Extremophiles

Pushing the limits of life
Life at the extreme

- An extremophile is an organism that thrives under "extreme" conditions.
- The term “extremophile” is relatively anthropocentric, we judge it compared to human extremes
  - e.g. we use $O_2$ but for many organisms $O_2$ is poisonous

‘waterbears’
Complex organisms (Eukarya) occupy a more restrictive thermal range than Bacteria and Archaea.

Eukaryotic organisms are not known to live above 60°C.

However, eukaryotes can be found in environments of great acidic, salt concentration, high pressure, toxic metals.
- Temperature scale for the presence of liquid water on Earth and for the observed enzyme activity and growth of microorganisms (Bacteria and Archaea).

- Notice limited region of Eukaryotic life
High temperatures

- Thermophiles – heat-loving extremophiles;
  - optimum growth temperature between 50-70°C or more
  - minimum of about 20 °C.

- Environment: geothermally heated regions of the Earth:
  - hot springs (Yellowstone National Park)
  - deep sea hydrothermal vents.

![Yellowstone hot spring](image1)

![Deep sea thermal vent](image2)
• *Obligate* thermophiles (extreme thermophiles) require very high temps for growth

• *Facultative* thermophiles (moderate thermophiles) can thrive at high temps but also at lower temperatures (below 50 °C).

• *Hyperthermophiles* are particularly extreme thermophiles for which the optimal temperatures are above 80 °C.
Hyperthermophiles

- Discovered in the 1960s, in hot springs in Yellowstone National Park. Since then, more than fifty species have been discovered.

- Most heat-tolerant hyperthermophile discovered is the ‘Strain 121’
  - Able to double its population during 24 hours in an autoclave at 121°C (hence its name).

Sphere in the upper left is a Strain 121 specimen, with about dozen flagella dangling. The scale bar at lower left is one micrometer.
• Ability to grow at 121 degrees Celsius is significant because medical equipment is exposed to this temperature for sterilization in an autoclave.
  ◦ Previously a 15min exposure to autoclave temperatures was believed to kill all living organisms.

• The upper temperature for life is still to be determined
  ◦ There are some evidence of intact microorganisms with DNA and RNA in hydrothermal vent sulfides at temperatures exceeding 200°C.
Consequences at high T

- Solubility of O and CO$_2$ drops significantly - aquatic organisms that rely on O or CO$_2$ will not survive.
  - Fish expire above 40°C for this reason.

- T>75°C chlorophyll degrades, problem for many photosynthesizers

- T >100°C most organisms cease to function.
  - T corresponds to the thermal content that denatures the essential polymers (proteins unfold, unable to perform functions)
  - The fluidity of the membrane is increased so much that cells cannot control the input or output of molecules.

- >150°C DNA and other vital molecules begins to break down
Adaptation techniques hyperthermophiles

T effects compensated with higher pressure or with increasing salt concentration.

1. Some organisms ingest/produce salts enhancing the stability of the DNA chain

2. All hyperthermophiles have a protein that positively supercoils (over-winds) DNA, which increases the thermal stability of DNA.

3. Their protein molecules can maintain structural stability (and therefore function) at high temperatures.

4. Membranes - different proportion of saturated (no double or triple bonds with carbon) versus unsaturated fats, which optimized membrane stability at high temperature.

Fundamental changes in protein and lipid structure used to compensate for increased mobility and fluidity at high temperatures
Hydrothermal vents

- Where crustal plates slowly spread apart and magma is coming up from below to form mid-ocean ridges.
  - Seawater seeps 1-2 miles down into the hot rock.
  - Enriched with minerals leached from the rock, water heats and rises to the ocean floor to form a vent.
  - Water pouring out of vents can reach temps up to about 400°C. High pressure keeps water from boiling.

- Intense heat is limited to a small area.
  - Large temperature gradient - within less than an inch of the vent opening, the water temperature drops to 2°C

- Most creatures that congregate around vents live at temps just above freezing. Thus chemicals are the key to vent life, not heat!
  - Harsh combination of toxic chemicals, high temperatures, high pressures, and total darkness at these vents.
Pompeii Worm

- Reside in tubes near hydrothermal vents
- 5 inches in length with red tentacle-like gills on their heads
- Tail end is resting in temperatures as high as 80º C, while their head sticks out into much cooler water, 22º C
- Bacteria form a "fleece-like" covering on their backs - living in a symbiotic relationship, the worms secrete mucous from tiny glands on their backs to feed the bacteria, and in return they are protected by some degree of insulation.
Low temperature - Psychrophiles

- Capable of growth and reproduction at or below 15°C.

- Environments ubiquitous on Earth
  - alpine and arctic soils (permafrost)
  - high-latitude and deep ocean waters
  - arctic ice, glaciers, snowfields & refrigerated appliances

1) Obligate psychrophiles - optimum growth temperature of 15°C or lower and cannot grow in a climate hotter than 20°C.
   - (Antarctica or at the freezing bottom of the ocean floor)

2) Facultative psychrophiles - can grow at 0°C up to ~ 40°C, exist in much larger numbers than obligate psychrophiles.
Many phychrophiles are polyextremophiles:

- The ones living in deep ocean waters => extremely high pressures
- Organisms in sea ice are exposed to high salt concentrations.
- On snow, glaciers, polar surface organisms are exposed to strong UV radiation.
- Organisms found in rocks in Antarctic dry deserts - low water and nutrients.

*Subglacial stream - Glacier du Mont Mine, Swiss Alps.*
Psychrophiles represented in all 3 domains of life

- Obligate psychrophiles have evolved only among the Bacteria (blue).
• At very low temperatures the water becomes ice

• However, small amounts of liquid water are available for life in different types of ice formations, especially at brine inclusions.

*Brine is water saturated or nearly saturated with salt*
Water can remain liquid at temperatures lower than -30°C in the presence of salts and other solutes.

Many species of snow algae were observed on Alaskan glaciers (green algae and cyanobacteria).

Microorganisms are abundant in frozen environments. Possibility of life on Mars, and other icy bodies?
TABLE 15.1 Bodies of ice on Earth and unfrozen (liquid) water within them

<table>
<thead>
<tr>
<th>Type of ice formation</th>
<th>Global surface area covered (%)</th>
<th>Volume of ice ($10^6$ km$^3$)</th>
<th>Fraction of liquid water within the ice</th>
<th>Volume of liquid water ($10^3$ km$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice sheets</td>
<td>3</td>
<td>30</td>
<td>0.0001</td>
<td>3</td>
</tr>
<tr>
<td>Mountain glaciers</td>
<td>0.1</td>
<td>0.1</td>
<td>0.001</td>
<td>0.1</td>
</tr>
<tr>
<td>Marine ice shelves</td>
<td>0.1</td>
<td>0.1</td>
<td>0.001</td>
<td>0.1</td>
</tr>
<tr>
<td>Sea ice</td>
<td>5</td>
<td>0.04</td>
<td>0.08</td>
<td>3</td>
</tr>
<tr>
<td>Permafrost$^a$</td>
<td>3</td>
<td>0.025</td>
<td>0.01</td>
<td>0.25</td>
</tr>
<tr>
<td>Seasonal snow</td>
<td>9</td>
<td>0.002</td>
<td>0.01</td>
<td>0.02</td>
</tr>
</tbody>
</table>

*South Pole bacteria. NSF*
**TABLE 15.2 Bacterial abundance in ice***

<table>
<thead>
<tr>
<th>Type of ice formation</th>
<th>Sampling location</th>
<th>Sample $T$ ($^\circ$C)</th>
<th>Particle-poor ice</th>
<th>Particle-rich ice</th>
</tr>
</thead>
<tbody>
<tr>
<td>Snow</td>
<td>South Pole</td>
<td>$-15$</td>
<td>$0.2-5 \times 10^3$</td>
<td></td>
</tr>
<tr>
<td>Ice sheet</td>
<td>Over Lake Vostok (2–4 km)</td>
<td>$-3$</td>
<td>$0.2-8 \times 10^3$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Greenland (bottom of sheet)</td>
<td>$-9$</td>
<td></td>
<td>$&gt;6 \times 10^7$</td>
</tr>
<tr>
<td>Lake ice</td>
<td>Lake Bonney, Antarctica</td>
<td>$&lt;-5?$</td>
<td>$5 \times 10^3$</td>
<td>$0.1-4 \times 10^5$</td>
</tr>
<tr>
<td></td>
<td>Imikpuk Lake, Alaska</td>
<td>$-5$</td>
<td>$7 \times 10^4$</td>
<td>$7 \times 10^5$</td>
</tr>
<tr>
<td>Sea ice</td>
<td>Southern Ocean, summer</td>
<td>$-2$</td>
<td>$0.01-3 \times 10^6$</td>
<td>$0.02-2 \times 10^6$</td>
</tr>
<tr>
<td></td>
<td>Southern Ocean, winter</td>
<td>$-2$</td>
<td>$0.2-2 \times 10^6$</td>
<td>$1 \times 10^7$</td>
</tr>
<tr>
<td></td>
<td>Arctic Ocean, summer</td>
<td>$-2$</td>
<td>$0.4-2 \times 10^6$</td>
<td>$0.05-1 \times 10^7$</td>
</tr>
<tr>
<td></td>
<td>Arctic Ocean, winter</td>
<td>$-2$ to $-20$</td>
<td>$0.2-1 \times 10^5$</td>
<td>$0.5-3 \times 10^6$</td>
</tr>
<tr>
<td>Permafrost</td>
<td>Northeast Siberia</td>
<td>$-10$</td>
<td></td>
<td>$&gt;1 \times 10^8$</td>
</tr>
</tbody>
</table>

*Note:*

*a Number ml$^{-1}$ melted ice or g$^{-1}$ soil for permafrost; data compiled from Carpenter et al. (2000), Delille et al. (1995), Gradinger and Zhang (1997); Grossmann and Dieckmann (1994); Helmke and Weyland (1995); Junge et al. (2001, 2003, 2004a); Karl et al. (1999), Priscu and Christner (2004), Rivkina et al. (2000), and Sheridan et al. (2003).*
• Some of them produce brilliant colored spores. They alter the albedo of the snow and induce snowmelt, increasing the availability of liquid water.

• Some organisms produce extracellular enzymes that lead to pitting of ice.

*Chlamydomonas nivalis*
This is most well-known snow alga. Bloom of this alga causes visible red snow (watermelon snow). This species is common in North America, Japan, Arctic, Patagonia. The algae prefer snow surface rather than ice on glaciers.

www-es.s.chiba-u.ac.jp/.../snowalgae_ak.html
Reviving 32,000 yr old bacteria

NASA astrobiologist takes ice samples from the permafrost in Alaska. The samples, dating back some 32,000 years, contained living organisms.

Carnobacterium pleistocenium - alive after been thawed from ice dating back some 32,000 years. Living bacteria are stained green. Image credit: University of Alabama at Birmingham

Microorganisms can be preserved in ice for geological periods of time!
Example eukaryote psychrophile: Himalayan midge

A novel cold-tolerant insect found in a Himalayan glacier

Shiro Kohshima

Department of Zoology, Kyoto University,
Kitashirakawa-Oiwakecho, Sakyo-ku, Kyoto 606, Japan

Here we report the discovery of a new species of cold-tolerant midge (Chironomidae, Diamesa Meigen sp.) in a high-altitude glacier of the Nepal Himalayas. The adult insect, characterized by reduced wings and antennae (Fig. 1a), is unable to fly, and is found walking on the surface of the glacier and in small cavities beneath it. The larvae grow in melt-water drainage channels under the ice and feed on blue-green algae and bacteria. The insect is the first to be found which spends its entire life cycle in the snow and ice of a glacier—the coldest insect habitat ever recorded\textsuperscript{1,2}. The insect was active at temperatures as low as $-16^\circ$C, well below those at which activity has been seen in insects living in other cold habitats, including Antarctic ones. The study also reveals a previously unsuspected ecosystem based on the algae and bacteria growing on glacial ice.
The Antarctic nematode *Panagrolaimus davidi* is the only animal known to survive extensive intracellular ice formation. (Nematode = unsegmented worm-like organisms)

If freezing rate is slow, the nematodes appear not to freeze. Instead they dehydrate due to the vapor pressure difference between the supercooled body fluids within the nematodes and that of the surrounding ice—a process known as cryoprotective dehydration.
Psychorophiles - Polyextremophile - Tardigrades

- Tardigrades (water bears) = small, segmented animals; length 0.1-1.5mm.

- Environment:
  - From Himalayas (above 6,000 m), to the deep sea (below 4,000 m)
  - From the polar regions to the equator
  - In beaches, soil and marine or freshwater sediments (up to 25,000 animals per litre).

Known to survive the following extremes:
1. T - a few minutes at 151°C; days at minus -200°C.
2. Radiation 100 times higher than lethal dose for humans
3. Pressure very low (vacuum); very high pressures 6,000 atm
4. Dehydration
• Adaptation: capable of entering a latent state - **cryptobiosis** - when environmental conditions are unfavorable.

• Cryptobiosis = the state of an organism when it shows no visible signs of life and when its metabolic activity becomes hardly measurable, or comes reversibly to a standstill
  ◦ a unique biological state between life and death - poorly understood
  ◦ (read more in Y. Neuman / Progress in Biophysics and Molecular Biology 92 (2006) 258–267)
High salinity - Halophiles

- Environment: places where exposure to intense solar radiation leads to evaporation and concentration of NaCl to near- or even super-saturation
  - Hypersaline bodies of water that exceed the 3.5 % salt of Earth’s oceans, Great Salt Lake in Utah, The Dead Sea.

- Cyanobacteria, the first ever oxygenic photosynthesizers, said to be the source of chloroplasts in eukaryotes.
- Can survive in small pockets of water within deposits of salt after water evaporation.
- These type of deposits found on Mars. Jupiter's moon Callisto may have an underground saline ocean, as well as on the neighboring moon, Europa.
What happens at high salinity to most organisms?

- The greater the difference in salt concentration between in and outside the cell - the greater the osmotic pressure

- If we drink salty water we dehydrate the cells => enzymes and DNA break!

Natural salts were used to remove moisture from the body during mummification
• Plants: trigger ionic imbalances => damage to sensitive organelles such as chloroplast.

• Animals: a high salt concentration within the cells => water loss from cells => brain cells shrinkage => altered mental status, seizures, coma, death.

Adaptation:
Two strategies to cope with osmotic stress:
1. Maintain high intracellular salt concentration. Requires extensive adaptation of the intercellular machinery (few specialized organisms).
2. Cells maintain low salt concentration in the cytoplasm, the osmotic pressure being balanced by:
   ◦ Producing or taking from the environment, and accumulating in the cytoplasm organic molecules (glycerol, amino acids, sugars).
More forms of extremophiles:

- Acidophile: organisms that thrive under highly acidic conditions (pH 2.0 or below)
  - Acid springs and rivers, old mines drainage

- Alkaliphiles: thrive in alkaline environments with pH 9-11
  - Soda lakes, carbonate-rich soils

Mono Lake, located in California’s Eastern Sierra, is both alkaline and hypersaline.
Radiotolerant: property of organisms capable of living in environments with very high levels of radiation

- Survival of animal/plants around the Chernobyl accident; uranium mines in Brasil with radioresistant insects, worms, plants, scorpions

Deinococcus radiodurans: can survive extreme levels of radiation, extreme temperatures, dehydration, and exposure to genotoxic chemicals. They have the ability to repair their own DNA, usually with 48 hours.

- Damages cells, most severe for the DNA sometimes breaking both strands
- Physiological effects: cataracts, sterility, cancer, death
• Endoliths: lives inside rocks, between mineral grains or in pores.
  ◦ Very deep rocks, also deal with extreme T, P, complete darkness and anoxic conditions
  ◦ Down to 3km depths, including Dry Valleys and permafrost of Antarctica
  ◦ Survive by feeding on traces of iron, potassium, sulfur

 Courtesy of NOAA ocean explorer
• Barophiles: organisms which live in high pressure environments
  ◦ Deep ocean floors, subsurface rocks
  ◦ Grow in darkness -> very UV sensitive, lacking mechanisms of DNA repair
  ◦ Mariana trench: deepest sea floor at 10,897m
  ◦ 180 species of organisms found in 1996, many were extreme barophiles

Amphipods, Hirondellea gigas, shrimp-like animals were collected by baited traps. The total length of the largest specimen was over 45mm

Barophilic bacteria isolated from seafloor mud of the Mariana Trench
- **Anaerobes:** cannot tolerate oxygen
  - Methanogenes: produce methane as byproduct of metabolism
  - Suggestions that presence of methane in the Martian atmosphere indicative of methanogenes on Mars

- **Oligotroph:** can live in very low carbon environment

- **Xerophiles:** can grow with a low water content
  - Atacama desert