Add life, plate tectonics, planetary evolution, and incorporate advances of the past 25 years.

Underlying themes are the connections among the different parts of the Earth system: solid earth, climate, biology, and human beings.

http://press.princeton.edu/titles/9691.html
www.habitableplanet.org

**Anthropocene or Anthropozoic?**

- Energy and relationship revolutions of human civilization are more significant planetary events than any of the past eon boundaries
- Energy revolution larger than the aerobic respiration
- Relationship on an entire species and planetary scale
- Directed Evolution
- Technologically assisted intelligence and physical capability
- Possibility of communication and exchange with other planetary bodies

**Big Earth/Climate questions**

- Do relationship revolutions occur in the climate system? Has there been greater connectivity and stability with time?
- The "Walker World" model (weathering feedback leads to climate stability) looks ripe for a paradigm shift
- Is the Hayes and Waldbauer concept of progressive addition of CO₂ to the surface correct?
- What are the implications of volatile outgassing and recycling for solid Earth models?

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**MANTLE MELTING - CLIMATE CONNECTIONS**

CHARLES LANGMUIR, PETER HUYBERS
HARVARD UNIVERSITY

**Planetary Evolution as progressive transformation of energy and relationship**

- Planetary evolution as energy transformation: the development of a "planetary fuel cell"
- The geological evidence for when events happened
- Perspectives on the rise of oxygen
- Planetary evolution as relationship transformation
- Human civilization from this perspective
- Implications for planetary evolution in the cosmos
WHERE WE ARE HEADED

- Climate puzzles on ice age time scales that have been difficult to resolve
- Evidence that volcanism fluctuates with ice age cycles on land
- How melting happens at ocean ridges and convergent margins
- How pressure changes associated with ice age cycles may influence melting in both types of plate margins
- Potential feedbacks between climate and volcanism
- Research questions

Climate Puzzles

Ice volume and CO$_2$ vary in near lock-step during the Pleistocene

1. Why does CO$_2$ change?
2. What links CO$_2$ to ice-volume?
3. Why is the record saw-toothed?
4. Why is 100 ka the dominant period?
5. Why does the Pleistocene have glacial cycles?

Of course climate is influenced by the ocean and biosphere... but no convincing solutions to the puzzles have emerged.

Might the solid Earth also be important?

The mantle is by far the largest carbon reservoir

<p>| | |</p>
<table>
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<tr>
<td>Other rocks</td>
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<td>MANTLE</td>
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</table>

Data from Hayes and Waldbauer (2006) Units in examoles (10$^{18}$ moles)

Might there be an elephant in the room?
Basaltic glass can be recovered routinely from ocean ridge volcanoes, providing a pristine petrological signal.

There is a physical basis for a linkage between deglaciation and mantle melting.
The effect of deglaciation on mantle melting beneath Iceland
Jull and McKenzie (JGR, 1996).

Is there a deglacial effect elsewhere than Iceland?

Volcan Llaima, Chile

Mt. Mazama
Eruption
Record,
Cascades
Range, NW
USA

Even volcanoes at low latitudes can be glaciated

~65% of eruptive Volume occurs within a few thousand years of deglaciations

Bacon and Lanphere, 2006

Data from Nowell, Jones & Pyle 2006

Even volcanoes at low latitudes can be glaciated.
Eruption frequency (events/ky) during the glacial (40-20ka)

Huybers and Langmuir (2009)

Eruption frequency during the deglaciation (18-7ka)

Eruption frequency during the late Holocene (5-0ka)

Eruption frequency ratio: deglaciation/glaciation

Laacher See
Eruption 12,900B.P.

Temporal distribution of observed subaerial volcanic events

Data from Volcanoes of the World dataset of Siebert and Simkin (2002) and a compilation by Bryson, Bryson and Reuter (2006).
Eruption frequency ratio: deglaciation/late Holocene

Rates of observed eruptions

Volcanic activity over the last 40 Ka.

Comparison with the GISP2 (Greenland ice core) volcanic sulphate record

Mechanisms: Is glacial unloading sufficient to provide such an increase in volcanism?

Possibly. Melt production caused by 200m of ice removal from a 60km swath over 15,000km of convergent margin produces requisite magma volume. ~10% of mountain glaciers and small ice caps (Denton and Hughes, 1981).
Mechanisms: Eruption pacing may also be a viable mechanism.

Glaciers pressurize magma reservoirs. Assume ±5% variation in eruption threshold that scales with ice volume (oxygen isotope record).

No change in rate of melt production.

But the deglacial pulse can be far from glaciers

Data from Nowell, Jones & Pyle 2006

Kutterof et al 2012
The observational evidence shows a link between deglaciation and subaerial volcanism.

One mechanism could be enhanced melt production due to pressure release.

Another mechanism could be eruption pacing.

And there is more to the story, because neither of these mechanisms explain enhanced volcanism adjacent to ice sheets.

All of these would have a positive feedback with CO$_2$ volcanic emissions.

Are the CO$_2$ emissions large enough to influence the climate system?

For this, we need to estimate the magnitude of CO$_2$ emissions from eruptions— not a straightforward problem.

- Scaling our estimate of global volcanic rates by 0.1 to 0.15 Gt CO$_2$/yr for modern rates leads to 1000 to 5000 Gt CO$_2$ emitted above a baseline scenario of current volcanic emissions.

Are the volcanic emissions significant?

- Atmosphere: 750 Gt CO$_2$
- Deglacial Emissions: 1000-5000 Gt CO$_2$

But only about 15% of emissions stay in the atmosphere. Most are taken up by the oceans.
Volcanogenic contribution to atmospheric CO₂

**IMPLICATIONS**

**OCEAN RIDGES**
- 80% of Earth’s Volcanism
- Continually Creating 70% of Earth’s Surface
- Primary Flux of Material from Mantle to Surface
- Rest Directly on the Mantle and Reveal Mantle Properties
- Have the Advantage of Glasses that Directly Reveal Magma Compositions

Volcanic emissions

Melting Ice Causes Rising Sea Level

Does sea level change also have an impact?
There is a physical basis for a linkage between sea level and mantle melting. The pressure effect of sea level rising decreases mantle melting, while falling increases it. East Pacific Rise and Clipperton Transform Fault are shown.

PUZZLE: What is the origin of Abyssal Hills, and what controls their spacing?

Juan de Fuca bathymetry and magnetic isochrons

Time series and spectral estimates from bathymetry
There is also a potential link between magmatism and ridge crest hydrothermal activity

Lund and Asimow, 2011

Piston Cores with Basalt

Piston cores can sample seafloor lavas and overlying sediments

Time Series Have Never Been Possible for Ocean Ridge Basalts
You cannot date the basalts
Dredges off axis are restricted to fault scarps, and are altered by long exposure to seawater

There may now be the possibility of obtaining million year times series of glass compositions from global ridge segments.
Methodology: Construct chronology of MORB glass compositions for Clef segment (JDF) using pyroclastic material (Limu Pele) from sediment cores taken near ridge axis.

Results: Electron-probe analysis of glass shards from one piston core (~80 kys)

Possible interpretation of magmatic time-series:

1. Spatial versus temporal signal? i.e. on versus off-axis volcanism?

2. Change in primary melt flux due to mantle dynamics — longer residence time in crust, change in primary composition (why offset?)

3. Potential control by sea-level on crustal residence times and mantle melting

Preliminary d18O data indicates a possible climate transition

Ongoing work to analyze more cores, trace elements, isotopes and climate/sedimentary record

Summary

Basaltic glass shard recovered from sediment cores can be used to measure a time-series of MORB compositions over 10s kys

These records can be compared to changes in climate and hydrothermal activity from measurements made in the same sediment horizons

Preliminary data for the d18O documents significant shifts in magmatism driven by changes in crustal and mantle processes

On-going work at this and other ridges will be used to test the extent to which MORB magmatism/volcanism may be coupled to the climate system

Might the Subaerial and Oceanic Influence be a Coupled System?

1. Slight warming triggers subaerial volcanism, raising CO2 and leading to rapid exit from glacial maximum

2. Sea level rises, suppressing CO2 with a 40,000 year time lag (?)

4. Glaciers grow, suppressing subaerial volcanism

5. Sea level falls, and CO2 emissions from ridges rise

6. Milankovitch forcing causes glaciers begin to melt, triggering next CO2 rise and warming
Emerging Questions

1. Is the volcanic response 2-3x or 3-5x?
2. Does this effect extend beyond the most recent deglacial?
3. Eruption frequency is not eruptive volume...
4. Does CO$_2$ emission change with frequency and volume?
5. Are CO$_2$ contents of primary arc magmas 1 wt. %?
6. Do other aspects of ocean ridges, such as hydrothermal activity, and basalt composition respond to sea level change?
7. Is there a coupled feedback in the solid Earth/climate system on Milankovitch time scales?

Data from Andy Calvert, Tom Sisson, Charlie Bacon--USGS

Conclusions

1. Global volcanism increases between 12 to 6 Ka consistent with deglacial forcing.
2. Increased volcanism may emit an additional 1000 to 5000 Gt CO$_2$, consistent with the secondary rise in CO$_2$ coming out of the last glacial. By similar logic, a deficit of volcanic activity during glacialiation draws down CO$_2$.
3. Ocean ridges must also be influenced by sea level change. Initial tests show Milankovitch periodicities in sea floor bathymetry.
4. Volcanism may be an important feedback influencing whether Milankovitch Cycles are expressed as ice age cycles.
5. If volcanic forcing from 3000 Gt CO$_2$ over 5000 years has such an influence on the climate system, what will happen from 5000 Gt CO$_2$ in 100 years from human civilization?