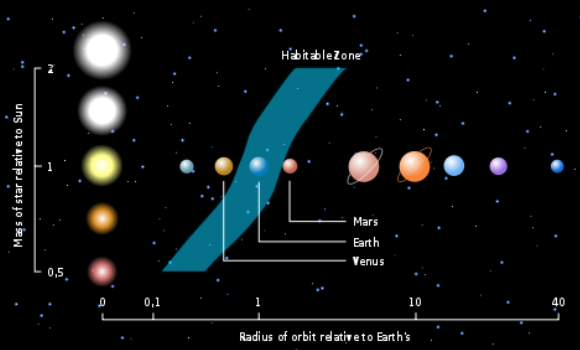
YILIANG LI, Assistant Professor of Astrobiology
Department of Earth Sciences, The University of Hong Kong. E-mail: yiliang@hku.hk

Habitability & Habitable Zone

- Some extended environments with liquid water, conditions favorable for the assembly of complex organic molecules, and energy sources to sustain (biological) metabolism.
- Earth is within the habitable zone of our solar system. The subsurface of Mars, the ocean of Europa are marginal.
- Our Solar system is within the habitable zone of Milky Way.
- The current universe is at a time-point with suitable physico-chemical conditions for life.







Time, Space and Increasing Complexity

Extremophiles & the Search for Extraterrestrial Life

- Extremophiles thrive in ice, boiling water, acid, the water core of nuclear reactors, salt crystals, and toxic waste and in a range of other extreme habitats that were previously thought to be inhospitable for life. Extremophiles include representatives of Bacteria, Archaea, and Eucarya; however, the majority are microorganisms. Knowledge of extremophile habitats expands the number and types of extraterrestrial locations that may be targeted for life detection.

Extreme environments

are hostile to human life and were thought to be uninhabitable by other organisms.

(Richard Johnson)

Extreme Environments

Deep Ocean

Atacama Desert, Chile

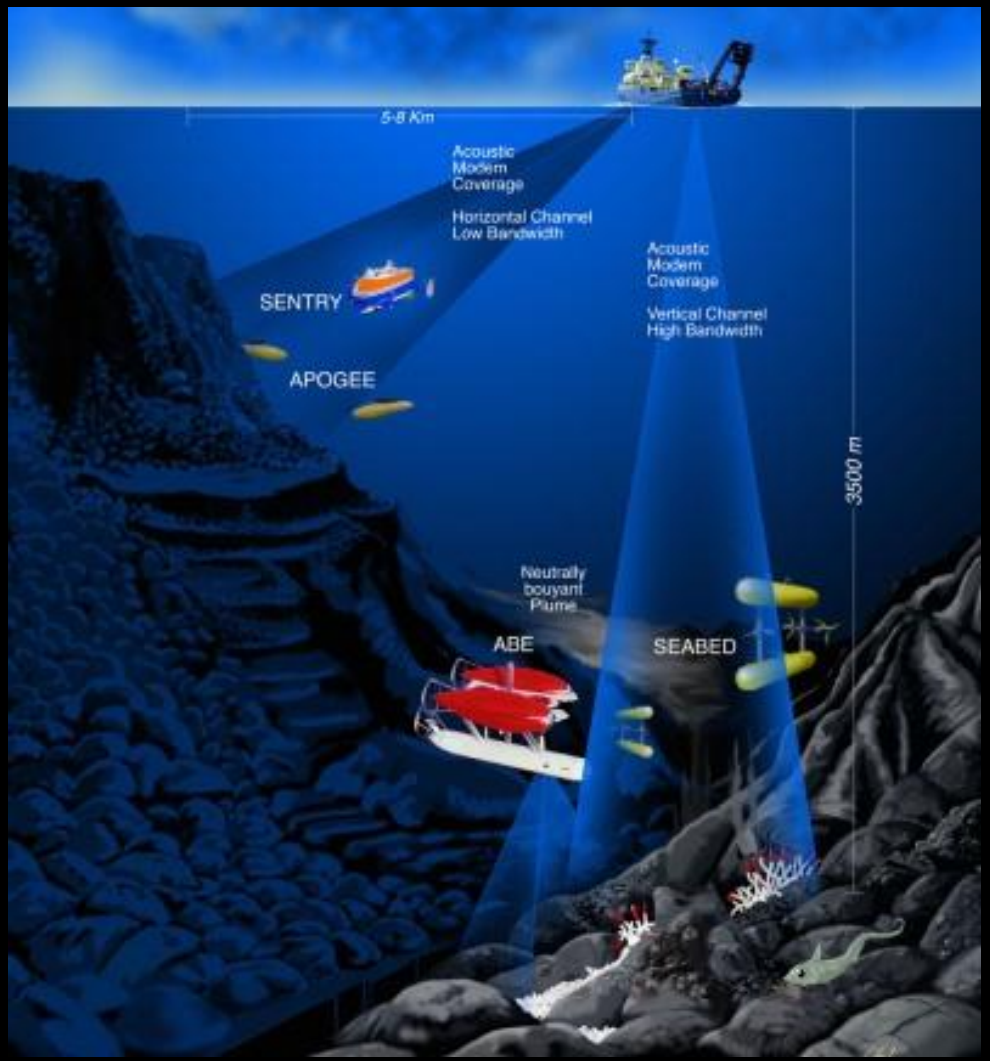
Permafrost Area

Grand Prismatic Spring (Yellowstone)

Acid Mine Drainage

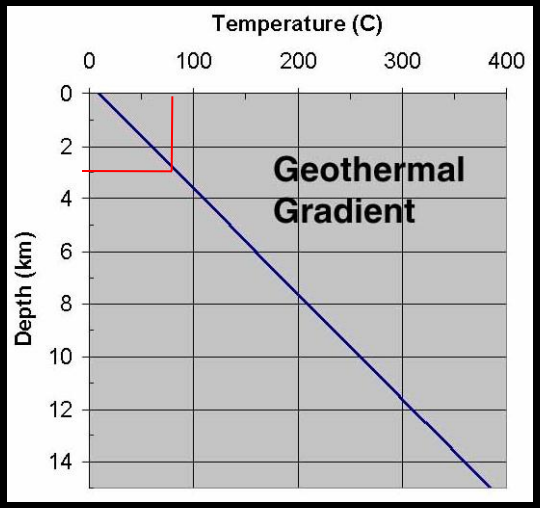
Salty Lake

Extreme Environments

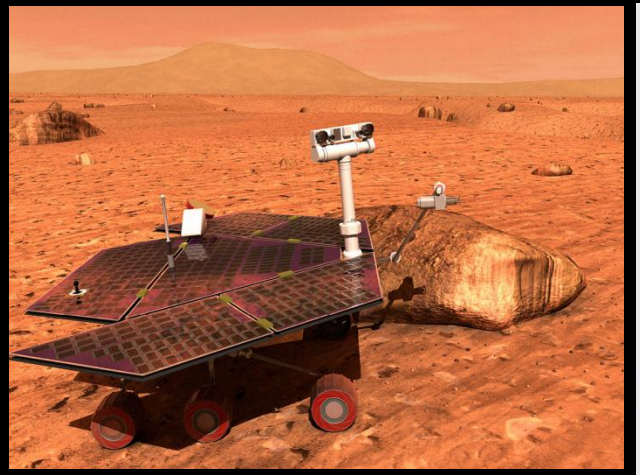


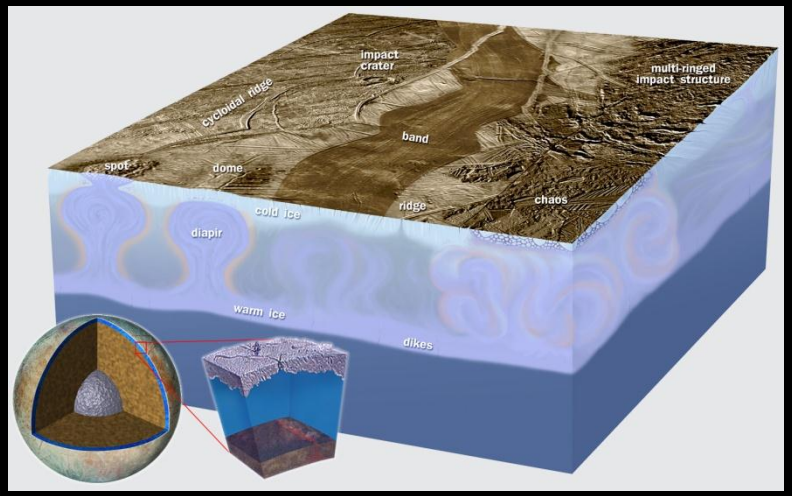
Deep Ocean with high P & low T

Gold mines 2 miles underground



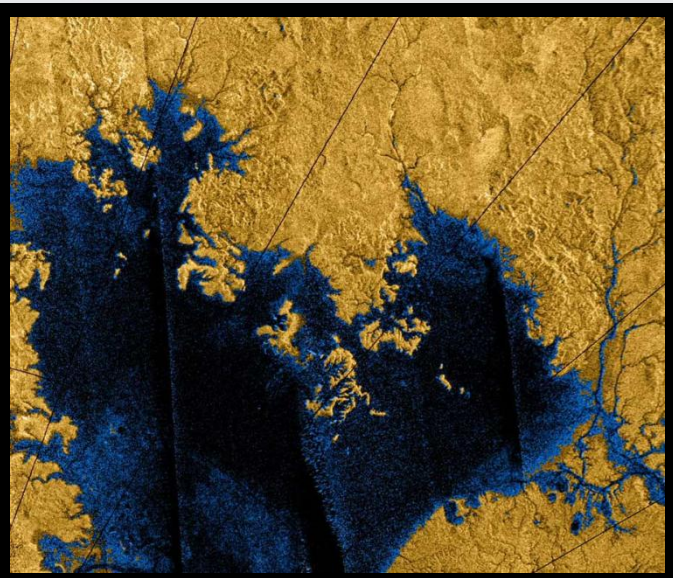
Extraterrestrial Environments Similar to Extreme Environments on Earth





120 km
Deep Ocean
Of Jupiter's
Europa

(Sub)surface of Mars



Pool of liquid organics on the surface of Saturn's Titan

Extreme Habitats are environments with a restricted species diversity and the absence of some taxonomic groups.

(Thomas D. Brock)

Extreme physico-chemical factors:

Temperature - high; low
Pressure - high
pH value – high (alkaline); low (acid)
Salinity (salt content) - high
Water activity - low
Ionizing radiation - high
Toxic substances - high conc.
Nutrients (carbon, other) - low conc.

Classes and examples of extremophiles

Extreme factor	Descriptive term	Genus/ species	Do-main	Habitat	Min.	Opt.	Max.
Temperature high	Hyperther-mophile	*Pyrolobus fumarii*	Archaea	Hot hydro-thermal vents	90°C	106 °C	113 °C
" "	Hyperther-mophile	strain 121	Archaea	Black Smoker	85 °C		121 °C
Temperature low	Psychro-phile	*Polaromonas vacuolata*	Bacteria	Sea ice	0 °C	4 °C	12 °C
pH low	Acidophile	*Picrophilus oshimae*	Archaea	Acidic hot spring	-0.06	0.7	4
pH high	Alkaliphile	*Natronobacterium gregoryi*	Archaea	Soda lakes	8.5	10	12
Pressure	Barophile	*Moritella yayanosii*	Bacteria	Ocean sediment	500 atm	700 atm	>1000 atm
Salt	Halophile	*Halobacterium salinarum*	Archaea	Salterns	15%	25%	32% (satura-tion)

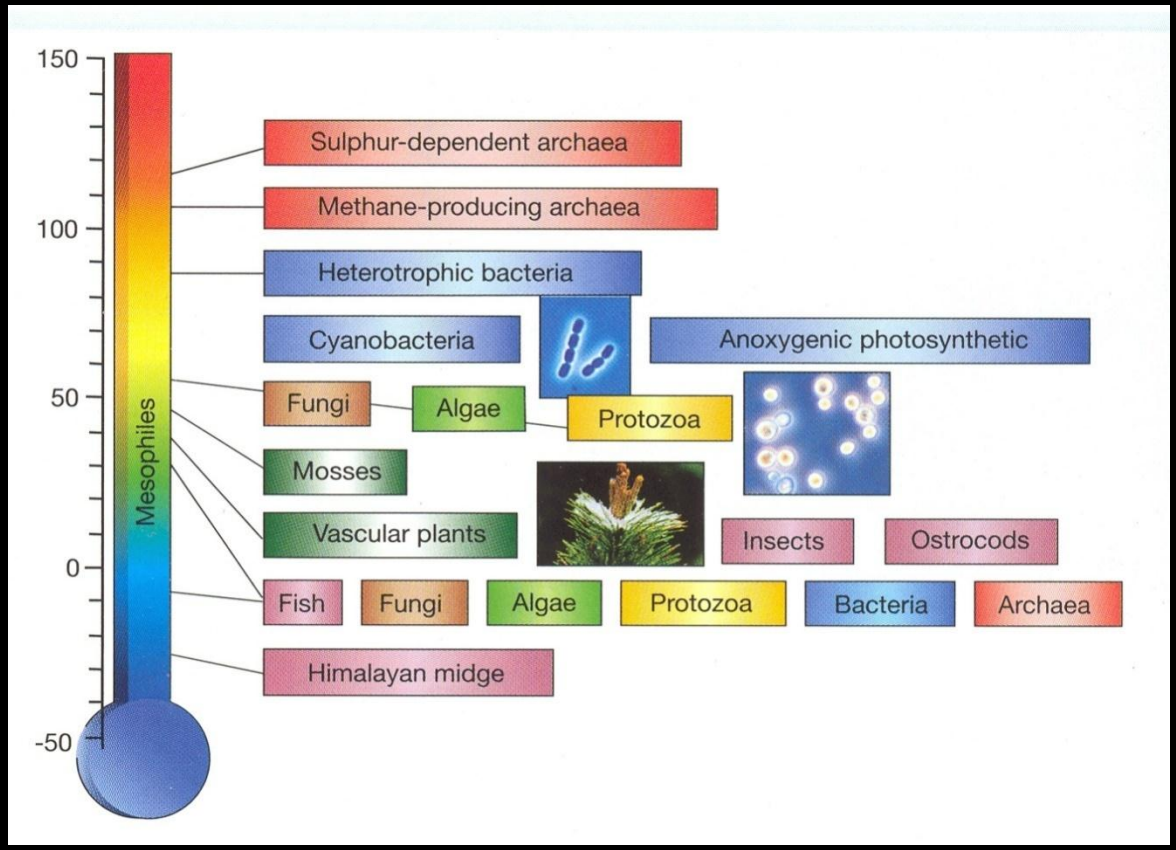
Survival of extreme conditions

Microorganism	physico-chemical parameter	time	other information
Deinococcus radiodurans	ionizing radiation		ca. 20.000 Gy
Streptococcus mitis	surface of the Moon	2.5 years	in a camera
numerous microorganisms	**-20°C**	ca. 10^6 years	Permafrost
numerous microorganisms*	**-193°C**	years	liquid N_2
numerous microorganisms*	$a_w < 0.75$	years	vacuum
Halococcus salifodinae	NaCl >30%	$>10^6$ years (?)	in salt crystals
endospores (*Bacillus, Clostridium*)	heat; chemicals	>3000y	mummies; sediments
endospores (*Bacillus*)	outer space	6 years	surface of space probe

* with protective substances (e.g. 25-40% glycerol)

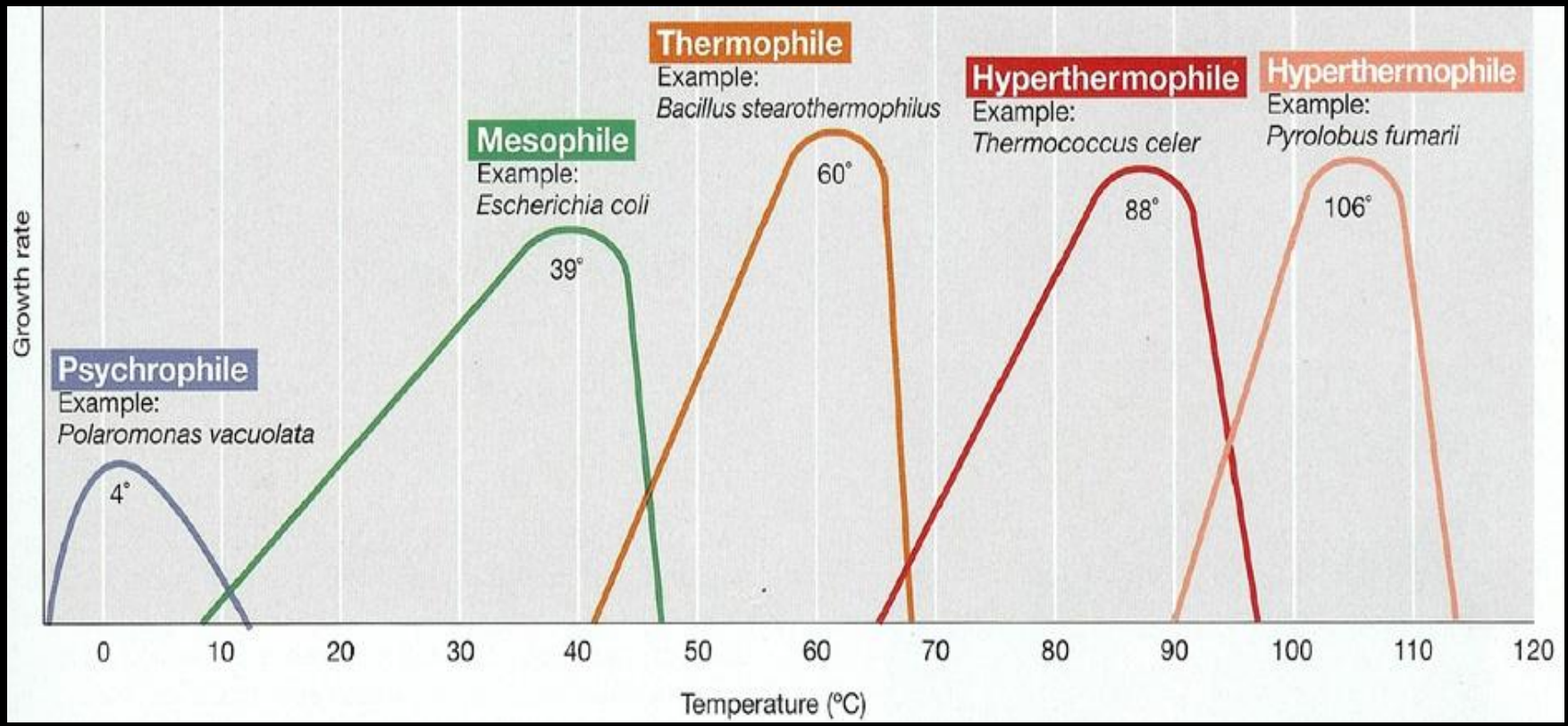
Temperature Limits for Life

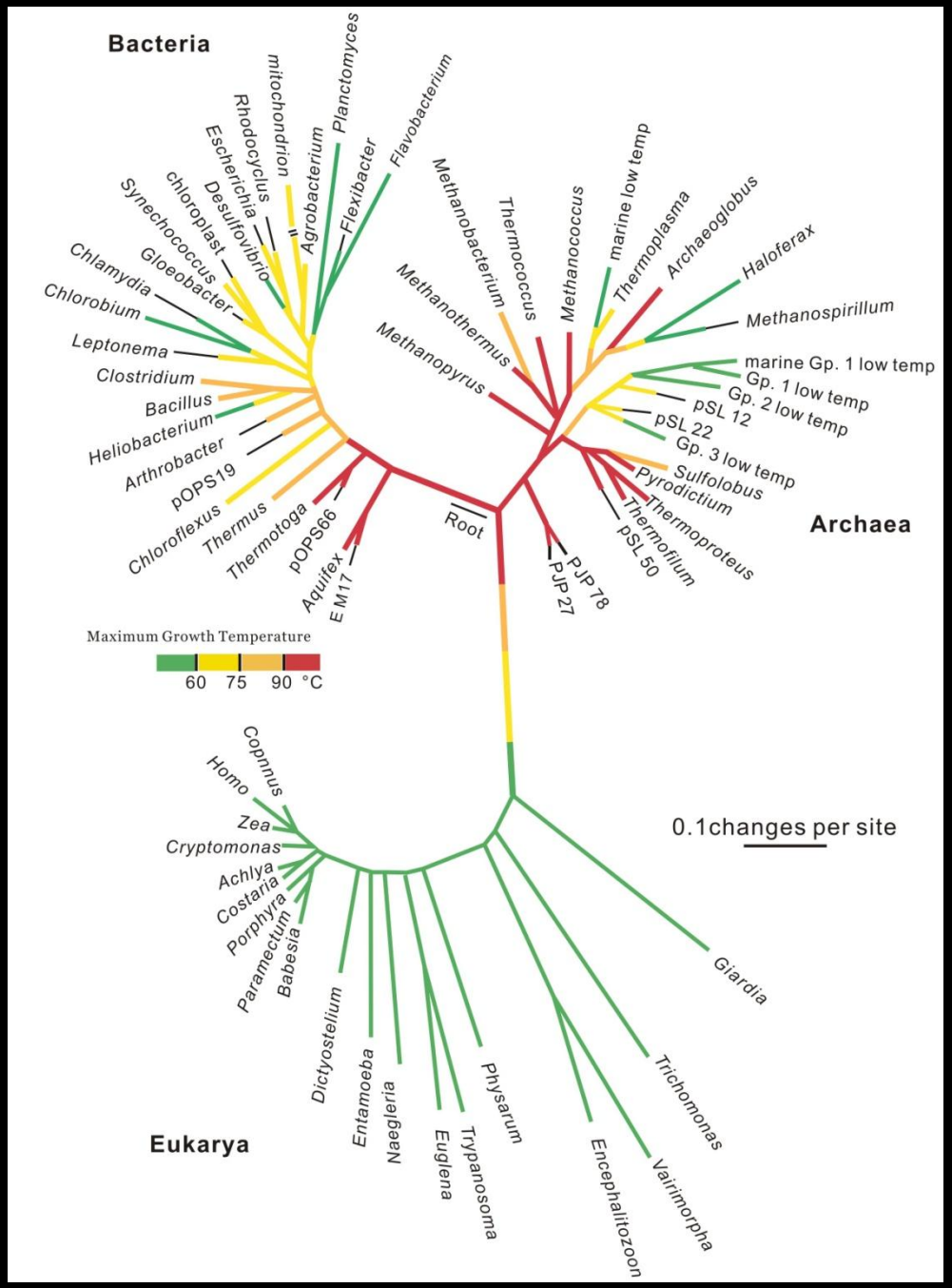
Rothschild & Mancinelli, 2001



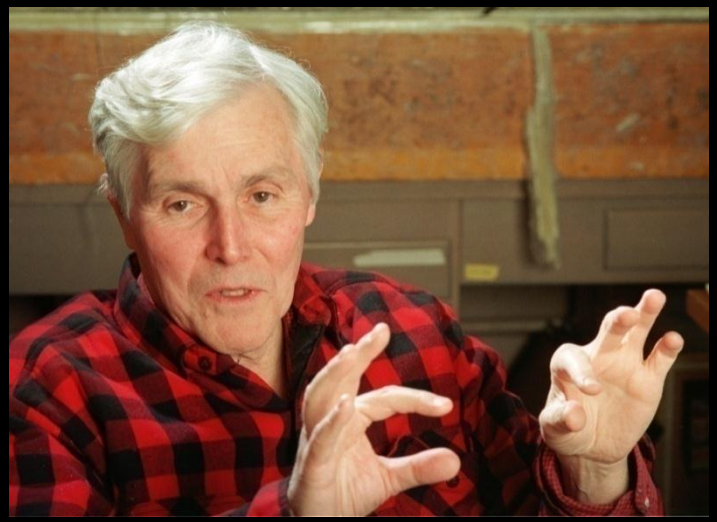
Archaea: red; Bacteria: blue; Algae: light green; Fungi: brown; Protozoa: yellow; Plants: dark green; Animal: purple.

Microorganisms in Different Temperature Domains

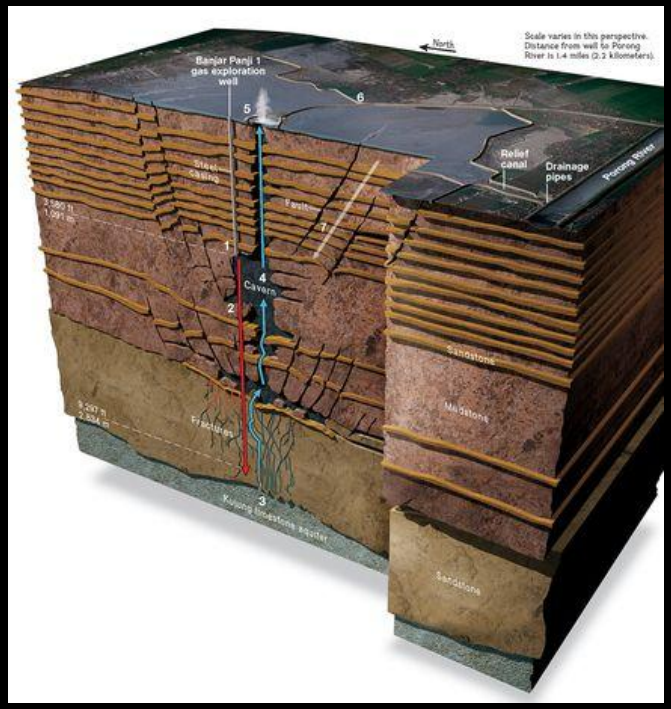


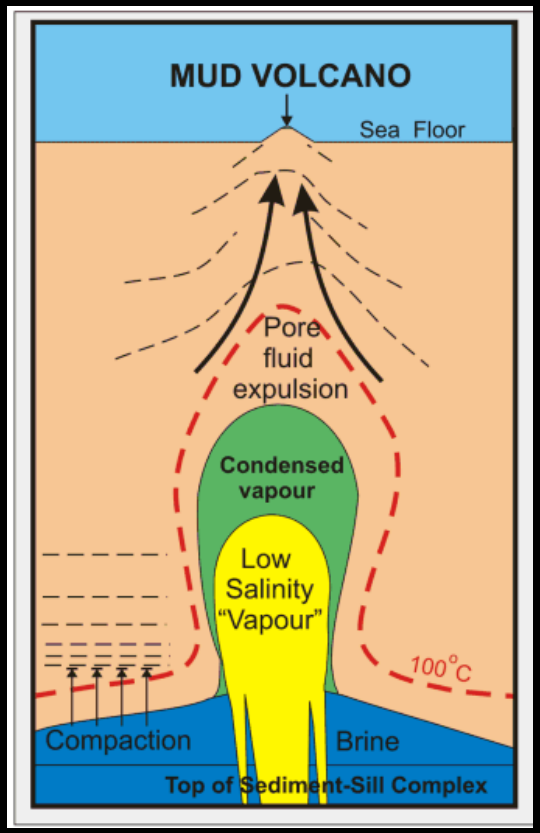


The earliest ocean was **hot**, therefore all the oldest lives were hyperthermophiles or thermophiles. **Many thermophiles discovered in modern biosphere are genetically close to the oldest life on Earth.**



Carl Woese, 1928-2012

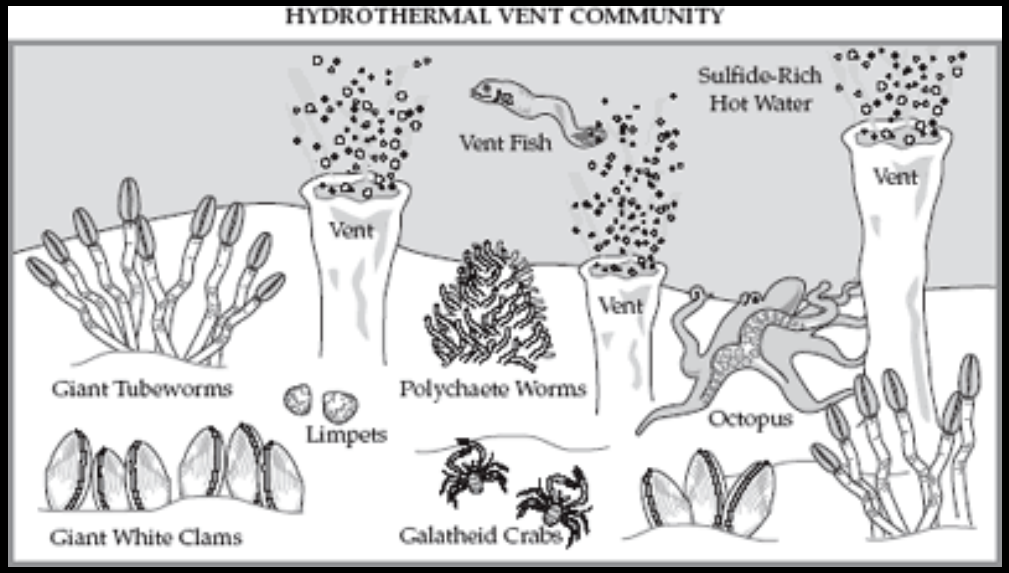




Lydon, 2004

Aerobic & anaerobic methanotrophic bacteria/archaea

Mud Volcano



Black smokers emitting sulfide- and mineral-rich water at temperatures of 350℃. The wall of the black smoker chimneys display a steep temperature gradient and contain several types of prokaryotes.

Black smokers and hydrothermal vents

Psychrophile: Cold-Adapted Life

- Vast deep ocean.
- Permafrost area.
- Surface of Mars?

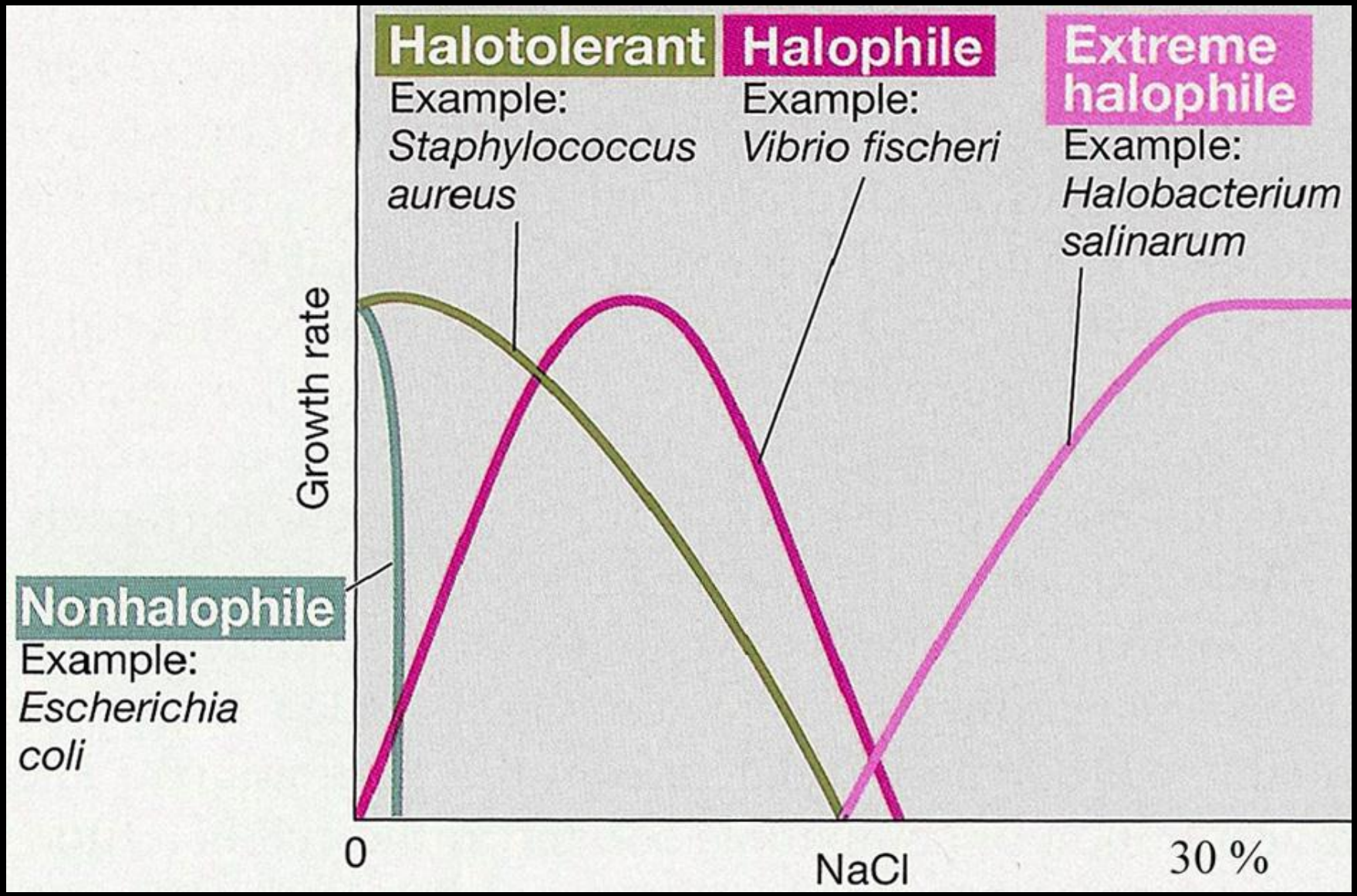
Courtesy: American Association for the Advancement of Science Presentation

Growth: OK @>20℃, best @ ca.15℃, survives T of 0℃.

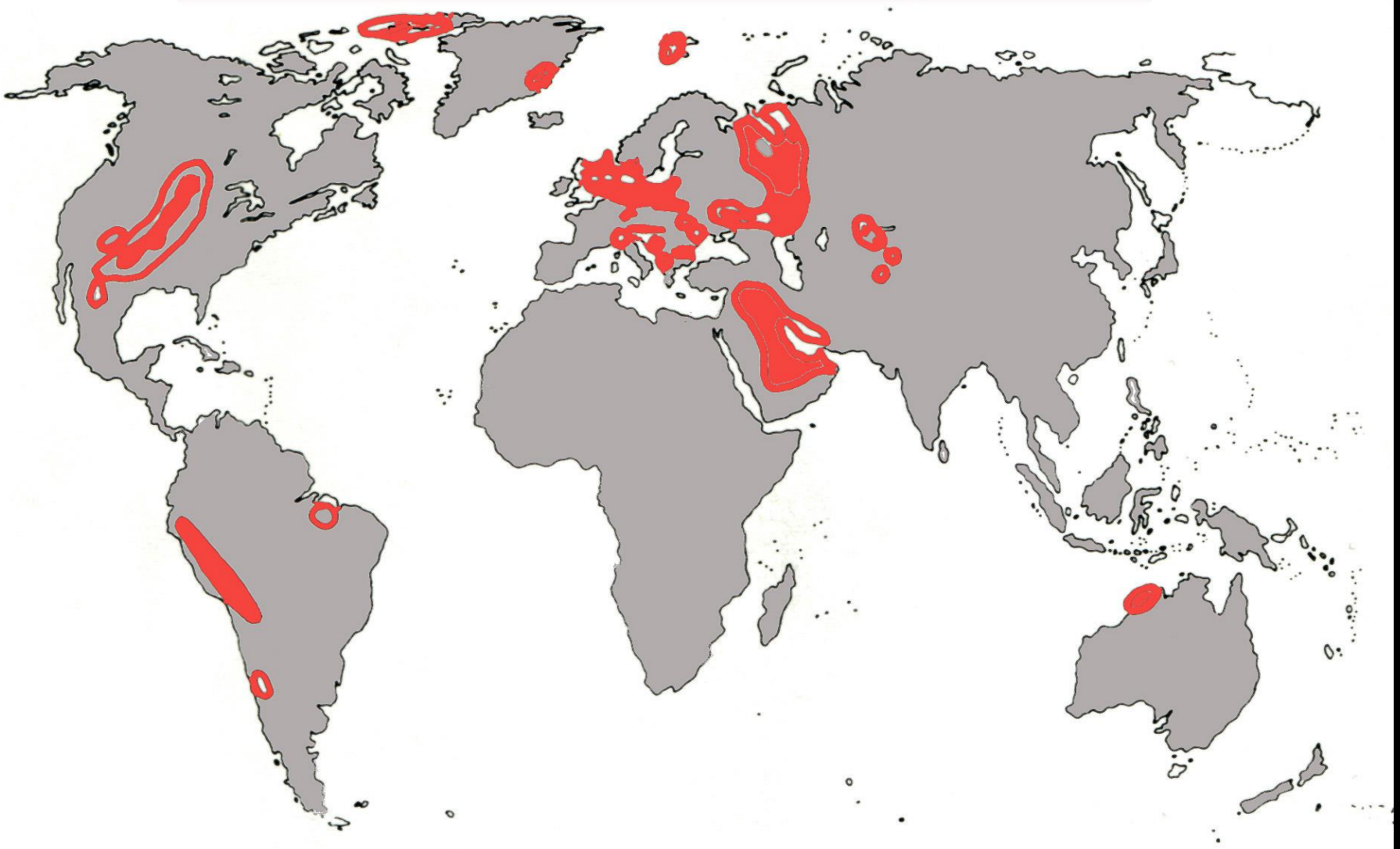
Ecosystem in cold-area

Halophiles: Life in Hypersaline Water

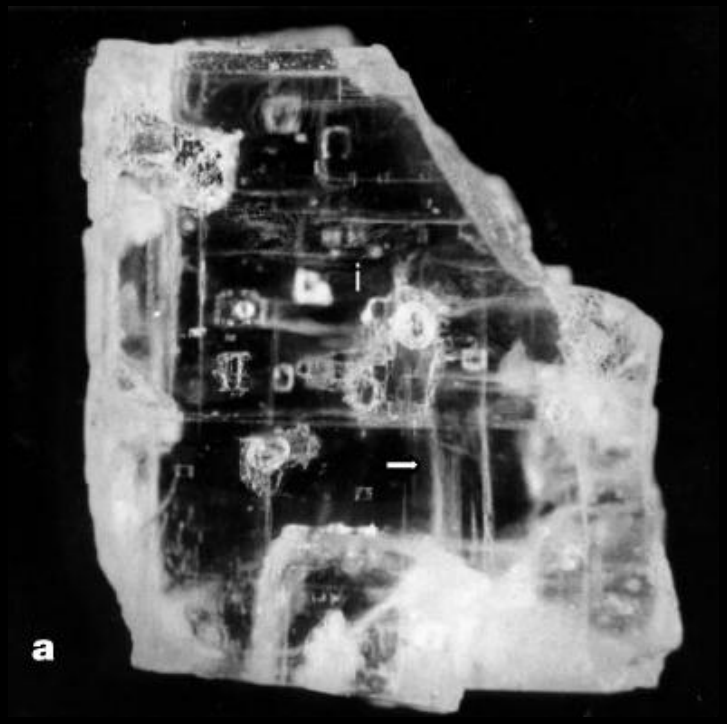
Swakopmund salterns (Namibia) (Credit: Helga Stan-Lotter)


Halotolerant
Example:
Staphylococcus aureus
Halophile
Example:
Vibrio fischeri
Extreme halophile
Example:
Halobacterium salinarum
Growth rate
Nonhalophile
Example:
Escherichia coli
0
NaCl
30 %

Distribution of Permian salt evaporite deposits (230 - 280 million years ago)

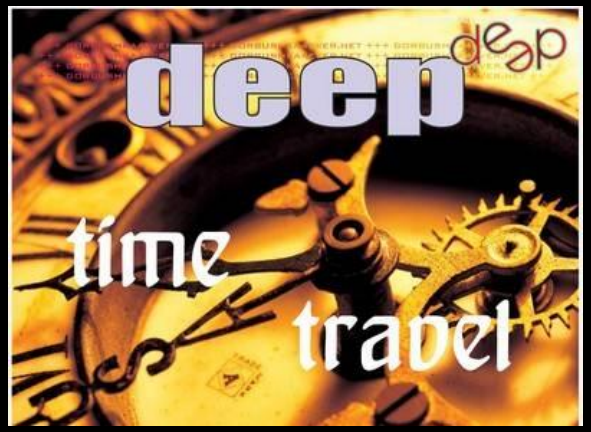


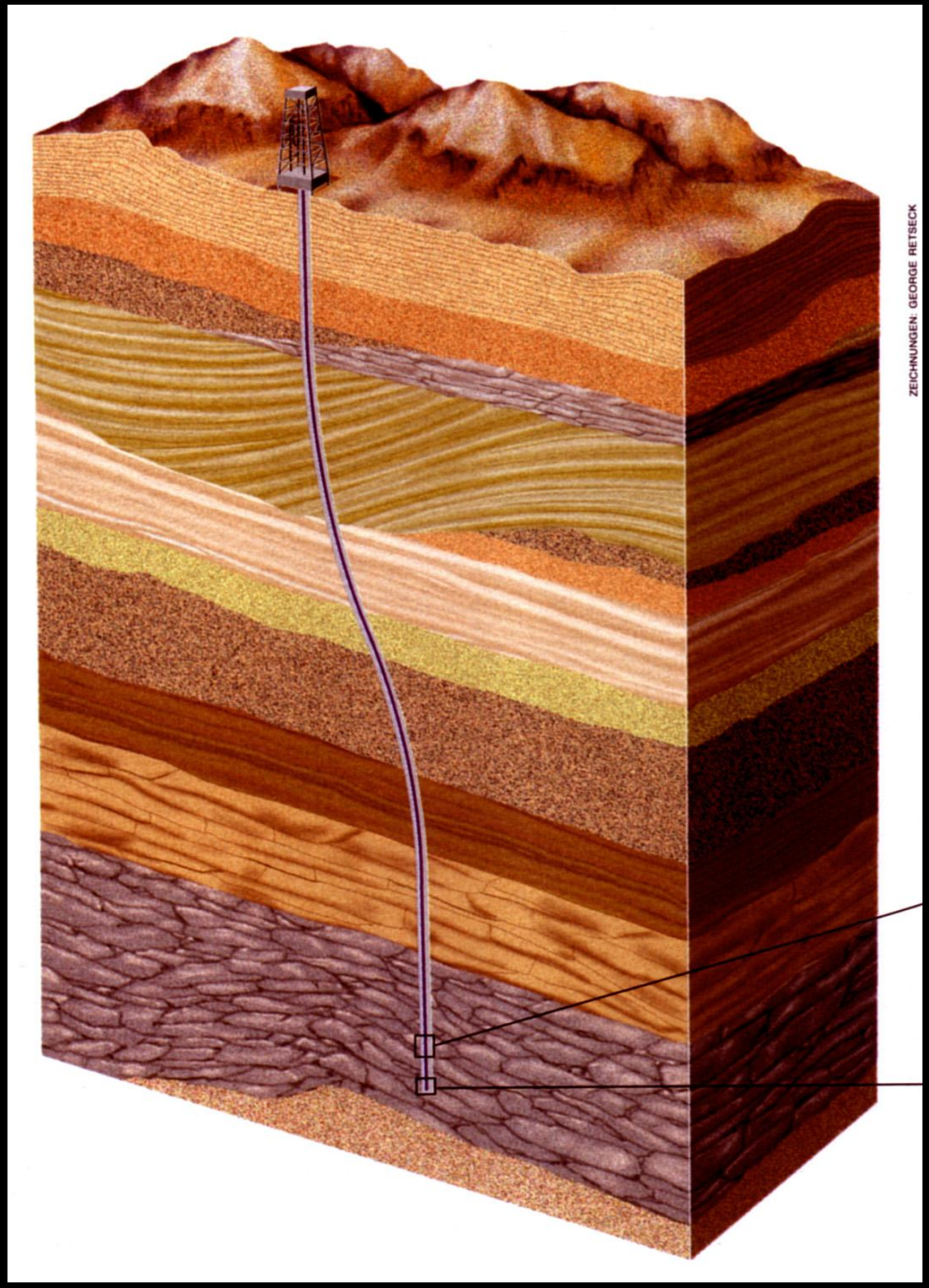
Reincarnated Dormant Life in 250 Million-Year-Old Salt!

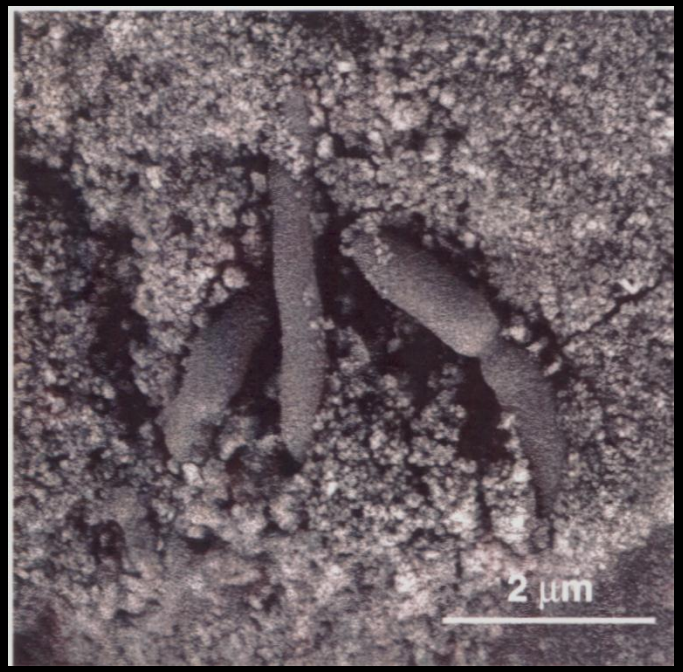


3.2×2.8×0.9 cm^3
Permian Salado Formation
(Vreeland et al., 2000, Nature)

This discovery expands dramatically the maximum proposed **age for** microbial **survivability**.







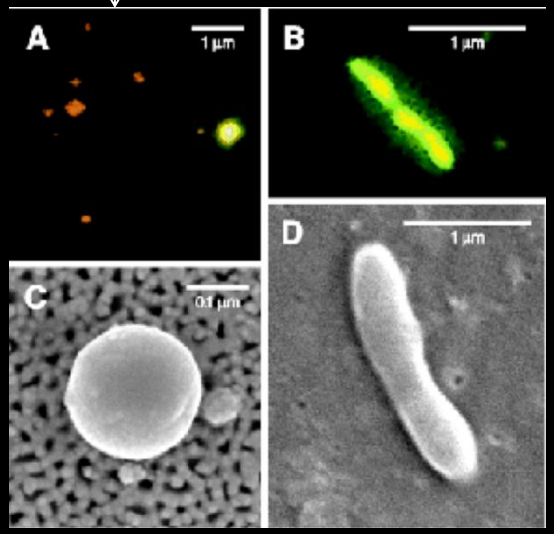
Thermoanaerobacter sp.
TOR39. 800-3000 m Depth.
T = 45-75℃

Life in Deep Terrestrial Subsurface

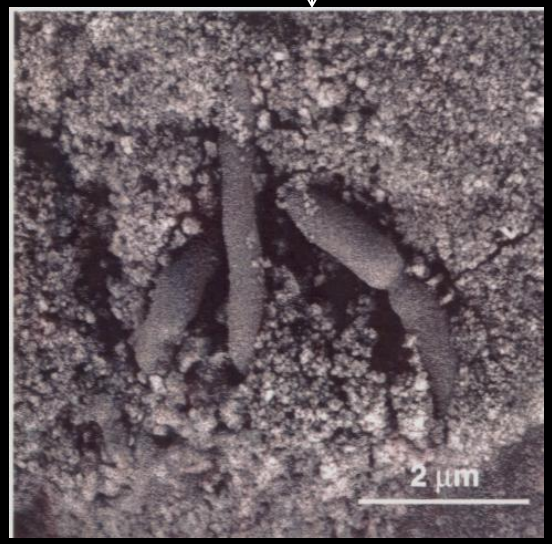
How Deep Does Earth's Life Go?

Currently Claimed Depths:

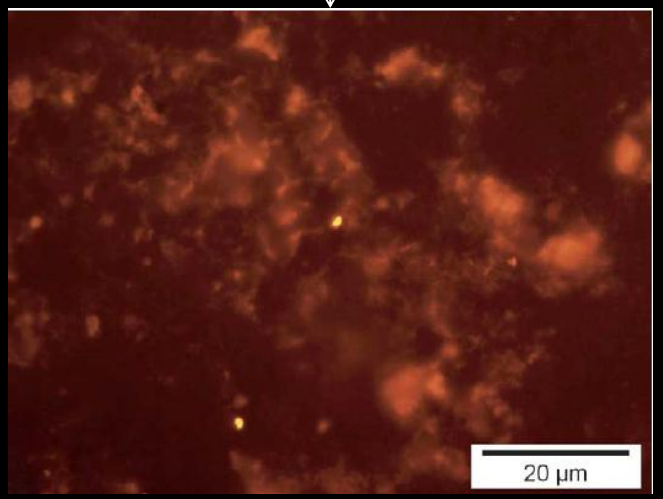
- 1.0 km in marine sediment.
- 2.8 km in continental rock.
- 3.6 km in Antarctic ice.



Karl et al. 1999, Science



Liu et al., 1997, Science



Teske, 2005, Trends Biol. (4 miles below the ocean surface)

Deep, Hot Biosphere

The deep, hot biosphere

(geochemistry/planetology)

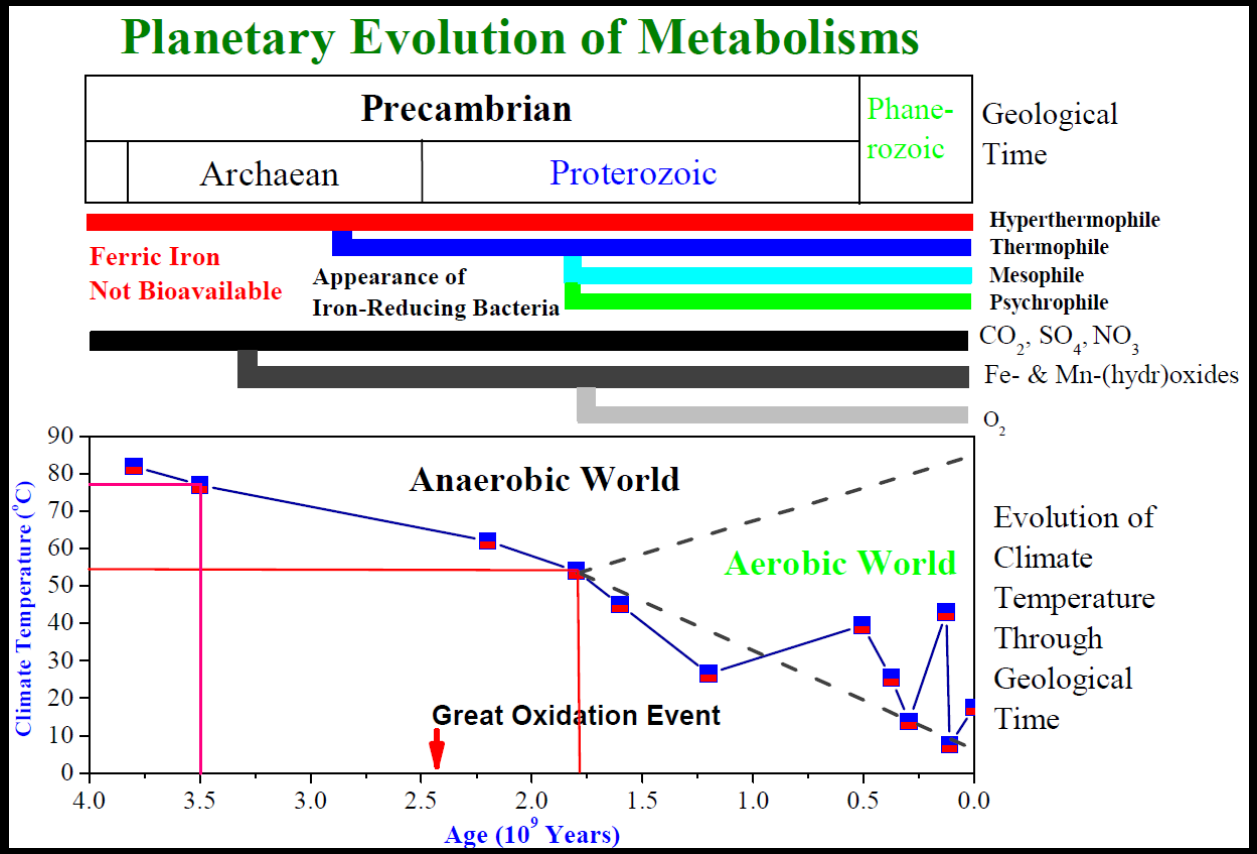
THOMAS GOLD

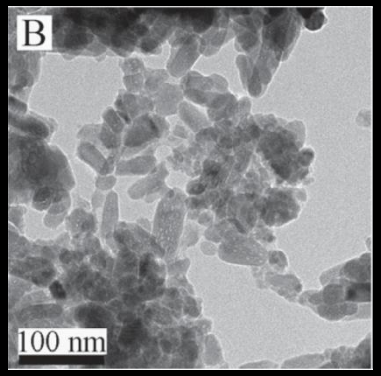
Cornell University, Ithaca, NY 14853

Contributed by Thomas Gold, March 13, 1992

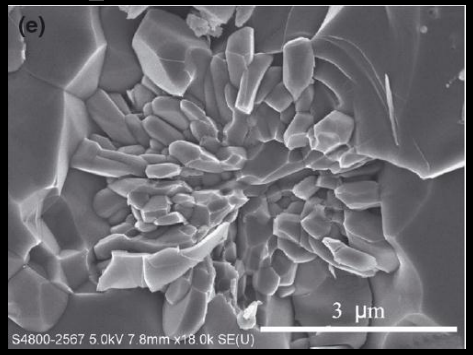
- **Was oil (fossil fuel) biogenic?**
- **Is there a deep, hot biosphere that has more biomass than the surface biosphere?**
- **Does this deep, hot biosphere need energy from the Sun?**

A Hot Biosphere Back in Deep Time





Apatite, 2480 Ma



Apatite, 2728 Ma

Li et al., Geology, 2011
Li et al., Ecol Evol, 2013

Acidophiles

Name: Acidophiles
Location: Lechuguilla Cave, Carlsbad, New Mexico
Description: These hardy organisms have been found living in a number of caves under conditions of pH of 0.0 -about as acidic as battery acid!

What this means for life in the universe:

Some scientists speculate that the clouds of Venus could be a plausible habitat for microbial life. The clouds are highly acidic, but that wouldn't be a problem for acidophiles.

The pH values of Something You Are Familiar With

$PbSO_4$ battery <1.0	Acid rain < 5.6
Gastric acid 2.0	Cancer patient's saliva 4.5-5.7
Lemon juice 2.4	Milk 6.5
Coca cola 2.5	Pure water 7.0
Vinegar 2.9	Healthy people's saliva 6.5-7.4
Apple juice 3.5	Blood 7.34 - 7.45
Beer 4.5	Seawater 8.0
Coffee 5.0	Soap 9.0 - 10.0
Tea 5.5	Bleach liquid 12.5

Biologically efficient radiation doses (in Gray):

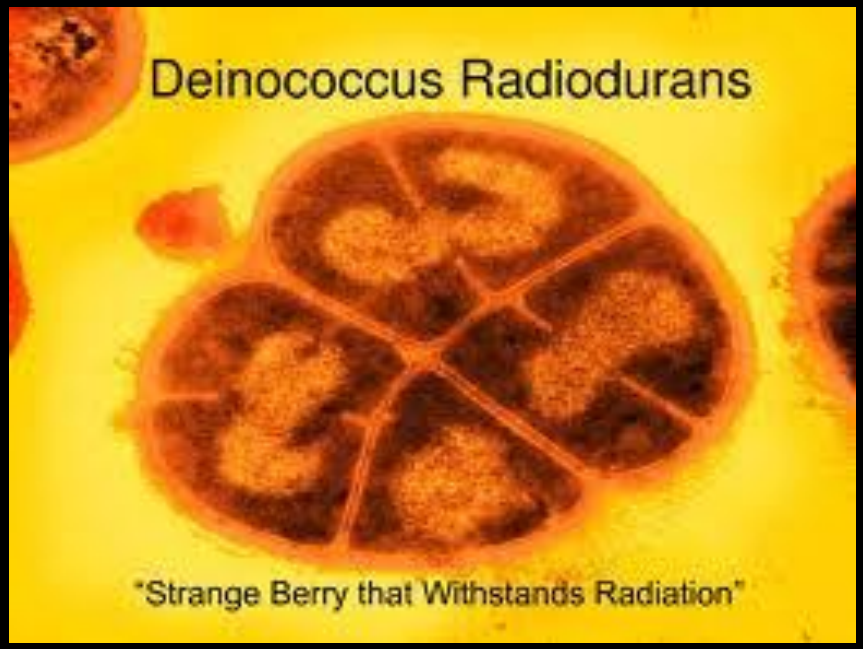
1 Gy = 1 Joule absorbed energy per kg of tissue

	Lethal doses
Humans	5–10 Gy
Salmonella, Bacillus sp.	2000–6000 Gy
Deinococcus radiodurans	30 000 Gy

Deinococcus radiodurans

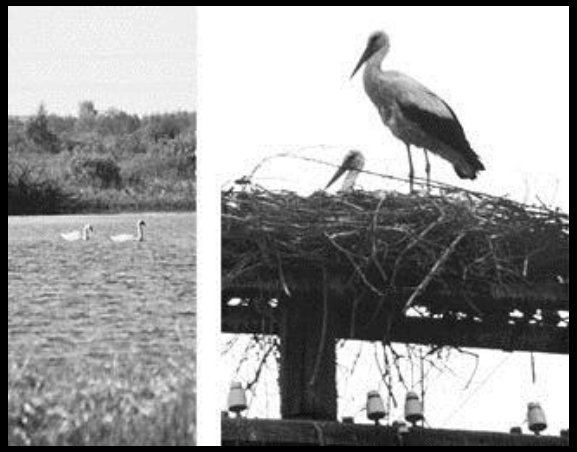
possesses an extremely efficient DNA repair system:

- **can excise and repair misincorporated bases;**
- **can repair breaks in single- or double-stranded DNA;**
- **can reassemble its chromosome from fragments.**



Brooks & Murray, 1981

Chernobyl Nuclear Disaster (April 26, 1986)



Highest Radiation Dose

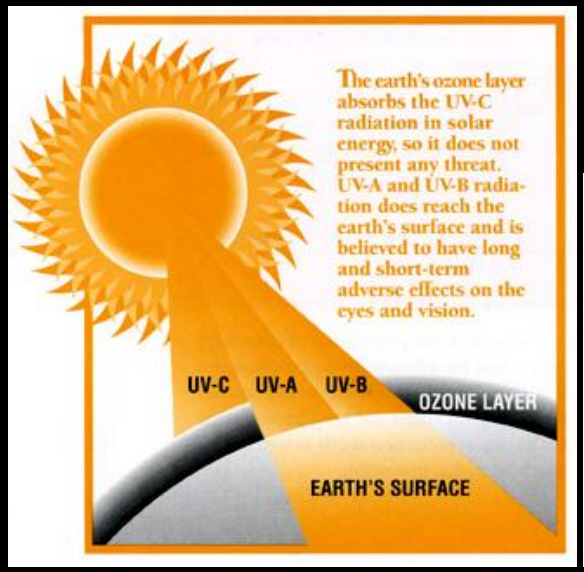
Name: *D. radiodurans*
Location: Hanford nuclear waste storage site, Washington state
Description: *D. radiodurans* has been humorously dubbed "Conan the Bacterium." It's the most radiation-resistant organism known. These guys can withstand 15000 Gy - a thousand times more than any other life form on Earth.
What this means for life in the universe:
D. radiodurans species beats most of the constraints for survival of life on Mars, including radiation, cold, vacuum and dormancy.

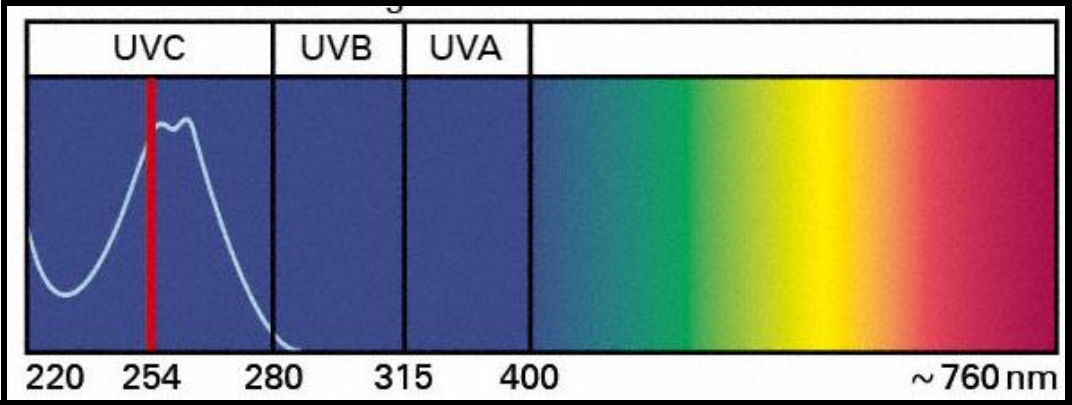
Before the mission's launch to Mars in 1996, microbiological assays are conducted on the Pathfinder lander and the Sojourner rover at NASA's Kennedy Space Center. The prelaunch cleanliness requirements are strictly monitored to avoid life contamination from the Earth. (Robert C. Koukol, JPL)

Radiation-Tolerant Microorganisms: Its meaning for life elsewhere

- Planetary surfaces that possess little to no atmosphere and have low water availability do not constitute a favorable environment for terrestrial microorganisms.

- The thick CO_2-H_2O dominated atmosphere of early Earth is important, a lately evolved O_3-containing atmosphere is more important for terrestrial life.

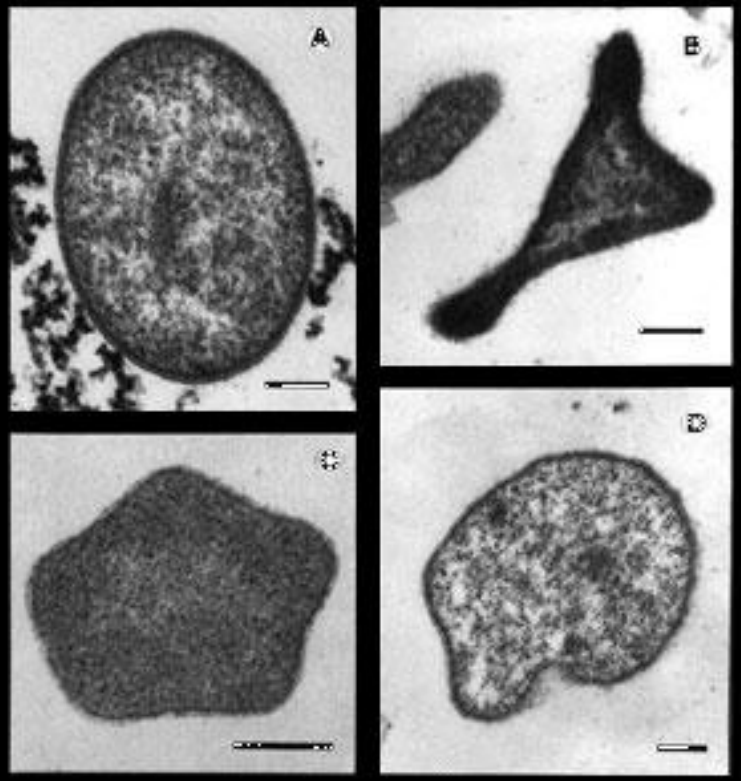




Living without Sunlight!

Name: Hydrothermal vent communities
Location: First discovered on the Galapagos Rift off the coast of Ecuador
Description: In 1977, scientists first discovered entire communities of organisms flourishing miles below the surface of the ocean, around openings in the ocean floor out of which hot, mineral-rich water erupts.
What it means for life in the Universe:
There is strong evidence that a liquid ocean exists below the icy surface of Jupiter's moon Europa. If this ocean contains hydrothermal vents as well, scientists speculate, they could be wellsprings of alien life.

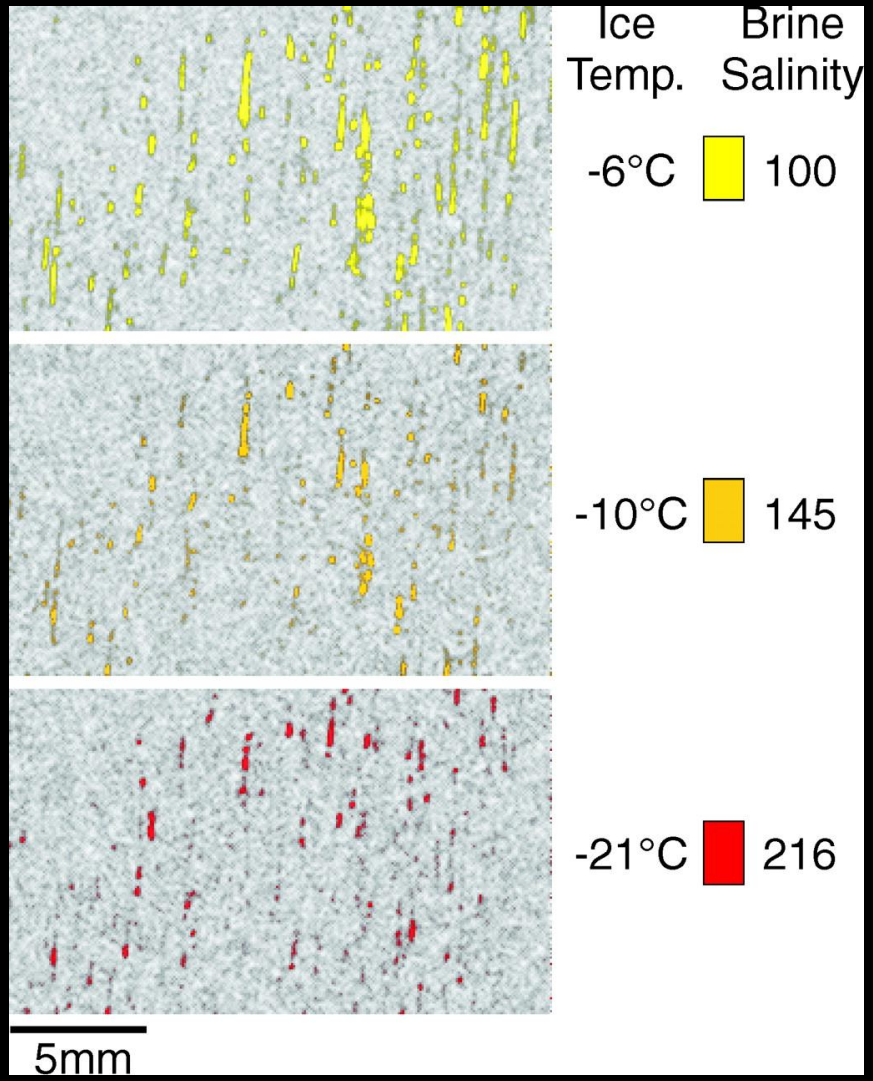
Hottest

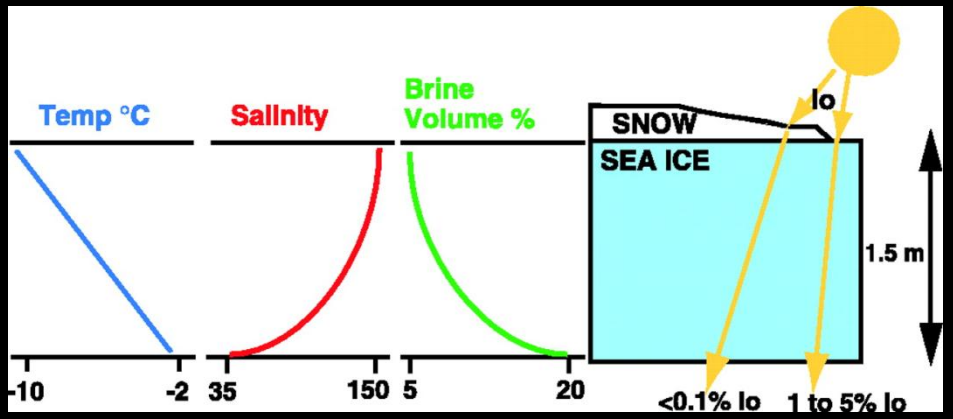


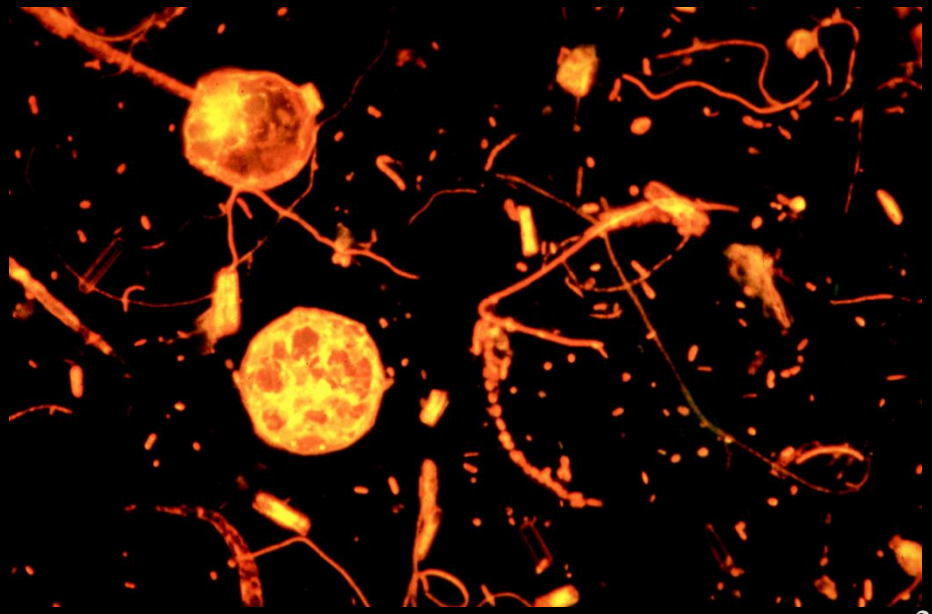
Name: Archaea Strain 121
Location: Hot springs at Yellowstone National Park, Wyoming
Description: This microbe belongs to a class called "hyperthermophiles," which live in extremely hot or acidic water. Some species can survive temperatures over 113℃-- hot enough to boil an egg in minutes.
What this means for life in the universe:
The discovery of organisms that thrive within a broad range of temperatures opens up new prospects for finding microbial life elsewhere in the universe.

We are cool!

Psychrophilic & Barophilic Micro.



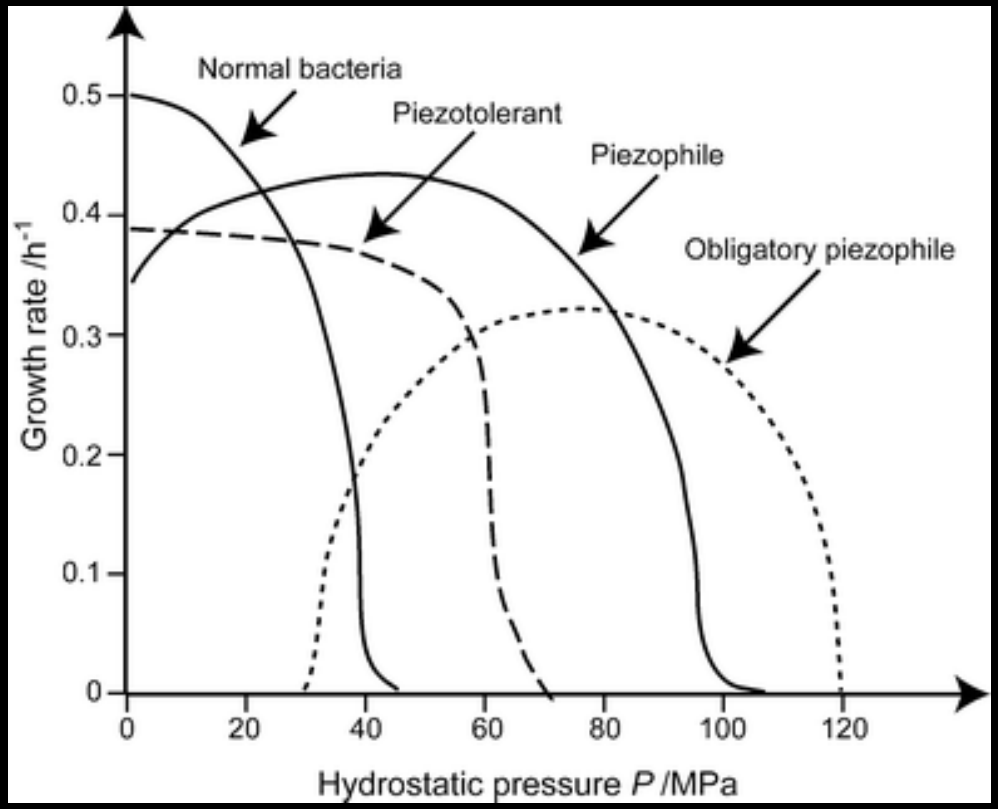


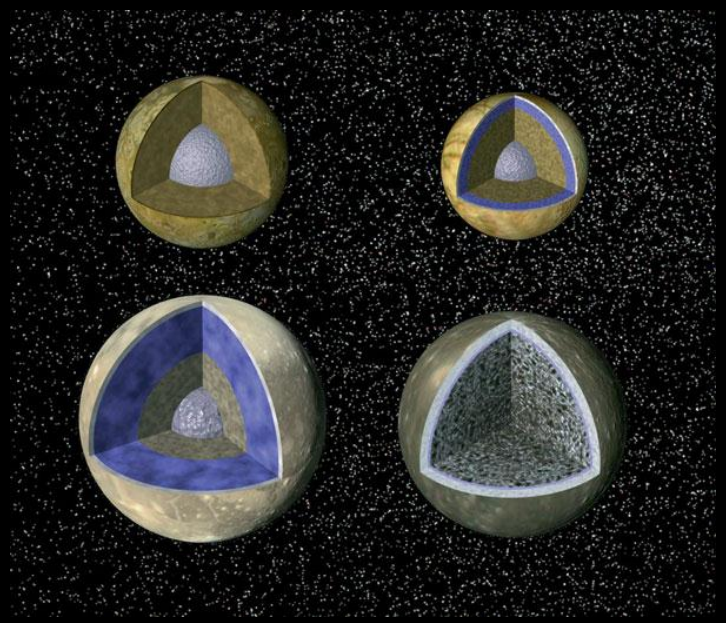


Some Microorganisms Love High Pressure and Temperature (Piezo-Hyperthermophile)!

Sulfate-Reducing Bacteria thrive @98ºC & 500 Atm

Pressure Constrains of Piezophilic/Barophilic Microorganisms





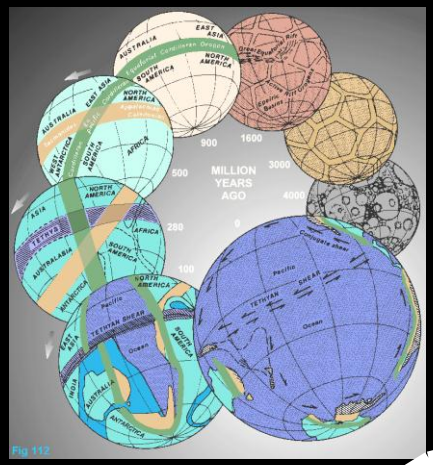
Galilean Satellite:
Deep Oceans With Life?

Subsurface Microbial Life May Be Common in the Universe

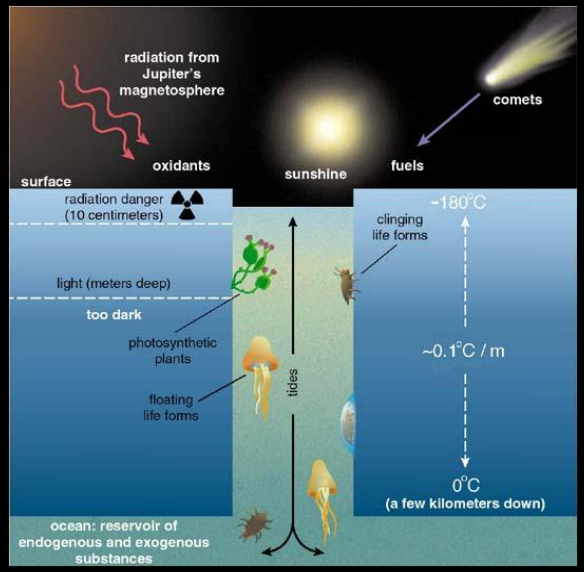
- Conditions can be found on Earth
- Using bio-harvestable chemical energy
- Shield by rocky crust from fatal radiations

Modeling Conditions for Extraterrestrial Life

Evolution and Longevity of Earth ecosystem



Habitability of exoplanet



Life in the Ocean of Europa

Extraterrestrial civilization