The Structure and Seismicity of West Antarctica and Implications for the Evolution of the West Antarctic Ice Sheet

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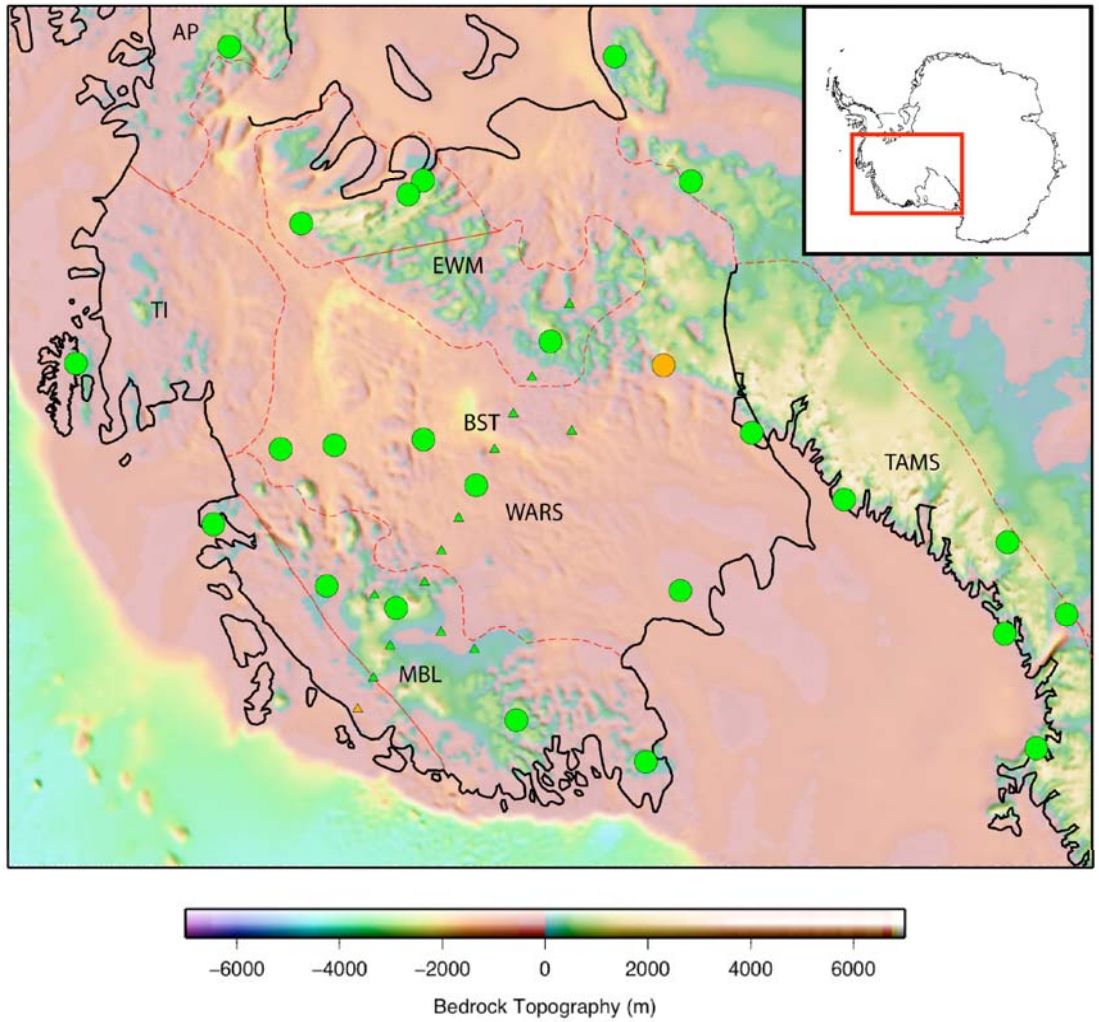
Polenet/ANET Seismic Deployment

- First installation in December 2007
- Sparse semi-permanent backbone network
- Temporary Linear Array installed from Jan 2010 – Dec 2011
- Goal is to image earth structure to get better constraints on Solid-Earth ice sheet interactions
- Most backbone stations have open data access and co-located GPS receivers
- Funding has been renewed through 2018



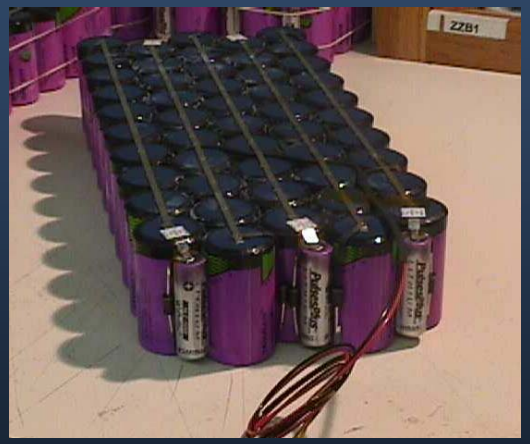
Large circles are backbone stations, small triangles are temporary; Topography from Fretwell et al [2013]

Polar Seismic Instrumentation

developed by 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

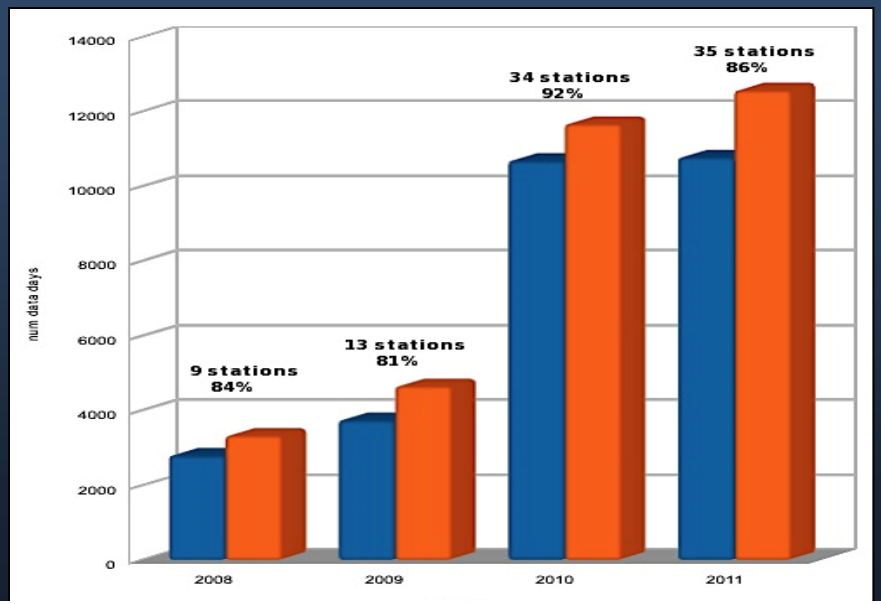
Insulated Box



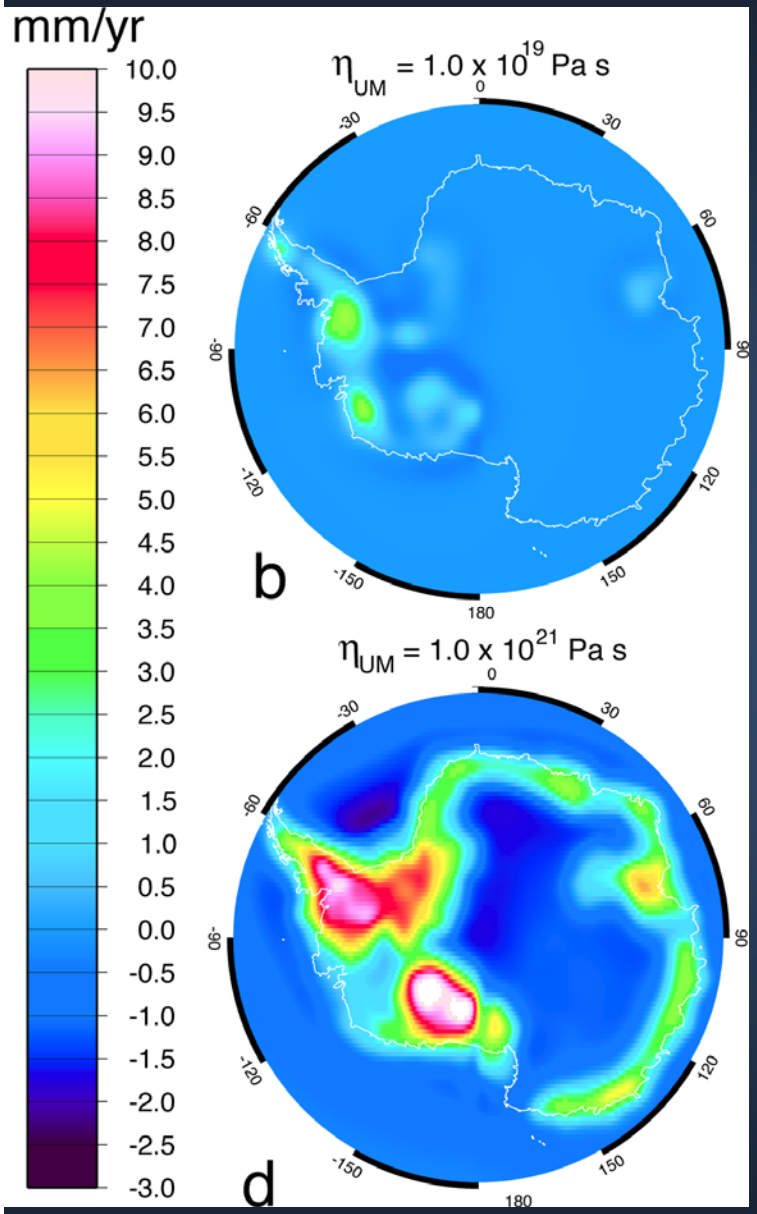
Lithium batteries

Polenet/ANET Data Return

Orange bars show possible data – blue bars show actual return



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

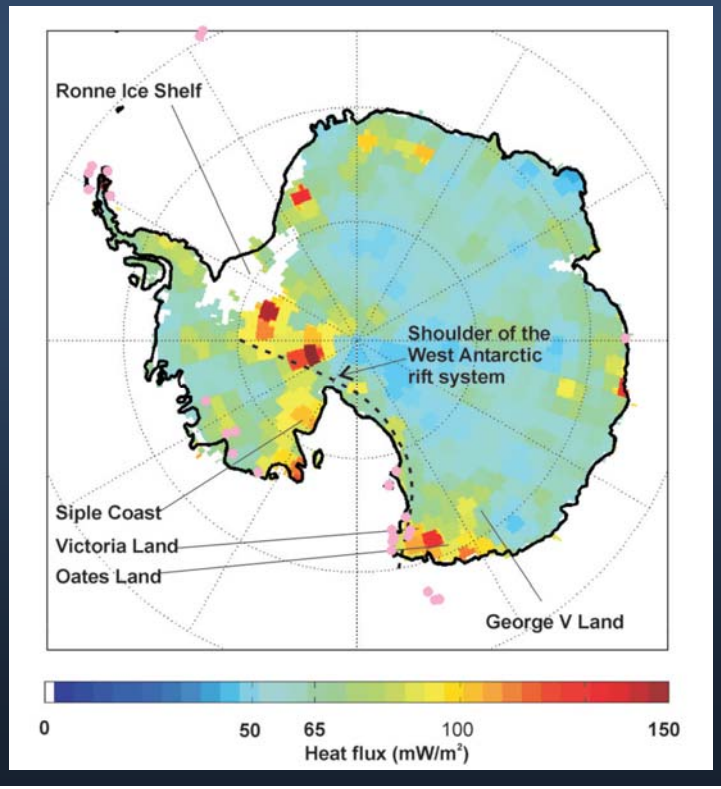
High Viscosity:
long-term memory
Sensitive to LGM

Ivins & James 2005

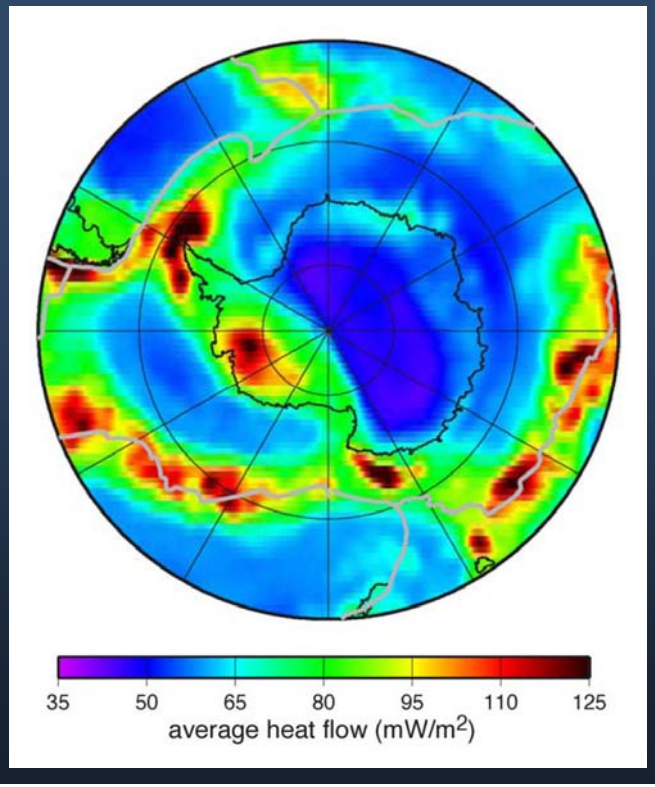
Antarctic Geothermal Heat Flow?

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

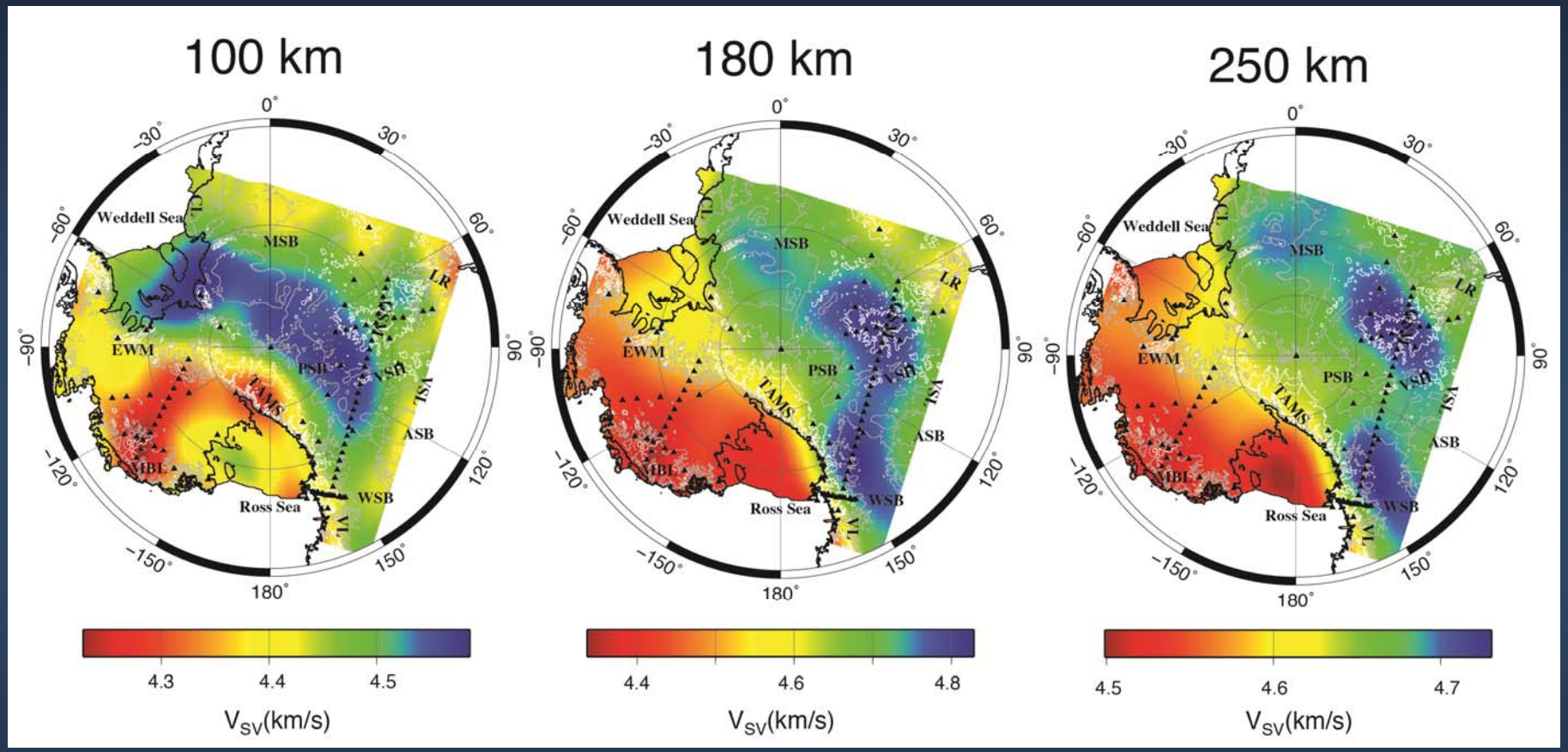
Heat Flow estimated from magnetics
Fox Maule et al. [2005]



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



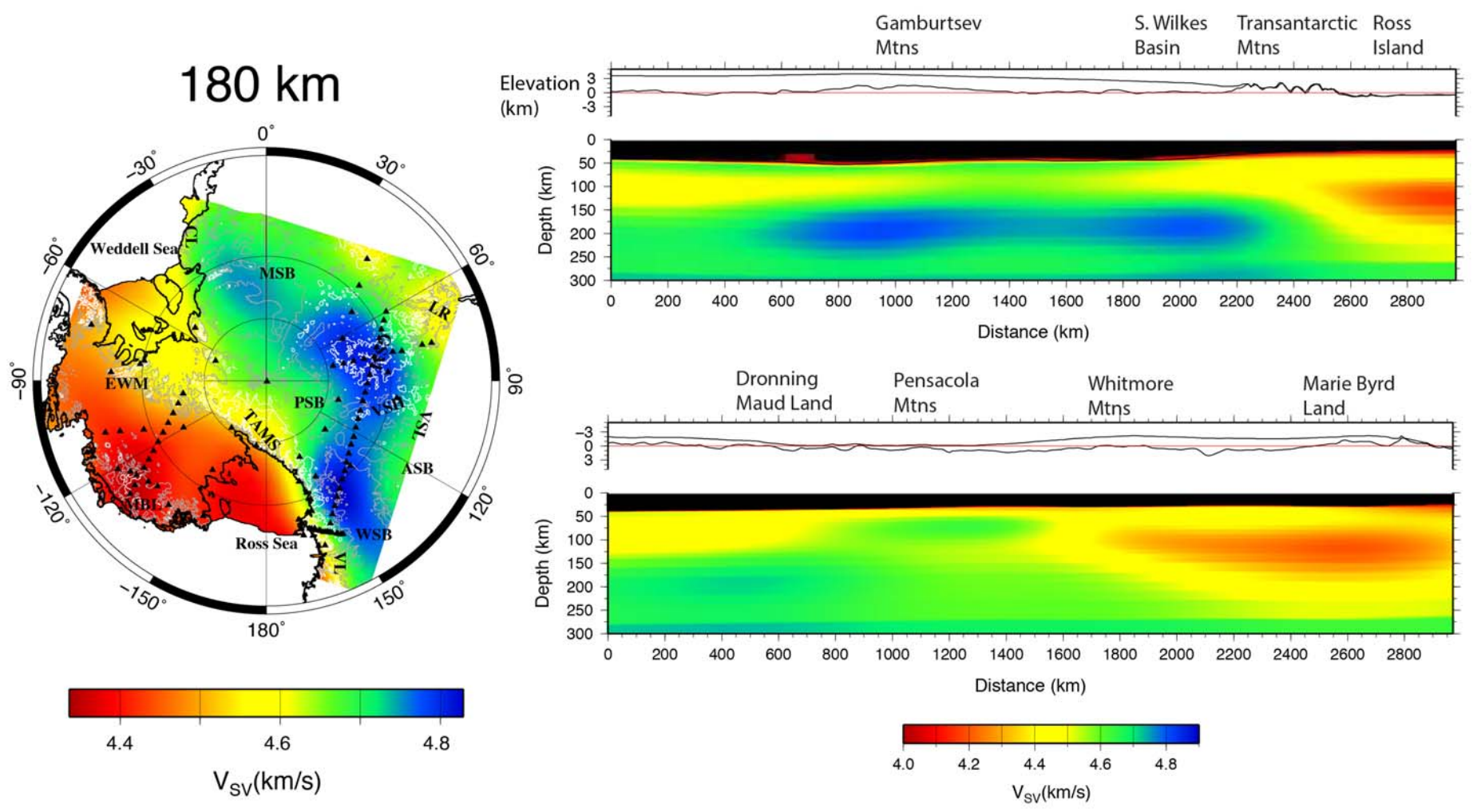
Large-scale upper mantle structure
Rayleigh wave phase velocity tomography



- 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

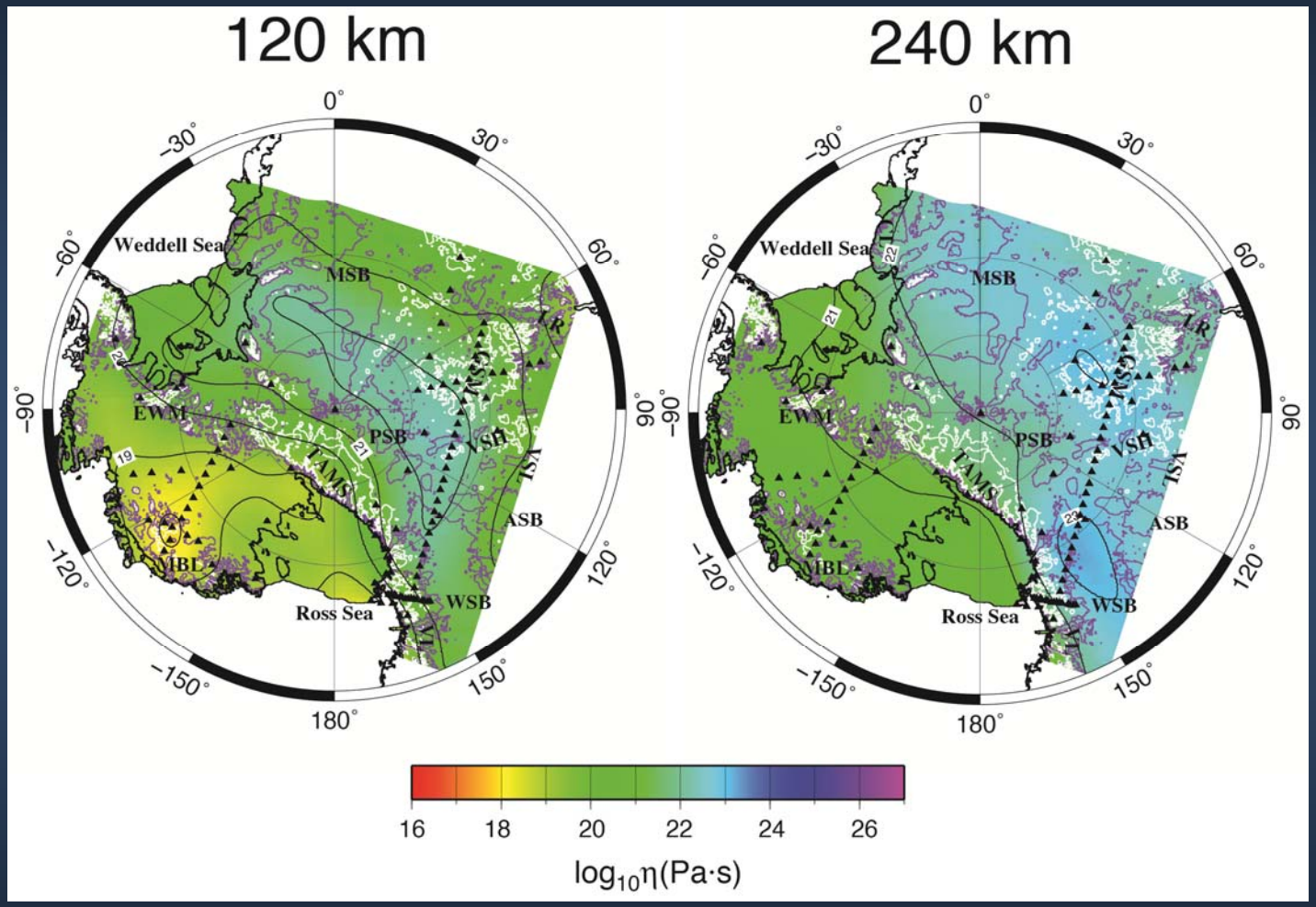
Estimating Mantle Viscosity Heterogeneity from Shear Velocity

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 and the thermal model from *Turcotte and Schubert* with Tp = 1350° C)
- a reference 1D viscosity model corresponding to the reference thermal model (here we use *Whitehouse et al*, 2012)
- experimentally derived formulas for the temperature derivative of shear velocity (here we use *Karato*, 2008)
- experimentally derived relationships for the temperature dependence of dislocation creep

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

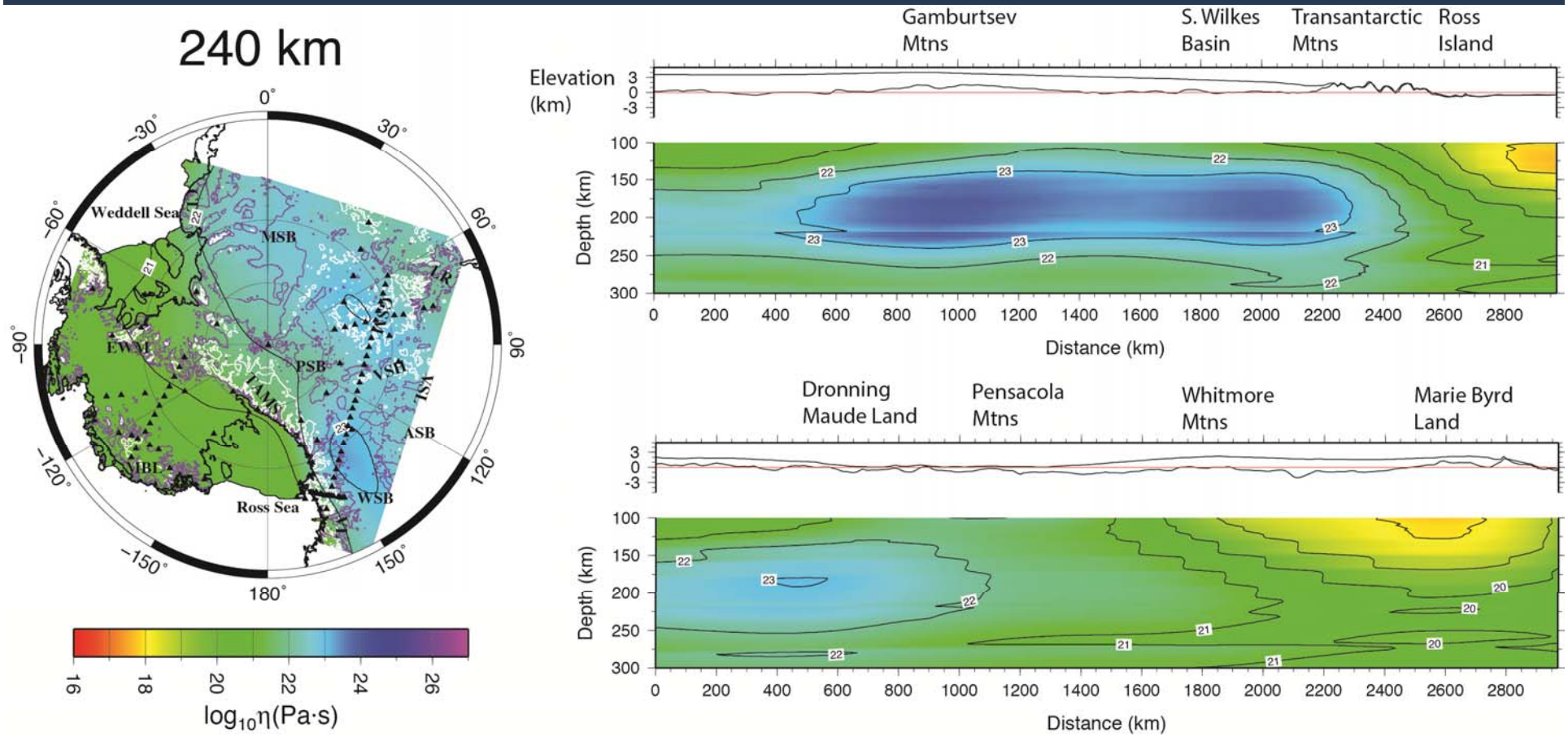
Estimated Mantle Viscosity Variations



- Large viscosity variation between Marie Byrd Land and craton
- This suggests GIA in West Antarctica reflects Holocene; East Antarctica shows LGM

Heeszel et al., in prep

Estimated Viscosity Structure



Heeszel et al., in prep

Thin Crust in West Antarctica – A History of Extension

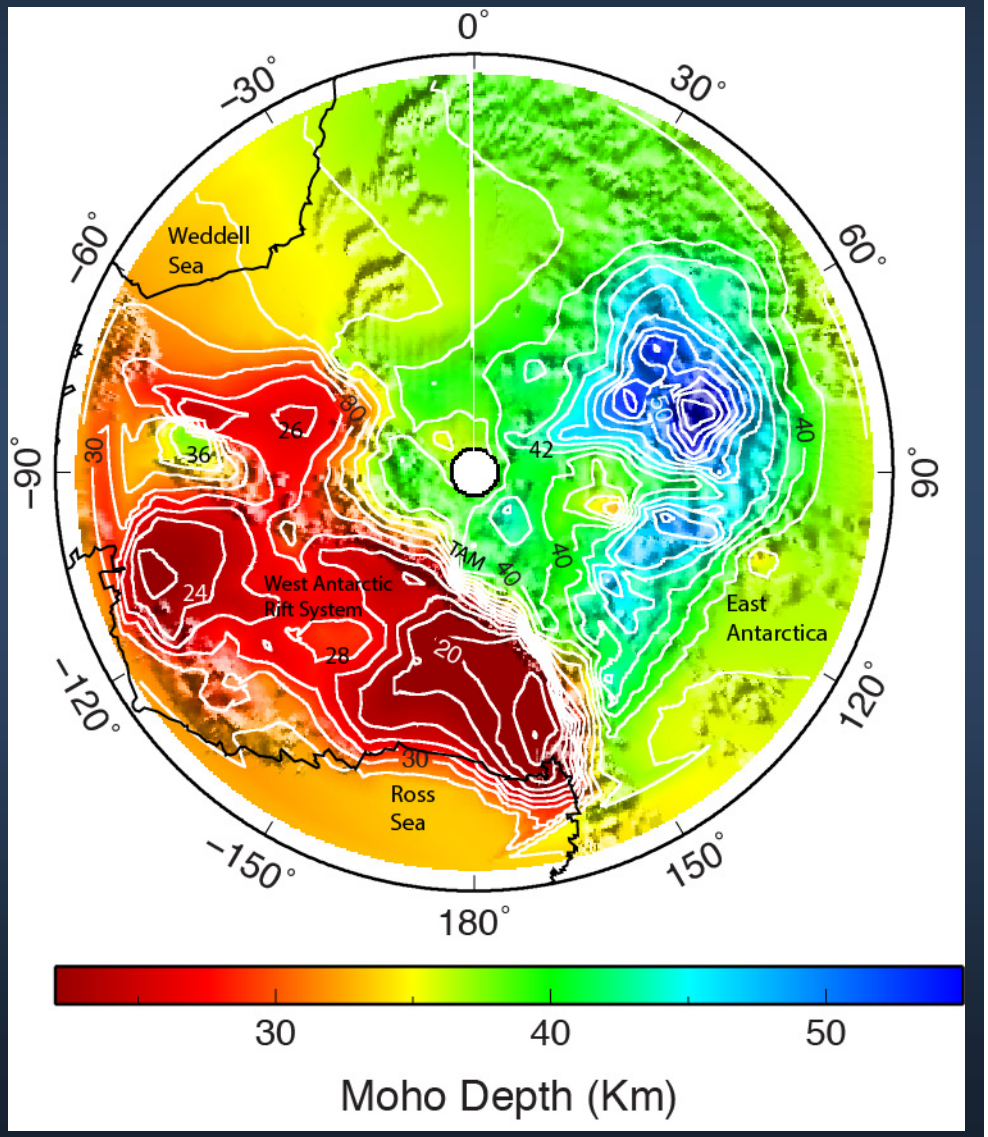
Seismic Noise Correlation -
Large-scale Estimates

Dramatically shows the difference between East and West Antarctica

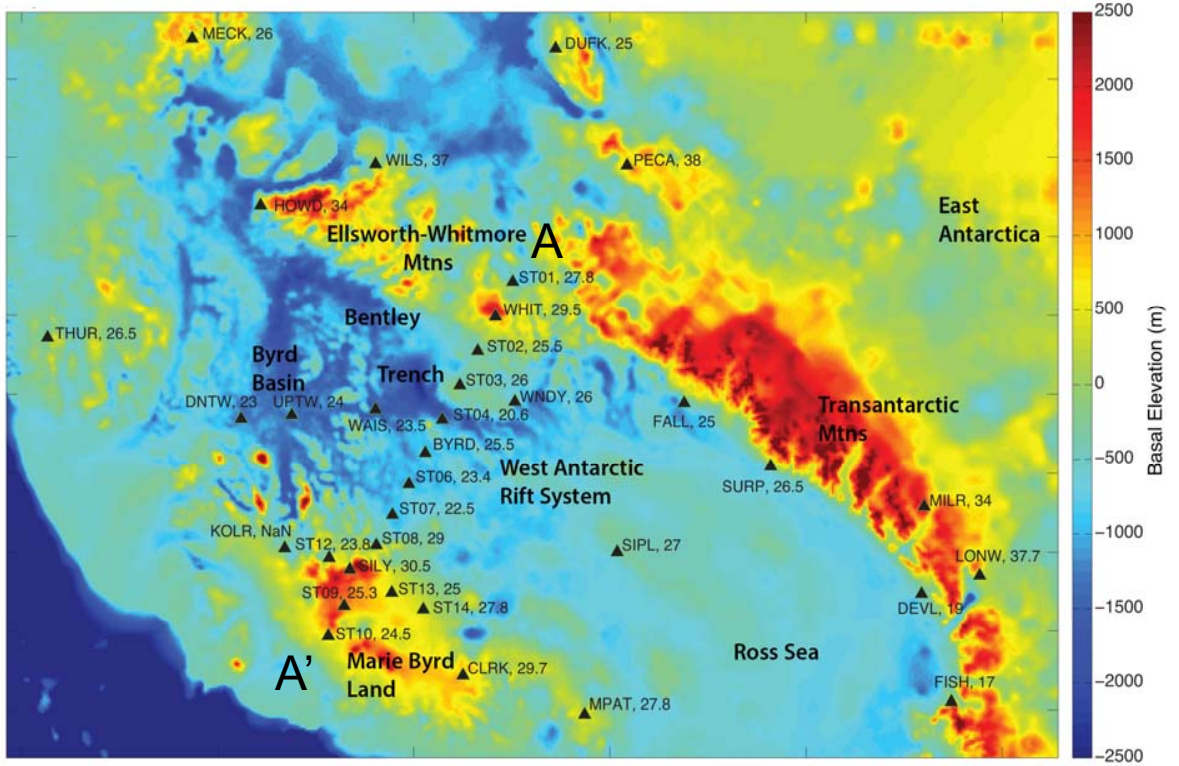
Very thin crust in:
Ross Sea
Pine Island/Thwaites
Ronne Ice Shelf region?

Suggests large tectonic extension
Recent extension would produce high heat flow

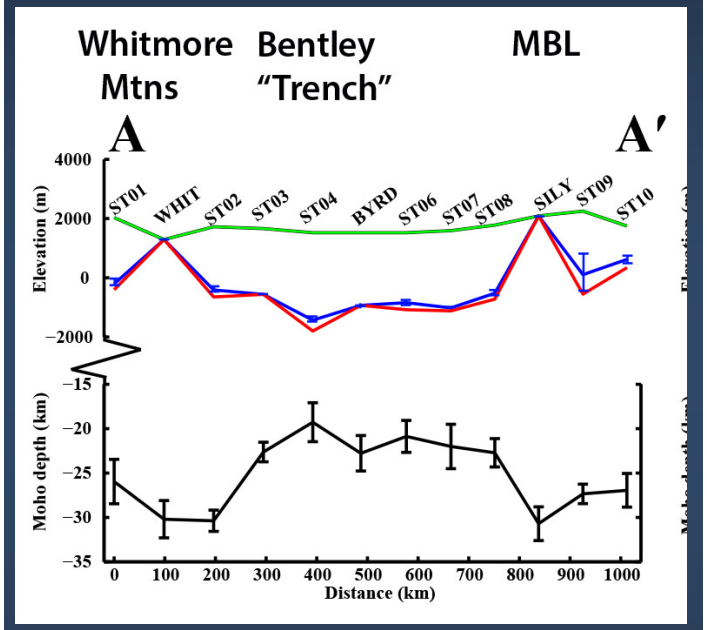
Sun et al., in prep



West Antarctic Basins – Cenozoic Rifts?



Moho Depth along Transect

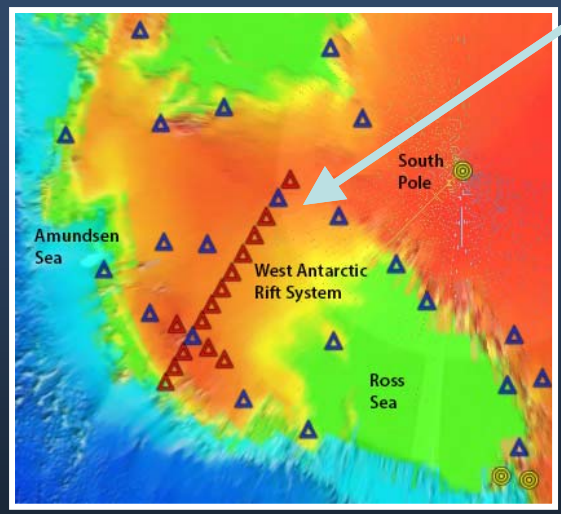


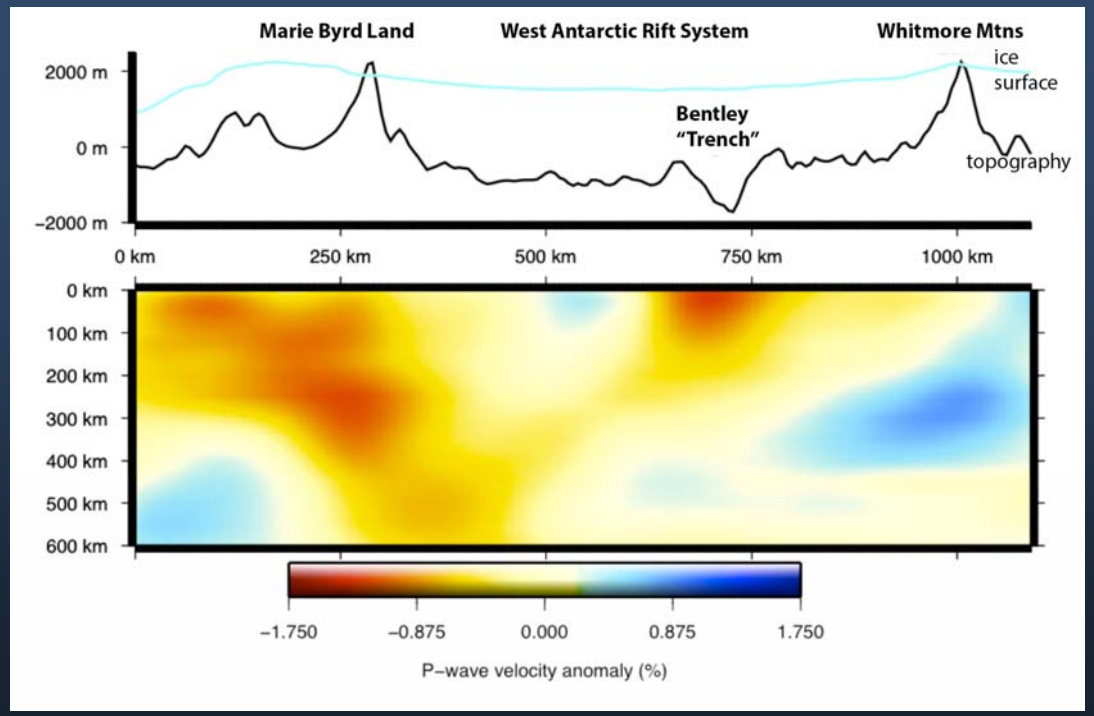
Chaput et al, submitted

- 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

Mantle Structure across West Antarctica

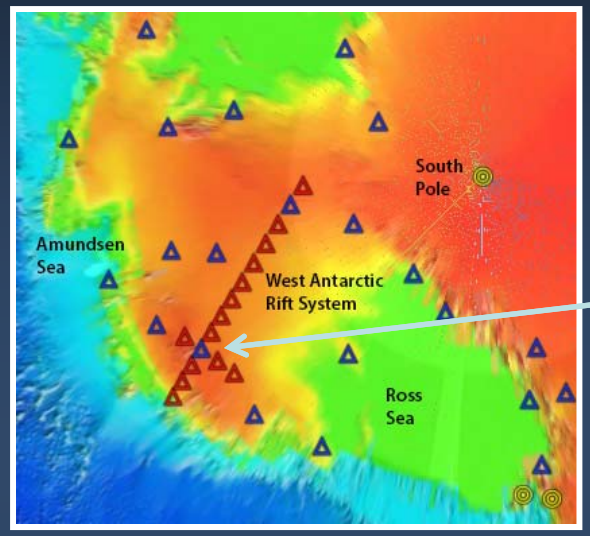
- P-wave tomography along the seismic transect across West Antarctica
- Shows very slow and hot upper mantle down to ~ 400 km in Marie Byrd Land
- Consistent with a plume head, suggests high heat flow
- Faster, colder continental lithosphere beneath the Whitmore Block
- Slow anomaly beneath the Bentley Trench – thermal signature of Cenozoic Rift
- Recent kinematic analysis [Granot et al, 2010] suggests ~ 17 - ? Ma extensional pulse
- Remanent mantle thermal anomaly helps explain extremely high heat flow at WAIS ice core
- High heat flow from Cenozoic Rift basins may exert profound effect on WAIS



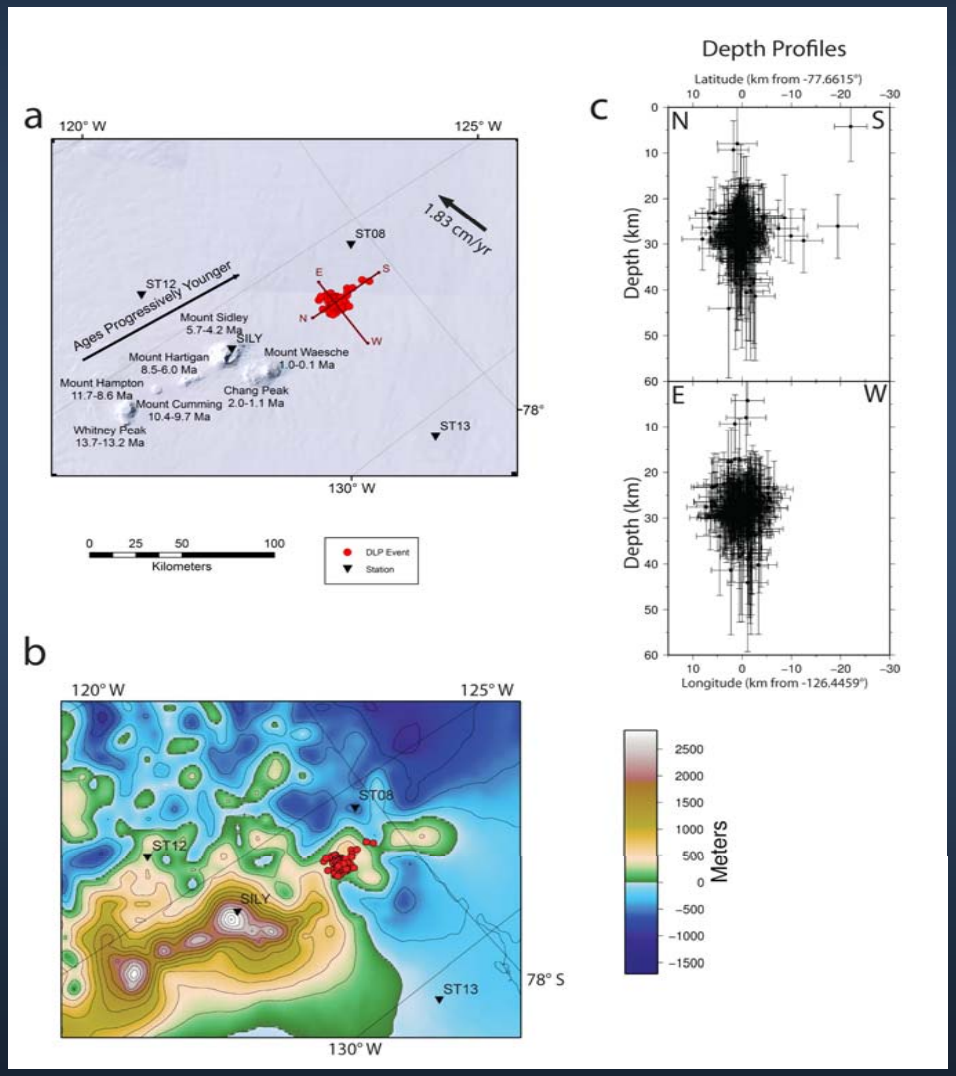


Lloyd et al., ms in prep

Sub-glacial Active Volcanoes in Marie Byrd Land demonstrate thermal perturbation to ice sheet



Deep (30 km) LP Volcanic Earthquakes

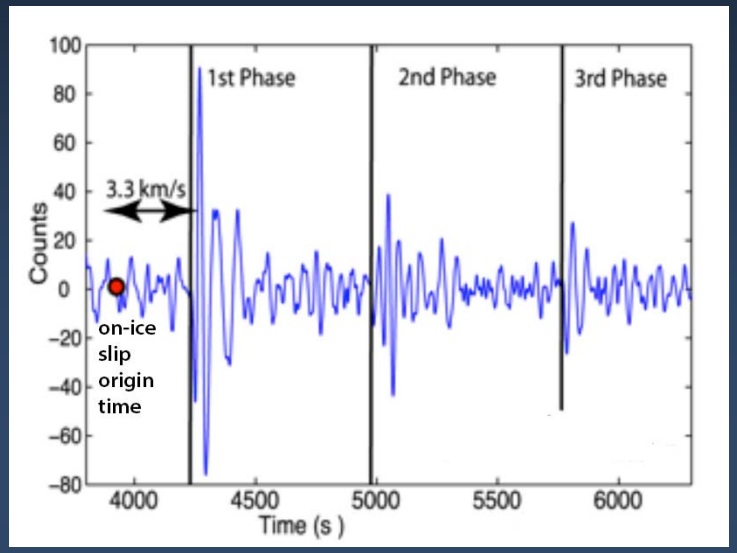


- Ongoing deep long-period volcanic earthquakes discovered
- Identified by depth, unusual spectra
- Produced by an active magma system
- Radar images show ~ 8K old ash layer
- Demonstrates that active volcanism along Executive Com. Range continues southward migration
- Eruption would suddenly supply huge amounts of water into the MacAyeal I.S. drainage

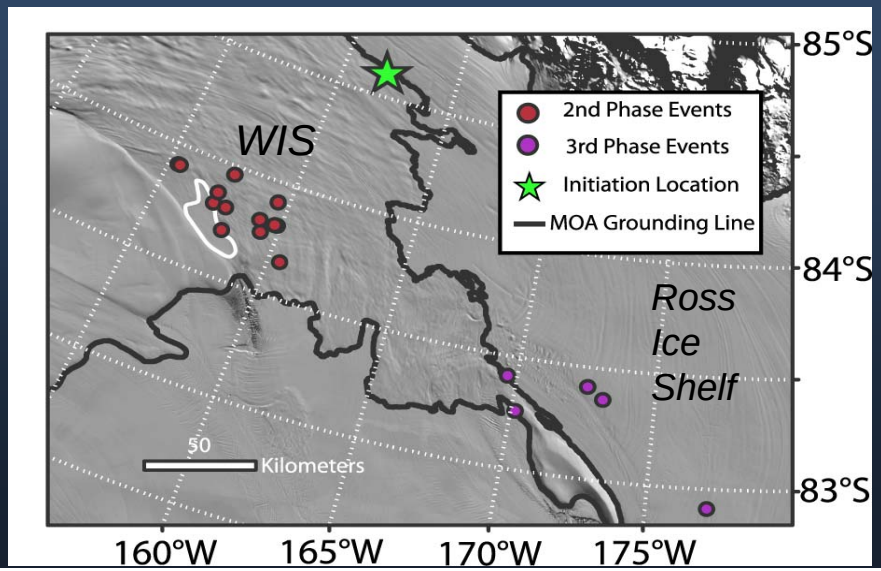
Lough et al., Nature Geosciences, in press

Whillans Ice Stream Slip – Analysis of Polenet data

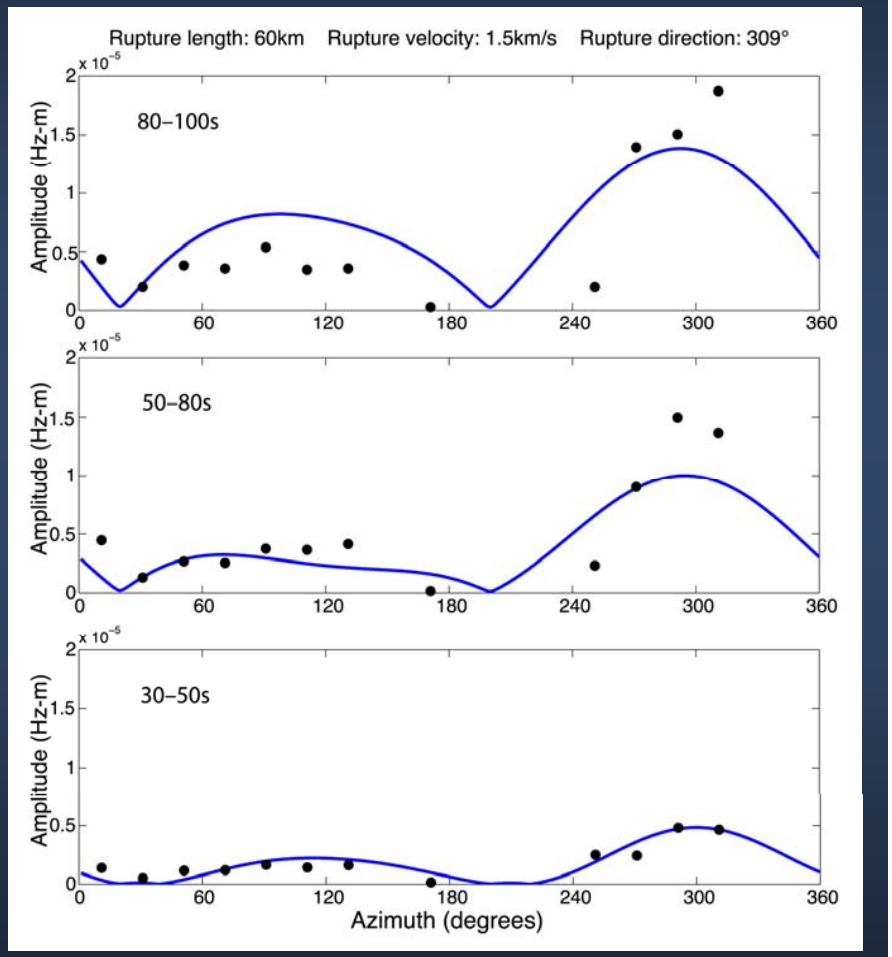
Vertical Seismogram (VNDA - distance 990 km)



Teleseismic locations of 2nd and 3rd asperities

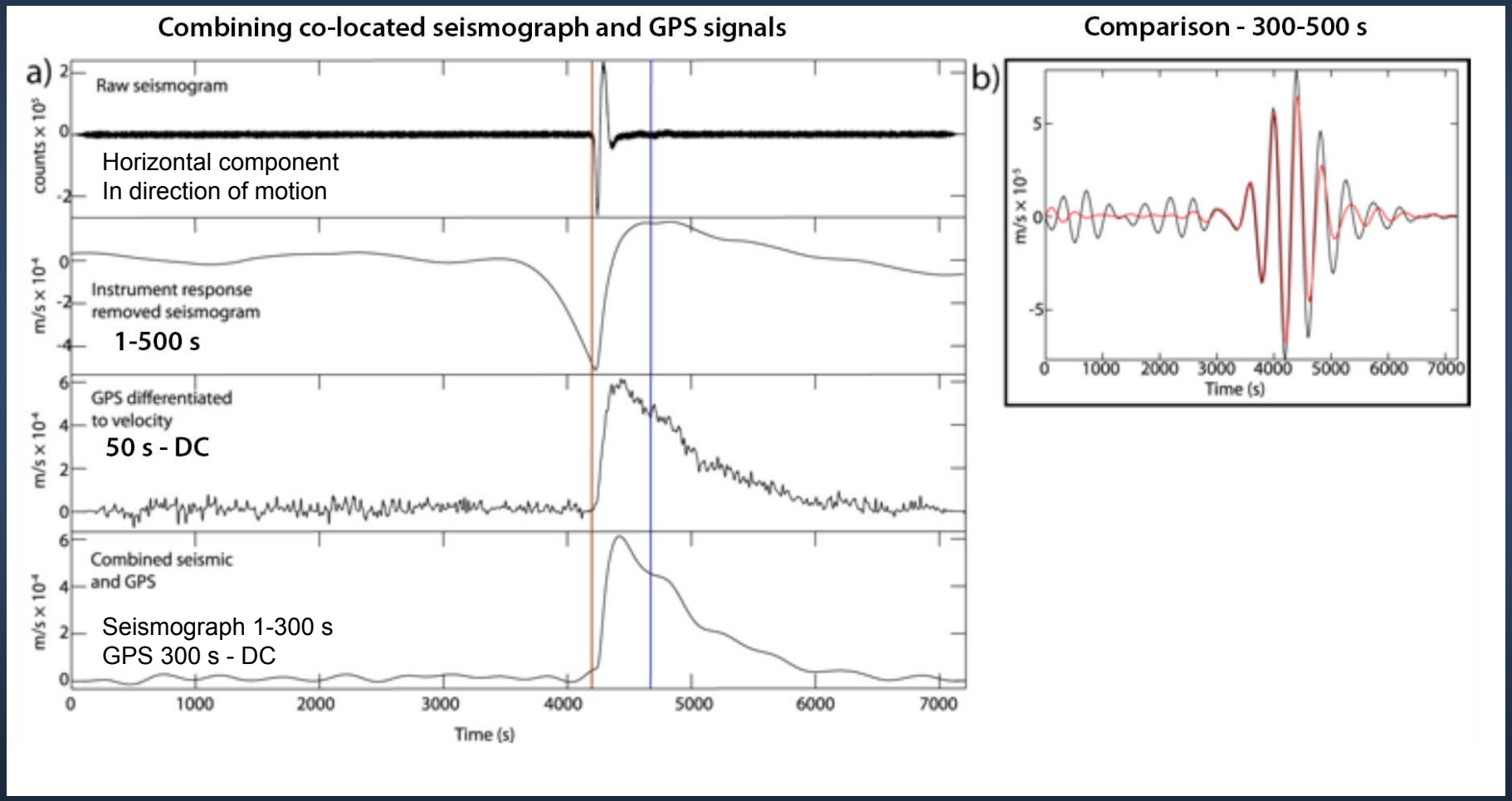


Directivity Analysis – 1st Asperity



Pratt et al, submitted

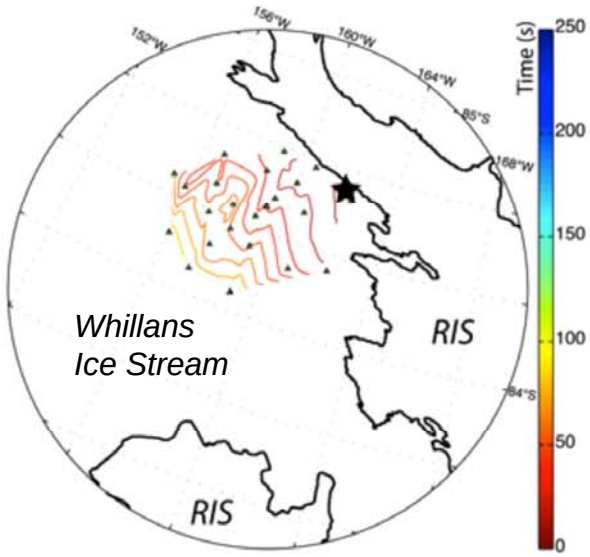
Broadband *in situ* records of the rupture pulse from co-located seismograph and GPS



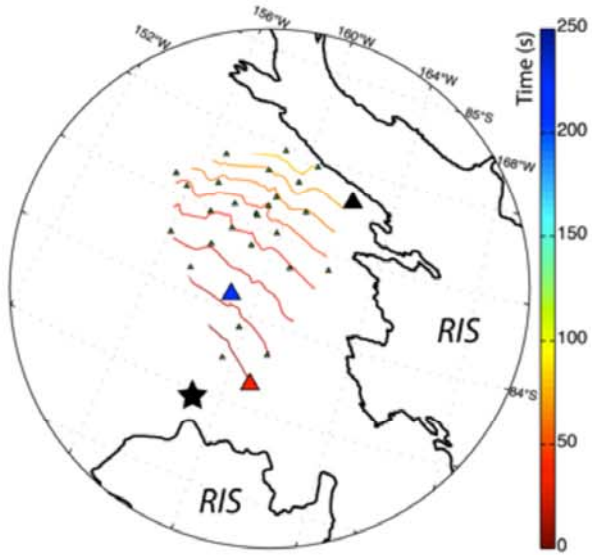
Pratt et al., submitted

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

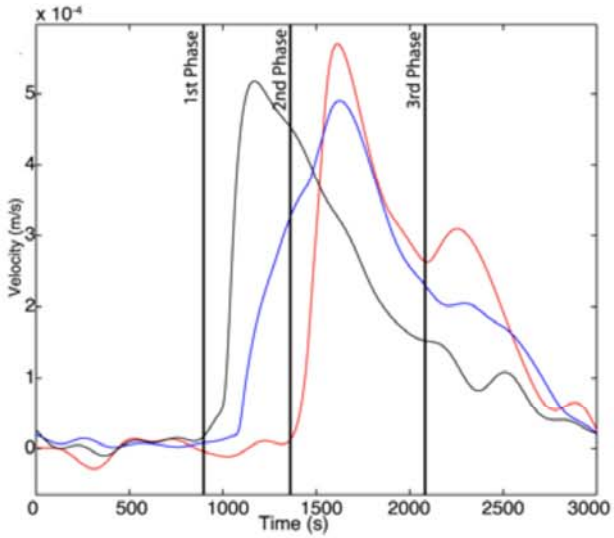
Initial Rupture



2nd Asperity



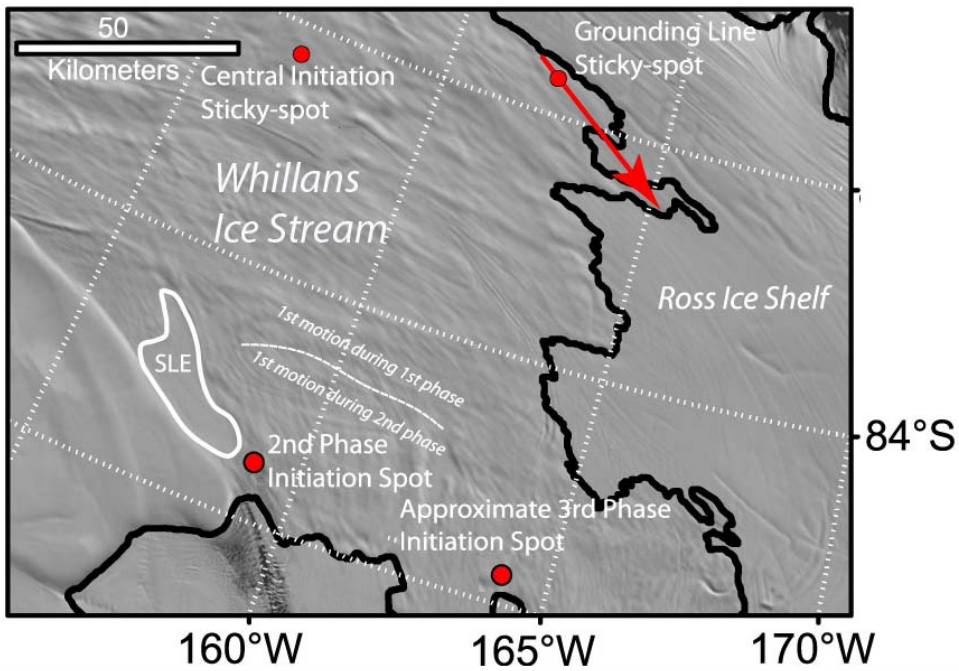
Velocity Records



- 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., submitted

Whillans Ice Stream Summary



All 3 “sticky spots” (asperities) radiating seismic energy are along the grounding line

A 4th “sticky spot” upstream iniitates high tide slip events but does not radiate due to slower rupture propagation

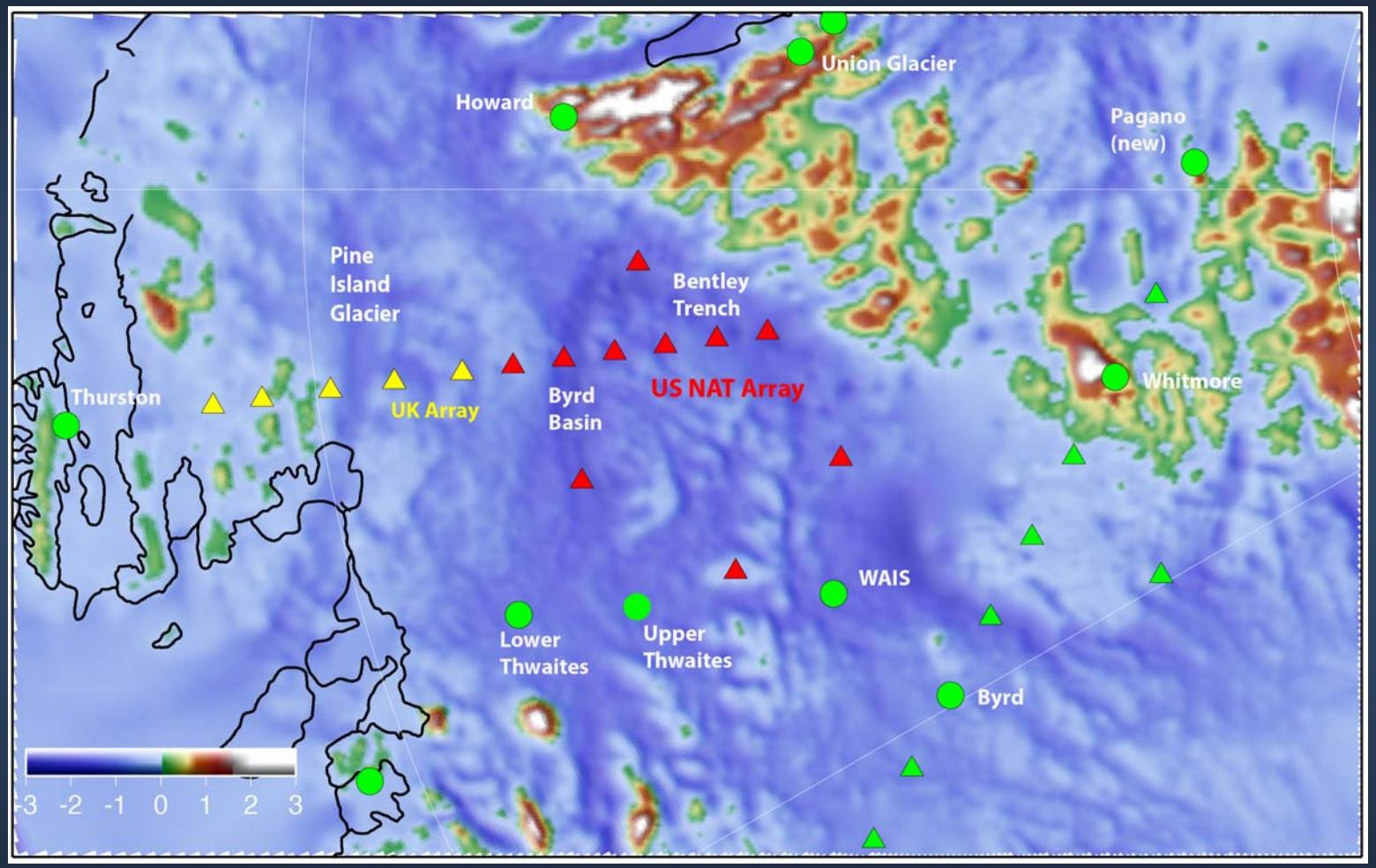
Aperities have little creep between slip events and show fast rupture propagation (1.5 km/s) relative to the average (0.2 km/s).

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

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.

The next phase – POLENET2



- 3 New backbone stations south of Ronne Ice Shelf
- Temporary array of 10 stations in 2014-16 (in red, above) coordinated with UK
- Goal is to investigate structure of the deep extensional basins

Topography from Fretwell et al [2013]

Conclusions

Mantle structure and viscosity

- Antarctica shows extremely large variation in mantle seismic structure.
- Viscosity estimates derived from shear velocity suggest approximately 4 orders of magnitude viscosity variation in the upper mantle.
- Highest estimated viscosities are beneath the East Antarctic craton and the lowest viscosities are beneath the Marie Byrd Land dome, which may represent a mantle plume.

Geological controls on ice Sheet Dynamics

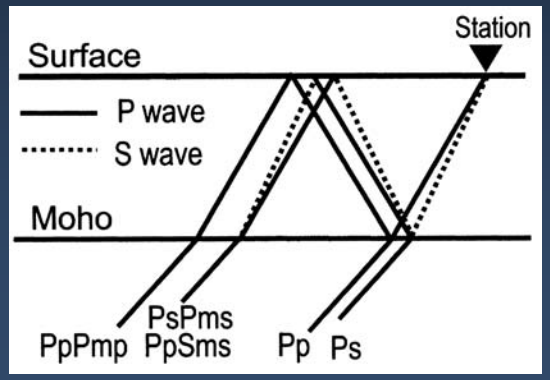
- Mantle anomalies beneath the Marie Byrd Land dome and Deep Cenozoic rift zones suggest high heat flow that will have a strong influence on the development and stability of the West Antarctic Ice Sheet.
- The discovery of an active subglacial volcano in Marie Byrd Land suggest that the ice sheet may be altered by subglacial volcanism

Whillans Ice Stream Seismic Signals:

- Basal stick-slip of the Whillans Ice Stream is controlled by three zones of high friction (asperities or sticky spots) along the grounding line.

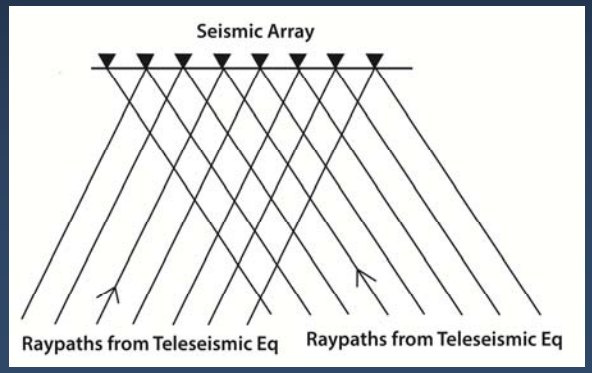
Seismological Analysis Methods

Receiver Functions



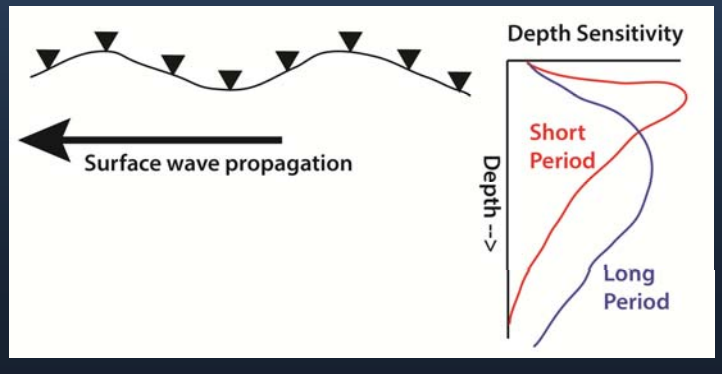
Good for: Imaging discontinuities
(Moho, sed/rock interface, 410)
Weakness: can't see gradients
can't constrain velocities well
results limited to immediately below station

Body Wave Tomography



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

Surface (Rayleigh) wave tomography



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

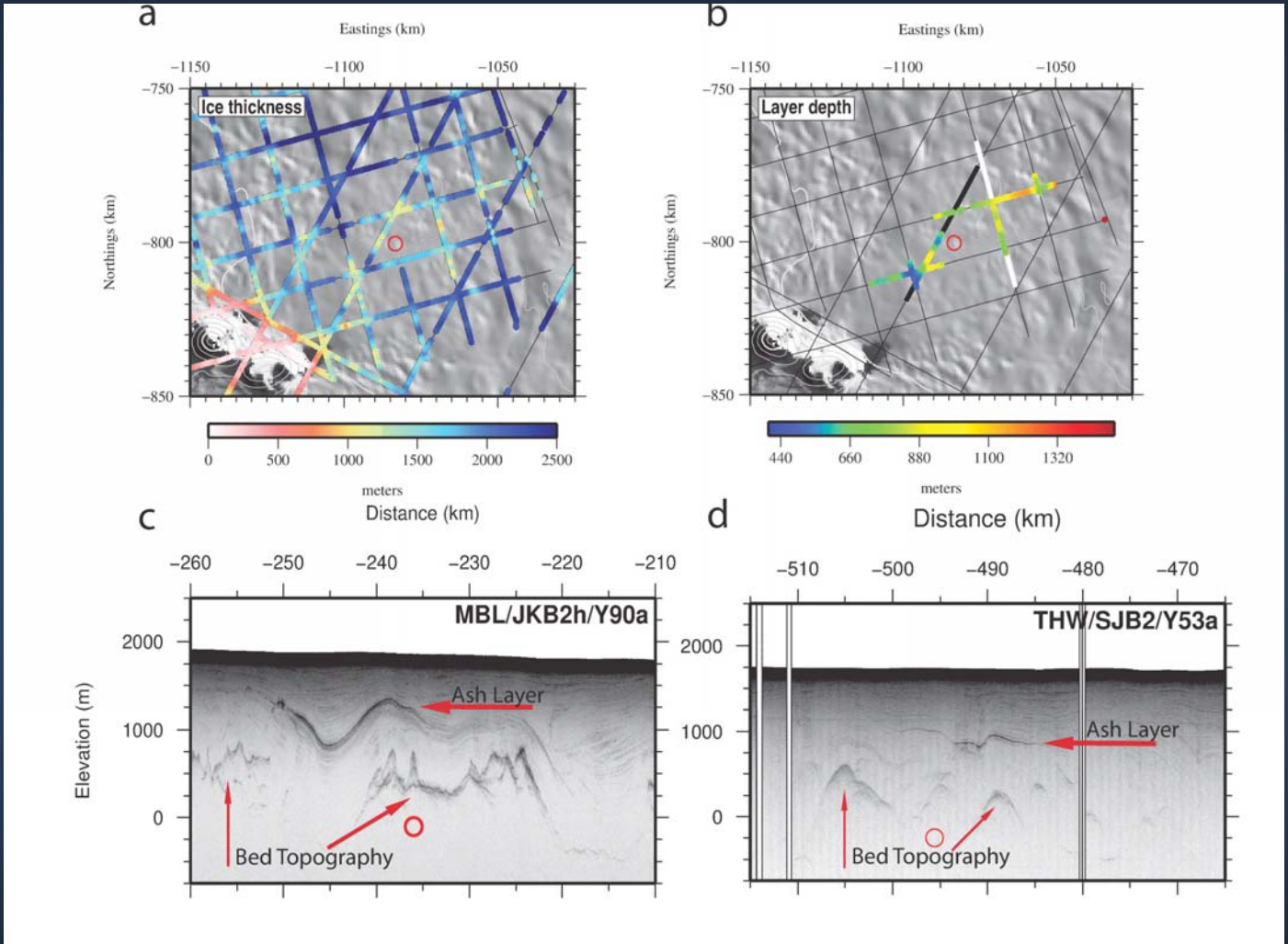
Estimating mantle viscosity from seismic structure: Concerns

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!

Ash layers from subaerial eruptions? Airborne SAR image

Image courtesy Duncan Young, UTIG

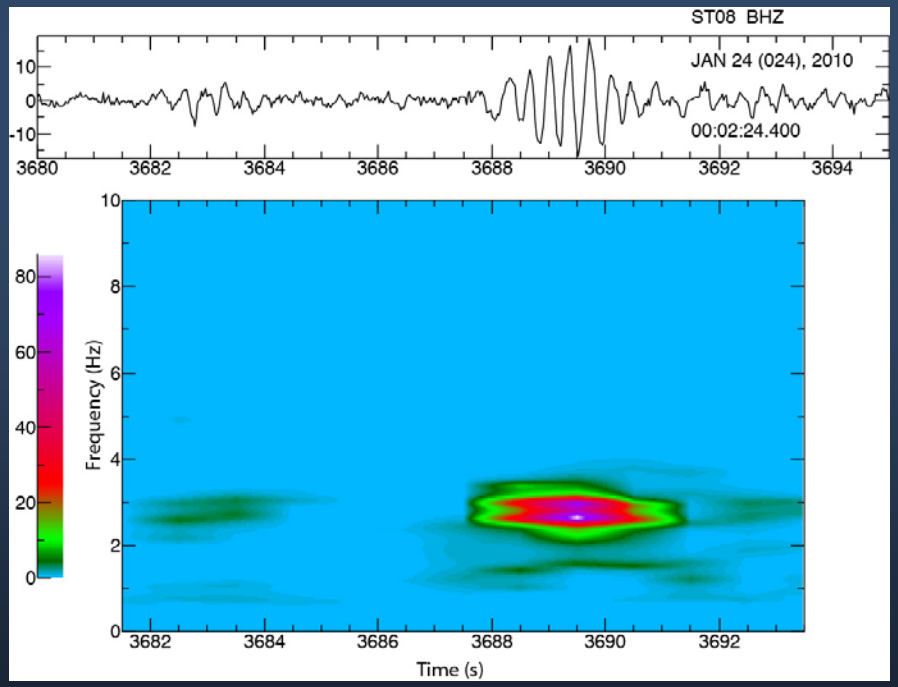


Ash layer centered around DLP earthquake nest
Accumulation rate indicates eruption occurred several thousand years ago
Could have originated from the subglacial volcano or from Mt Waesche

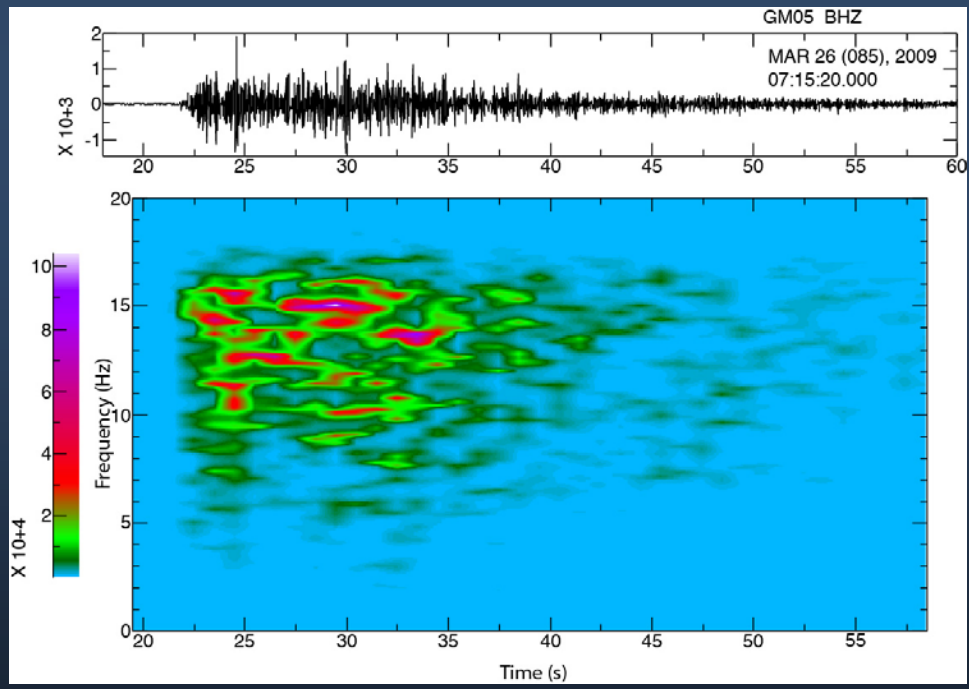
Subglacial Deep LP Volcanic Earthquakes

- 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



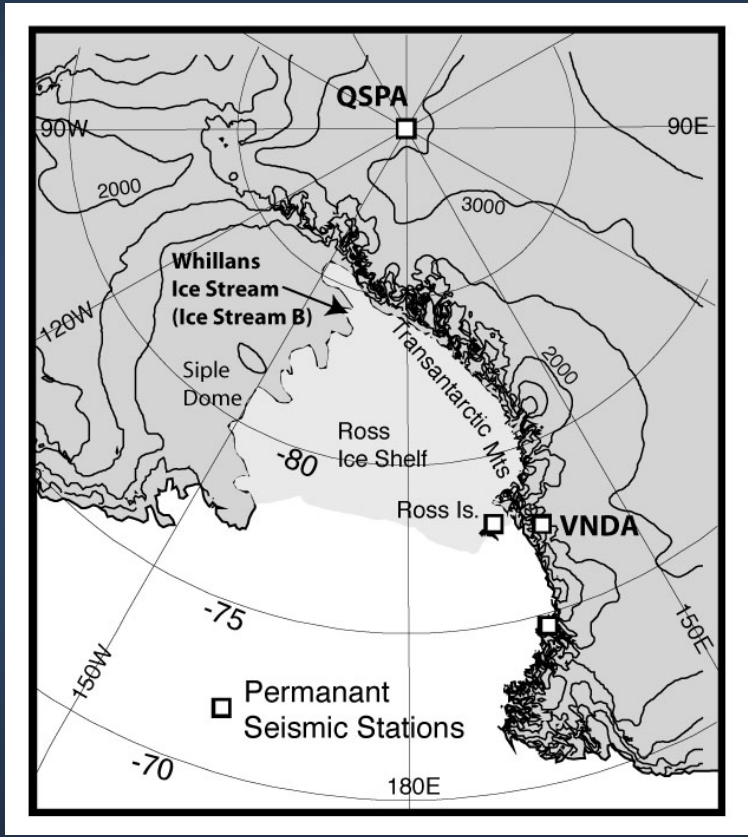
Spectrogram of typical tectonic event of similar magnitude (~ Ml 2)



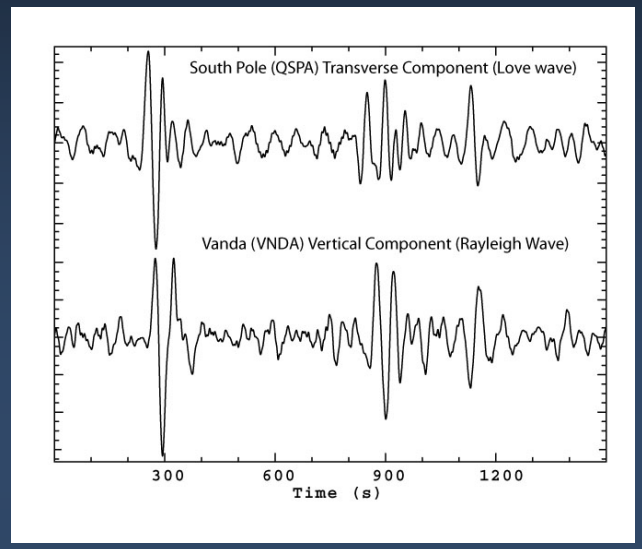
Lough et al., in prep

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

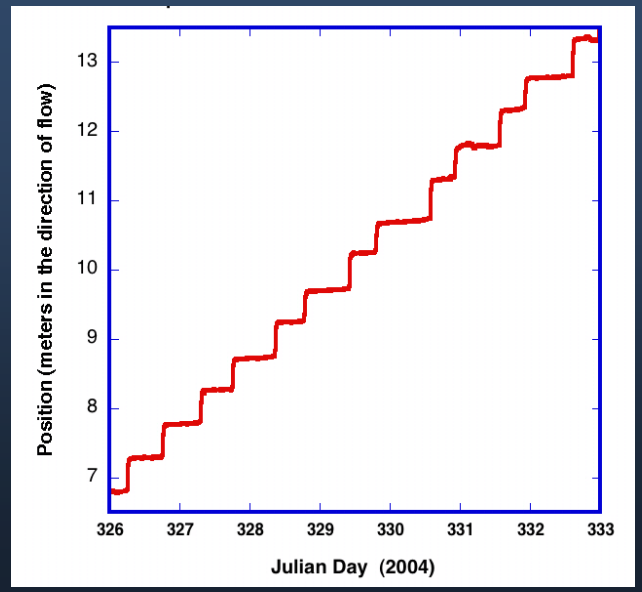
Location



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

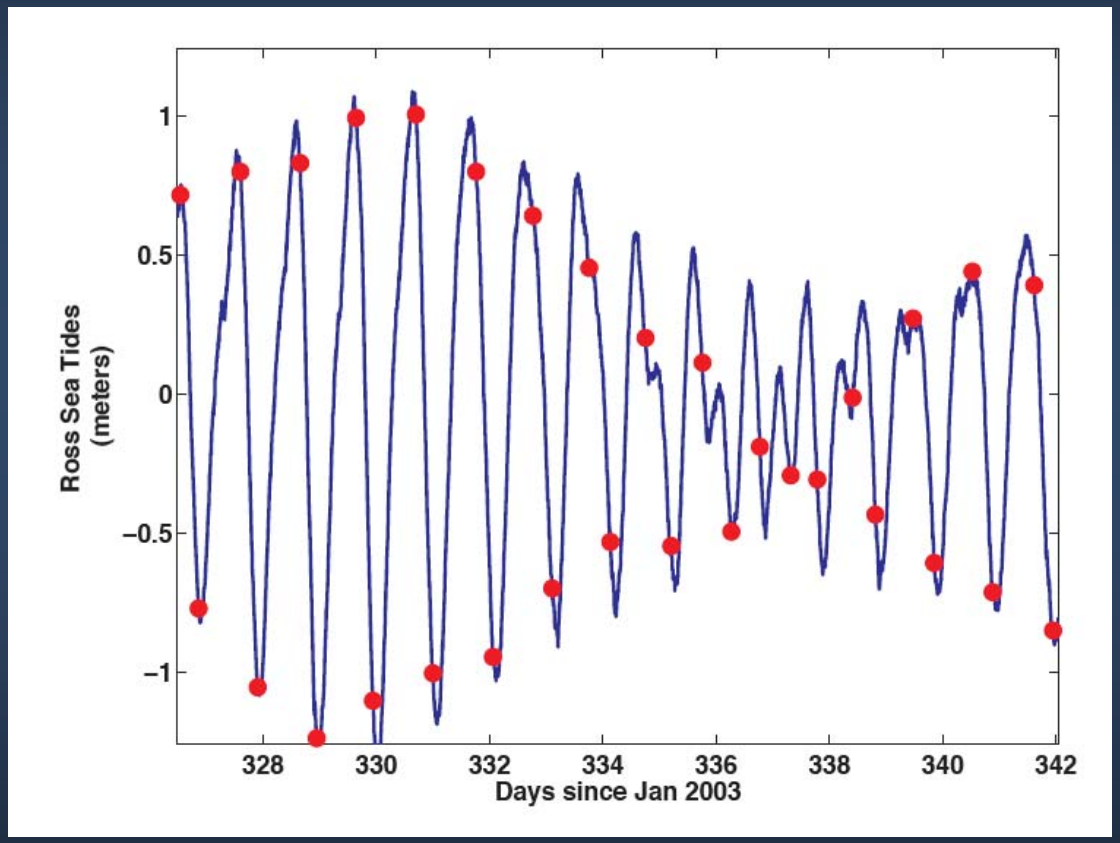


GPS data
-Two slips/day
- ~40 cm each
-Tidally triggered
-Slip area is 200 x 100 km



Wiens et al., Nature, 2008

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]