Extremophiles & Life in Extreme Environments
Karen Meech
With input from: Bob Bowers, Doug LaRowe

Green House Effect: 2 Key Points
- Energy has to get in
  - It does not matter what wavelength
  - Short wavelengths are most effective (most energy)
  - The energy heats the surface of the planet (how much depends on albedo)
- Infrared radiation (heat) has to be trapped
  - Much or all of IR region of atmosphere has to be blocking light

Early Earth & Solar System Lectures
- Understanding how to build a habitable world & how it evolved
  - When did Earth form? When did atmosphere and oceans form?
  - When did life originate on Earth (what evidence)?
  - What were the 4 major epochs in Earth history and how are they characterized?
- The chemistry of the atmosphere can regulate planetary temperature, and environmental conditions on the surface that may make it more or less habitable to life. There is a lot of interaction between life, atmosphere and geology, and we don’t fully understand all the feedback. Human affects cannot be fully predicted.
- We need to understand what life requires and how this relates to a habitable environment - and what are considered extremes.

Review of Essentials from Life Requirements & Origins
- We don’t have a consensus on the definition of life
  - Life requires water, energy, produces waste, replicates and evolves
  - Life is Carbon based (carbon has the ability to make complex molecules)
  - Life occurs in a microQenvironment (cell)
- Steps required in origin of life:
  - creating monomers (organic building blocks), creating compartments, creating long complex molecules (polymers), creating metabolic networks (E production)
- Quest for the origin of life
  - Most of life on earth through time has been microbial ➔ not leave many fossils (biomarkers)
  - Phylogenetic trees ➔ expressing relatedness of life
  - 3 major groupings of life: Eukarya (nucleated cells), Archaea (no nucleus), bacteria

Life at the Extremes
- What environmental factors are important for classification of the boundaries of life?
  - Water availability
  - Temperature
  - Pressure
  - Salinity
  - pH
  - Availability of energy
  - Radiation environment
- Classification of Microorganisms related to habitats
- The Energy of life
- Extreme Environments and their residents on Earth
- Where might we look for life on other planets?

Extreme Habitats & Organisms
- Life has occupied every possible niche on Earth
  - Two key habitability markers: water and energy
  - Explore the environments and how organisms take advantage of habitability
  - This gives clues to other habitable solar system environments
- Extremophile
  - Life living in an “extreme” environment (to us)

<table>
<thead>
<tr>
<th>Microbe class</th>
<th>T tolerances</th>
</tr>
</thead>
<tbody>
<tr>
<td>Psychrophiles</td>
<td>-10 to -20°C</td>
</tr>
<tr>
<td>Mesophiles</td>
<td>10 to 50°C</td>
</tr>
<tr>
<td>Thermophiles</td>
<td>40 to 70°C</td>
</tr>
<tr>
<td>Hyperthermophiles</td>
<td>&gt; 80°C</td>
</tr>
</tbody>
</table>

Arrows show T limits for plant and animal life
Making a Living in the Microbial World

- **Metabolism Definition**
  - The chemical processes that occur within a living organism in order to maintain life
  - Metabolism makes the molecules life uses

- **Redox Reactions**
  - Chemical energy is stored in high-energy electrons that are transferred from one atom to another
  - Oxidation – loss of electrons
  - Reduction – gain of electrons

**ATP** – molecule that life uses for energy storage

Making a Living in the Microbial World

- **What do microbes do? Catalyze reactions**
  - Anabolism – constructs molecules from smaller units → requires E
    - Synthesize biomolecules, polymerization, maintain membranes
  - Catabolism – breaking down molecules to release energy
  - Metabolism = Catabolism + Anabolism

Metabolic Sources: Energy for Life

- **Autotrophs**
  - Produce food
  - Photoautotrophs: photosynthesis – plants convert CO₂, H₂O and sunlight to sugar (glucose) and O₂
  - Chemoautotrophs – make energy from chemicals

- **Heterotrophs**
  - Feeders

Microbial metabolic diversity

- **Constraints on Metabolism**
  - Nutrients
  - Trace metals
  - Energy available
  - Environment: T, Pressure, salinity

- **Gibbs Energy**
  - Amount of chemical energy available

Quantifying the Metabolic process

- **e-Donors**
  - Organics
  - H₂
  - NH₄⁺
  - H₂S
  - Fe²⁺
  - CH₄

- **e-Acceptors**
  - O₂
  - SO₄²⁻
  - NO₃⁻
  - Fe(III)
  - CO₂
  - Mn(IV)
Potential Microbial Metabolic Processes

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Electron (energy) donor</th>
<th>Electron acceptor</th>
<th>C source</th>
<th>Metabolic process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerobic</td>
<td>$H_2$</td>
<td>$O_2$</td>
<td>$CO_2$</td>
<td>$H_2$ oxidation</td>
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<tr>
<td></td>
<td>$H_2S$, $S^0$, $SO_4^{2-}$, $S_2O_3^{2-}$</td>
<td>$O_2$</td>
<td>$CO_2$</td>
<td>$S$ oxidation</td>
</tr>
<tr>
<td></td>
<td>$Fe^{2+}$</td>
<td>$O_2$</td>
<td>$CO_2$</td>
<td>$Fe$ oxidation</td>
</tr>
<tr>
<td></td>
<td>$Mn^{2+}$</td>
<td>$O_2$</td>
<td>$CO_2$</td>
<td>$Mn$ oxidation</td>
</tr>
<tr>
<td></td>
<td>$NH_4^+$, $NO_2^-$</td>
<td>$O_2$</td>
<td>$CO_2$</td>
<td>Nitritification</td>
</tr>
<tr>
<td></td>
<td>$CH_4$ &amp; other C-1 compounds</td>
<td>$O_2$</td>
<td>$CH_4$, $CO_2$, CO</td>
<td>Methane (C-1) oxidation</td>
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<tr>
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<td>$NO_3^-$</td>
<td>$CO_2$</td>
<td>Methanogenesis</td>
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<tr>
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<td>$H_2$</td>
<td>$SO_4^{2-}$</td>
<td>$CO_2$</td>
<td>$S$ &amp; sulfate reduction</td>
</tr>
<tr>
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<td>$H_2$</td>
<td>$CO_2$</td>
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<td>$H_2$ oxidation</td>
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<td>$CH_4$</td>
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<td>Organics</td>
<td>Organics</td>
<td>Organics</td>
<td>Heterotrophic metabolism</td>
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<tr>
<td></td>
<td>$NO_3^-$</td>
<td>Organics</td>
<td>Organics</td>
<td>Denitrification</td>
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<td>Organics</td>
<td>Organics</td>
<td>Organics</td>
<td>$S$ &amp; sulfate reduction</td>
</tr>
<tr>
<td></td>
<td>Organics</td>
<td>Organics</td>
<td>Organics</td>
<td>Fermentation</td>
</tr>
</tbody>
</table>

Thermodynamics – Energy limitations

- **Amount of Energy available in chemical reactions**
  - Depends on temperature and pressure
  - How this changes with T and P is different for every compound
  - A negative value of Gibbs energy indicates there is a thermodynamic drive for the reaction to proceed (useful for the organism to get energy)

Microbial life exploits energy gradients with redox transitions

- From Yellowstone Hot springs
  - Each line is a possible catabolic reaction
  - Each depends on T and composition of hot spring
- Example Redox reactions
  - Methanogenesis
    $$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$
  - $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$
- Sulfur oxidation or reduction
  $$S + 1.5O_2 + H_2O \rightarrow SO_4^{2-} + 2H^+$$
  $$S + H_2 \rightarrow H_2S$$

Energetics Examples

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Extremophiles & Limits

- What do we mean by limit?
  - Does it move or grow or do anything?
  - Maintains a constant population?
  - Dying slowly enough to be observed?
  - Boundaries between these states are not well known

How much E is needed?

- **Energetics of Growth**
  - E to capture biomolecules (depends on environ)
  - Polymerization into bigger molecules
  - Aerobic conditions: 18.4 kJ (g cells)$^{-1}$
  - Anaerobic conditions: 1.4 kJ (g cells)$^{-1}$
- **Energetics of Steady State**
  - Defense against chemical stress
  - Maintaining cell
  - In some environments, this is a very small number! (1.6 J/yr/cm$^2$)
- **Energetics of Persistence**
  - Not well understood – but very low

Power supply (energy per unit time) > demand

- Power supply < demand
- Power supply = demand
- Power supply (energy per unit time) > demand

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Summary of Important Points

- **Classification of Microorganisms related to habitats**
  - Temperature: psychrophiles, mesophiles, thermophiles, hyperthermophiles
  - Environment: barophiles, xerophiles, halophiles, acidophiles, alkaliphiles
- **The Energy of life – Redox**
  - Chemical energy is stored in high-energy electrons that are transferred from one atom to another
  - Organisms get energy from light or chemicals and the carbon from inorganic (CO2) or organic
  - How much energy is “real” (Gibbs energy) depends on environment (T, P, chemistry)
  - Classification of organisms by whether it makes food or eats food produced
- **Extreme Environments and their residents on Earth**
  - Examples: hydrothermal vents, deep earth, polluted areas, deserts, antarctic...
- **Where might we look for life on other planets?**
  - Habitability markers: water and redox potential

Parting Thoughts

- **The mantra for searching for life**
  - Follow the water has been NASA’s goal – is the the right mantra?
  - Follow the energy (redox)?
- **What does it mean to be a mesophile?**
  - Are we the extreme organisms?

A Preview of Future Lectures

- **Ancient Crater lakes on Mars**
  - There was clearly a period in Mars history where substantial water was present on surface
  - How long? How much?
  - How long is needed for life development?
  - Where to look for fossils of that early life?
- **Many icy satellites have oceans**
  - Europa, Callisto, Enceladus

Psychrophiles

- **Cold lovers**
  - Temps 0-20°C
  - Survive freeze/thaw
  - Reproduce 2°C
  - Often tolerant of salty conditions
- **Habitats**
  - Soils
  - Deep ocean water
  - Sea ice
- **Least studied of - extremophiles**

Mesophiles

- **Moderate temperatures – most common**
  - Soil bacteria
  - Pathogens
- **Most pathogens grow best at 37°C**
  - Most food spoilage due to mesophiles

Eukaryotic Thermophiles

- **Habitats**
  - Moderate Temperatures
    - 30-60°C
  - Acidic environments
    - pH 1-4
- **All are anaerobes**
  - Solubility of O2 in water above 85°C is very low

Psychrobacter, Antarctic

CH4 worms, Sea of Cortez, Ice

Thermus aquaticus

Pyrodictium occultum – grows 105-115°C at hydrothermal vents. Most primitive

Sofolbus acidocaudarius (Italy)
Hyperthermophiles

- **Prokaryotes**
  - Temperatures
    - Low: 45-90°C
    - Optimal: 45-80°C
    - High extreme: 125°C
  - pH: 7-5
  - Can survive high pressure
- **Discovered within last 30 yr**
- **Location (submarine/terrestrial)**
  - Geothermal areas
  - Oil fields, 3 km deep
- **Energy**
  - Chemolithoautotrophic
  - Inorganic redox for E
  - CO₂ is only carbon source
  - e donors: H₂, Fe, reduced S

Barophiles – Deep Dwellers

- **The Geothermal gradient**
  - T increases with depth (~10°C per km below 100 km)
- **Deep, dark dwelling bacteria**
  - Tolerate high T, P (>100 atm)
  - Are usually thermophilic
  - Grow best at P = 500-600 atm
  - Tolerate periods up to 2.5 yr in vacuum
- **Habitats**
  - Up to 4 km depth
  - Barophilic mass > all surface life

Acidophiles / Alkaliphiles

- **Acidophiles**
  - Tolerate acidic habitats (pH 1-4)
  - Produce special enzymes to prevent cell destruction
  - (commercial application) – survive by keeping acid out
  - Environments: Volcanic regions, Coal mines
- **Alkalophiles**
  - Grow at pH > 10
  - Environments: Mud volcanos (subduction zones)
- **Acids & Bases**
  - Acid – substance that gives H⁺ into water
  - Base – decrease the concentration of H⁺ ions in H₂O
  - **pH Scale**
    - In 1 liter H₂O there are 1.0x10⁻⁷ mole of H⁺ and OH⁻
    - pH = -log[H⁺]
    - Pure water has pH=7

Deinococcus Radiodurans

“Conan, the Bacterium”

- **Characteristics**
  - Radiation resistant
    - Loss of viability 300x that which would kill most complex organisms
  - Genetic code repeats lots → identify & repair
  - Cold resistant
  - Vacuum resistant
  - Long dormancy
  - Oxidation resistant
- **History – around at life beginnings?**

Halophiles – Hypersaline Environments

- **Habitats**
  - Dry lake beds
  - Salt flats
  - Often very alkaline
  - Often very hot (thermophiles)
- **Adaptation**
  - Avoid dehydration – balance solution outside/inside
  - Require extreme NaCl for growth (saturated brines)

Xerophiles

- **Characteristics**
  - Surviving very dry conditions
  - Spores dormant in amber for > 130 Myr
- **Desert varnish**
  - Mineral precipitation on rocks (arid)
  - Magnetite producing bacteria

Dead Sea
Endoliths – Rock dwellers

- **Survival strategy for arid environments**
  - Bacteria / algae near surface of rock
  - Need access to sunlight
- **Characteristics**
  - Psychrophilic
  - Xerophilic
  - Phototrophs

Why show all these organisms?

- To show the possible environments in which life can exist
- To show how organisms have adapted
- To show that life fills every niche where T permits it and there is water

Chemoautotrophy on the Seafloor

- **Interaction of seawater & ocean floor**
  - Earth’s heat removal
  - Crust evolution: Changes in mineralogy, chemistry
- **Biological community support**
  - Concentration of trace chemical species
  - Potential for extensive biomass
  - Potential for exotic metabolisms
- **Analog for extraterrestrial fluid covered rocky bodies**

Geologic Settings – Water Rock Interactions

- **Mid ocean ridge axis**
  - Hot springs and hydrothermal plumes (80% of magma activity)
  - Mid ocean ridge flanks – warm springs
- **Subduction zones**
  - Forearc – mud volcanoes, gas hydrates
  - Arc volcanoes – hot springs
  - Hot spot volcanoes (50% e.g. Hawaii, Iceland)
- **Ocean basement** – solid rock portion under sediments
- **Making a Living**
  - Low cell abundance
  - Slow growing
  - Diverse metabolisms
  - Uneven distribution

Chemical transformations in Hydrothermal Systems

- Biogenic oxid-reduction reactions during fluid-SW mixing
- Abiogenic (degassing/ fluid-rock rxns)
Energetics at Hydrothermal Vents

- Amundsen et al., 2011

Chimney Life

- Conditions
  - Steep T gradients
  - Narrow living zone
- Macroscopic
  - Tubeworms
  - Blind shrimp – but with organs sensing 300k radiation

Serpentinization

- Chemical hydration of olivine
  \[(\text{Mg}_2\text{Fe}_3\text{Si}_2\text{O}_5)+\text{H}_2\text{O}+\text{C} = \text{Mg}_3\text{Si}_2\text{O}_5(O\text{H})_2 + \text{Mg(OH)}_2 + \text{Fe}_2\text{O}_3 + \text{H}_2 + \text{CH}_4 + \text{C}_2\text{QC}_5\]
  - Potential for supporting high-pH chemical ecosystems?
  - Can occur on continents too
- A process on Mars?
  - Evidence of the right chemistry on mars (olivine rich basalts) + water

Life in frigid places - Antarctica

- Physical characteristics
  - 5.4 x 10^6 sq mi
  - 7000 ft elevation
  - 75% all fresh water
  - \(T_\text{avg} = -70^\circ F\) (low \(-128.6^\circ F\) – \(-89^\circ C\))
  - Winds up to 300 km/hr
- Historical
  - Coal beds \(\rightarrow\) once clement
  - Pangea \(\rightarrow\) Myr
- Dry Valley Lakes
  - 1991 Expedition
  - Penetration 1978
  - H_2O just above freezing \(\rightarrow\) greenhouse effect
  - Enriched from spring runoff

Antarctic Dry Valleys – Hyper-Arid Cold Polar Desert

- Characteristics
  - 4000 km^2 mountainous
  - Coldest, driest deserts on Earth
  - Mean annual T \(-20^\circ C\)
  - Mean annual snow 0.6-10 cm – snow sublimates
  - Strong katabatic winds
  - Biology very sparse
- Excellent analog for Mars climate change studies
  - Lifetime & location of subsurface ice

Courtesy J. Head, NAI WS 2005 presentation
Mullins – debris covered glacier
**Lake Vostok**

- Largest of 70 sub-glacial lakes
- Discovered by radar imaging in 1996
- 1,500 km from coast, 3,500 m elevation
- 250km x 50km, max depth 800m, avg depth 340m
- The lake has 2 separate basins separated by a ridge → two different ecosystems?

**Most isolated aquatic environment on Earth**

- Cut off from outside environment 35-40 Myr ago
- \[ T_{air} = -89^\circ F, T_{lake} = -3^\circ C \]
- Oligotrophic environment – super saturated in oxygen (50x most lakes), likely due to pressure of ice sheet

**1998 Russian Core \( \rightarrow \) 3.623 km**

- Living organisms from 500-2,750 m (2.5 x 10^19 yr old)
- Low population diversity
- Utilized dissolved organic C and O migrating through ice
- 4 climate changes 20,000 to 100,000 yr periods ([CO₂])

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**Current Drilling Status**

- Russians approved in 2011 for penetration
  - Bio protection: pressure will cause lake water to enter borehole and freeze
  - They will return and sample the frozen ice
  - Feb. 2011 – had to stop for winter, 30 m above lake
  - Concern over kerosene poured into drill hole to keep it open?
  - Work now on accretion ice reported that 3700 species have been identified
    - eukarytes (6%), bacteria (94%), multicelled organisms – anerobic, aerobic, psychrophilic, halophilic

**Lake Whillans - Antarctica**

- US team drilled through 800 m of ice 2/2013
- Cell count 1000 bacteria per milliliter (1/10 ocean abundance)
- Lifestyle unknown – but must be chemoautotrophs

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**Life in Antarctic sea ice**

- Salts concentrate in veins in ice
  - Cold temperatures < -30°C
  - This suppresses the freezing point → brines
  - Bacteria found in liquid H₂O veins
  - May sustain bacterial metabolism

Deming, JW et al. 2002 Curr Opin in Microbiol

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**Lake Hoare – Taylor Valley**

- Environment much like Mars
  - Permanent ice cover
- Microbial mats
  - Increased oxygen levels
  - 1% sunlight
  - Algae draw Fe, S and calcite from water

10\% 80\%
**Life under ice (Glaciers)**

- **Source of energy**
  - Pyrite oxidation leads to dissolution of bedrock carbonate
  - This drives autotrophy – generates CO₂ for methanogens
  - Grinding up of bedrock by glacier makes H₂ – food for the methanogens

**Atacama Desert**

- **Conditions**
  - Driest place on Earth
  - Thin atmosphere
  - High radiation (UV) exposure
- **Sparsest life on Earth**
- **Terrain to test space bio detection instruments**

**Life on the Socompa Volcano rim– Atacama desert, Chile**

- **Microbial Environments**
  - Small vents producing CO₂, CH₄
  - Life surviving on small oases
  - Rain < 200 mm / yr
  - T averages -2°C
  - Altitude ~ 20,000 ft

**The atmosphere**

- **Microbes in the Atmosphere**
  - Serve as cloud condensation nuclei
  - Believed to be airborne spores
- **Could life live only in the clouds?**
  - Ideas on how to make membranes

**Rio Tinto**

- **Mined since 3000 BC**
  - Acidic (pH = 2)
  - Red = dissolved iron
  - Rocks → sulfides
  - Fe-oxidizing bacteria thrive here
- **Possibly similar to Mars wet environments?**
  - Opportunity / Spirit
  - S & Fe, Jarosite mineral

**“Recent” Microbial Developments**

- 1977 – Woese discovers 3rd domain: Archaea
- 1977 – Hydrothermal vents discovered
- 1986 – K. Mullis uses heat stable enzyme from *T. aquaticus* to amplify DNA
- 1995 – First microbial genome sequenced *H. influenzae*
- 2010 – 1st chemically synthesized bacterial genome, *Mycoplasma mycoides*
- Above – grand prismatic spring, Yellowstone
- Right – changing conditions drastically change microbial community