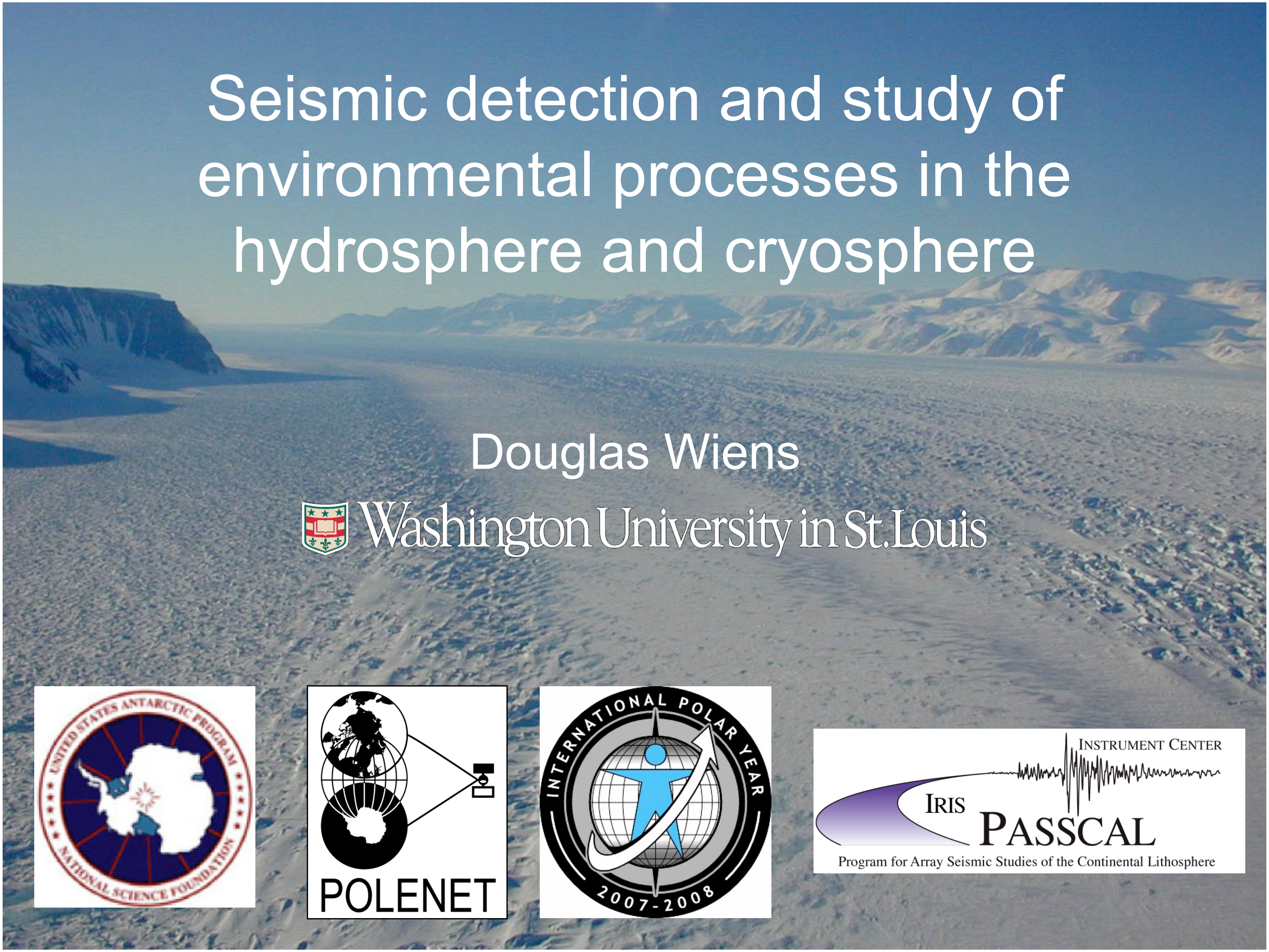
Seismic detection and study of environmental processes in the hydrosphere and cryosphere

Douglas Wiens

Washington University in St. Louis



United States Antarctic Program · National Science Foundation

POLENET

International Polar Year 2007-2008

IRIS PASSCAL Instrument Center

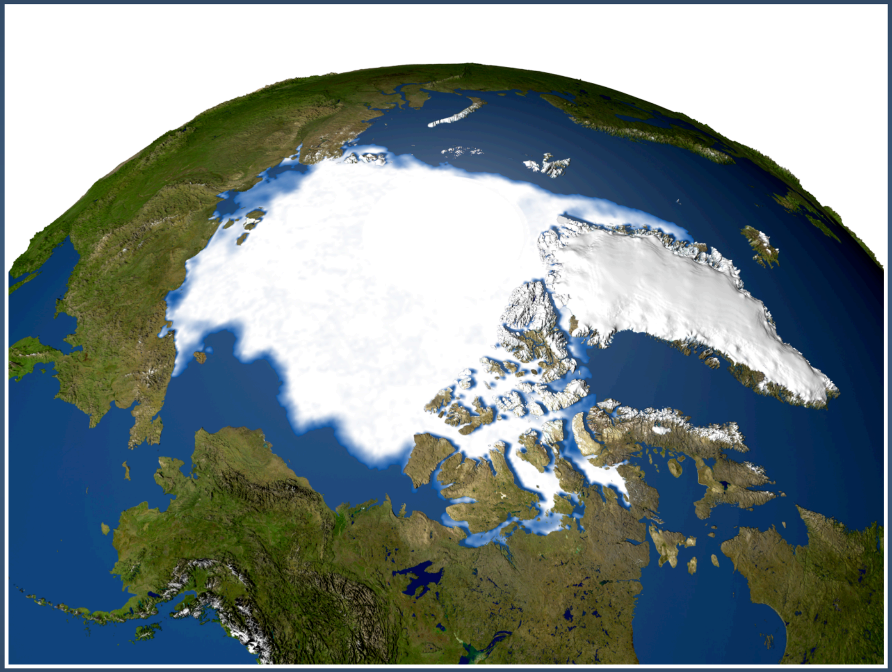
Program for Array Seismic Studies of the Continental Lithosphere

Environmental processes are a new science focus

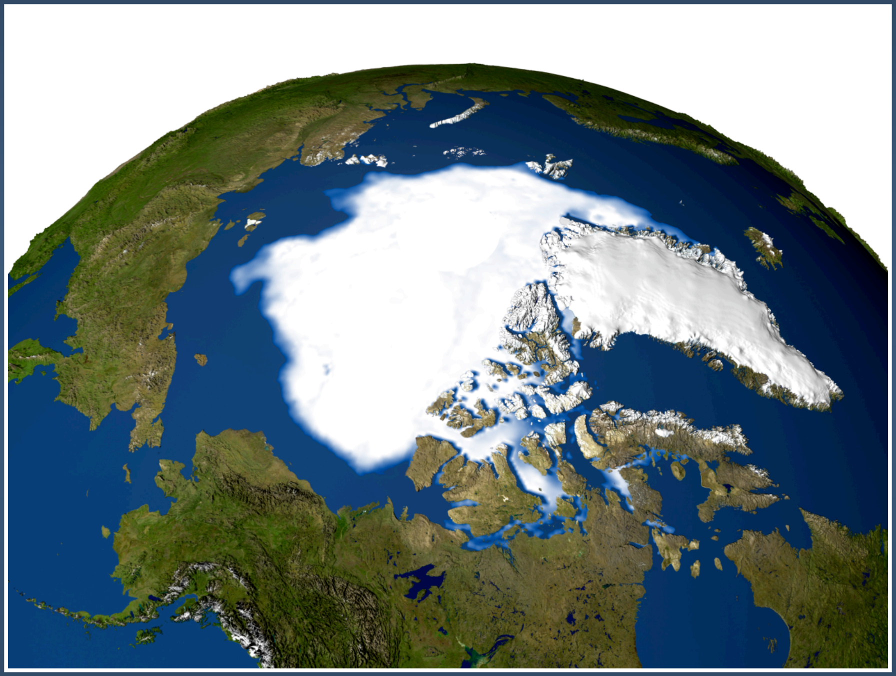
Huge interest in global change - the world is 4D!

Interdisciplinary science is not passive and active seismologists working together!

Minimum Sea Ice, 1979



Minimum Sea Ice, 2005



How can seismology contribute?

Examples: Ice streams, glaciers, icebergs
Ocean storms
Ocean ridge hydrothermal systems

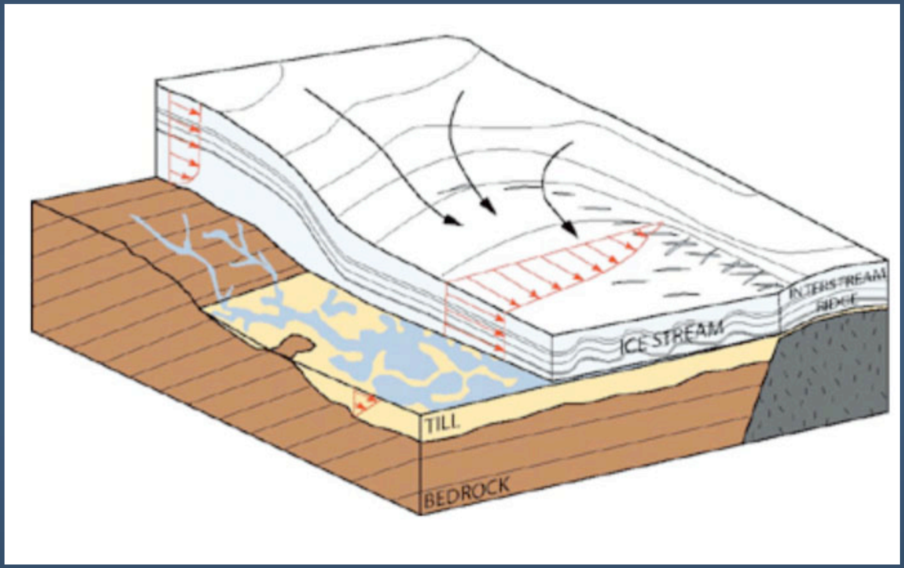
Is seismology important for studying global change ?

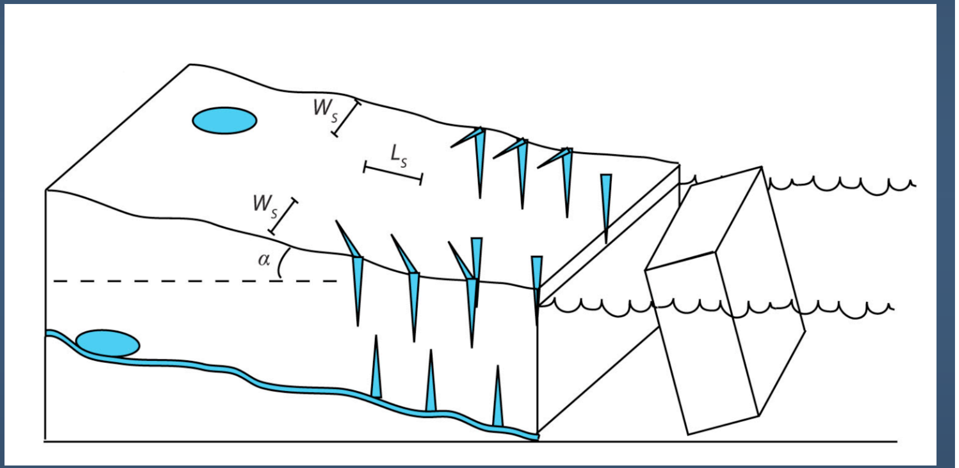
To a fool with a hammer,
All the world is a nail

"Glaciers and ice sheets are the components of the natural surface environment that are expected to change the soonest in response to environmental change."
"These changes all involve mass movements that may both be monitored and investigated using seismological techniques."
"So far, seismology is only scratching the surface of glaciology; there is likely to be a lot of opportunity to learn about ice-sheet/climate interaction through the vision of seismology..."

Doug MacAyeal,
glaciologist, U Chicago

Seismic characterization of glacial processes



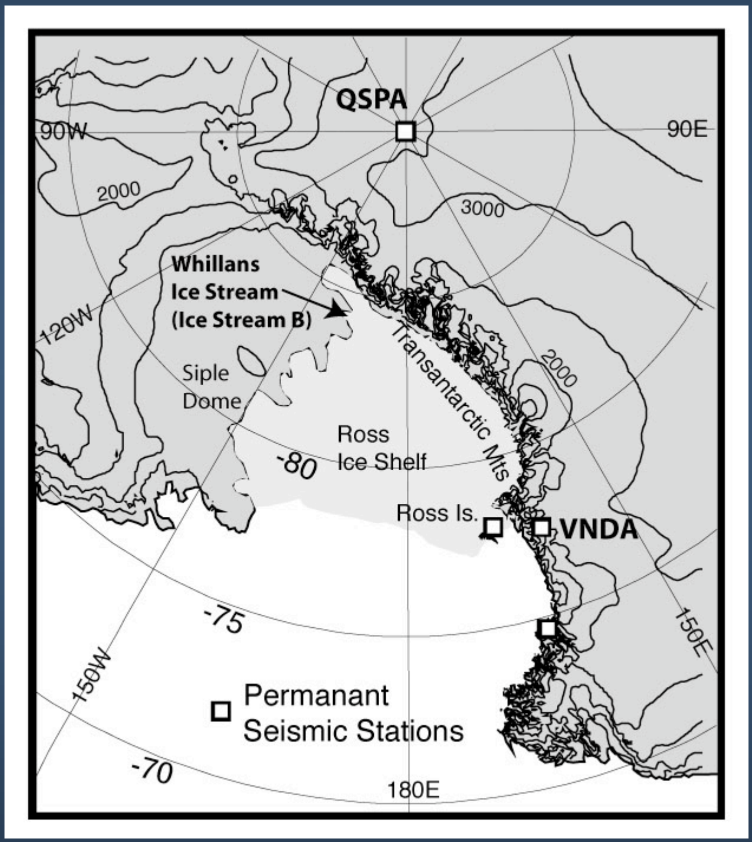


Mechanics of basal sliding:
- why low friction?
- what causes stick-slip?

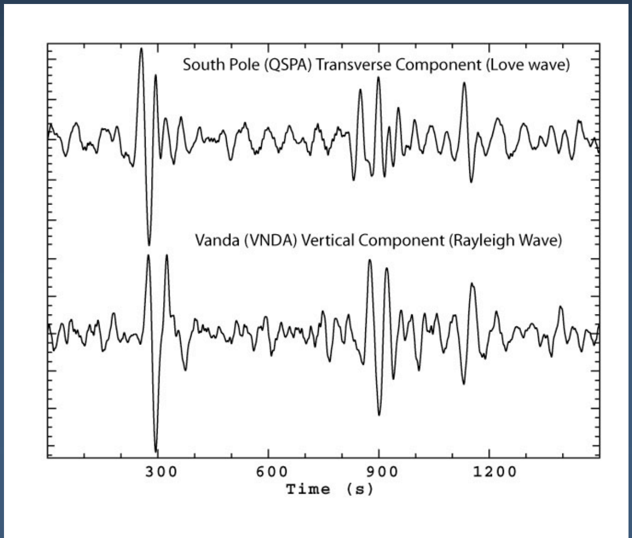
Mechanics of calving
Ice shelf break up?

Glacial “stick-slip”: Whillans Ice Stream, Antarctica

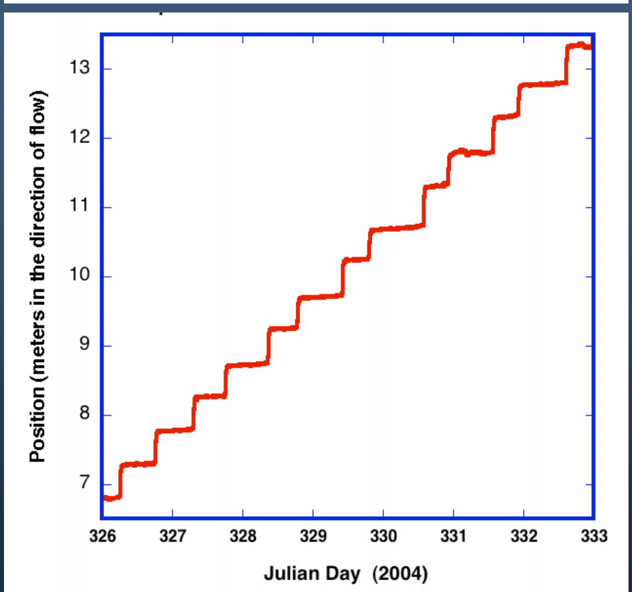
Location



Seismograms
- -2 or 3 pulses
- -duration ~25 min
- -1st pulse onset
- -Last pulse is stopping phase



GPS data
- -Two slips/day
- - ~40 cm each
- -Tidally triggered
- -Slip area is 200 x 100 km



Seismic moment = μ D A = 3 x 10^{19} N-m
(Mw ~ 7.0 earthquake)

Wiens et al., Nature, 2008

Whillans Ice Stream Stick-Slip

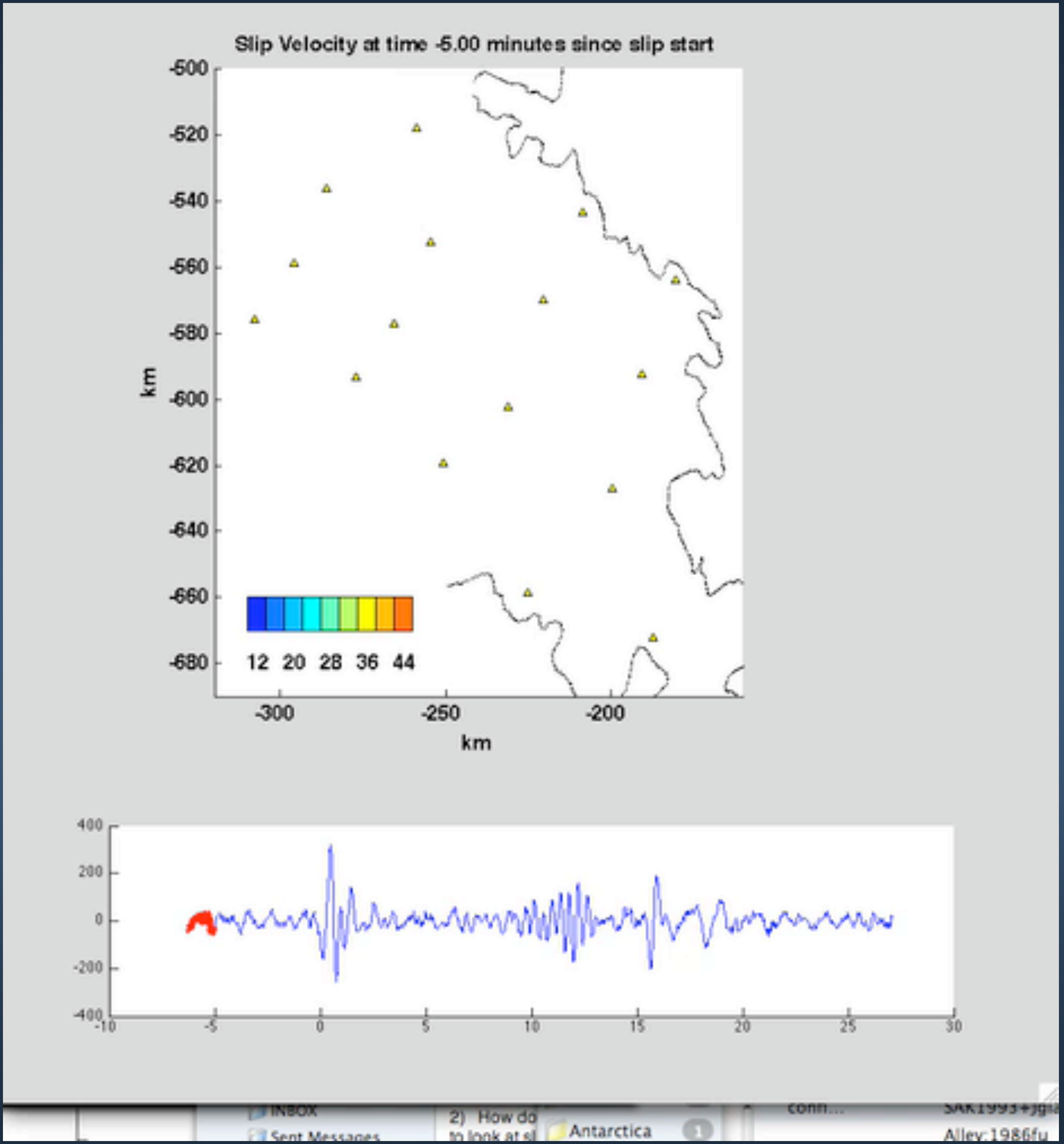
Upper figure shows slip velocity from GPS receivers on the ice Stream

Lower figures shows seismogram from South Pole (QSPA) 650 km away

Slip initiates at the same location for every event;

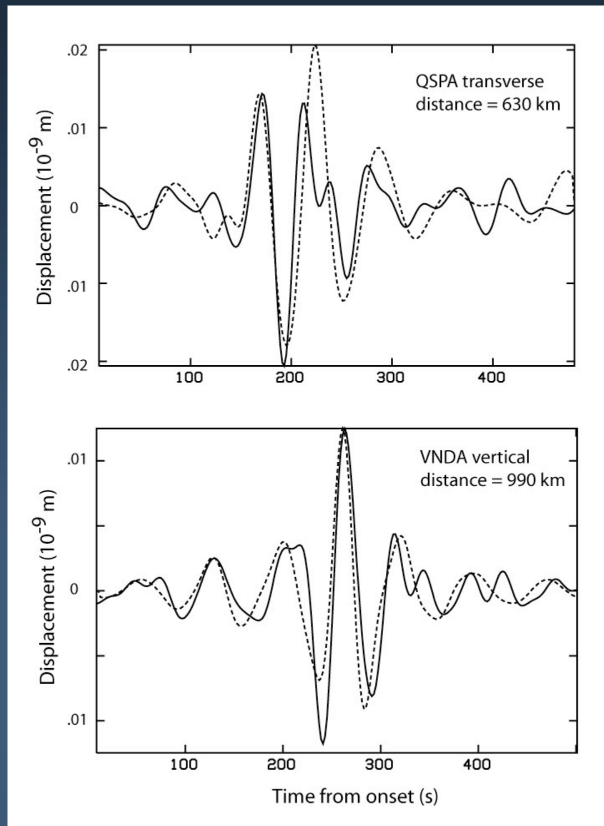
Rupture origin represents an "asperity" in the bed

Movie by Paul Winberry
GPS data from Sridhar Anandakrishnan & the TIDES project

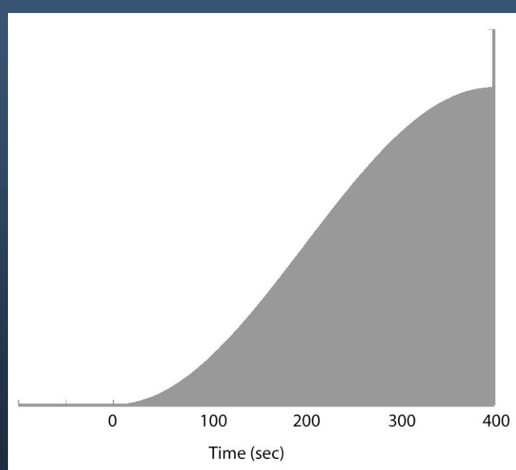


Waveform modeling of slip onset

Observed & modeled waveforms



Source Time Function



Method:

- Assume double couple @ 1 km depth
- Compute synthetics with reflectivity algorithm, regional structure [*Lawrence et al.,* 2006]

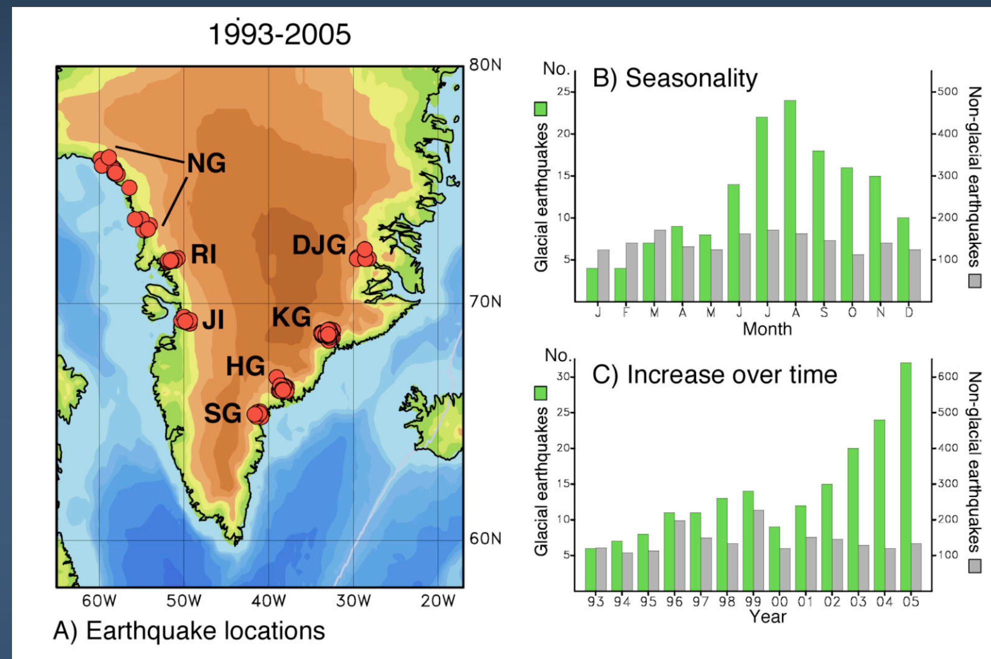
Results:

- Amplitudes well fit by fault shallowly dipping down the ice stream
- If extended out ~ 20 minutes gives expected seismic moment (M_W 7.0) within an order of magnitude
- Exact shape, seismic moment highly non-unique due to band-limited signal
- Later two arrivals more complex, presumably due to interference from stopping phases from different regions

Wiens et al., Nature, 2008

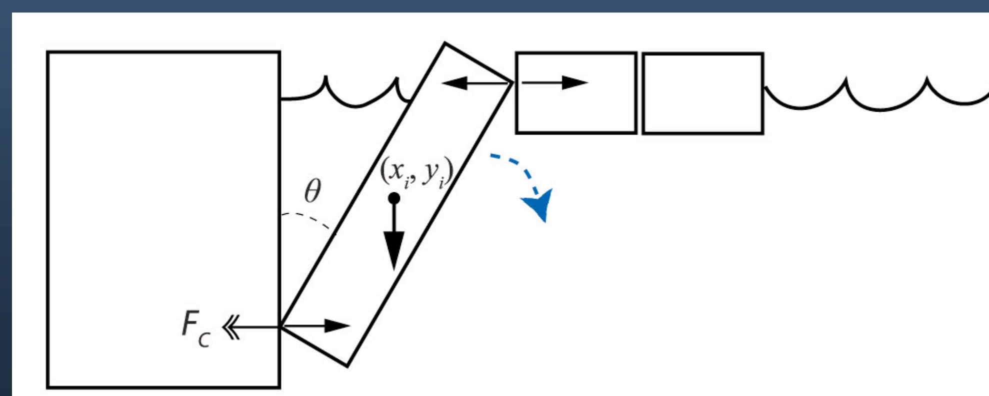
Greenland Glacial Earthquakes – large calving events ?

Northern Hemisphere
Long-Period Glacial Sources
Ekstrom et al., [2006]



- Located where outlet glaciers meet the coast
- Have sources with ~ 50-100 s duration
- Consistent with motion in the direction of ice movement
- Recent results show events simultaneous with iceberg calving at the seacoast
- Motion limited to near the calving front

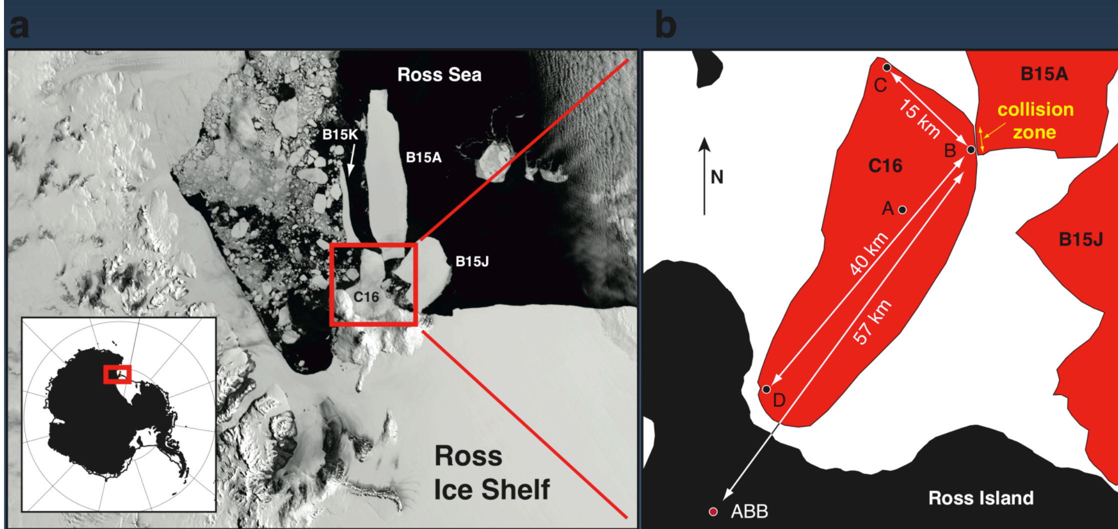
Mechanical calving model for glacial earthquakes
Tsai et al., 2008



Calving of Greenland Outlet Glaciers (Jakobshavn)

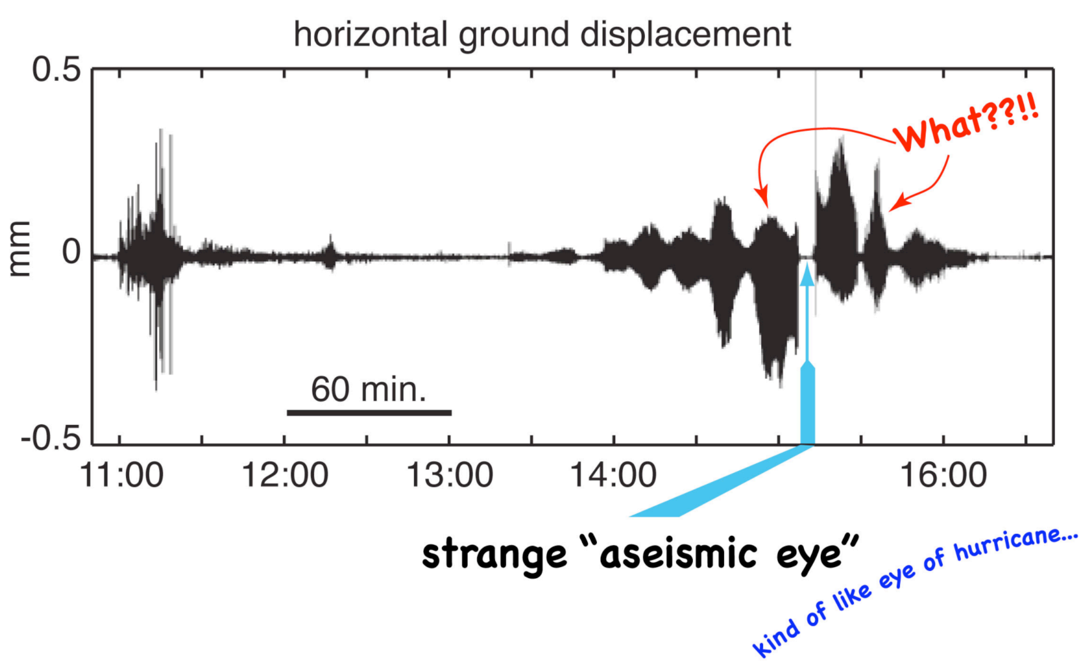
Movie by J. Amundson
25 times actual speed
Seismogram converted to audio

Iceberg Harmonic Tremor



Map of icebergs and seismic deployment

- Very large icebergs located near McMurdo
- Harmonic tremor detected at land stations
- Seismographs installed on berg C16
- Source localized to a collision zone
- Tremor well recorded by stations on iceberg

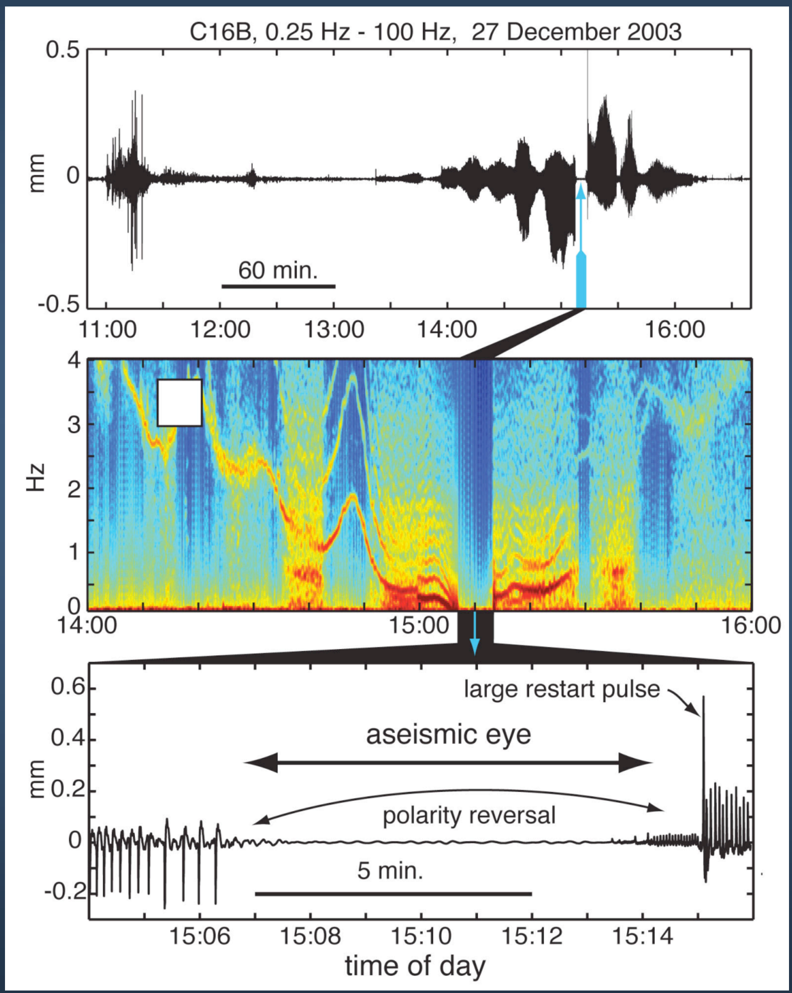


Typical tremor record

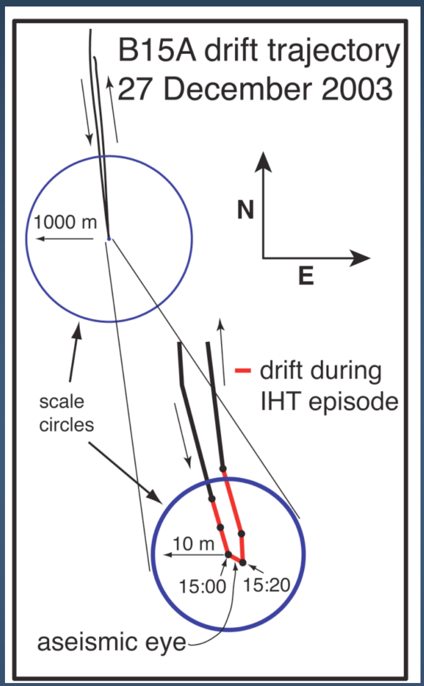
MacAyeal et al., 2008

The mechanism of iceberg tremor

Tremor Details



Iceberg Motion



- Tremor caused by “stick-slip” between icebergs
- Made up of many small slips
- Interslip time varies with velocity, giving various harmonics
- Tides cause the berg to stop and reverse direction
- “Aseismic Eye” corresponds to the stopping time

MacAyeal et al., 2008

The Goal: Understanding the mechanics of ice shelf collapse

Ice Shelf Breaks Up in a Fast-Warming Antarctic Region...

"All the News That's Fit to Print"

The New York Times

20 March, 2002

VOL. CLI . . . . No. 52,063 — Copyright © 2002 The New York Times — WEDNESDAY, MARCH 20, 20

National — Colorado: Part... Highs in the low... 40's in the m... partly sunny sk... sections. Weath... — Printed in Colorado

S.E.C. Had Sought $500 Million In Failed Talks With Andersen

Negotiations Ended When Auditor Was Indicted

By KURT EICHENWALD

The Securities and Exchange Commission was demanding that Arthur Andersen pay $500 million to settle claims stemming from the Enron investigation, but the negotiations broke down after the firm was indicted by the Justice Department on charges of obstruction of justice, people involved in the case said yesterday.

At the time that the talks between Andersen, the accounting giant, and securities regulators collapsed, the two sides were as much as $150 million apart on the amount of a financial settlement. But these people said that there were strong signs of progress. The firm had already indicated that other terms of a deal — including requirements that Andersen adopt wide-ranging reforms recommended by a committee led by Paul A. Volcker, the former chairman of the Federal Reserve — would be readily accepted.

The proposed settlement — roughly equal to two times the amount in fees that Andersen received over the last five years from Enron — was intended to finance a government-monitored compensation fund to reimburse investors who lost large sums of money in the collapse of Enron last December. Andersen was the longtime accountant to Enron and provided advice on its use of a series of partnerships that ultimately played a critical role in the company's downfall.

But with the company under indictment, its client base rapidly shrinking and its overseas offices likely to be sold to a competitor, the chances for the large-scale settlement incorporating significant reforms appear to have slipped away.

"There is little doubt that the settlement number would have been in the many hundreds of millions of dollars," one person involved in the case said yesterday. "But everything has changed very quickly, and now it's unlikely that those kinds of numbers will be in reach."

Another person involved in the case added: "It would have been an all-time world-shattering record. But now there aren't even talks in progress."

Throughout the negotiations, the S.E.C and the Justice Department were said to be in consultation. But

HEWLETT DECLARES

JAN. 31 — FEB. 17 — FEB. 23 — MARCH 5

National Snow and Ice Data Center, University of Colorado/NASA

Ice Shelf Breaks Up in a Fast-Warming Antarctic Region

Satellite images over little more than a month show the disintegration of an ice shelf about the size of Rhode Island on the eastern side of the Antarctic Peninsula. The speed of the breakup stunned scientists. Page A11.

CHENEY, SAYS HE TO TALK

A TRUCE MU

Vice Preside... Says Meeti... as Early

By MICHA... and JAM...

JERUSALEM... shift of Bush ... egy, Vice Pre... said today tha... meet soon wit... Palestinian lea... dle East peace ... steps to curb ... and to impose ... Mr. Cheney s... take place as e... would occur in ... vice president ... senior Bush a... to meet with M... Standing at ... Prime Minister ... el indicated tha... end a travel ba... could attend a ...

Richard Alley: the worst case scenarios of sea level rise in the next 100 years are associated with ice-shelf collapse.

Major glaciological questions that seismology should help solve – Doug MacAyeal

- Ice stream flow mechanisms:

  what causes speed up and slow down

  do ice streams (other than Whillans) show stick-slip?

  what controls stick-slip behavior?

- What is the mechanism of Greenland “glacial earthquakes”?

  How are they related to calving events?

  What can they tell us about calving?

  Can these events be used as a proxy for glacier discharge?

- What can seismology tell us about collapsing ice shelves?

  What are the enabling conditions for ice shelf collapse?

  Are there seismic precursors to ice shelf collapse?

- What are the hydrological conditions beneath ice sheets?

  ephemeral lakes and streams exist beneath ice sheets

  what types of seismic signals are associated with meltwater transport?

Polenet

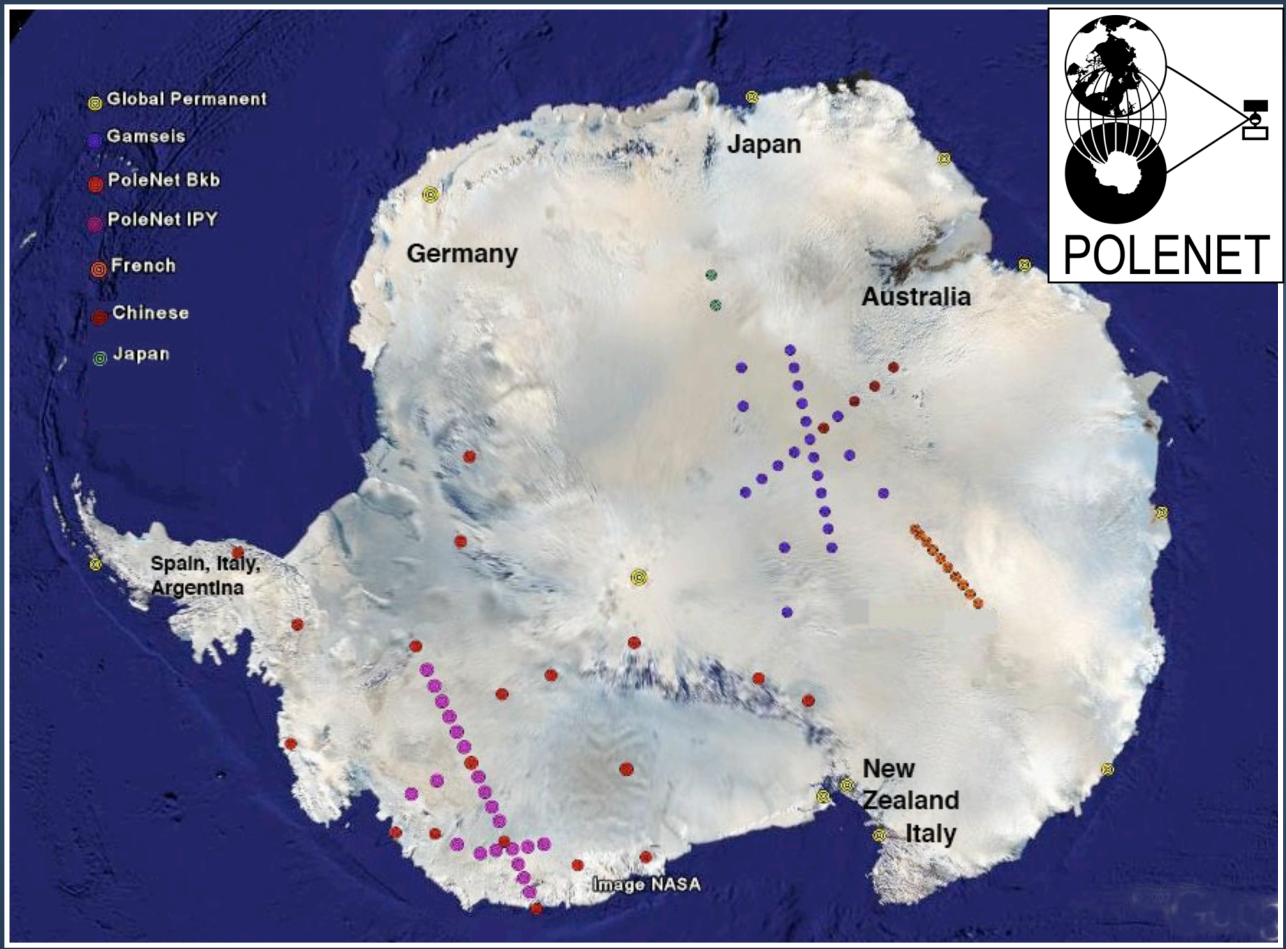
Simultaneous deployment of broadband seismic stations around Antarctica during the International Polar Year (IPY)

Total number of stations deployed during IPY is on the order of 100

Initial sites deployed during 2007-2008

Some stations have co-located GPS and weather instruments

Year-around operation of seismic stations throughout Antarctica for the first time

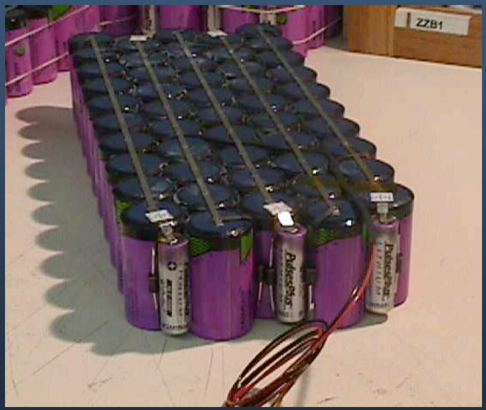


Polenet seismic stations deployed during IPY; not all coastal stations are shown

Polar Seismic Instrumentation
developed by IRIS-Passcal Instrument Center

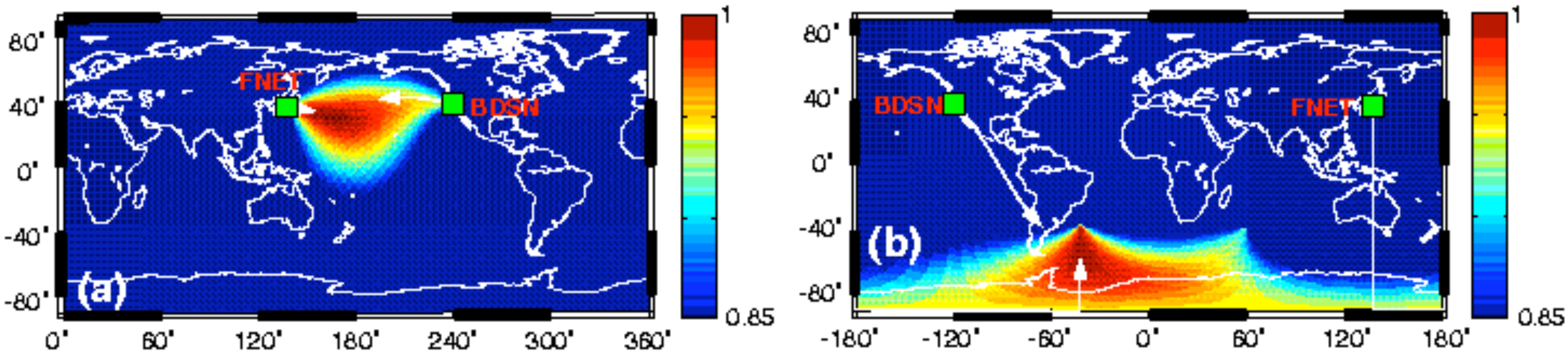
- Sensor: Trillium 240 or Guralp 3T - operates to -55C
- Datalogger: Quanterra Q330 with solid state recording operates to -45C
- power source is solar panels (summer) and primary lithium batteries (winter)
- total power required ~ 2 Watts
- datalogger, batteries, and sensor enclosed in buried insulated vaults to maintain temperature 15-20 C above ambient

Needed: improvements in portability, data return

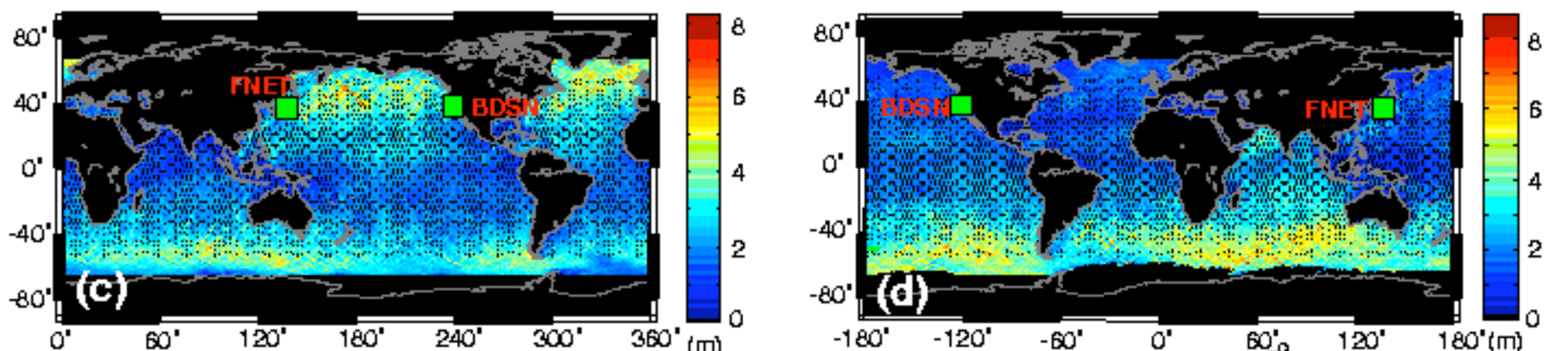


Seismic “Noise” and Oceanic Storms

Beamformed Seismic Data



Significant Wave Height (Topex-Poseidon)

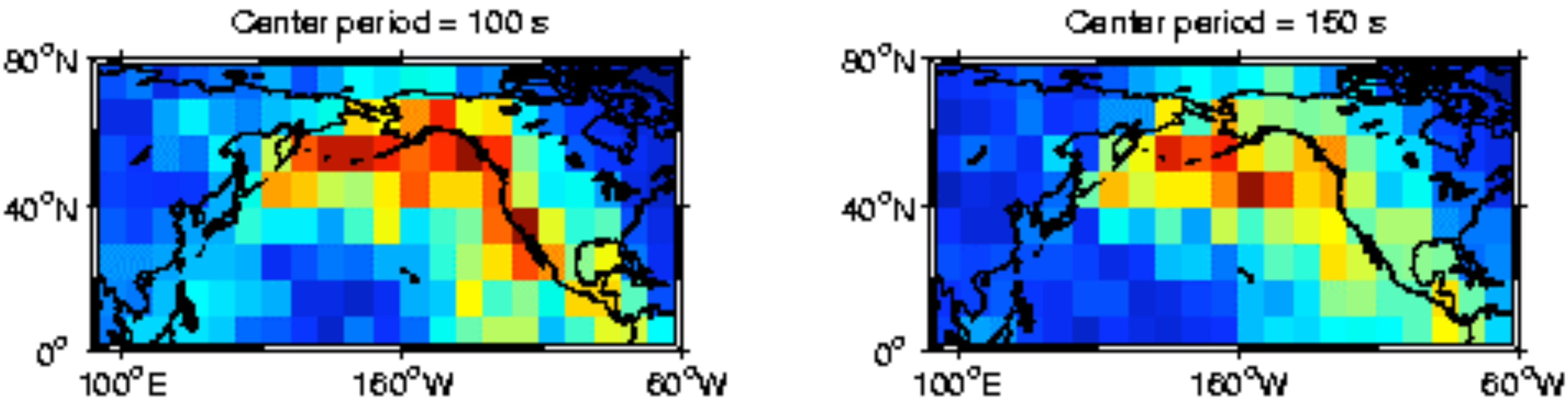


Winter

Summer

Rhie and Romanowicz, Nature, 2004

Grid search for source locations, maximizing stack Amplitudes at F-NET, BDSN and 10 stations in Europe



Time interval: 6 hours on 2000.031

Rhie and Romanowicz 2006

Rhie and Romanowicz 2006

Seismic studies of ridge hydrothermal vents

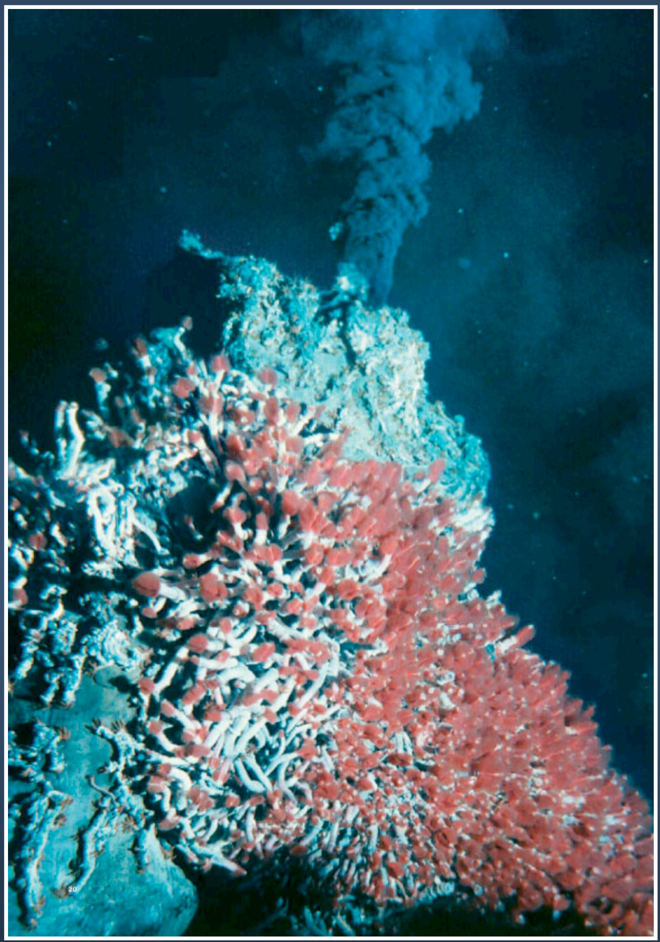
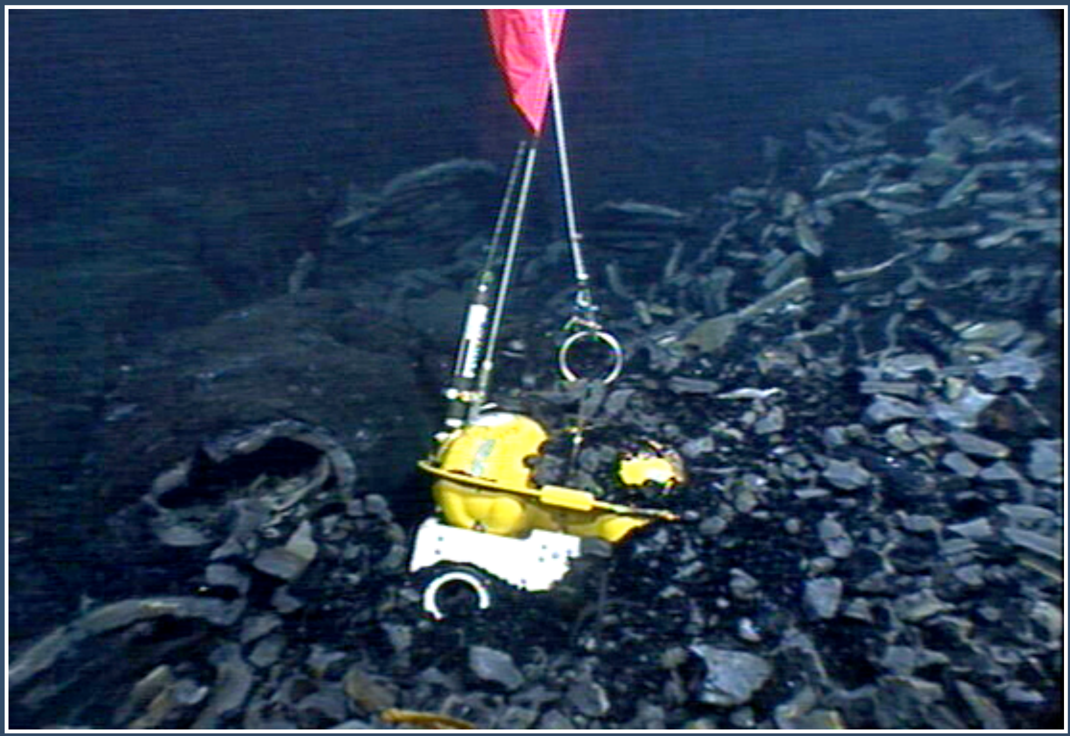


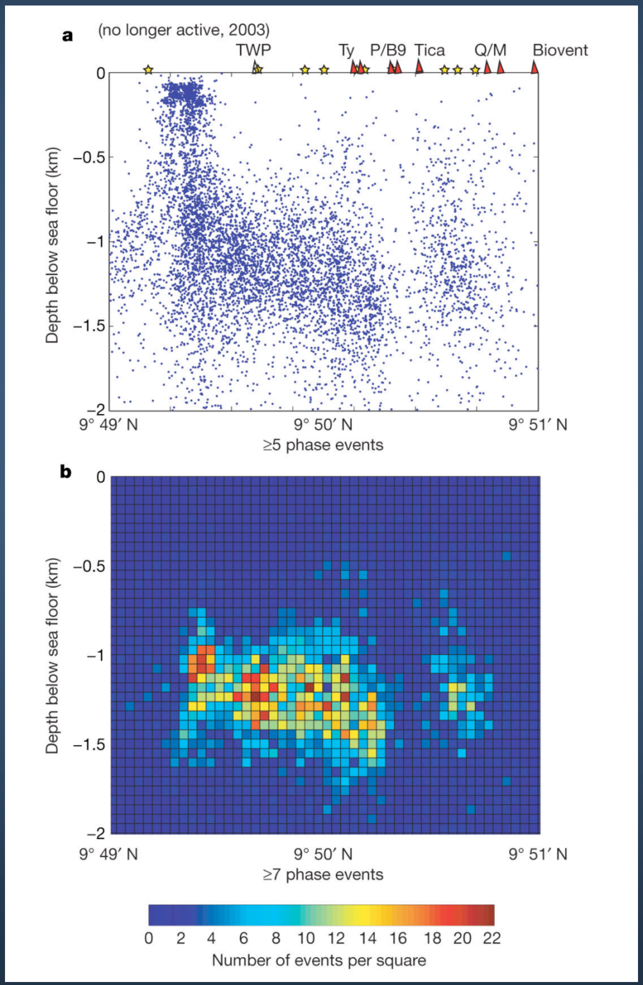
Photo by D. Kelley



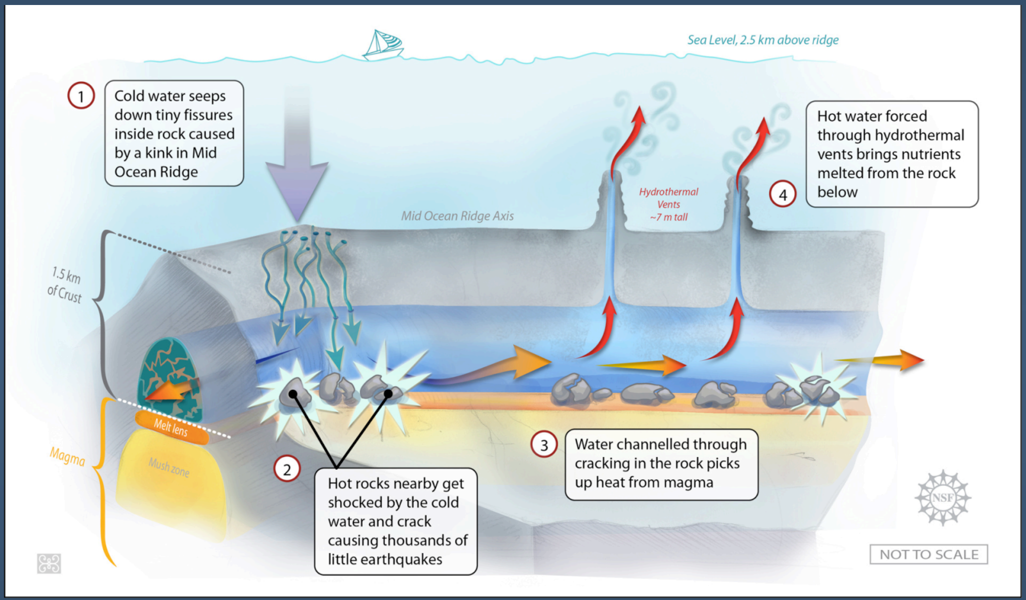
- Mid ocean ridge hydrothermal systems contain entire ecosystems
- Vitally important for planetary evolution and perhaps origin of life
- Yet very little is known about the these systems
- Much of what is known comes from OBS studies

Hydrothermal flow patterns from microseismicity

Microseismicity from OBS array



New model for ridge hydrothermal vents

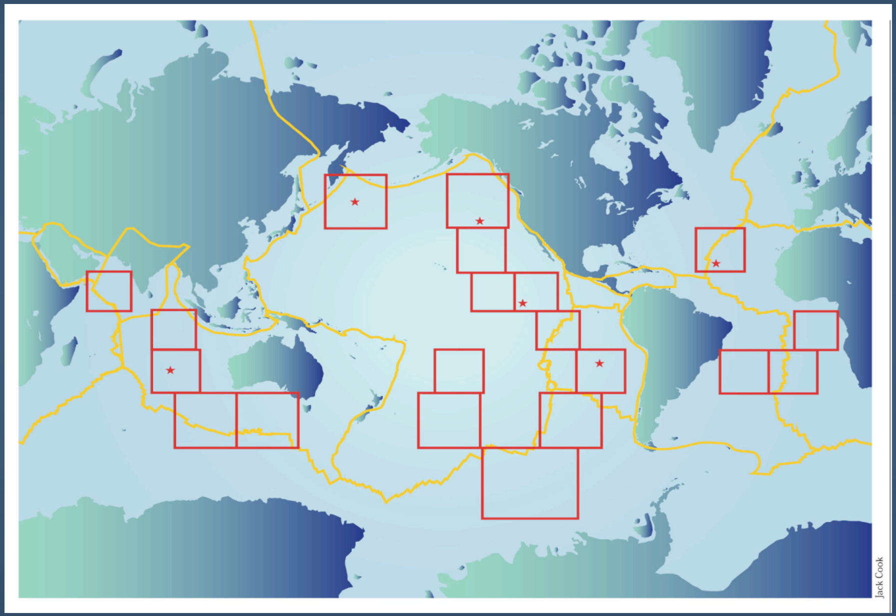


- •Previously thought that recharge happened off-ridge
- •Microseismicity at 1-1.5 km depth is due to thermal cracking
- •Pattern of microseismicity shows recharge occurs from downwellings elsewhere along the strike of the ridge

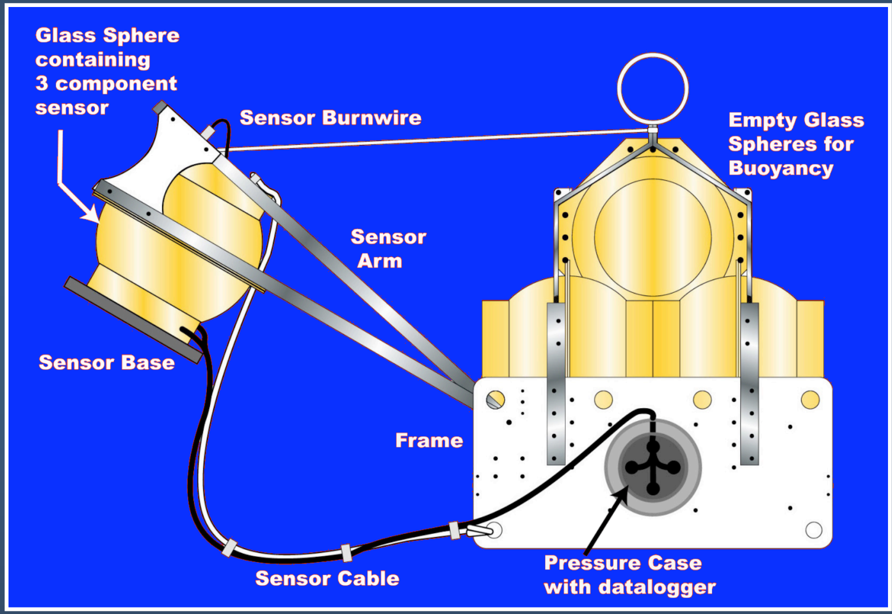
Tolstoy et al., Nature, 2008

Needed: Investments in ocean bottom seismology

Ocean Seismic Network – 1990's plan



Current OBS pool



Needed: a feasible plan for long-term seismographs in the oceans

Needed: more OBSs, increased reliability, buried OBSs

Conclusions

- Seismology is highly important for a variety of “environmental change” problems
- Examples:

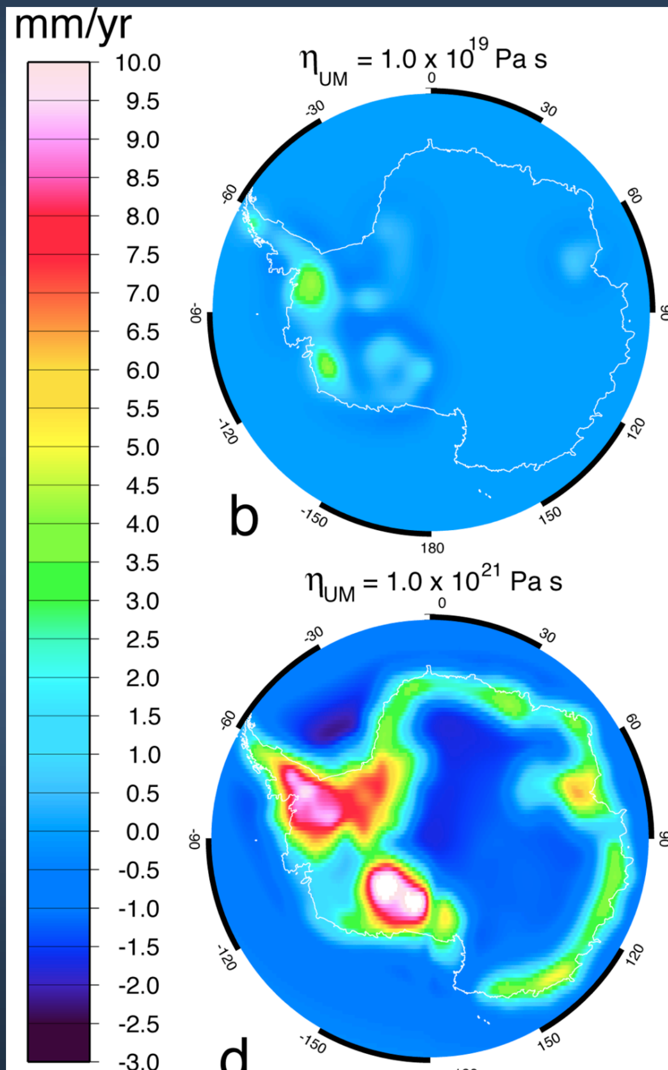
  Ice streams

  Icebergs and ice shelves

  ocean storms

  ridge hydrothermal systems
- Seismic sensors should be a part of multidisciplinary environmental sensor networks
- Further progress requires additional investments in instrumentation for the polar regions and oceans

Post-Glacial Rebound Dependence on Mantle Viscosity

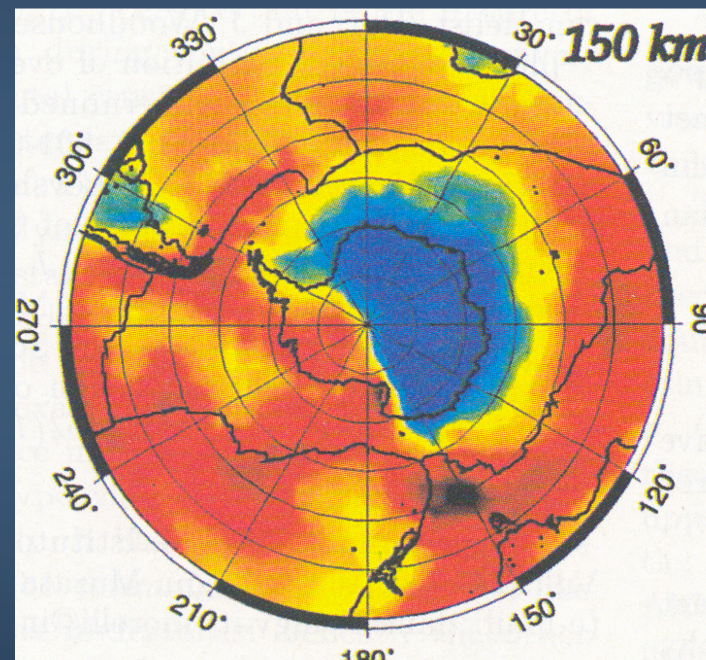


Low viscosity: short-term memory
- Holocene

High Viscosity: LGM
Peak rates
~ 9-10 mm/yr

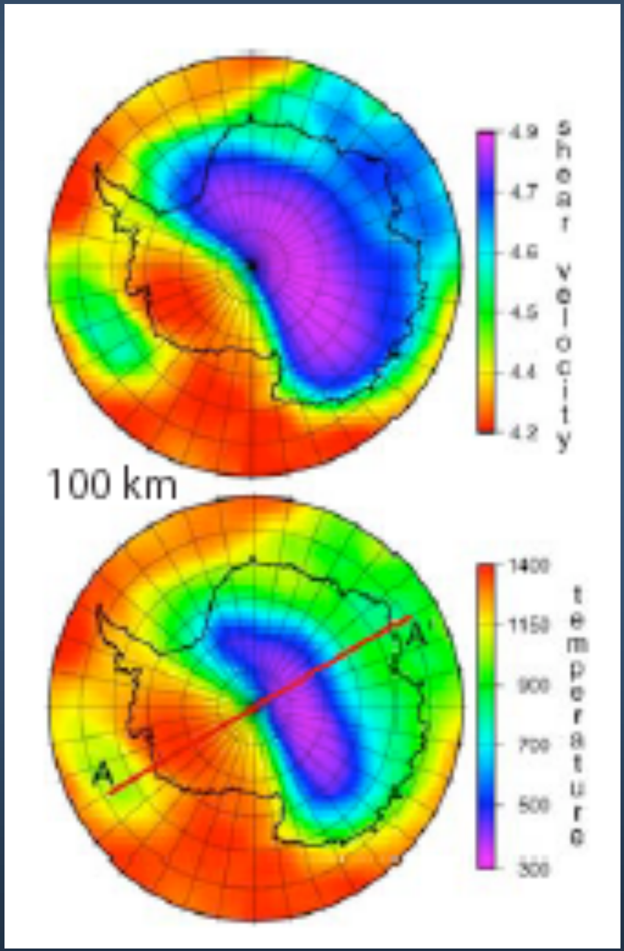
Ivins & James 2005

Seismic Tomography suggests strong lateral variations



Danesi & Morelli 2001

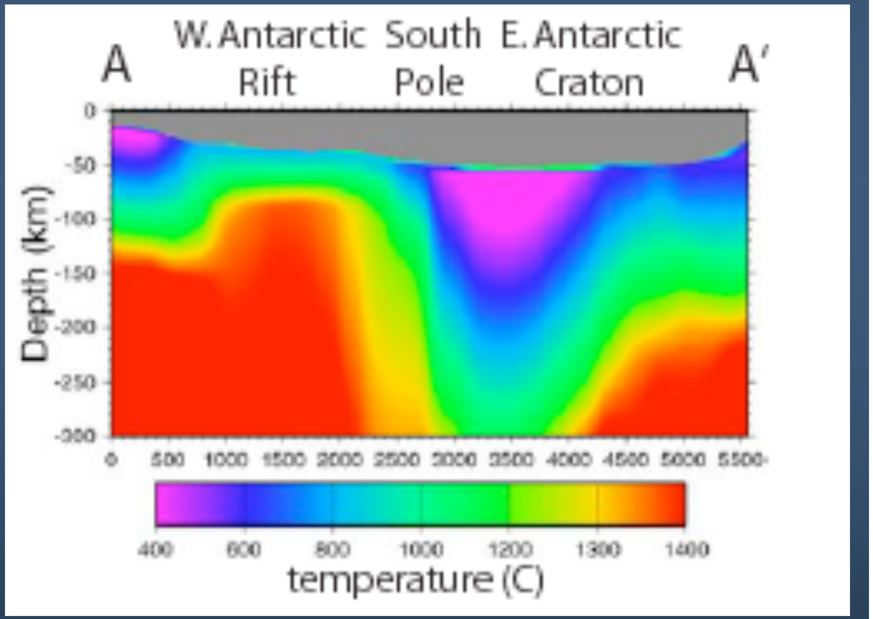
Seismological Constraints on Mantle Temperature and Viscosity Structure



Seismic Velocity

Inferred Temperature

Inferred Temperature Profile



Shapiro and Ritzwoller [2004]

Modeling seismic wave generation