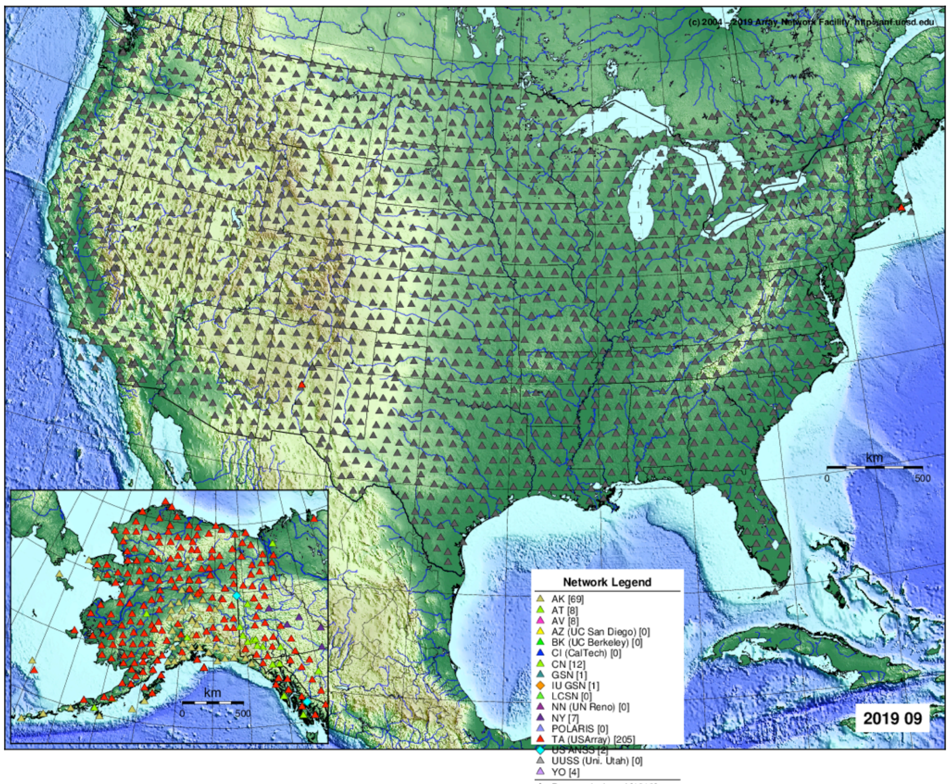
A seismological perspective on the strength of the lithosphere-asthenosphere system

Weisen Shen, Siyuan Sui, Lingli Li, Douglas Wiens, Andrew Lloyd, Andy Nyblade;
Team of POLENET(Terry Wilson et al); TAMNNET (Sam Hansen and students); RIS/DRIS (Rick Aster et al.)
GeoPATH program @ Stony Brook University, IRIS, and NSF

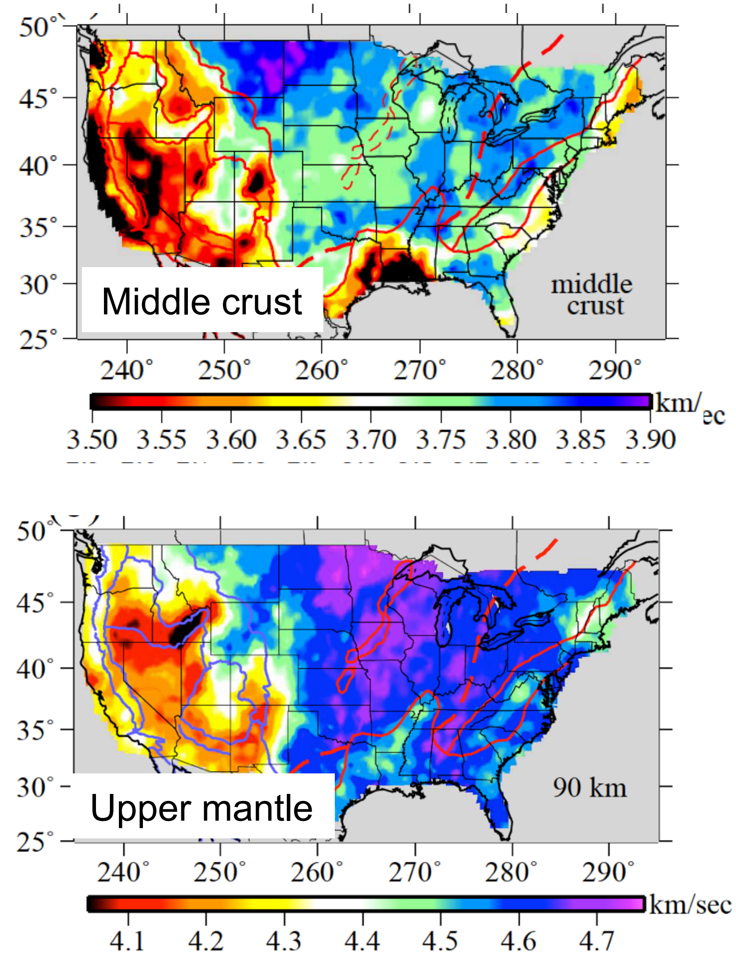
- **Antarctica**: geothermal heat flux and mantle viscosity
- **North America:** crustal composition of and its implications on crustal strength

Large scale seismic arrays across major continents
Sharp seismic images for the crust and uppermost mantle are then produced:

USArray/Transportable Array, 2004 – present, 1679 sites in L48



Crust and uppermost mantle beneath the US



Shen and Ritzwoller, 2016, JGR

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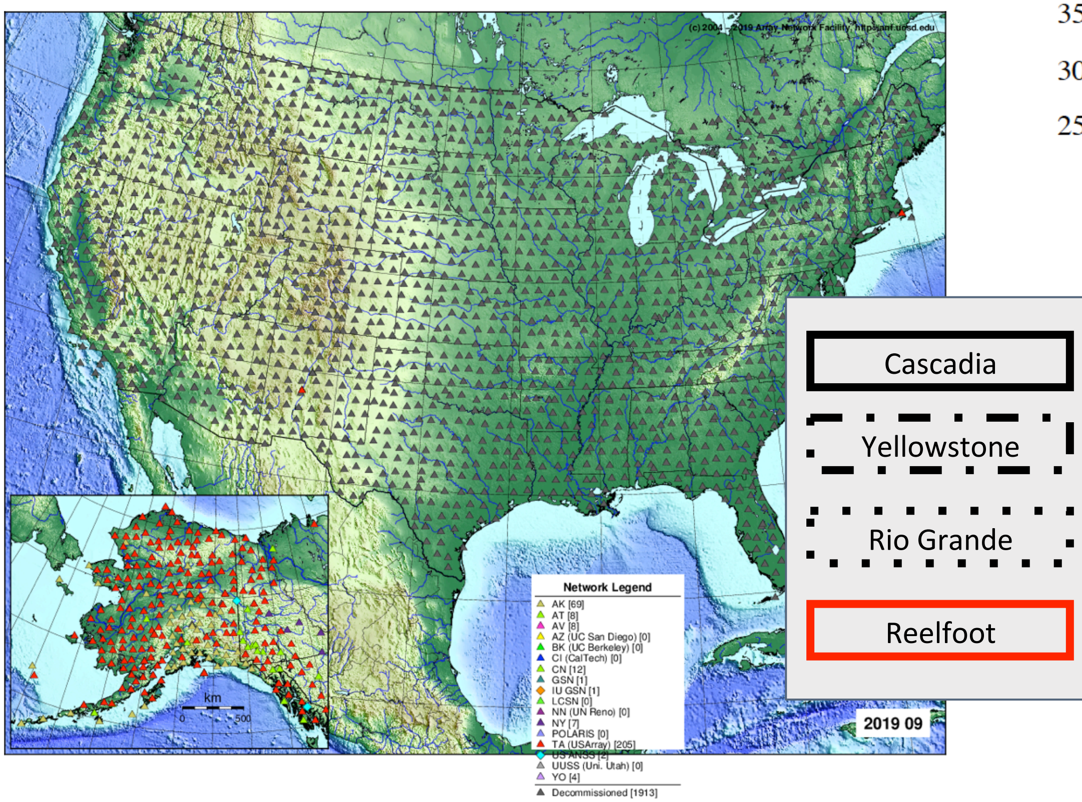

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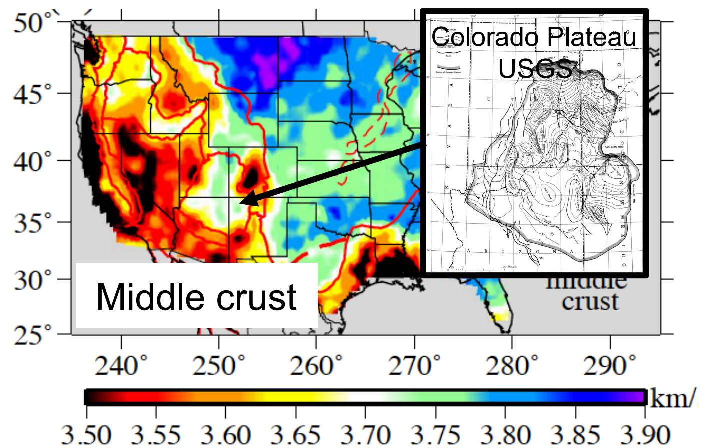
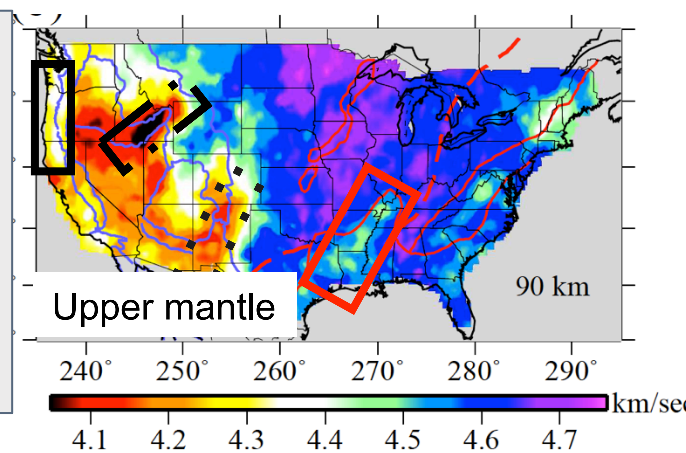
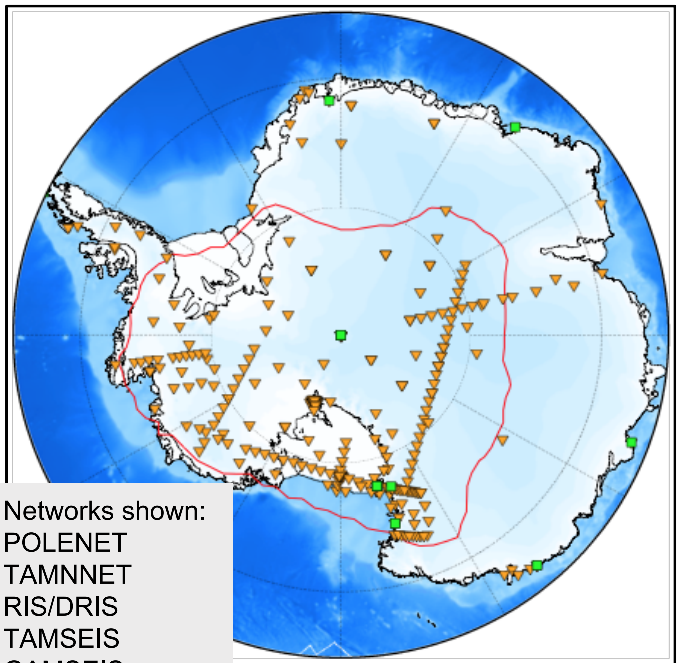




Shen and Ritzwoller, 2016, JGR

Large scale seismic arrays across major continents
Sharp seismic images for the crust and uppermost mantle are then produced:

Seismic stations in Antarctica (2001-2018)



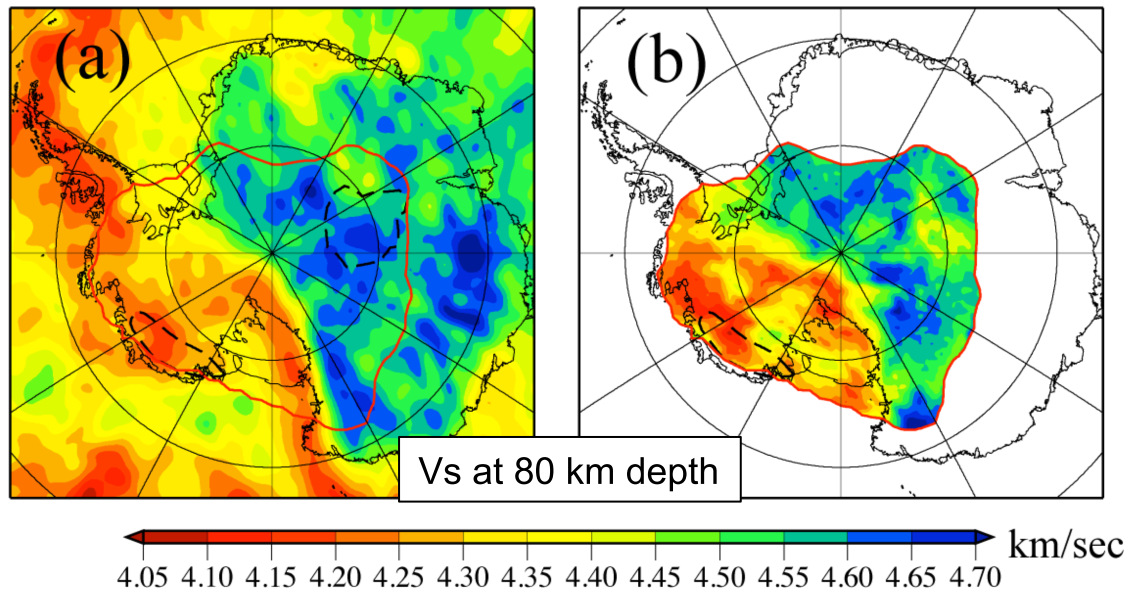
Networks shown:
POLENET
TAMNNET
RIS/DRIS
TAMSEIS
GAMSEIS
etc.…

Model 1 (Lloyd et al 2019):
Adjoint full-waveform inversion
Surface to > 600 km depth;

Complete coverage of the whole continent and Southern Oceans

Model 2 (Shen et al., 2018):
Monte Carlo inversion of surface wave and receiver functions
Surface to ~ 200 km depth;

West and central Antarctica but better resolution for crust/shallow mantle



Lloyd et al., 2019, JGR in review

Shen et al., 2018, JGR

Regarding the strength/rheology, what we can learn from these seismic models:

Rheology of the Lower Crust and Upper Mantle: Evidence from Rock Mechanics, Geodesy, and Field Observations

Roland Bürgmann[1] and Georg Dresen[2]

[1]Department of Earth and Planetary Science, University of California, Berkeley, California 94720; email: burgmann@seismo.berkeley.edu

[2]GeoForschungsZentrum Potsdam, D-14473 Potsdam, Germany; email: dre@gfz-potsdam.de

Burgmann and Dresen, 2008

Assessing the mechanical properties of rocks for the broad range of thermodynamic boundary conditions prevalent in Earth's interior remains a daunting task. Rock rheology varies as a function of a number of constitutive and environmental aspects, including mineralogy, fluid content and chemistry, mineral grain size, melt fraction, temperature, pressure, and differential stress conditions. The range in mineralogical and chemical composition of rocks is enormous, and our knowledge of even the most important boundary conditions, such as regional heat flow and tectonic forces, is often rudimentary. Relevant timescales range from fractions

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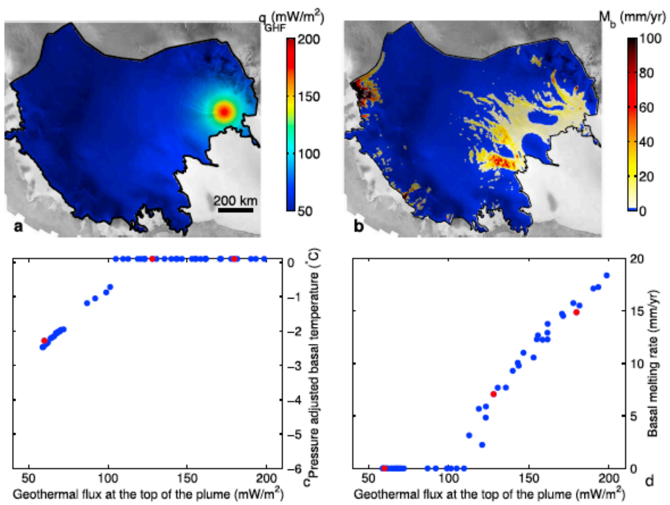
Seismic observables

What we can learn from these seismic models: part 1

- **Antarctica**: geothermal heat flux and mantle viscosity
- **North America:** crustal composition of and its implications on crustal strength

The need for geothermal heat flux and mantle viscosity models of Antarctica

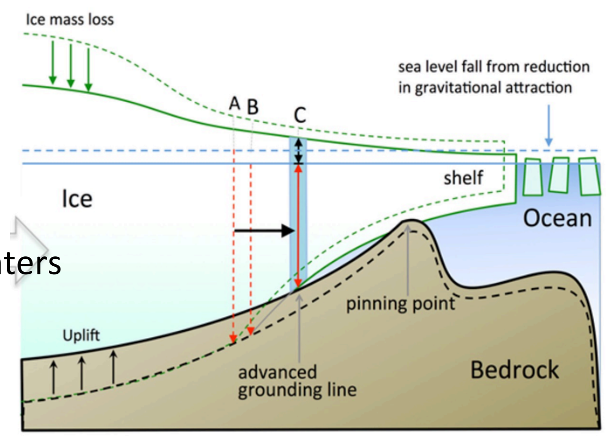
Ice-sheet modeling shows that **higher geothermal heat flux** would increase the basal temperature, which can lead to basal and **may accelerate the movement of the ice-sheet**.



Seroussi et al., (2017)

Uplift rates from GPS do not match predictions of **1-D viscosity models**

Rapid GIA caused by low viscosity mantle reverses bed slope, may **slow the rate of ice sheet retreat**



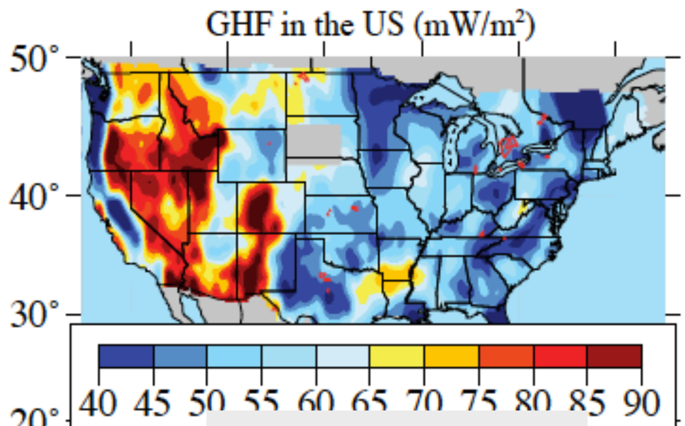
Barletta et al. (2018)

Geothermal heat flux: correlated with mantle shear velocity

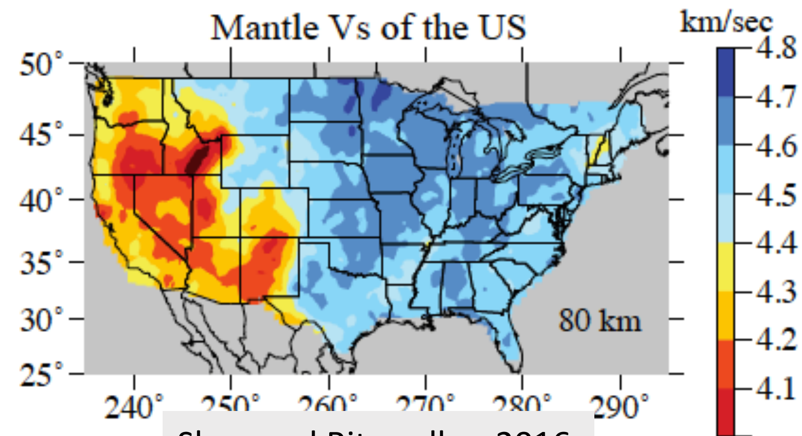
Large-scale variation in GHF is highly correlated with uppermost mantle velocity structure.

Effect from the heat generation within the crust perhaps plays a secondary role.

Much of the variation of seismic speed in the mantle is perhaps thermal origin.



Blackwell et al., 2011



Shen and Ritzwoller, 2016

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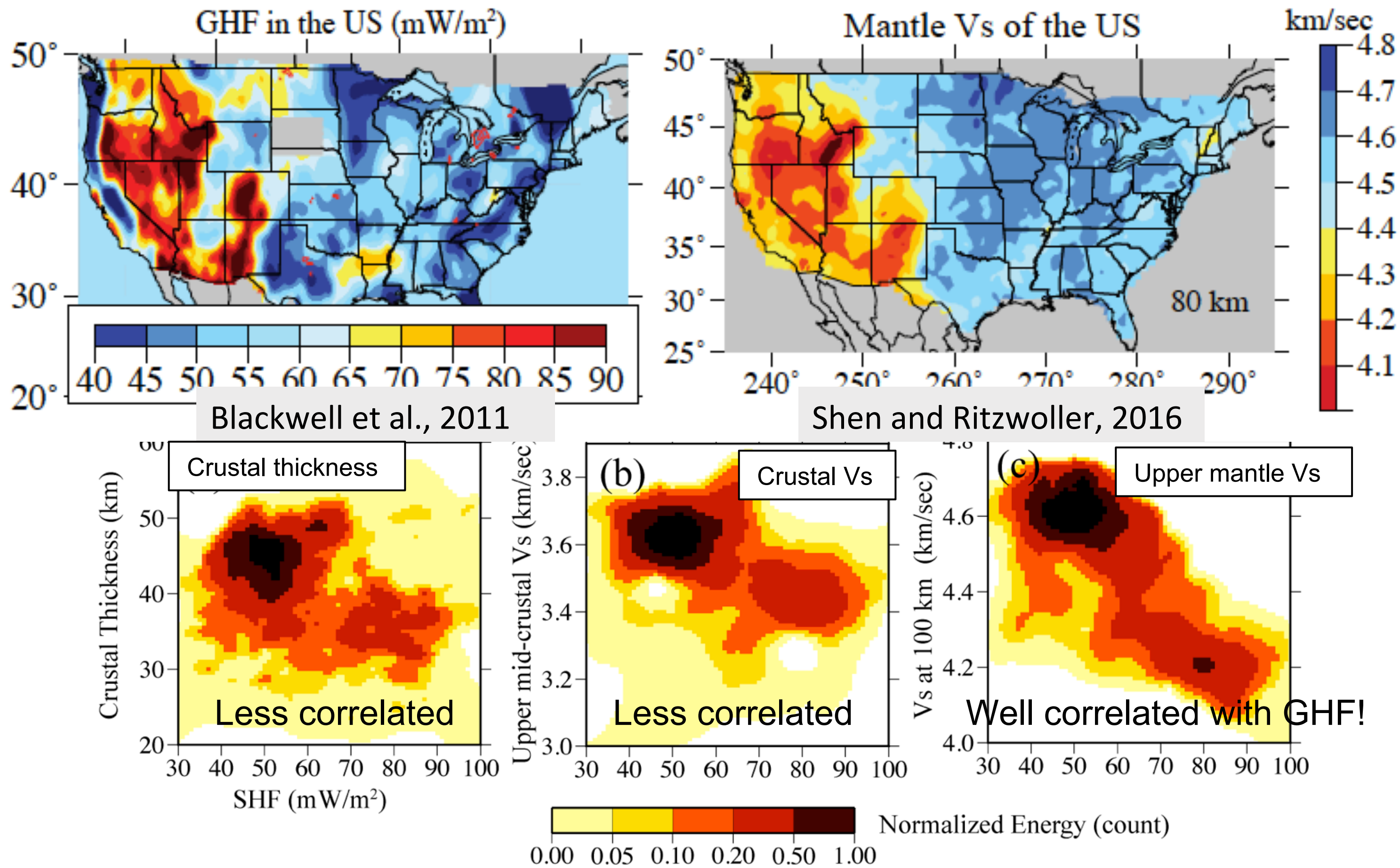
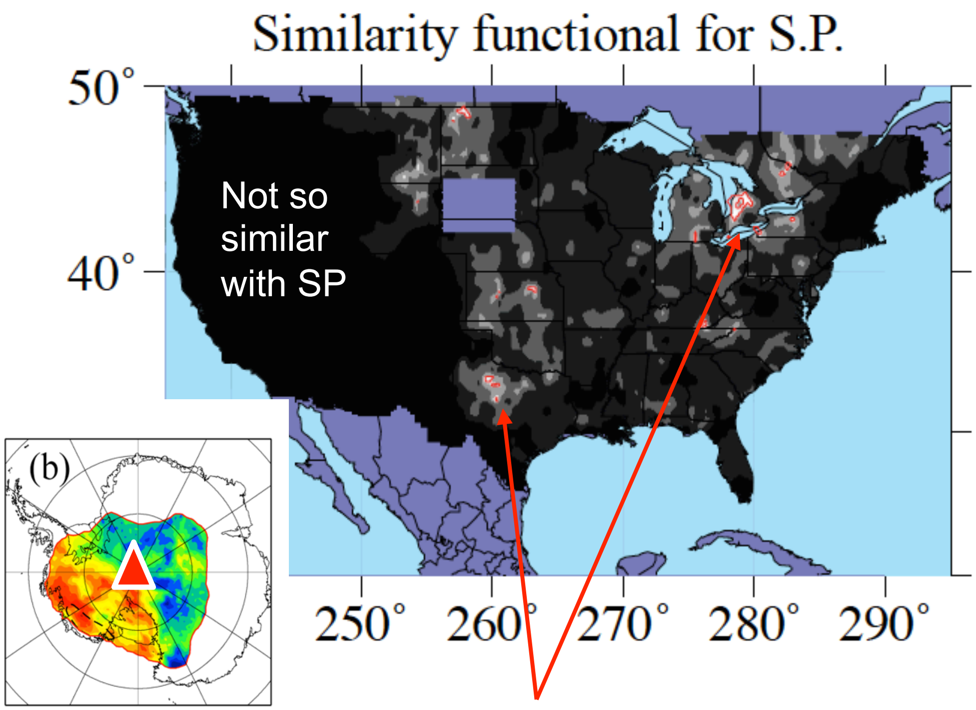
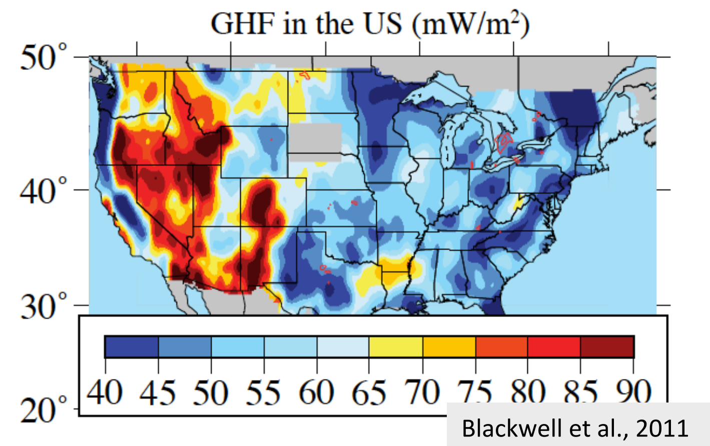


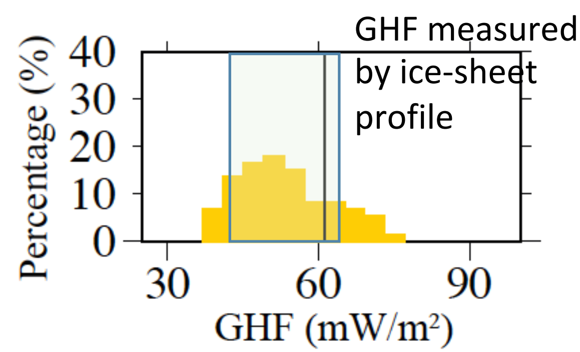
Seismologically determined geothermal heat flux beneath South Pole



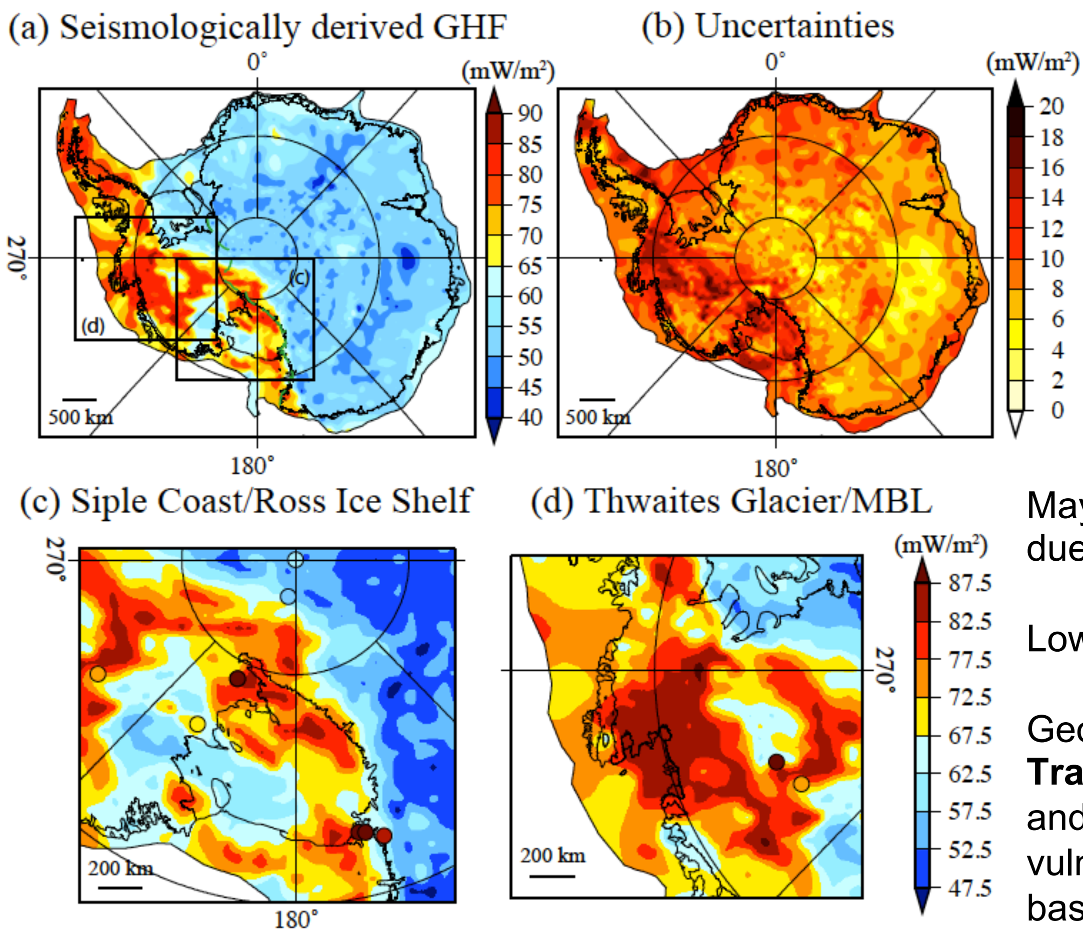
High similarity to the South Pole in terms of upper mantle structure



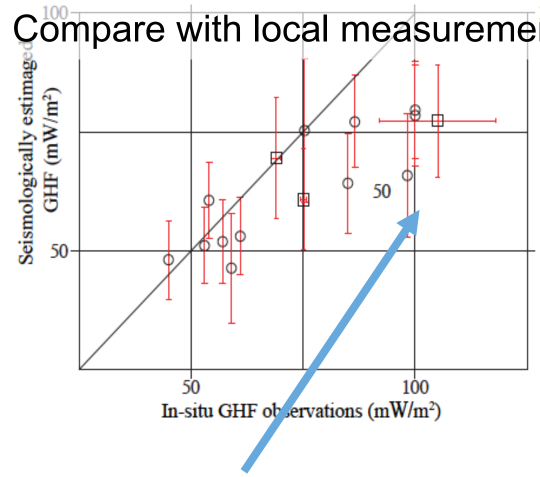
Estimated GHF distribution for the South Pole



A seismologically determined geothermal heat flux map of Antarctica



Compare with local measurements

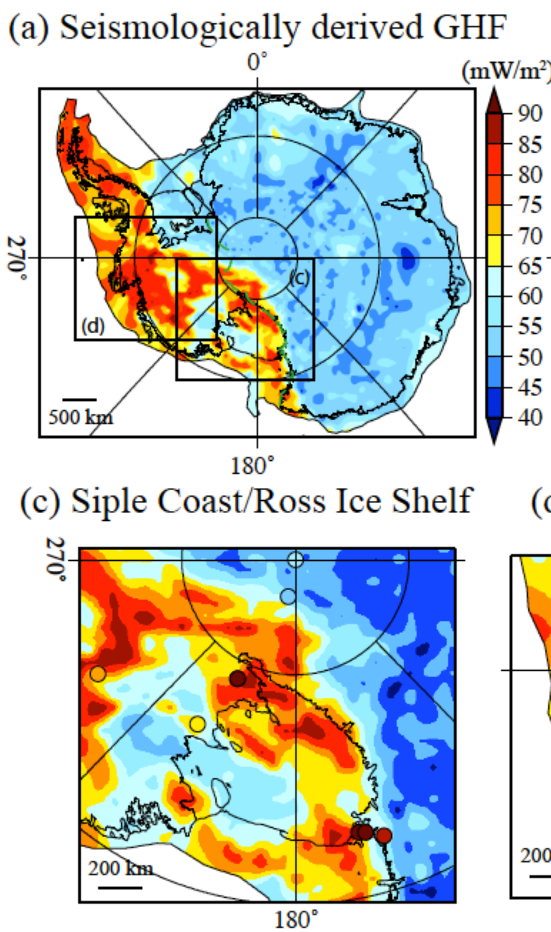


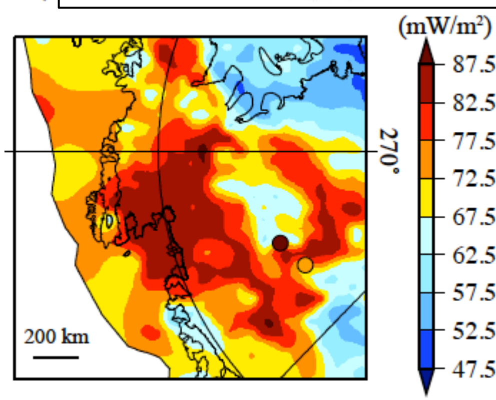
May underestimate localized GHF variations due to the usage of smooth seismic model.

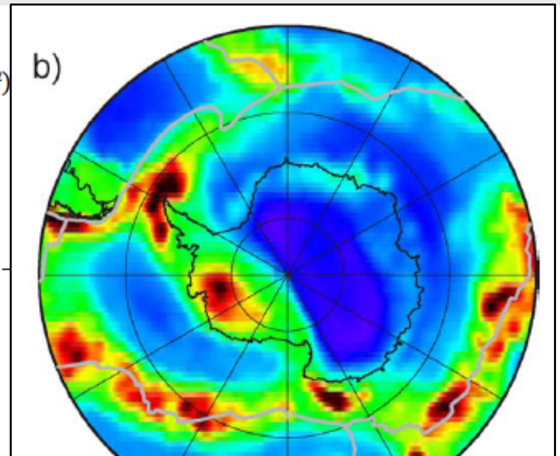
Low GHF in the E. Antarctica and Siple Coast.

Geothermal heat flux is high along the **Transantarctic Mountains**, **Marie Byrd Land**, and **Amundsen Sea Coast**, indicating higher vulnerability from basal melting and faster basal sliding.

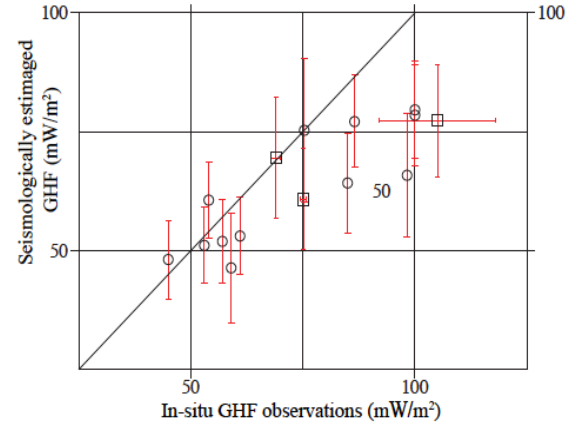
A seismologically determined geothermal heat flux map of Antarctica







Shapiro and Ritzwoller, 2004



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Estimating Viscosity Structure from the Seismic Model

- Using seismic anomalies relative to a global 1D reference model (STW105) to compute temperature anomalies relative to a temperature geotherm, and then viscosity variations relative to reference viscosities. We assume linear viscosity.
- Other approaches estimate the mantle temperature and then directly use experimental flow laws to determine viscosity, but they require more assumptions, such as composition and grain size
- Use (*Wu et al*, 2012):

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

-- Temperature derivative from *Karato* (2008)

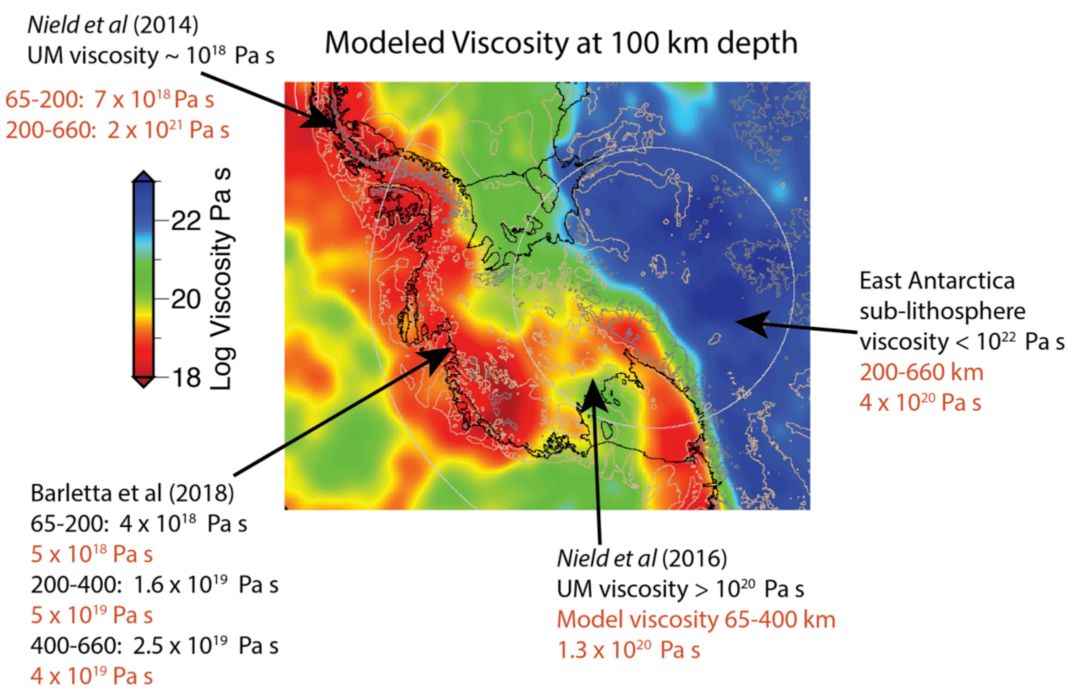
-- T_0 - reference temperature – assume 1315 °C adiabat

-- E^* and V^* - activation energy and volume –from *Hirth & Kohlstedt* (2003); initially use dry olivine but test others (hydrous olivine, etc)

-- β - percent of seismic anomaly due to temperature

Wiens, Lloyd et al., in prep

Calibrating Viscosity Conversion



Compare various viscosity calculations to estimates from geodetic observation

Choose:

Dry olivine diffusion creep rheology from *Hirth & Kohlstedt* (2003)

Background upper mantle viscosity IJ05-R2 (*Ivins & James*, 2013)

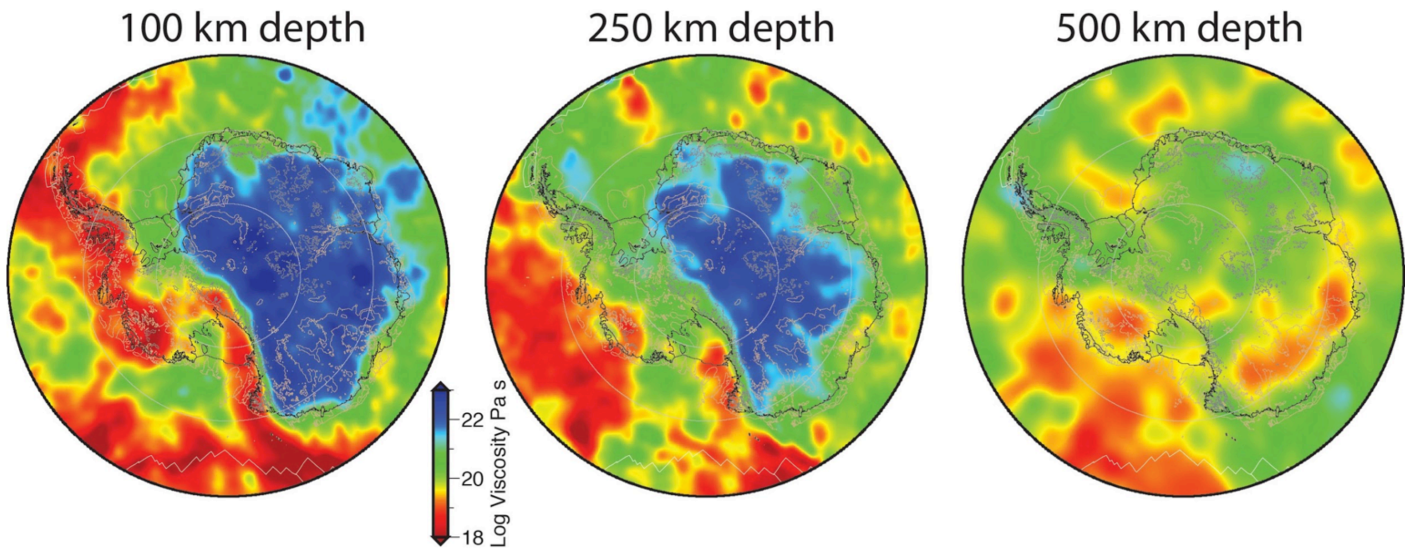
Velocity anomalies entirely due to temperature (β = 1.0)

Made a correction for depleted continental lithosphere in East Antarctica (*Lee* , 2003)

Preferred viscosity model values shown in red

Wiens, Lloyd et al., in prep

Estimated Mantle Viscosity Maps



- Extremely low viscosity (~ 10^{18} – 10^{19} Pa s) throughout the upper mantle beneath Marie Byrd Land and the Amundsen Coast
- This indicates that the mantle response time to ice mass loss is ~ 100 years, rather than ~ 1000s years.
- Very low viscosity shallow (< 200 km) beneath the Peninsula, but high viscosity deeper, perhaps due to subducted slab material.
- Higher viscosity (~ 10^{20} Pa s) beneath Siple Coast and Ronne Ice Shelf region

Wiens, Lloyd et al., in prep

Main Message

3-D seismic models are useful for investigating the rheology/strength of the lithosphere-asthenosphere system:

- **Upper mantle seismic velocity provides constraints to thermal properties (e.g. geothermal heat flux) and mantle viscosity in Antarctica.**

What we can learn from these seismic models: Part 2

- **Antarctica**: geothermal heat flux and mantle viscosity
- **North America:** crustal composition of and its implications on crustal strength

Part 2. Crustal strength of North America:
Some new constraints from seismic investigations to composition

Rheology of the Lower Crust and Upper Mantle: Evidence from Rock Mechanics, Geodesy, and Field Observations

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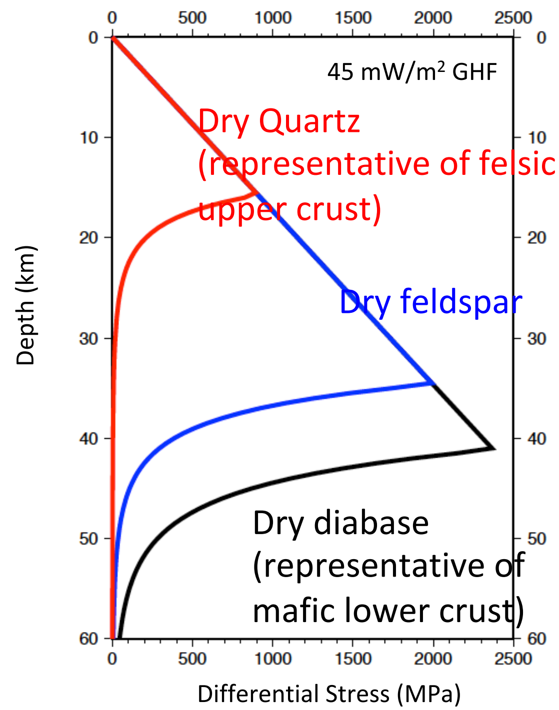

P.120 of Karato's *Physics and Chemistry of the Deep Earth*

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California 94720; ...

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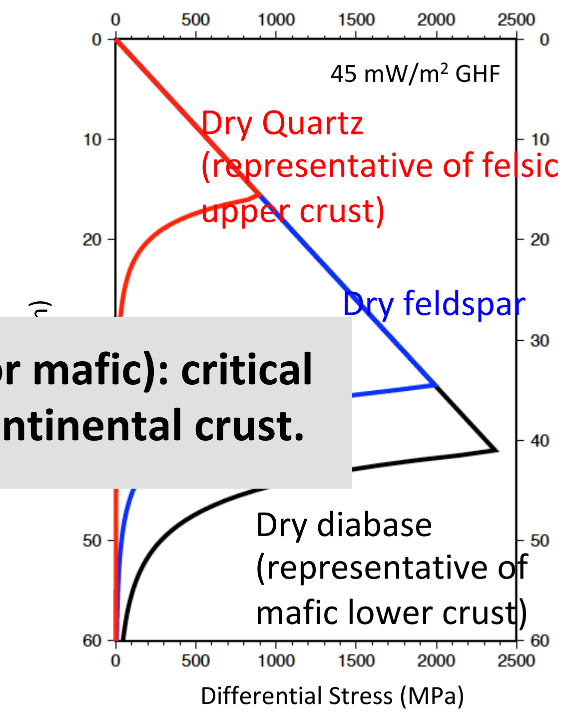
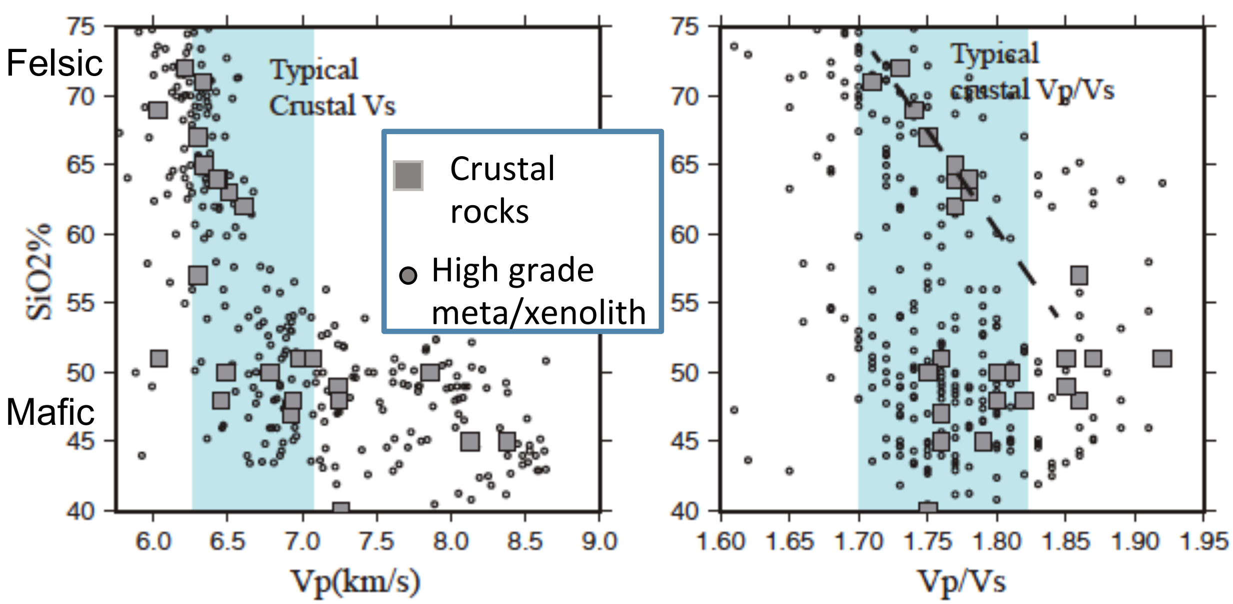
Deep crustal composition (felsic or mafic): critical for quantifying the strength of continental crust.



P.120 of Karato's *Physics and Chemistry of the Deep Earth*

Seismic signature of major element (SiO_2) content

Vp – SiO_2 wt% Vp/Vs - SiO_2 wt%



Vp ~ 6.5 km/sec, 45-72% of SiO_2;

Vp/Vs ~ 1.75, 40-75% of SiO_2

Christensen, 1995; Hacker et al., 2015;

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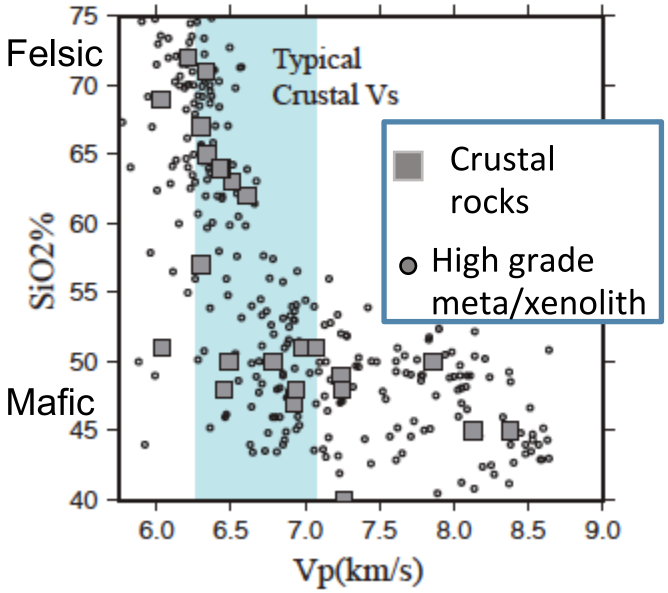
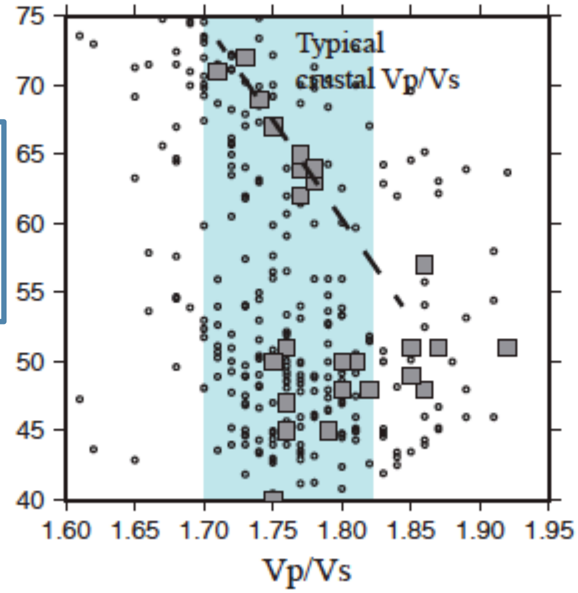
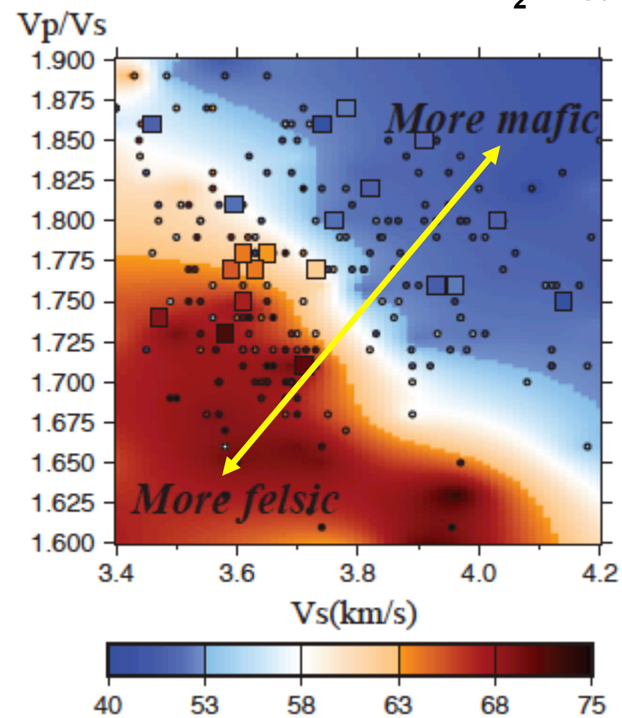


Vp/Vs - SiO_2 wt%



Both Vs and Vp/Vs should be used to constrain SiO_2 wt%!



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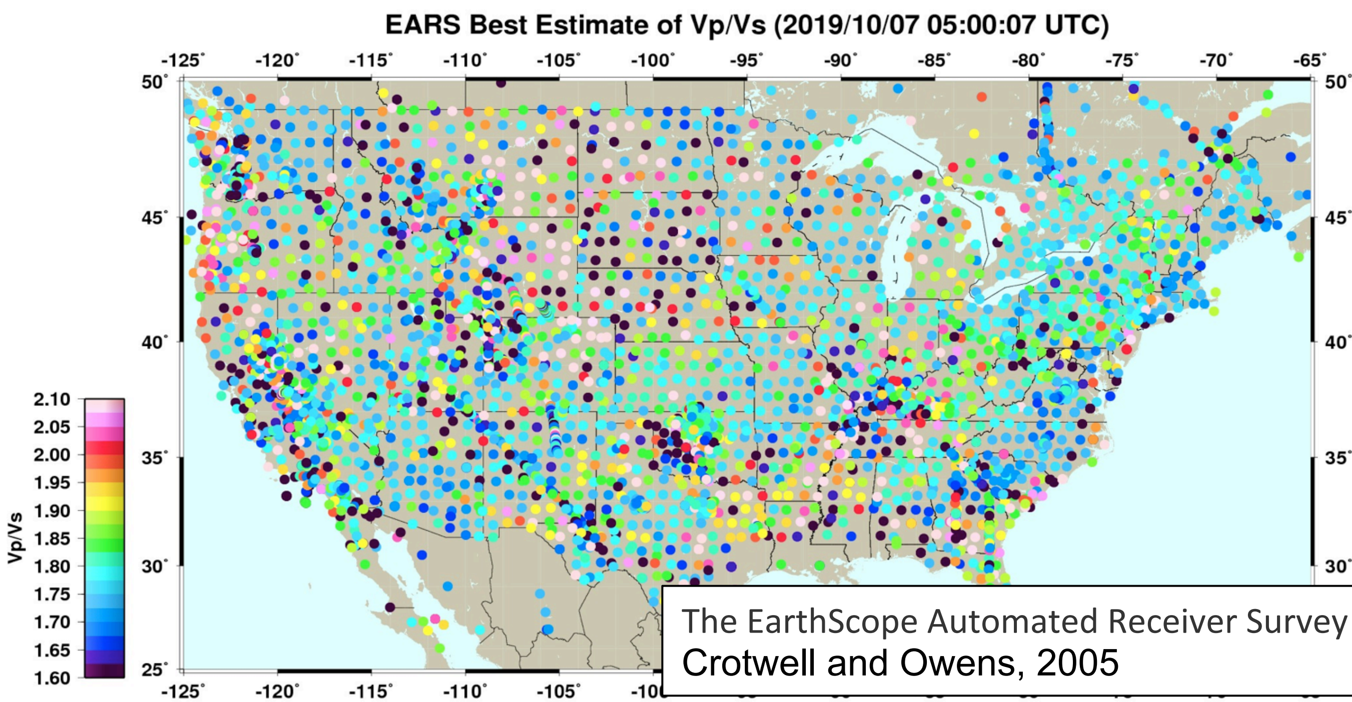
Vp/Vs ~ 1.75, 40-75% of SiO2

Christensen, 1995; Hacker et al., 2015;

Because seismic phases that are used to determine the crustal Vp/Vs are easily:

1. Biased by the sedimentary cover (slow seismic velocity)
2. Contaminated by noise due to 3-D structure of the Earth

The resulting Vp/Vs from EARS shows some extreme values at short scales.

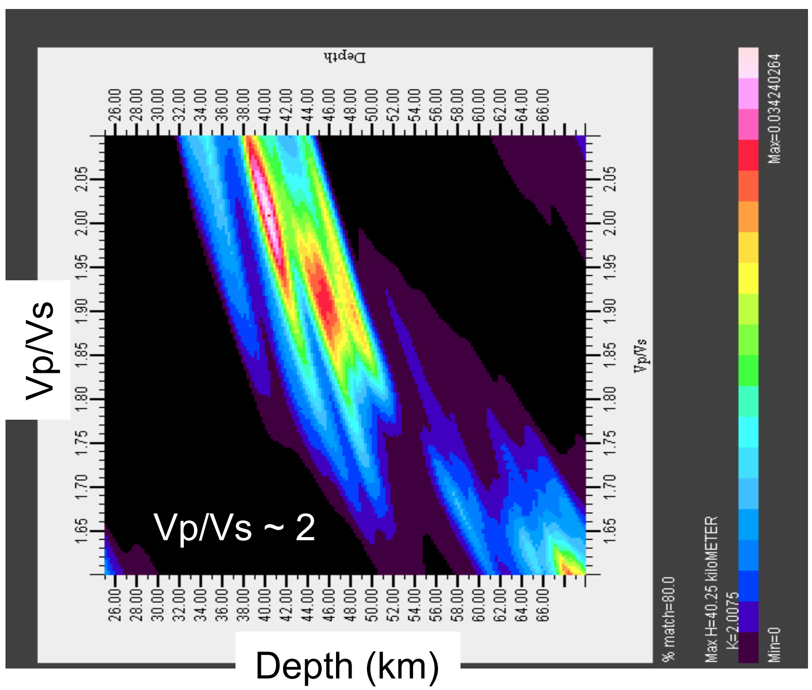


The EarthScope Automated Receiver Survey (EARS), IRIS
Crotwell and Owens, 2005

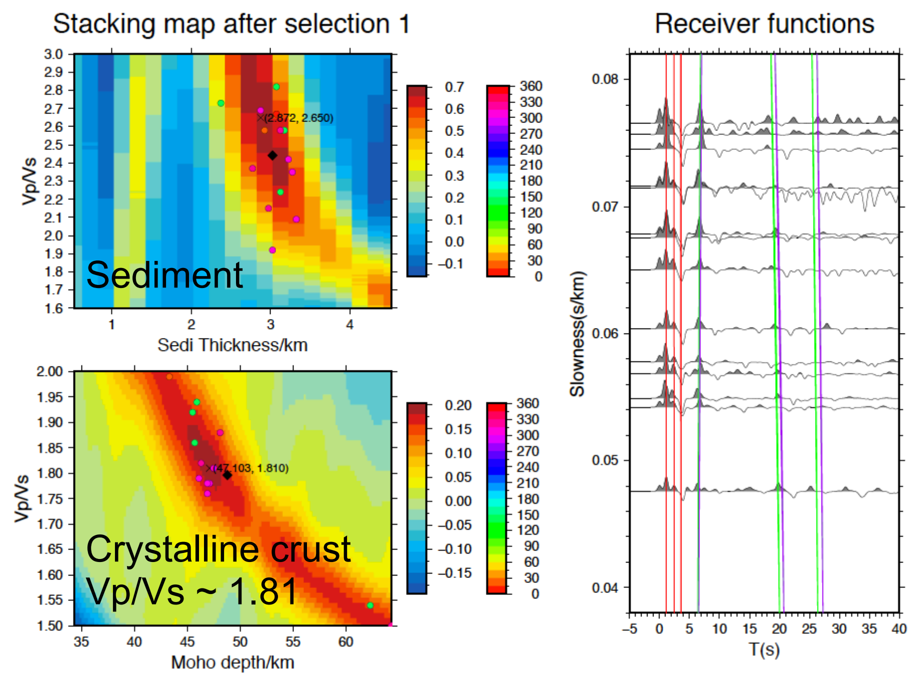
We:

1) adopted a 5-stage quality control (QC) to the P wave receiver functions.
2) adopted a 2-layer stacking method to analyze the P wave and its multiples in the receiver functions.

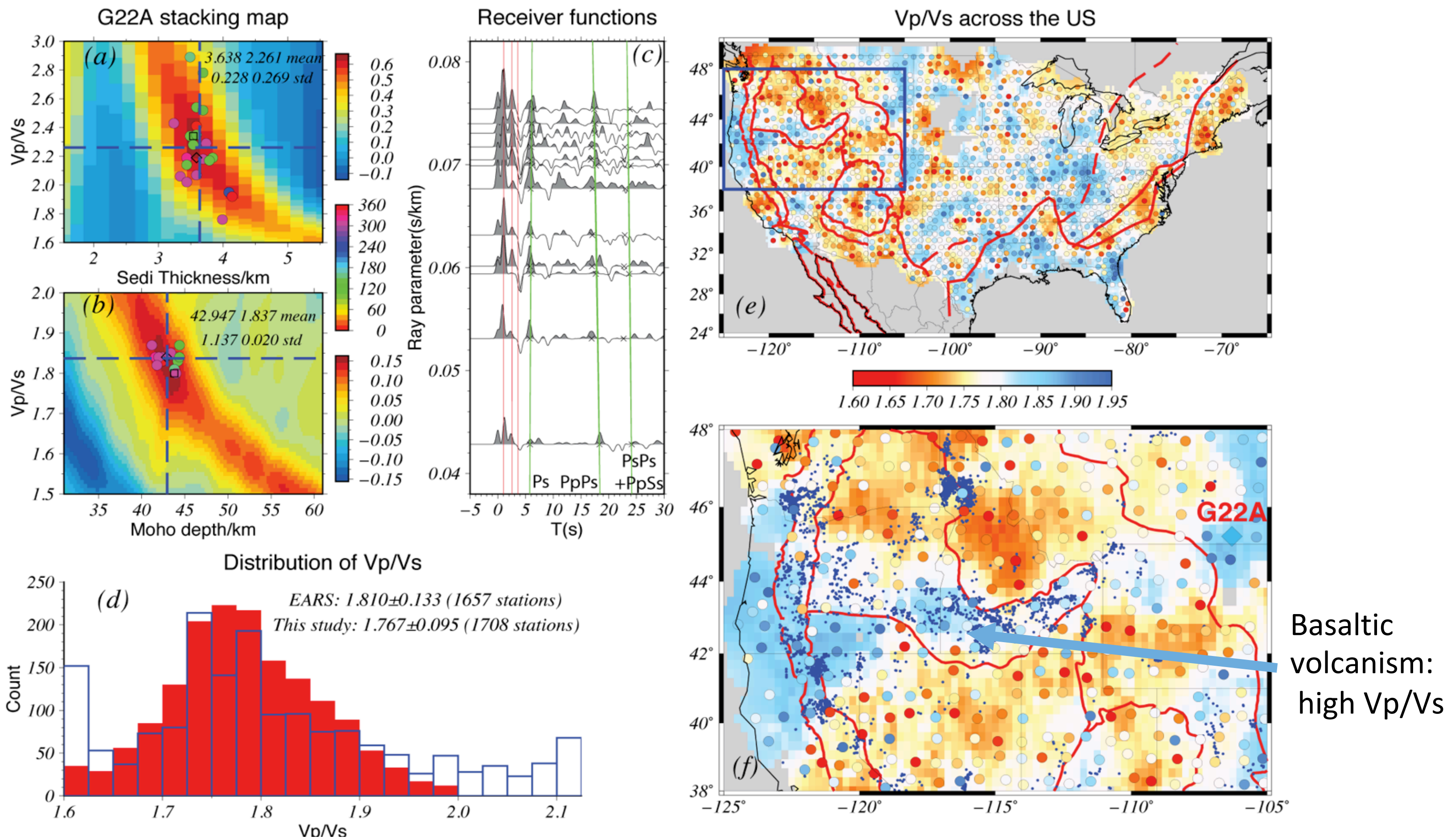
EARS result for a USArray station in Denver Basin



Sui and Shen, submitted, 2019

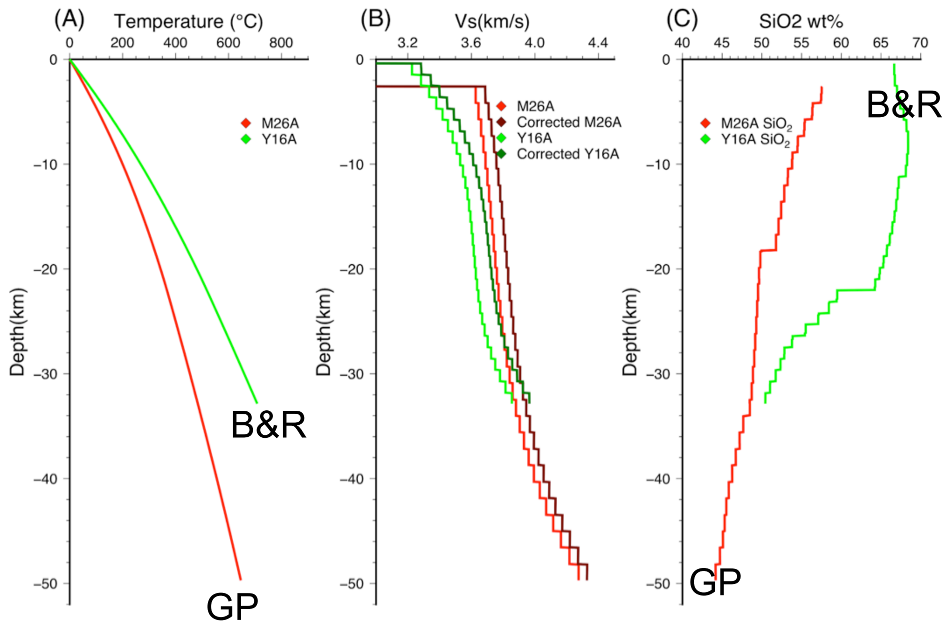


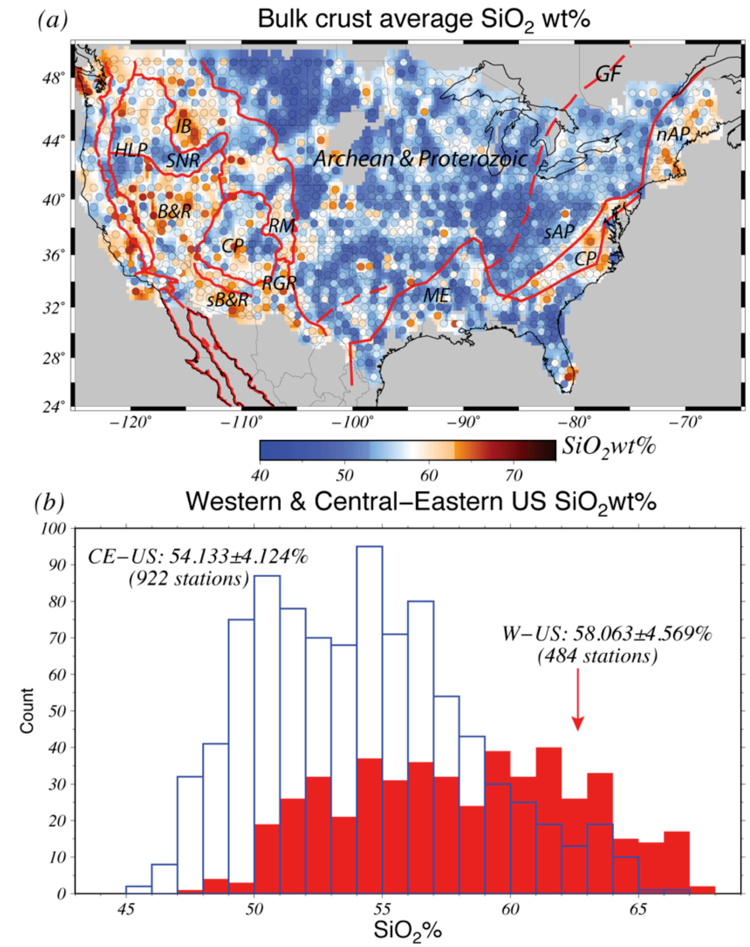
A new map of Vp/Vs of the continental US revealed by USArray/Transportable Array



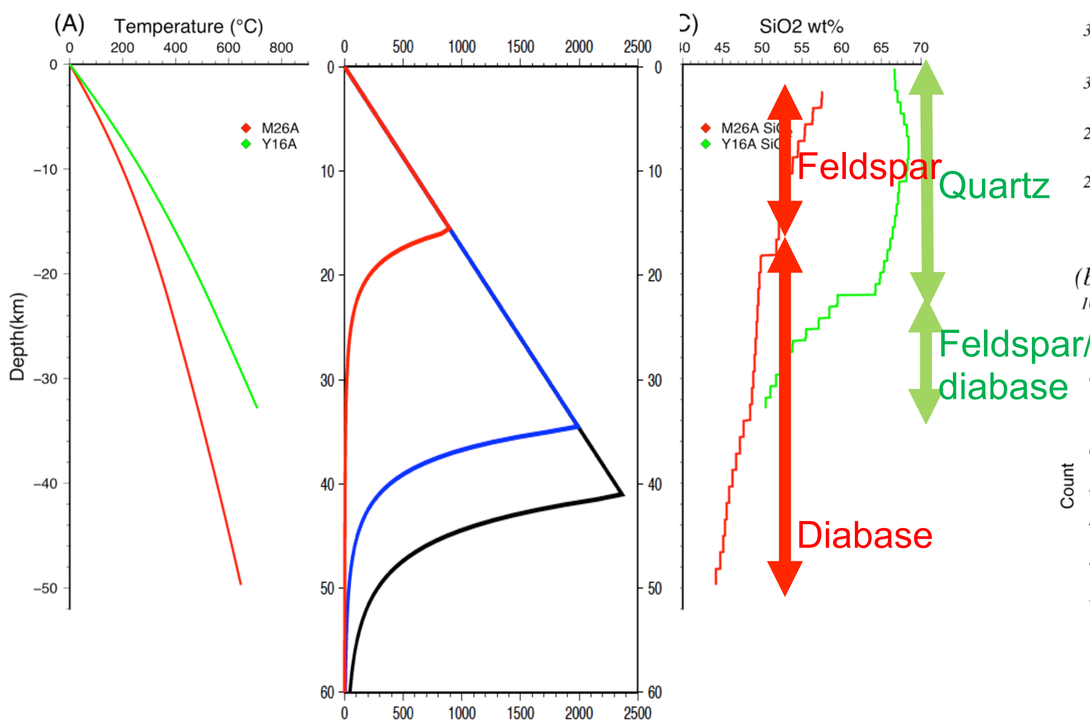
Sui and Shen, submitted, 2019

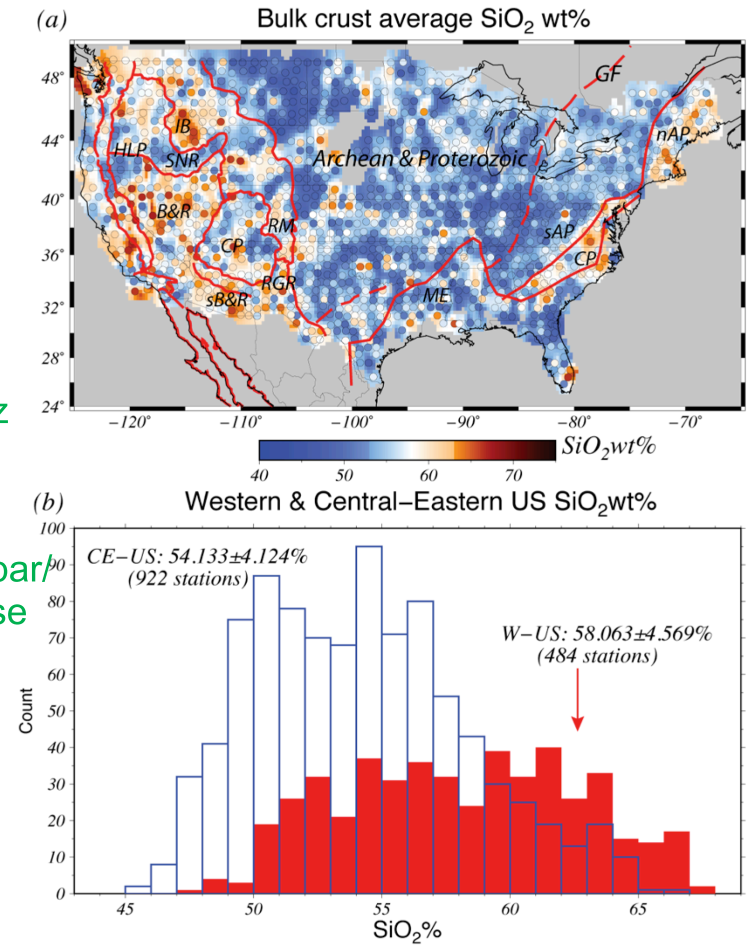
A new map of SiO_2 of the continental US revealed by USArray/Transportable Array





Sui and Shen, submitted, 2019; more info see **poster by Sui and Shen #57**





Sui and Shen, submitted, returned, and in prep for resubmission, 2019, more info see **poster of Sui and Shen #57**

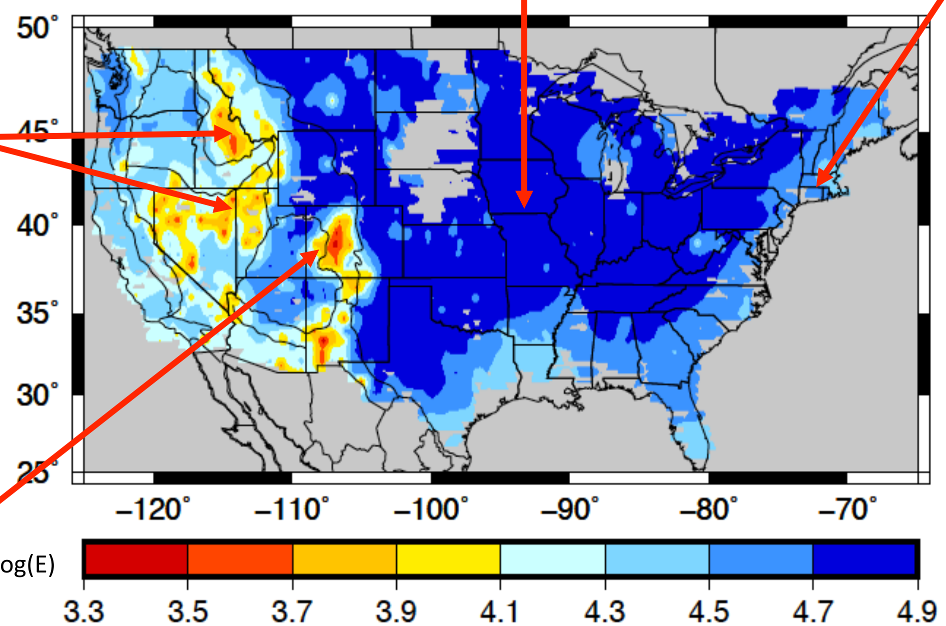
Crustal strength map of the continental US:

N. Basin and Range and Idaho batholith are weak, correlated with the higher seismicity surrounding the Snake River Plains.

Colorado Rockies and Rio Grande Rift: Weak crust bounded by strong Colorado Plateau, Wyoming Craton, and Great Plains.

Central and eastern US including the S. Appalachians: very strong crust.

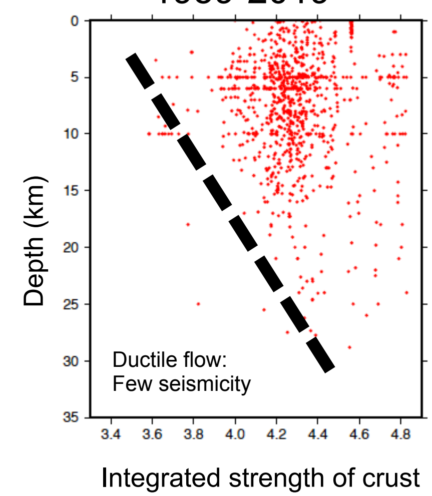
Relatively weaker zone in the N. Appalachian and coastal plains.



1/10 strength of the "very strong crust"

"Very strong crust"

Intra-plate crustal earthquakes 1959-2019

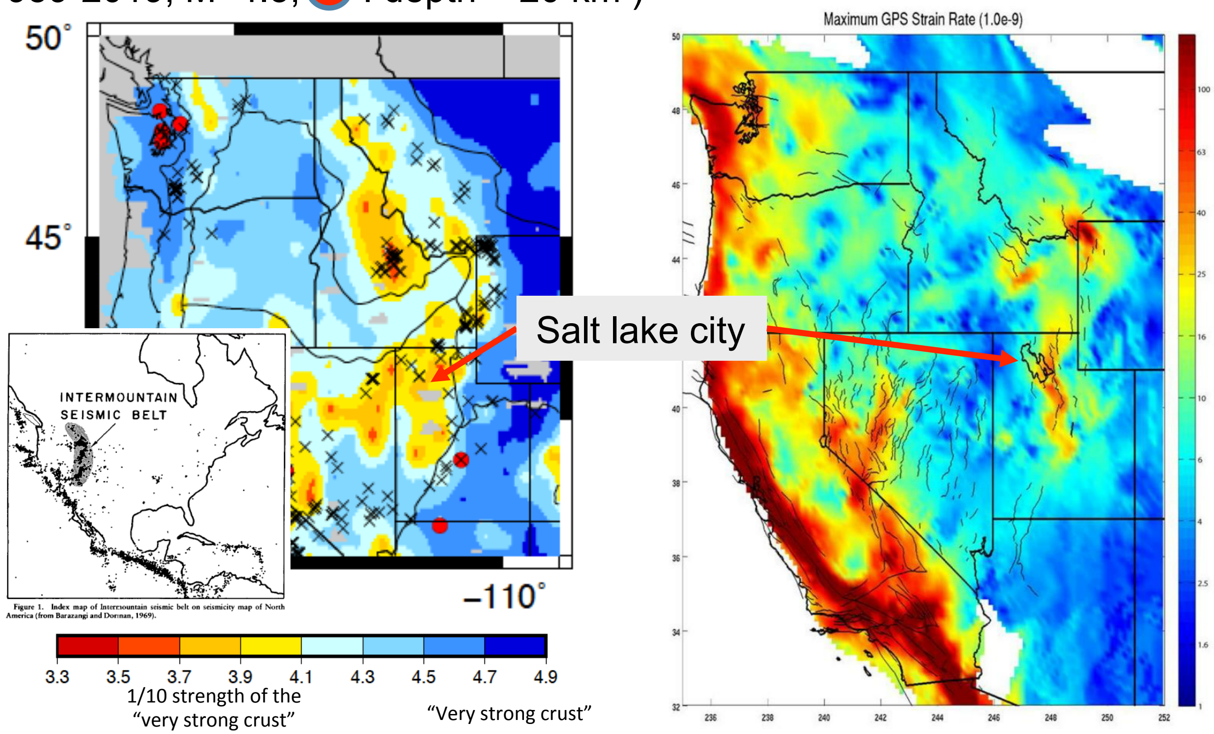


A chemically originated weak zone in the intermountain seismic belt.

Deep crust earthquakes tend not to be triggered in the area with the weakest crust, perhaps due to the fact that the deformation deep crust is under the plastic flow law.

(Chemically originated) weak zone in the intermountain west (including Idaho batholith, northern Rocky Mountains, and NE Basin and Range) perhaps provides the basis for the high seismicity and strain-rate near the intermountain seismic belt region.

Intra-plate crustal earthquakes
(1959-2019, M>4.5; ● : depth > 20 km)



Petersen et al., 2008

Main Message

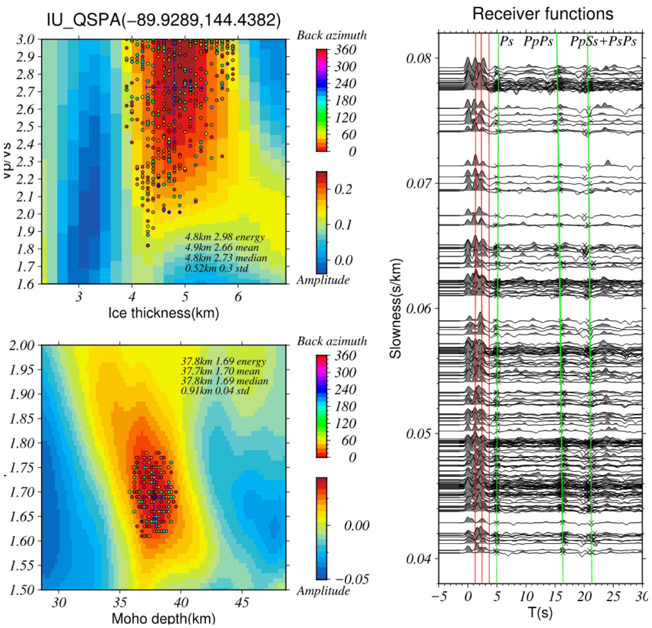
3-D seismic models are useful for investigating the rheology/strength of the lithosphere-asthenosphere system via ...

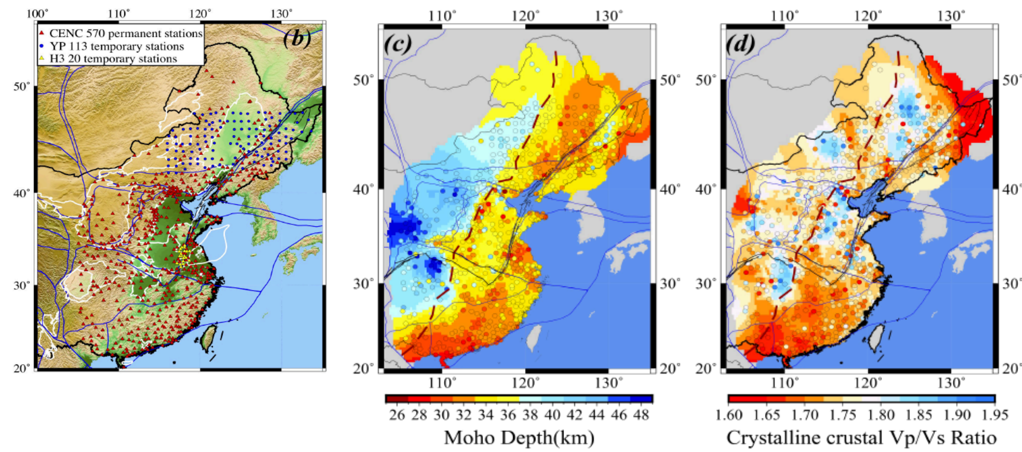
- **Relating upper mantle seismic velocity provides with other thermal properties (e.g. geothermal heat flux and mantle viscosity in Antarctica).**

- **Combing crustal seismic properties and petrology/mineral physics sheds light to mapping the strength of the crust; the map of crustal strength of the continental US matches the large-scale tectonism, showing strong correlation with the deformation intra-plate seismicity and strain rate in the intermountain west.**

Other continents are also under investigation

Moho depth of South Pole: ~ 38 km.
Crustal Vp/Vs at South Pole: ~ 1.70

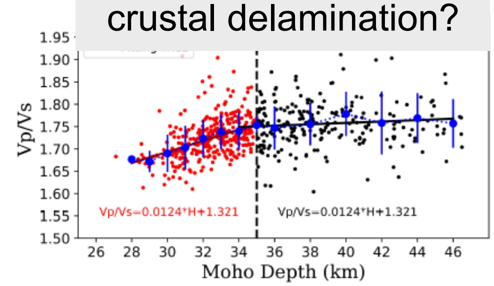




In Eastern China, RFs at ~ 700 stations have been examined and new crustal thickness and Vp/Vs maps are revealed.

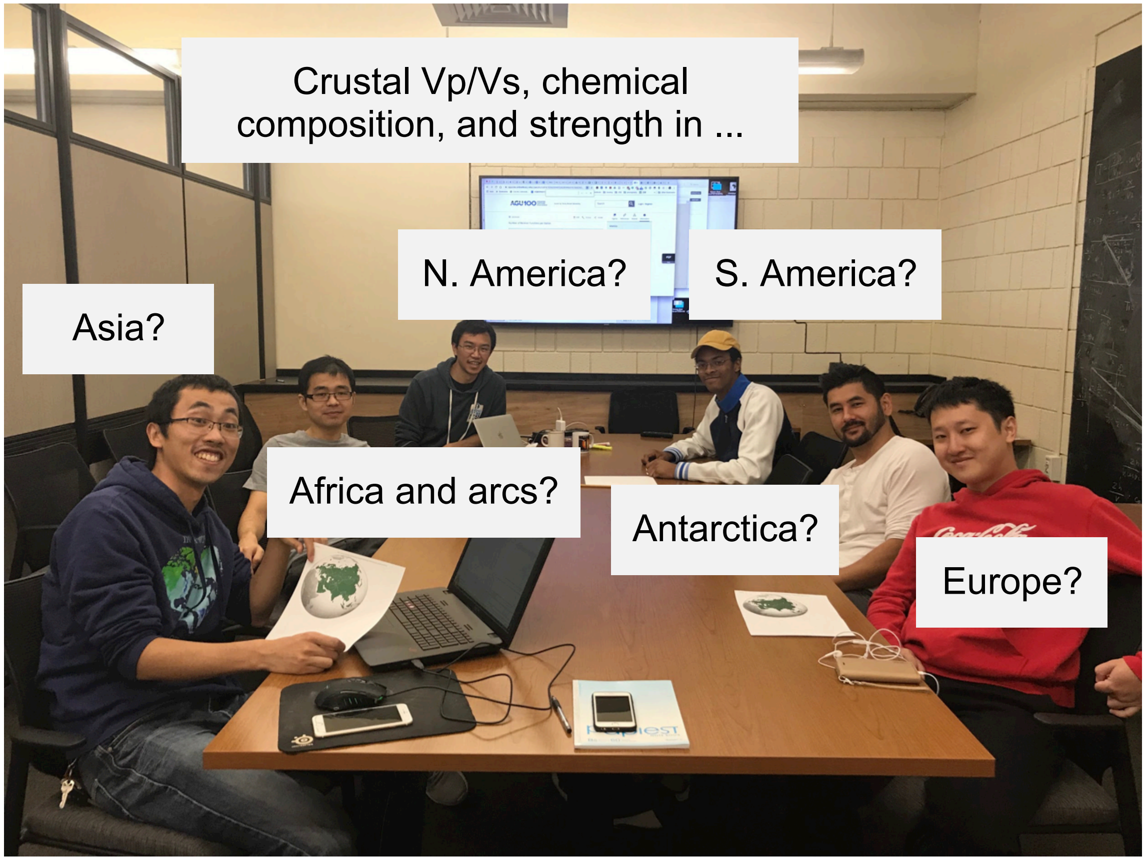
See **Poster by Li et al. "Crustal architecture beneath eastern China" (#58)**

Indicative of lower crustal delamination?



Expanding the expedition to global scale

In order to answer more general questions, such as the governing rule for strength of continental lithosphere, requires ...



Undergraduates from underrepresented groups and community colleges are incorporated in the effort of compiling Vp/Vs...

And this belongs to a greater effort ...

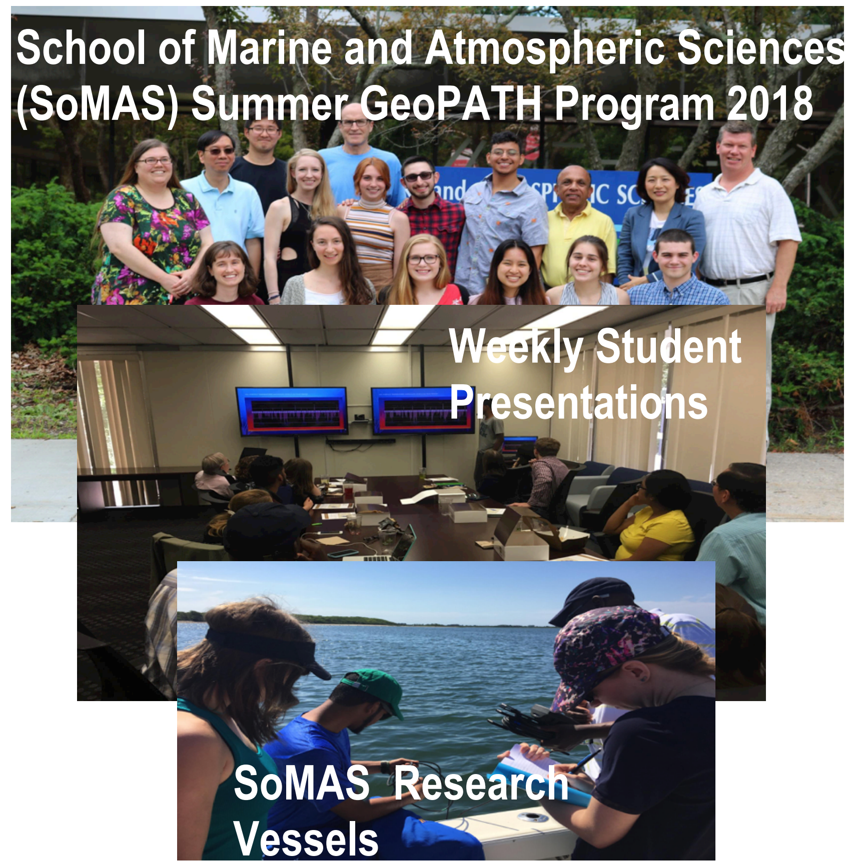
Incorporating undergraduates and community college students in global seismology and geosciences: GeoPATH @ Stony Brook

<u>Lead Institutions:</u>
<u>School of Marine and Atmospheric Sciences and Department of Geosciences</u>
Stony Brook University / SUNY

<u>Partners:</u>
Suffolk Community College
Nassau Community College
Several Long Island High Schools

What we do at Stony Brook:

- 4-6 week summer research program and faculty mentoring for 8-10 community college (CC) and high school students (for past 2 summers)
- 5-6 now majoring in geosciences with $2K Scholarship so far to 3-4 students continuing Geoscience studies at Stony Brook (SBU)
- CC and high school visits/mentors/clubs
- Curriculum adjustments to facilitate transition from CC to 4-year SBU B.S. degree.
- Two CC students have conducted Antarctica-related seismological research and have successfully enrolled in the geosciences program at SBU to continue their expeditions.



Main Message

3-D seismic models are useful for investigating the rheology/strength of the lithosphere-asthenosphere system:

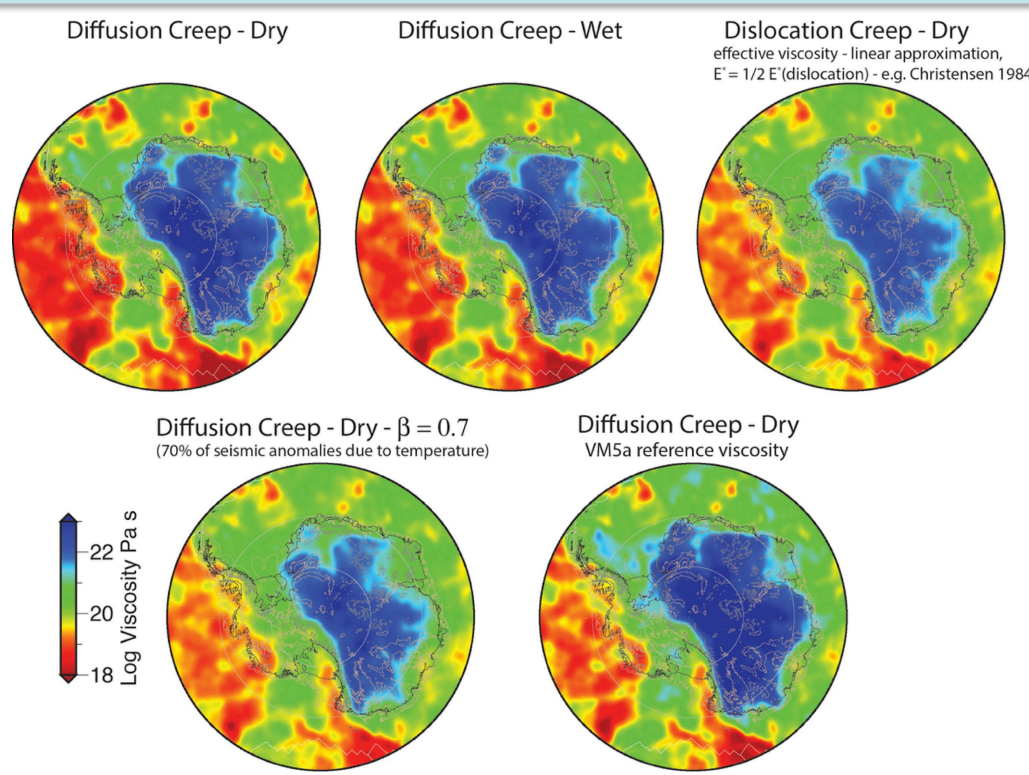
- **Relating upper mantle seismic velocity with other thermal properties (e.g. geothermal heat flux and mantle viscosity in Antarctica).**

- **Combing crustal seismic properties and petrology/mineral physics sheds light to mapping the strength of the crust; the map of crustal strength of the continental US matches the large-scale tectonism, showing strong correlation with the deformation intra-plate seismicity and strain rate in the intermountain west.**

- **Seismic investigations to NA and Antarctica attract future geoscientists through involvement of students from CC and underrepresented students at Stony Brook University.**

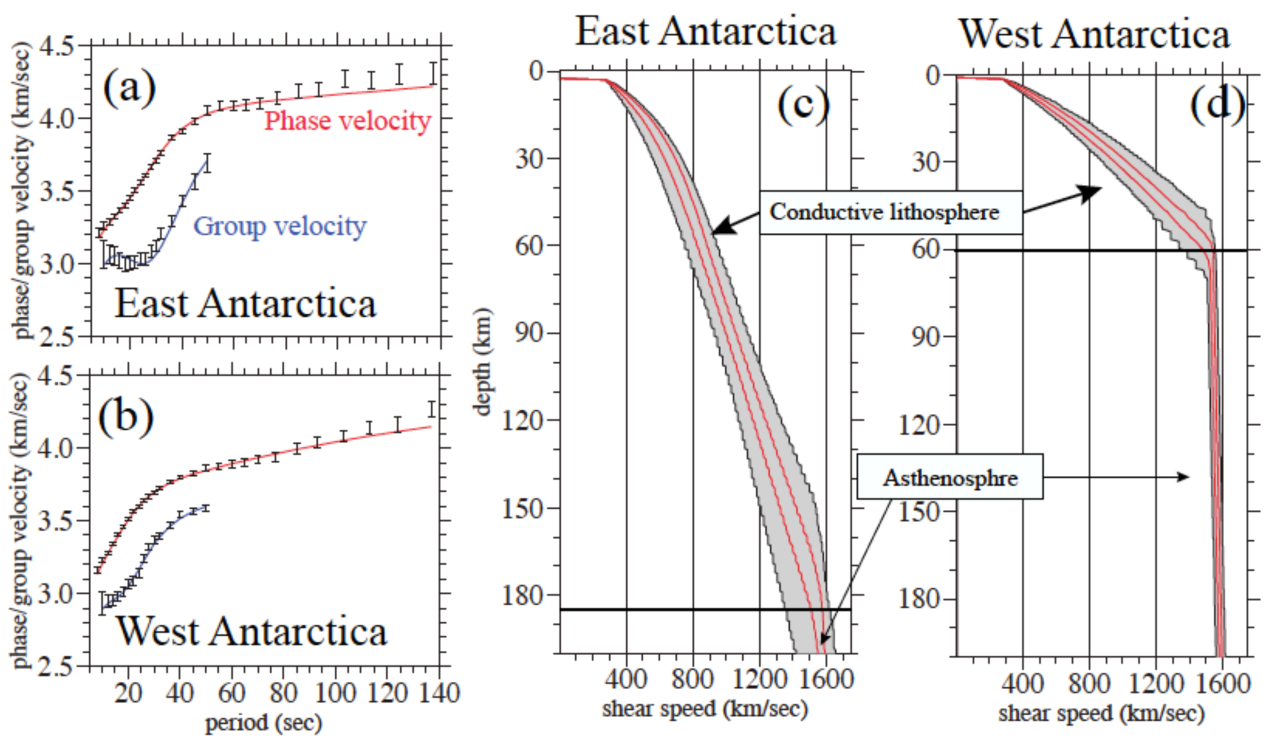
Thanks to:
Siyuan Sui, Lingli Li, Douglas Wiens, Andrew Lloyd, Andy Nyblade;
Team of POLENET(Terry Wilson et al); TAMNNET (Sam Hansen and students); RIS/DRIS (Rick Aster et al.)
GeoPATH program @ Stony Brook University, IRIS, and NSF

Sensitivity Analysis

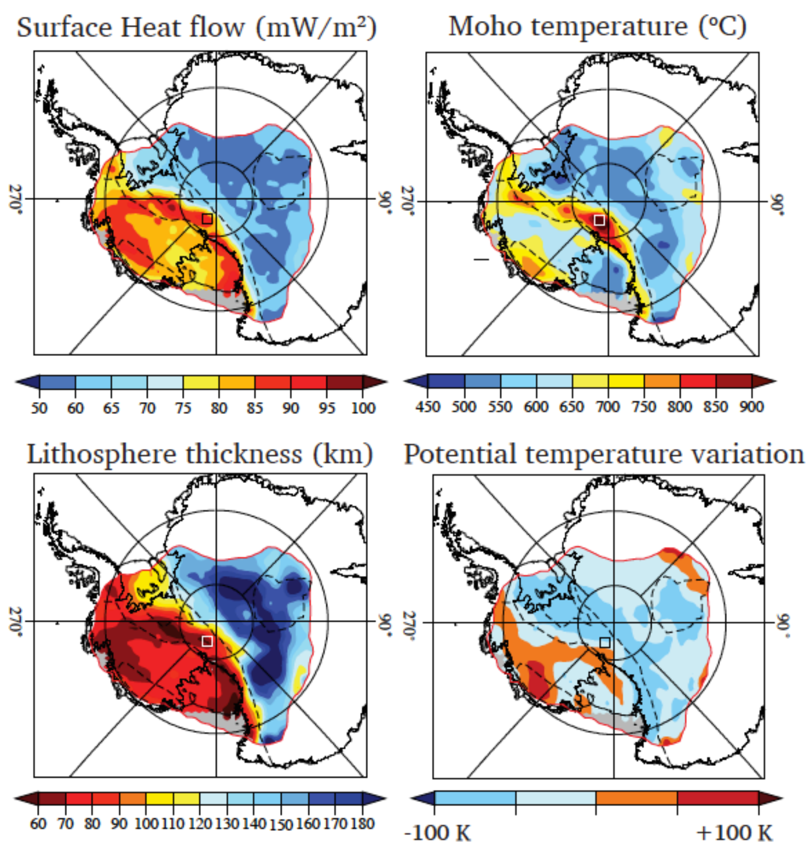


Perturbation of assumptions generally results in similar patterns with somewhat less viscosity variation
Use of VM5a reference viscosity model raises viscosities by about 1/3 order of magnitude
These models do not attain the very low viscosities inferred for Amundsen Sea and the Peninsula

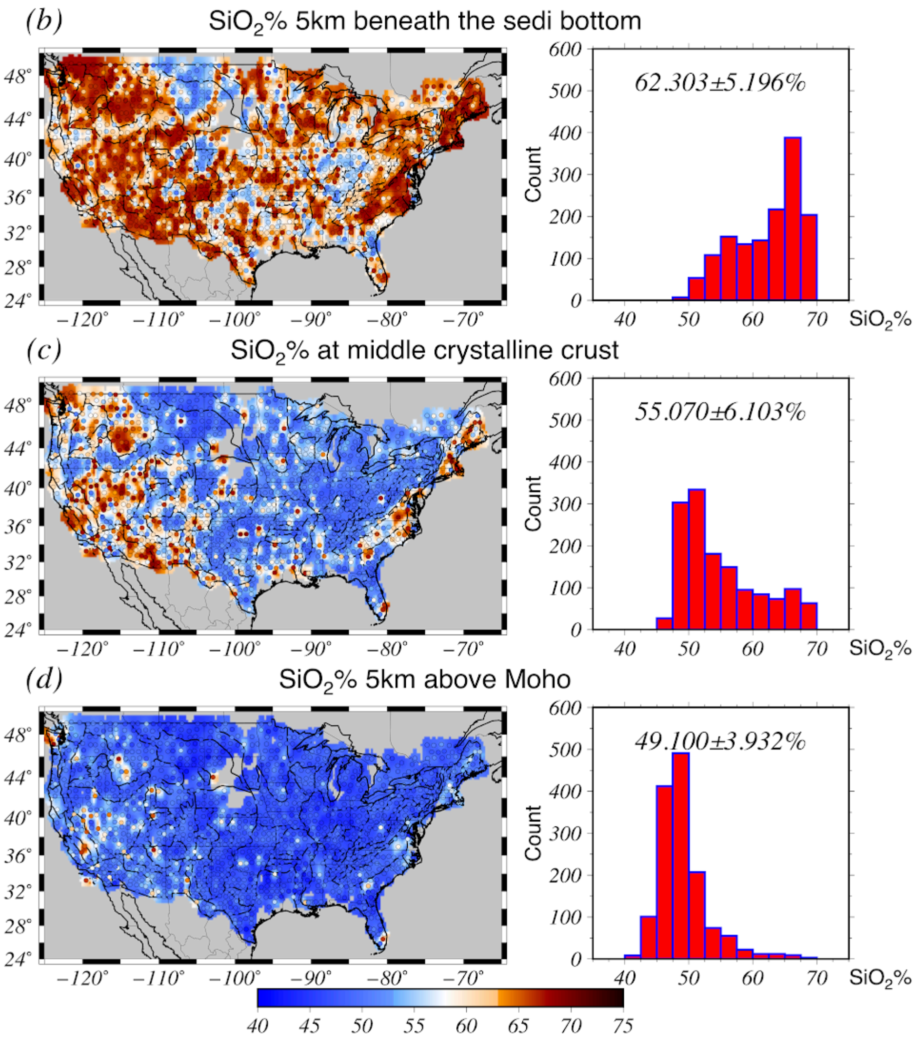
Thermodynamic modeling of the GHF of using seismic observables.



Why do high GHF areas have high GHF?



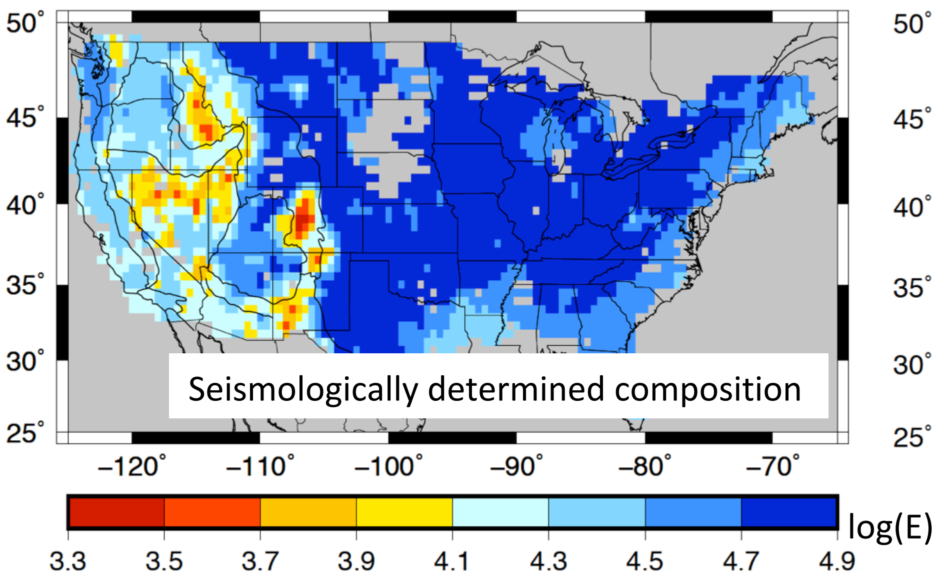
- High Temperature of the Moho in the S. TAM area where a lithospheric removal event has been reported.
- The main variation in GHF is caused by lithospheric thickness variation.
- The high MBL GHF is partially caused by the higher temperature in the asthenosphere, indicating a deeper source of the GHF anomaly.

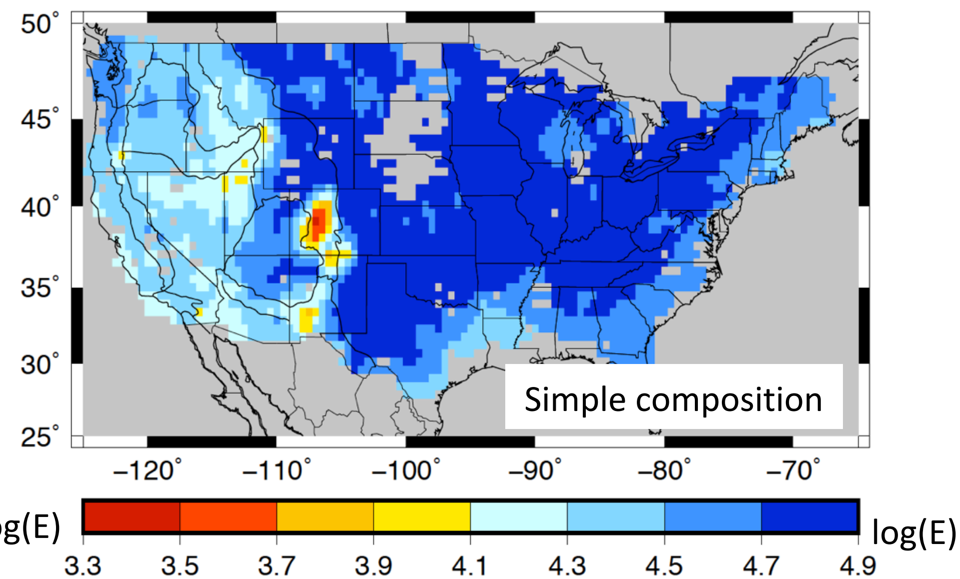


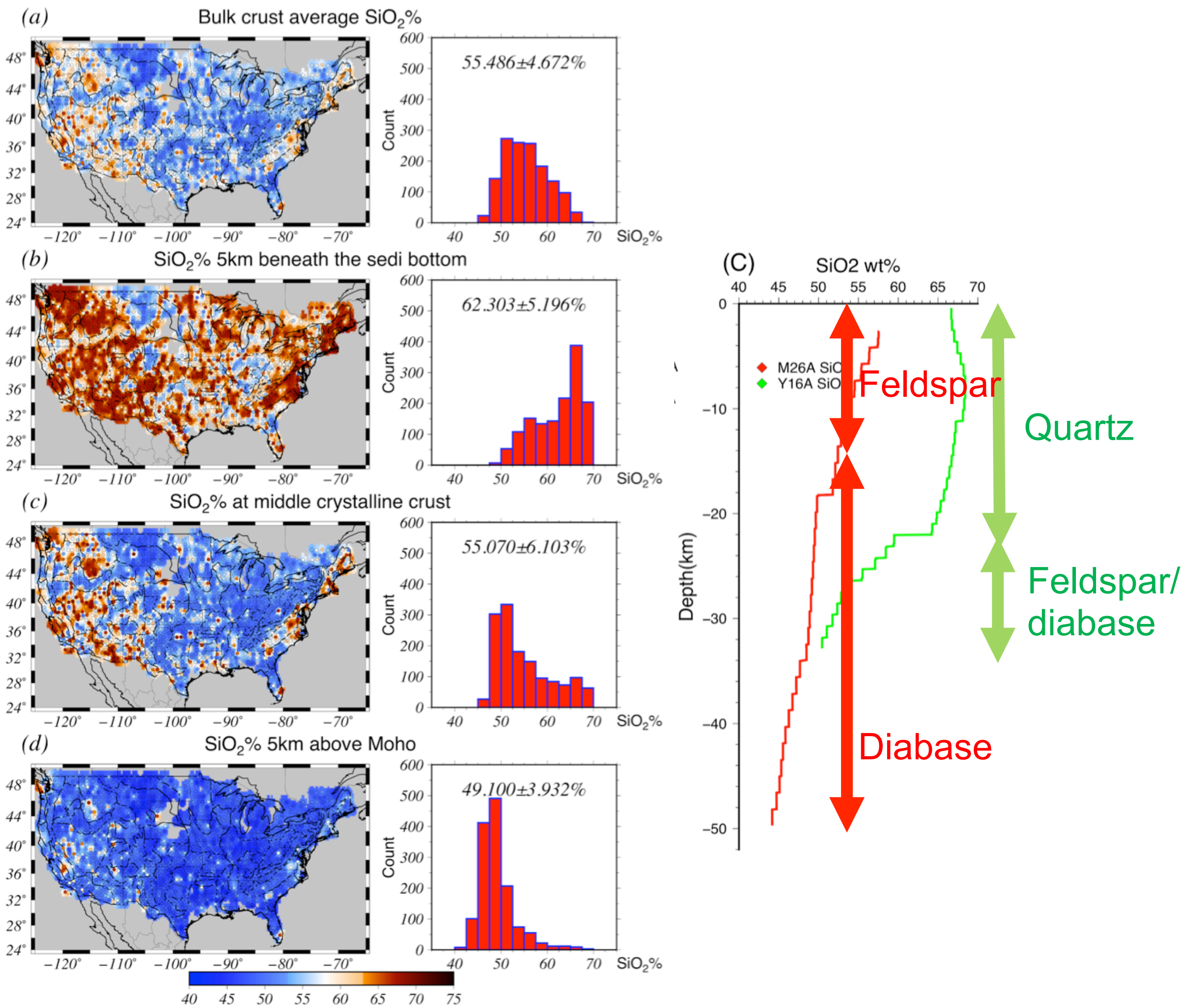
(b)
SiO2% 5km beneath the sedi bottom
62.303±5.196%
(c)
SiO2% at middle crystalline crust
55.070±6.103%
(d)
SiO2% 5km above Moho
49.100±3.932%
Count
SiO2%
48°
44°
40°
36°
32°
28°
24°
−120°
−110°
−100°
−90°
−80°
−70°
0
100
200
300
400
500
600
40
50
60
70
40
45
50
55
60
65
70
75

Deep crustal composition (and can be inferred by seismology) contributes significantly for crustal strength

Chemical composition of the crust contributes significantly to the weak zone surrounding the Snake River Plain.

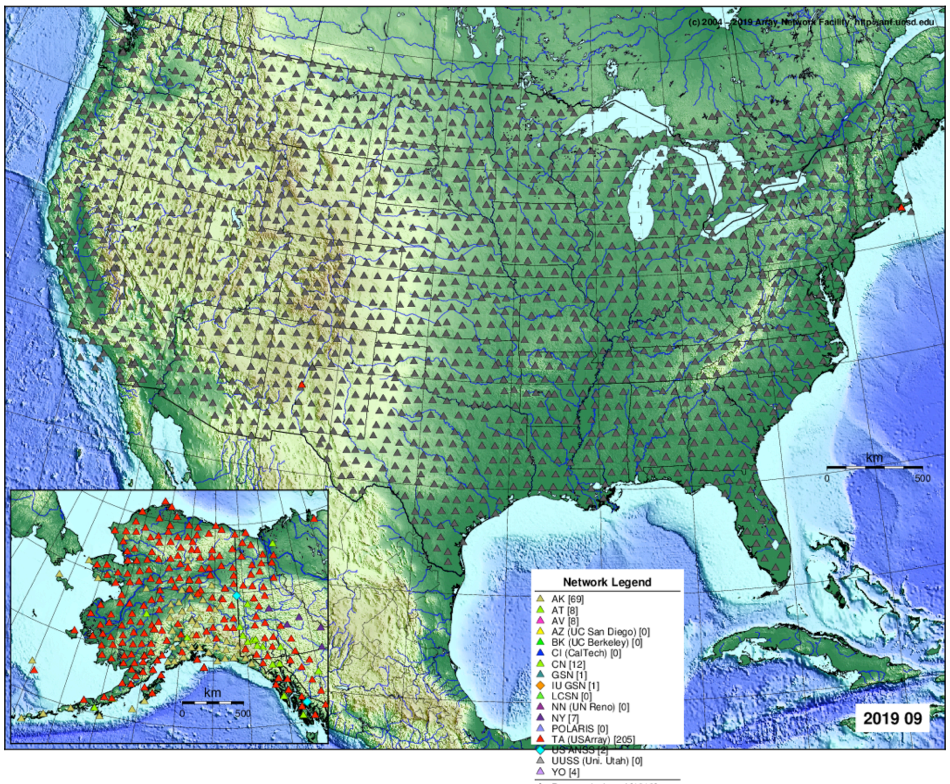




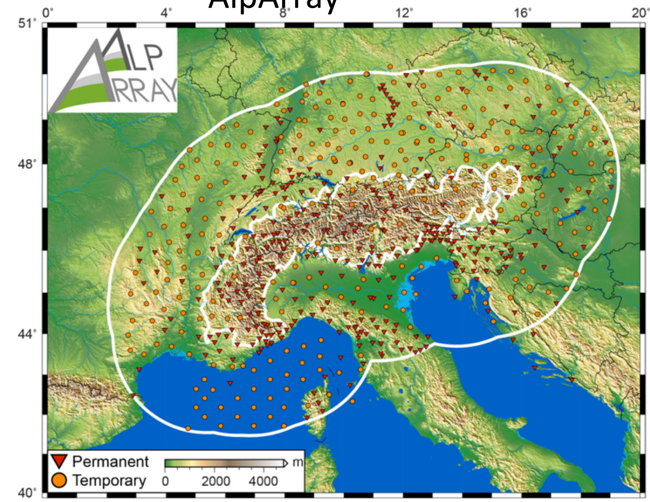

(a)
Bulk crust average SiO2%
55.486±4.672%
(b)
SiO2% 5km beneath the sedi bottom
62.303±5.196%
(c)
SiO2% at middle crystalline crust
55.070±6.103%
(d)
SiO2% 5km above Moho
49.100±3.932%
Count
SiO2%
(C)
SiO2 wt%
Depth(km)
M26A SiO
Y16A SiO
Feldspar
Diabase
Quartz
Feldspar/
diabase

Large scale seismic arrays across major continents

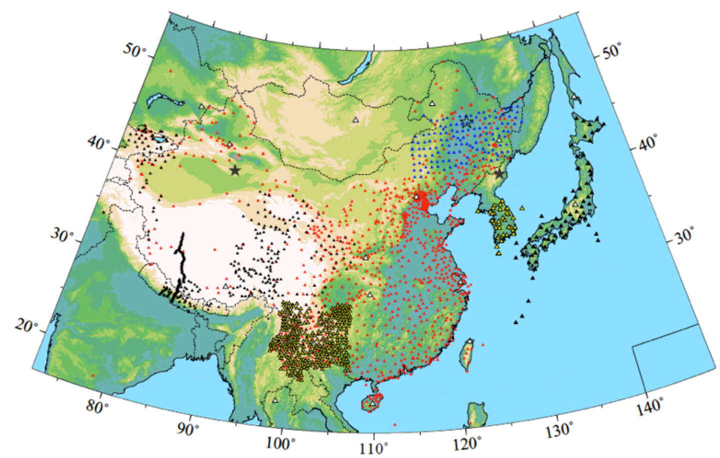
Earthscope/USArray (2004-present)



AlpArray



CEArray/China Array/F-net,etc (2015)



GP-IMPACT: Increasing Geosciences Enrollment through Research Experiences, Mentoring, and Curriculum Interactions With Community Colleges and High Schools

PI: Dr. Brian A. Colle

Co-PIs: Edmund Chang, Hyemi Kim, Gilbert Hanson, and Kamazima Lwiza

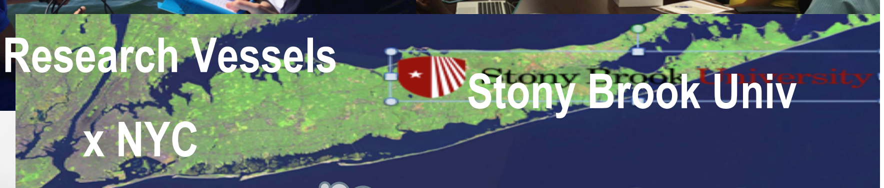
Stony Brook University / SUNY

Partners:

Suffolk Community College

Nassau Community College

Several Long Island High Schools



Motivation*: Numerous obstacles limit students involvement in Geosciences, especially minorities and high-needs students.*

Hands-on
Multi-disciplinary
Teamwork

GP-IMPACT: Increasing Geosciences Enrollment through Research Experiences, Mentoring, and Curriculum Interactio[n] ... and High Schools

How Addressed?

- *4-6 week summer research program and faculty mentoring for 8-10 community college (CC) and high school students (for past 2 summers)*
- *5-6 now majoring in geosciences with $2K Scholarship so far to 3-4 students continuing Geoscience studies at Stony Brook (SBU)*
- *CC and high school visits/mentors/clubs*
- *Curriculum adjustments to facilitate transition from CC to 4-year SBU B.S. degree.*

Hands-on
Multi-disciplinary
Teamwork

Broader Impacts?

- *Recruiting and engagement with a diverse body of*