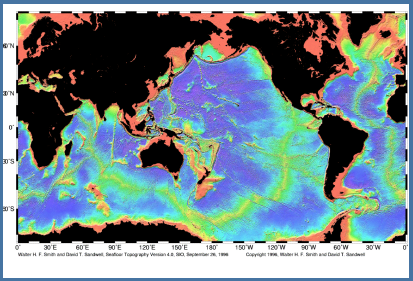
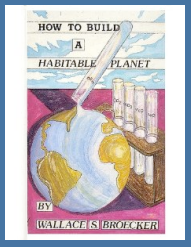
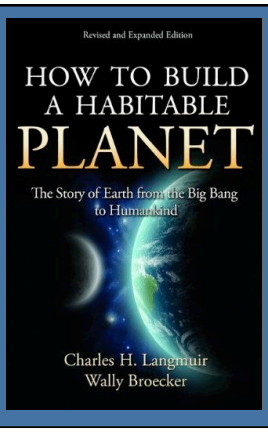
MANTLE MELTING - CLIMATE CONNECTIONS



CHARLES LANGMUIR, PETER HUYBERS
HARVARD UNIVERSITY

Wally Broecker





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

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

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

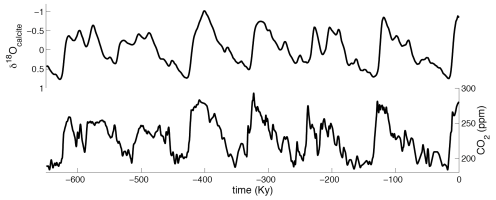
- Do relationship revolutions occur in the climate system? Has there been greater connectivity and stability with time?
- The "Walker World" model (weathering feedback leads to climate stability) looks ripe for a paradigm shift
- Is the Hayes and Waldbauer concept of progressive addition of CO_2 to the surface correct?
- What are the implications of volatile outgassing and recycling for solid Earth models?

WHERE WE ARE HEADED

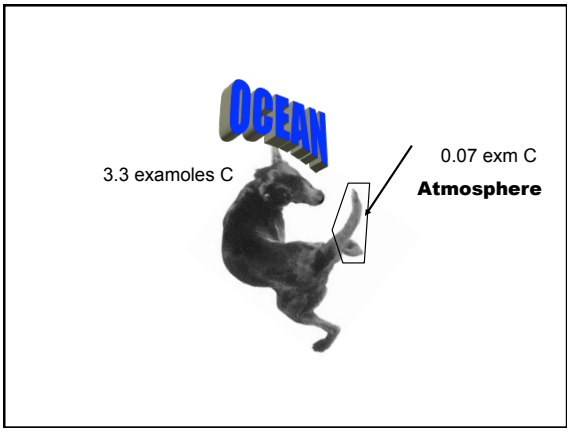
- ❑ Climate puzzleson ice age time scales that have been difficult to resolve
- ❑Evidence that volcanism fluctuates with ice age cycles on land
- ❑How melting happens at ocean ridges and convergent margins
- ❑How pressure changes associated with ice age cycles may influence melting in both types of plate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

Climate Puzzles

Ice volume and CO_2 vary in near lock-step during the Pleistocene



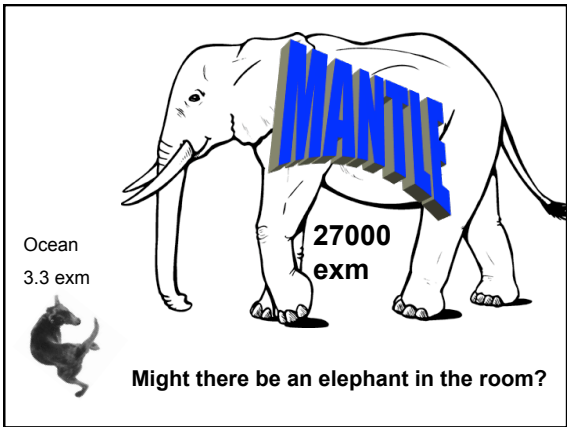
1. Why does CO_2 change?
2. What links CO_2 to ice-volume?
3. Why is the record saw-toothed?
4. Why is 100 ka the dominant period?
5. Why does the Pleistocene have glacial cycles?

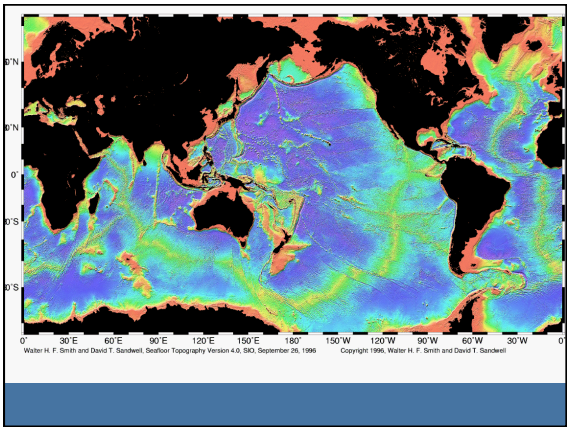


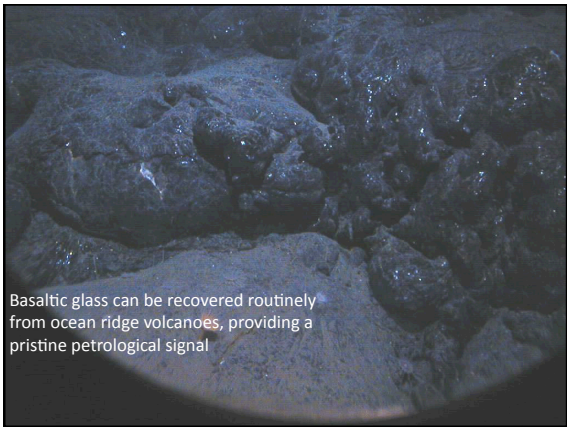
The mantle is by far the largest carbon reservoir

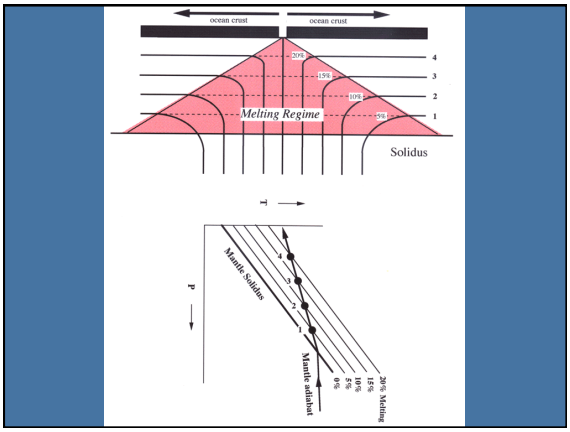
Atmosphere	0.07
Biosphere	0.13
Hydrosphere	3.3
Deep Sea Sediments	1360
Continental Margins	>1370
Sedimentary Rocks	4250
Other rocks	300-500
TOTAL SURFACE	**~7350**
MANTLE	**27000**

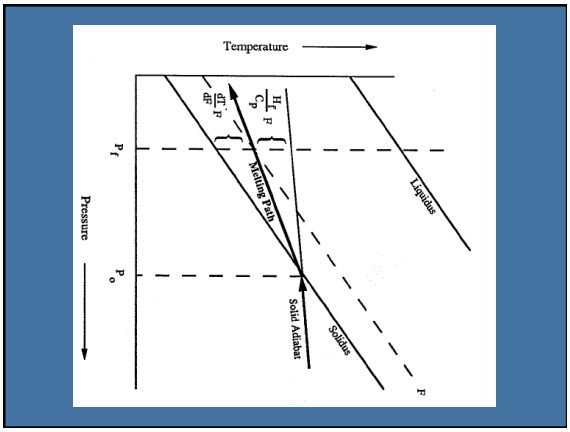
Data from Hayes and Waldbauer (2006) Units in examoles (10^{18} moles)

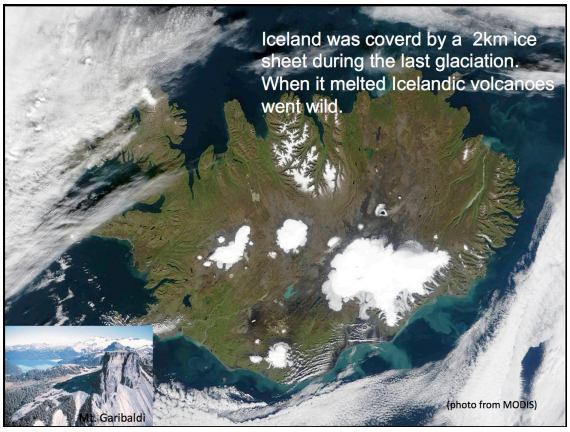


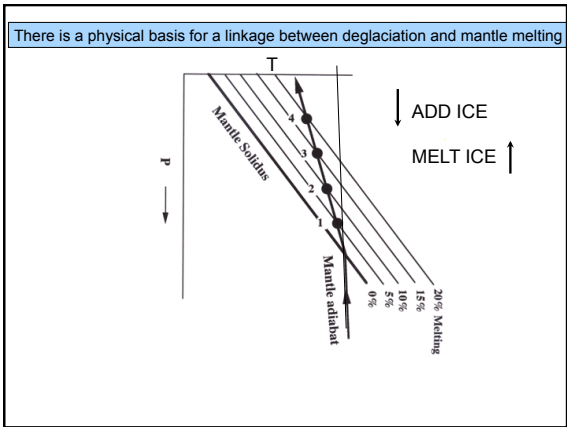

60°N
30°N
0°
30°S
60°S
0° 30°E 60°E 90°E 120°E 150°E 180° 150°W 120°W 90°W 60°W 30°W 0°
Walter H. F. Smith and David T. Sandwell, Seafloor Topography Version 4.0, SIO, September 26, 1996
Copyright 1996, Walter H. F. Smith and David T. Sandwell


Basaltic glass can be recovered routinely from ocean ridge volcanoes, providing a pristine petrological signal

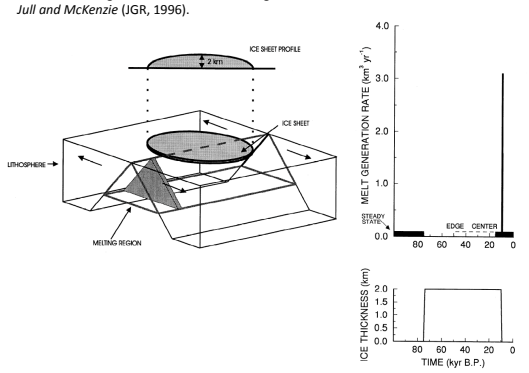

ocean crust
ocean crust
Melting Regime
Solidus
T
P
Mantle Solidus
Mantle adiabat
0%
5%
10%
15%
20% Melting


Temperature
Pressure
Pf
Po
Melting Path
Liquidus
Solid Adiabat
Solidus
F

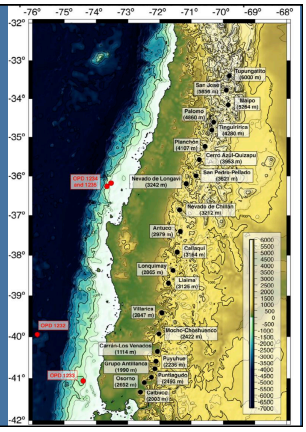

Iceland was coverd by a 2km ice sheet during the last glaciation. When it melted Icelandic volcanoes went wild.
Mt. Garibaldi
(photo from MODIS)

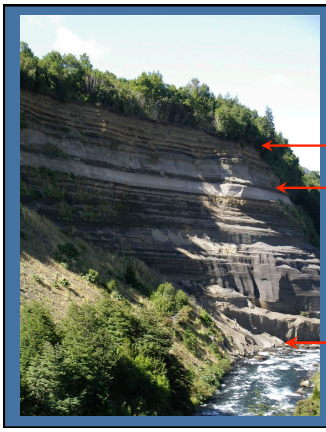

There is a physical basis for a linkage between deglaciation and mantle melting
T
P
Mantle Solidus
ADD ICE
MELT ICE
Mantle adiabat
0%
5%
10%
15%
20% Melting

The effect of deglaciation on mantle melting beneath Iceland
Jull and McKenzie (JGR, 1996).



Is there a deglacial effect elsewhere than Iceland?





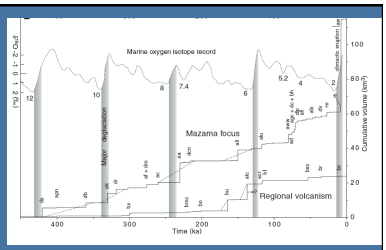
Volcan Llaima, Chile

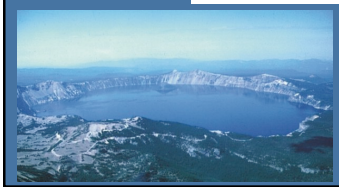
Present

7,500 yrs B.P.

13,500 yrs B.P.

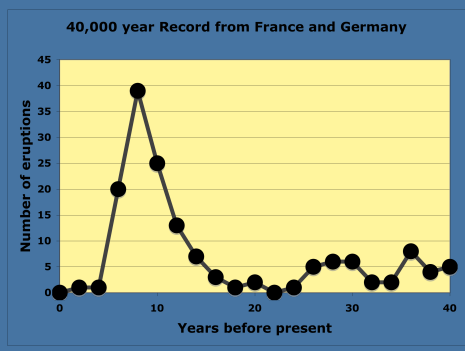
Mt. Mazama Eruption Record, Cascades Range, NW USA



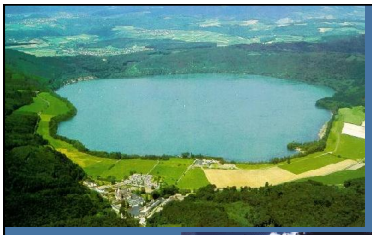


~65% of eruptive Volume occurs within a few thousand years of deglaciations

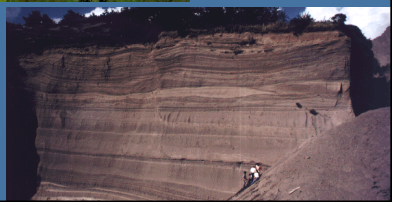
Bacon and Lanphere, 2006



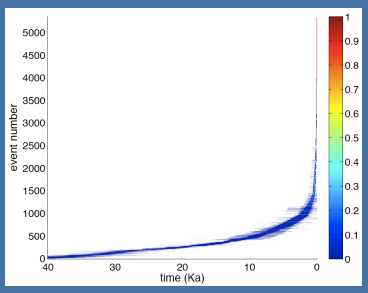
Data from Nowell, Jones & Pyle 2006



Laacher See Eruption 12,900B.P.

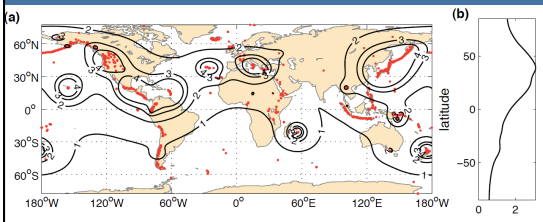


Temporal distribution of observed subaerial volcanic events



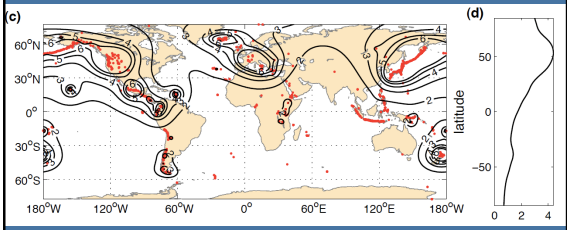
Data from Volcanoes of the World dataset of Siebert and Simkin (2002) and a compilation by Bryson, Bryson and Reuter (2006).

Eruption frequency (events/ky) during the glacial (40-20ka)

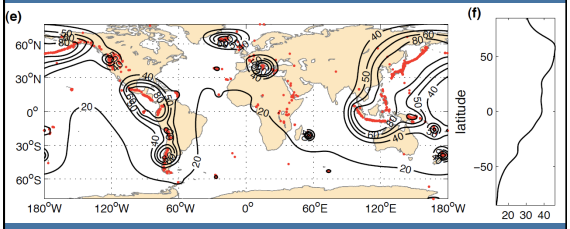


Huybers and Langmuir (2009)

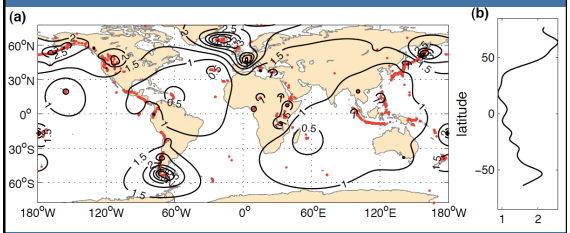
Eruption frequency during the deglaciation (18-7ka)



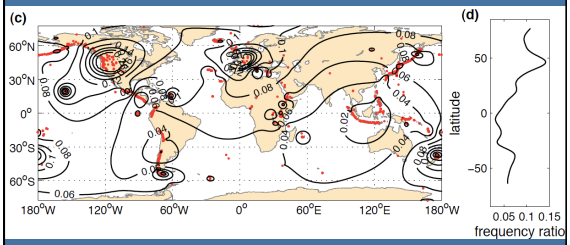
Eruption frequency during the late Holocene (5-0ka)



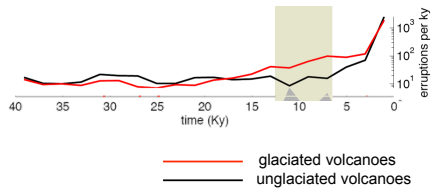
Eruption frequency ratio: deglaciation/glaciation



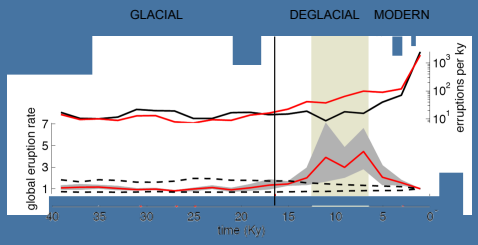
Eruption frequency ratio: deglaciation/late Holocene



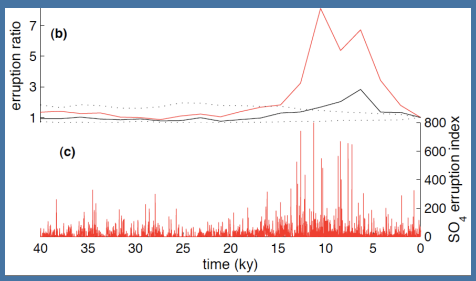
Rates of observed eruptions



Volcanic activity over the last 40 Ka.

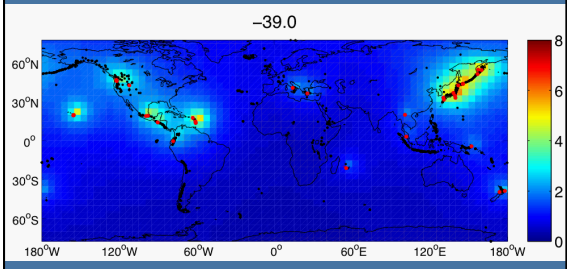


Comparison with the GISP2 (Greenland ice core) volcanic sulphate record



(Zielinski, QSR 2000)

Estimate of global subaerial volcanic activity

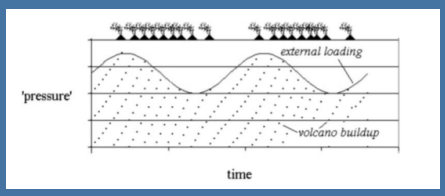


Mechanisms: Is glacial unloading sufficient to provide such an increase in volcanism?

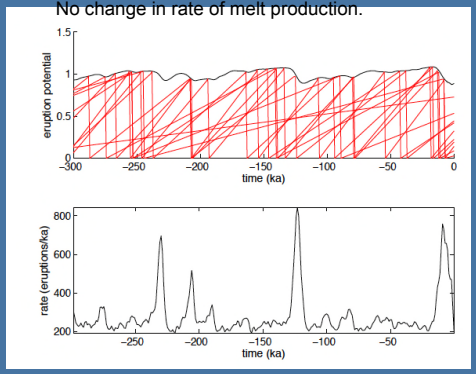
Possibly. Melt production caused by 200m of ice removal from a 60km swath over 15,000km of convergent margin produces requisite magma volume. ~10% of mountain glaciers and small ice caps (Denton and Hughes, 1981).

Mechanisms: Eruption pacing may also be a viable mechanism.

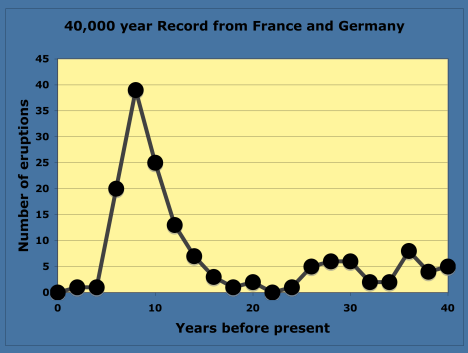
Glaciers pressurize magma reservoirs. Assume ±5% variation in eruption threshold that scales with ice volume (oxygen isotope record).



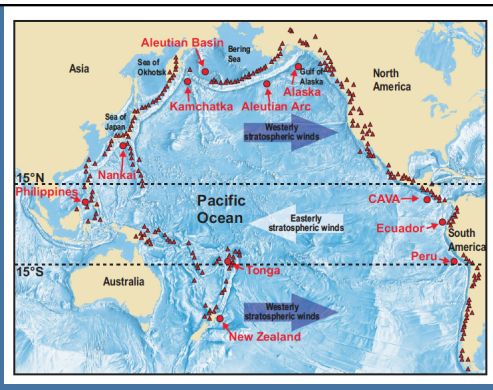
No change in rate of melt production.



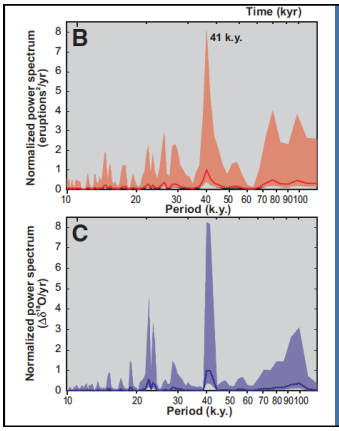
But the deglacial pulse can be far from glaciers



Data from Nowell, Jones & Pyle 2006



Kutterof et al 2012



Power Spectrum of Tephra Layers

Power Spectrum of $\delta^{18}O$ record

Kutterolf et al 2012

WHAT WE KNOW

- 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.

How much CO_2 do subaerial volcanoes emit?

- **THREE ESTIMATES AGREE**
- Modern magmatic production at arcs is ~3 km³/yr (*Crisp*, 1984; *Carmichael*, 2002; *Dimilanta*, 2002), times 1% CO_2 in primary magmas puts emissions at 0.1 Gt CO_2 per year (*Marty and Tolstikshin*, 1998; *Fischer et al.*, 1998). Subaerial emissions at non-converging margins may contribute another 0.05 Gt CO_2 per year (*Hilton et al.*, 2002). **~0.15Gt CO_2 / yr**

- The CO_2/Nb ratio of mantle derived rocks is ~500. 3 ppm Nb in arc magmas leads to 0.15% mantle CO_2. $pCO_2/^3He$ suggests 80-90% of CO_2 is not mantle derived, hence 1% CO_2 in arc magmas, or **~0.15Gt CO_2 / yr.**

- Direct measurements of CO_2 indicate a range of 0.05 to 0.15 Gt CO_2 per year (*Goff et al.*, 2001; *Varekamp et al.*, 1992; *Sano and Williams*, 1996; *Gorman et al.*, 2006). Mt Etna alone was observed to emit ~0.04 Gt CO_2 per year (*Williams*, 1992). **0.05 to 0.15Gt CO_2 / yr**

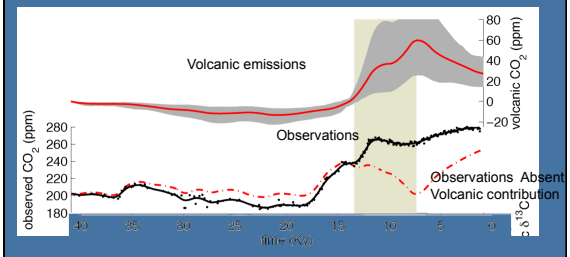
- Scaling our estimate of global volcanic rates by 0.1 to 0.15 Gt CO_2/yr for modern rates leads to **1000 to 5000 Gt CO_2** emitted above a baseline scenario of current volcanic emissions

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 .

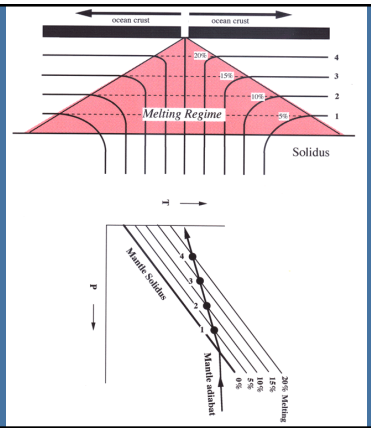
Volcanogenic contribution to atmospheric CO_2

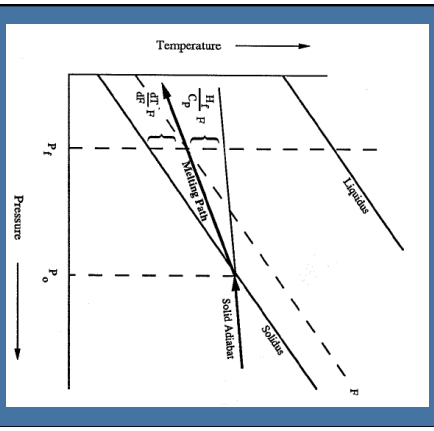


IMPLICATIONS

OCEAN RIDGES

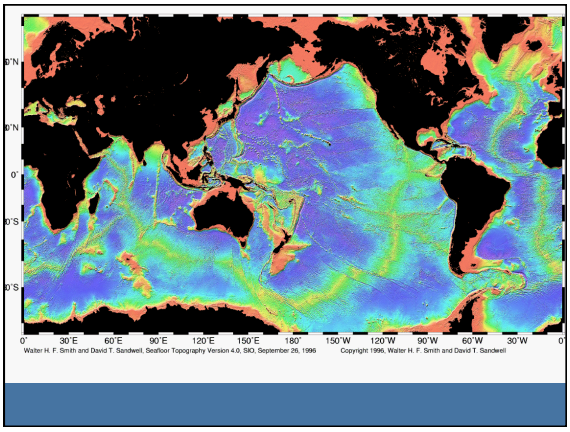
- 80% of Earth's Volcanism
- Continually Creating 70% of Earth's Surface
- Primary Flux of Material from Mantle to Surface
- Rest Directly on the Mantle and Reveal Mantle Properties
- Have the Advantage of Glasses that Directly Reveal Magma Compositions



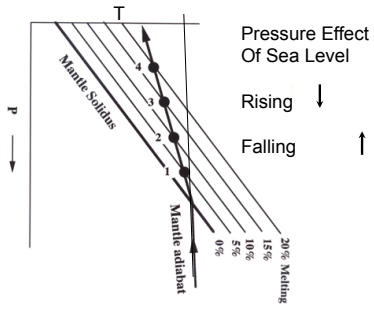


Melting Ice Causes Rising Sea Level

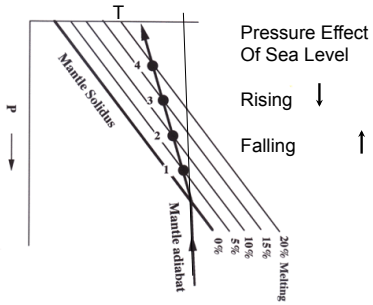
Does sea level change also have an impact?



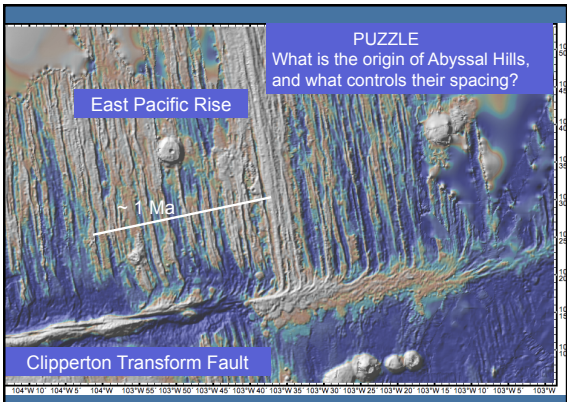
There is a physical basis for a linkage between sea level and mantle melting

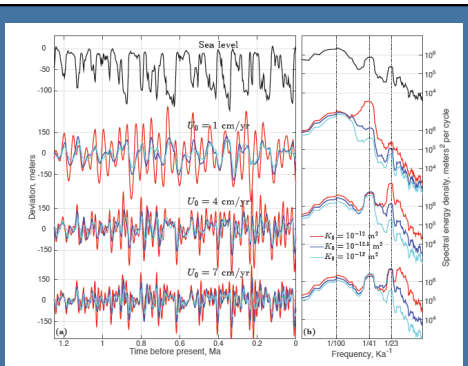


There is a physical basis for a linkage between sea level and mantle melting



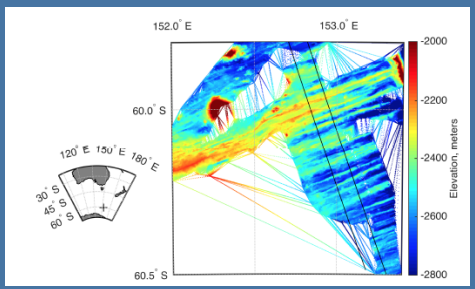
PUZZLE
What is the origin of Abyssal Hills, and what controls their spacing?





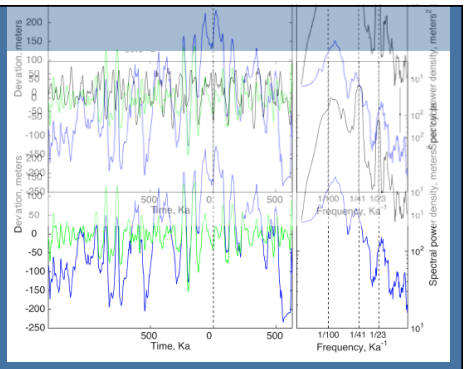
From Crowley, Katz, Huybers, Langmuir and Park, Science Feb 6, 2015

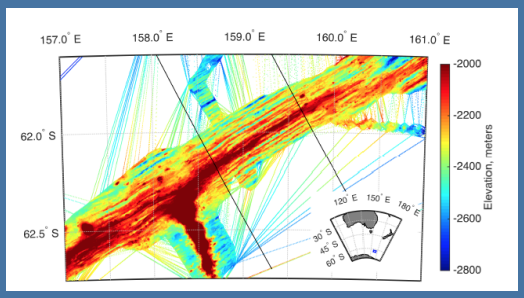
Australian-Antarctic Ridge Bathymmetry

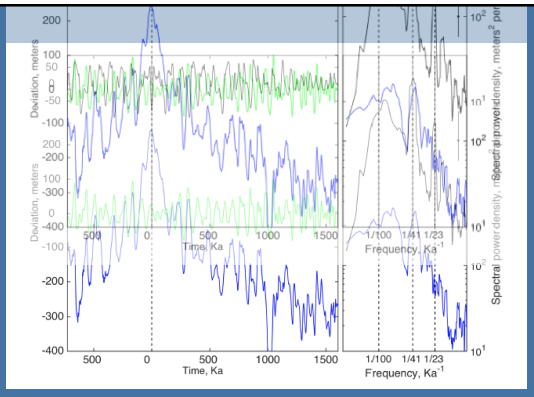


Predicted

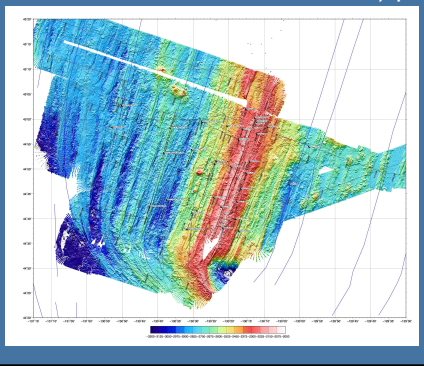
Observed



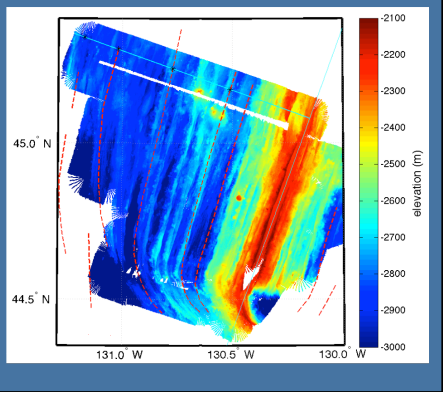




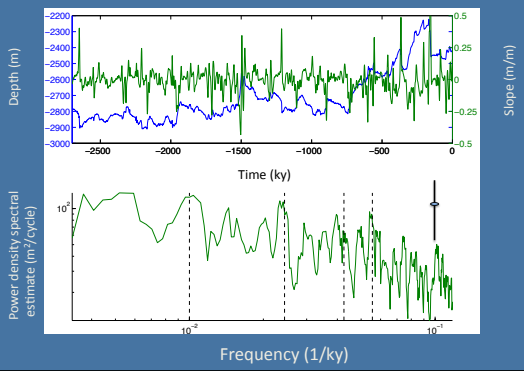
SEAVOICE, 9/2015



Juan de Fuca bathymetry and magnetic isochrons

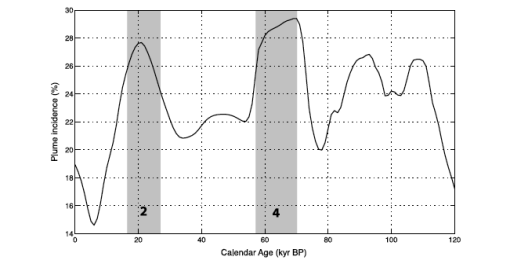


Time series and spectral estimates from bathymetry

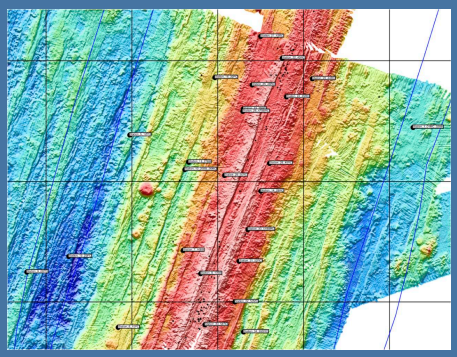


There is also a potential link between magmatism and ridge crest hydrothermal activity

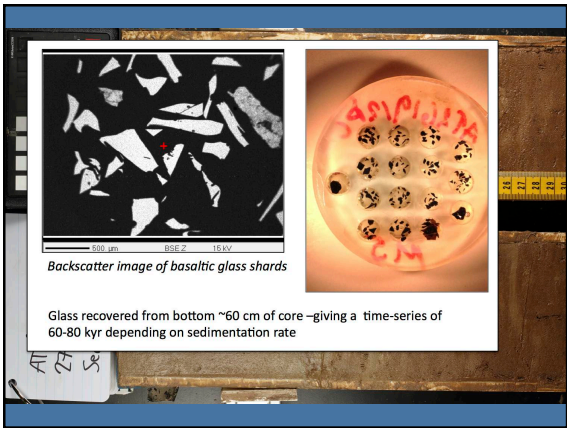
Lund and Asimow, 2011



Piston Cores with Basalt



Piston cores can sample seafloor lavas and overlying sediments



Backscatter image of basaltic glass shards

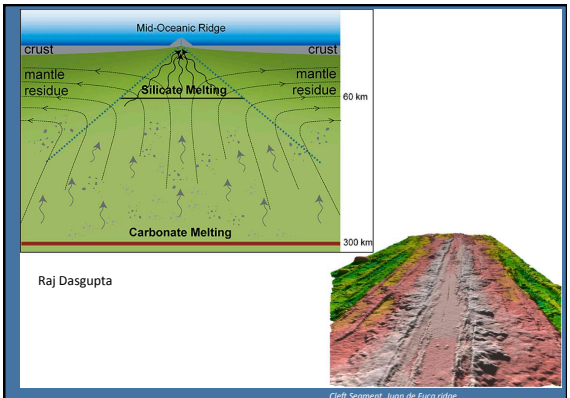
Glass recovered from bottom ~60 cm of core –giving a time-series of 60-80 kyr depending on sedimentation rate

Time Series Have Never Been Possible for Ocean Ridge Basalts

You cannot date the basalts

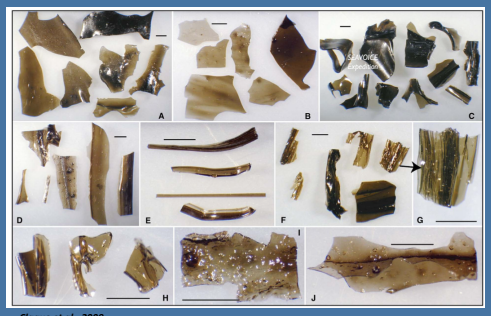
Dredges off axis are restricted to fault scarps, and are altered by long exposure to seawater

There may now be the possibility of obtaining million year times series of glass compositions from global ridge segments.



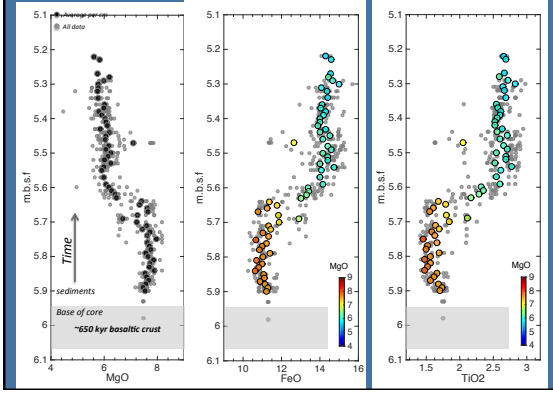
Cleft Segment, Juan de Fuca ridge
Stokes et al. 2006

Methodology: Construct chronology of MORB glass compositions for Cleft segment (JdF) using pyroclastic material (*Limu o Pele*) from sediment cores taken near ridge axis

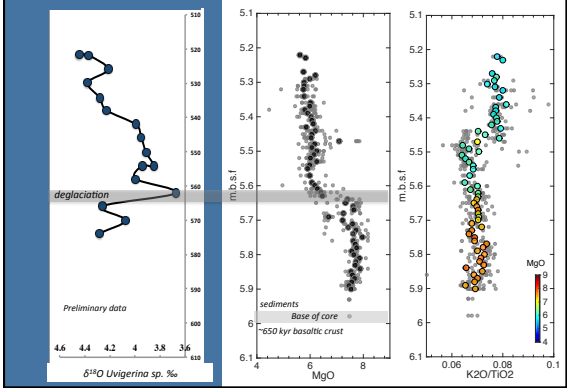


Clague et al., 2009

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



Ongoing work – comparison to $\delta^{18}O$ *record*



Summary

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

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

Preliminary data for the JdF 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 MOR magmatism/volcanism may be coupled to the climate system

HARVARD UNIVERSITY Lamont-Doherty Earth Observatory COLUMBIA UNIVERSITY | EARTH INSTITUTE

Possible interpretation of magmatic time-series……

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

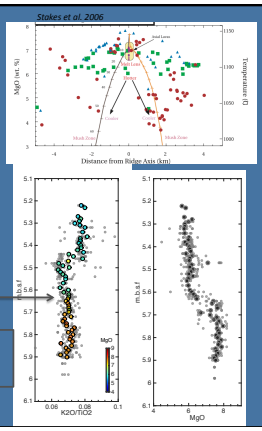
2. Change in primary melt flux due to mantle dynamics – longer residence time in crust, change in primary composition (why offset?)

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

Stokes et al. 2006



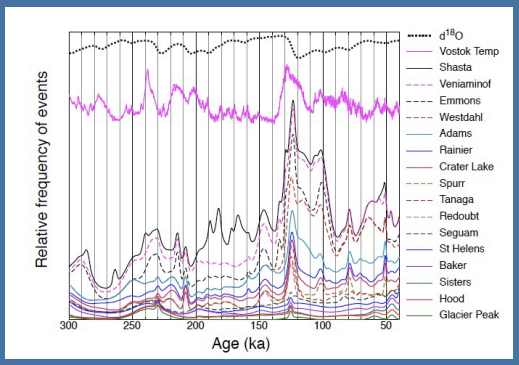
Might the Subaerial and Oceanic Influence be a Coupled System?

1. Slight warming triggers subaerial volcanism, raising CO_2 and leading to rapid exit from glacial maximum
2. Sea level rises, suppressing CO_2, with a 40,000 year time lag (?)
4. Glaciers grow, suppressing subaerial volcanism
5. Sea level falls, and CO_2 emissions from ridges rise
6. Milankovitch forcing causes glaciers begin to melt, triggering next CO_2 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?

Argon dated eruptions (>40 Ka)



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 reglaciation 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 3000Gt 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?