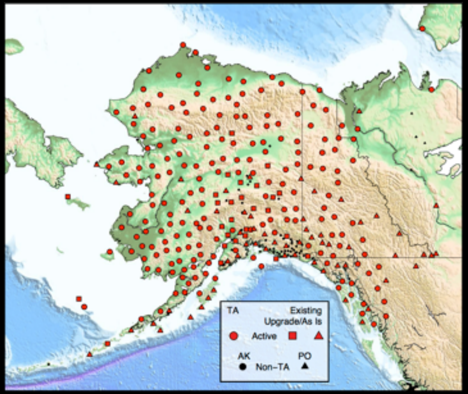
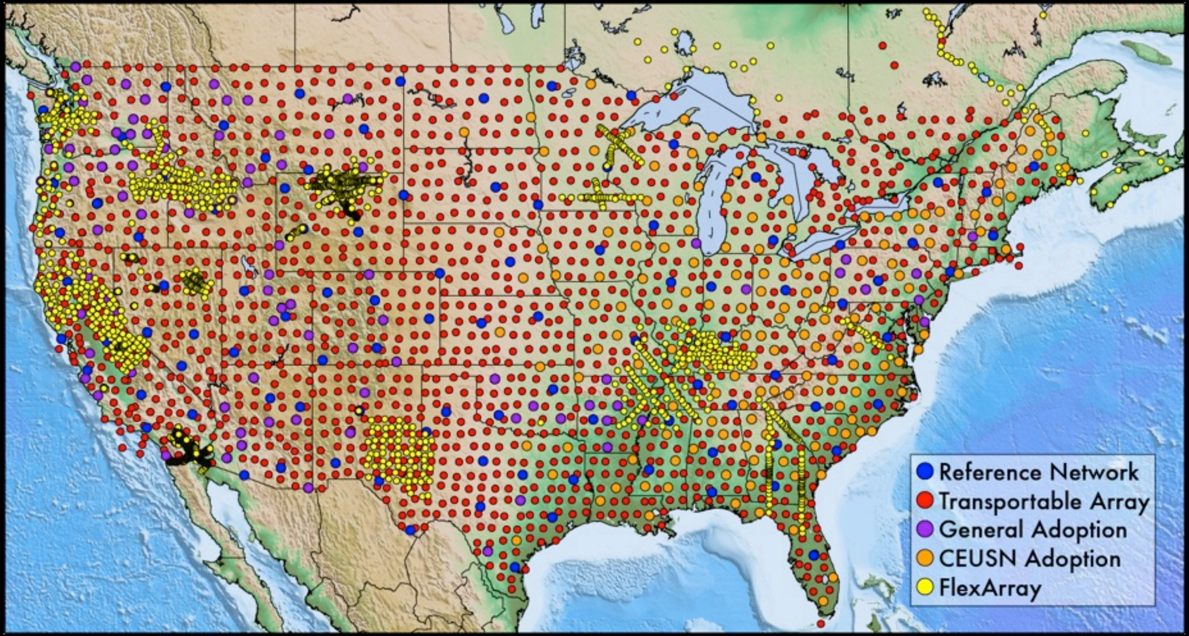
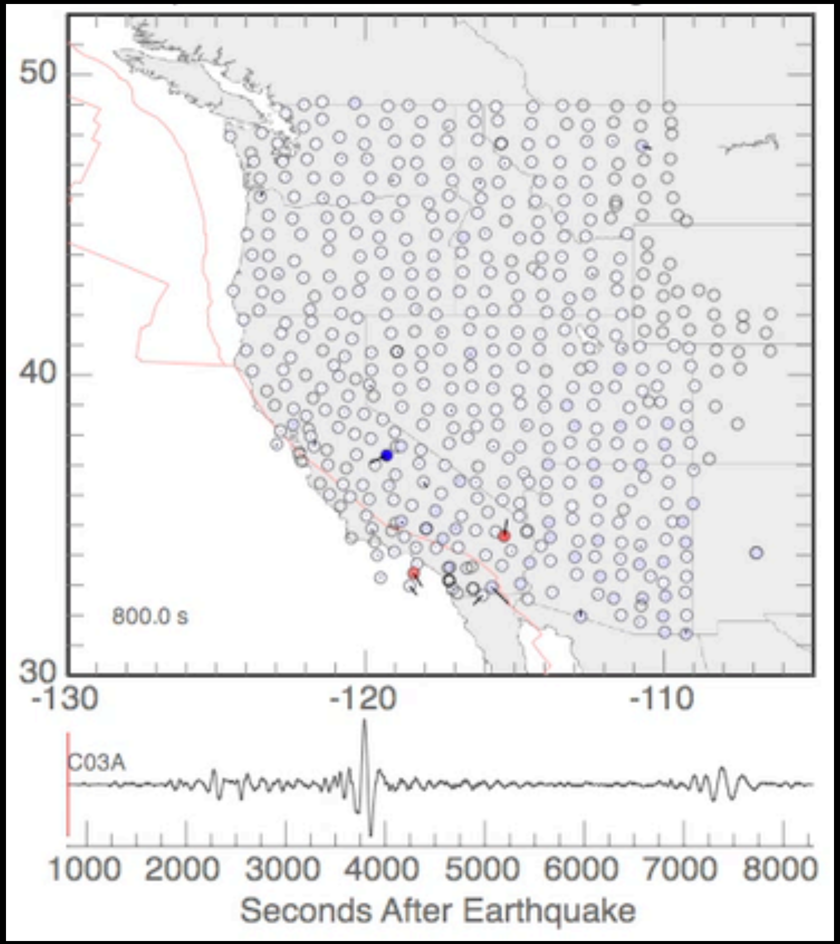
EarthScope's USArray:
A new window into solid Earth processes beneath North America







from Chuck Ammon

Brandon Schmandt

EarthScope's USArray:
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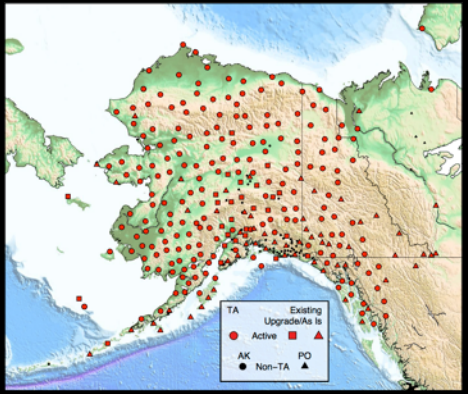
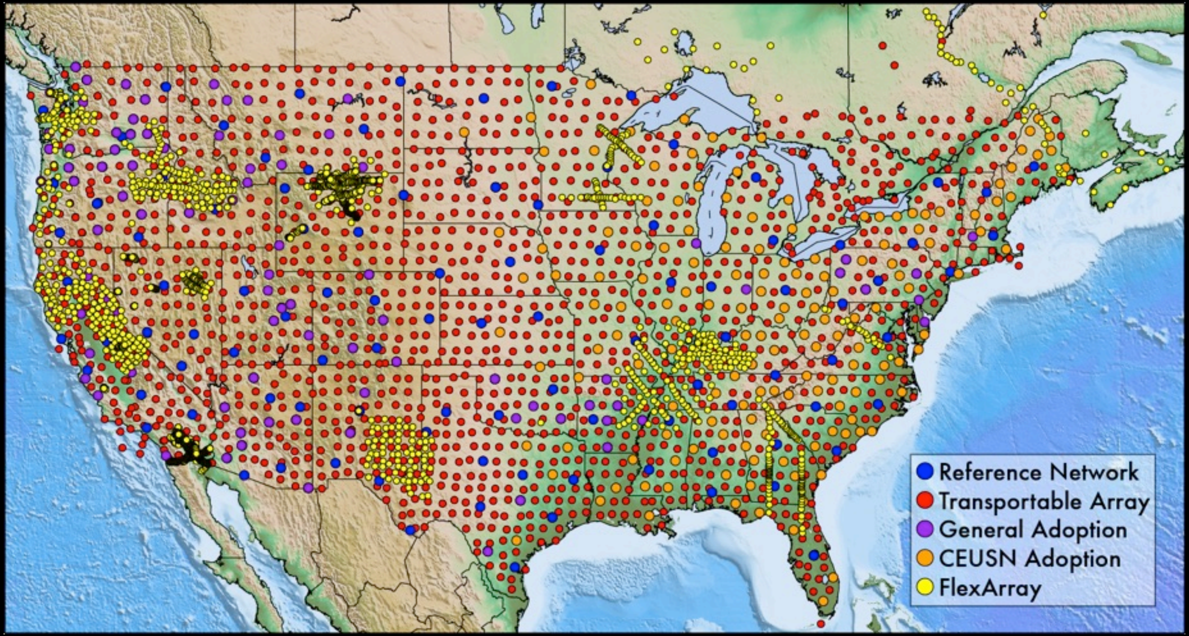
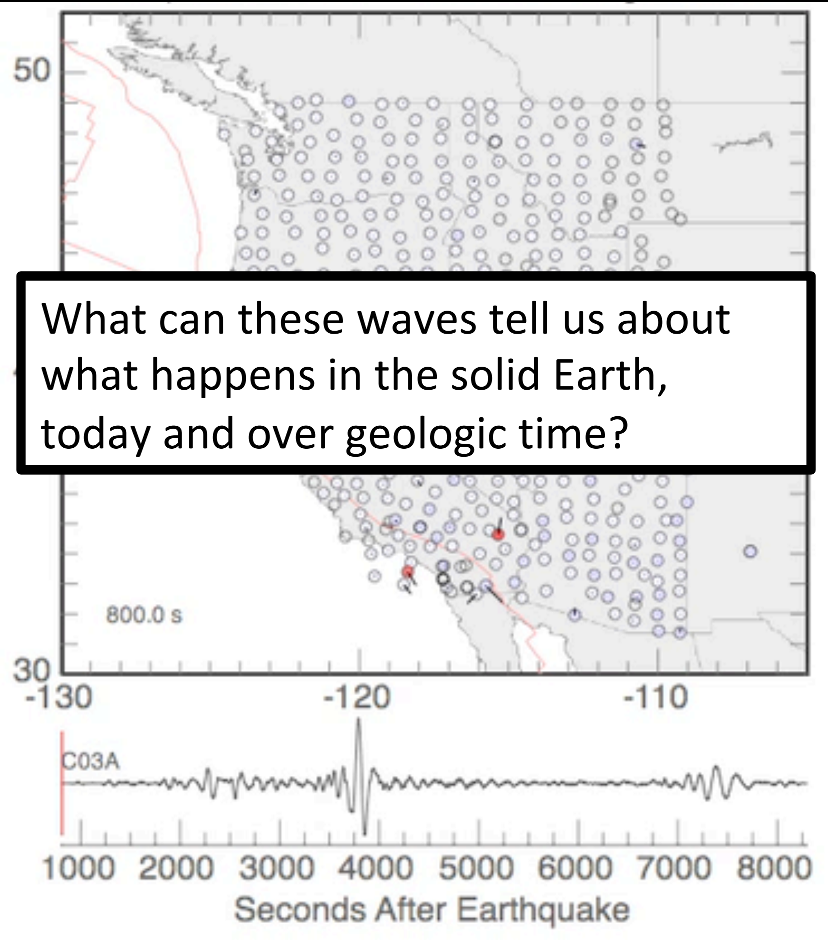






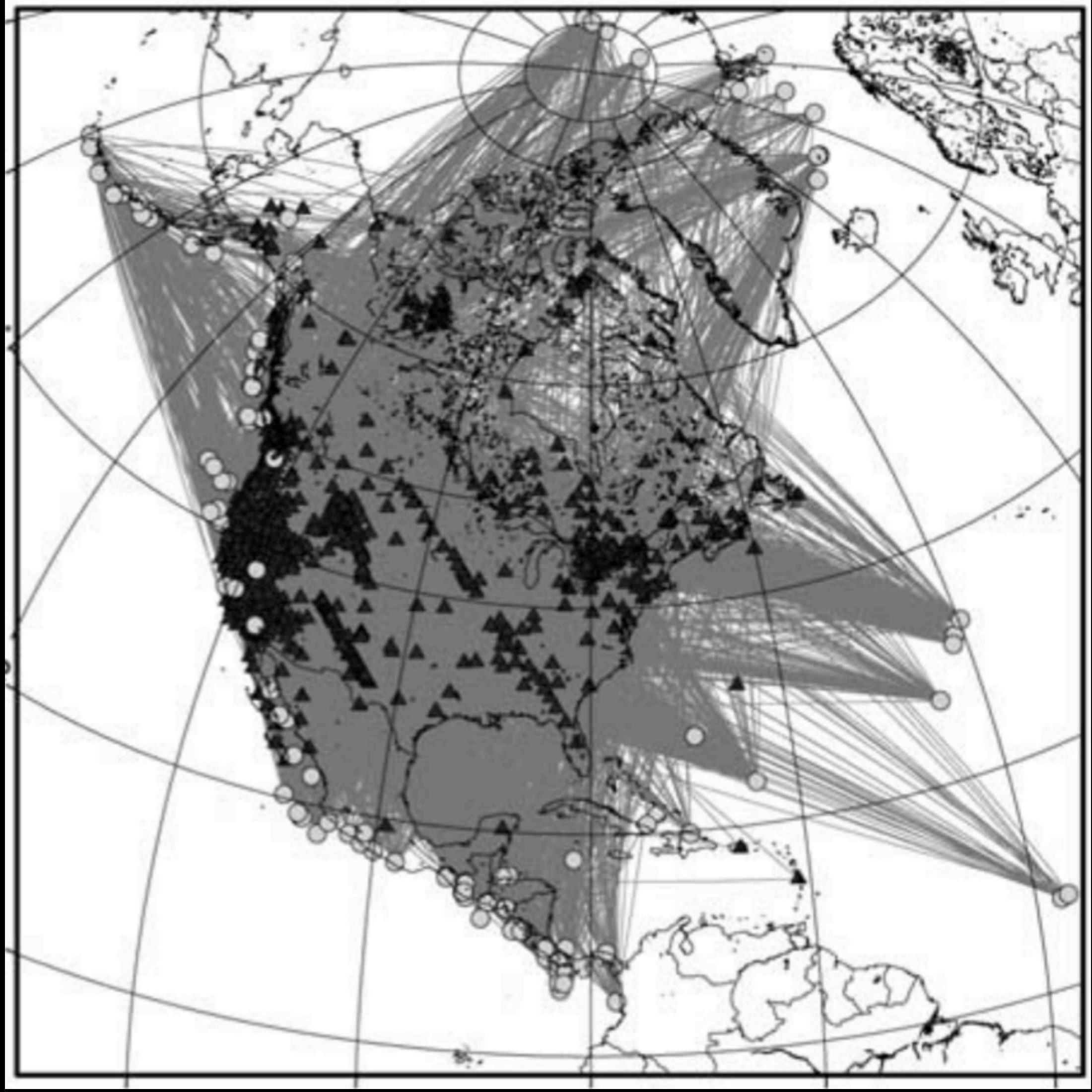
What can these waves tell us about what happens in the solid Earth, today and over geologic time?

from Chuck Ammon

Brandon Schmandt

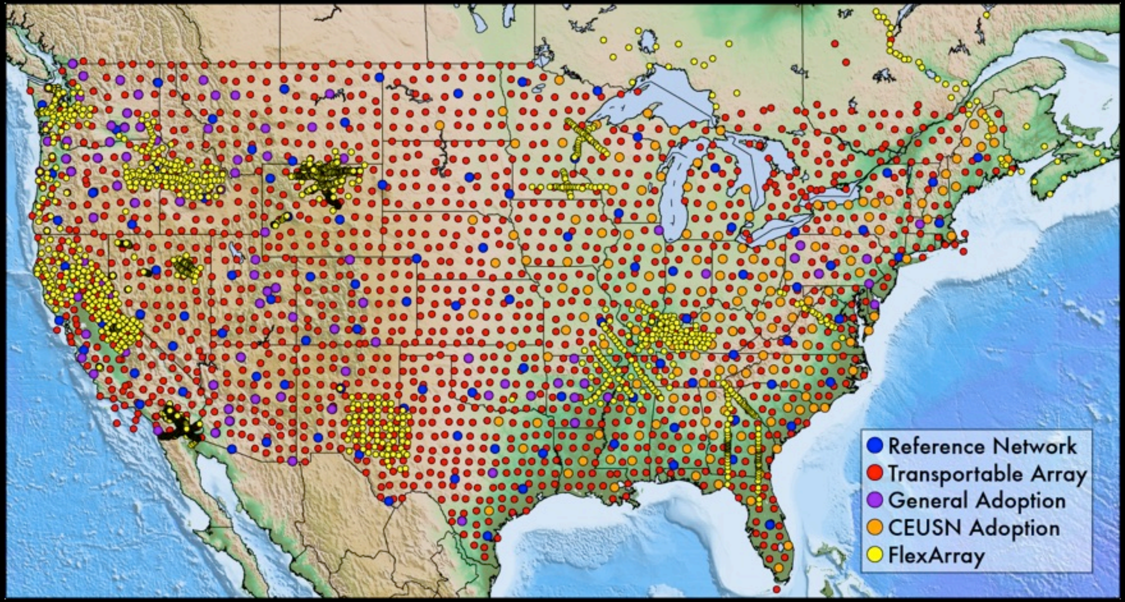
A scale change in observational seismology

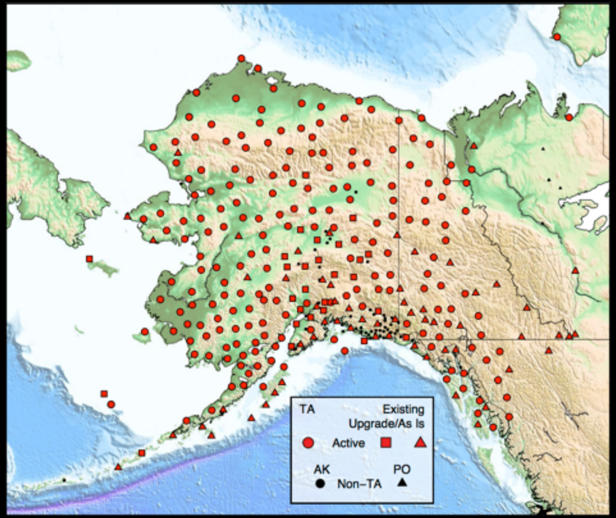
Cumulative broadband seismic data as EarthScope began



Bedle and van der Lee, 2009

Broadband seismic data from EarthScope





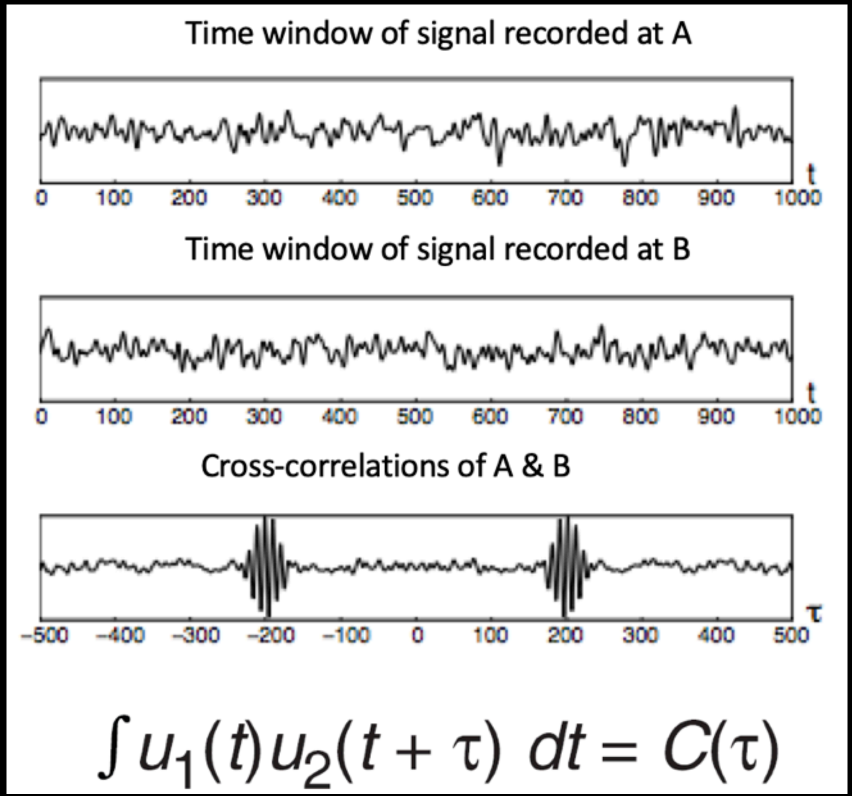
How EarthScope advanced seismology and its insights into the solid Earth system

The impact of world-class and immediately open access data

- Pace of progress in methods and observational discoveries
- Seismic noise interferometry as an example

(oceans are the dominant noise source on Earth)

Seismic station



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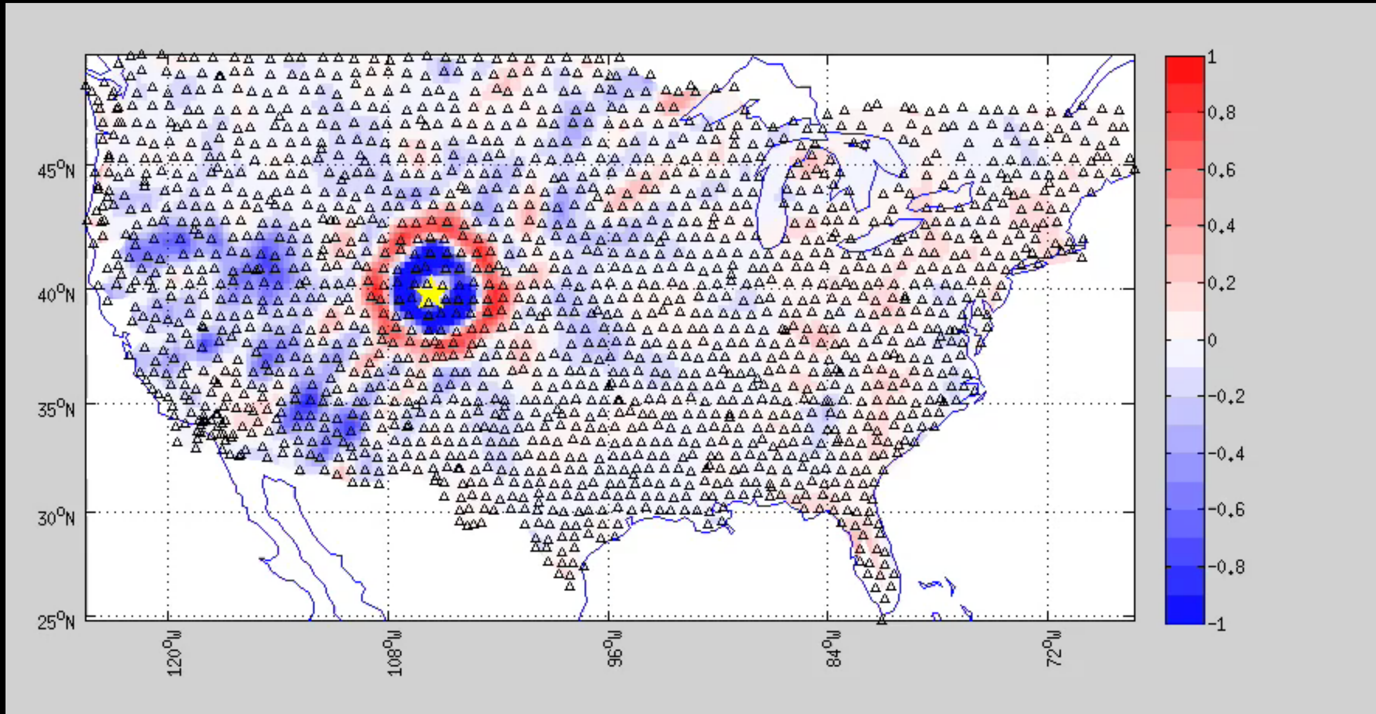
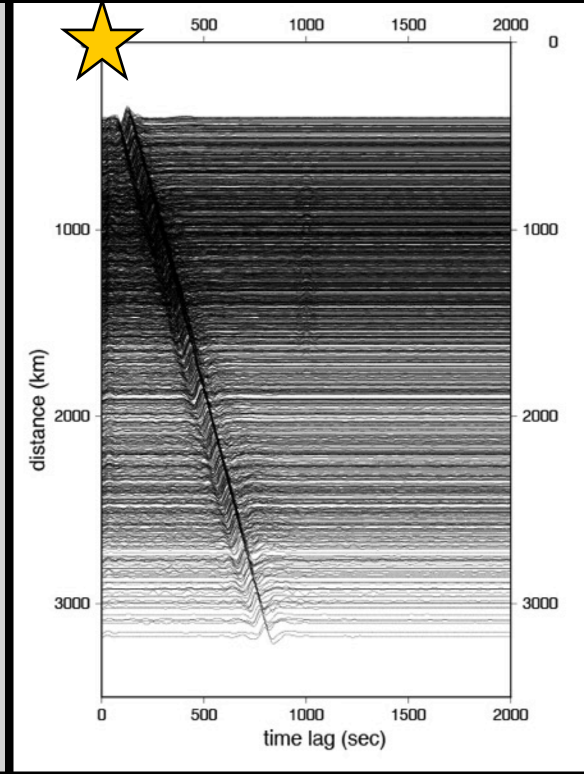


from Kai Wang



How EarthScope advanced seismology and its insights into the solid Earth system

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- Pace of progress in methods and observational discoveries
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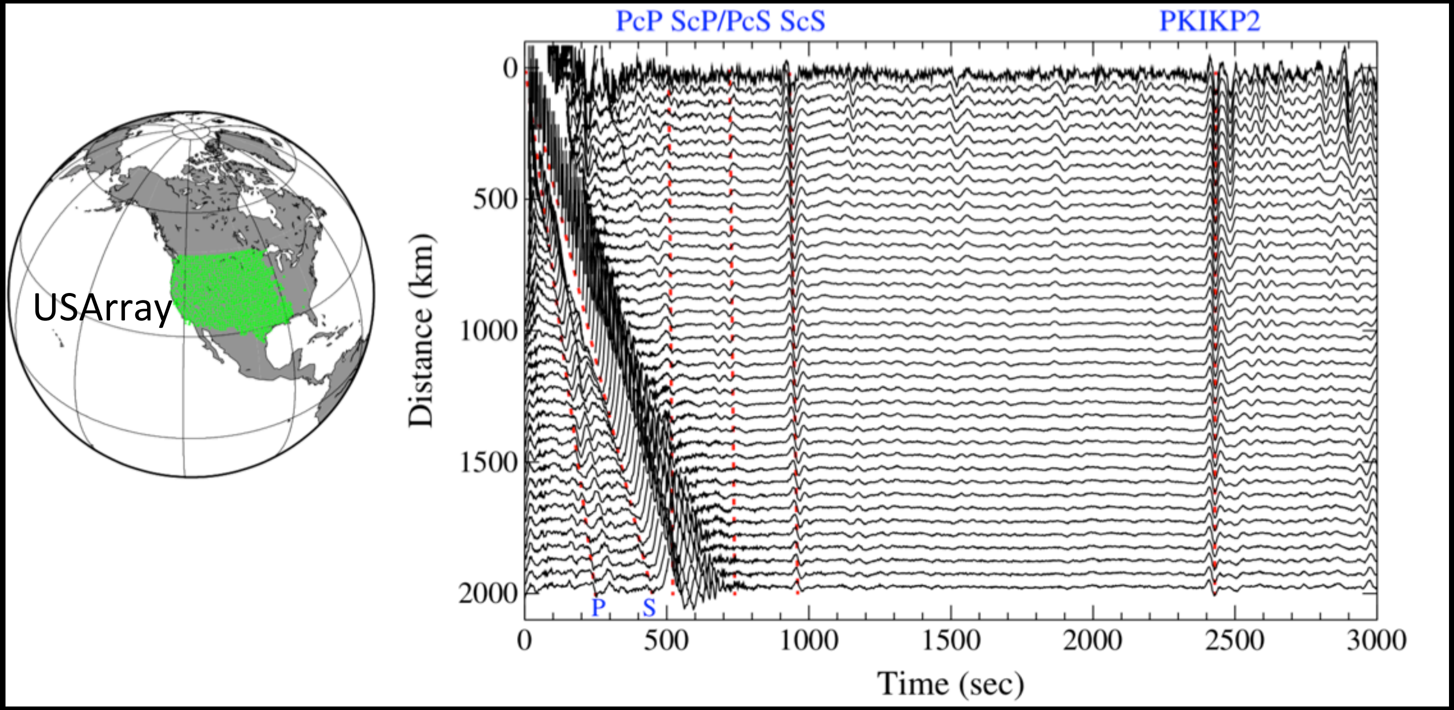
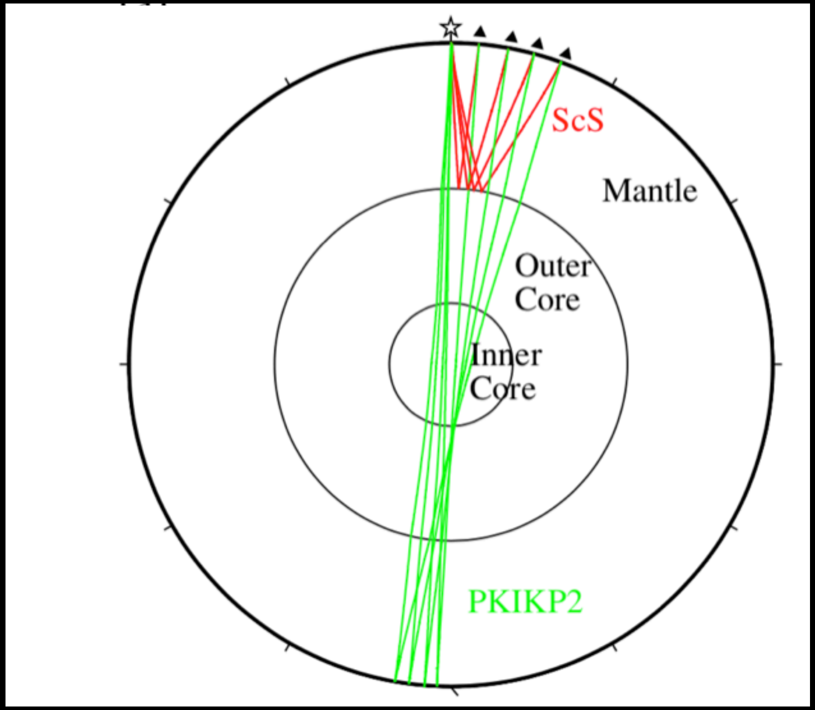


Body-wave sampling from crust-to-core extracted from noise

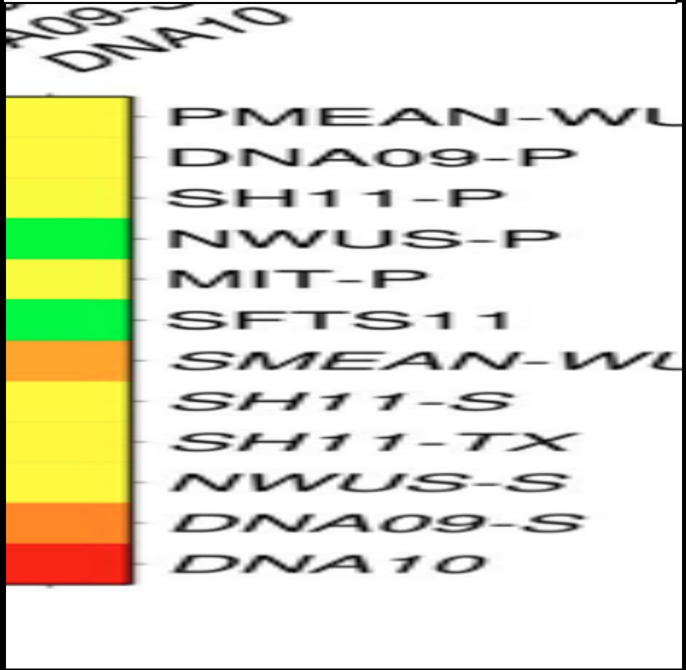


Lin et al., 2013

How EarthScope advanced seismology and its insights into the solid Earth system

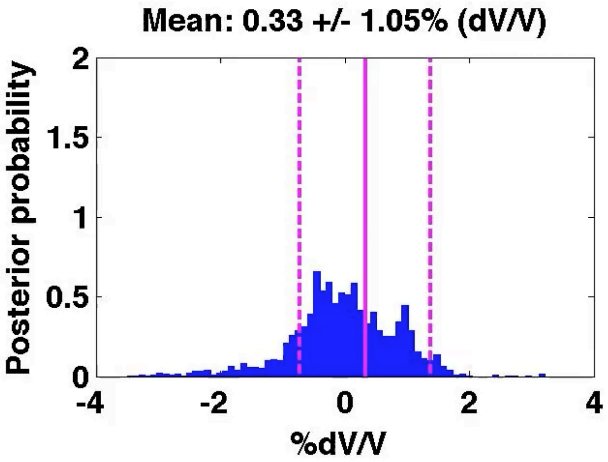
The impact of world-class and immediately open access data

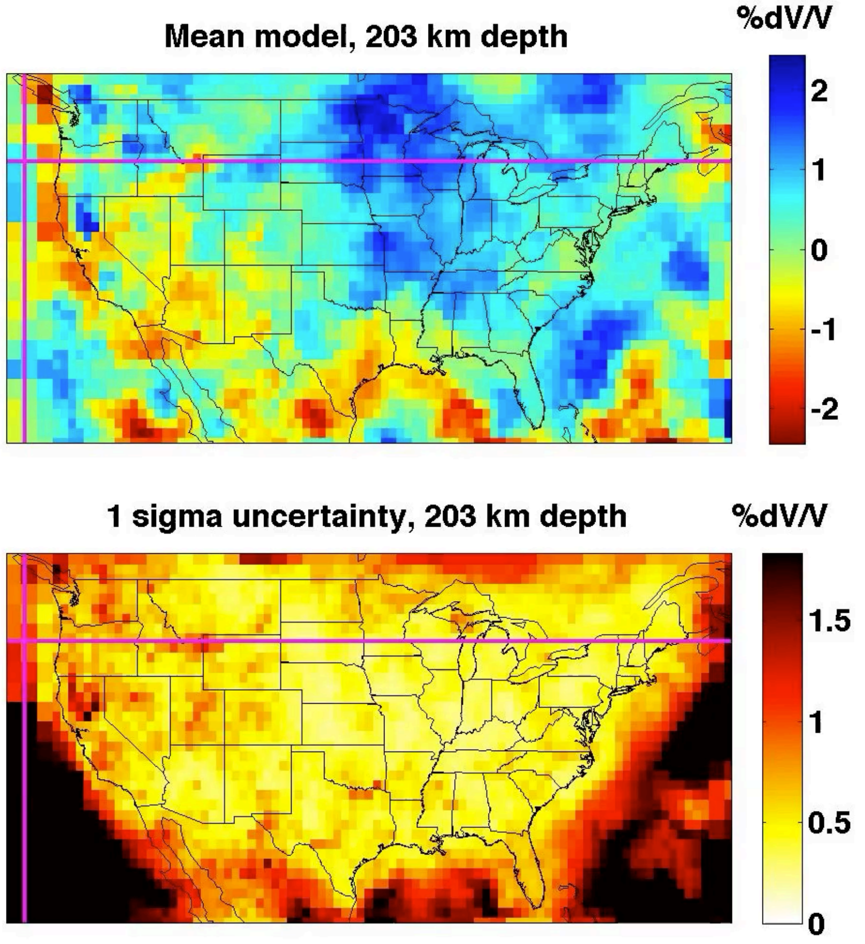
Quantitative model comparison



Becker, 2012

Confronting uncertainty in large inverse problems

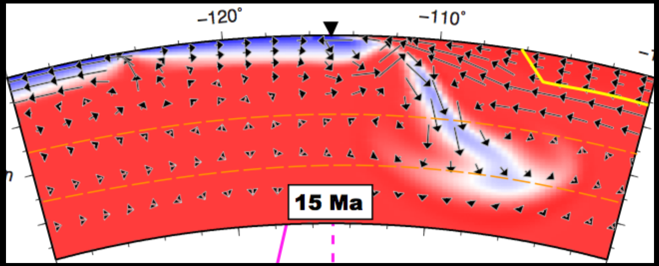




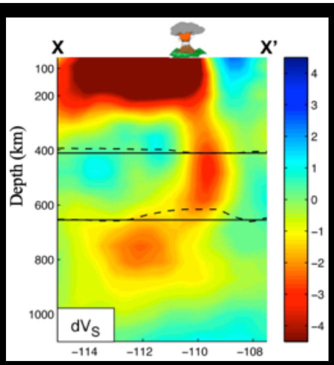
From Scott Burdick and Ved Lekic

Examples of solid Earth systems addressed by EarthScope science

1) Fates of subducted slabs and their effects on geological activity at the surface.

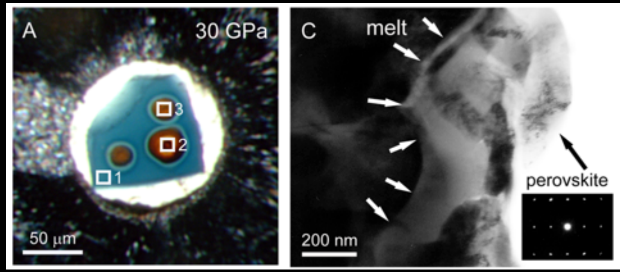


Liu and Stegman, 2011



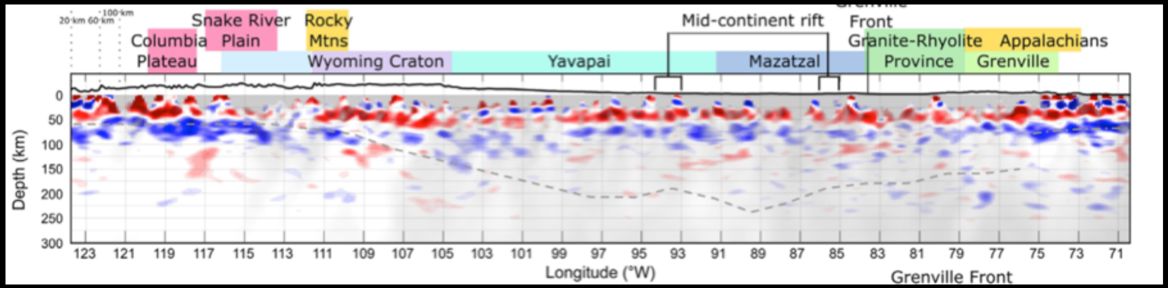
Schmandt et al., 2012

2) Storage and cycling of water in the deep Earth



from Steve Jacobsen

3) Where does the continent end? – Mapping the base of tectonic plates



Hopper and Fischer, 2018

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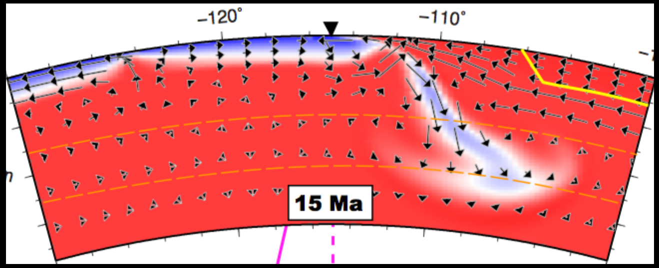
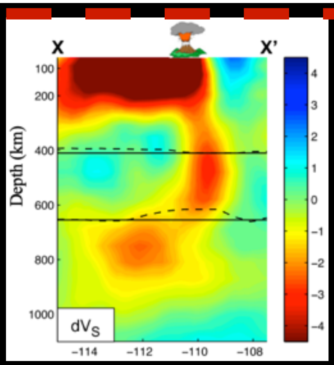


Liu and Stegman, 2011



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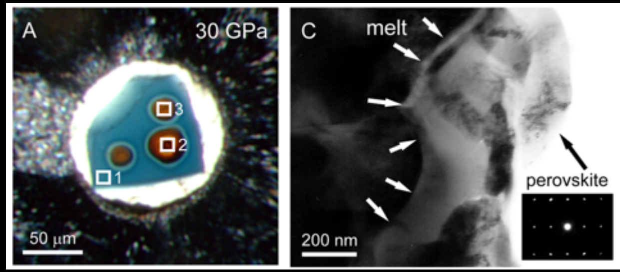

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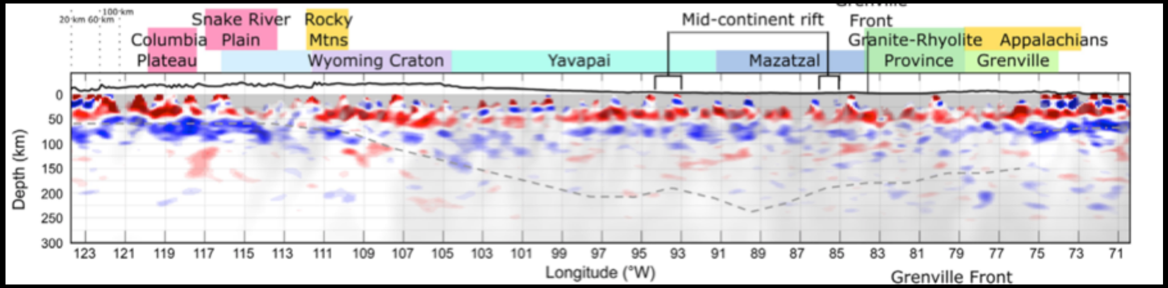


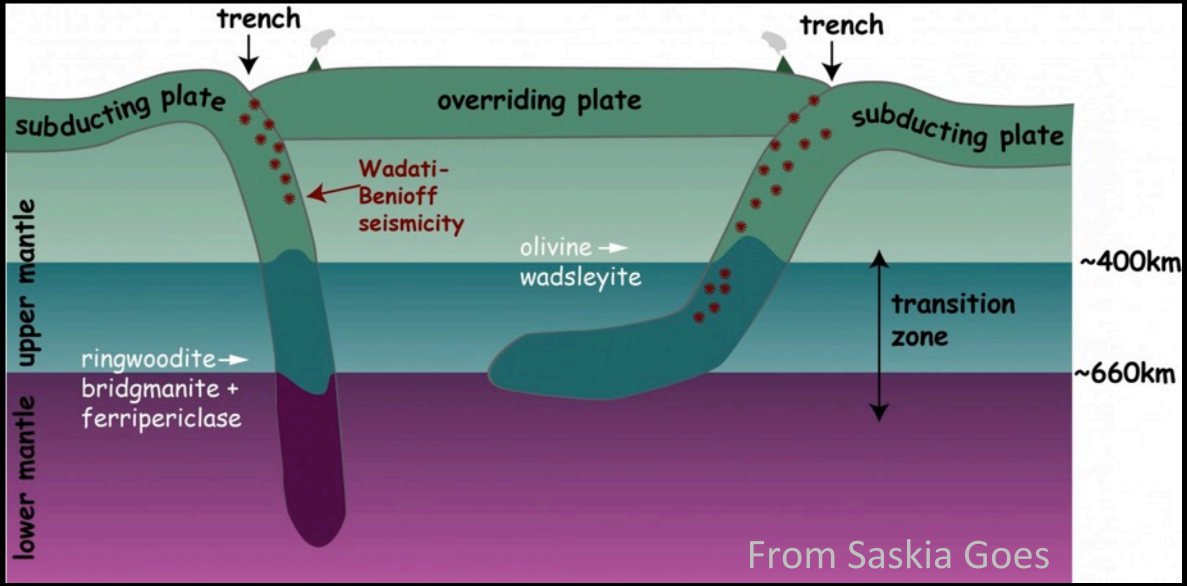
Hopper and Fischer, 2018

1) Fates of subducted slabs and their effects on geological activity at the surface

Steep to shallow dip angles

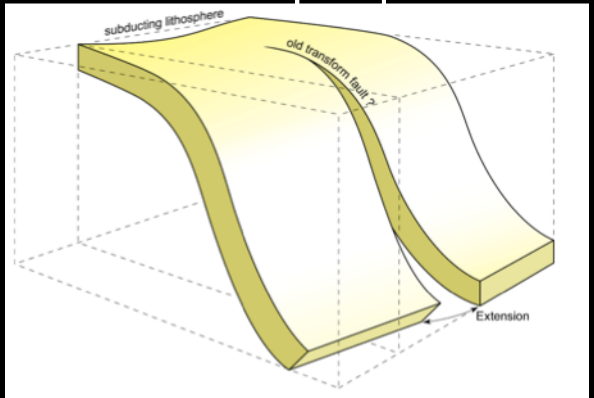
Continuous sheets ←→ Fragmentation

Does slab rupture matter at the surface?

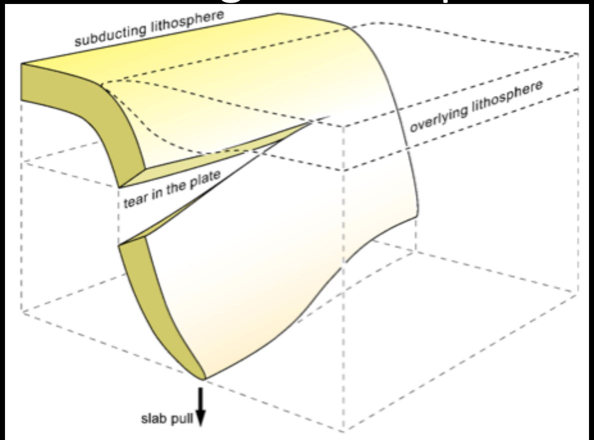


From Saskia Goes

Down-dip rupture



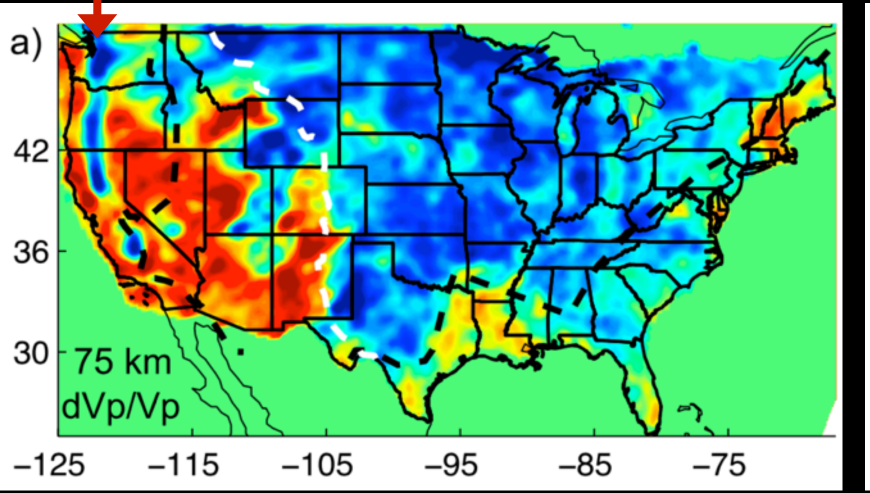
Along-strike rupture



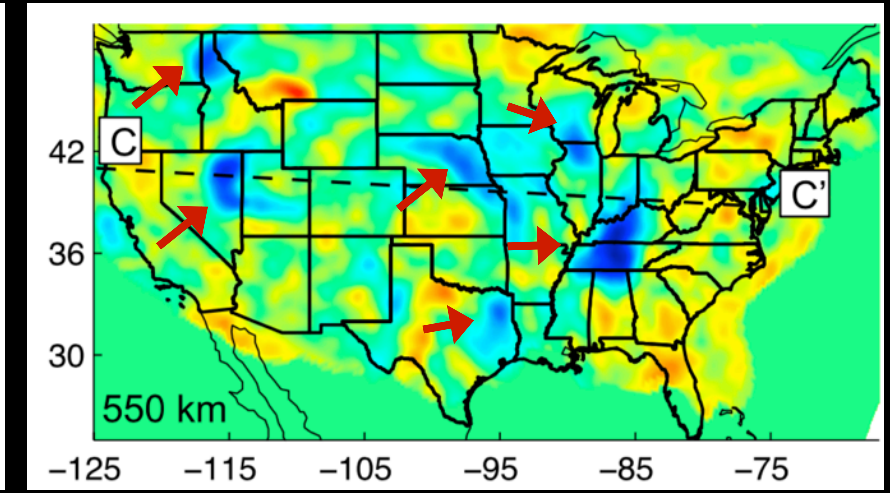
From Jean-Pierre Burg

1) Fates of subducted slabs and their effects on geological activity at the surface

Shallow, ~coherent young slab



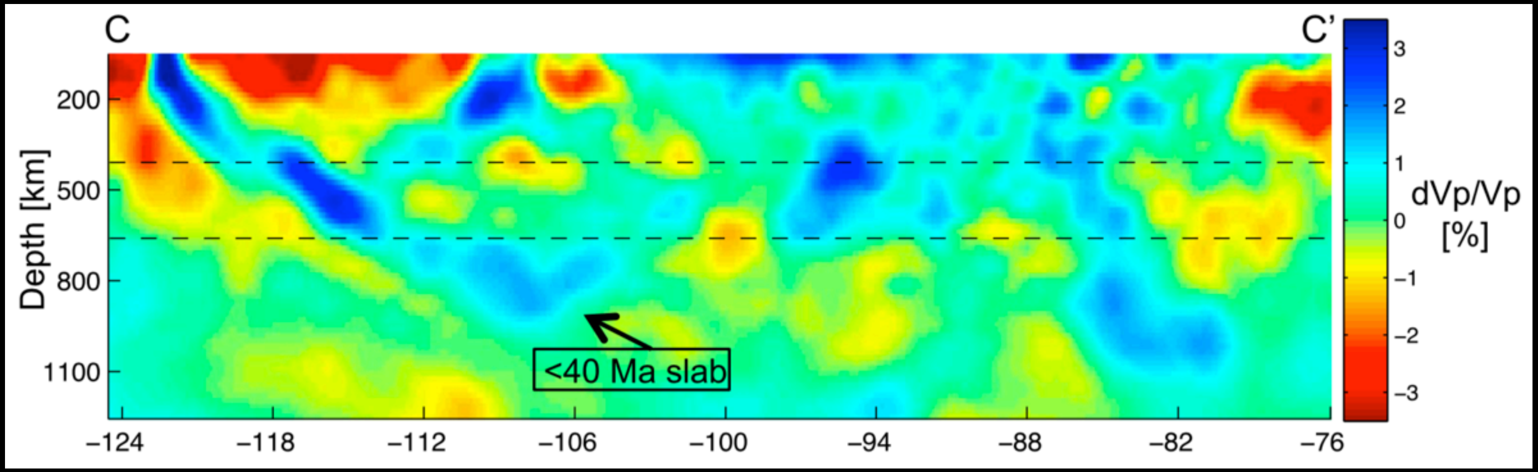
Deeper, older slab fragments (>15 Ma)



The challenge is to provide a history for these slab fragments.

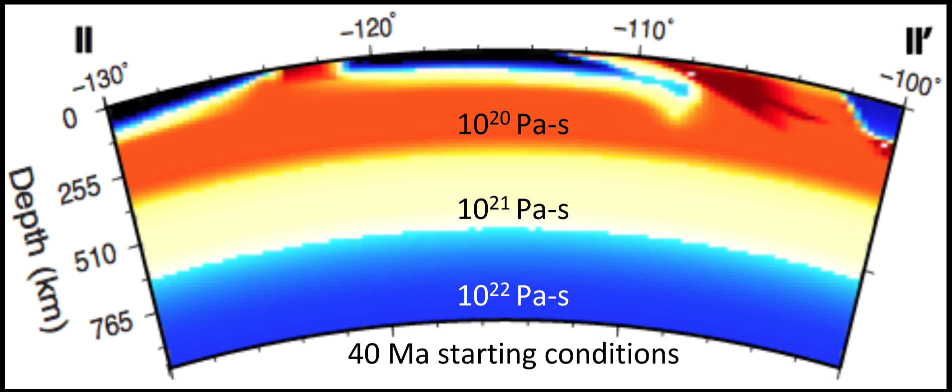
What caused the breaks?

What were the surface consequences, if any?



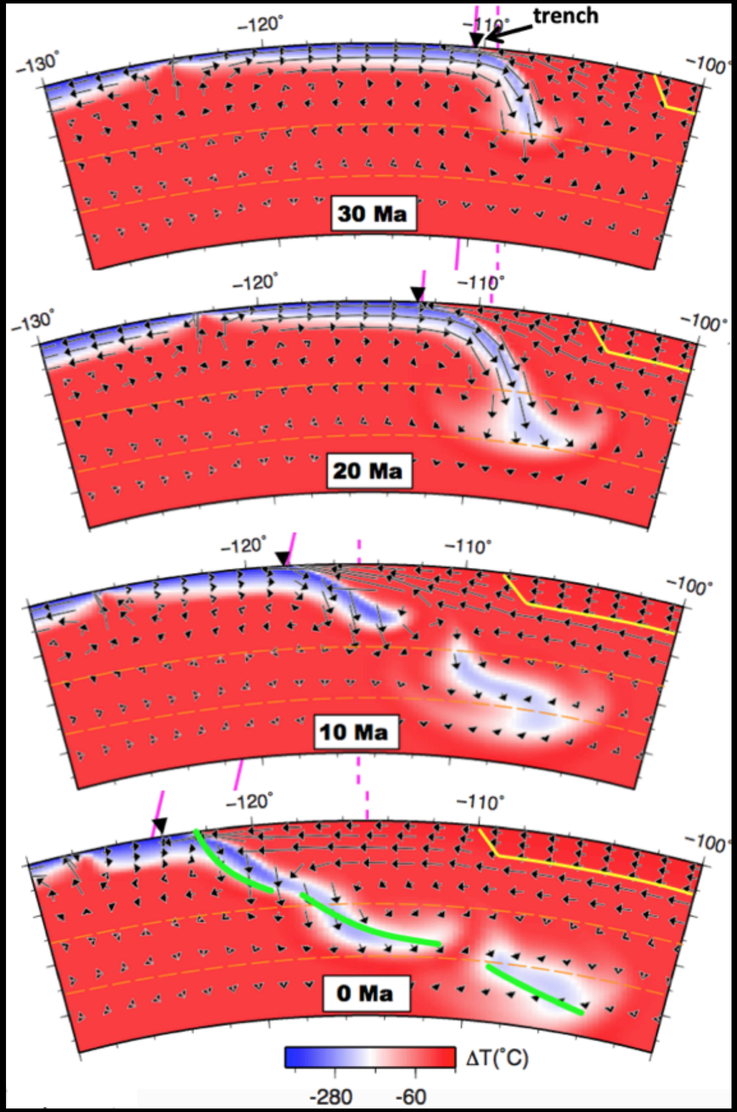
Schmandt and Lin, 2014

1) Fates of subducted slabs and their effects on geological activity at the surface

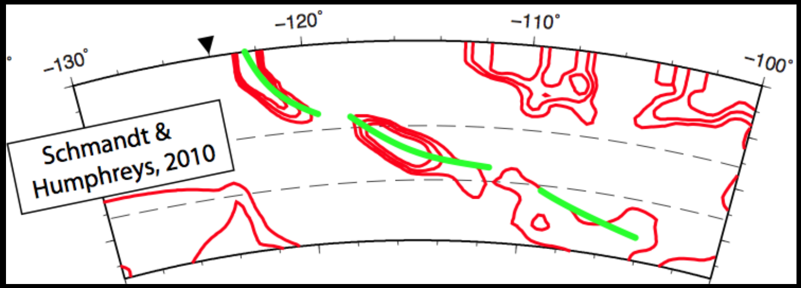


Liu and Stegman, 2011

Are convection models constrained by plate tectonic motions consistent with complex structures detected by EarthScope seismology?

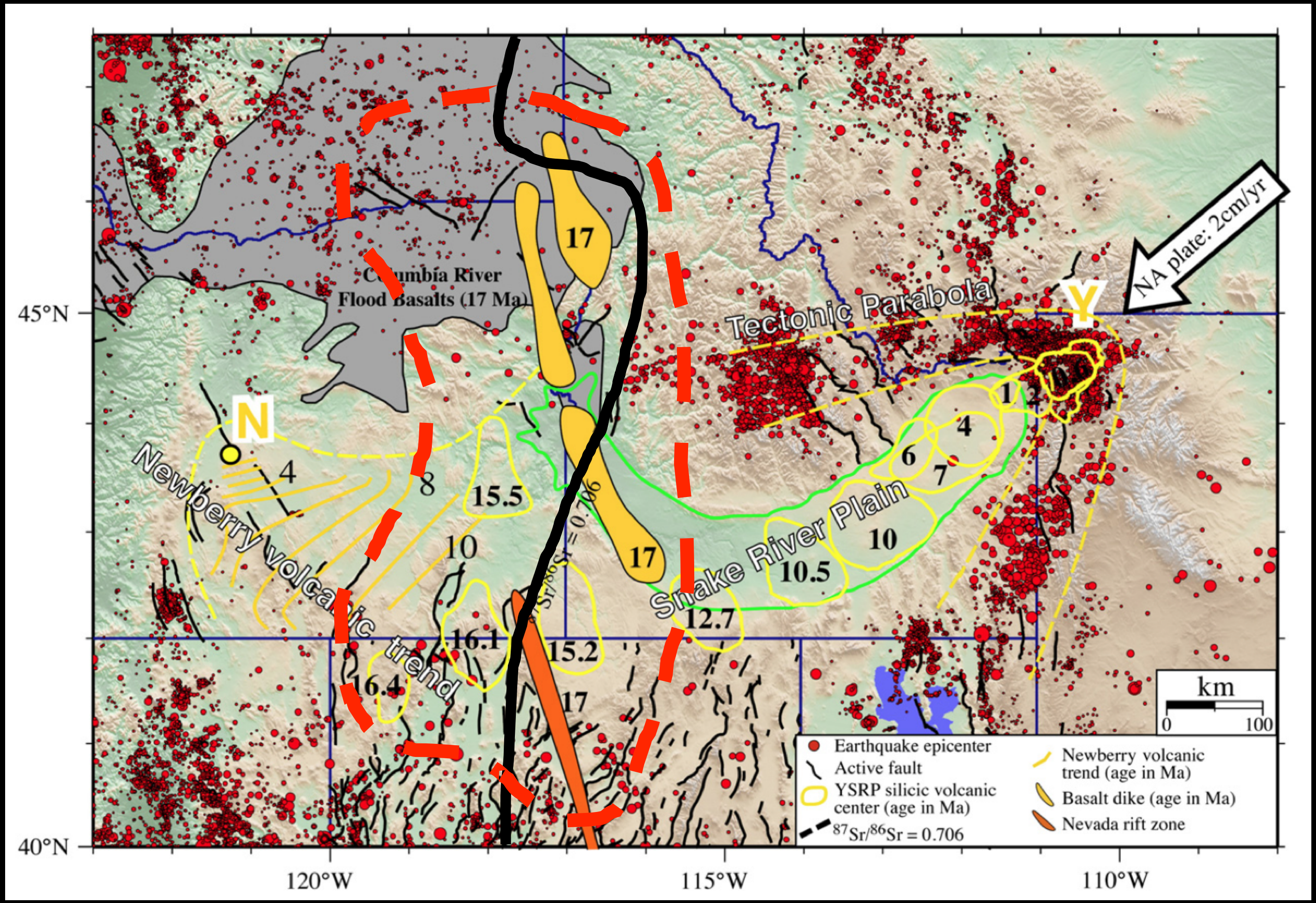


Miocene slab rupture, ~15 Ma



1) Fates of subducted slabs and their effects on geological activity at the surface

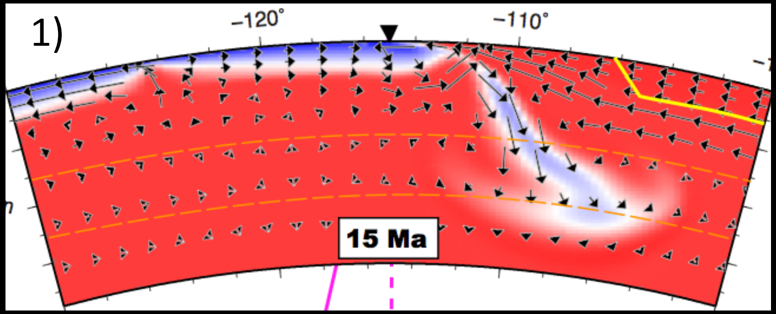
17-15 Ma major silicic and basaltic eruptions



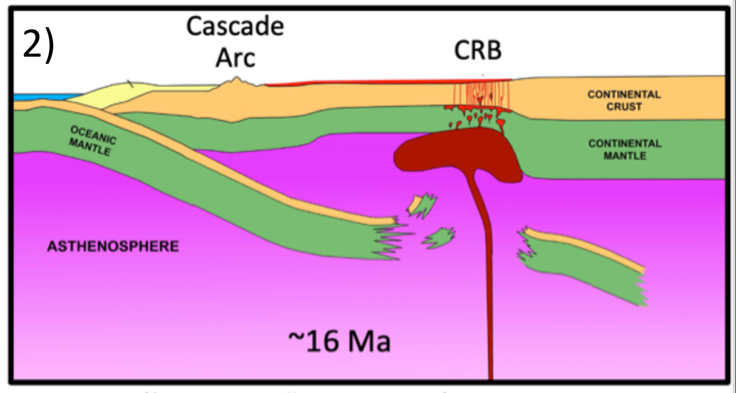
(Smith et al., 2009)

Slab rupture driven by:

1) Roll-back of weak slab (Liu & Stegman, 2011)
2) Buoyant thermal plume (Geist and Richards, 1993)
3) both?

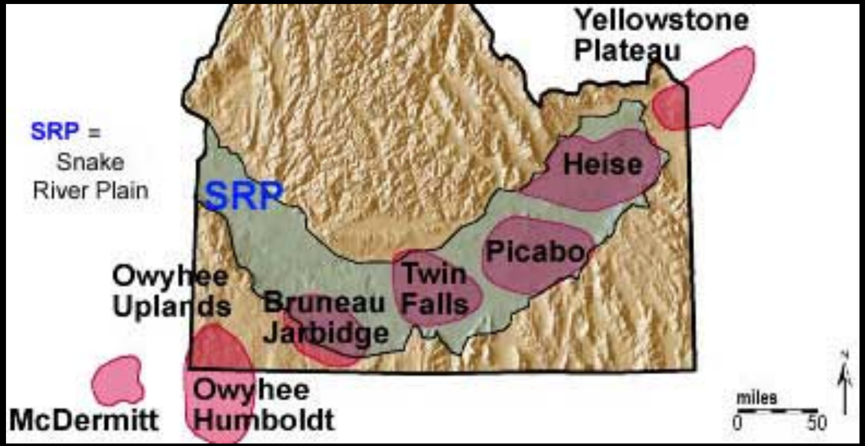


Liu and Stegman, 2011



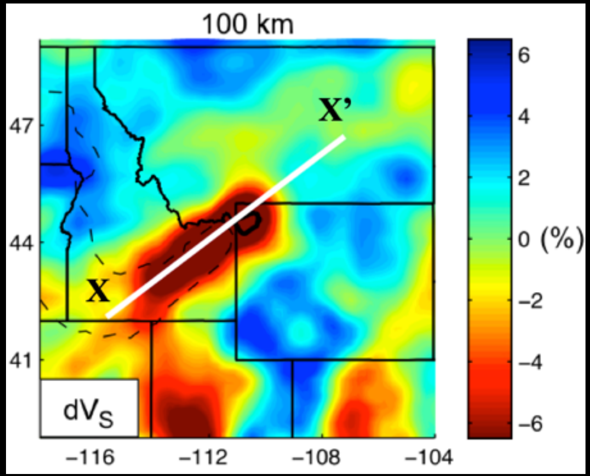
From Ray Wells

1) Fates of subducted slabs and their effects on geological activity at the surface

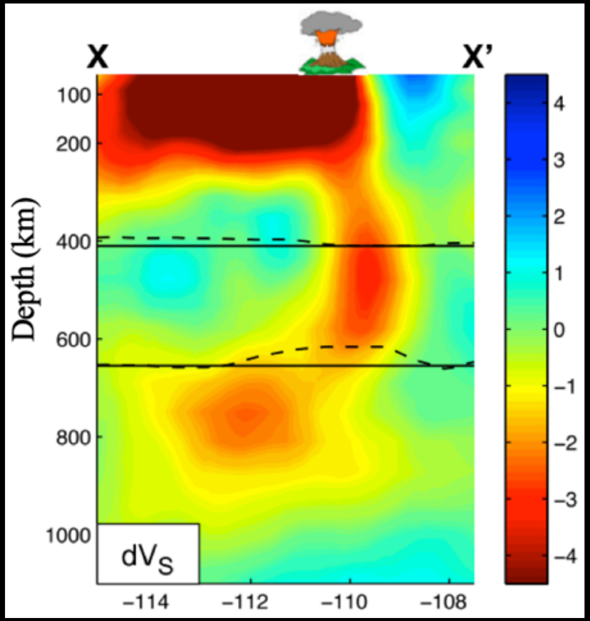


What's been driving the Yellowstone hotspot since ~15 Ma?

- Seismic imaging detects a narrow deeply rooted thermal anomaly (e.g., Obrebski et al., 2009; Schmandt et al., 2012; Nelson and Grand, 2018)
- Debate continues, challenges remain in modeling interactions between subduction and thermal upwellings (e.g., Zhou et al., 2018; Leonard and Liu, 2016)

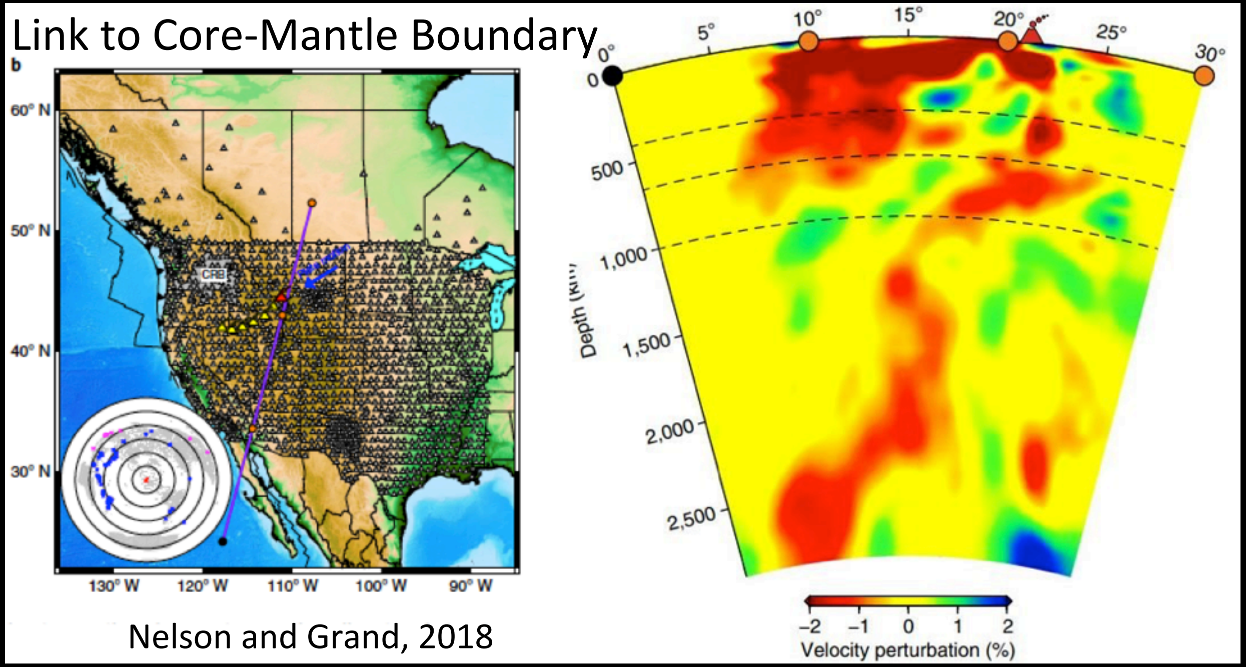


Upwelling across the Transition Zone



Schmandt et al., 2012

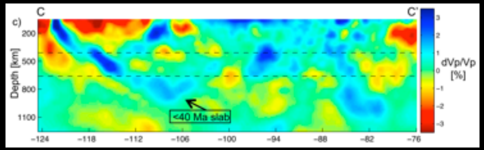
Link to Core-Mantle Boundary



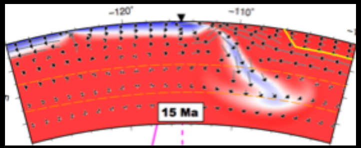
Nelson and Grand, 2018

1) Fates of subducted slabs and their effects on geological activity at the surface

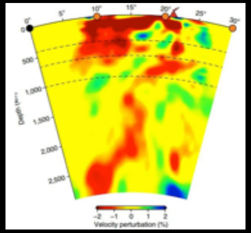
Slab fragmentation is common beneath NA despite long periods of continuous subduction

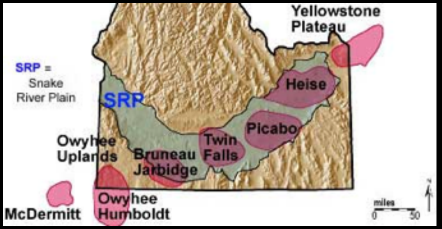


Some breaks correspond to major surface events like initiation of the Yellowstone hotspot track



There is probably a narrow upwelling mantle thermal anomaly underlying Yellowstone.
Slab rupture would have allowed it to reach the base of NA





seismic imaging

plate tectonic reconstructions

petrology & geochemistry

geodynamic modeling (data assimilation)

Interdisciplinary advance accelerated by a scale-change in seismic data and immediate open access

Examples of solid Earth systems addressed by EarthScope science

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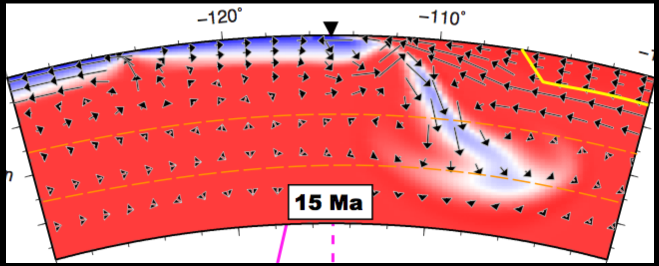
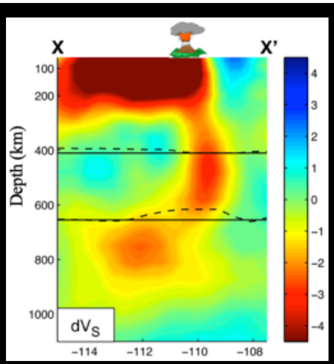
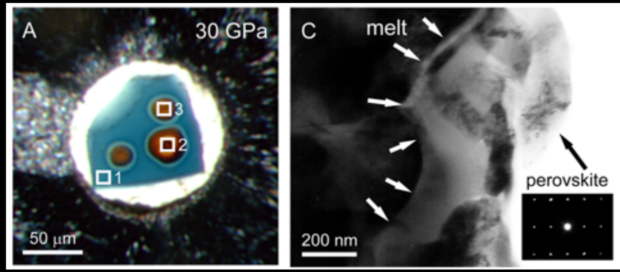


Liu and Stegman, 2011



Schmandt et al., 2012

2) Storage and cycling of water in the deep Earth



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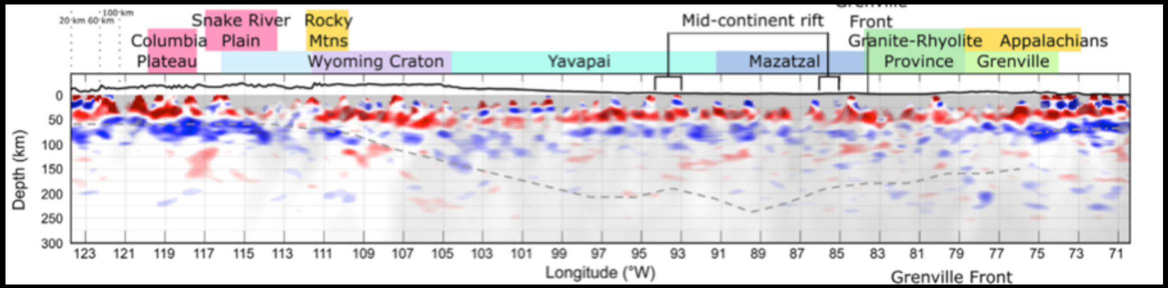

Hopper and Fischer, 2018

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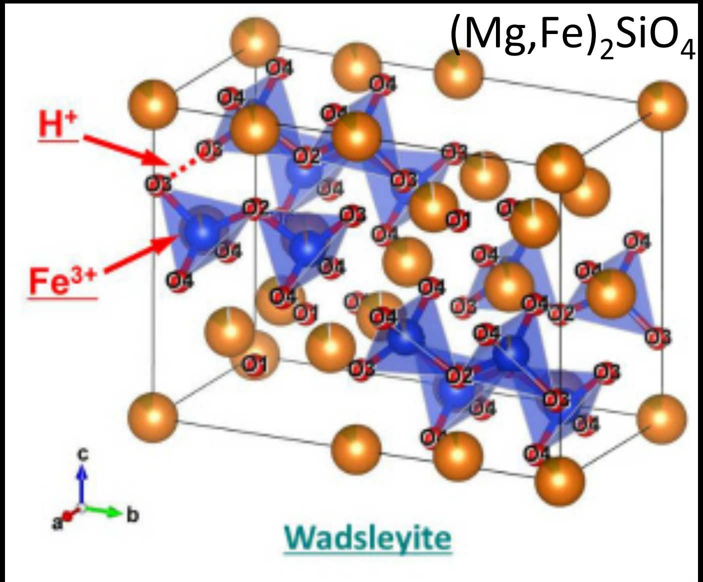
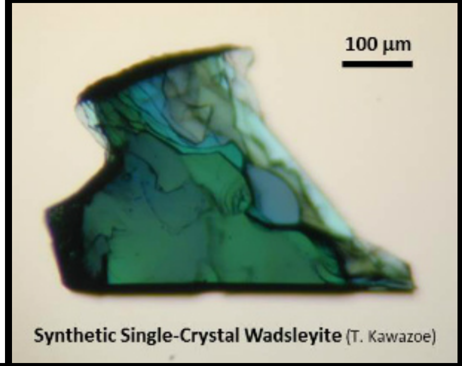


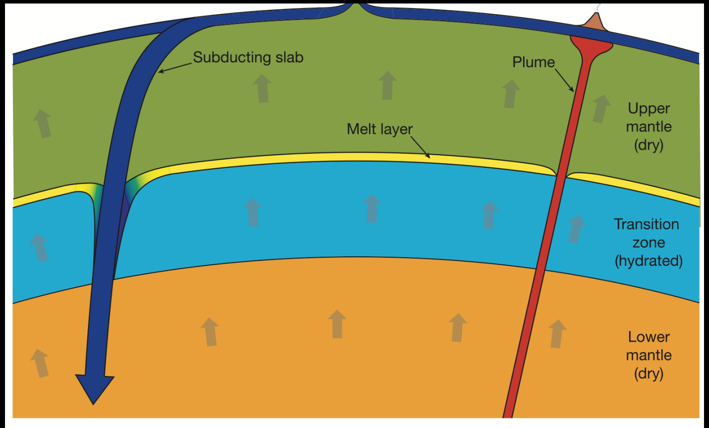


A water-rich layer in Earth?

olivine

wads./ring.

bridg.



dry

hydrated?

drier

(Bercovici and Karato, 2003)

Water = geochemical water reservoir

= hydrogen 'defects' in typically anhydrous silicate minerals

Why care about 'water' locked in inaccessible minerals?

- Where did the early Earth's water come from?
- How has surface to solid Earth cycling varied through Earth's history?

2) Storage and cycling of water in the deep Earth

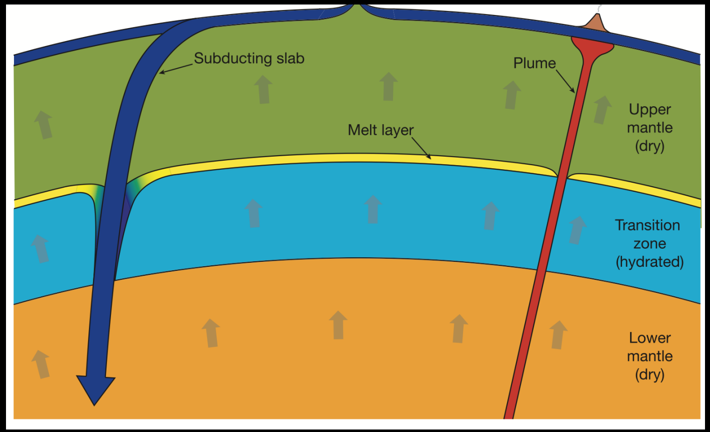
Mantle Water Cycle

Reservoirs (focusing on olivine polymorphs)

- Asthenosphere, basalt source ~0.01 wt% H_2O (e.g., Saal et al., 2002)
- **Transition Zone capacity is ~1-2 wt% (e.g., Kohlstedt et al., 1996)**
- Lower Mantle, bridgmanite capacity estimated ~0.0001 wt% (Panero et al., 2015)

Fluxes

- Input - Subduction
- Output – Magmatism, Metasomatism
- Transfer between mantle reservoirs



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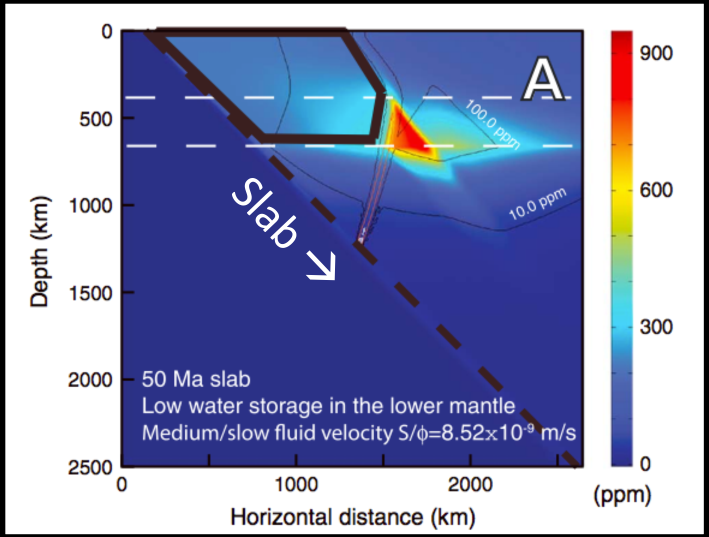
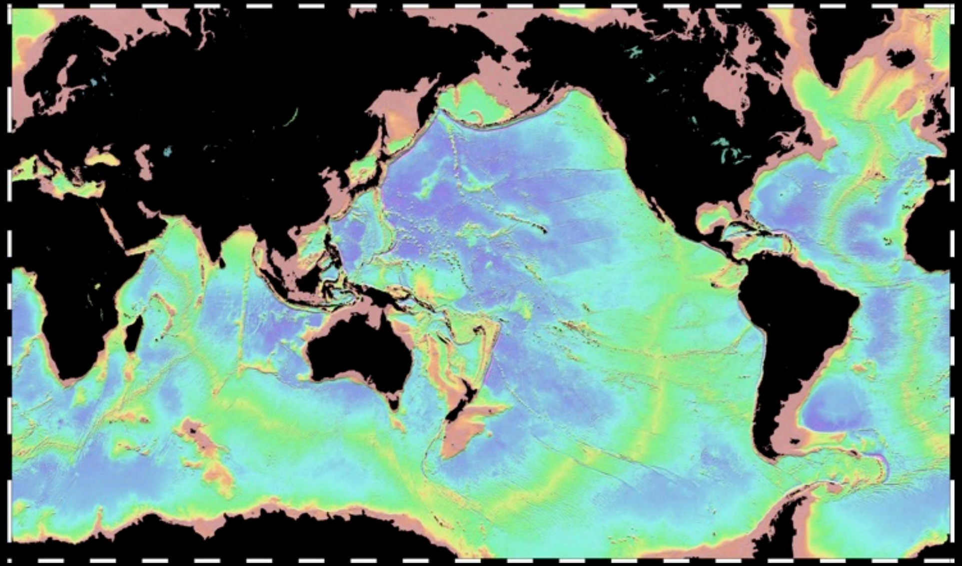


(Hebert and Montesi, 2014)

2) Storage and cycling of water in the deep Earth

The transition zone has the capacity to store multiple oceans worth of H_2O

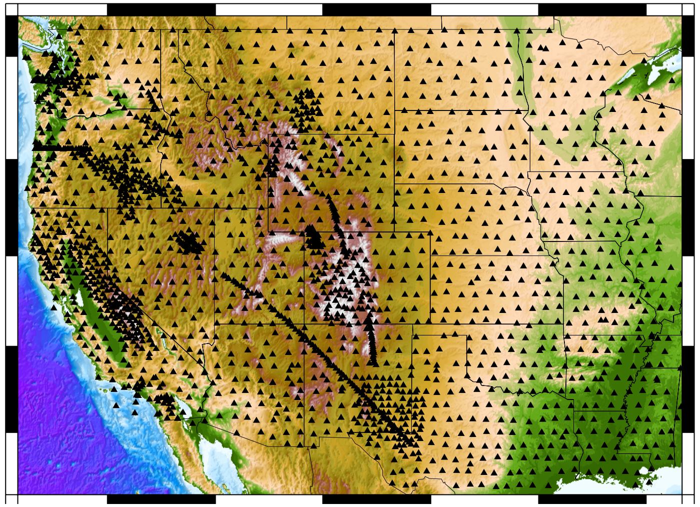
(e.g., Smyth, 1987; Inoue et al., 1995; Kohlstedt et al., 1996, many others…)

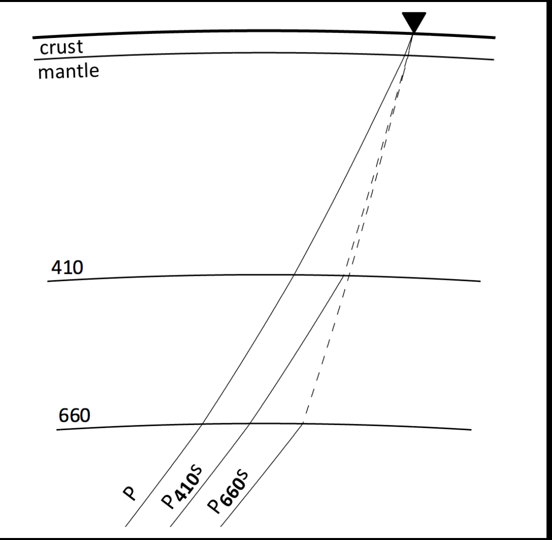


But is that reservoir empty?

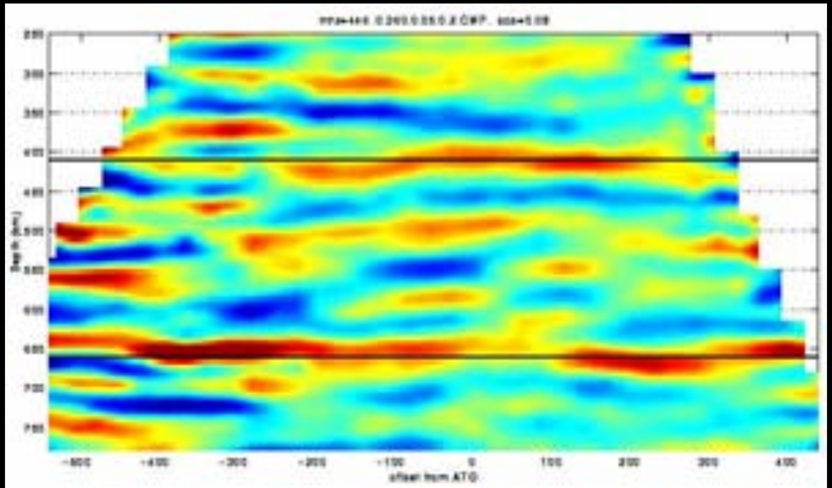
2) Storage and cycling of water in the deep Earth

Dense, wide-aperture seismic array





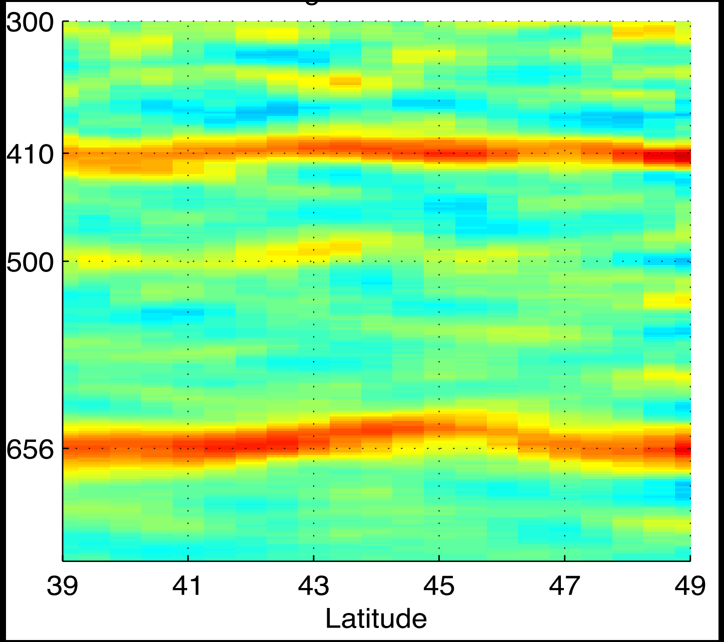
Pre-EarthScope CCP image
from a small-aperture linear array



(Dueker and Sheehan, 1997)

EarthScope's USArray data provided a major advance in our ability to image the transition zone

Post-EarthScope CCP image

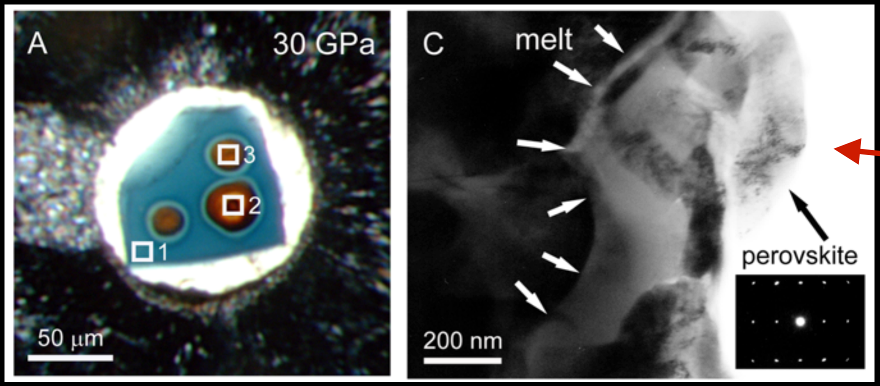


2) Storage and cycling of water in the deep Earth

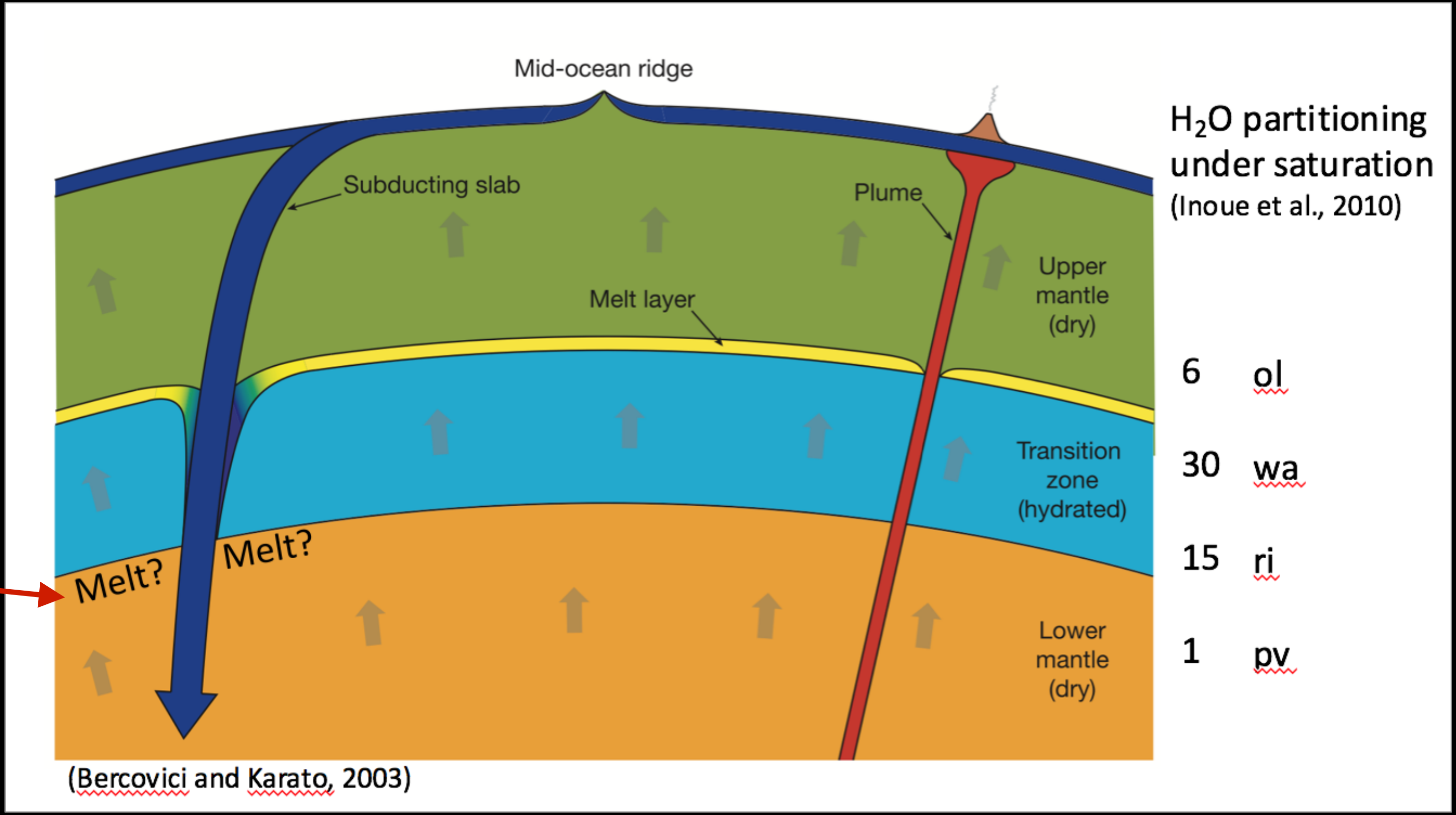
Consequences of a hydrated Transition Zone and vertical flow

-possibility of dehydration melting for upwelling across 410 and downwelling across 660

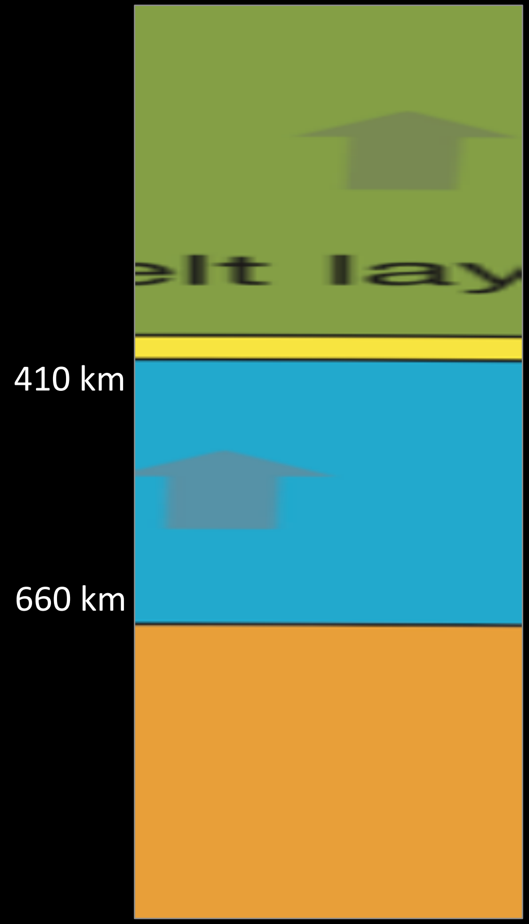
Laboratory experiments of dehydration melting in diamond anvil cells



Steve Jacobsen, Zhenxian Liu

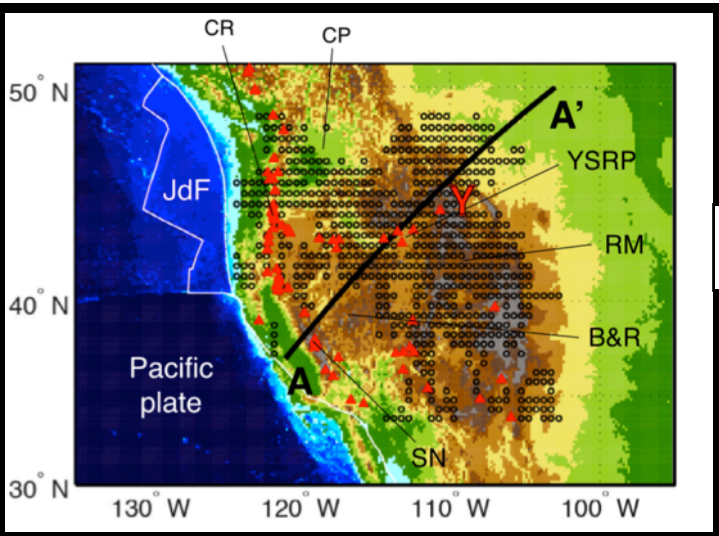


2) Storage and cycling of water in the deep Earth

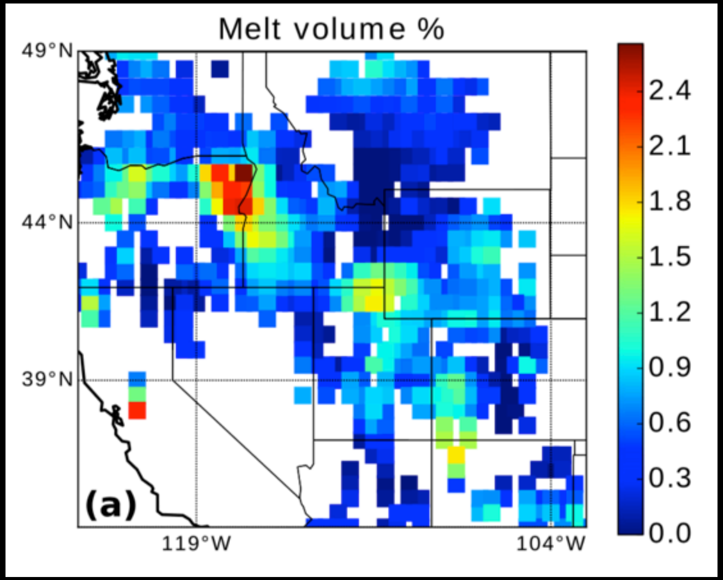


Bercovici and Karato, 2003

Can we map such a gravitationally stable melt layer with EarthScope seismic data?

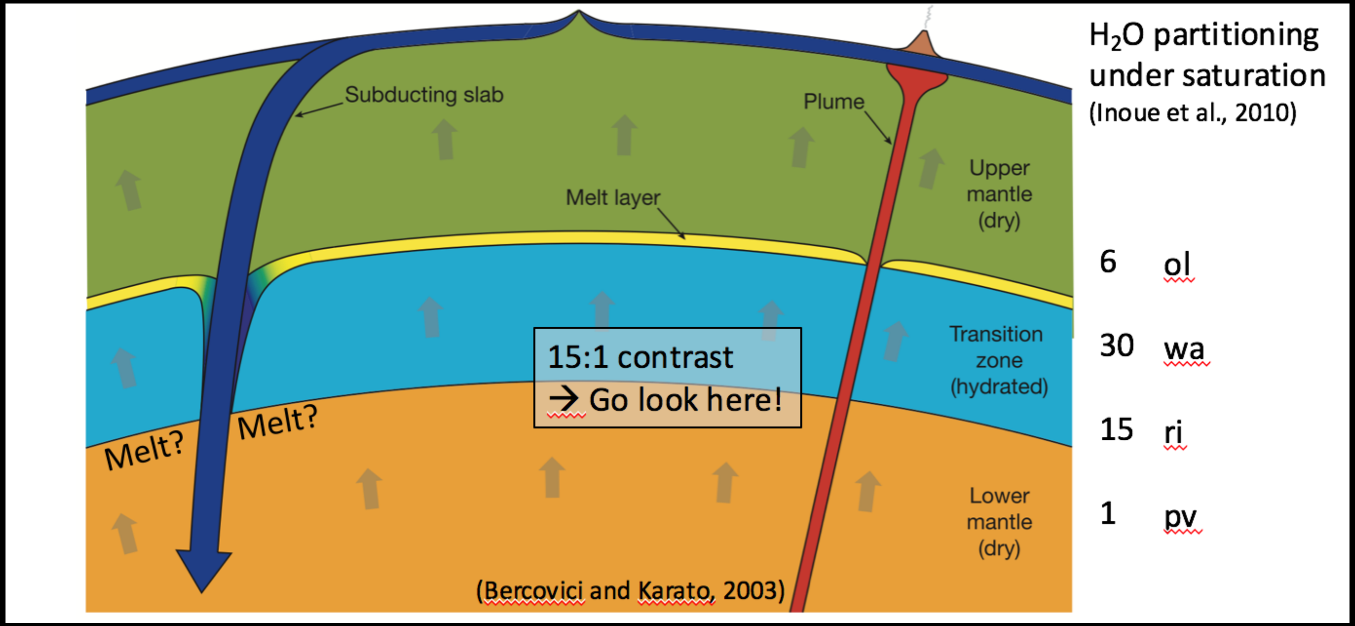


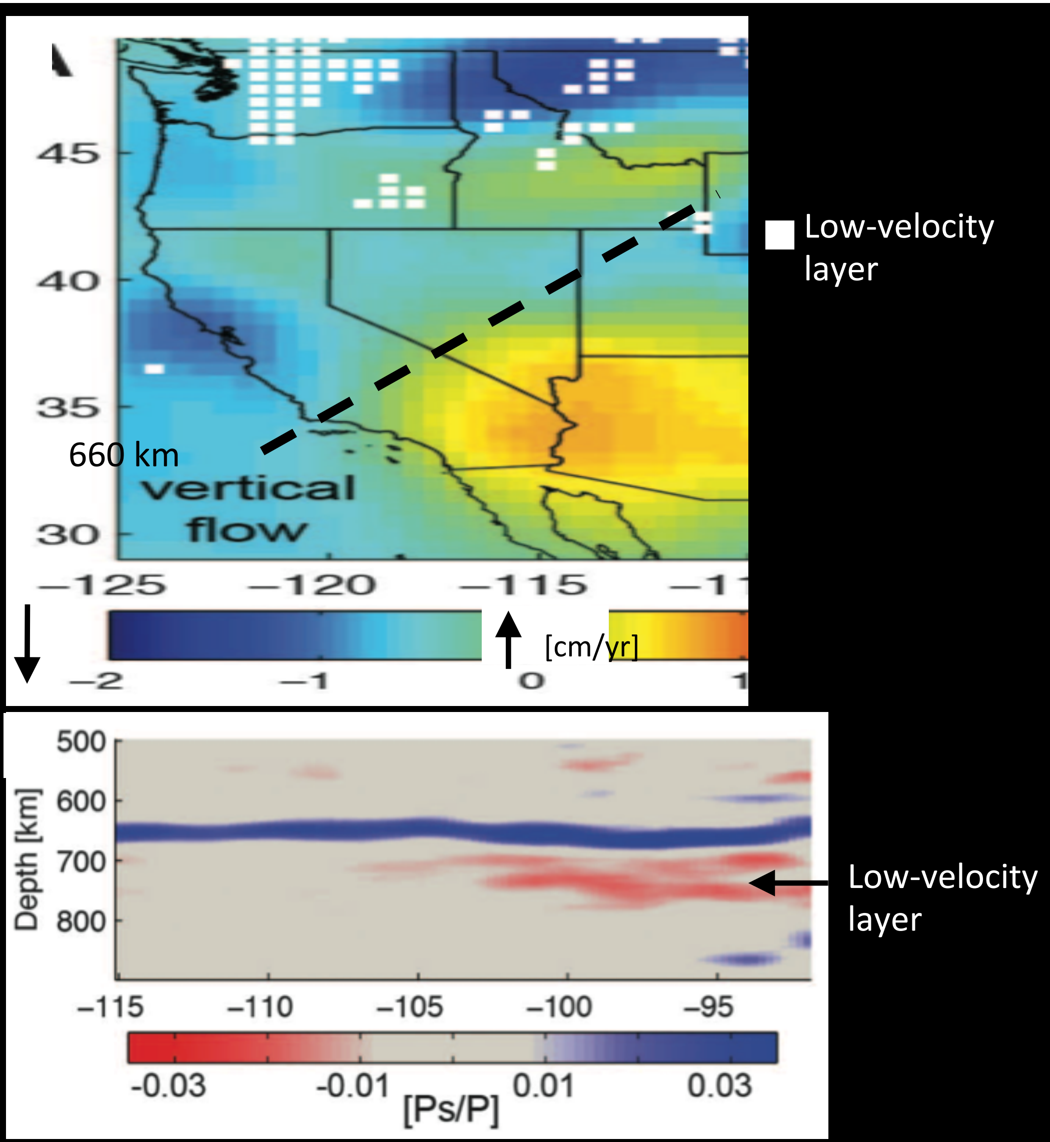
o - Low-velocity layers



Hier-Majumder and Tauzin, 2017

2) Storage and cycling of water in the deep Earth



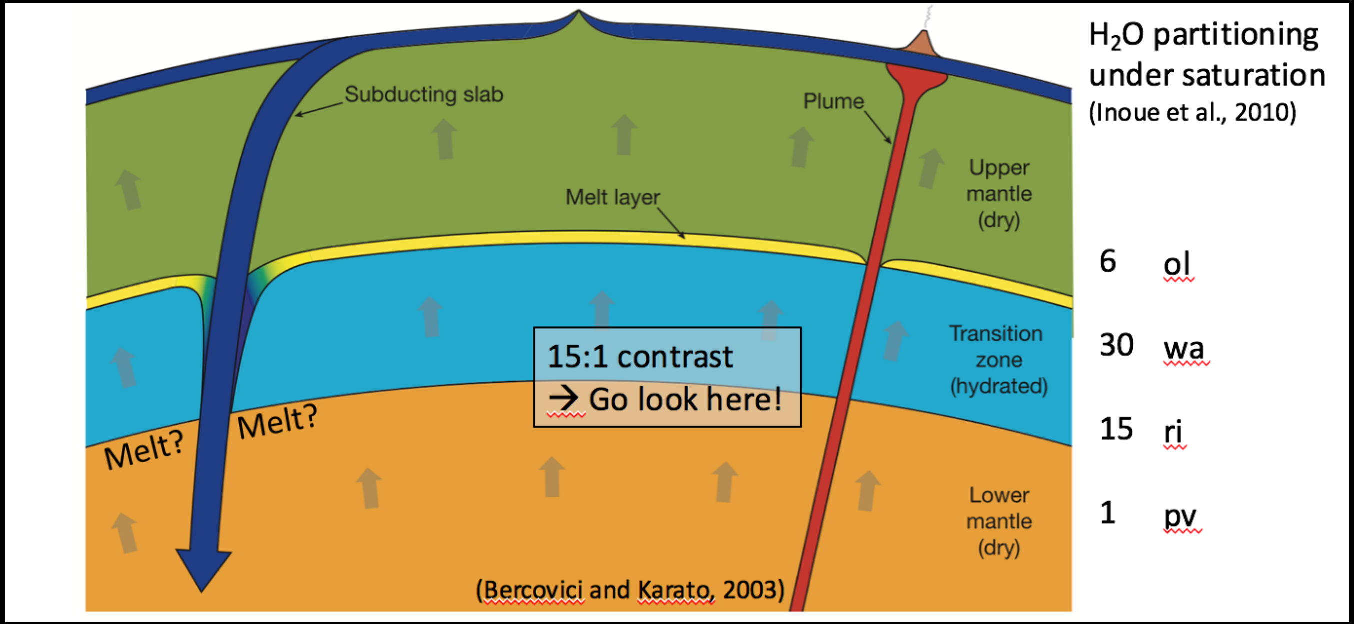


Schmandt et al., 2014

How about potential transient melt due to downwelling into the lower mantle?

- requires comparison of mantle flow vectors with distribution of low-velocity layers

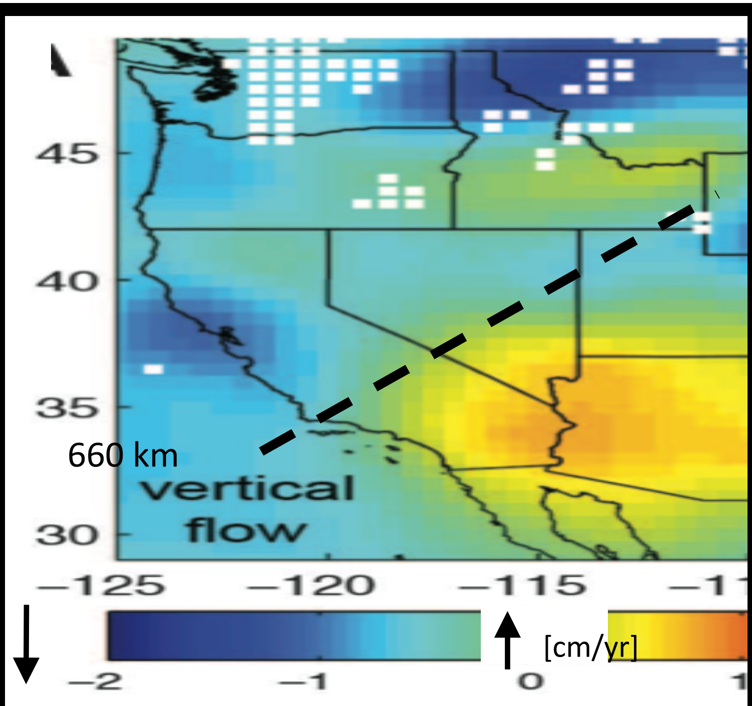
2) Storage and cycling of water in the deep Earth



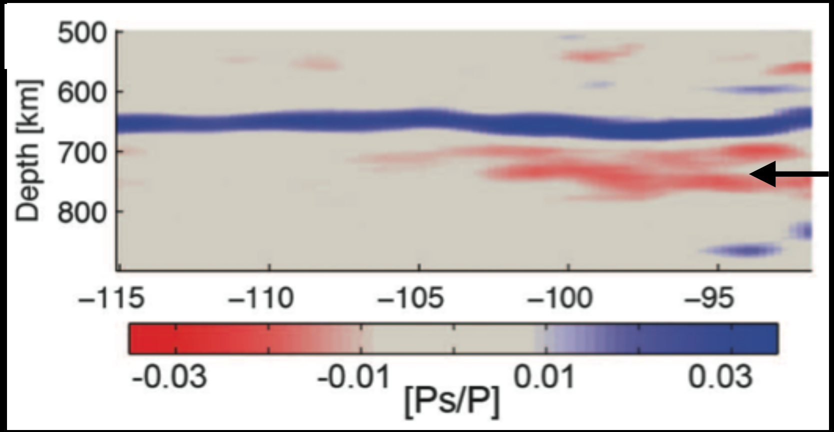
Is the transition zone water reservoir empty?

Probably not based on EarthScope seismic evidence for small melt fractions near transition zone boundaries.

However, even a 1/10 full reservoir may be enough to explain these observations.



Low-velocity layer

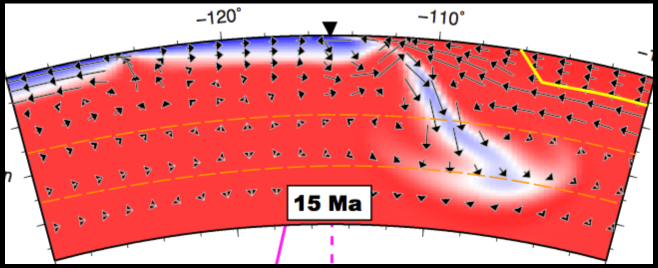


Low-velocity layer

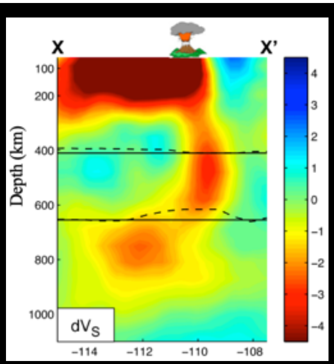
Schmandt et al., 2014

Examples of solid Earth systems addressed by EarthScope science

1) Fates of subducted slabs and their effects on geological activity at the surface.

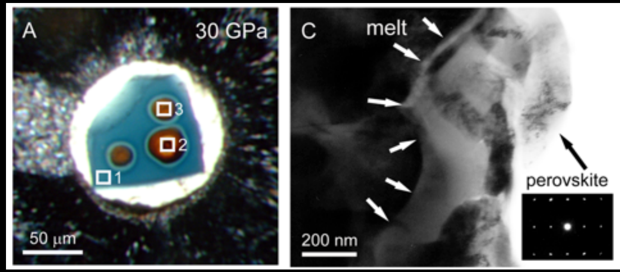


Liu and Stegman, 2011



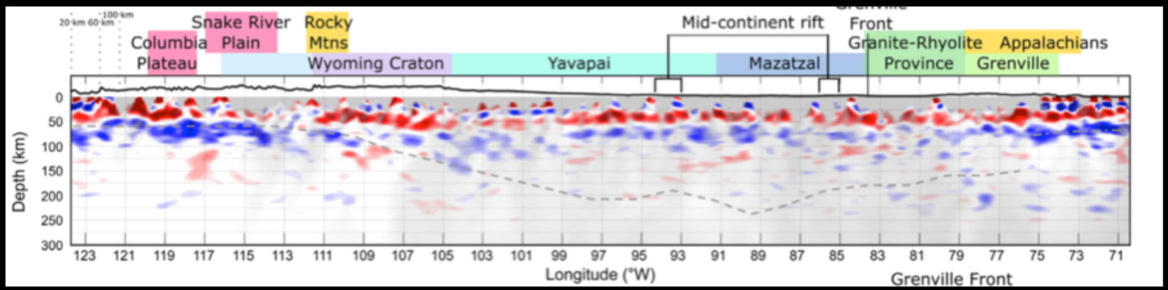
Schmandt et al., 2012

2) Storage and cycling of water in the deep Earth



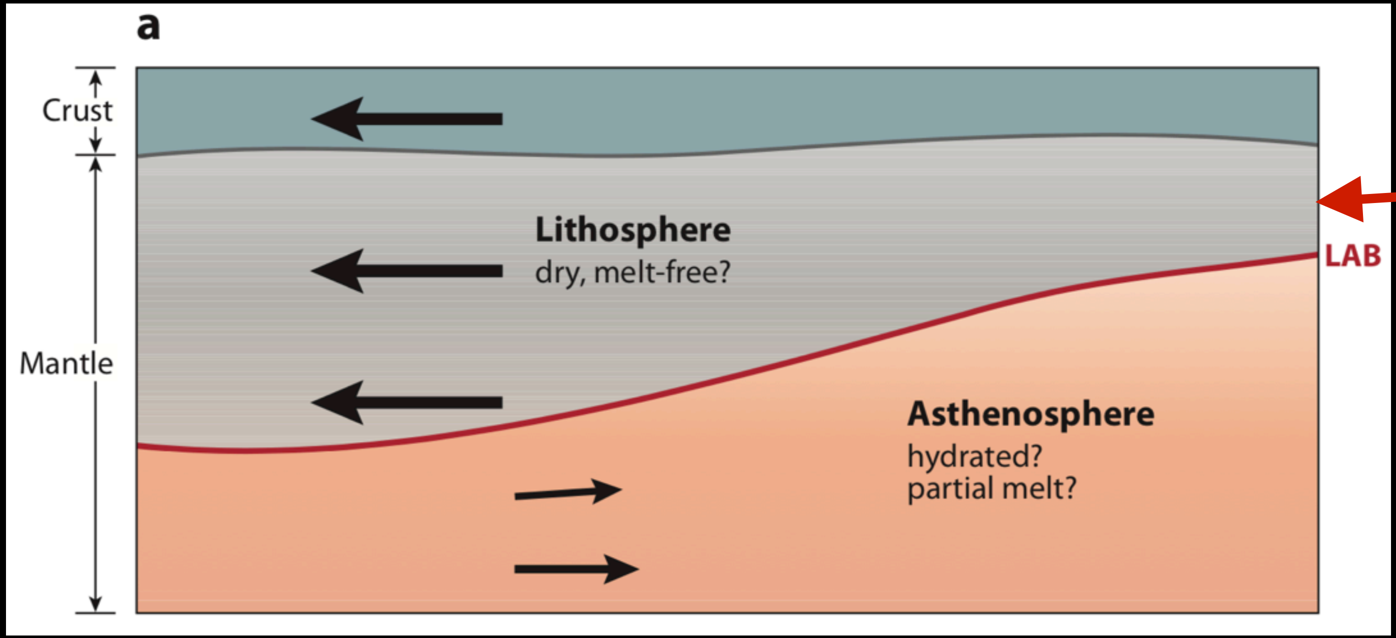
from Steve Jacobsen

3) Where does the continent end? – Mapping the base of tectonic plates



Hopper and Fischer, 2018

3) Where does the continent end? – Mapping the base of tectonic plates



Fischer et al., 2010

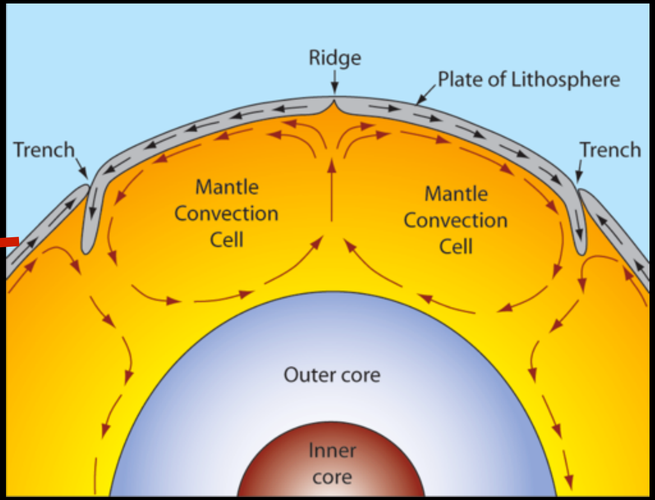
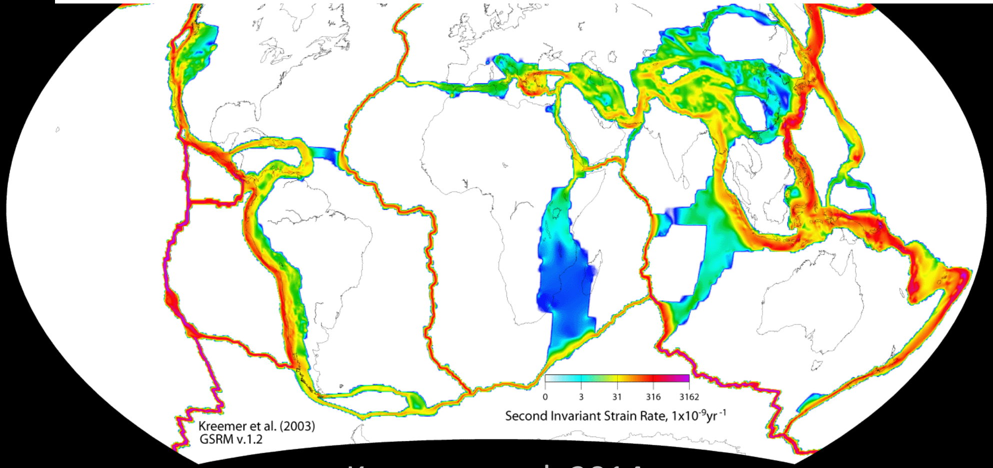


Plate sides are sharply defined by high strain rates

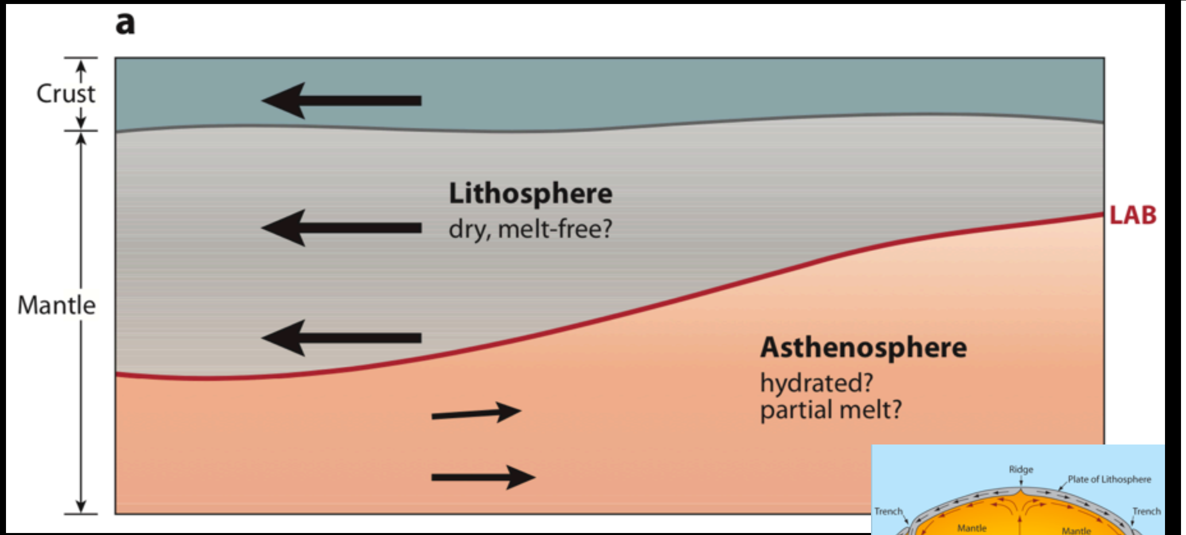


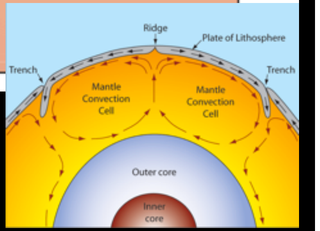
Kreemer et al. 2014

Is the boundary between plates and the convecting interior sharp or gradual?

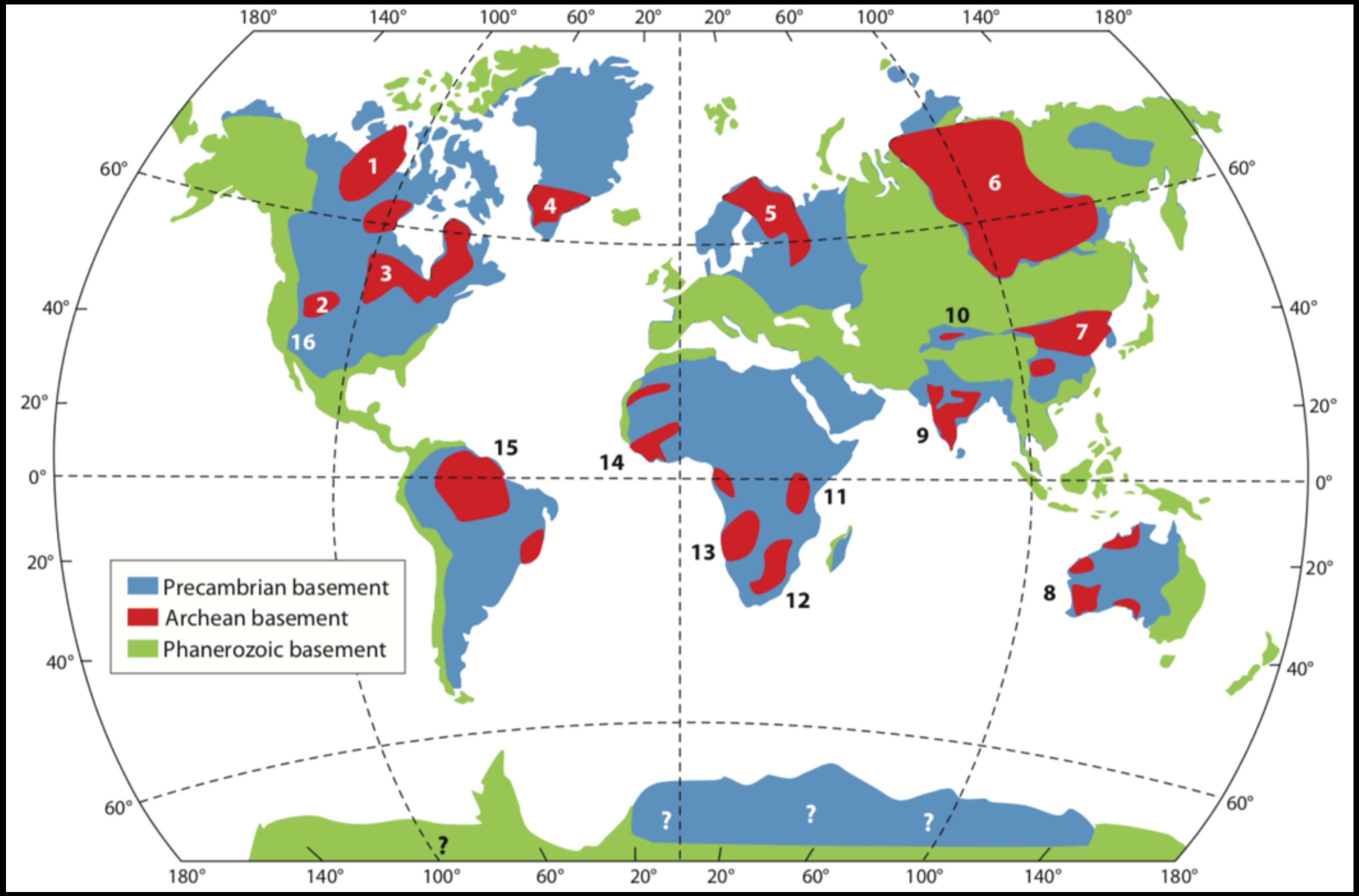
How does it vary with age?
(parts of continents are >2.5 billion years old)

3) Where does the continent end? – Mapping the base of tectonic plates





Fischer et al., 2010

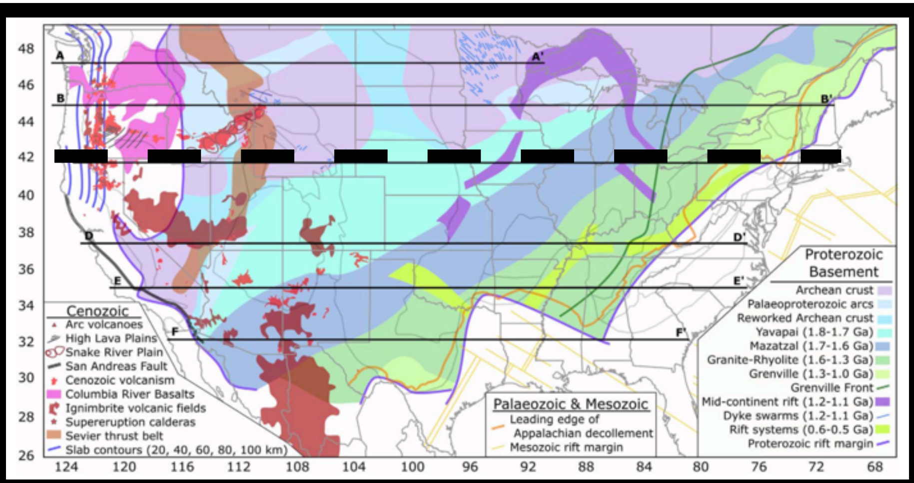


Lee et al., 2010

Is the boundary between plates and the convecting interior sharp or gradual?

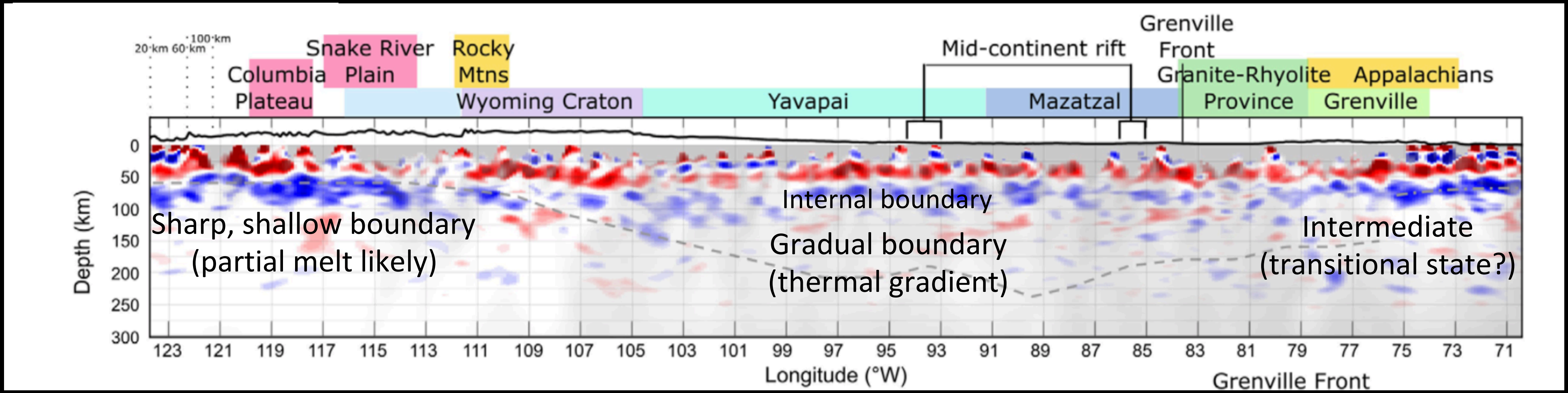
How does it vary with age?
(parts of continents are >2.5 billion years old)

3) Where does the continent end? – Mapping the base of tectonic plates



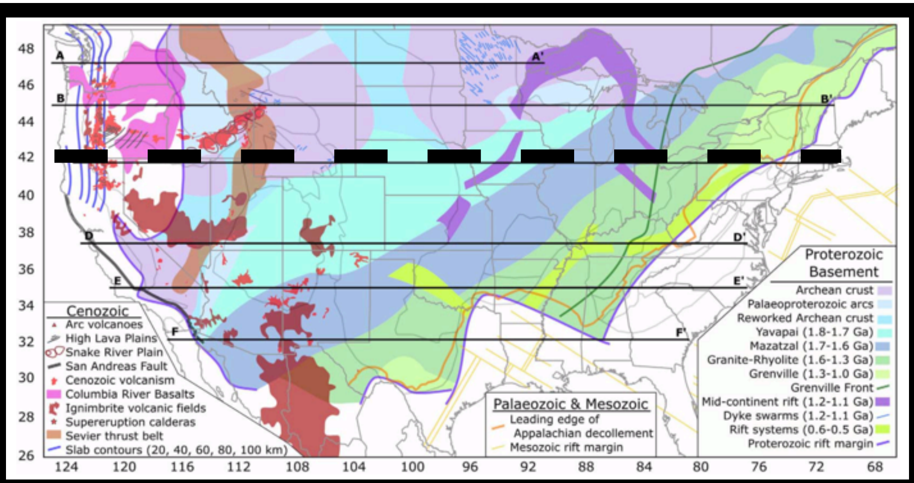
First opportunity continuous transcontinental imaging of lithospheric boundaries

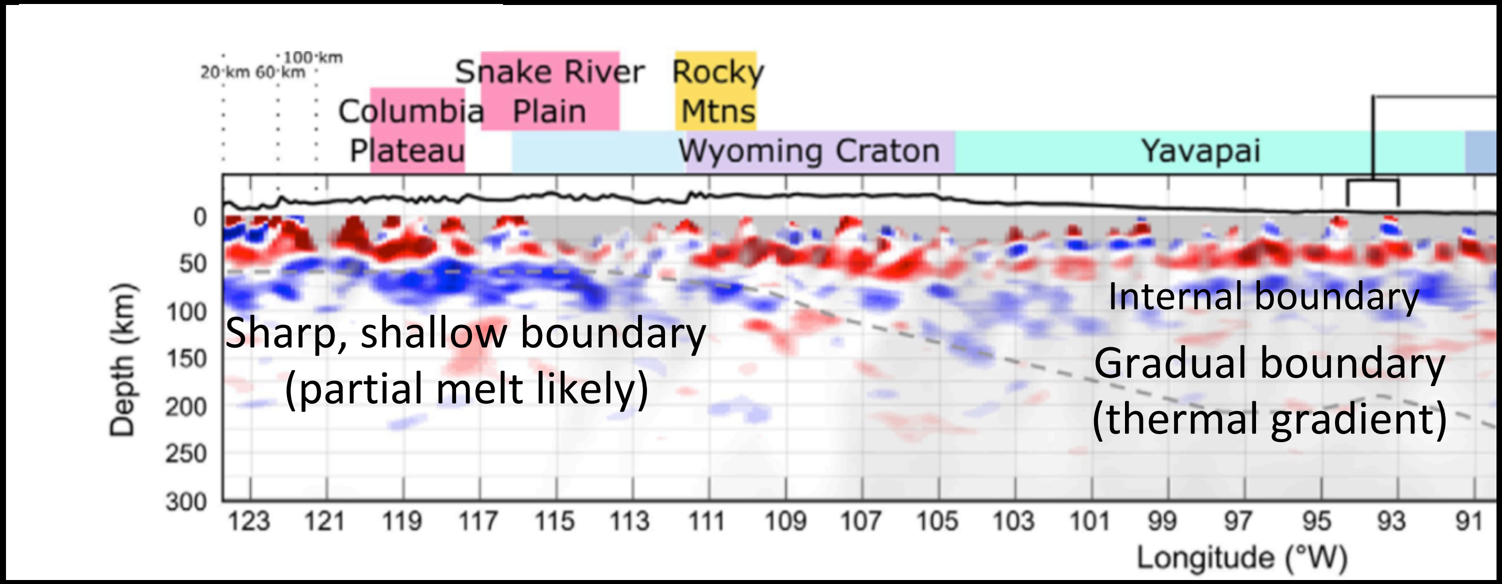
Differences in the lithosphere-asthenosphere boundary beneath the active western Cordillera, cratonic interior, and eastern passive margin



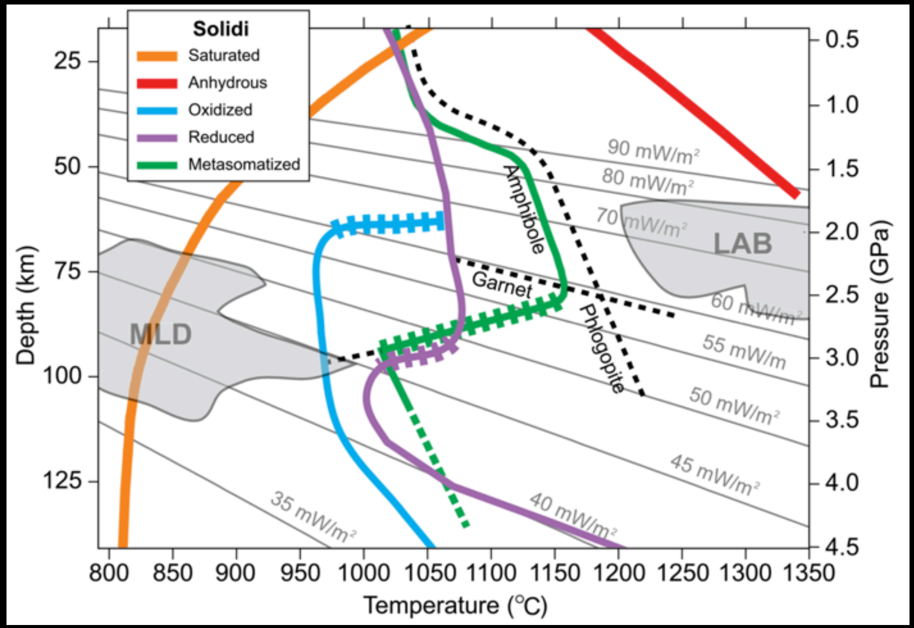
Modified from Hopper and Fischer, 2018

3) Where does the continent end? – Mapping the base of tectonic plates





Modified from Hopper and Fischer, 2018



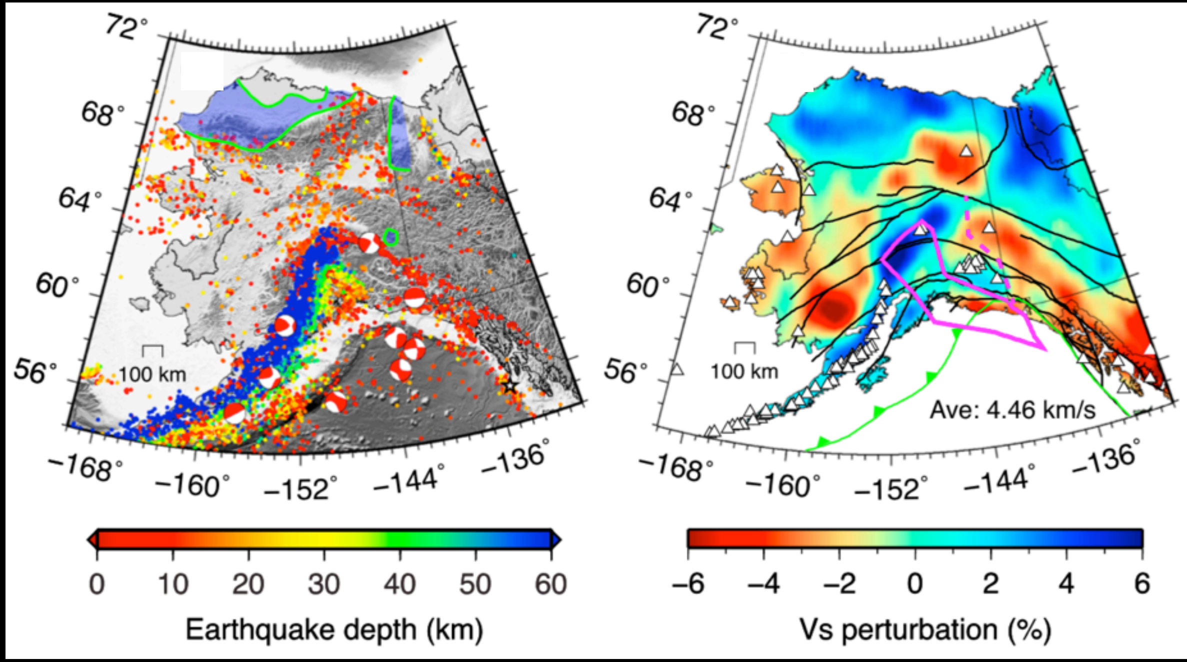
Hansen et al., 2015

EarthScope tomography helps constrain thermal structure and potential compositional or partial melting influences on seismic boundaries.

EarthScope's USArray: A new window into solid Earth processes beneath North America

Many more systematic advances…

4) Crustal shear velocity structure and composition
5) Seismic anisotropy ←→ past/present strain
6) Buoyancy to support evolving topography
7) Lithospheric instabilities
8) …



Jiang et al., 2018

- Much more potential for advance and integration
- Alaska structural studies are just getting started

EarthScope will have a rich and long legacy in studies of solid Earth systems