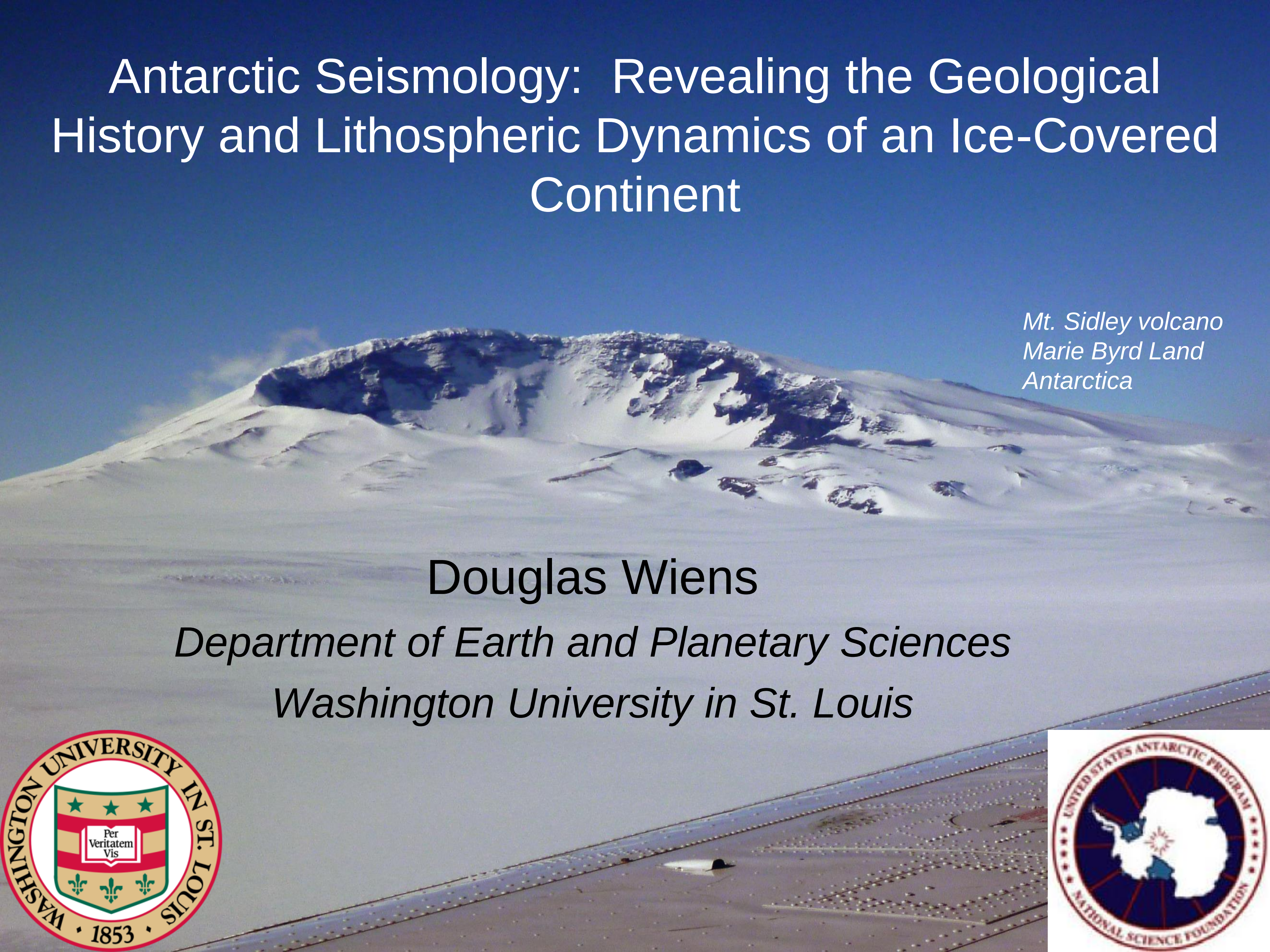
Antarctic Seismology: Revealing the Geological History and Lithospheric Dynamics of an Ice-Covered Continent



Mt. Sidley volcano
Marie Byrd Land
Antarctica

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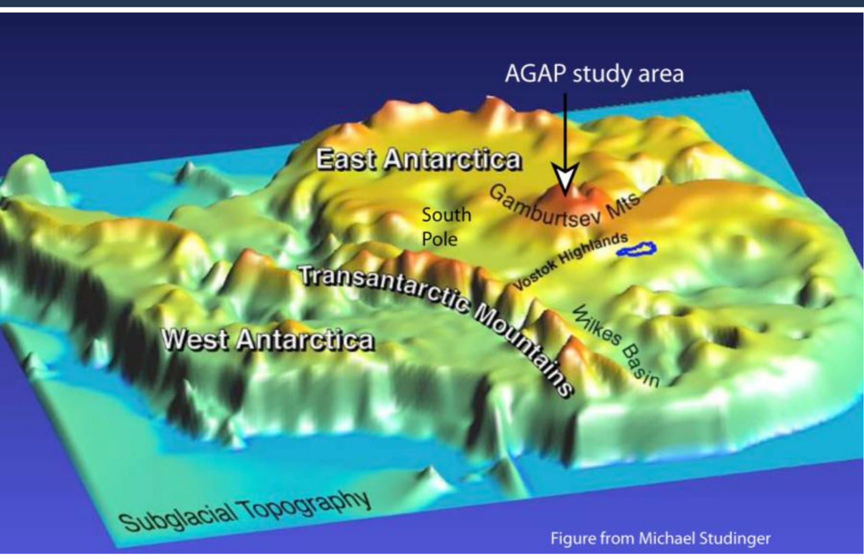
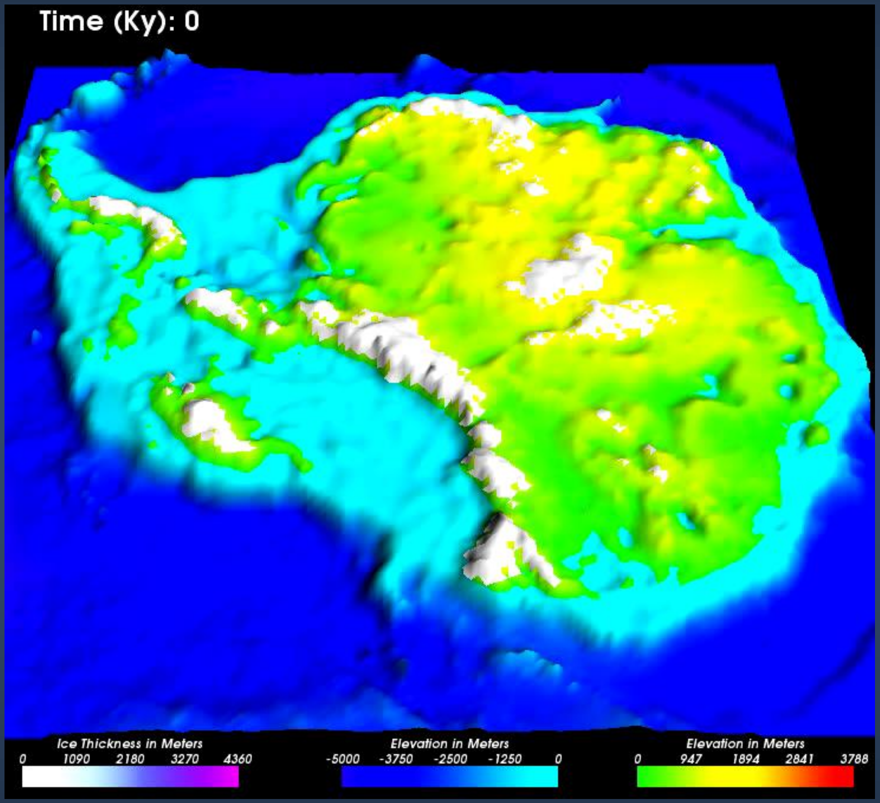
Outline

1. Why seismology in Antarctica?
2. Data Collection and Analysis
3. Results

- Constraints on mantle viscosity for inferring ice mass change
- Mountain building and relationship to ice sheet history
- Volcanic and tectonic effects on heat flow into the base of ice sheets
- Physics of glacial processes from “glacial earthquakes”

The Importance of Mountains for Climate History





- Mountains control the birth and development of the Antarctic Ice Sheet
- The ice sheet probably originated in the Gambutsev Mountains
- When and how were the mountains formed?
- The structure beneath the mountains is the key evidence

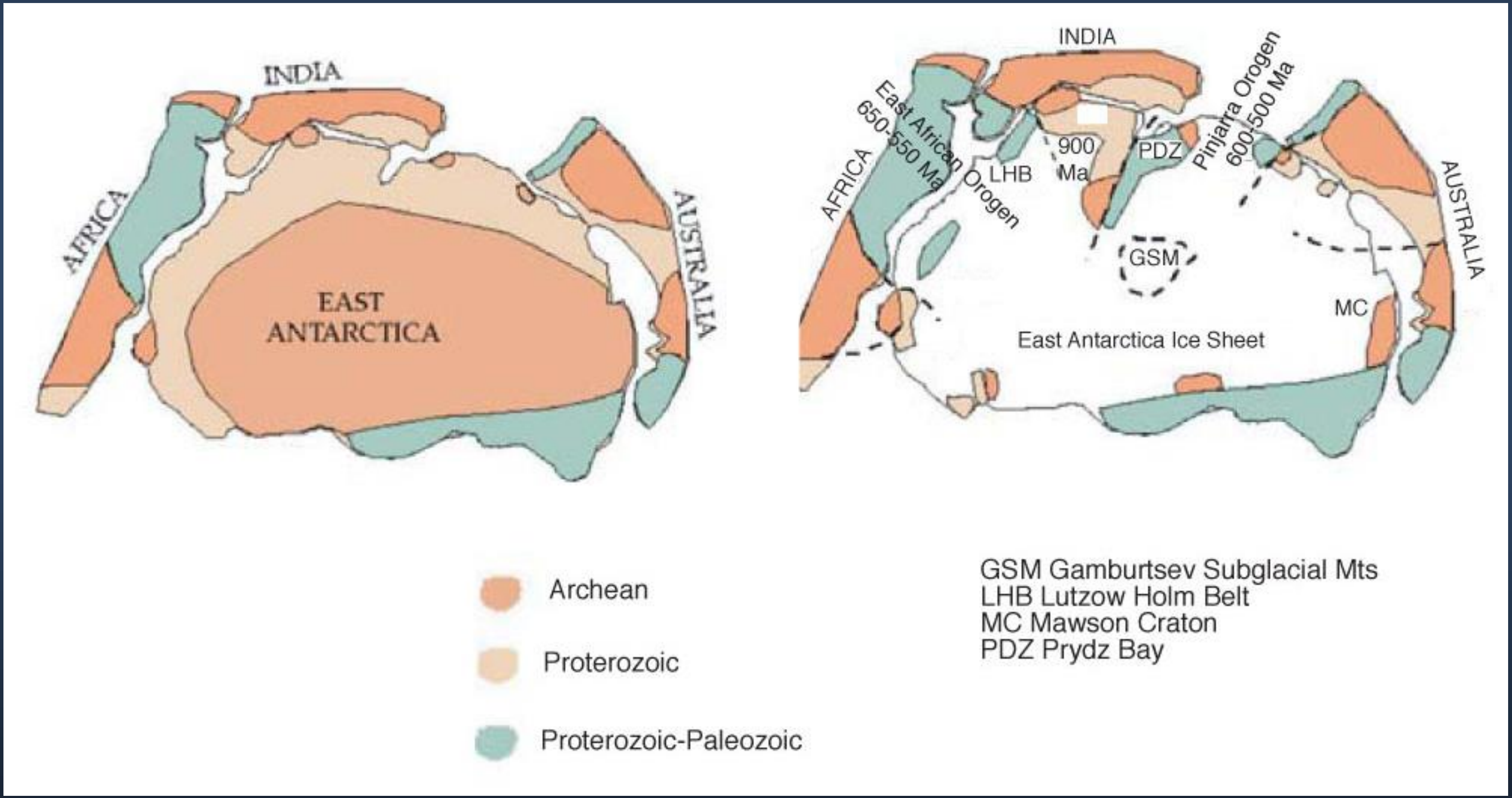
Deconto & Pollard [2003]

Understanding the ice-covered geology of Anarctica

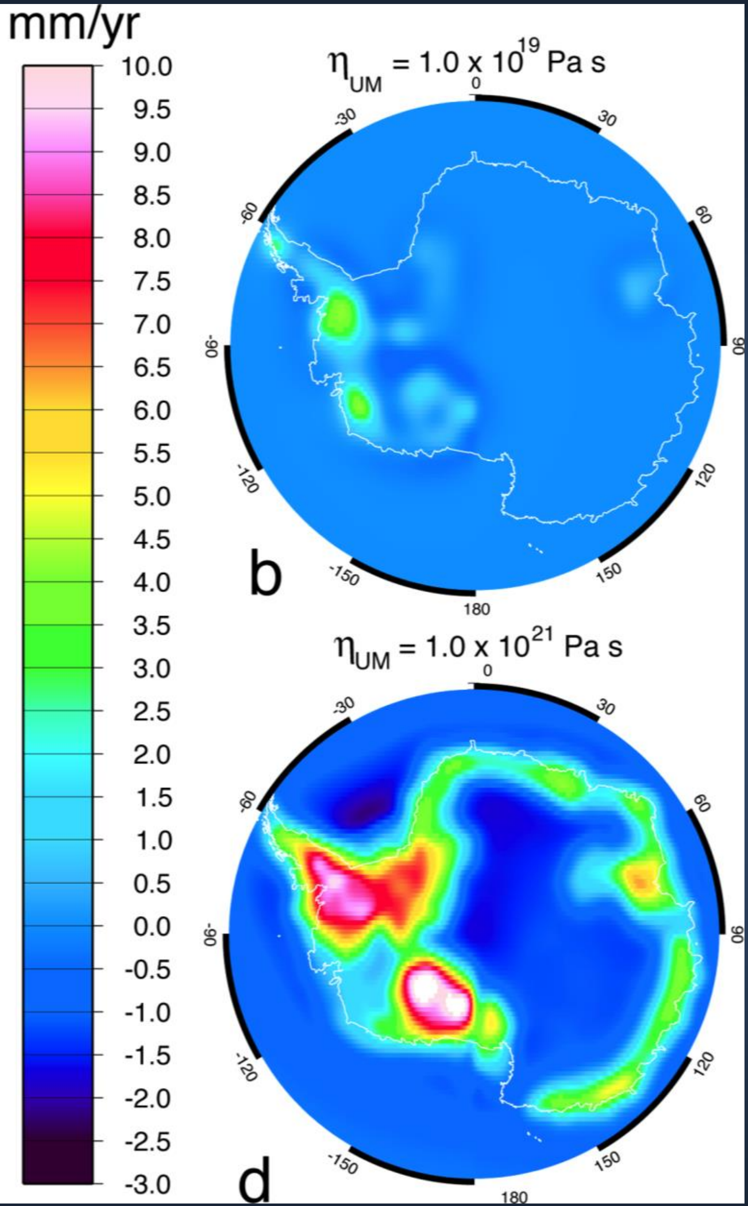
Two views of the geology of East Antarctica

Archean Craton (Tingley, 1991)

More Recent Orogenic Belts (Fitzsimons, 2003)



Glacial Isostatic Adjustment (GIA) Dependence on Mantle Viscosity



Low viscosity:
short-term memory
Sensitive only to Holocene

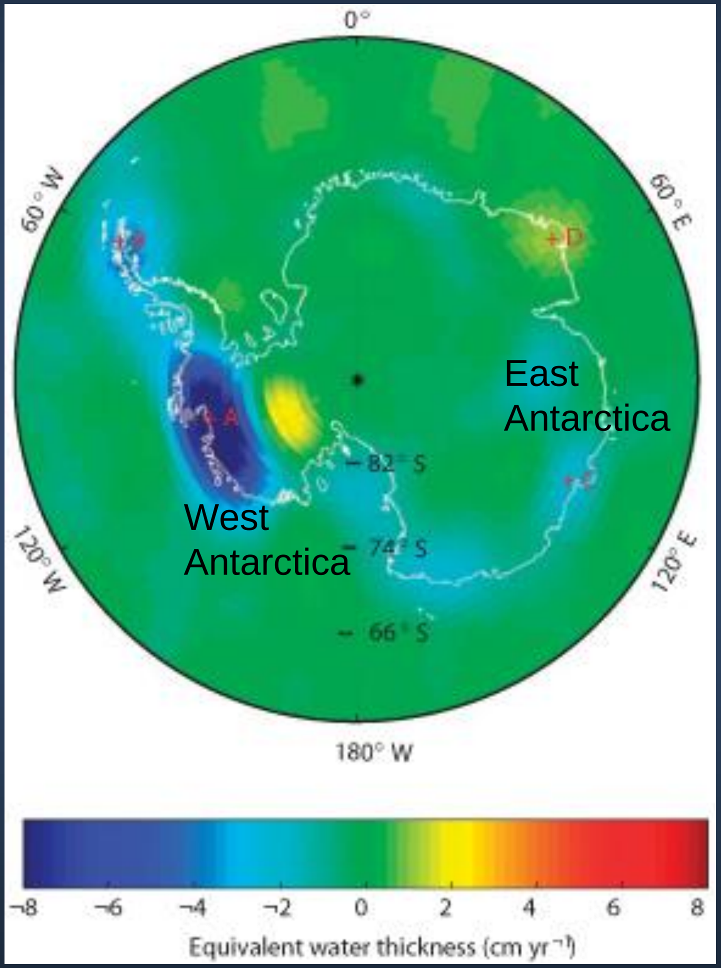
- Use Ivins & James ice sheet history
- Compute uplift for different mantle viscosities
- Larger viscosity gives much larger uplift
- “Memory” is a strong function of viscosity
- Viscosity is expected to be highly variable
- Yet current models use uniform viscosity
- Use seismology to constrain lateral variations

High Viscosity:
long-term memory
Sensitive to LGM

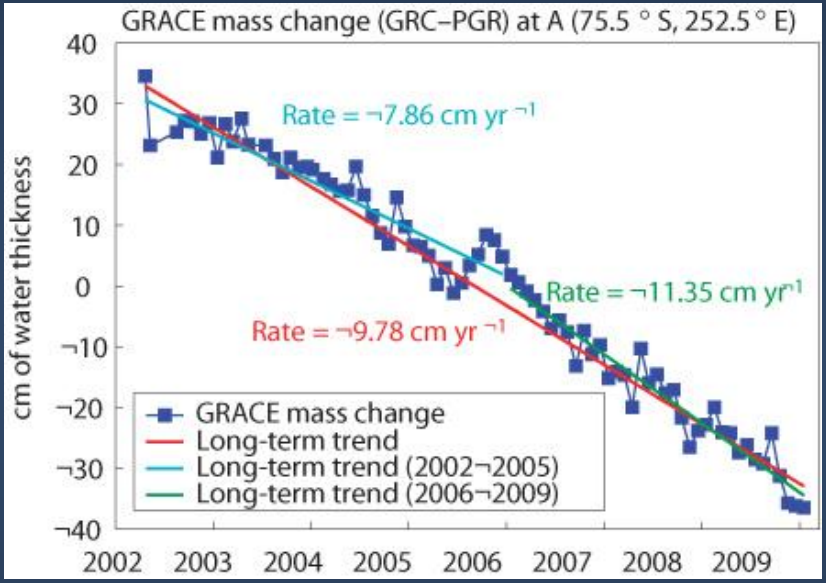
Ivins & James 2005

Weighing the ice sheets with gravity: Need a correction for Glacial Isostatic Adjustment

Mass Loss in Antarctica from GRACE 2002-2009



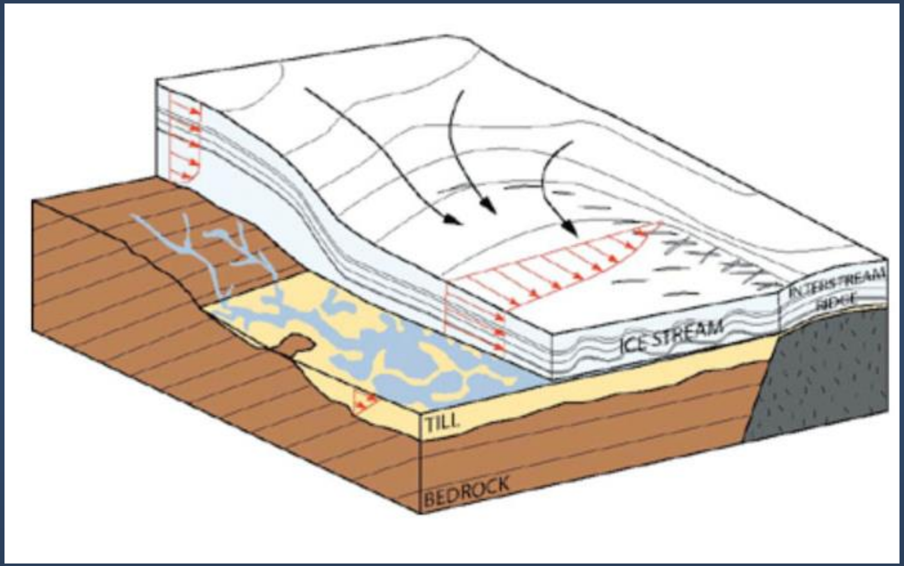
Ice Mass in West Antarctica

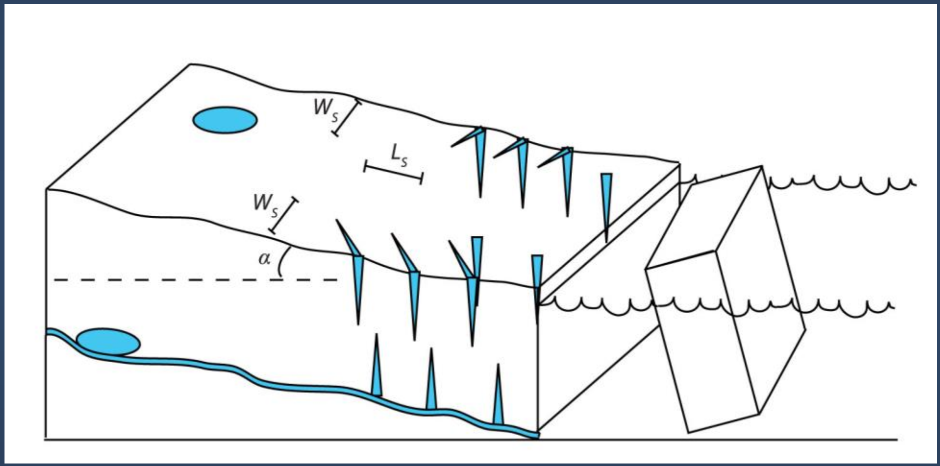


- But how much of signal is due to isostatic adjustment?
- GPS uplift signal includes elastic and GIA components
- Need to remove the effect of long-term GIA

Chen et al. [2009]

Seismic characterization of glacial processes





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

Mechanics of calving
Ice shelf break up?

Recording Seismic Data in Antarctica

- Mean ambient temperatures as low as -55° C
- Winter surface temperatures as low as -80° C
- 6 months of darkness
- Inaccessible most of the year

Broadband Seismograph deployments initiated during the International Polar Year (IPY)

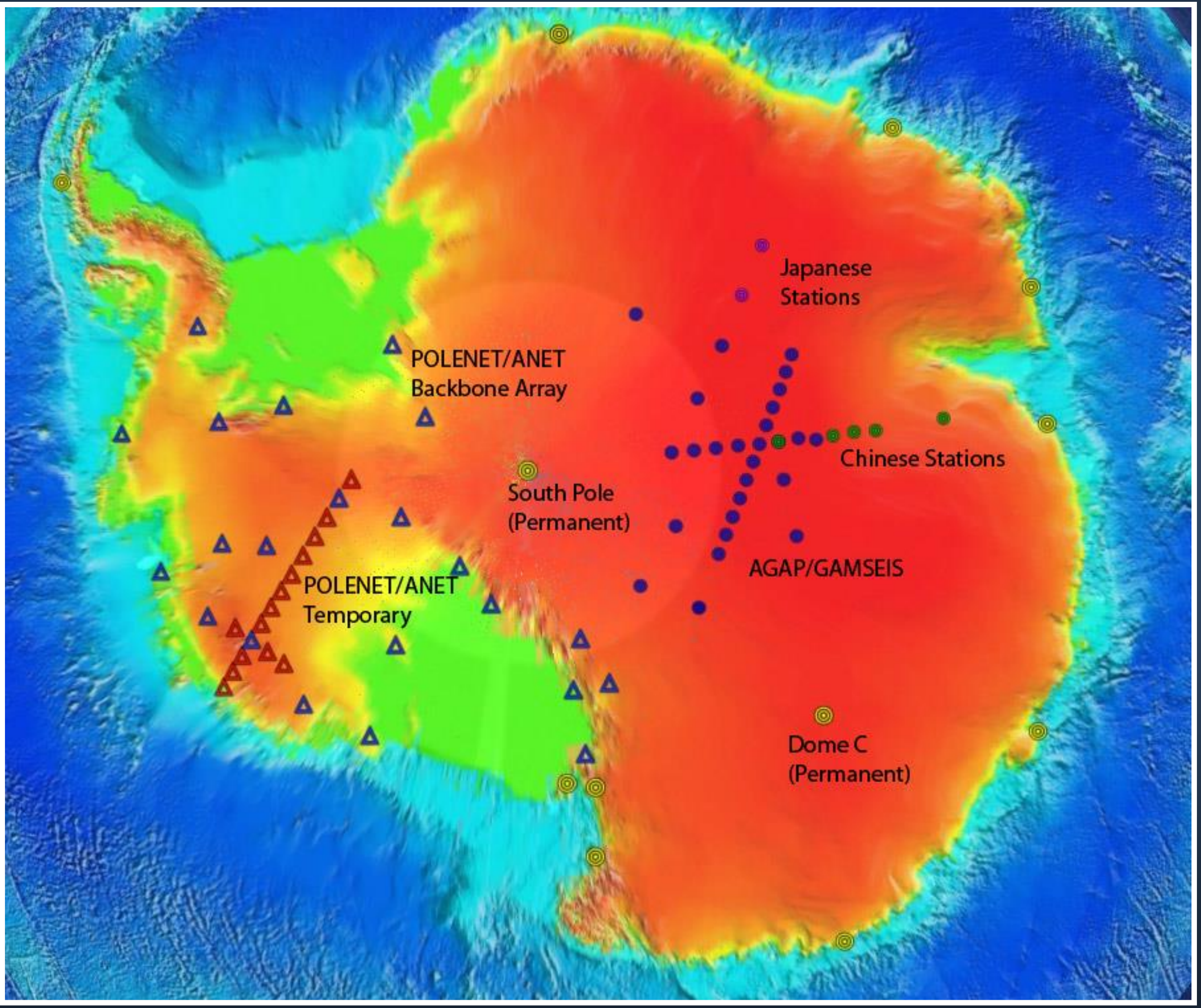
Large Experiments in East Antarctica (AGAP) and West Antarctica (POLENET/ANET)

First time seismographs have been deployed across Antarctica and operated year-around.

Deployed starting in 2007; many stations moved from East to West Antarctica in 2009-2010

PIs: Wiens, Nyblade, Aster, Anandakrishnan, Huerta,

13 POLENET stations (backbone) have open data access

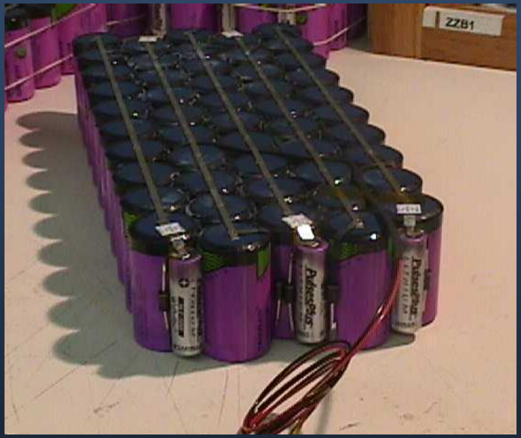


Polar Seismic Instrumentation

Developed along with the IRIS-Passcal Instrument Center

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

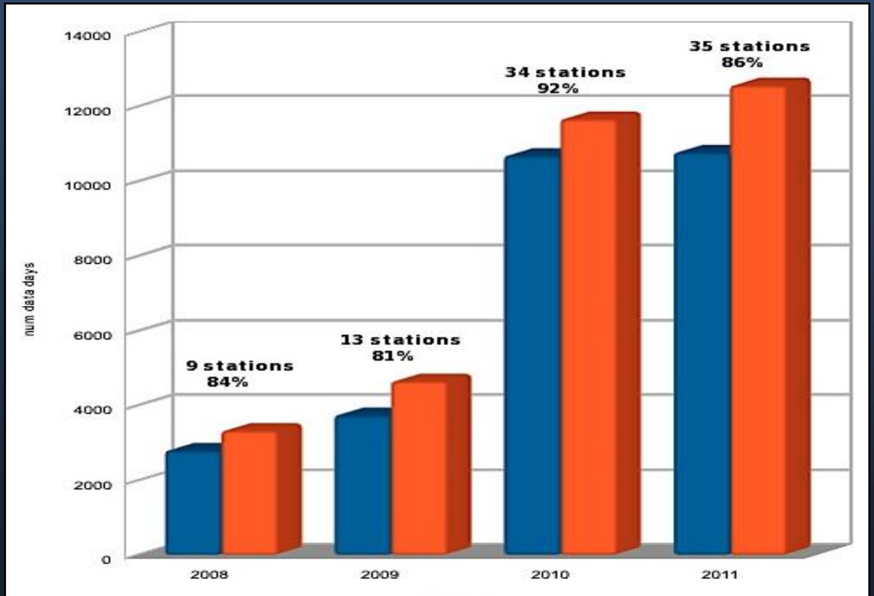
Insulated Box



Lithium batteries

Polenet/ANET Data Return

Orange bars show possible data – blue bars show actual return



Installation

- We generally operate from a field camp
- Equipment and supplies delivered by LC-130 aircraft
- Fly out to sites on Twin Otters aircraft with skis
- Have also used Ski-doo traverse

Equipment Installation

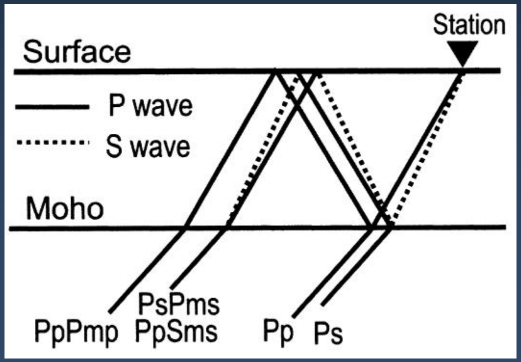
Sensor and Pad

Datalogger, Batteries, and Solar Panels

Seismological Imaging Methods

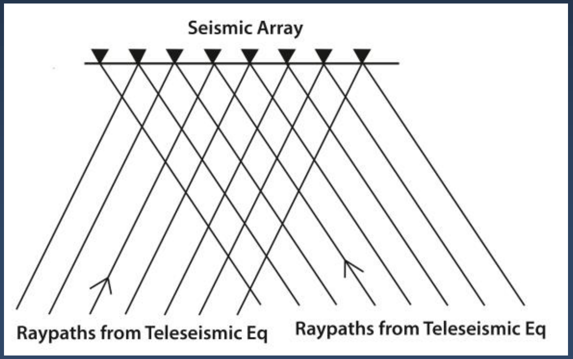
Use signals from distant earthquakes

Receiver Functions



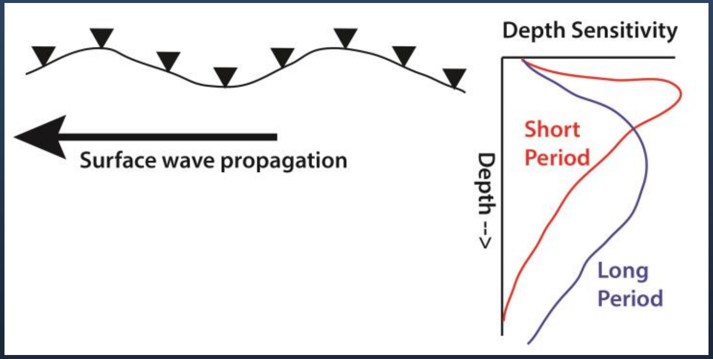
Good for: Imaging discontinuities
(Moho, sed/rock interface)
Weakness: poor for gradients, actual velocities
results limited to immediately below station

Body Wave Tomography



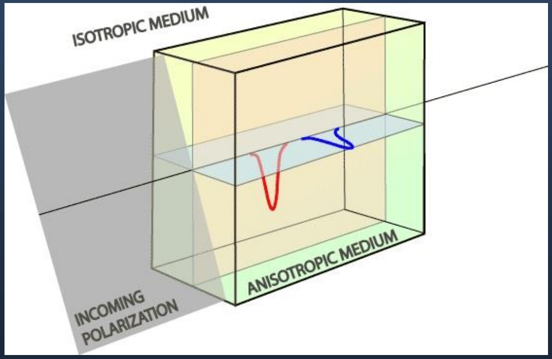
Good for: lateral variations at 100-600 km depth
Weakness: need close station spacing,
often poor depth resolution
velocities are relative, not absolute

Surface (Rayleigh) wave tomography



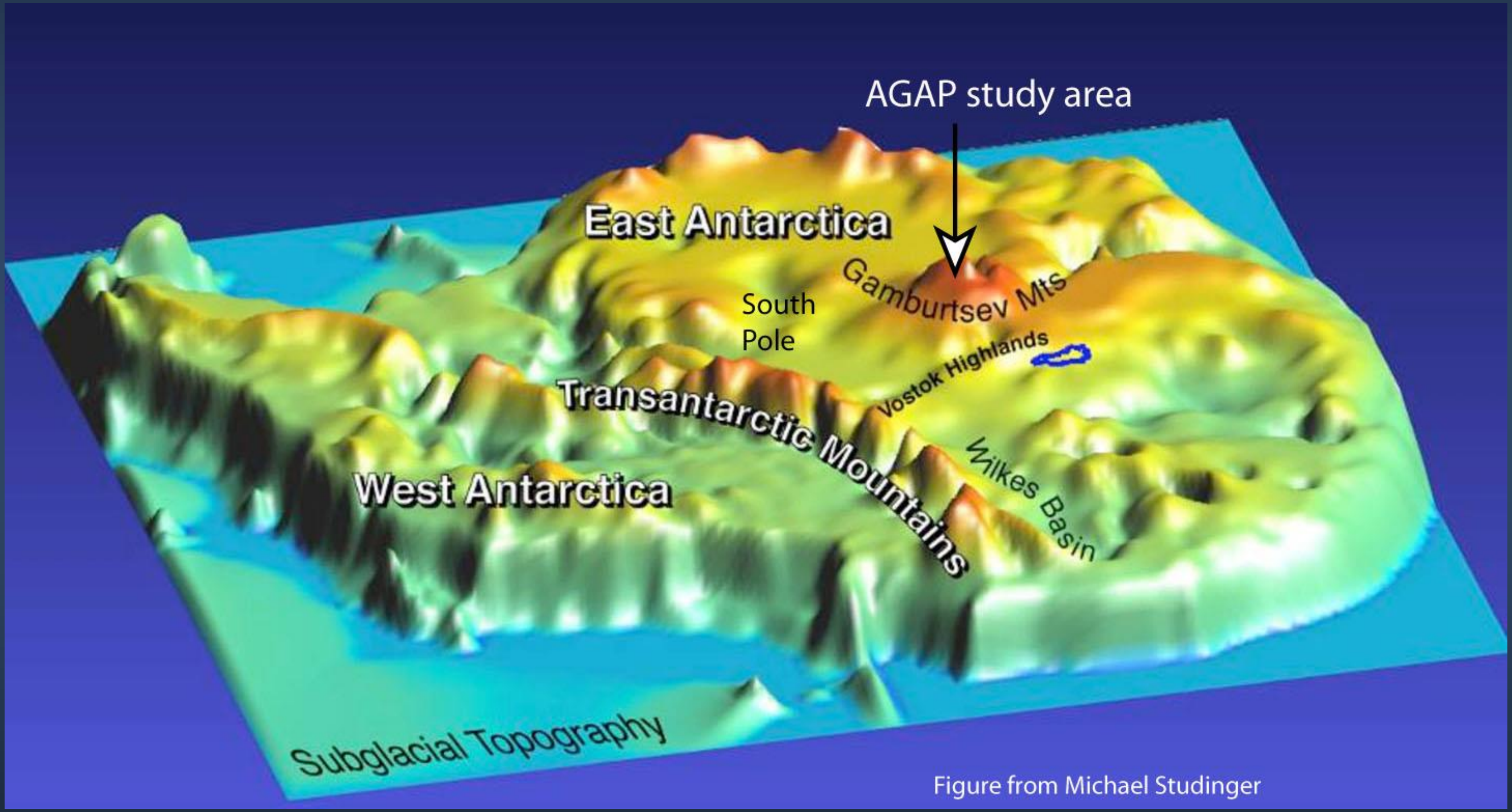
Good for: depth variations, absolute velocities
Weaknesses: often poor lateral resolution
limited to upper 300 km

Shear wave splitting

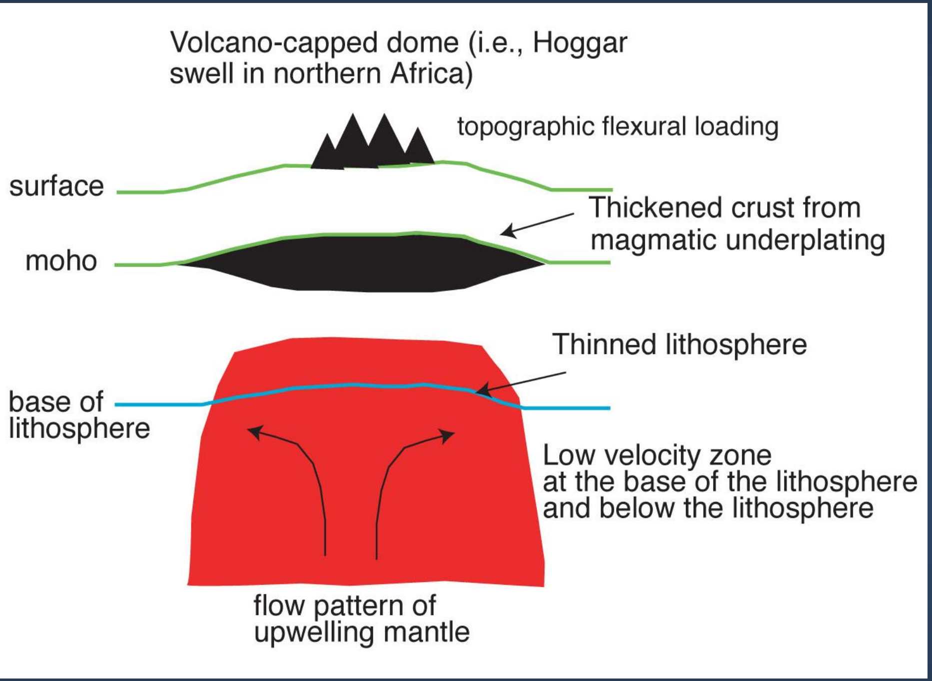


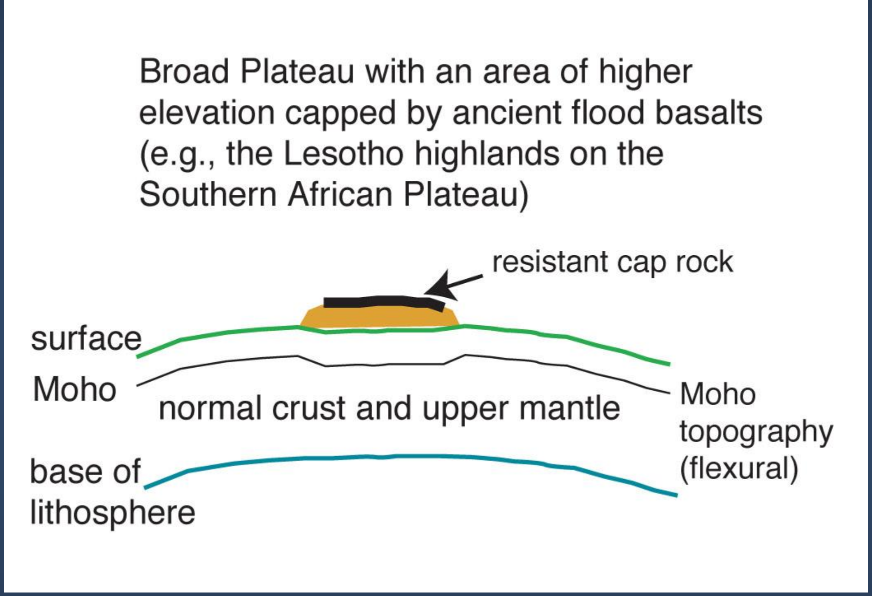
Good for; constraining azimuthal anisotropy
Weaknesses: does not constrain radial anisotropy
poor depth resolution

AGAP - An International Polar Year project to study Antarctica's Gamburtsev Province



Tectonic models for Gamburtsev uplift



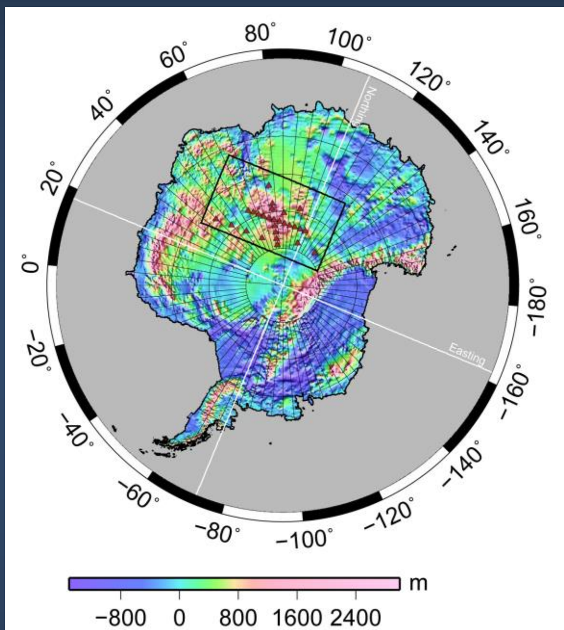


Cenozoic uplift

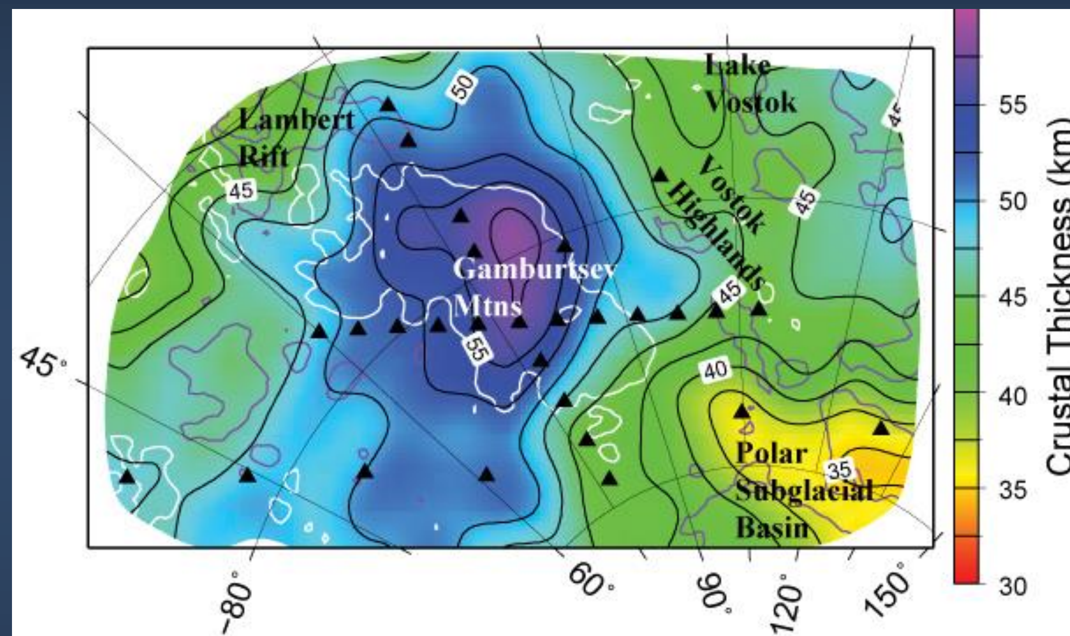
Proterozoic or Paleozoic uplift

A crustal root beneath the Gamburtsev Mtns

Bedrock Topography



Crustal Thickness



Heeszel et al., [2013]

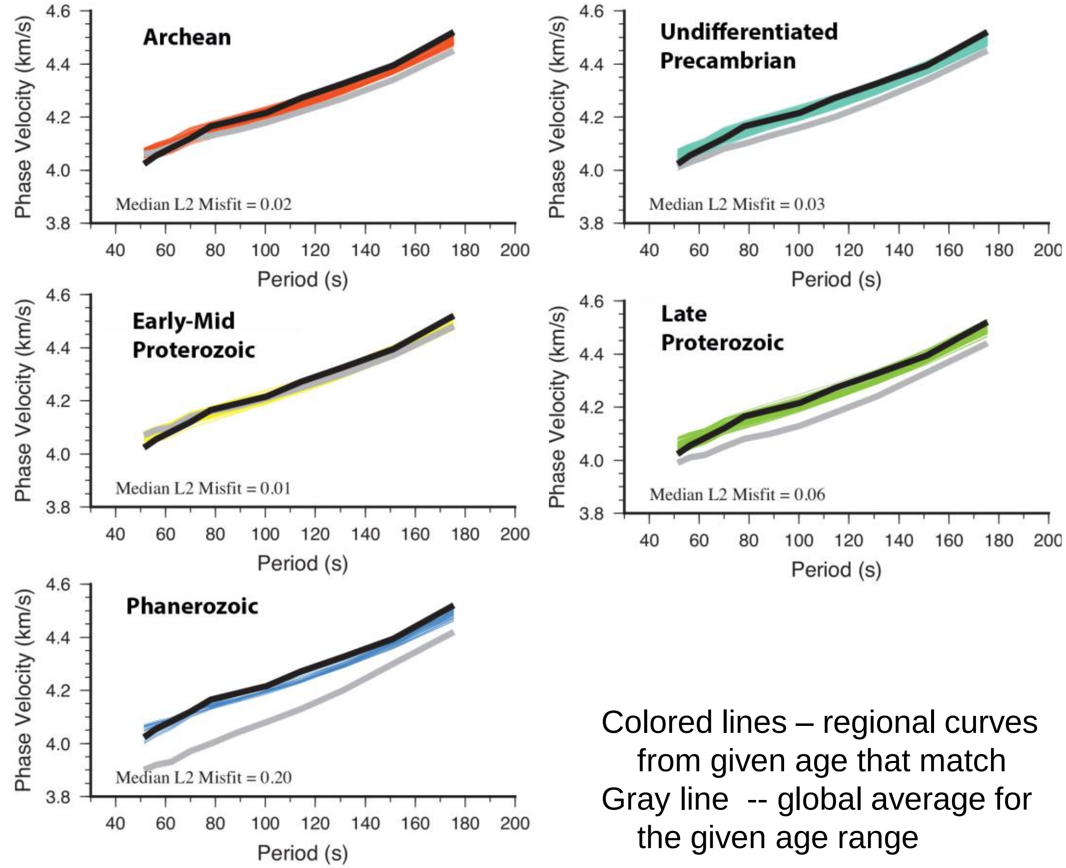
- Crustal thickness from receiver functions and surface waves
- Thickness exceeds 55 km beneath the center of the Gamburtsev Mtns
- Elevation of the mountains supported by thickened crust

What is the age of Gamburtsev Lithosphere?

- Compare average Gamburtsev Rayleigh phase velocity curve with phase velocities from a global study (Visser et al., 2008)
- Find regions with best match
- Compare Gamburtsev results with average curves for different lithospheric ages

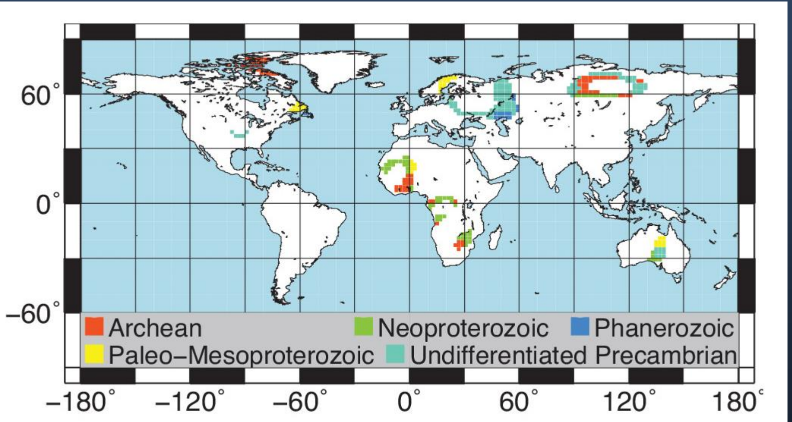
- Strong match for Archean, Early Proterozoic
- Poor fit for late Proterozoic and Phanerozoic

Rayleigh Phase Velocity Comparison



Colored lines – regional curves from given age that match
Gray line -- global average for the given age range

Similar Regions Worldwide

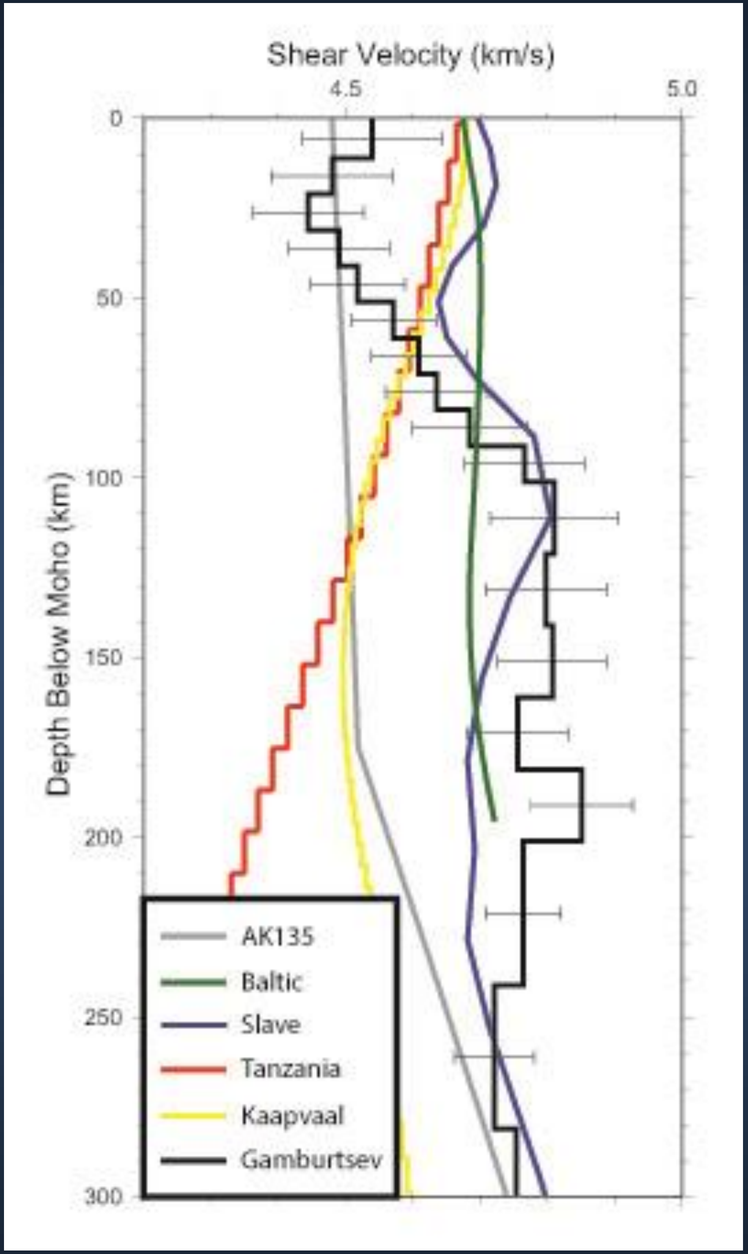


Heeszel et al, [2013]

Comparison of Gamburtsev Mantle Velocity Structure with Other Cratons

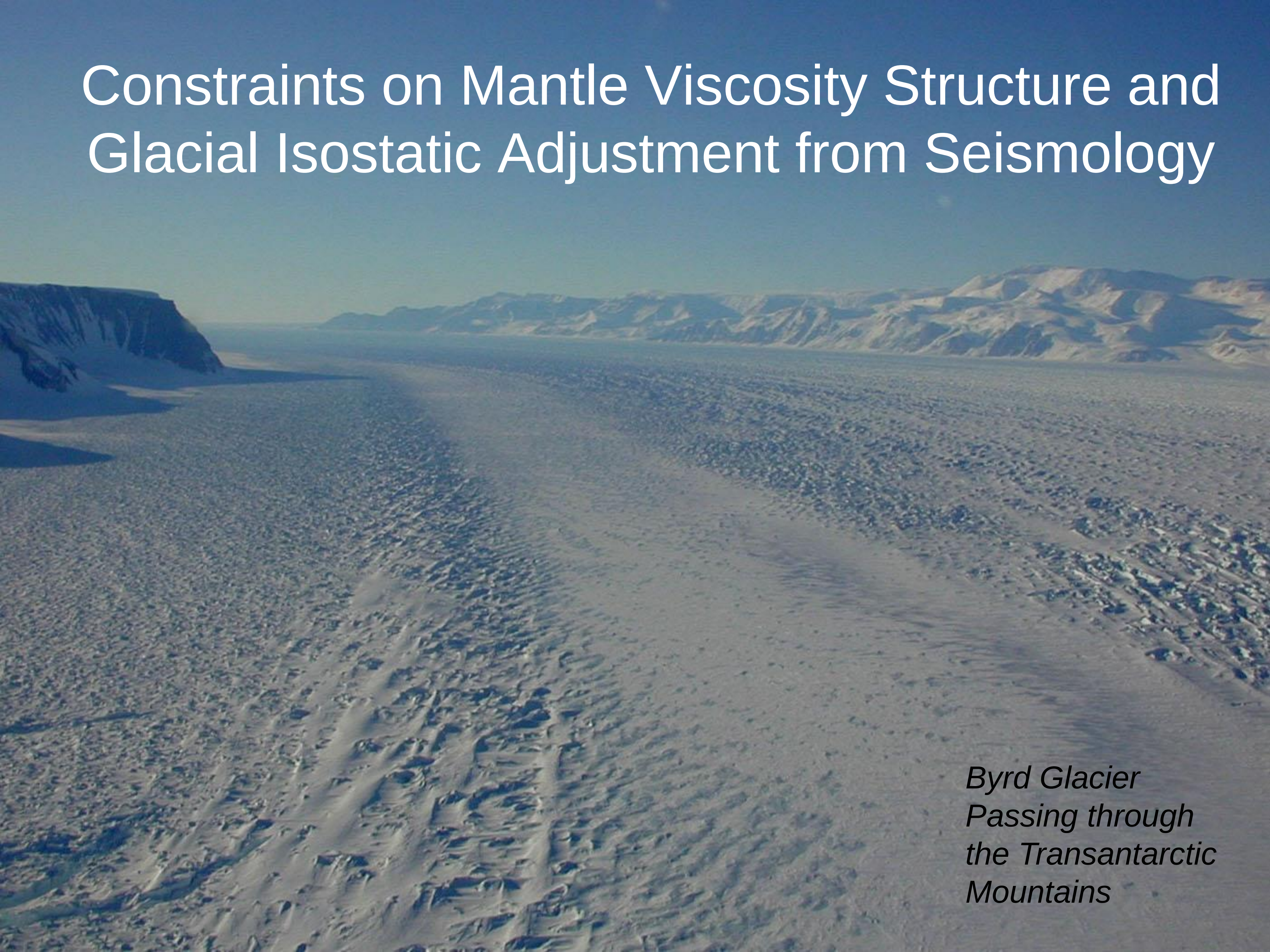
• All of these results obtained with the same method
  (2-plane wave Rayleigh phase velocities)
• Faster structure than the global average (AK135) down to
  ~300 km depth
  Similar structure overall to Slave and Baltic cratons
• Gamburtsev has slower velocities in upper 50 km of mantle
• Much faster structure at depth compared to Tanzania
  which is surrounded by continental rift zones

Gamburtsev Mountains conclusions:
• Elevation supported by thick (~ 55 km) crust
• Underlain by Mid-Proterozoic/Archean lithosphere
• No evidence of lithospheric thinning or recent tectonic activity
• Most likely interpretation is that high elevations result from a compressional orogeny in Paleozoic (?) time
• Mtns have been at high elevation for much of Mesozoic and Cenozoic time - Elevation has been preserved by low erosion rates



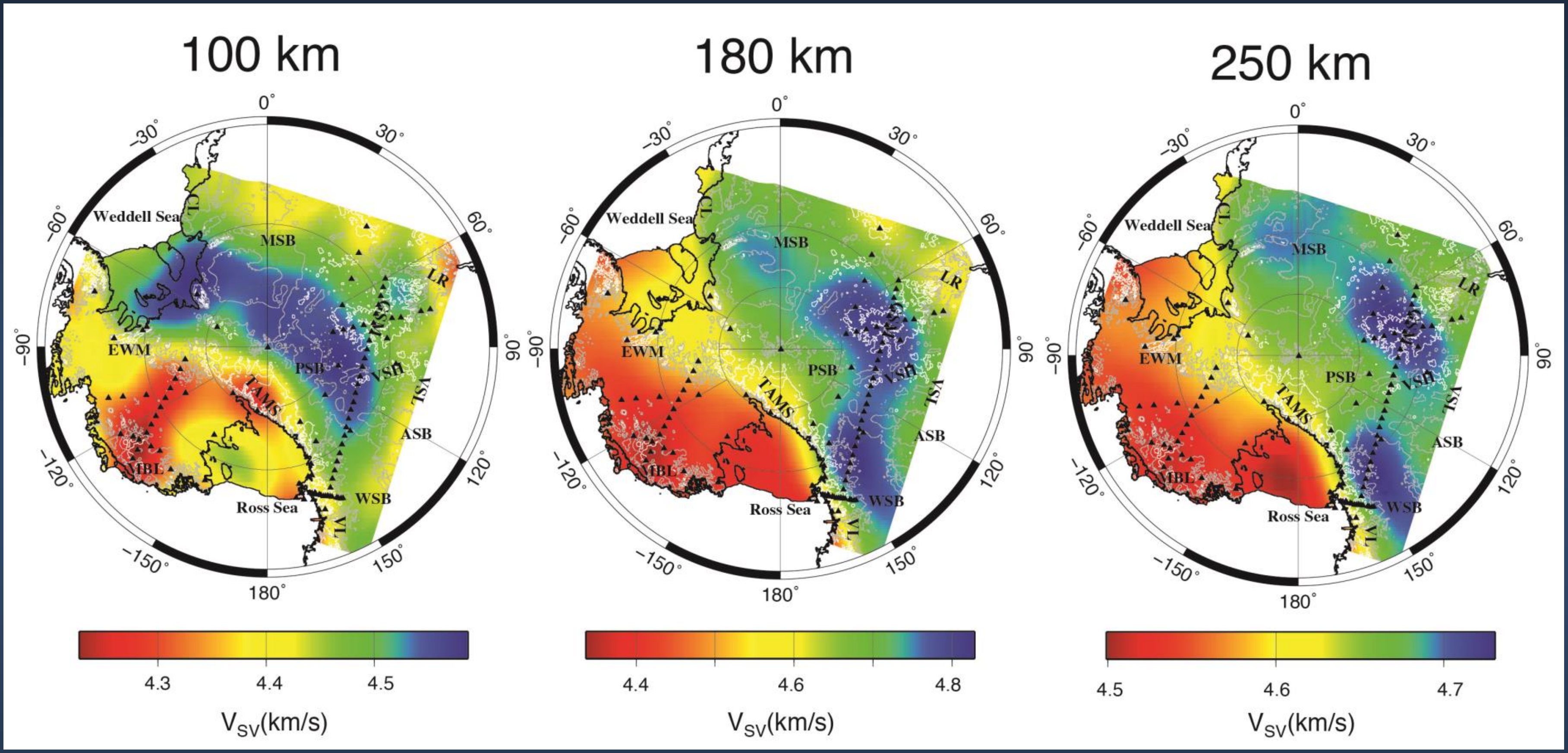
Heeszel et al. [2013]

Constraints on Mantle Viscosity Structure and Glacial Isostatic Adjustment from Seismology



Byrd Glacier Passing through the Transantarctic Mountains

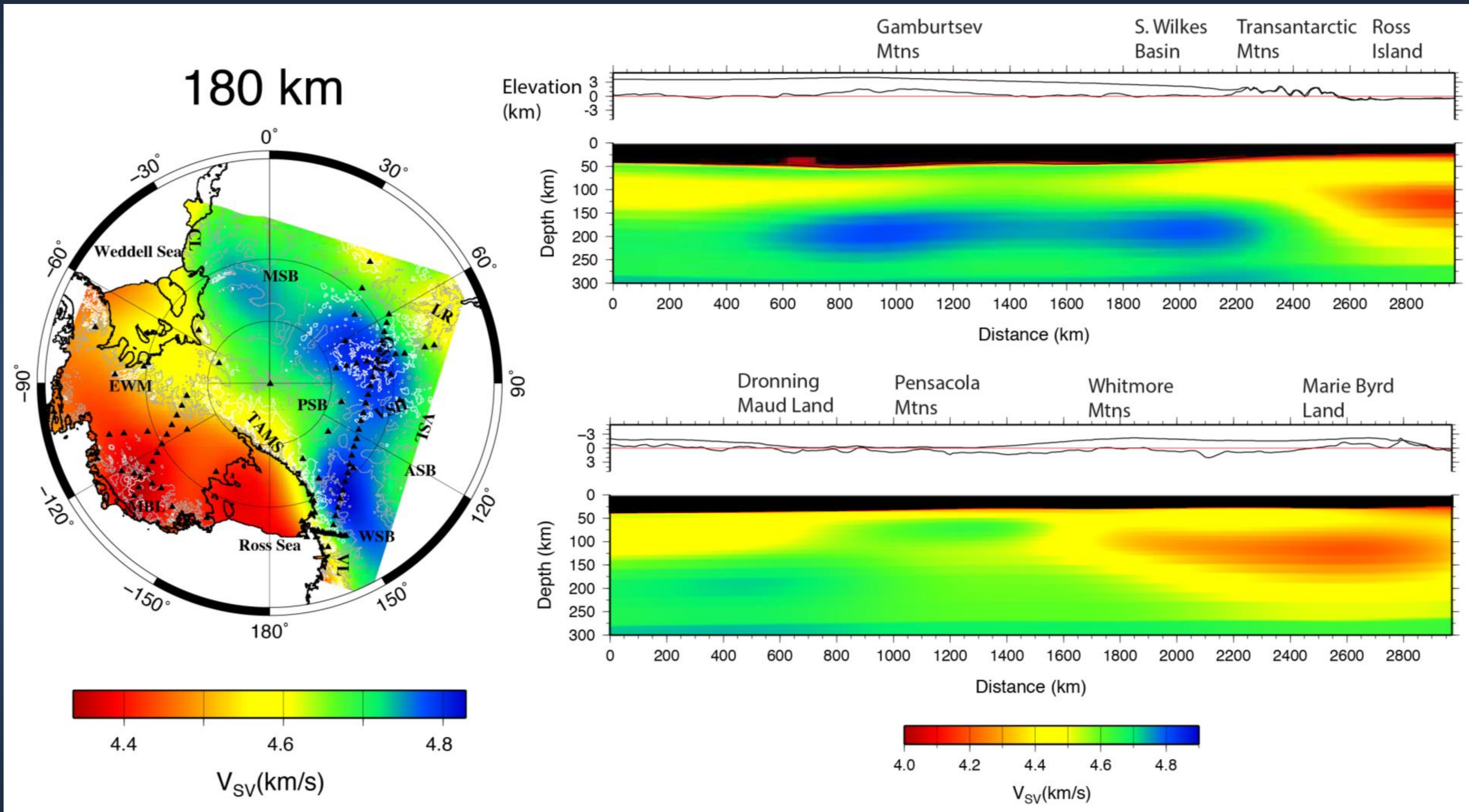
Large-scale upper mantle structure
Rayleigh wave phase velocity tomography



- Use the two plane wave method with finite frequency kernals [*Yang and Forsyth*, 2006]
- High velocity cratonic lithosphere in East Antarctica down to ~ 250 km depth
- Slow velocities in the Ross Sea and along the West Antarctic Rift System (WARS), suggesting high heat flow and low upper mantle viscosity
- Evidence of a low velocity thermal plume beneath Marie Byrd Land

Heeszel et al., in prep

Upper Mantle Cross Sections



Heeszel et al., in prep

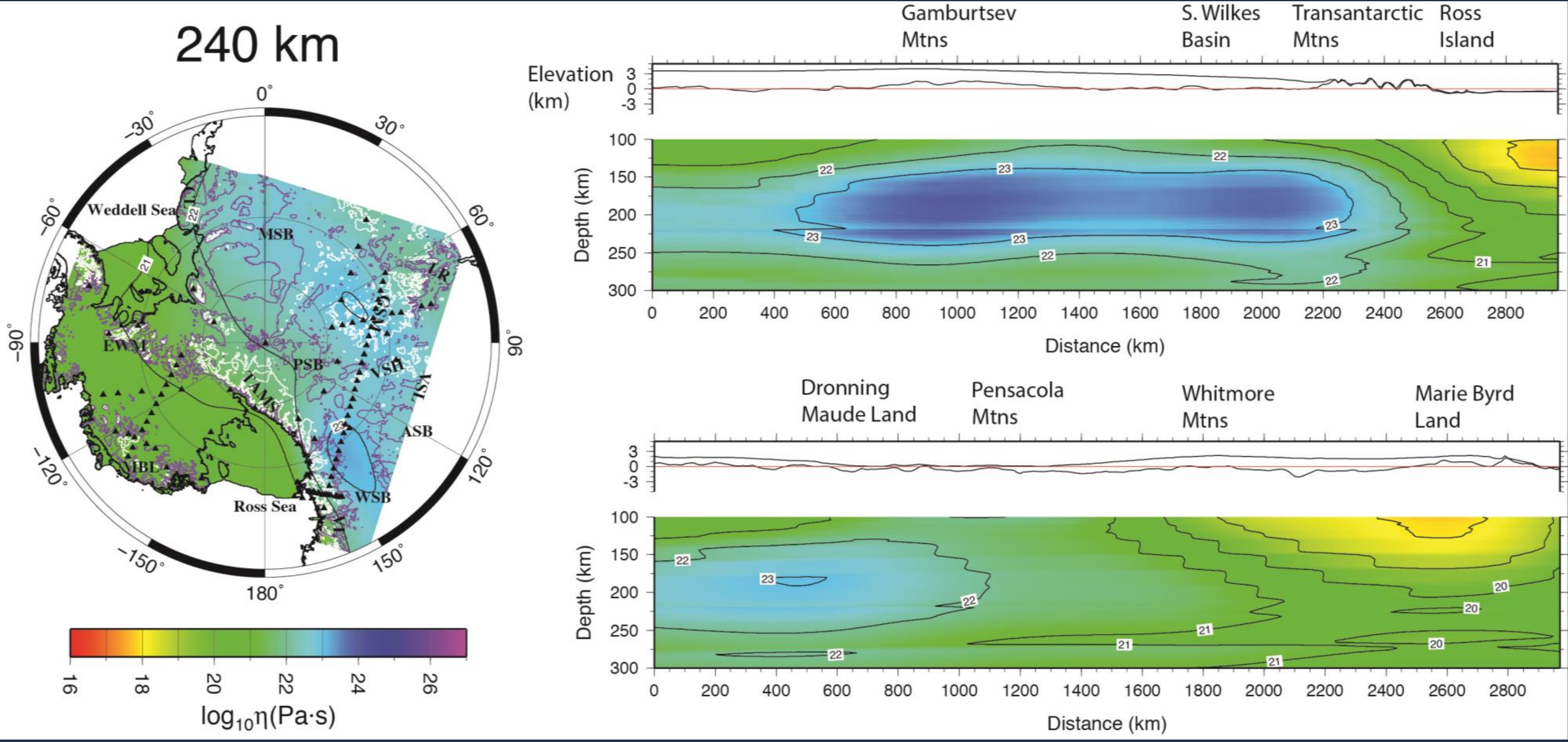
Estimating Mantle Viscosity from Seismic Shear Velocity

Assume (following *Wu et al.*, 2012):

- Some fraction (β) of the shear velocity anomalies result from thermal anomalies relative to a reference 1D thermal model (here we use β = 0.65)
- a reference 1D viscosity model corresponding to the reference thermal model
- experimentally derived formulas for the temperature derivative of shear velocity
- experimentally derived relationships for the temperature dependence of dislocation creep (viscous flow)

$$\log_{10}(\Delta\eta) = \frac{-0.4343\beta}{[\partial \ln v_s/\partial T]_{\mathrm{ah+an}}} \frac{(E^* + pV^*)}{RT_0^2} \frac{\delta v_s}{v_s}.$$

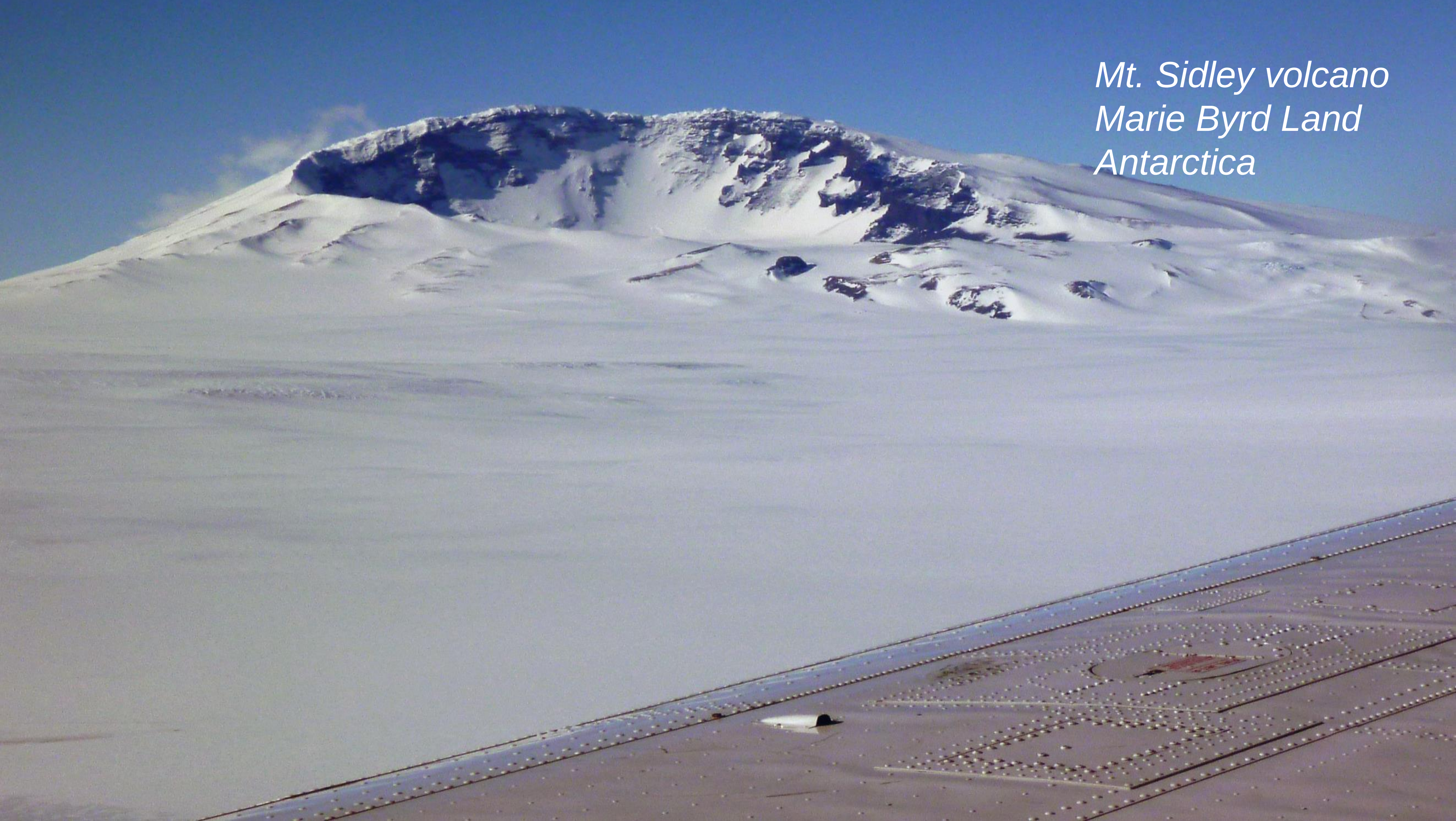
Mantle Viscosity Cross Sections



Heeszel et al., in prep

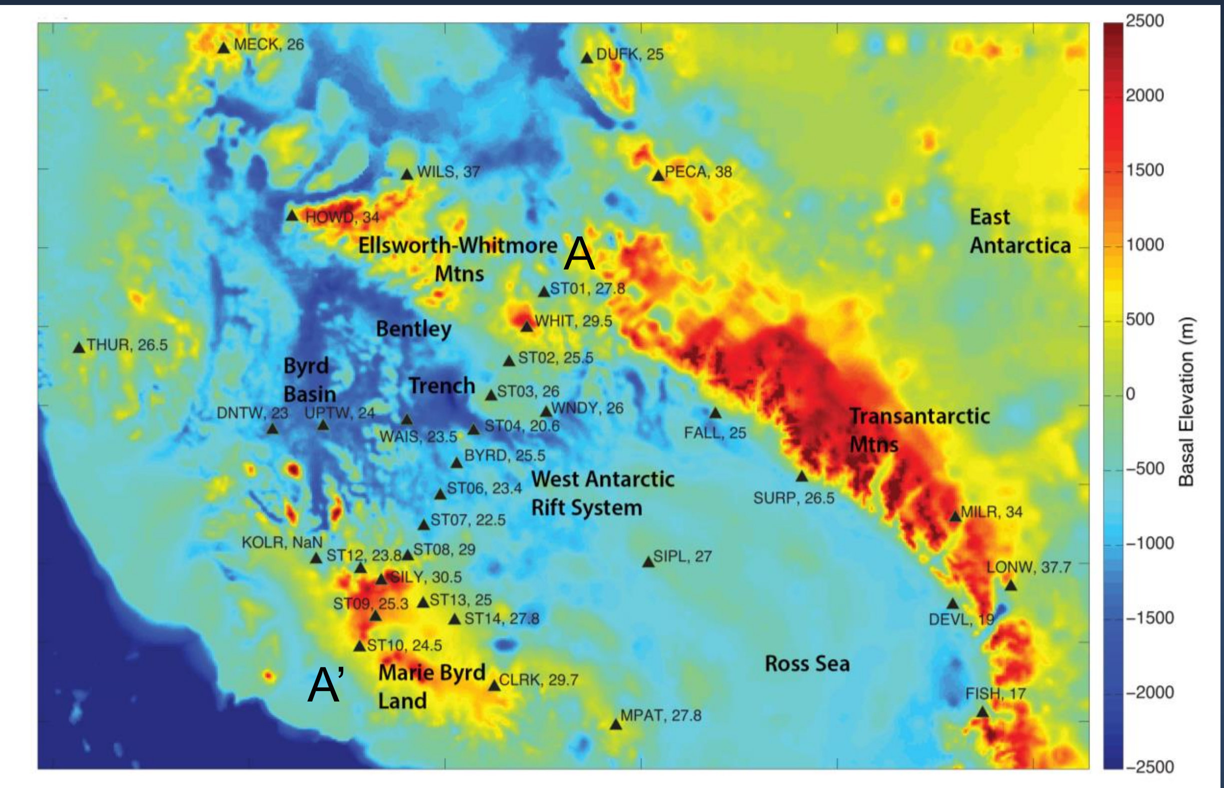
- Huge viscosity variation between West Antarctica and craton
- Suggests Glacial Isostatic Adjustment in West Antarctica reflects last few thousand years; East Antarctica shows last glacial maximum

Volcanic and tectonic effects on heat flow into the base of ice sheets

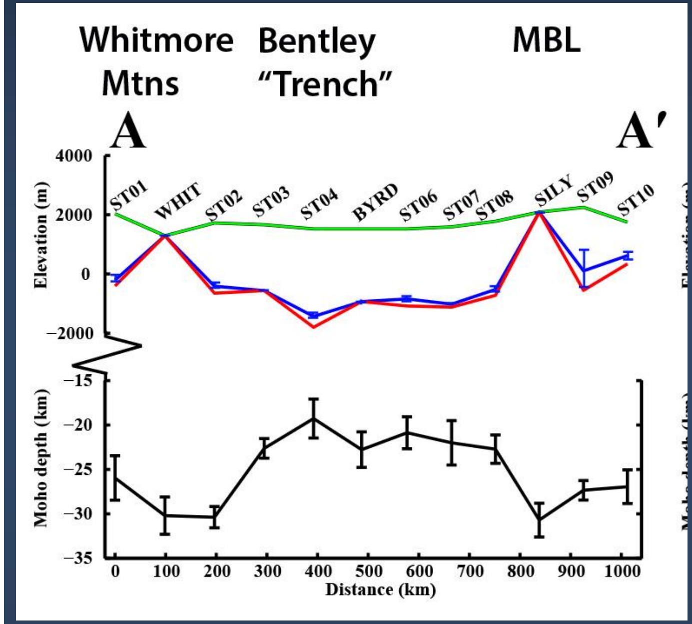


Mt. Sidley volcano
Marie Byrd Land
Antarctica

West Antarctic Basins – Cenozoic Rifts?



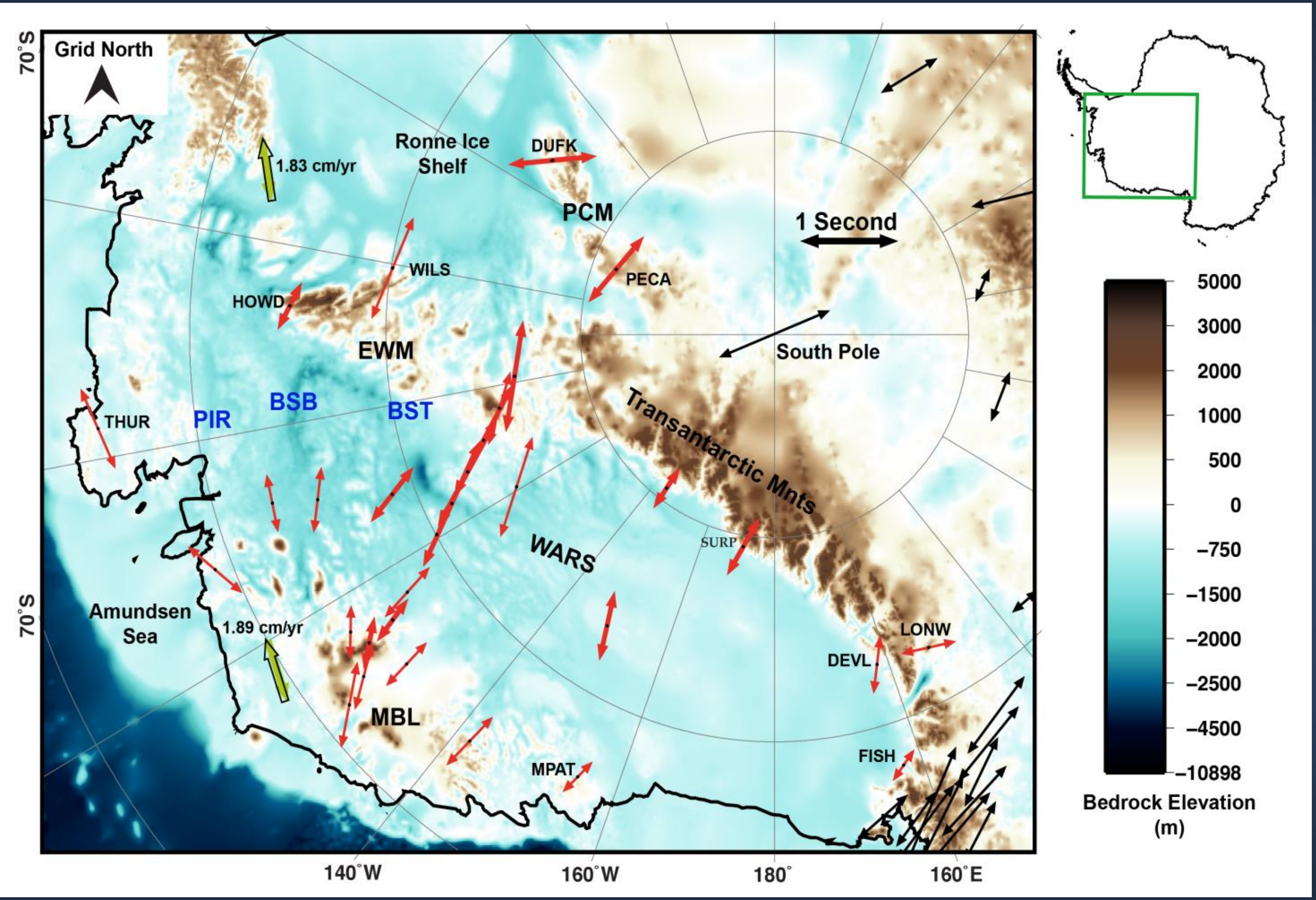
Moho Depth along Transect



Chaput et al, [2014]

- Receiver functions provide local crustal thickness
- Very thin crust (< 25 km) along TAM front, Bentley Trench and Byrd Basin
- Evidence that west Antarctic deeps represent Cenozoic rift valleys

Seismic Anisotropy in West Antarctica: Evidence for recent extension

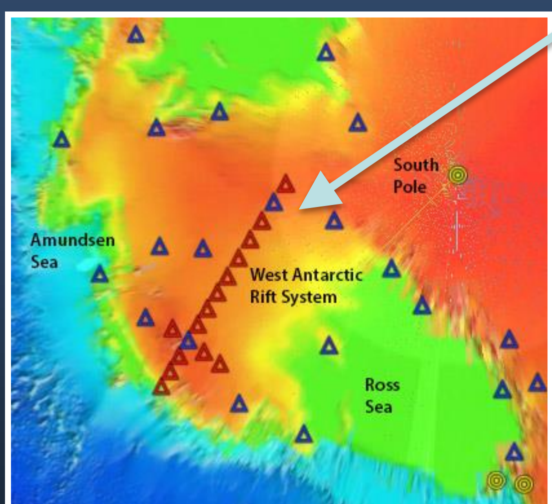


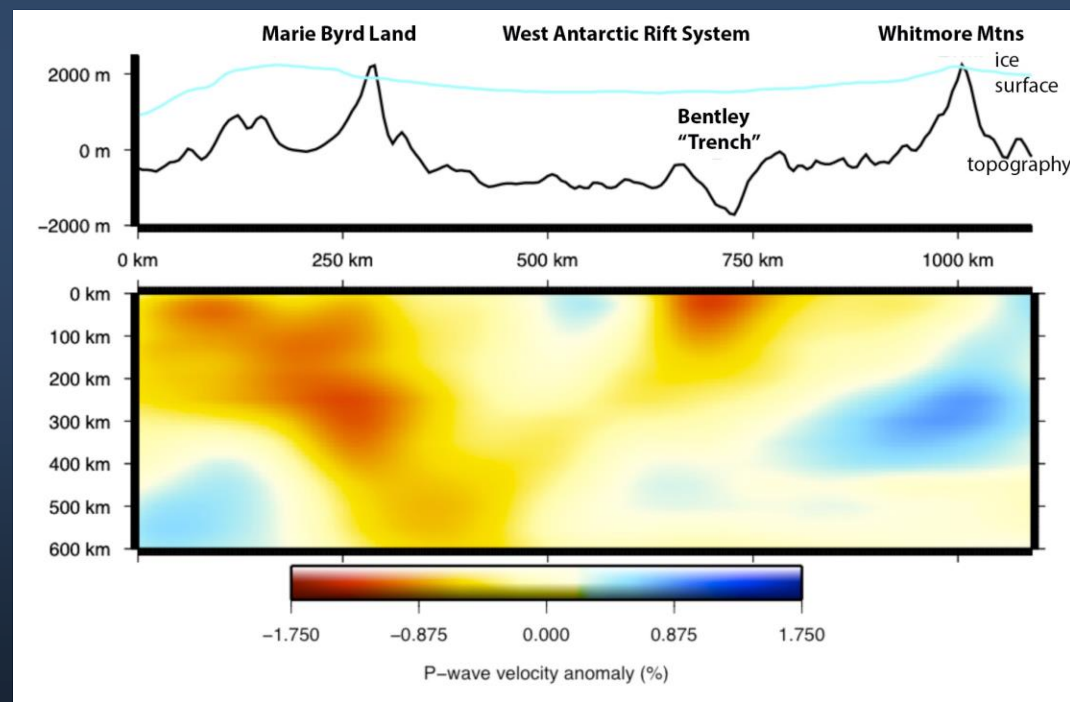
Accardo et al, In review

- Extremely strong rift perpendicular mantle fabric near Bentley Trench
- Suggests large amount of recent extension

Detailed structure of the West Antarctic Rift System

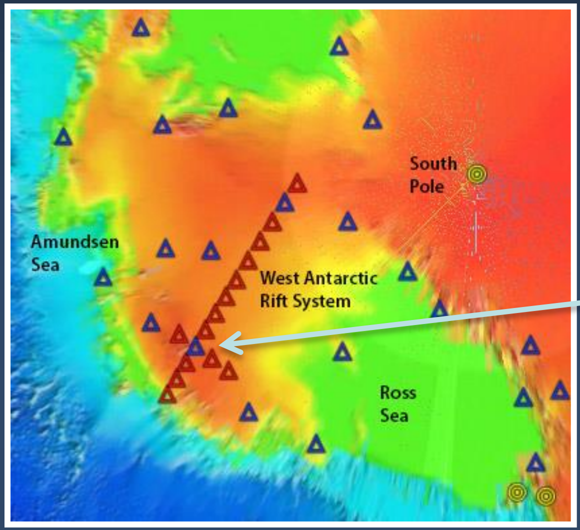
- P-wave tomography along the seismic transect across West Antarctica
- Shows very slow and hot upper mantle down to ~ 400 km in Marie Byrd Land
- Consistent with a plume head, although no evidence for deeper source
- Faster, colder continental lithosphere beneath the Whitmore Block
- Slow anomaly beneath the Bentley Trench – thermal signature of Cenozoic Rift?



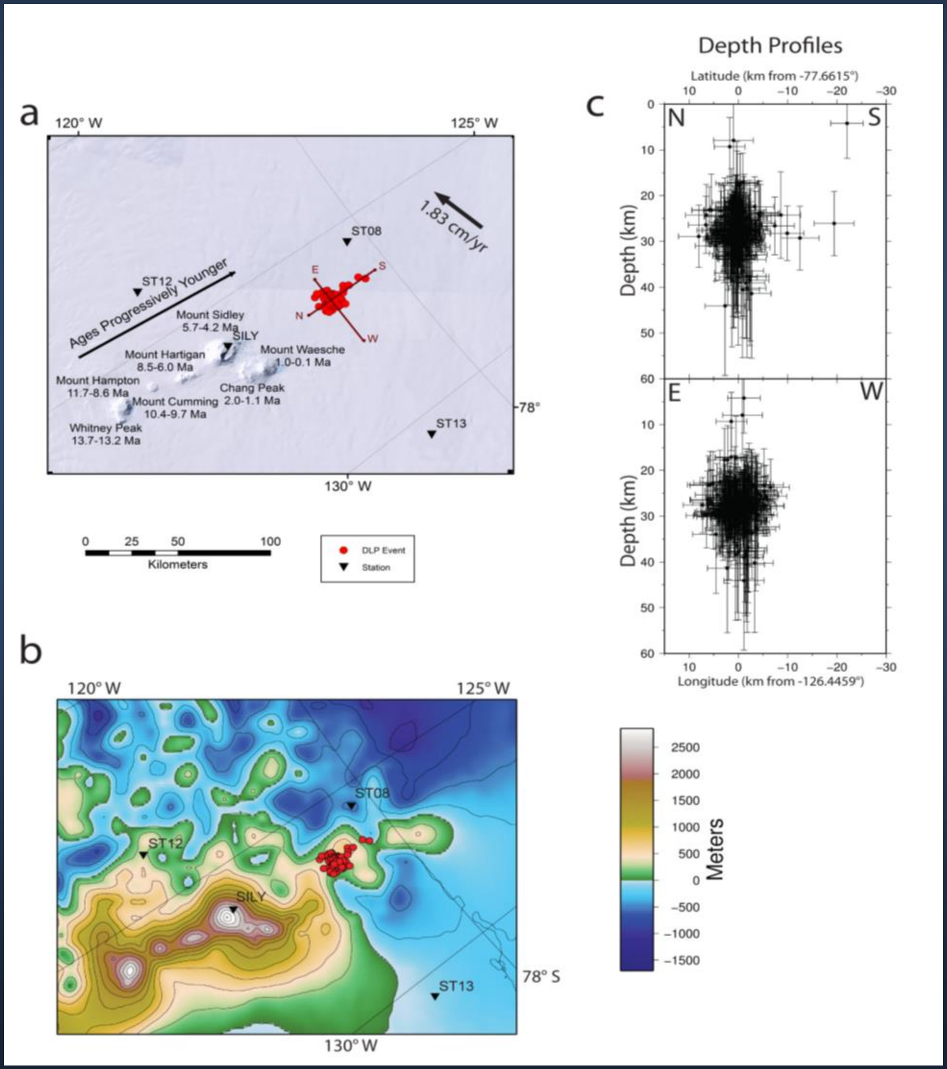


Lloyd et al, in prep.

Sub-glacial Active Volcanoes in Marie Byrd Land



Deep (30 km) LP Volcanic Earthquakes



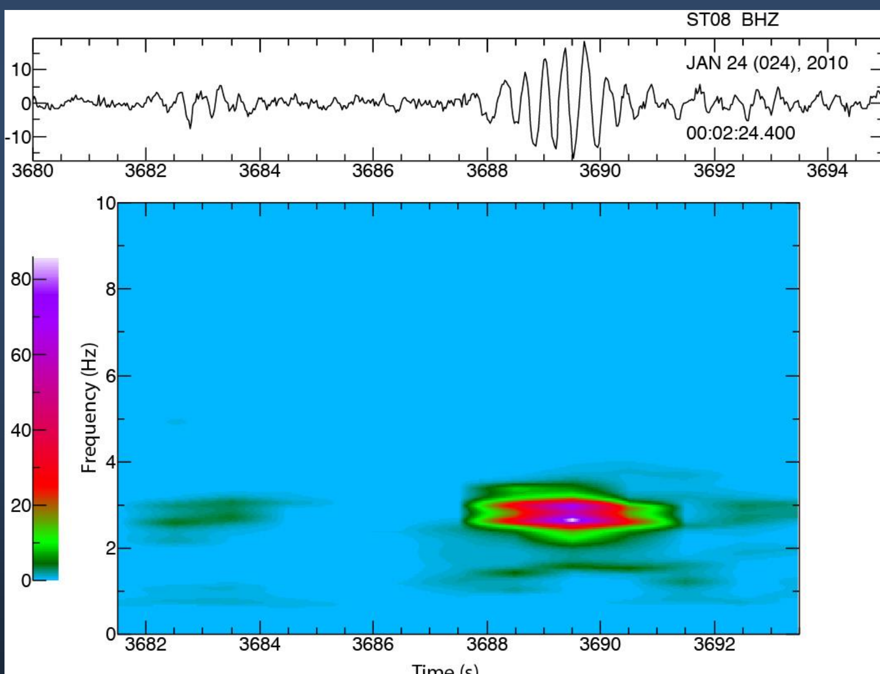
- Ongoing deep long-period volcanic earthquakes discovered
- Indicative of an active magma system
- Demonstrates that active volcanism along Executive Com. Range continues southward migration
- Volcanic eruption would melt many km^3 of ice, lubricate the ice sheet

Lough et al., Nature Geosciences [2013]

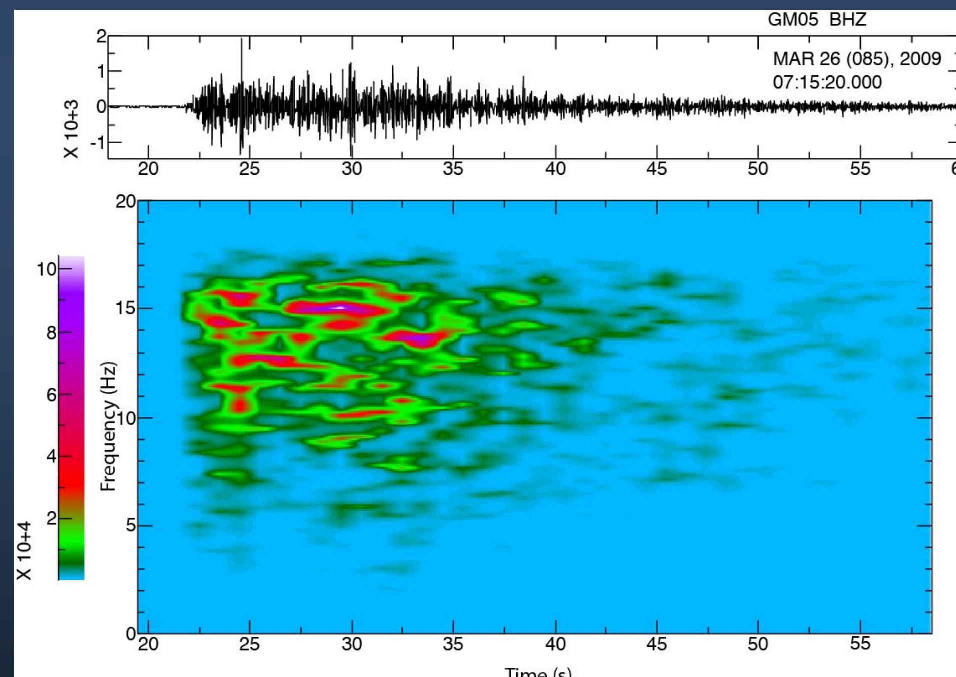
Subglacial Deep LP Volcanic Earthquakes

- Observed at many active volcanoes
- Thought to result from magma movement near the bottom of the crust
- Generally 20-30 km deep
- Have low frequency, monochromatic waveforms

Spectrogram of Marie Byrd Land Deep LP event



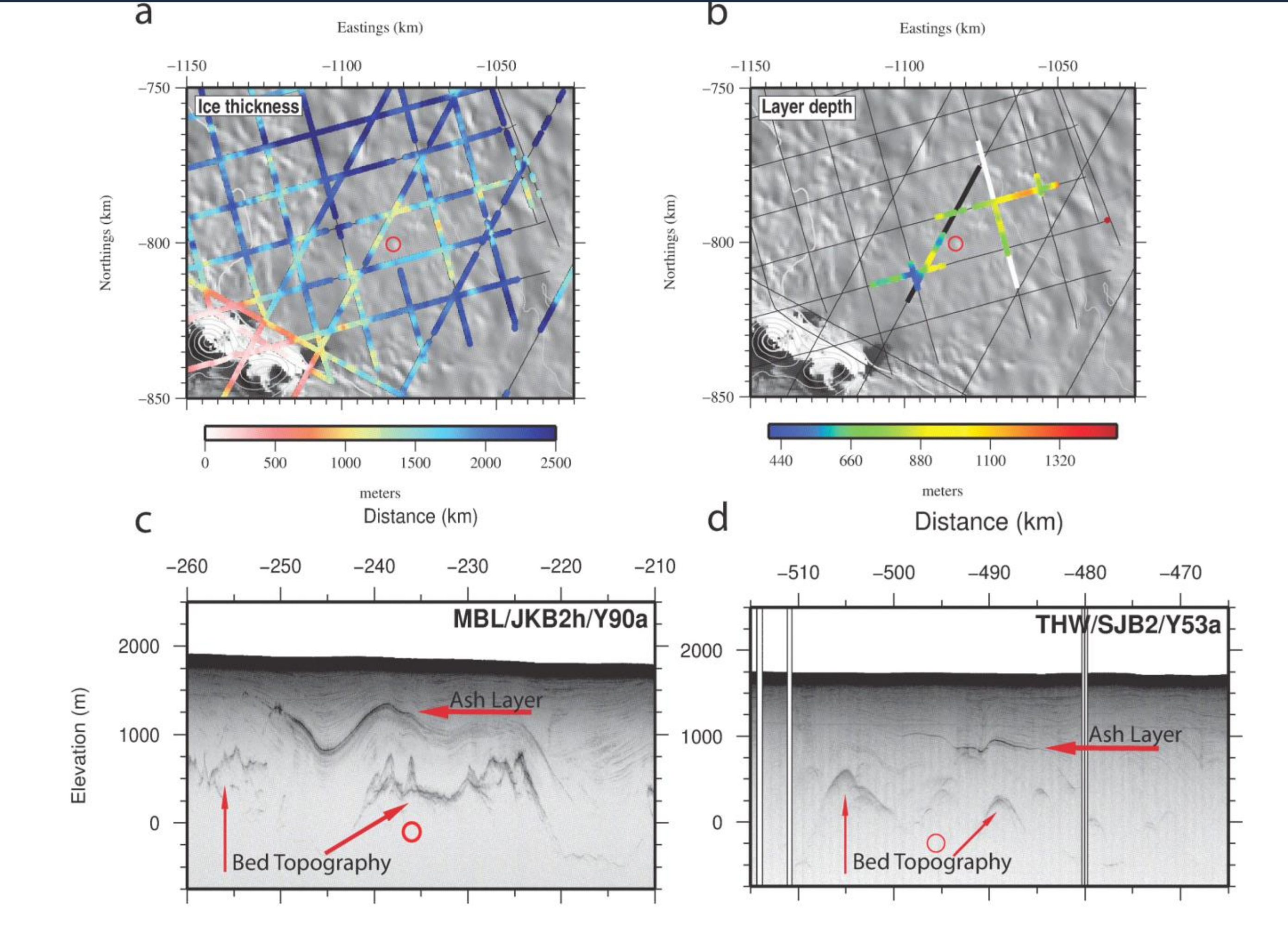
Spectrogram of typical tectonic event of similar magnitude (~ Ml 2)



Lough et al., Nature Geosciences [2013]

Ash layers from subaerial eruptions?
Airborne SAR image

Lough et al., [2013]



Ash layer centered around DLP earthquake nest
Accumulation rate indicates eruption occurred several thousand years ago
Could have originated from the subglacial volcano or from Mt Waesche

Does the newly-discovered volcano erupt subaerially?

Thermal Energy required to melt the overlying ice:

$E = H_{fus} * \rho_{ice} * V_{ice}$

H_{fus} the heat of fusion for ice is 334 kJ/kg
ρ_{ice} the density of glacial ice is 850 kg/m3
V_{ice} is the volume of ice being melted.

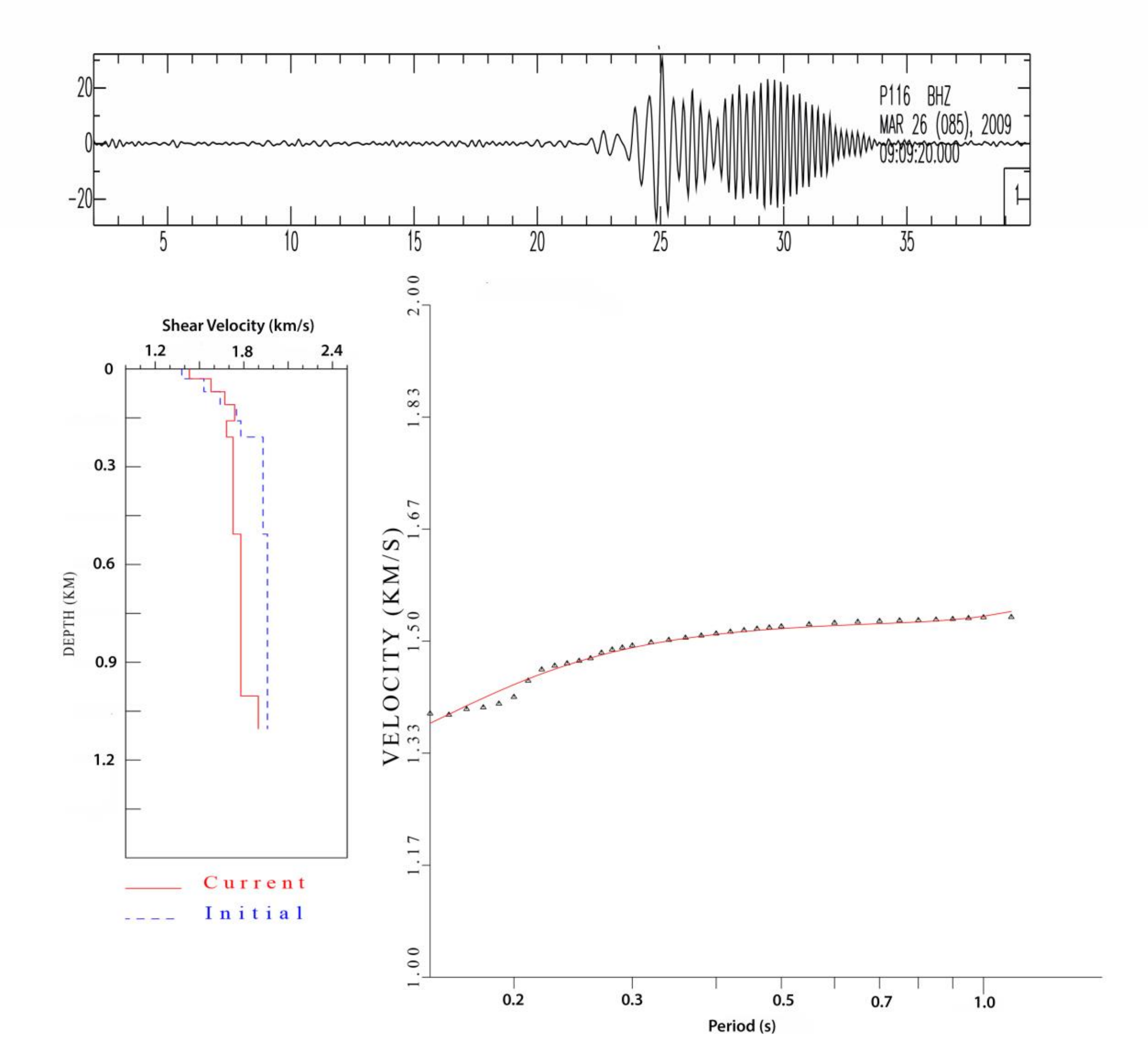
5 km diameter cylinder of ice 1 km thick:
$E = (2500\text{m}*2500\text{m}*1000\text{m}*\pi)*(334\ \text{kJ/kg})*(850\ \text{kg/m3}) = 6 \times 10^{15}$ kJ

A few examples:

Santorini, Aegean Sea	1500 B.C.E	1.0×10^{17} kJ
Mauna Loa, Hawaii	1950 C.E.	1.4×10^{15} kJ

Listening to the ice sheets using seismology

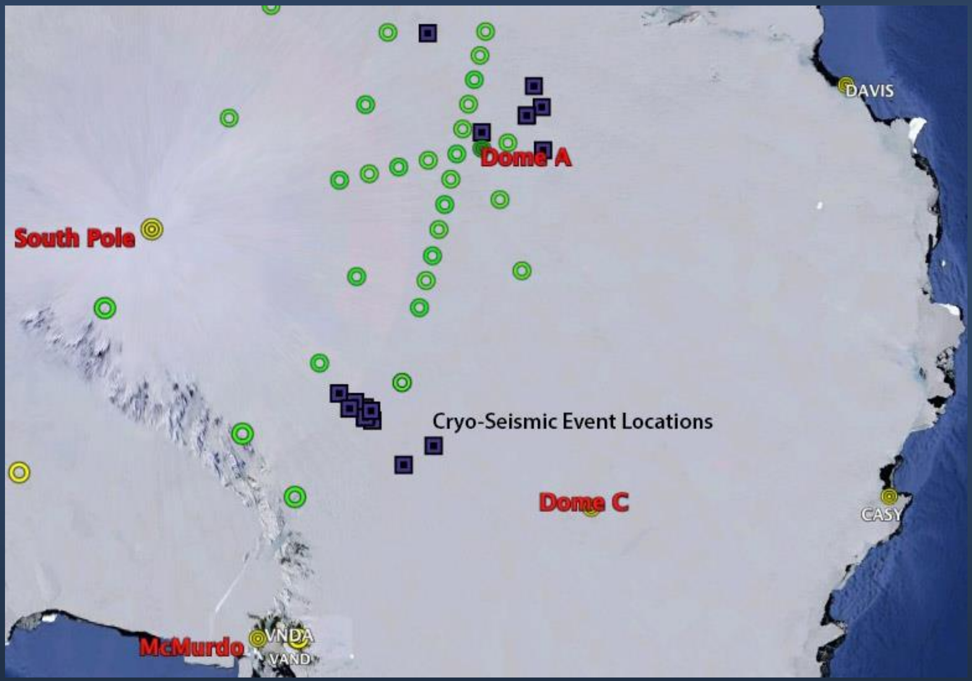
Firn Layer Cryo-Seismic Events



- Observed up to 1000 km away
- Dispersed Rayleigh Waves
- No body wave arrivals
- Rayleigh wave group velocity analysis gives ice velocity
- Modeling shows source must be in upper 20 meters

Firn Layer Cryo-Seismic Events

Locations

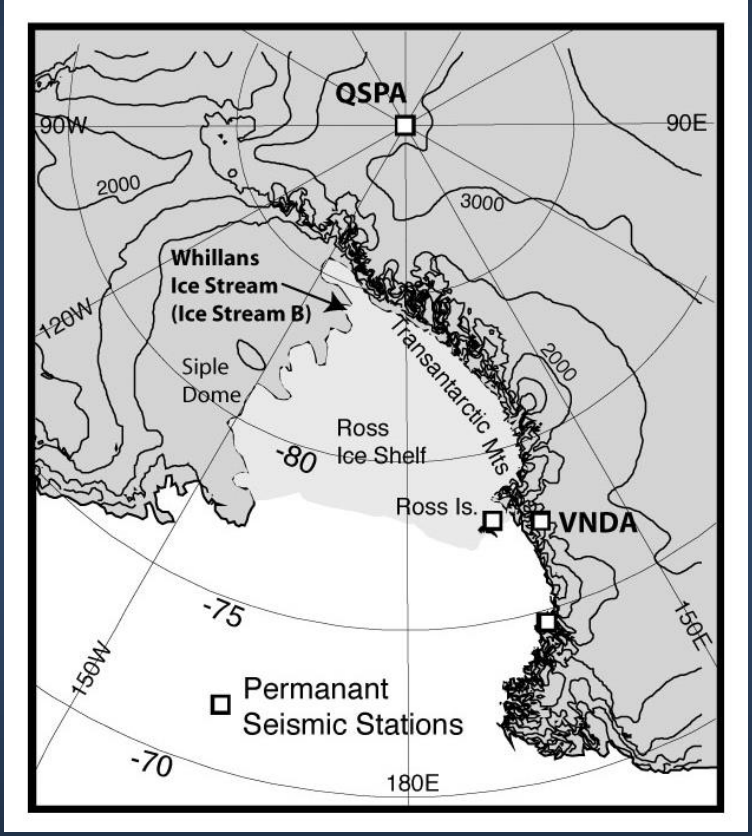


Possible Interpretation: Firn Cracking due to Temperature Cycling

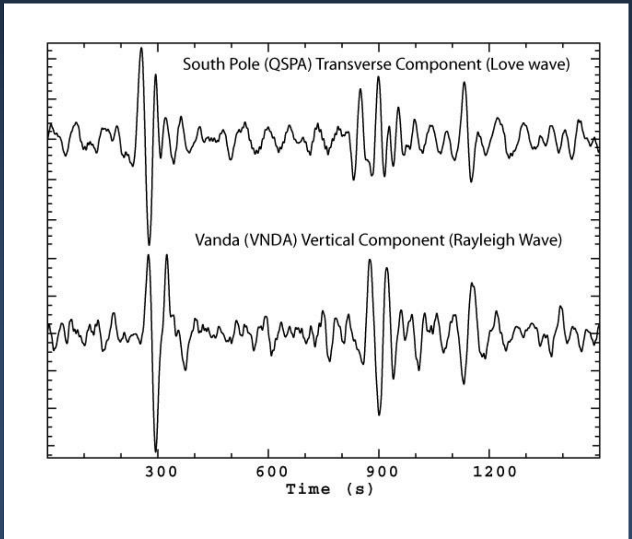
Severinghaus et al 2010

Glacial "stick-slip": Whillans Ice Stream, Antarctica

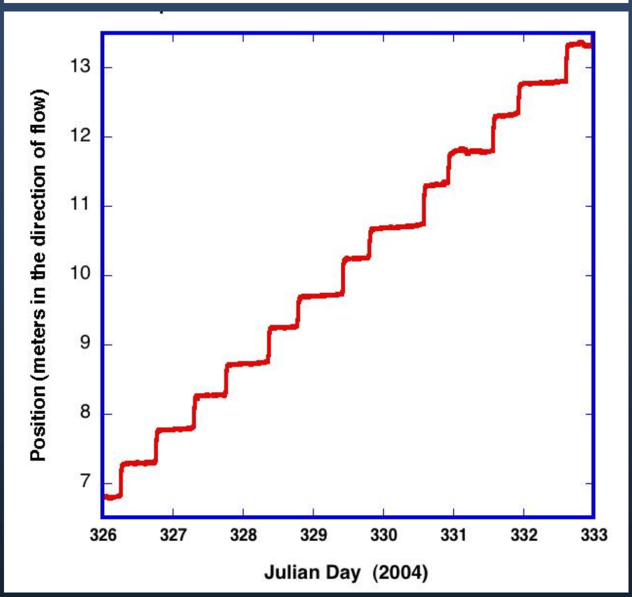
Location



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



Wiens et al., *Nature*, 2008

Ice Stream Rupture Propagation

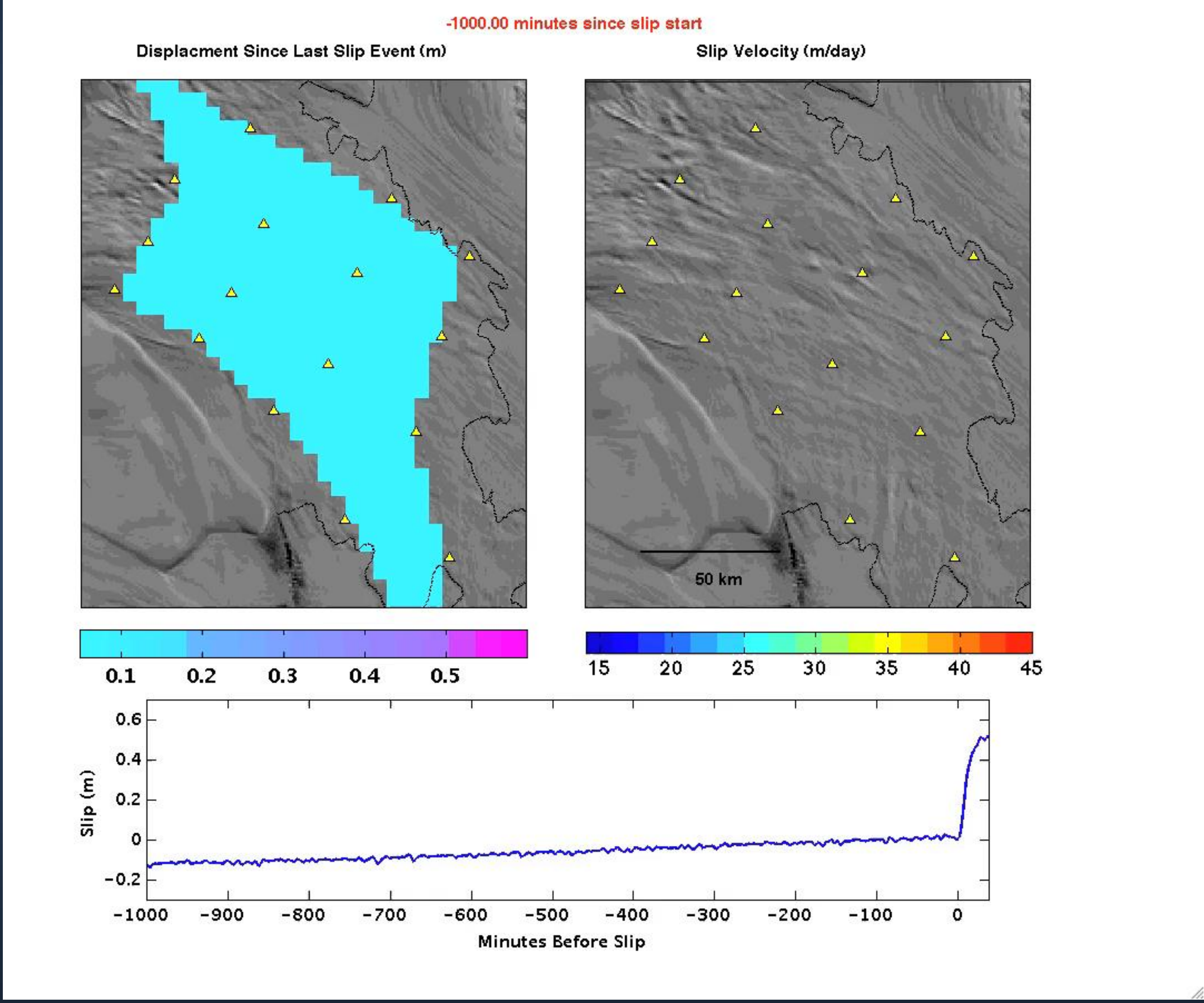
"Asperities", mostly along the grounding line, are locked between slips

Form stress concentrations

Slips start from southernmost 'asperity"

2nd and 3rd asperities rupture during slip event

Rupture velocity ~ 2 km/s during asperity break, ~ 200 m/s otherwise



Movie by P. Winberry

Whillans Ice Stream Stick-Slip

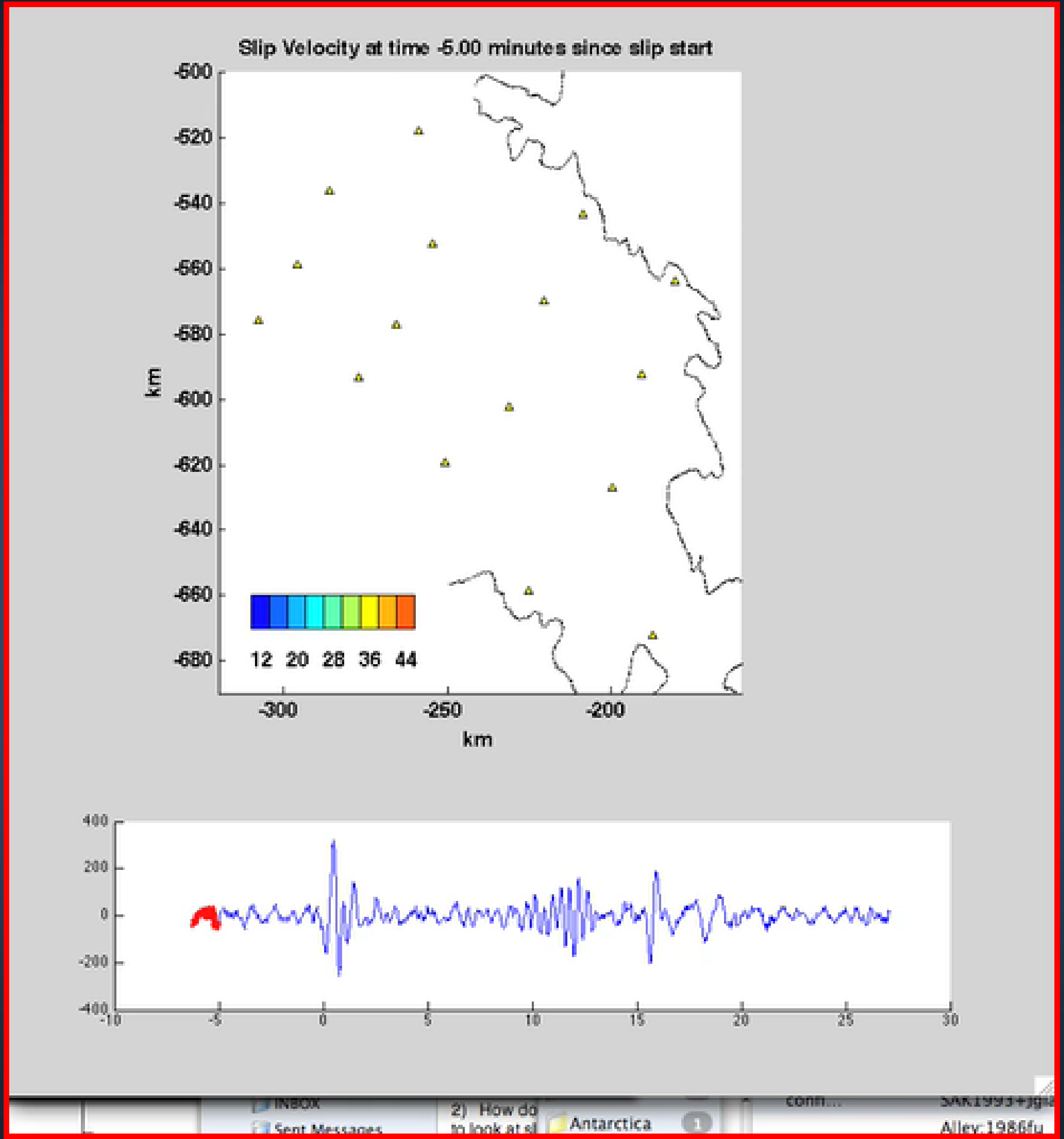
Upper figure shows slip velocity from GPS receivers on the ice Stream

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

Slip initiates at the same location for every event;

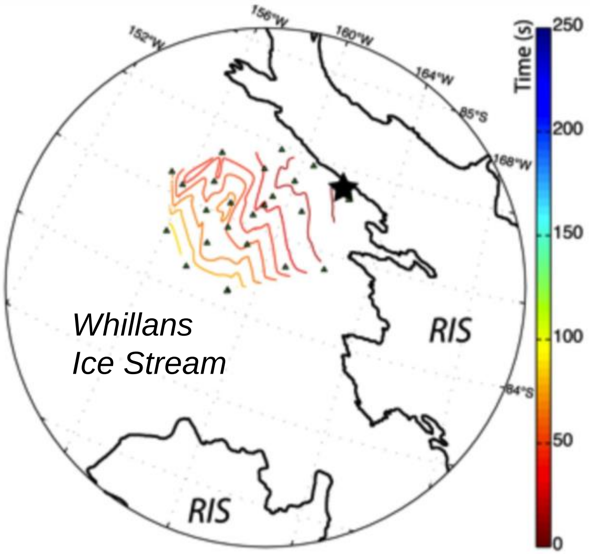
Rupture origin represents an “sticky spot” in the bed

Movie by Paul Winberry

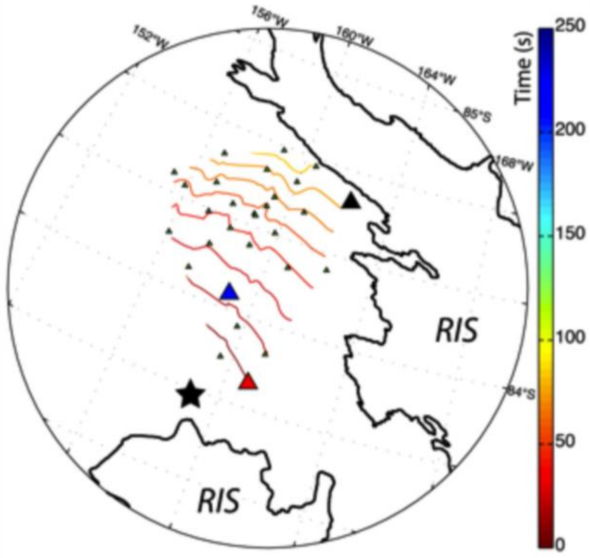


Evolution of a slip event: Rupture of 3 Asperities (sticky-spots)

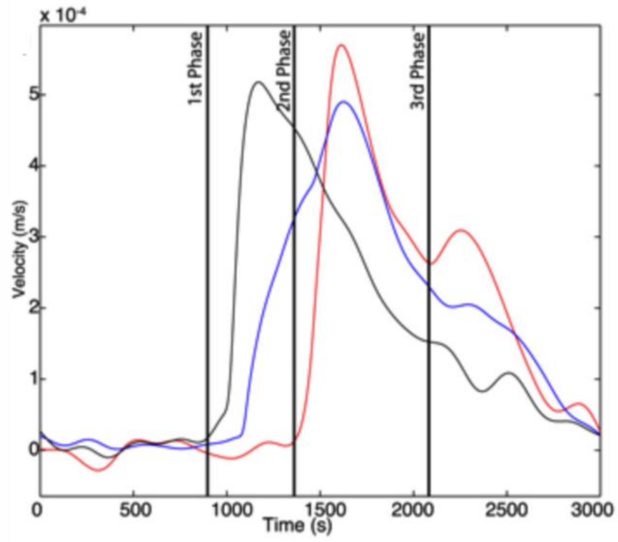
Initial Rupture



2nd Asperity



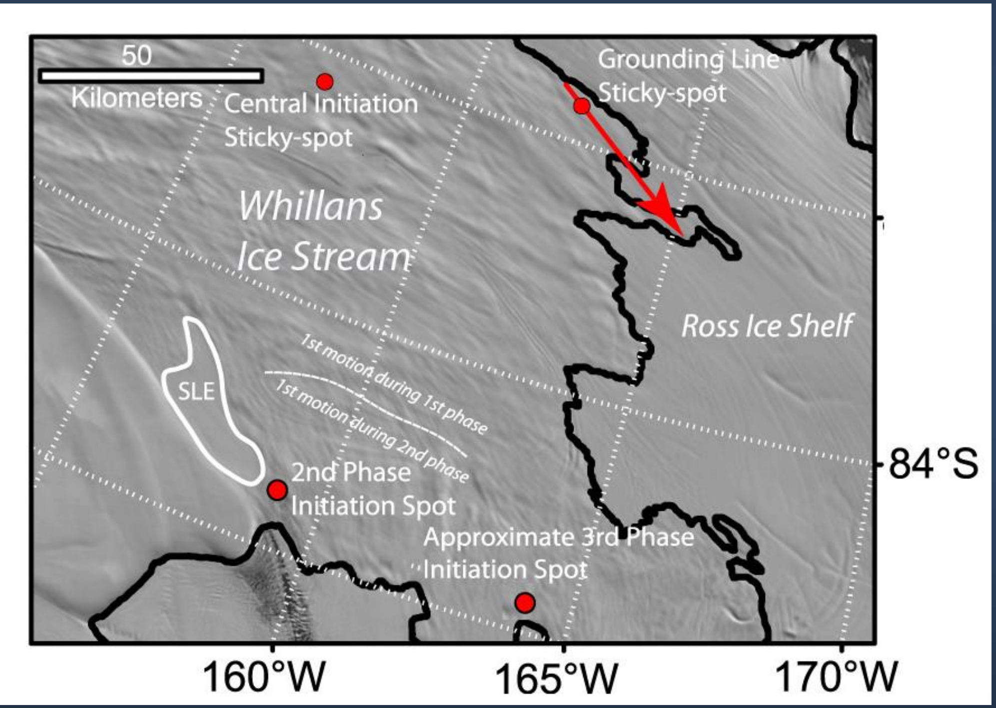
Velocity Records



- Initial rupture occurs along the grounding line – fast rupture but slows
- 2nd asperity breaks prior to clear arrival of initial rupture, slip pulse back-propagates
- 3rd asperity located outside our deployment but see slip pulse back-propagating

Pratt et al., [2014]

Whillans Ice Stream Summary



All 3 asperities radiating seismic energy are along the grounding line

Asperities have no creep between slip events and show fast rupture propagation (1.5 km/s) relative to the average (0.2 km/s).

The grounding line is a strong region of higher basal friction that controls WIS stick-slip dynamics

Consistent with recent glaciological evidence that the grounding line is dynamic and controls many ice stream properties

2nd asperity occurs downstream from Subglacial Lake Engelhardt, suggests free slip across the lake concentrates stress.

The 2nd and 3rd asperities generate slip pulses that back-propagate and re-accelerate slip at regions that have already slipped.

Conclusions

Mountain building and relationship to ice sheet history

- The Gamburtsev Mtns, the origin of the Antarctic glaciation, are supported by thickened crust on mid Proterozoic or older lithosphere. The Mtns have been at high elevation throughout the Mesozoic and Cenozoic

Constraints on mantle viscosity for inferring ice mass change

- Several orders of magnitude viscosity variation between West Antarctica and the East Antarctic craton
- Suggests Glacial Isostatic Adjustment in West Antarctica reflects last few thousand years; East Antarctica shows last glacial maximum

Volcanic and tectonic effects on heat flow into the base of ice sheets

- Deep Cenozoic rift zones with high heat flow have a strong influence on the development and stability of the West Antarctic Ice Sheet.
- Volcanic earthquakes in Marie Byrd Land suggest that the ice sheet may be greatly altered by occasional subglacial volcanism

Antarctic Cryoseismic Sources

- Cryo-seismic sources in the upper 20 meters of the firn layer show sudden formation of cracks.
- Basal stick-slip of the Whillans Ice Stream is controlled by three zones of high friction (asperities or sticky spots) along the grounding line.

Estimating mantle viscosity from seismic structure: Concerns

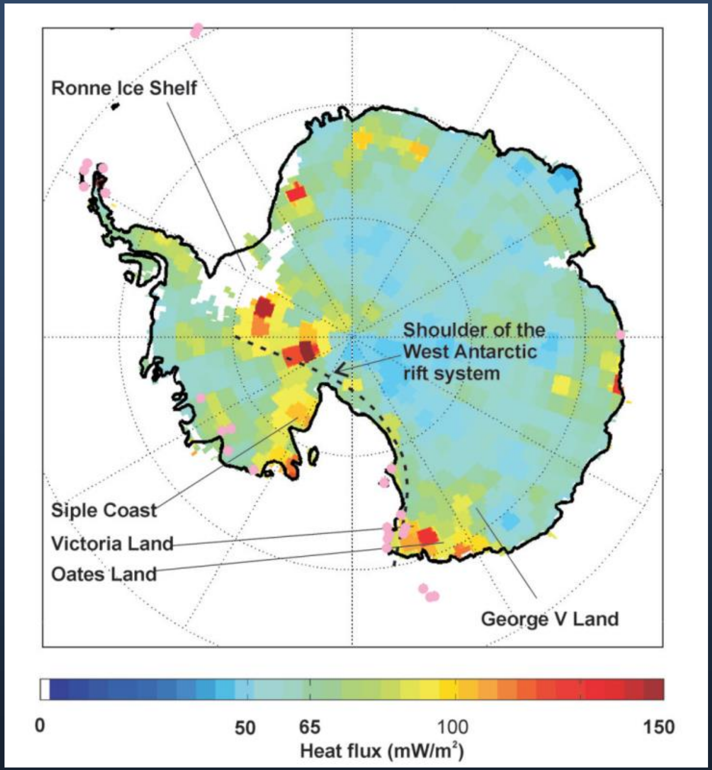
1. Difficulty of obtaining high resolution seismic models with good lateral extent and depth coverage.
2. Compatibility of reference viscosity, temperature, and seismic models. Reference models are biased.
3. How to treat the lithosphere. Elastic or high viscosity?
4. What about non-thermal effects on seismic velocity and viscosity?
    - $\beta = 0.65$ is a “fudge factor” for non-thermal effects
    - What mantle rheology should be used? Dry in the lithosphere and wet in the asthenosphere?
    - How about parameterizing depleted continental lithosphere effects on seismic velocity?

→ We need to hear from the GIA community about what kind of seismic models you need!

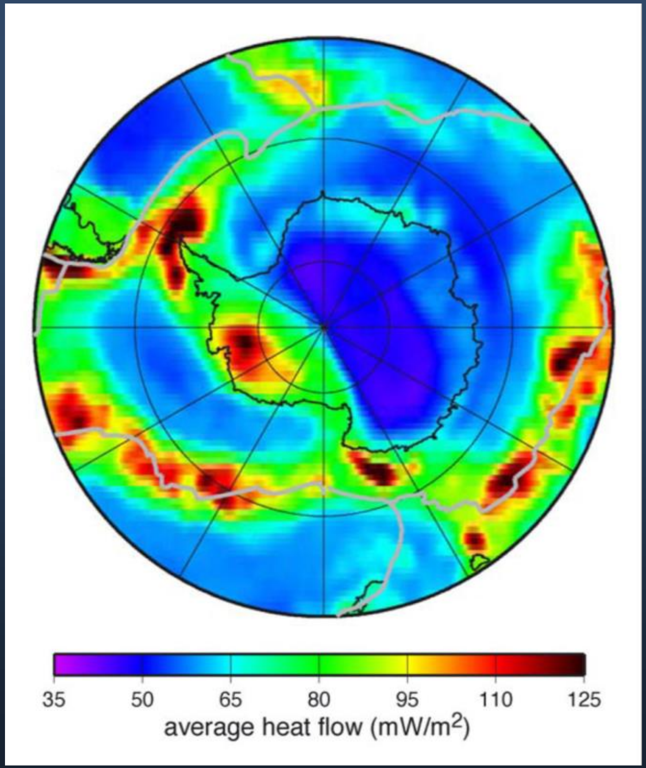
Antarctic Geothermal Heat Flow?

- Heat flow controls melting and water at the base of ice sheets
- May have a strong influence on ice sheet dynamics

Heat Flow estimated from magnetics
Fox Maule et al. [2005]

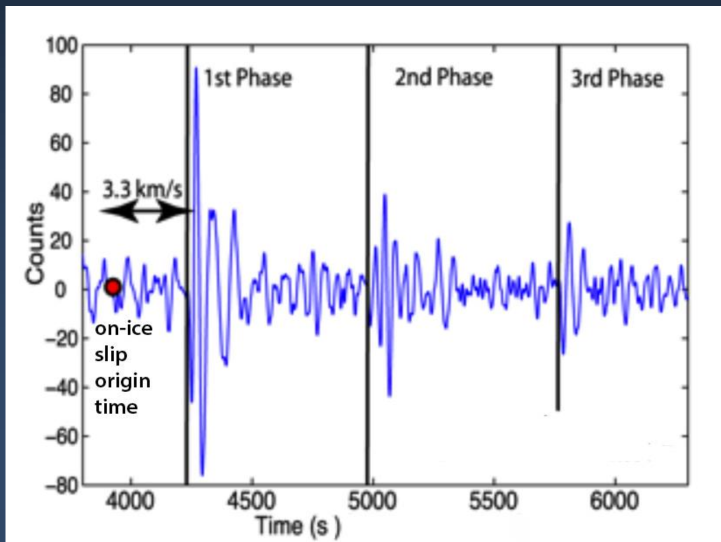


Heat Flow estimated from seismic structure
Shapiro & Ritzwoller [2004]

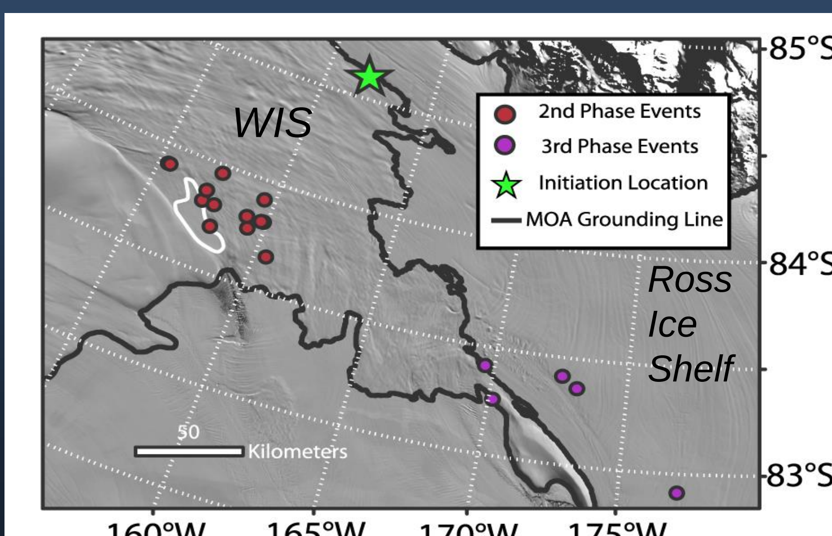


Far-Field Analysis

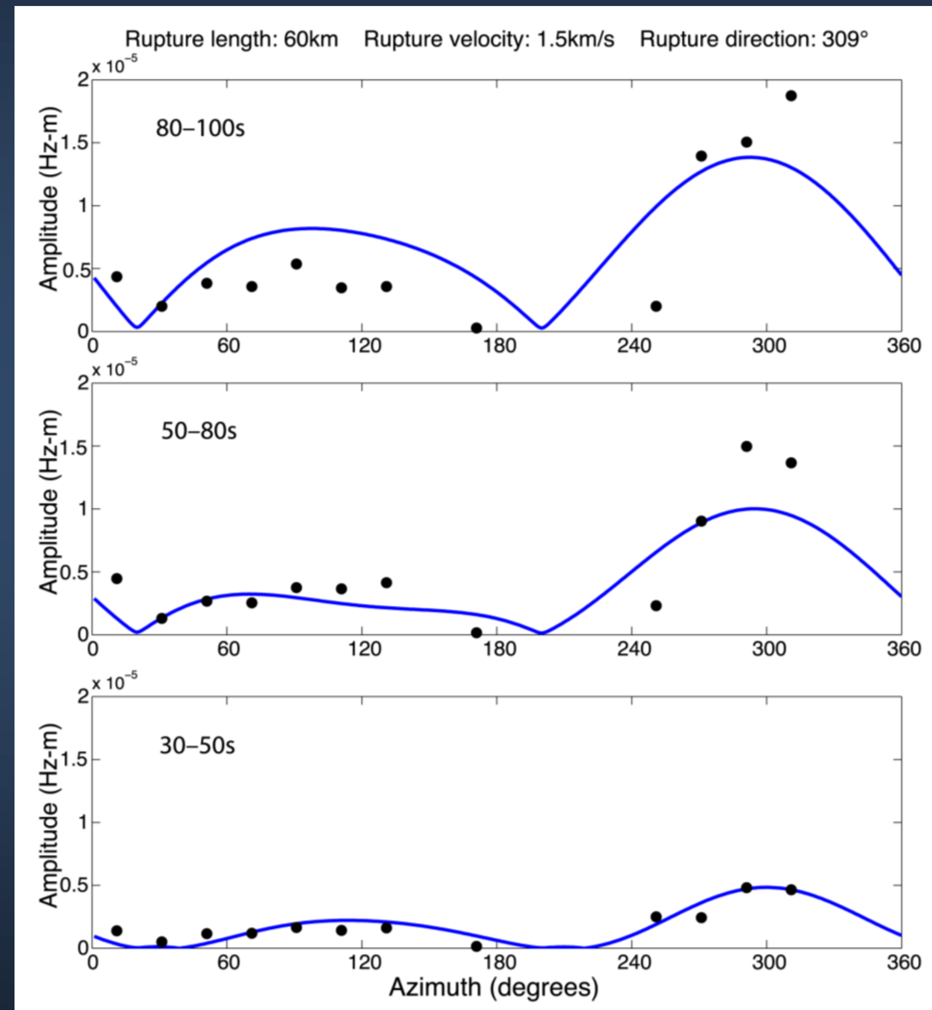
Vertical Seismogram (VNDA - distance 990 km)



Teleseismic locations of 2nd and 3rd asperities

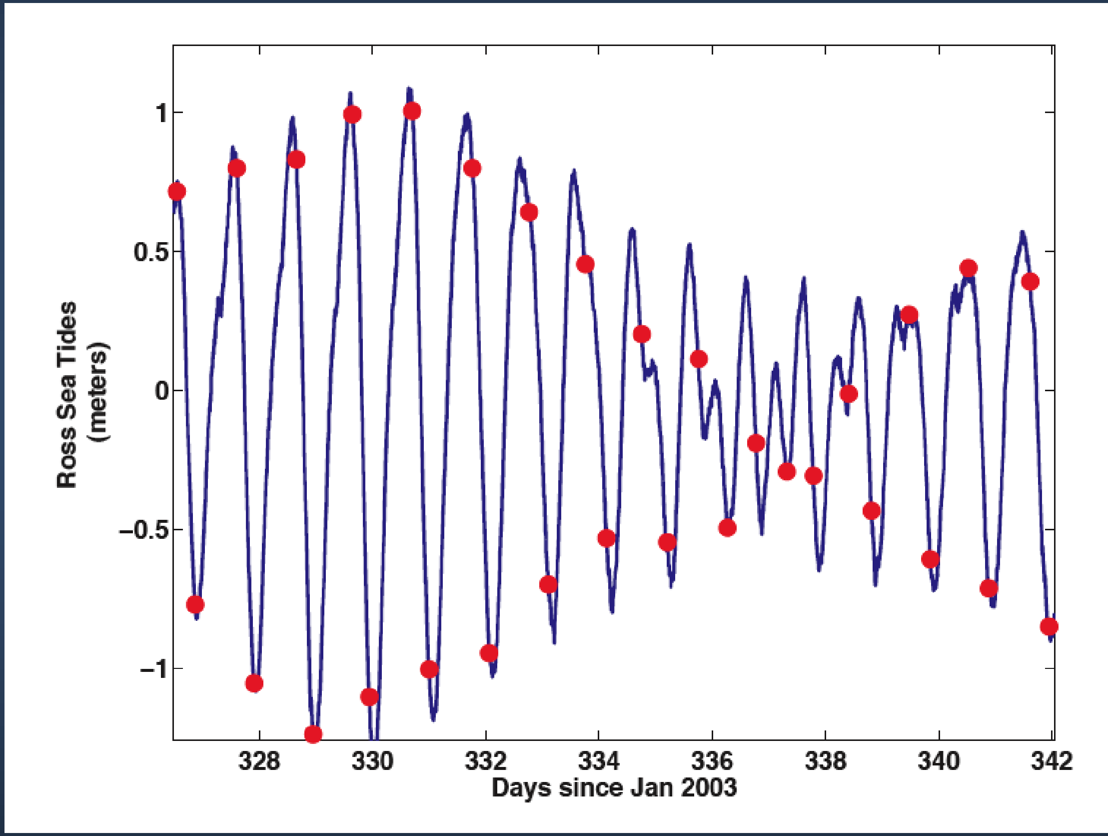


Directivity and Finiteness Analysis – 1st Asperity



Pratt et al, submitted

Tidal Modulation



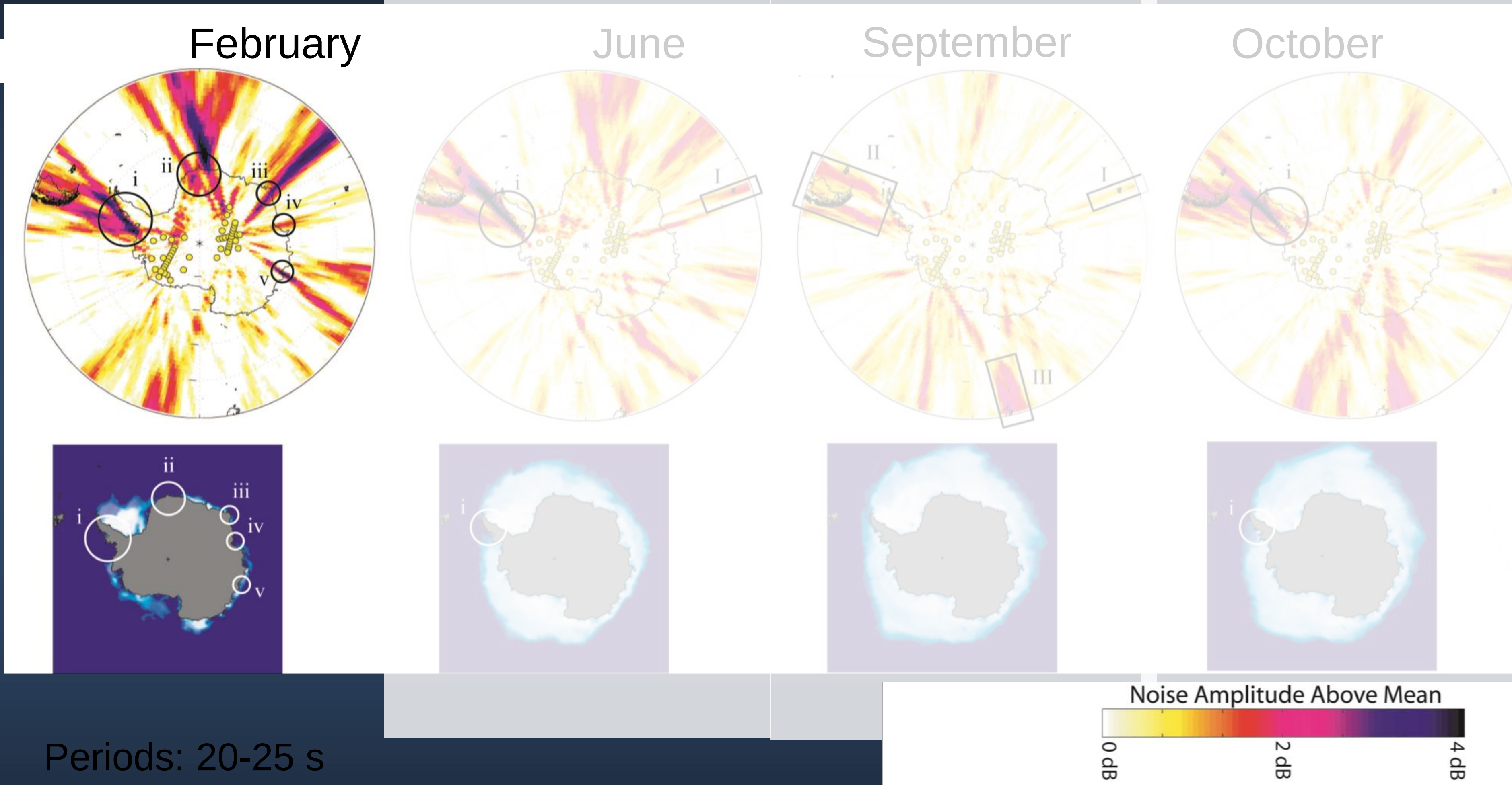
Slip events occur about 1 hour after high tide and Just before low tide

At neap tide, events occur 12 hours apart

Amount of slip is time predictable

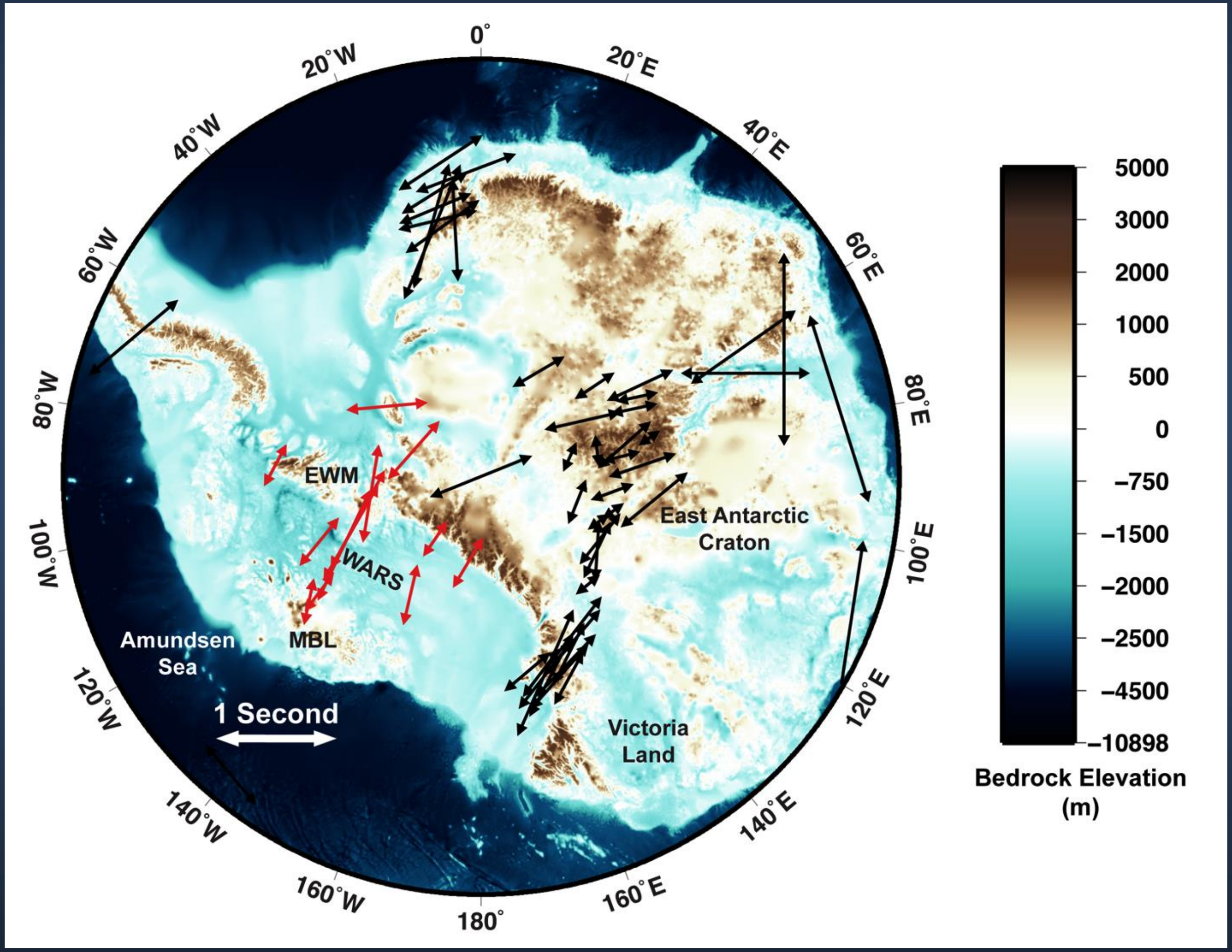
Winberry et al. [2009]

Noise Locations



Periods: 20-25 s

Shear wave splitting results for compiled for entire continent



Accardo et al., in review