CO- EVOLUTION and PHYSICAL AND CHEMICAL FORCES THAT SHAPE LIFE

DKN (microbial focus)
- How do we search for life (continued…)
- On a planetary scale, what biosignatures does life leave?
- What key principle underpins such biosignatures?

MMN (larger organism focus)
- How has the abiotic world shaped form and function of multicellular organisms?
Prof. John Johnson is on the hunt for Exoplanets

1. There are many more small planets than large planets in the galaxy.
2. As many as 1-3 small planets per star.
3. 25% of stars have an Earth-mass planet with orbital period < 50 days.
Can we define generic “biosignatures” that could help us search for life on other planets? What would you look for if you were the chief scientist?

*nucleic acids, structural mineral deposits, H2O*

Mars Science Laboratory (MSL) “Curiosity” lands Aug. 5, 2012
Sometimes Mars comes to us, so we have a head start…
Sometimes Mars comes to us, so we have a head start…

4.5 Ga - Crystallized on Mars
15 Ma - ejeted
11 ka - Antarctica
1984 - Allan Hills, Ant.
1996 → Clinton - greatest scientific discoveries
Search for Past Life on Mars: Possible Relic Biogenic Activity in Martian Meteorite ALH84001


Fresh fracture surfaces of the martian meteorite ALH84001 contain abundant polycyclic aromatic hydrocarbons (PAHs). These fresh fracture surfaces also display carbonate globules. Contamination studies suggest that the PAHs are indigenous to the meteorite. High-resolution scanning and transmission electron microscopy study of surface textures and internal structures of selected carbonate globules show that the globules contain fine-grained, secondary phases of single-domain magnetite and Fe-sulfides. The carbonate globules are similar in texture and size to some terrestrial bacterially induced carbonate precipitates. Although inorganic formation is possible, formation of the globules by biogenic processes could explain many of the observed features, including the PAHs. The PAHs, the carbonate globules, and their associated secondary mineral phases and textures could thus be fossil remains of a past martian biota.

Science, 1996
What do you think?

- Abiotic processes?

clamp

chain

50nm single domain
Extra credit challenge (worth 2 correct iClicker questions)

What configuration of magnetite (chains or clumps) do you think is energetically preferred in the absence of life? (i.e. what would happen to the magnetite in *M. magneticum* if you dissolved its membranes and proteins?)

Based on what you have learned in Ph 1c, discuss qualitatively and/or quantitatively.

How does this affect your thinking about whether the magnetite in ALH8001 is a robust biosignature?

You can ask TAs for general guidance and collaborate with your fellow students, but what you turn in must be in your own hand.

Turn in at the beginning of class next Tuesday.
Life Detection: Let’s ground-truth this discussion with the Earth

What features of Earth that are linked to life (i.e. necessary for it or a product of it) that you can see from space?

$H_2O \rightarrow \text{pre-reg.}$

$\frac{2}{3}$

$\frac{\text{green}}{\text{chlorophyll}}$

$\text{biogenic trace}$

$\rightarrow \text{N}_2\text{O}$

$\text{CH}_4$ can make

$\rightarrow \text{concentration}$
Why is water good for life?

- Dissolves most things
- Solvent/liquid?
  - Rates for biochemistry
- Covalent bond formation
- H-bonds
- Floats when freezes → expands
- High heat capacity → regulates $T$
  - Compatible seasons, diurnal
- Large l.g. range (pure $H_2O$ 0°C - 100°C
  +Salt ↓freezing $T$
  ↑pressure ↑boiling $T$
Prospects for ‘Weird Life’?

Water = Polar solvent.

Could life ‘work’ in a non-polar solvent?
For instance, the liquid methane and ethane lakes of Saturn’s moon Titan?

Titan

Huygens lander image of what may have been a methane river basin. The rocks of water ice are ~10 cm across.

False color Radar image of Titan’s surface showing methane/ethane lakes.

Images: NASA/JPL/ESA
Life Detection: Let’s ground-truth this discussion with the Earth

Planetary spectra

Chlorophyll absorption in red

Prof. Geoff Blake (CCE,GPS)

Sagan, 1993
Is $O_2$ a Robust Biosignature?

i.e. If you don't detect $O_2$, does that mean there isn't life?

$$\text{CO}_2 + \text{H}_2\text{O} \xrightarrow{\text{oxy.pho.}} \text{CH}_2\text{O} + \text{O}_2$$

- an aerobic metabolism
- below detection limit
- below equilibrium
- no net accumulation of $O_2$

What sets the steady state level?

- Test J: Reductant
  - Until abiotic reductants are scavenged
- $H_2$: escape to space
- $CH_2O$: buried (coal)

Complex combination of physical, chemical and biological processes set the planetary redox state. This can (and has!) changed through time.
When did oxygenic photosynthesis evolve?

Fe^2+ → Fe^3+

Fe(OH)₃(s) → Banded Iron Formation
Generic Reaction:

\[ \text{A}_{\text{red}} + \text{CO}_2 \rightarrow \text{A}_{\text{ox}} + \text{CH}_2\text{O} \]

\[ \text{A}_{\text{red}} = \text{H}_2, \text{S}_{\text{red}}, \text{Fe(II)}, \text{H}_2\text{Os} \]
When did $O_2$ accumulate to the present atmospheric level (PAL)? Was $CH_4$ an early Earth biosignature?

Kasting, Scientific American
\[ 4\text{H}_2 + \text{CO}_2 \rightarrow \text{CH}_4 + 2\text{H}_2\text{O} \]

methanogenic archaea

Baxter Pond Volta Flame Movie

Prof. Orphan

Week 8
symbiotic other bacteria
Concept of **BIOGEOCHEMICAL DISQUILIBRIUM**: predictable layered sequence of metabolites

- Kill/poison → layers disappear
- Biological consume/production of metabolites outpaces μ-meters diffusion → centimeters

Kinetic fingerprint

Diatoms

Black Sea meters

Nealson and Conrad

Microbial mat

Purple bacteria

Cyano bacteria

Sulfate red

\[ \text{O}_2 \]/\[ \text{NO}_3^- \]/\[ \text{Fe}^{2+} \]/\[ \text{Mn}^{2+} \]/\[ \text{H}_2\text{S} \]/\[ \text{NH}_4^+ \]
BIOGEOCHEMICAL DISEQUILIBRIUM plays by thermodynamic rules.

- Redox couples: $A_{red}/A_{ox}$ vs. $A_{ox}/A_{red}$
  - Oxidation (lose e-) vs. Reduction (gain e-)

Redox reaction:

- $A_{red} + Box = A_{ox} + Bred$
- e-donor e-acceptor
- Reductant oxidant

- Going downhill (low to high potential) generates energy
- Going uphill (high to low potential) requires energy

Kirschvink and Kopf, Royal Society Trans.
Thermodynamic underpinning:

From physics, recall:
energy change = electric charge × voltage difference

\[ J = C \times V \]

In biology, we can express this as:

Gibbs free energy \( \Delta G = -nF\Delta E \)

n = number of electrons transferred from reductant (e- donor) to oxidant (e- acceptor)
F = Faraday’s constant (96,500 C × mol⁻¹)
\( \Delta E \) = difference in potential between reductant and oxidant

Rule, more \( \Theta \), \( \Delta G \), ↑ energy

Week 4/5
CO-EVOLUTION and PHYSICAL AND CHEMICAL FORCES THAT SHAPE LIFE

DKN TAKE HOME MESSAGES
- How do we search for life (continued…)
  - Exhaust all possible abiotic alternative
  - "Geobiology" \( \Rightarrow \) Earth + control
- On a planetary scale, what biosignatures does life leave?
  - \( \text{O}_2 \), \( \text{N}_2\text{O} \), …
  - Photosyn. pigments
- What key principle underpins such biosignatures?
  - Chemical disequilibria driven by microbial metabolism \( \Rightarrow \) myriad variety of solutions
CO-EVOLUTION and PHYSICAL AND CHEMICAL FORCES THAT SHAPE LIFE

DKN (illustrating using microbes)
- How do we search for life (continued from Tuesday)
- On a planetary scale, what biosignatures does life leave?
- What key principle is behind this?

MMN (illustrating using larger organisms)
- How has the abiotic world shaped form and function of multicellular organisms?
Adaptations to aquatic vs. terrestrial (vs. aerial) existence:

* Supporting the body

   Exchanging $O_2$ and $CO_2$

* Reproducing

   Avoiding desiccation
Forces acting on biological systems:

- Compression
- Tension
- Bending
- Shear
- Torsion

Stress - intensity
Strain (measurement of deformation)
Forces that shape biological systems:

- Compression
- Tension
- Bending
- Shear
- Torsion
Perhaps, the most striking difference between water and air?

Density \( (\rho = \text{mass} / \text{volume}) \) [at sea level, 20°C]

\[
\begin{align*}
H_2O / m^3 &= 1000 \text{ kg} \\
+ Air / m^3 &= 1.2 \text{ kg}
\end{align*}
\]

\( 830 \times \)
Weight = \( m \cdot g \)

\[ \rho - \rho_f \]

\( \rho \) = density

\( \rho_f \) = density of medium

\((\rho - \rho_f)\) = effective density

Most biological forms density is \( \frac{1100}{1000} \, \text{kg/m}^3 \)

\( \approx \frac{1}{1000} \, \text{kg/m}^3 \)

\( \approx 1 \, \text{g/cm}^3 \)

\( \uparrow \)

Float
Compare a pine tree and kelp:

- 20 - 30 m length
- Canopy for photosynthesis
- Distal ends
- Both 1,000 kg/m³

<table>
<thead>
<tr>
<th>Pine</th>
<th>Kelp</th>
</tr>
</thead>
<tbody>
<tr>
<td>trunk diameter 0.5 m</td>
<td>0.05 m</td>
</tr>
<tr>
<td>height 1.2 m</td>
<td>1.2 m</td>
</tr>
</tbody>
</table>
Forces acting on biological systems:

- compression
- tension
- bending
- shear
- torsion

Principal forces in air: Compression (bending)

Principal forces in water: Tension (shear)
Structural members strained principally in:

- Tension
- Compression
Plants – investment in supportive materials

Intracellular material

Primary cell wall
Secondary cell wall
Plasma membrane

Lignocellulose (biofuels)

Cellulose

β 1-4-linked glucose

Lignin

Jarod Leadbetter

termite
Animals – structure/function of the skeleton in:

1. feeding
   - in water – **INCOMPRESSIBLE**
   - in air – **COMPRESSIBLE** (tongue muscle)

2. locomotion
   - in water – working against medium
   - on land – working against substrate (gravity)
<table>
<thead>
<tr>
<th>Animal</th>
<th>km/h</th>
<th>body-lengths/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cheetah</td>
<td>112</td>
<td>25</td>
</tr>
<tr>
<td>House cat</td>
<td>48</td>
<td>29</td>
</tr>
<tr>
<td>Human (Michael Johnson)</td>
<td>45</td>
<td>7</td>
</tr>
<tr>
<td>Tiger beetle</td>
<td>1.9</td>
<td>125</td>
</tr>
<tr>
<td>[Sailfish]</td>
<td>112</td>
<td>25</td>
</tr>
</tbody>
</table>
Adaptations to aquatic vs. terrestrial (vs. aerial) existence:

* Supporting the body
  Exchanging $O_2$ and $CO_2$
* Reproducing
  Avoiding desiccation
Reproductive 'Strategy'

Ploidy = # of chromosome sets

Haploid: 'n'
Diploid: 2n
Polyploid: 3n+2
Evolution in Reproductive ‘Strategy’ - Plants

In plant evolution:

Dominance: \[ \frac{n}{2n} \rightarrow \frac{2n}{n} \]

mosses - ferns - seed plants

seeds

motile sperm

pollen
Animals – Reproductive Strategy

broadcast
Animals – Reproductive Strategy


Take-home message:

The presence or absence of an aqueous environment has been a key driver of evolutionary selection pressure on the form and function of multicellular Eukarya.