Gaia Revisited: The Interplay Between Climate and Life on the Early Earth

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The Gaia Hypothesis

- Earth’s climate is regulated by (and for?) the biota

James Lovelock/
Lynn Margulis

1979

1988
<table>
<thead>
<tr>
<th>EON</th>
<th>ERA</th>
<th>Duration in millions of years</th>
<th>Millions of years ago</th>
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</thead>
<tbody>
<tr>
<td>Phanerozoic</td>
<td>Cenozoic</td>
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<tr>
<td></td>
<td>Mesozoic</td>
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<tr>
<td></td>
<td>Paleozoic</td>
<td>295</td>
<td>543</td>
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<tr>
<td></td>
<td>Late</td>
<td>357</td>
<td>900</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>700</td>
<td>1600</td>
</tr>
<tr>
<td></td>
<td>Early</td>
<td>900</td>
<td>2500</td>
</tr>
<tr>
<td></td>
<td>Late</td>
<td>500</td>
<td>3000</td>
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<td>Precambrian</td>
<td>Middle</td>
<td>400</td>
<td>3400</td>
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<tr>
<td></td>
<td>Early</td>
<td>400</td>
<td>3800</td>
</tr>
<tr>
<td></td>
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<td>800</td>
<td>4600</td>
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</table>

Geologic time

- First shelly fossils (Cambrian explosion)
- Snowball Earth ice ages
- Rise of atmospheric O₂ (Ice age)
- Ice age (?)
- Warm (?)
- Origin of life
The Faint Young Sun Problem

• From a theoretical standpoint, it is curious that the early Earth was warm, because the Sun is thought to have been *less bright*.

• This decrease in solar luminosity could have been offset either by higher CO$_2$, higher CH$_4$, or both.

The Carbonate-Silicate Cycle

- Silicate weathering slows down as the Earth cools
  ⇒ atmospheric CO$_2$ should build up
• Thus, atmospheric CO$_2$ levels may well have been higher in the distant past. However, there are good reasons for believing that CH$_4$ was abundant as well.

• The first is that atmospheric O$_2$ levels were low…
Geologic O$_2$ Indicators

H. D. Holland (1994)
• Even better evidence for low O$_2$ during the Archean is provided by *mass-independent fractionation (MIF)* of sulfur isotopes in ancient rocks ⇒
$\Delta^{33}S$ versus time

73 Phanerozoic samples

Farquhar et al., *Science*, 2000
Archean Sulfur Cycle

Sulfur photochemistry in an anoxic early atmosphere. The sulfur oxidation state is indicated along the horizontal axis. Sulfur is emitted to the atmosphere from volcanoes as SO₂ and H₂S and is removed by rain-out of soluble gases and by formation and deposition of sulfate and elemental sulfur particles.

Original figure drafted by Kevin Zahnle
• A second reason for suspecting that CH$_4$ was abundant on the early Earth is that the biological source of (most) methane is probably ancient.
• Today, CH$_4$ is produced in restricted, *anaerobic* environments, such as the intestines of cows and the water-logged soils underlying rice paddies
  – Update (Keppler et al., *Nature*, Jan., '06): Methane is also produced by plants!

• *Methanogenic bacteria* are responsible for most methane production
Archean CH$_4$ concentrations

• It can be shown that CH$_4$ production rates in an anaerobic biosphere could have been comparable to today (P. Kharecha et al., *Geobiology*, 2005)

• Because O$_2$ was low, the lifetime of methane would have been long (~10,000 yrs), and CH$_4$ could have accumulated to **1000 ppmv** or more (as compared to **1.7 ppmv** today)

• This is enough to produce a substantial *greenhouse effect* (~20-30 degrees) (Pavlov et al., *JGR*, 2000)
One of the most attractive features of the methane greenhouse model is that it correlates well with the *glacial record*.
Geologic time

First shelly fossils (Cambrian explosion)  
Snowball Earth ice ages

Rise of atmospheric O₂ (Ice age)

Ice age (?)

Warm (?)

Origin of life

~2.4 Ga

~2.9 Ga
Huronian Supergroup (2.2-2.45 Ga)

S. Roscoe, 1969
• The Paleoproterozoic glaciations (2.4-Ga) are nicely explained by the rise of atmospheric $O_2$ and the collapse of the methane greenhouse

• What about the mid-Archean glaciations (2.9-Ga)?
Mid-Archean glaciations

Diamictites dated at ~2.9 Ga are found in several different localities:

- Pongola Supergroup of S. Africa
- Witwatersrand Basin, also in S. Africa
- Belingue greenstone belt in Zimbabwe

_Courtesy of S. Ono_
$\Delta^{33}S$ vs. time (compiled by S. Ono)

H. Ohmoto and Y. Watanabe also have low-$\Delta^{33}S$ pyrite from the 2.76-Ga Hardey formation and the 3.0-Ga Mosquito Creek formation in Australia (Tokyo, May, 2005)

H. Strauss also has low-MIF sulfur from the Kaapvaal craton in South Africa from about this same time.
Possible mechanisms for causing the mid-Archean glaciations

1. “Yo-yo” atmosphere (Ohmoto; S. Ono)
   - $O_2$ levels go up briefly, then go back down

2. Highly reduced atmosphere (A. Pavlov)
   - $H_2$ and/or $CH_4$ levels are very high, so that all the sulfur exits the atmosphere as $H_2S$

3. Organic haze hypothesis (Goldman & Kasting; Peters, Farquhar, & Strauss)
   - Organic haze produced from $CH_4$ photolysis produces an *anti-greenhouse effect* that cools the climate
Titan’s organic haze layer

Haze is thought to form from photolysis (and charged particle irradiation) of CH$_4$

(Picture from Voyager 2)
• Organic haze is predicted to form in Earth’s early atmosphere when the CH$_4$/CO$_2$ ratio is > 1
• “MIF flux” = column-integrated dissociation rate of SO$_2$ at $\lambda < 220$ nm
### Possible Evolutionary Sequence

<table>
<thead>
<tr>
<th>Time (Ga)</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 3.2</td>
<td>CH₄ &lt;&lt; CO₂. No haze. Methanogens evolve during this time</td>
</tr>
<tr>
<td>3.2</td>
<td>CO₂ levels drop so that CH₄ ≈ CO₂. Thick organic haze forms, glaciation occurs</td>
</tr>
<tr>
<td>2.7</td>
<td>Cyanobacteria evolve, O₂ appears in water column (oxygen oases), sulfate increases, CH₄ production goes down, organic haze becomes thinner, climate warms</td>
</tr>
<tr>
<td>2.4</td>
<td>Atmospheric O₂ goes up, new episode of glaciation</td>
</tr>
</tbody>
</table>
Organic carbon isotopic record

Pavlov et al., *Geology* (2001) [Data from J. Eigenbrode and K. Freeman]

- The extremely light kerogens at 2.6-2.8 Ga have been interpreted (by John Hayes) as evidence for the onset of oxygenic photosynthesis.
Conclusions

• CH$_4$ was probably an important greenhouse gas during the Archean (1000 ppmv or greater)
• The Paleoproterozoic glaciations at ~2.4 Ga were likely triggered by the rise of O$_2$ and a corresponding decrease in CH$_4$
• The mid-Archean glaciations at 2.9 Ga may have been triggered by an increase in CH$_4$ and the corresponding development of a thick organic haze layer
• All of this is very “Gaian”. Score one for James Lovelock!