Challenges in lithospheric dynamics – Examples motivated by EarthScope

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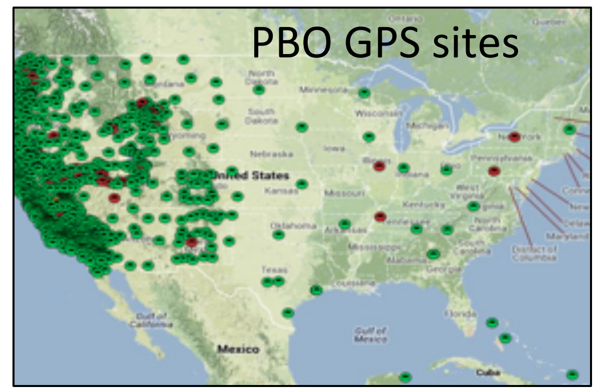
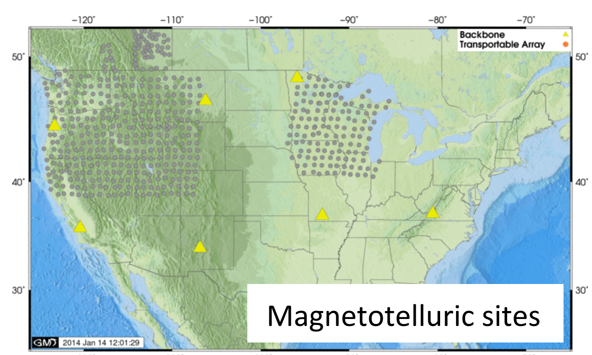
EarthScope Observatories

- Seismic
- Geodesy
- SAFOD

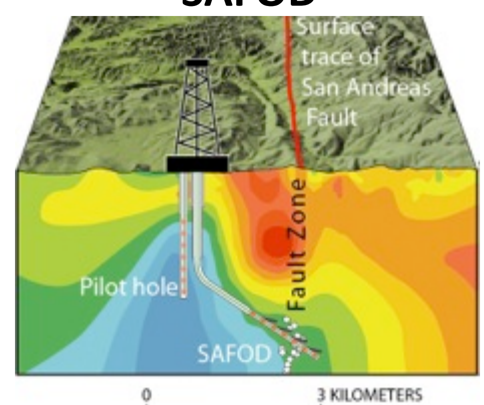
- Several other important components: MT, InSAR, LiDAR, Infrasound

USArray seismometers

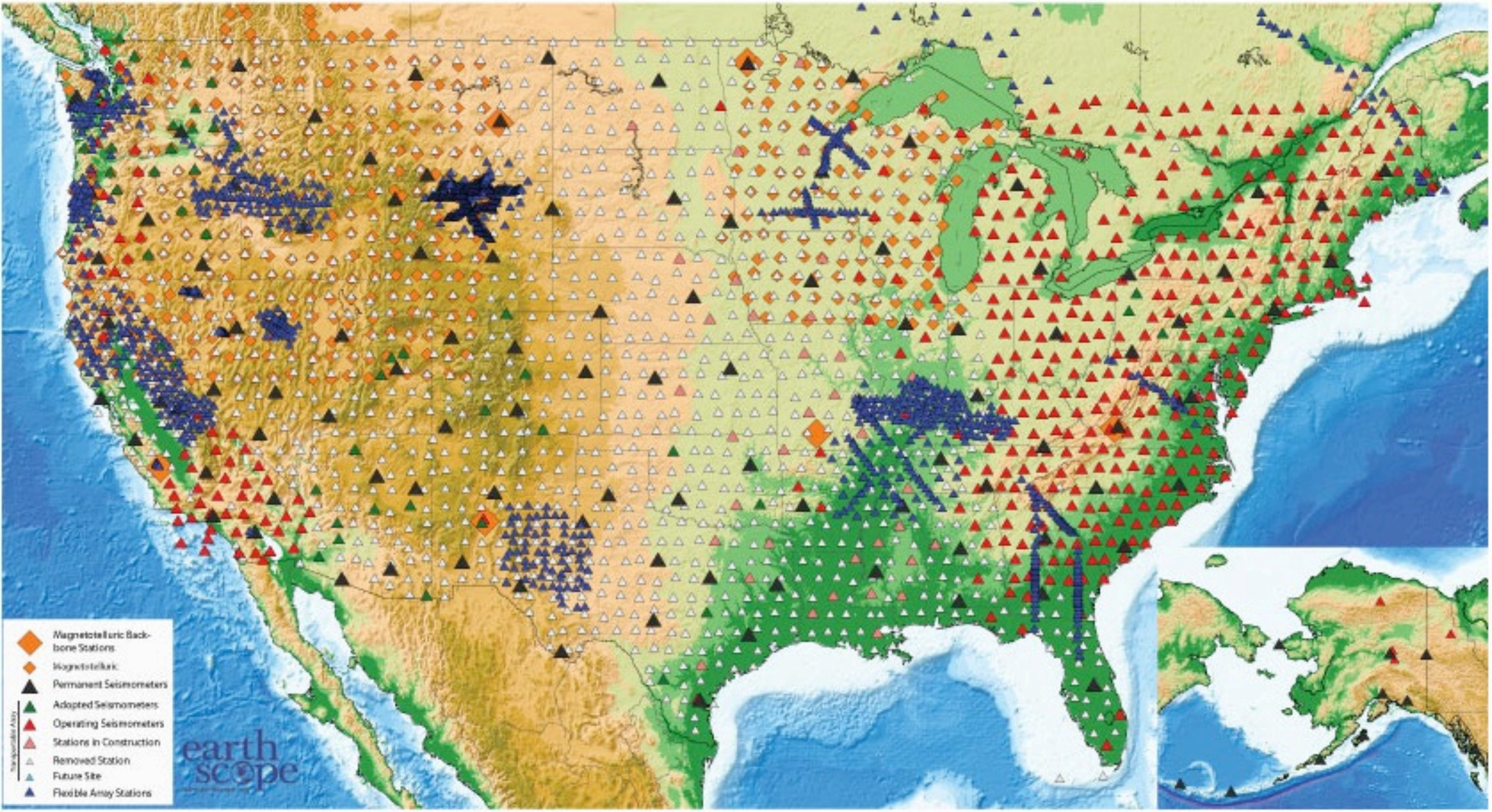




SAFOD



USArray Status as of January 2014

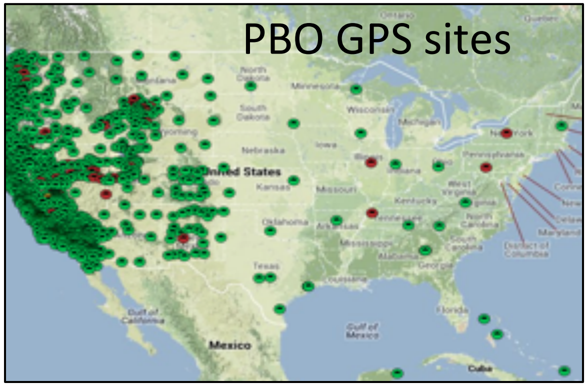


EarthScope Opportunities

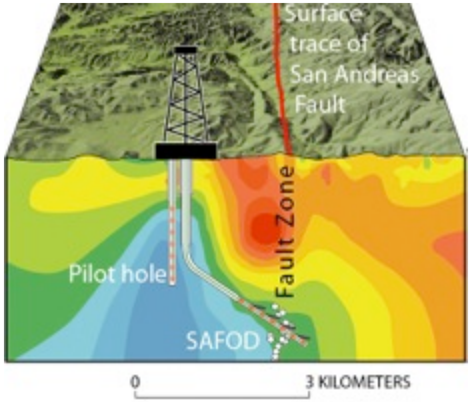
A multi-disciplinary community, beyond the core observatories, is primed for integrative studies of lithospheric dynamics

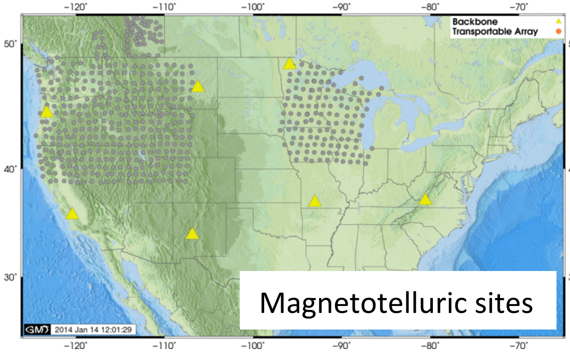
Computational geodynamics has a vital role for realizing the potential of these fantastic observatories

USArray seismometers



SAFOD





Challenges in lithospheric dynamics – Examples motivated by EarthScope

1) **Multi-scale heterogeneity and convection**
   - **Need to get beyond directly mapping seismic velocities to temperature**
   - **Need intense regional-scale heterogeneity/convection considered in global context, rather than only one process at a time in isolation**

2) Segmented Slabs – causes and consequences

3) Mantle melting, migration of melts and volatiles through lithosphere

3.5?) Structure and origin of continental mantle

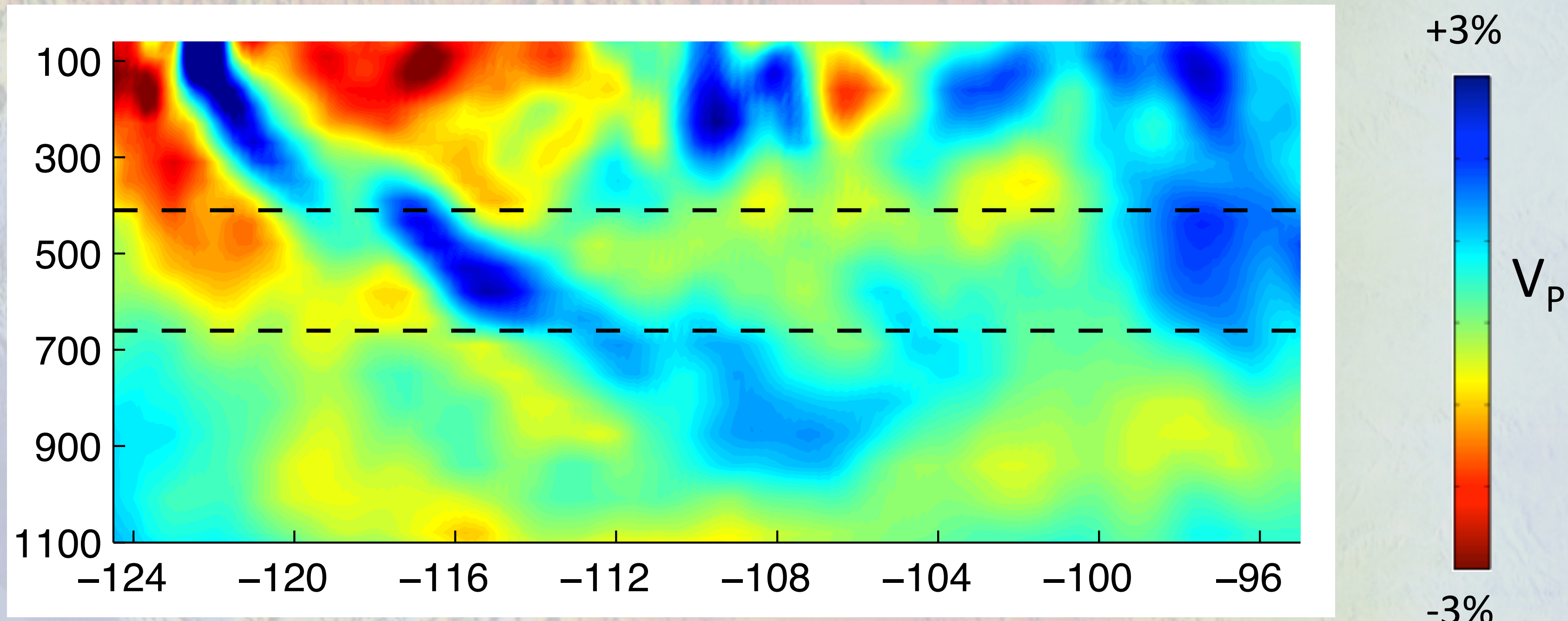
4) Vertical motions at the surface

5) Deformation in lower crust-uppermost mantle, past and present

Multi-scale heterogeneity/convection in the western U.S. mantle

~Normal subduction | Segmented, stagnant subduction | Edge erosion of heterogeneous provinces | Localized Delamination and 3-D drips

41° Latitude



For western U.S. subduction history, this broken slab is as simple as it gets…

Multi-scale heterogeneity/convection in the western U.S. mantle

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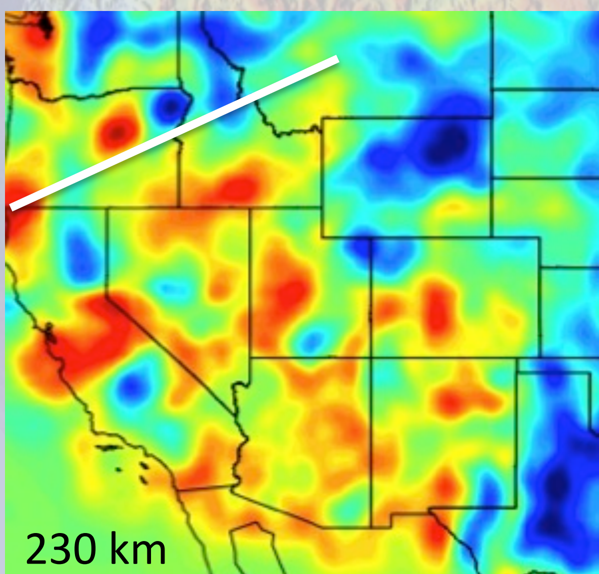
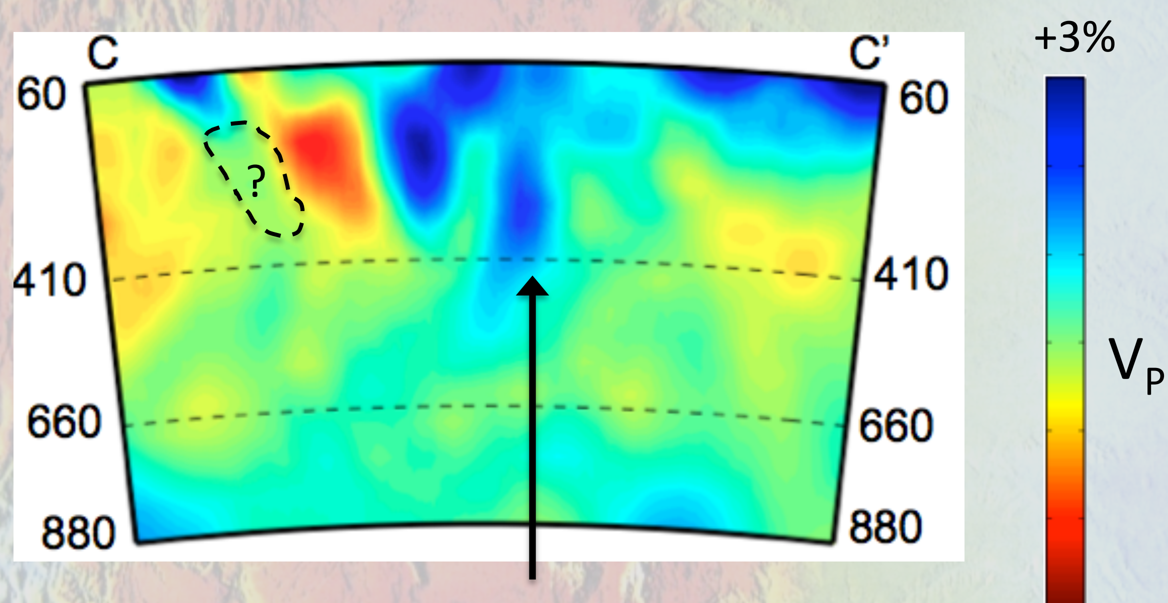
Edge erosion of heterogeneous provinces

Localized Delamination and 3-D drips





Slab "curtain", a relic from Eocene accretion?

Multi-scale heterogeneity/convection in the western U.S. mantle

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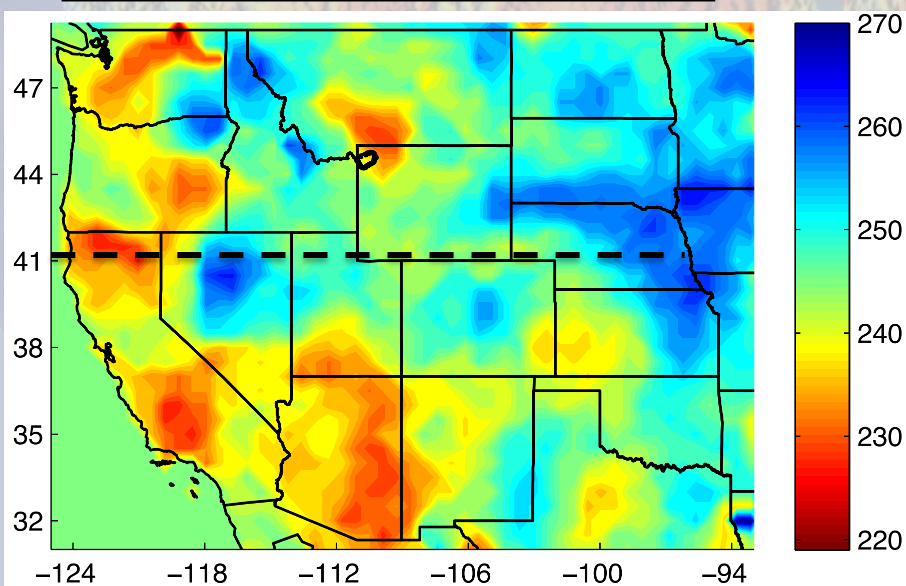
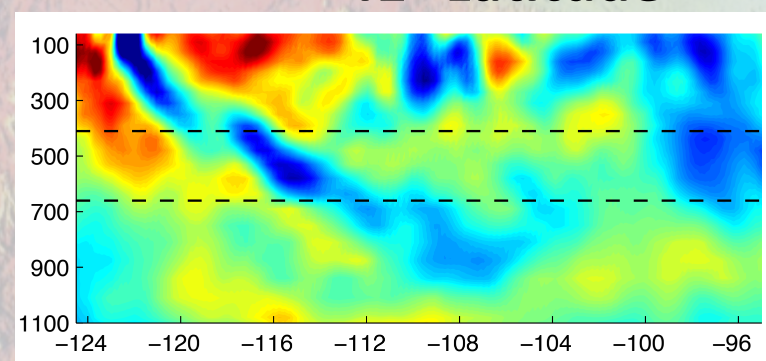
Edge erosion of heterogeneous provinces

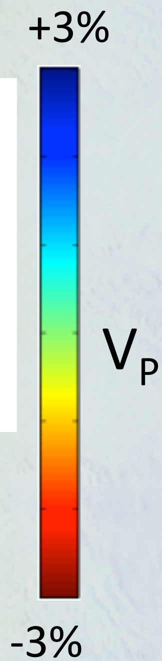
Localized Delamination and 3-D drips

Transition zone thickness



41° Latitude



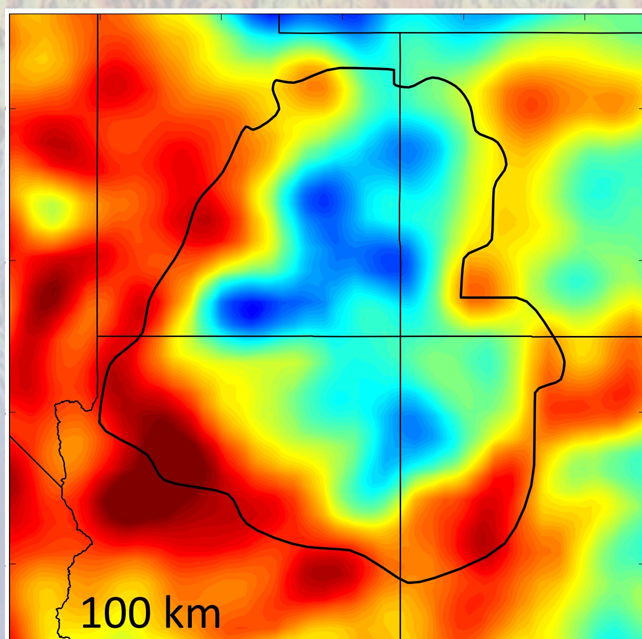


A large volume of slab in the central U.S. transition zone, while younger slab already through 660 beneath Colorado/Wyoming

Multi-scale heterogeneity/convection in the western U.S. mantle

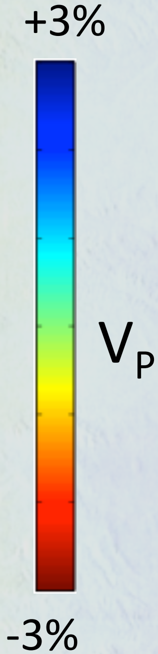
~Normal subduction | Segmented, stagnant subduction | **Edge erosion of heterogeneous provinces** | Localized Delamination and 3-D drips

Example: Colorado Plateau



Low-velocity ring correlates with

- elevated CP rim
- encroachment of magmatism onto the CP
- edge-driven convection? (van Wijk et al., 2010)



… also at the western edge of the Great Plains? (Gao et al., 2004; Song and Helmberger, 2007)

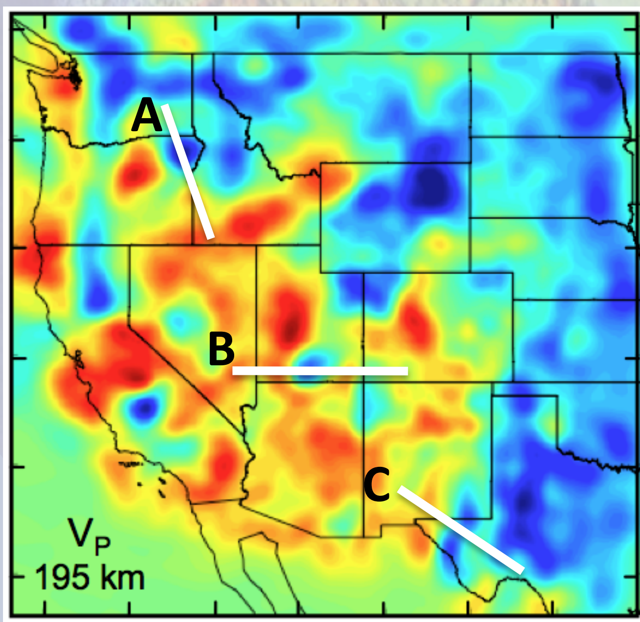
Multi-scale heterogeneity/convection in the western U.S. mantle

~Normal subduction

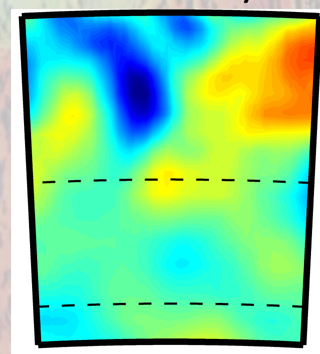
Segmented, stagnant subduction

Edge erosion of heterogeneous provinces ?

Localized Delamination and 3-D drips

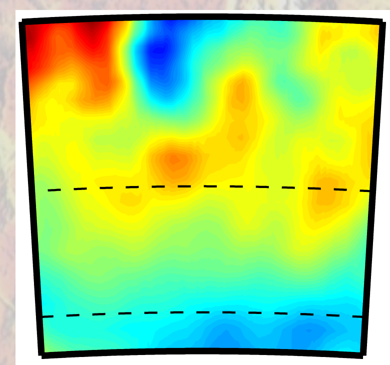


A Wallowa/CRB

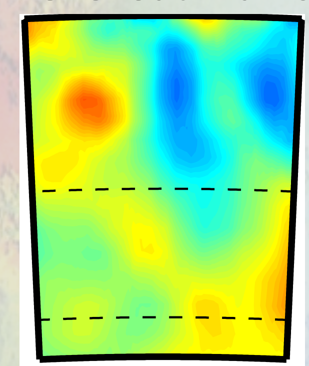


Some examples:

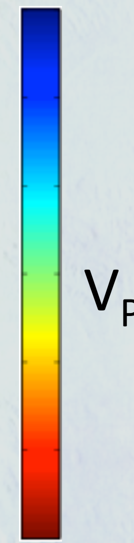
B Colorado Plateau



RGR –
C Great Plains



+3%

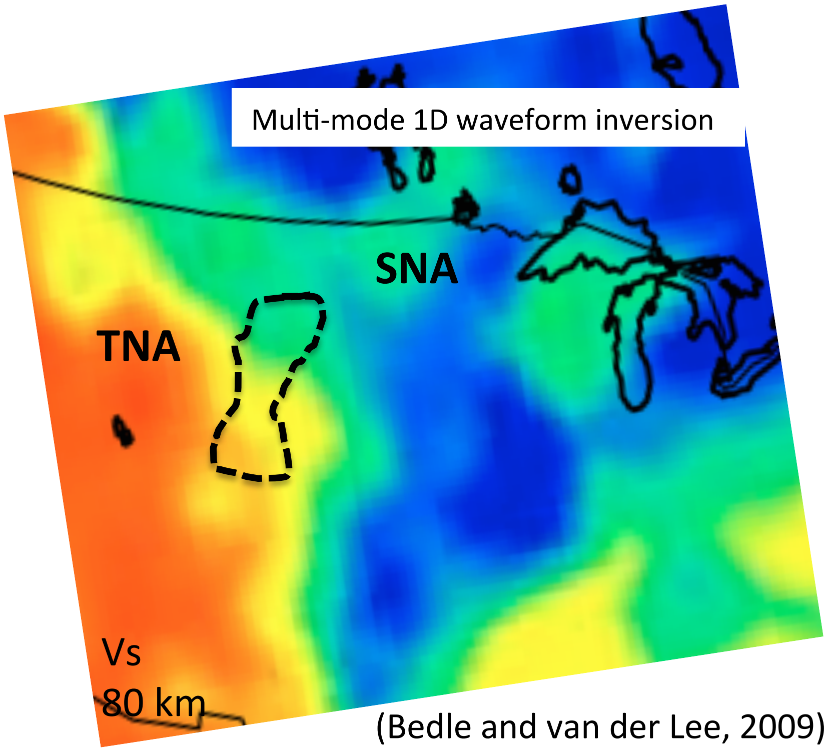


-3%

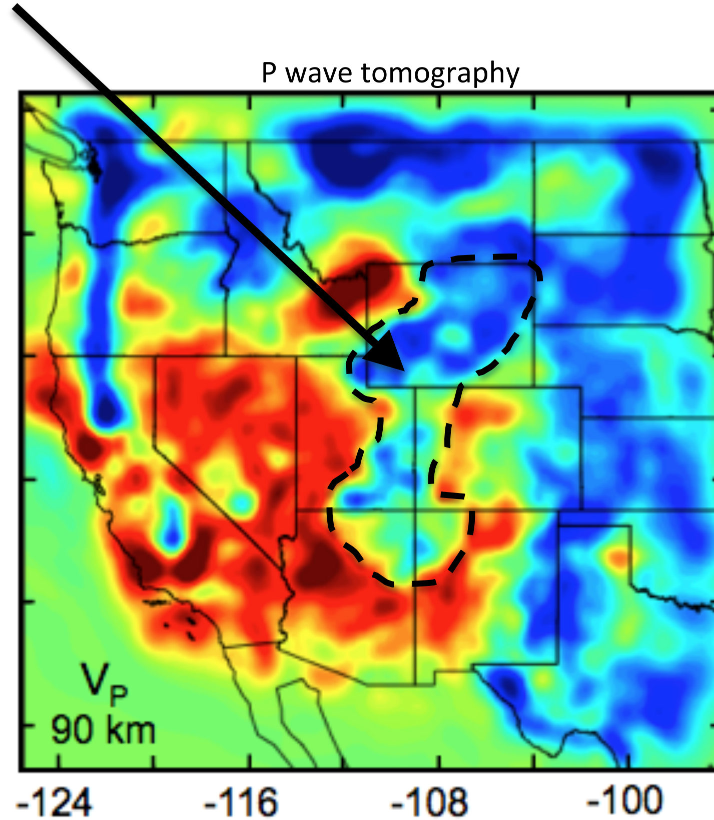
Is this normal for continents experiencing post-orogenic collapse and/or post-flat subduction?

Are these structures stable, and non-thermal effects are large?

High-velocity from Colorado Plateau N-NE across Wyoming



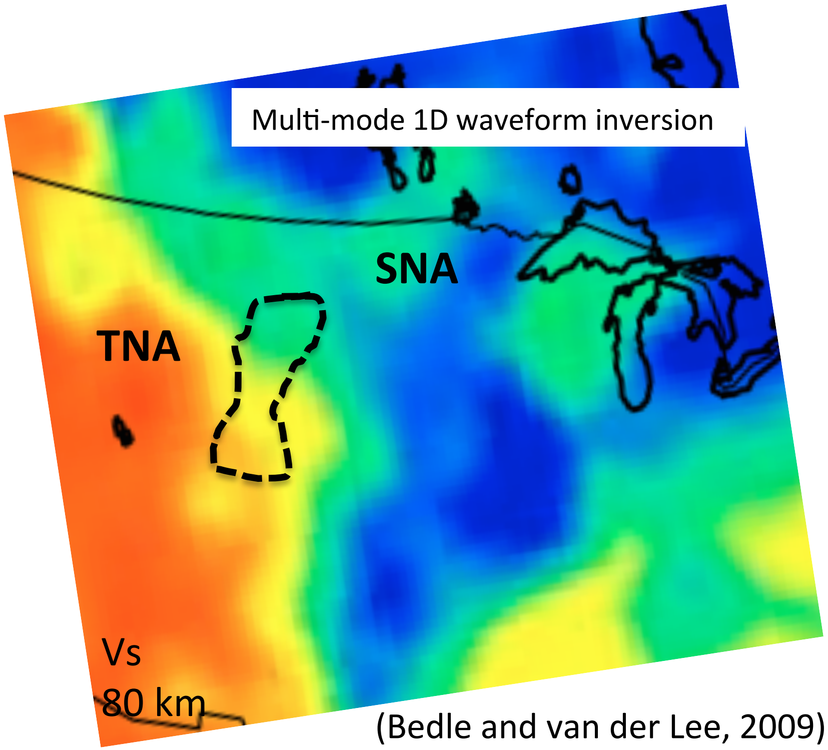
(Bedle and van der Lee, 2009)
TA had not yet left the west coast



Prior to USArray little high-velocity lithosphere was thought to remain beneath Wyoming and the Colorado Plateau, a challenge in understanding compensation for high elevations.

How to uplift WY by ~1-2 km since Cretaceous?

High-velocity from Colorado Plateau N-NE across Wyoming



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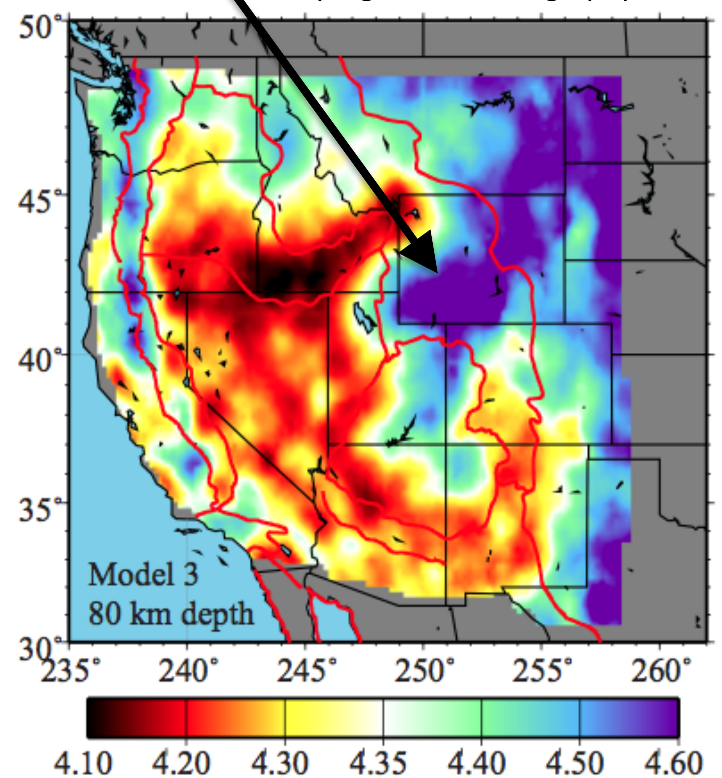
Rayleigh wave tomography



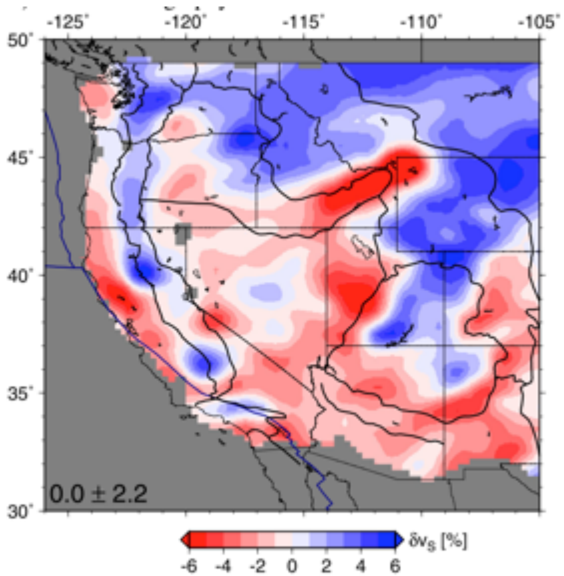
Prior to USArray little high-velocity lithosphere was thought to remain beneath Wyoming and the Colorado Plateau, a challenge in understanding compensation for high elevations.

How to uplift WY by ~1-2 km since Cretaceous?

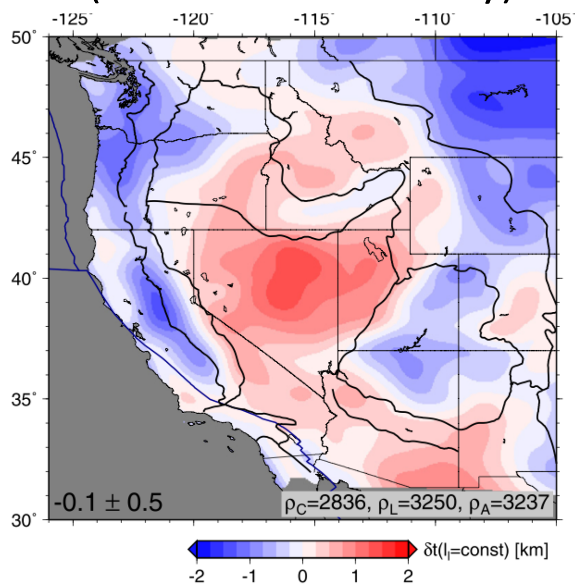
Upper mantle heterogeneity and convection:

High power at short wavelengths and need for non-thermal effects

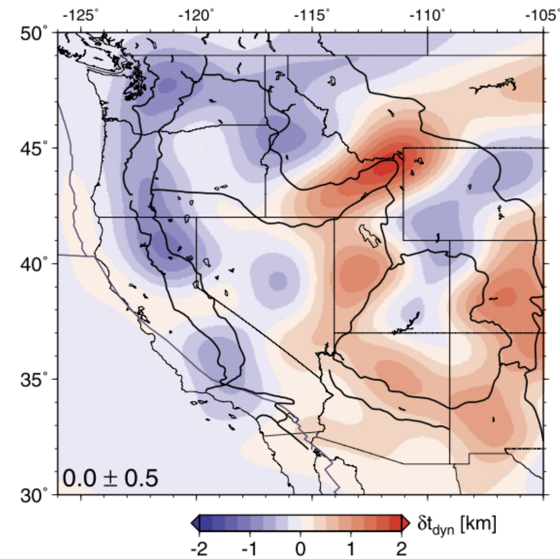
Vs tomography (60 – 160 km)



Residual Topography
(after crustal isostasy)



Mantle Flow Contribution



(Becker et al., 2013 EPSL)

Strong heterogeneity in upper 200 km. Mapping Vs tomography to temperature makes sense in some areas.

But this simple approach is obviously flawed over large areas of the western U.S. (especially Wyoming craton, Colorado Plateau, forearc/arc).

How to separate thermal and compositional effects?

Which structures are stable, buoyant, or dense?

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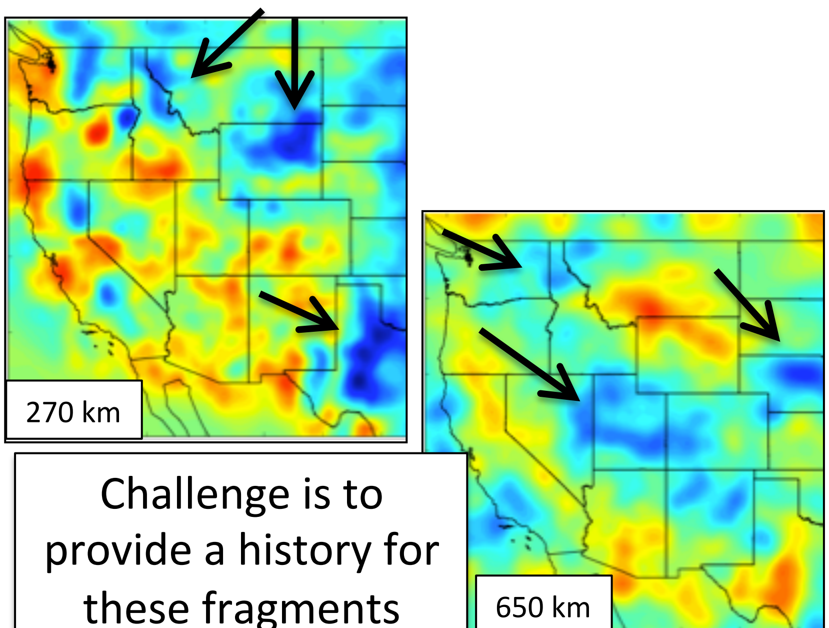
Segmented Slabs: causes and consequences?

Cenozoic slab is broken in fragments

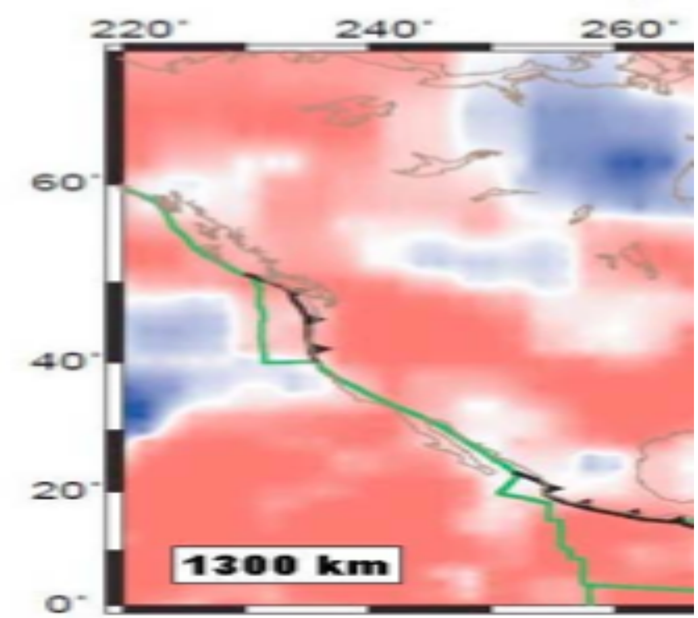
- Did rupturing events matter for the upper plate?
- What tectonic conditions, properties of slabs allow segmentation to occur?

Cenozoic slab?



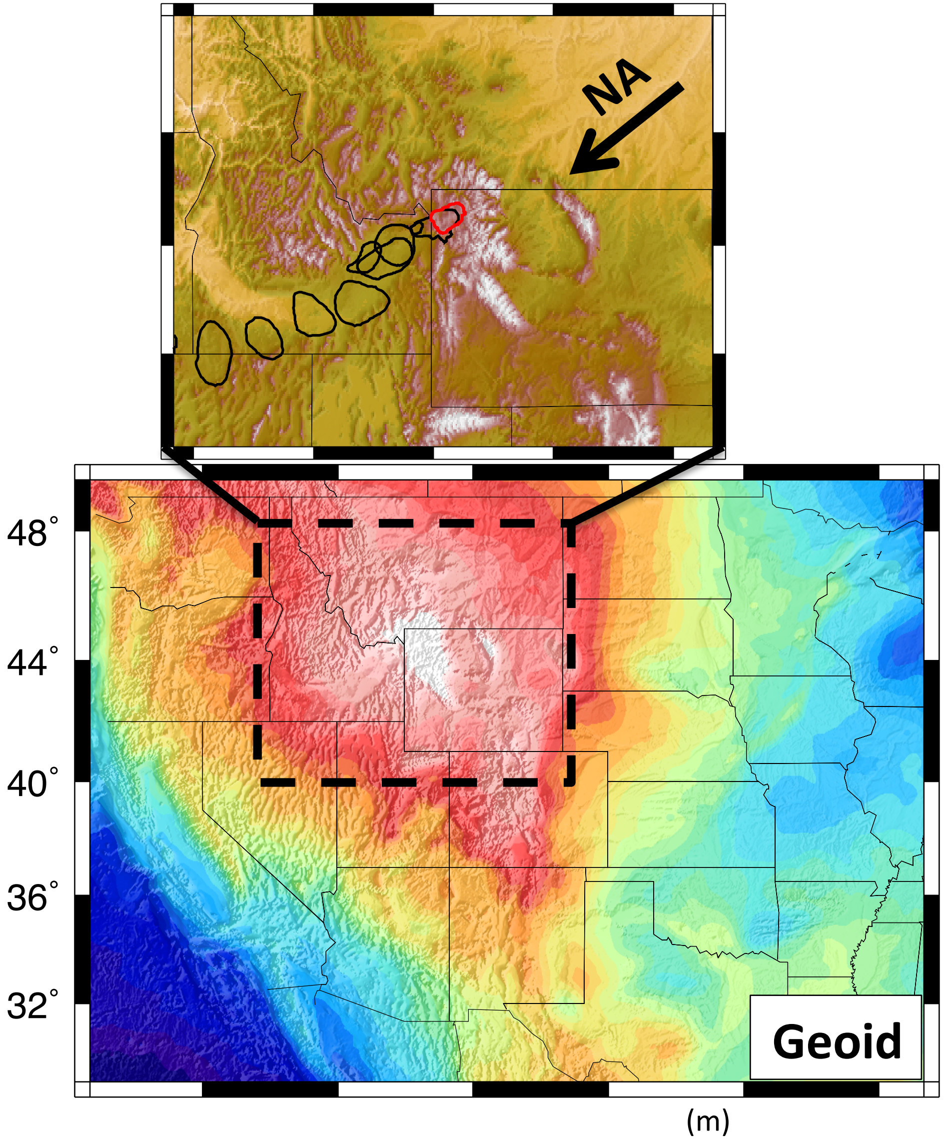
Challenge is to provide a history for these fragments

Cretaceous slab



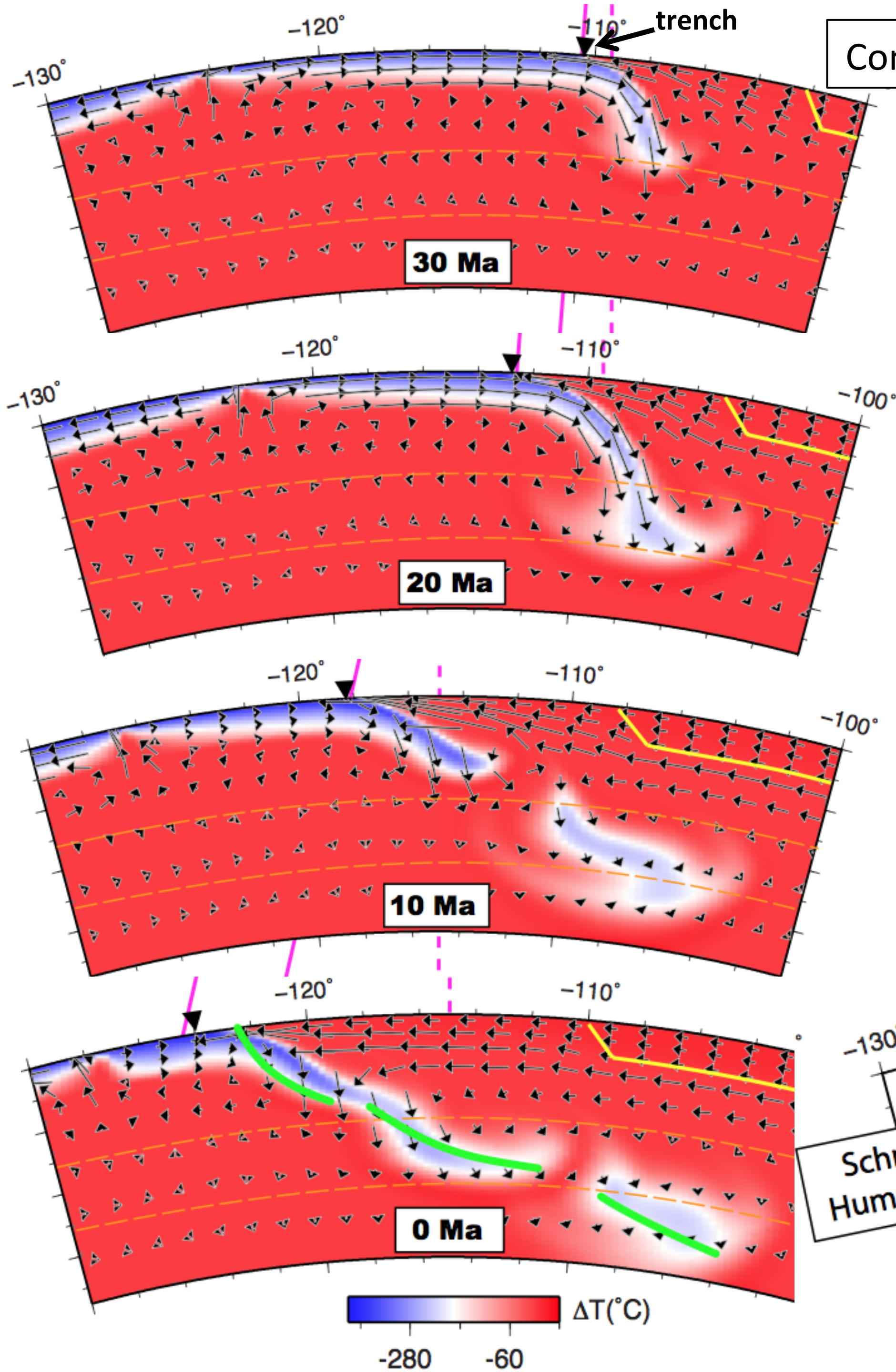
(S. Grand)

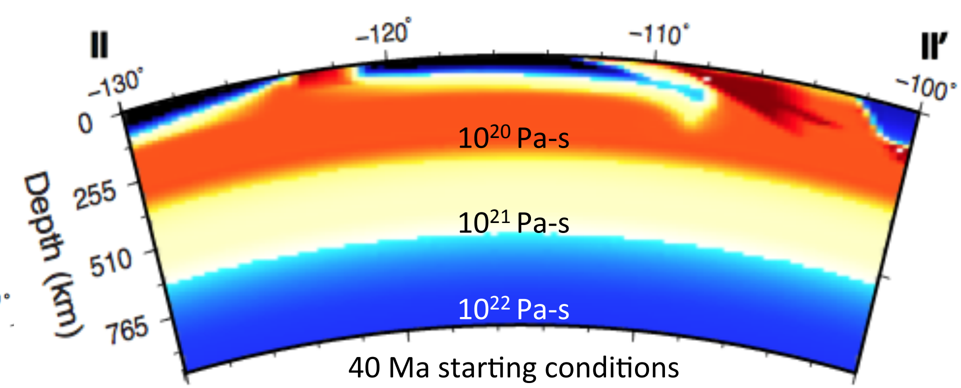
A slab rupture hypothesis that is important for the upper plate – Origin of the Yellowstone Hotspot



If the Yellowstone hotspot is driven by a lower mantle plume,
the plume would need a pathway through subducted slabs beneath the northwest U.S.

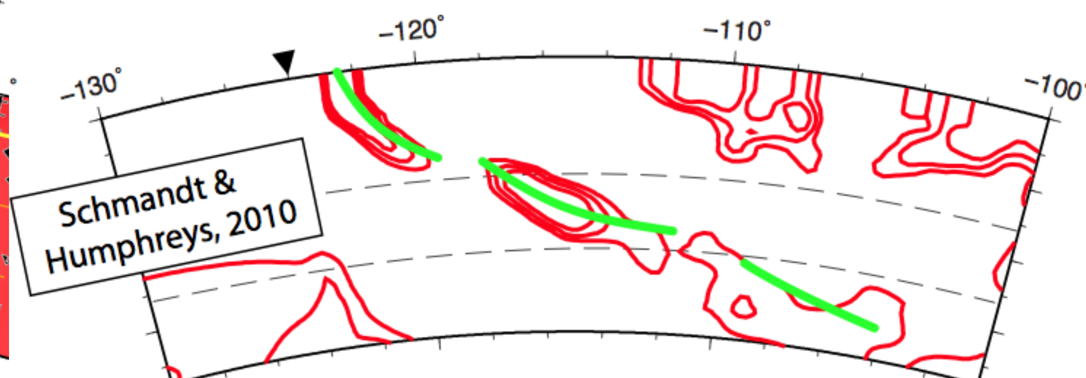
Convection modeling from Liu & Stegman (Illinois, Scripps)



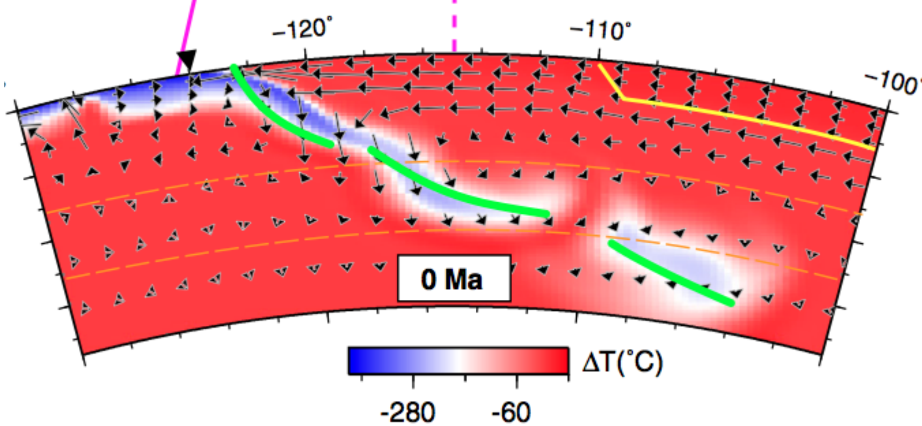


1) Trench retreat
2) increase in viscosity with depth,
3) a young/weak slab

Creates trench-normal slab segmentation similar to that imaged

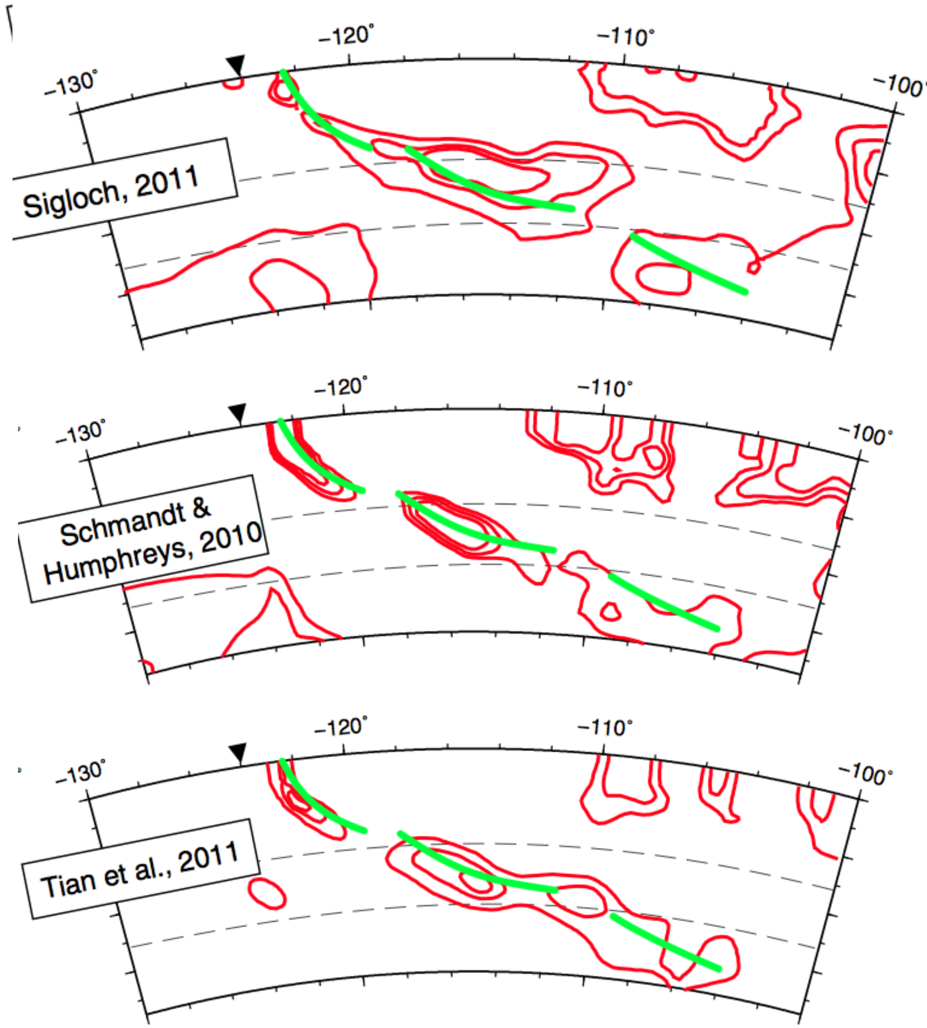


(Liu & Stegman, 2011 EPSL)



Along this latitude (~41 N), Tomography is generally consistent with expectations for subduction since about 40 Ma

Based on plate tectonic reconstructions (Muller et al., 2008) and convection modeling (Liu and Stegman, 2011)

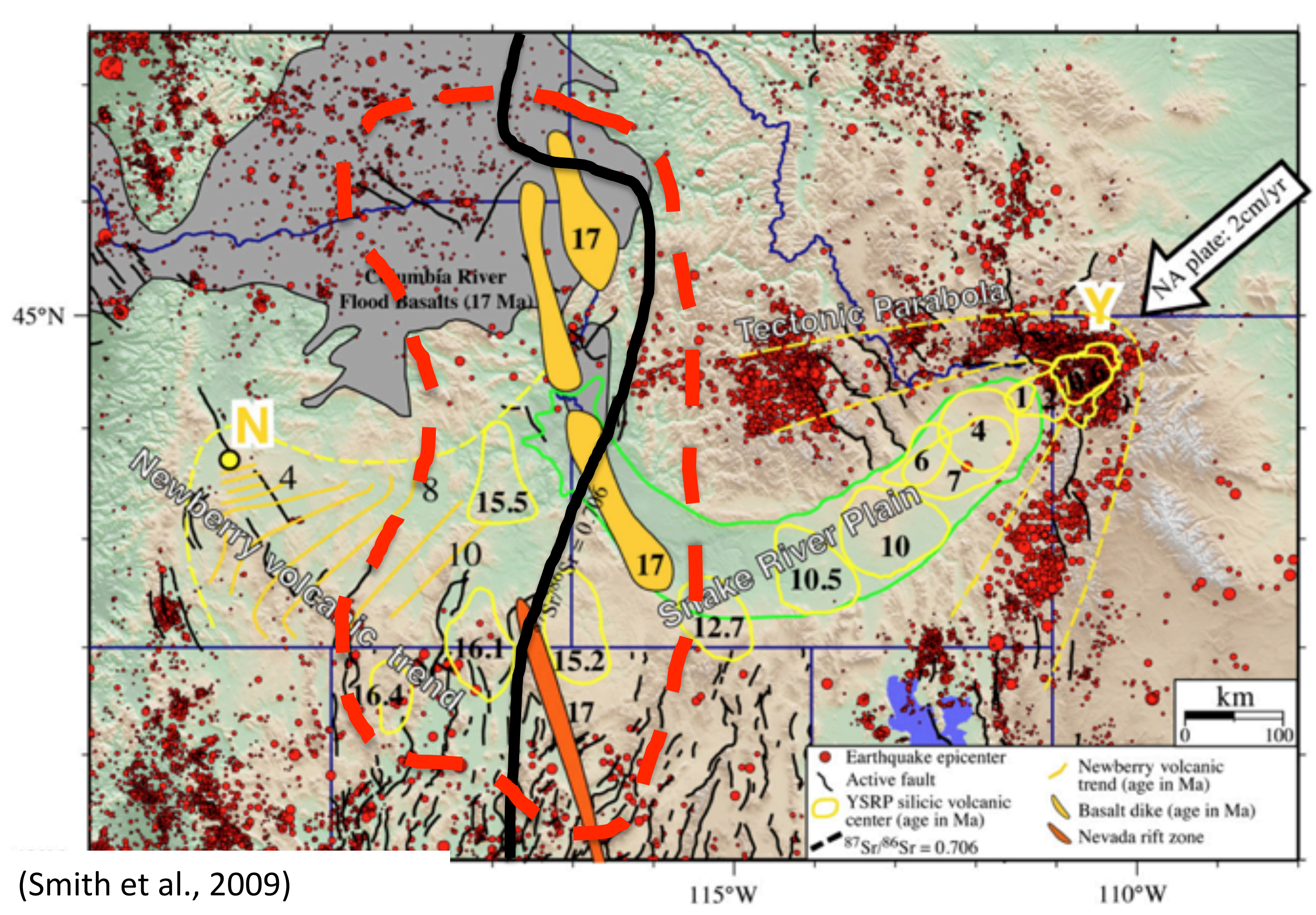


A BIG transition in western U.S. magmatism

17 Ma initiation of voluminous magmatism in N-S trend near the Sr 0.706 l

… Yellowstone plume first reaches the base of NA?

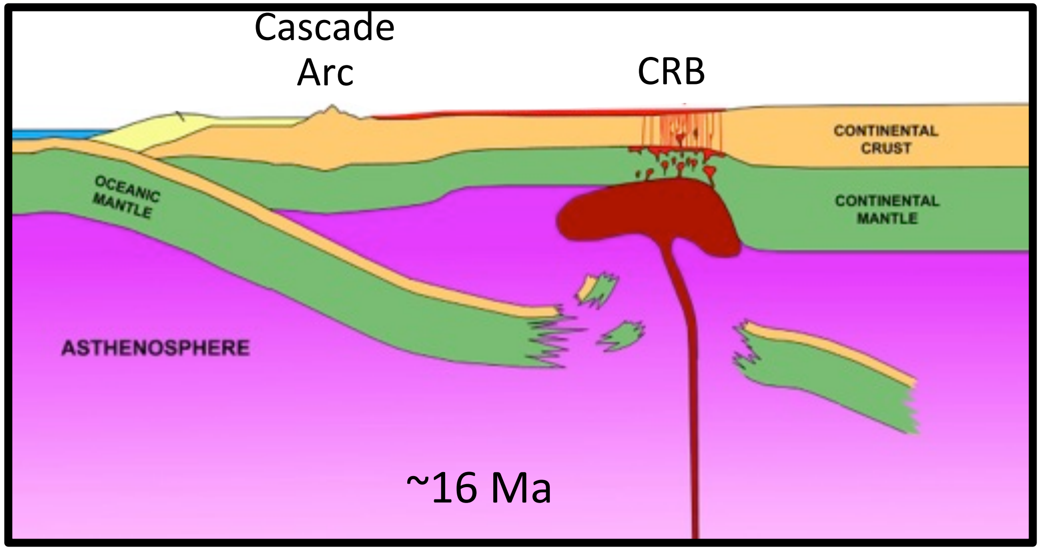
17-15 Ma major silicic and basaltic eruptions



(Smith et al., 2009)

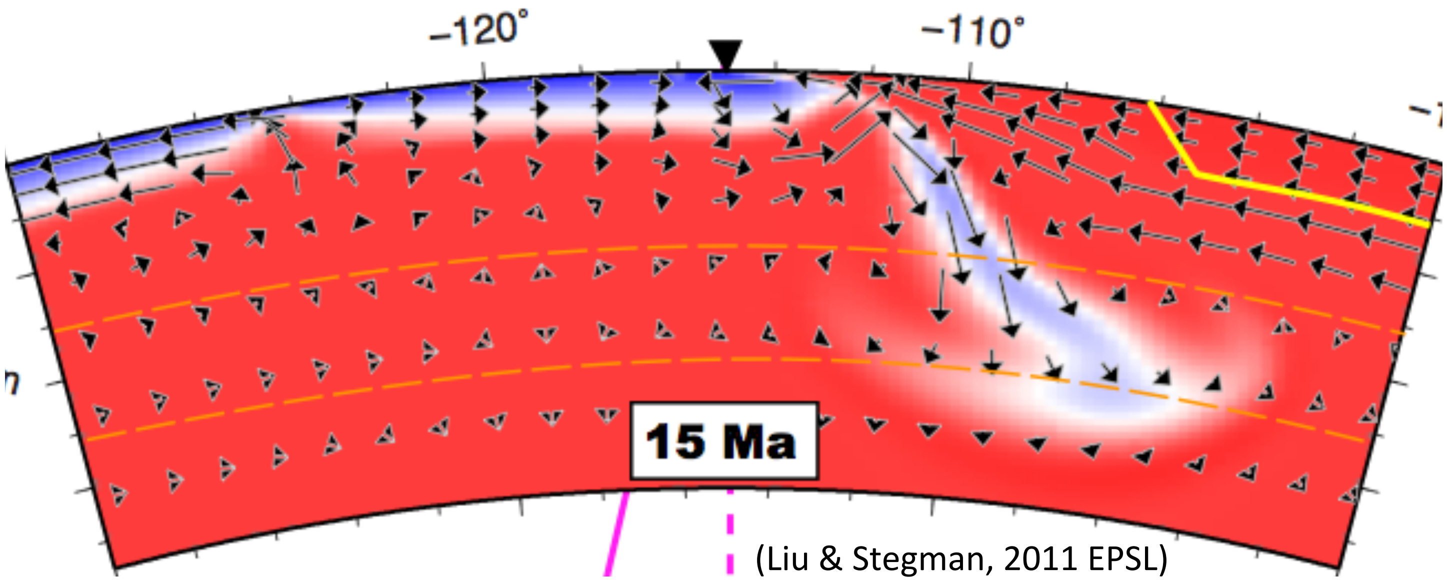
Segmentation driven by:

1) Roll-back of young weak slab (Liu & Stegman, 2011)
2) Vertical load and heat of the buoyant plume (Geist and Richards, 1993)
3) both?



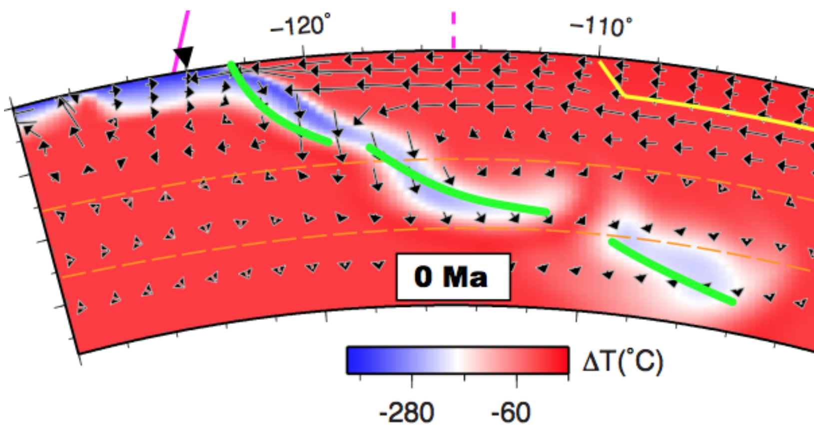
(from Vic Camp)

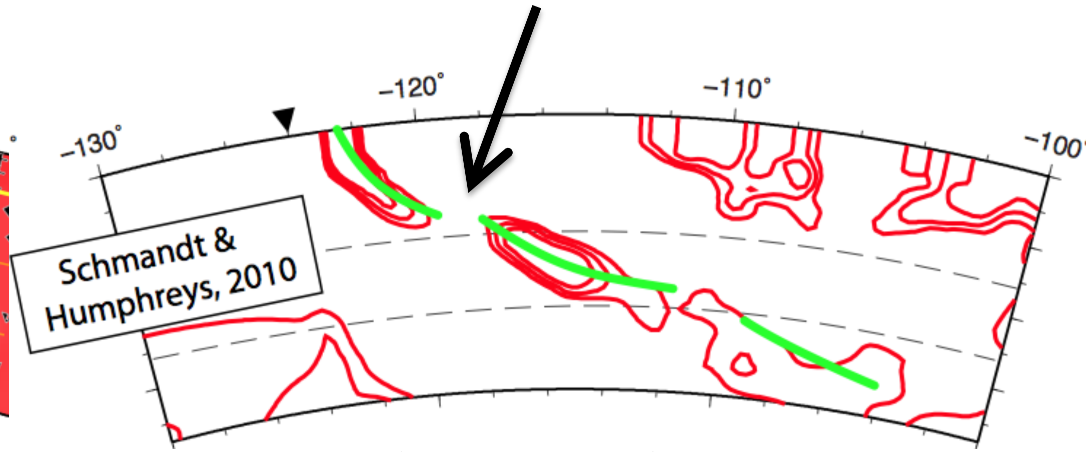
Slab segmentation at about the right time without a plume



(Liu & Stegman, 2011 EPSL)

A more recent slab rupture, how did this affect the upper plate?



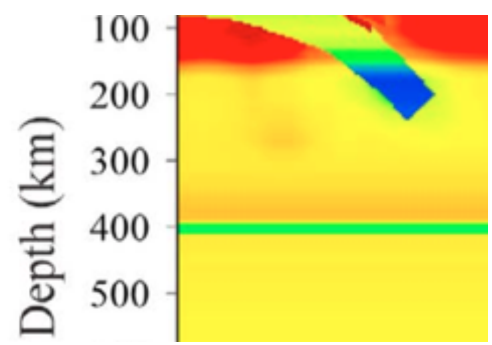


(Liu & Stegman, 2011)

This trench-normal break is not predicted by the Liu and Stegman 2011 model

It is clearly detected with seismic imaging, even obvious in raw travel-times

Must have occurred since 10 Ma



P waveform modeling suggests JdF slab continuous only to ~250 km

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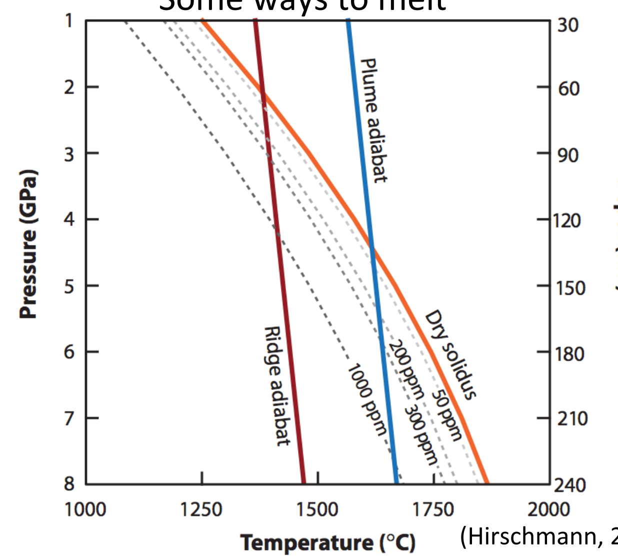
Mantle melting and migration of melt, volatiles through the lithosphere

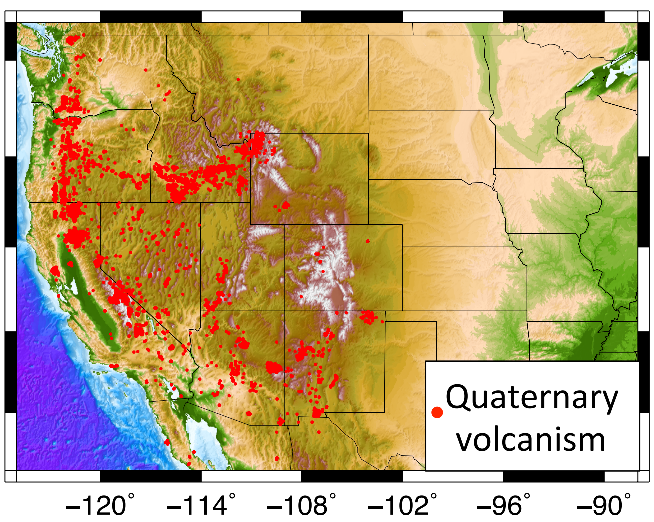
- What drives melting beneath the plate interior?

- Identifying melt
  - Seismic (Vp, VS)
  - MT (if interconnected over large distances)

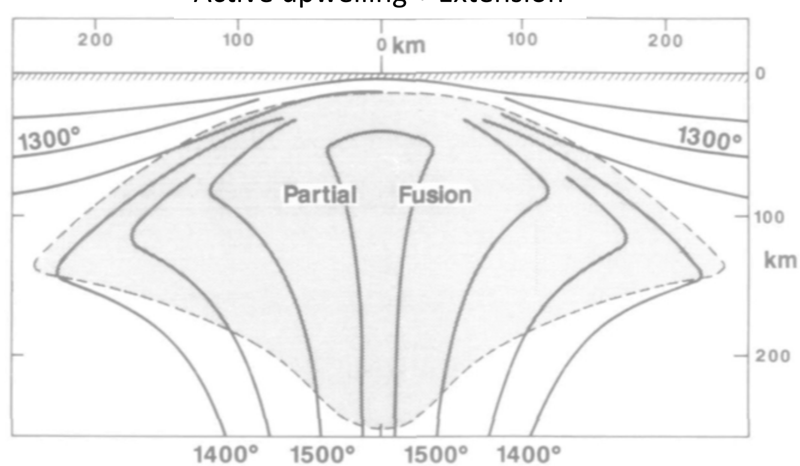
Some ways to melt



(Hirschmann, 2006)



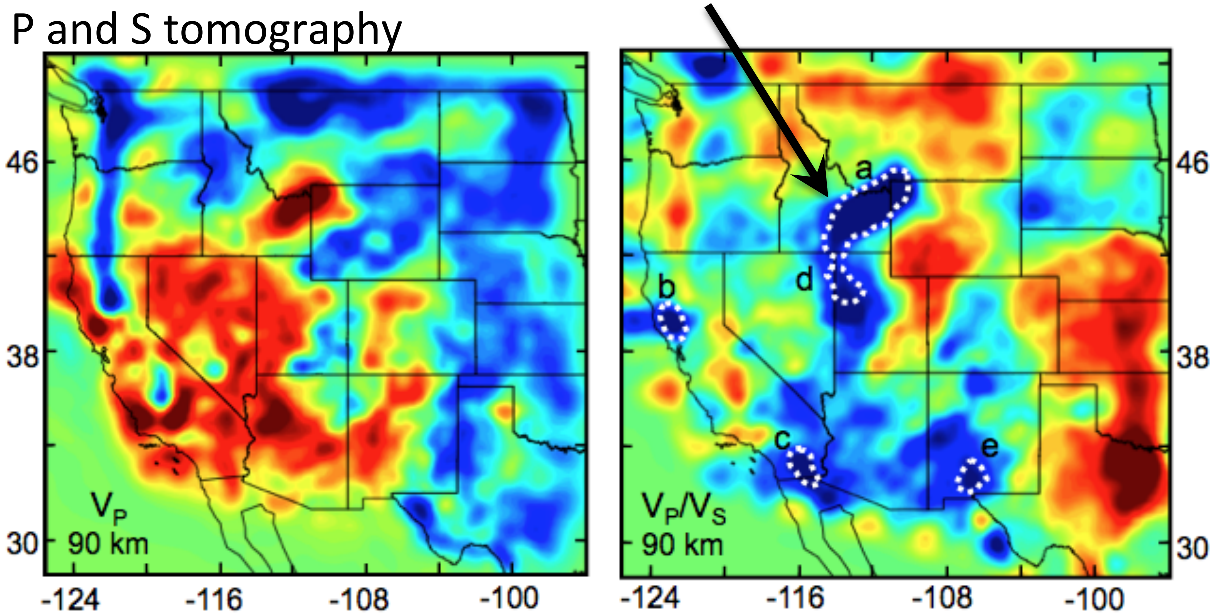
Active upwelling + Extension



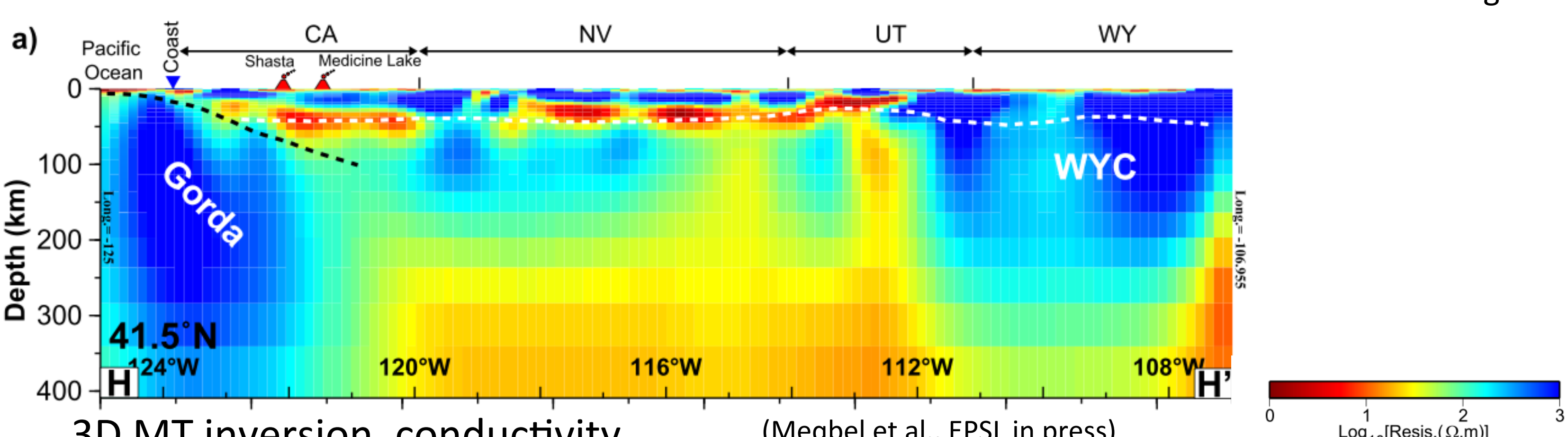
(McKenzie &Bickle, 1988)

Mantle melting and migration of melt, volatiles through the lithosphere

P and S tomography



- What drives melting beneath the plate interior?
- Identifying melt
  - Seismic (Vp, Vs)
  - MT (if interconnected over large distances)



3D MT inversion, conductivity

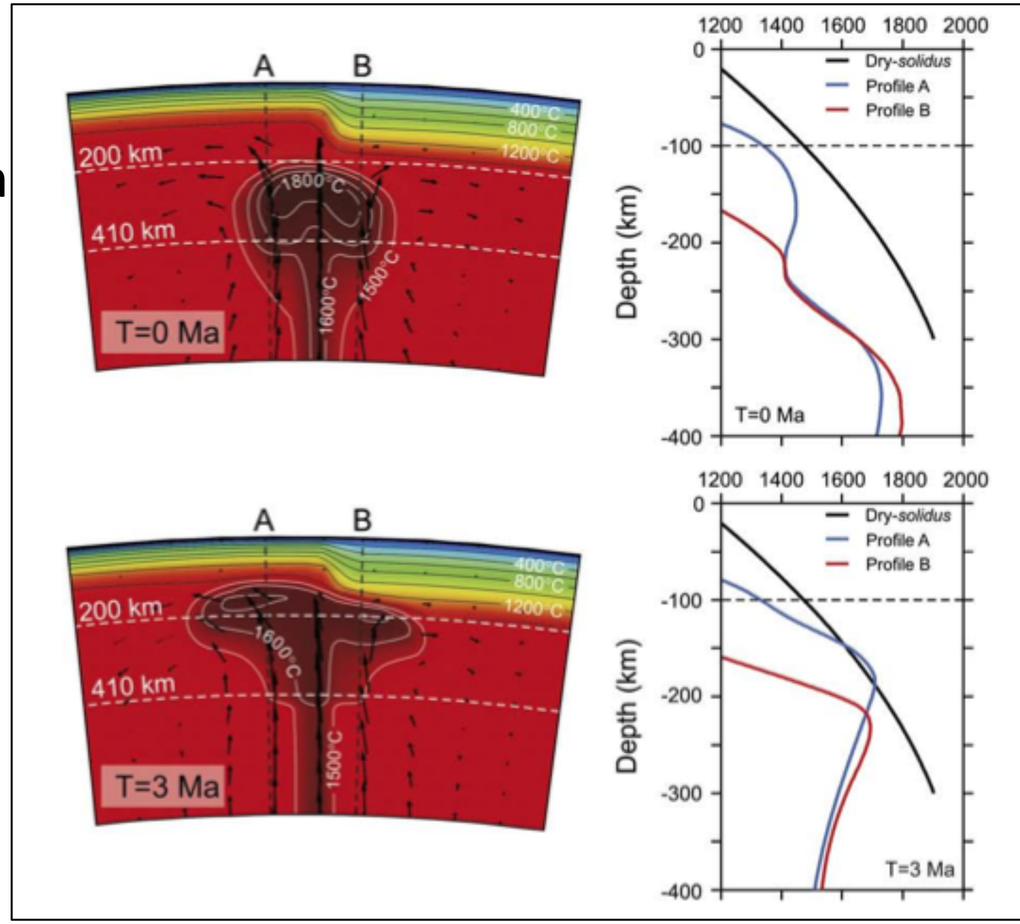
(Meqbel et al., EPSL in press)

Melt generation and migration through the lithosphere – **the Yellowstone Hotspot**

- How does the deep heat source create a focused hotspot track in thick continental lithosphere?
- Expected to impinge on lithosphere before dry solidus

Or

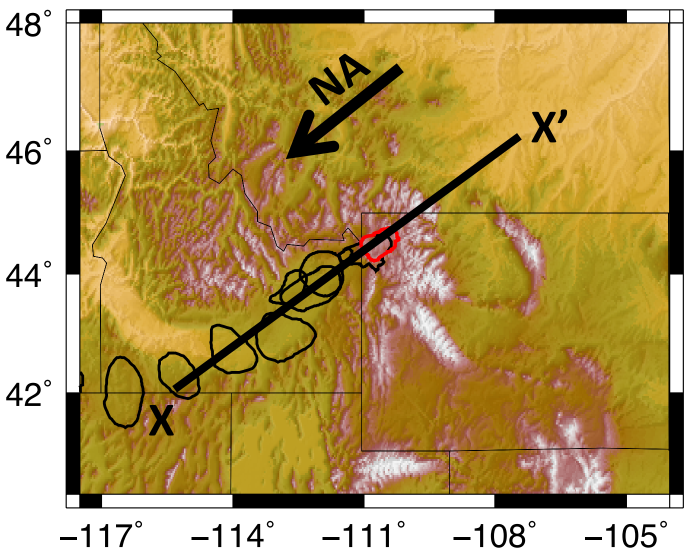
- – Or Precambrian NA lithosphere at 15 Ma was much thinner?
- – Or thinning of old lithosphere is more rapid than modeled? (feedbacks related to extension and/or deep low-degree damp melting, different rheology?)

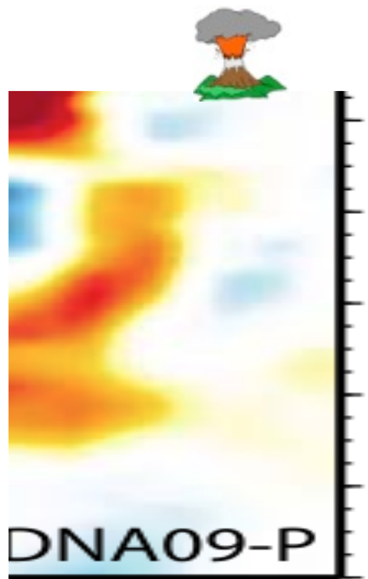


(Manea et al., 2009 JVGR)

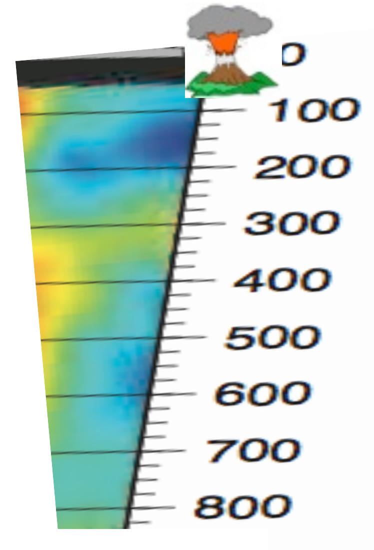
USArray imaging beneath Yellowstone

A vertically heterogeneous low-velocity anomaly extending into the lower mantle in all USArray tomography models. Three examples:

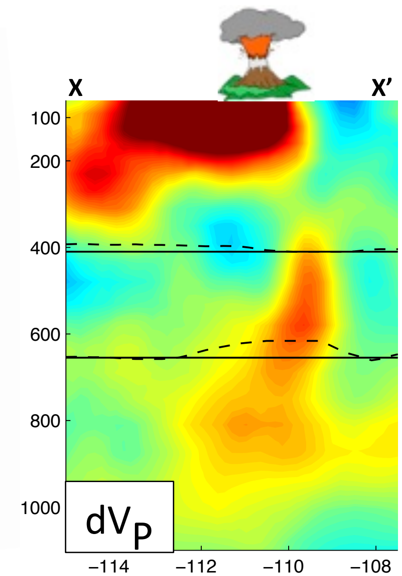




(Obrebski et al., 2010)

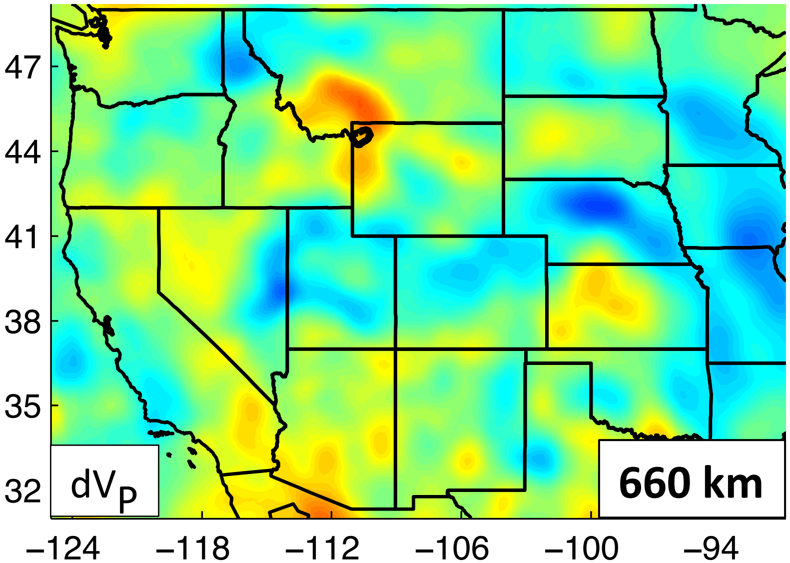


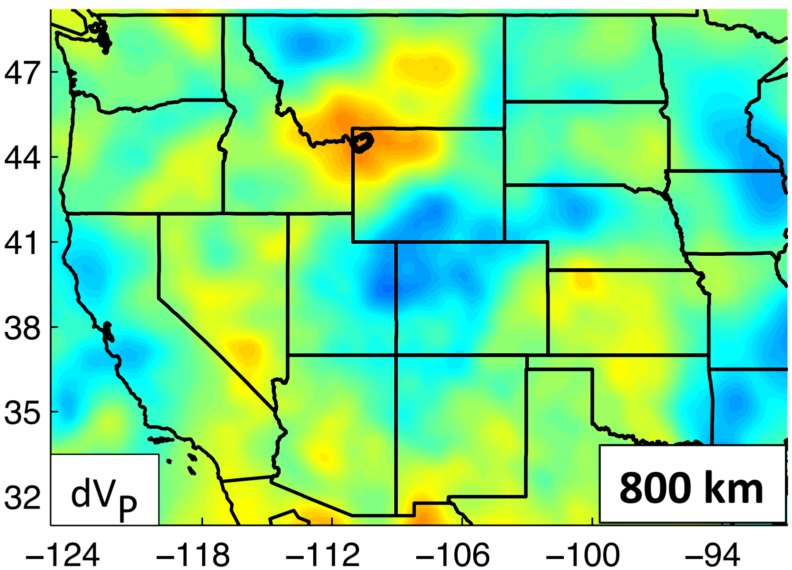
(James et al., 2011)



(Schmandt & Humphreys)

P tomography

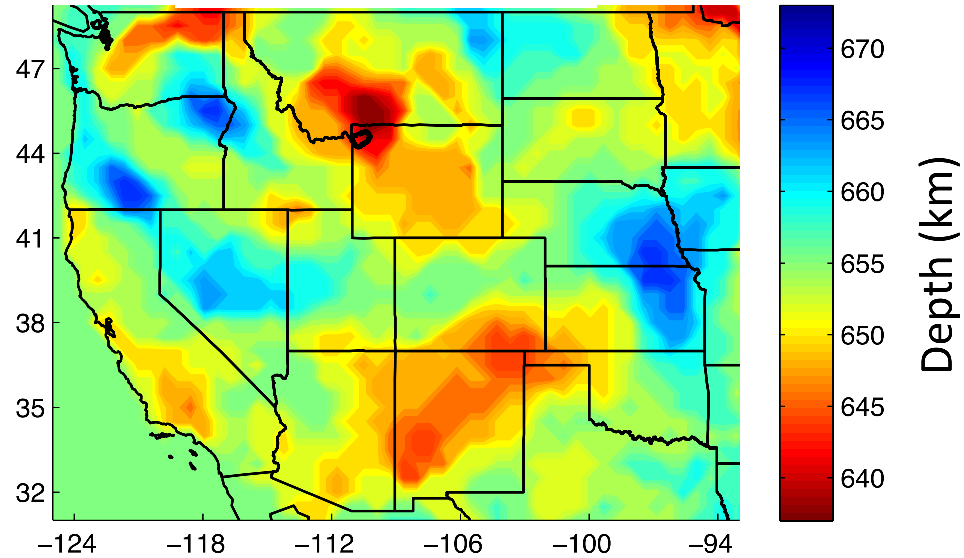




- 2.5 + 2.5

dV_P (%)

660 Topography



Shallowest 660 beneath USArray (~635 km)

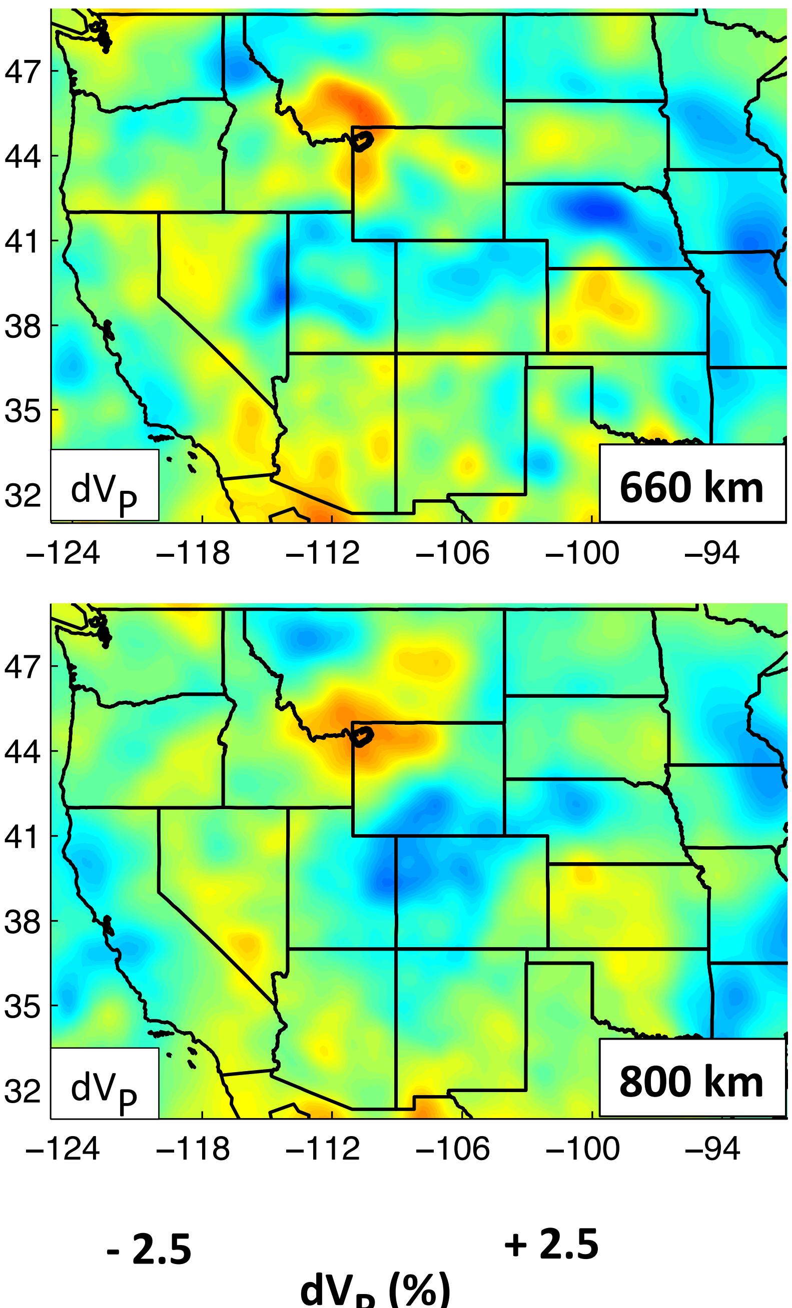
and

Strongest low-velocity anomaly from 500-900 km depth

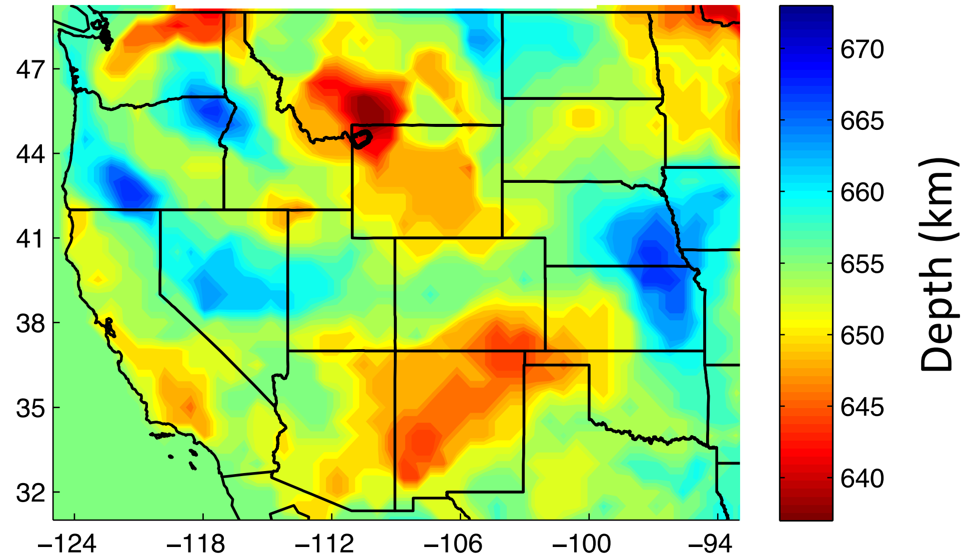
both underlie the Yellowstone hotspot

→ narrow hot upwelling (plume) across the lower-upper mantle boundary

P tomography



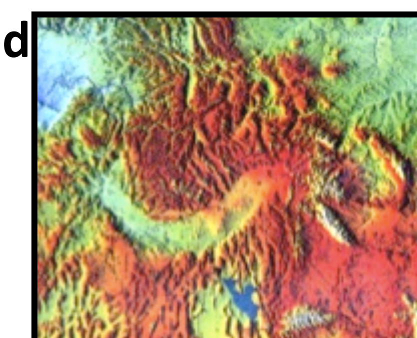
660 Topography



Temperature ~170-250 K higher than average at 660 km is consistent with both tomography and 660 topography

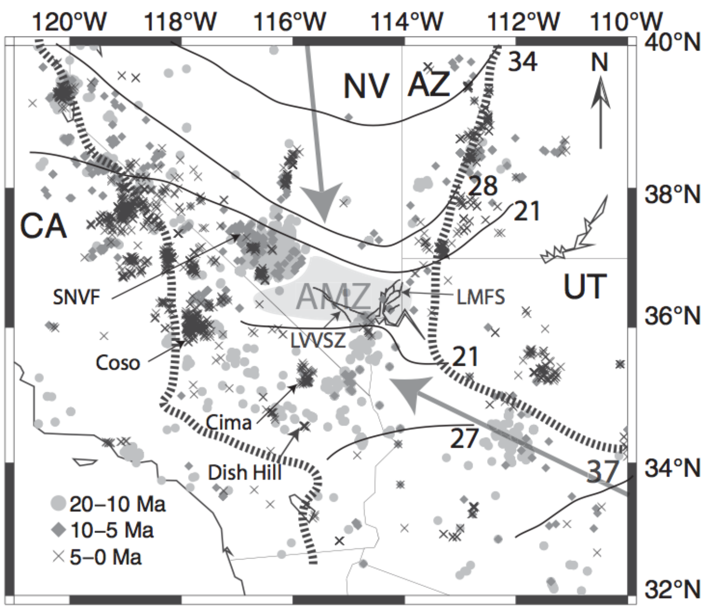
(depends on postspinel Clapeyron slope and anelastic dV/dT near 660)

How does this deep heat source create such a focused swath of volcanism in Precambrian continental lithosphere?

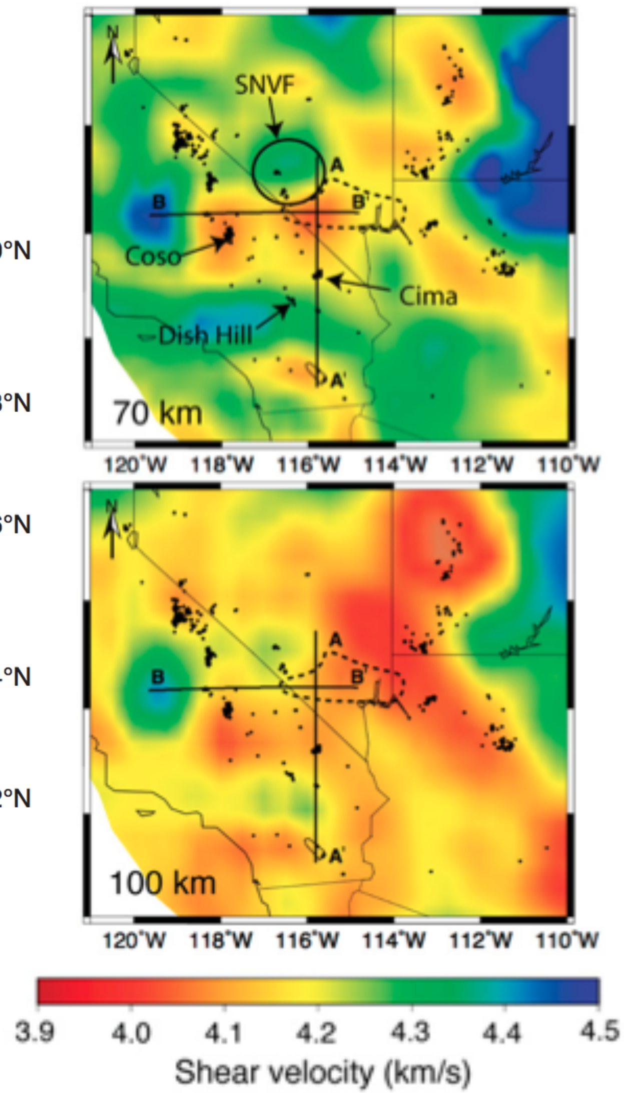


Melt generation and migration through the lithosphere – **when melt can't get through**

Melt beneath the Amagmatic Zone



(Rau and Forsyth, 2012 Geology)



Extension Miocene to present

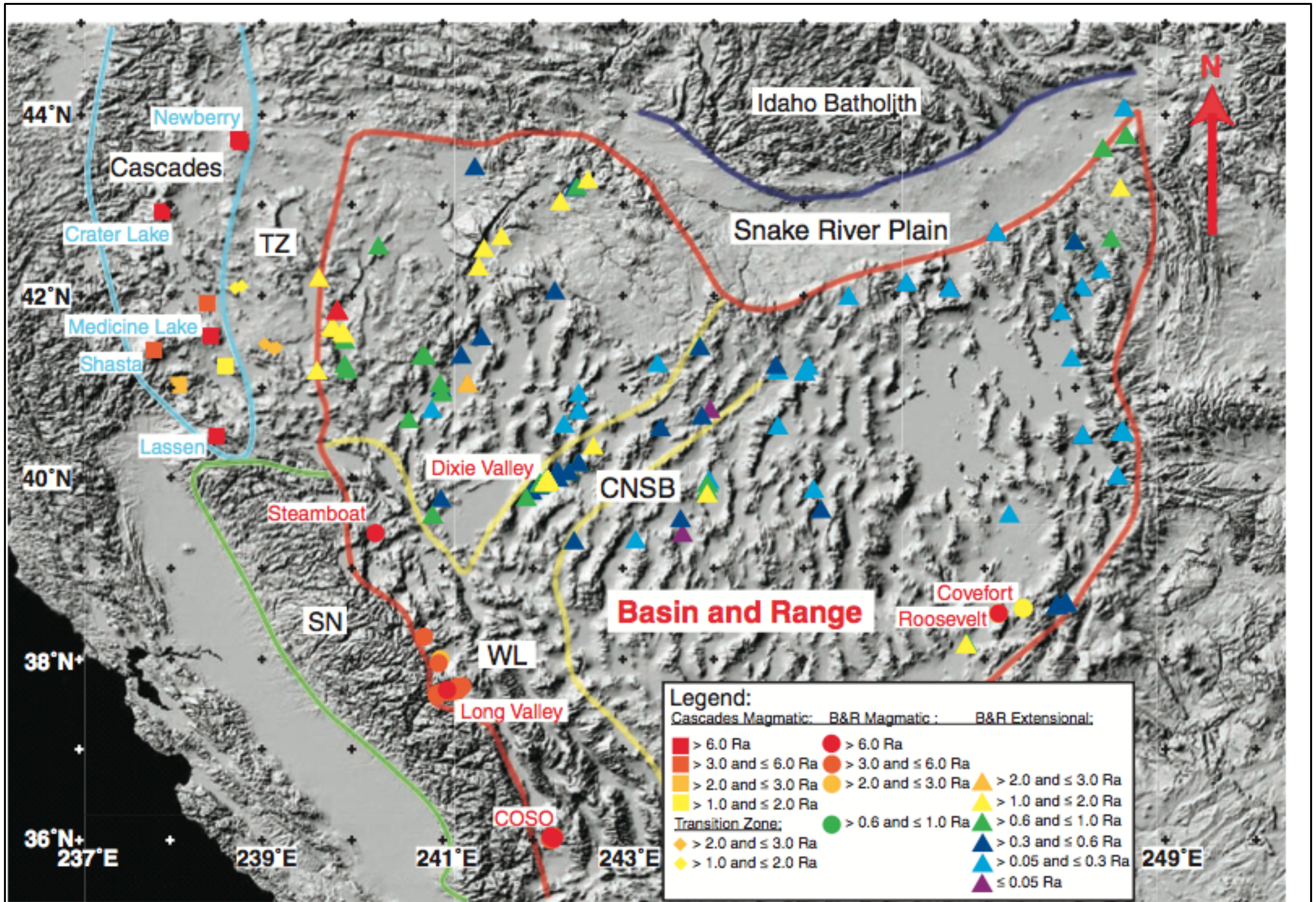
Melt in the shallow upper mantle today

But no magmatism.

(Rau and Forsyth, 2012)

What controls variations in permeability?

Mantle melting and migration of melt, volatiles through the lithosphere – mantle volatiles at the surface

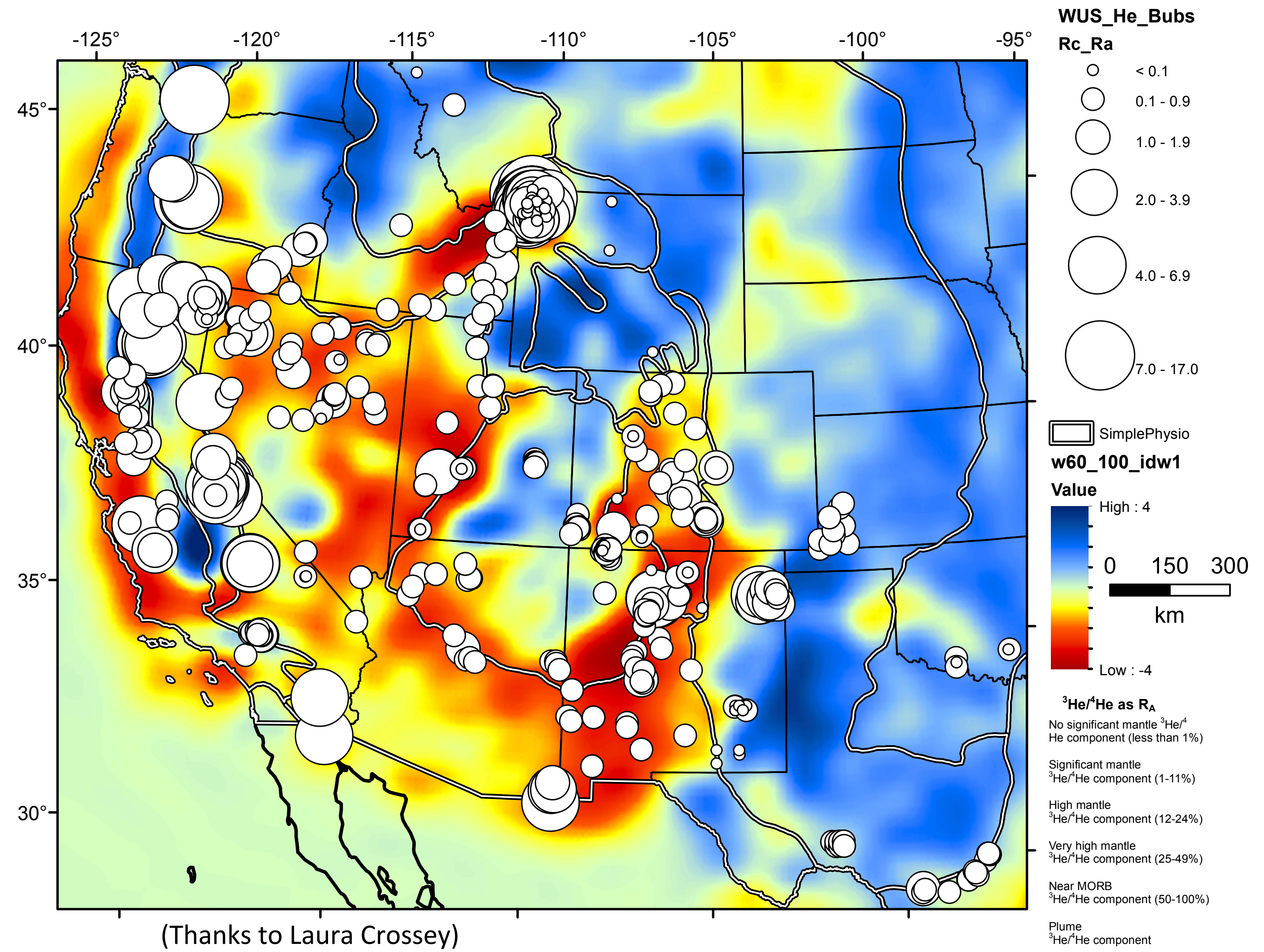


(Kennedy and van Soest, 2007 Science)

Mantle helium concentrations in Basin and Range correlated with horizontal strain rates

Motivated hypothesis that high strain rate and/or magmatism are necessary to get mantle volatiles through the ductile lower crust

Getting mantle volatiles to the surface, nearly everywhere



(Thanks to Laura Crossey)

$^3He/^4He$ from springs

Similarly high $^3He/^4He$ reaching surface in high and low strain rate regions

What controls permeability and volatile infiltration rates into lithosphere?

Challenges in lithospheric dynamics – Examples motivated by EarthScope

1) Multi-scale heterogeneity and convection

2) Segmented Slabs – causes and consequences

3) Mantle melting, migration of melts and volatiles through lithosphere

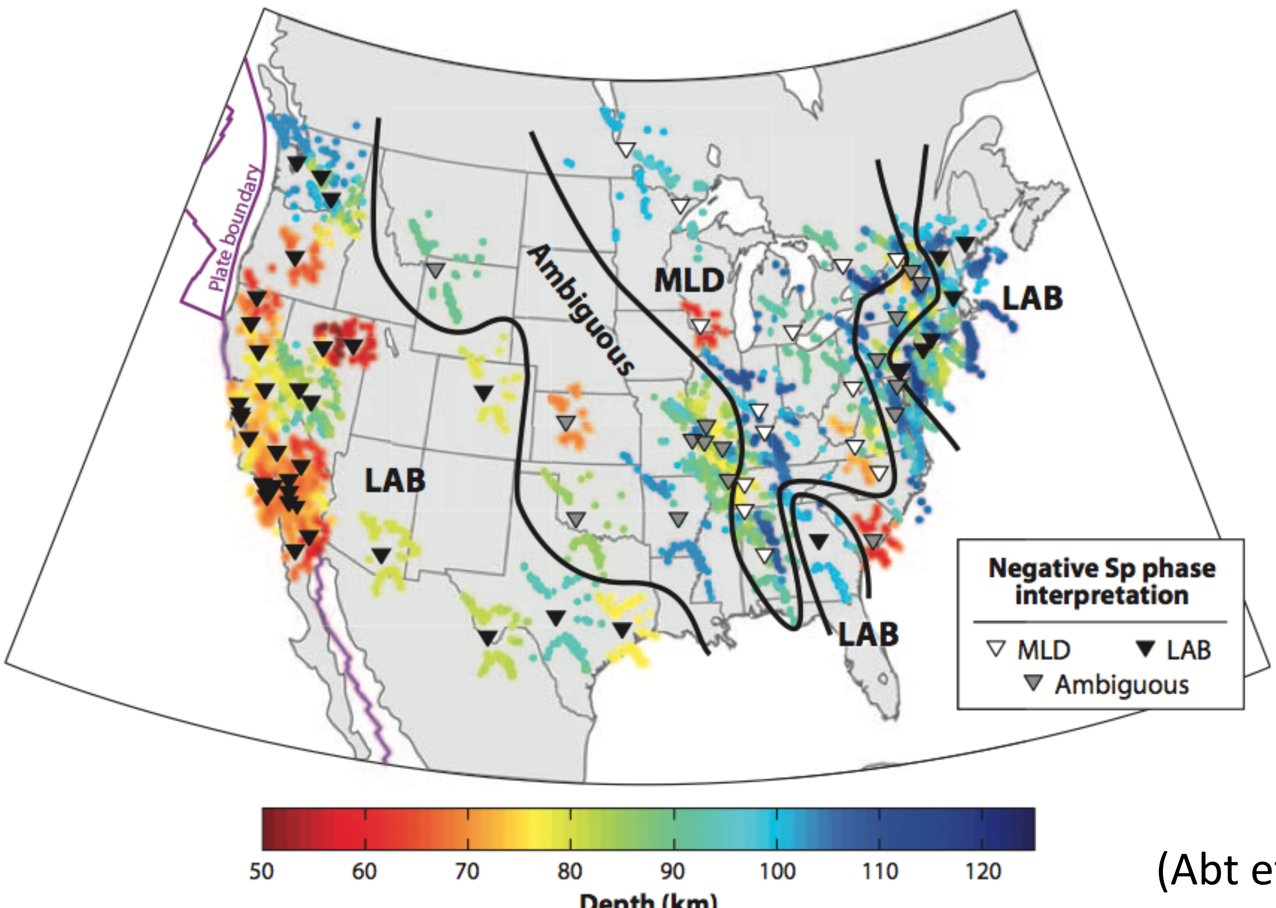
3.5?) Structure and origin of continental mantle

4) Vertical motions at the surface

Structure and Origin of Continental Mantle

Origin of widespread sharp negative velocity gradients in the upper 200 km?

How do they correlate with proxies for TBL thickness and tectonic boundaries?

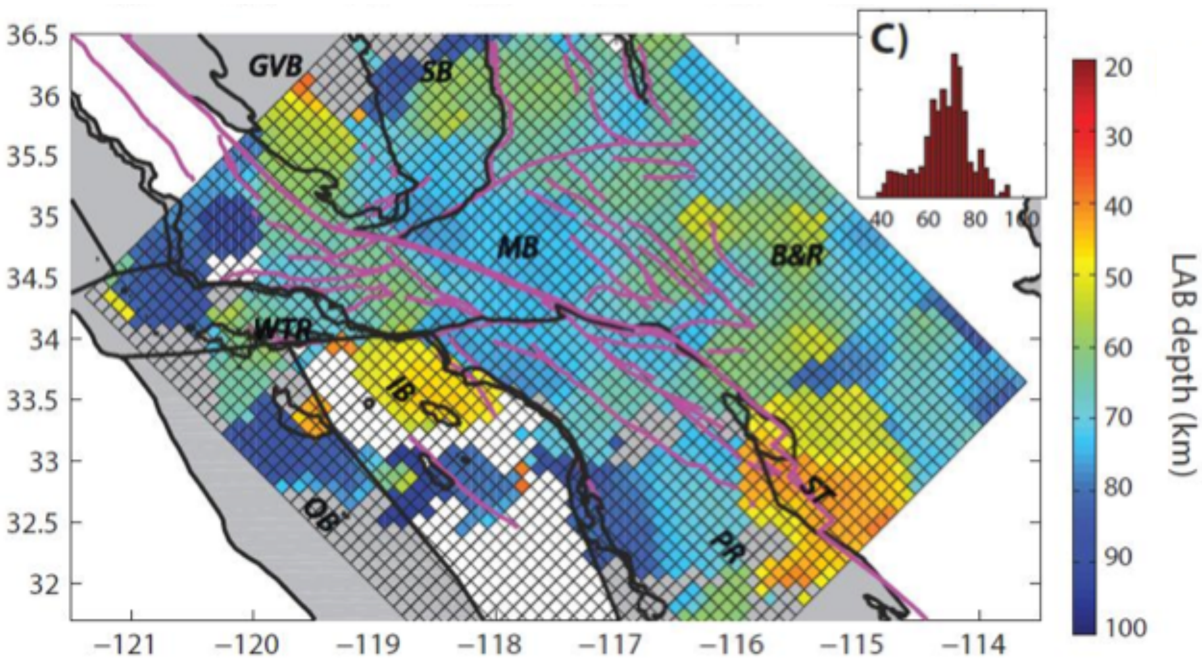


(Abt et al., 2010 JGR)

Stratification of the upper mantle beneath continents

Origin of sharp negative velocity gradients?

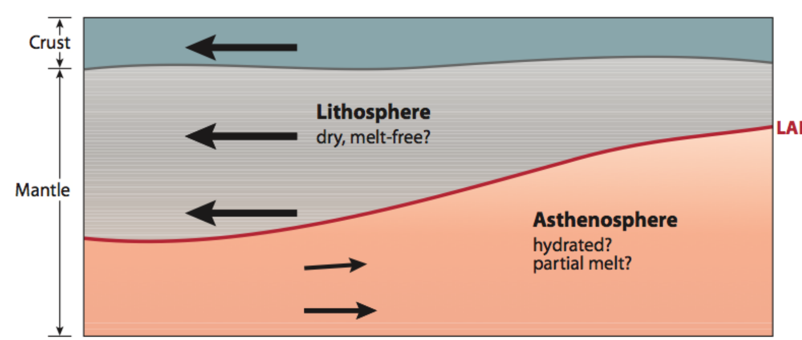
– The Lithosphere-Asthenosphere Boundary



(>10 yrs data, <40 km station spacing)

Consistent with surface wave tomography

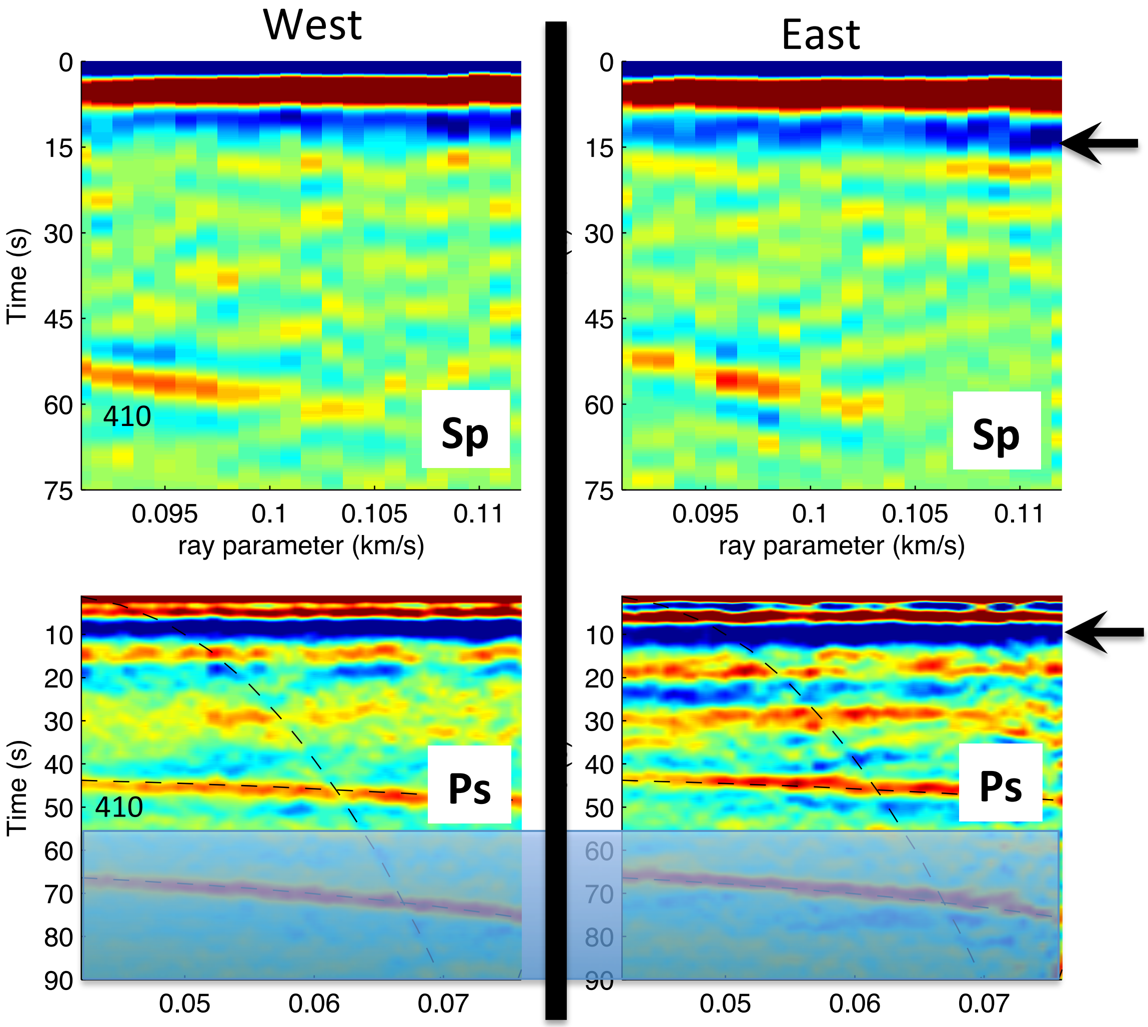
Shallows in rifted regions of southern California
(Lekic et al., 2011 Science)

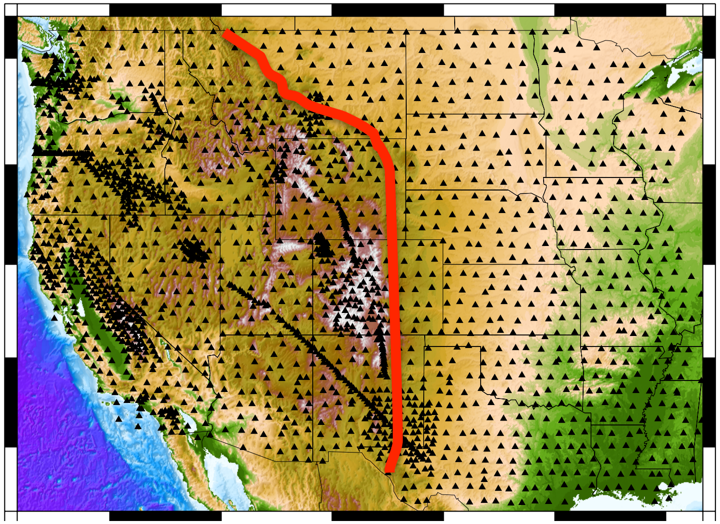


Fischer et al., 2010

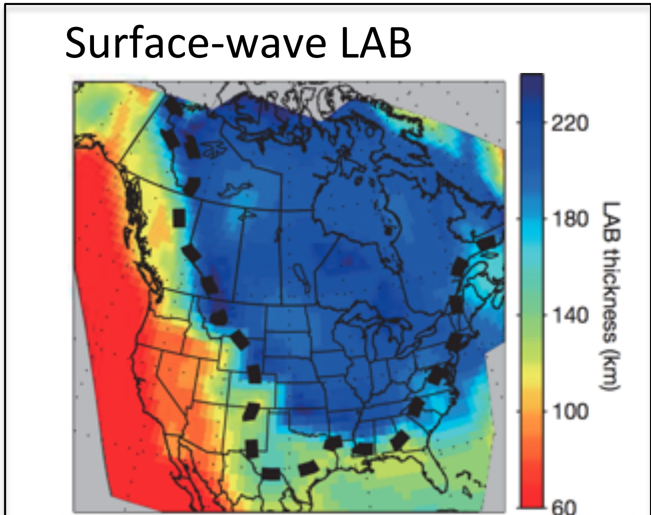
Stratification of the continental mantle

Average depth to negative gradient is deeper by only about 20-30 km east of the Rocky Mountain Front – must be a mid-lithospheric discontinuity (MLD) where TBL is thick



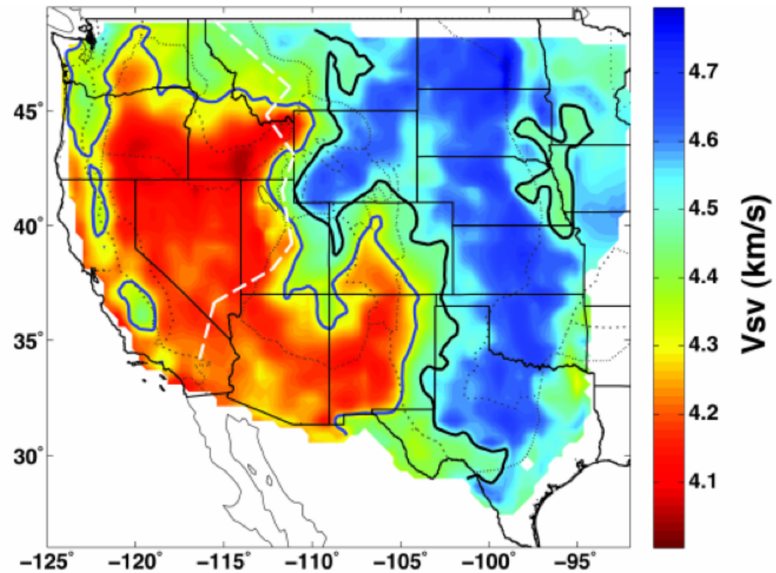


Sp receiver functions from Katie Foster, Ken Dueker



Yuan and Romanowicz, 2010

Origin of sharp Vs decreases in the upper 125 km?



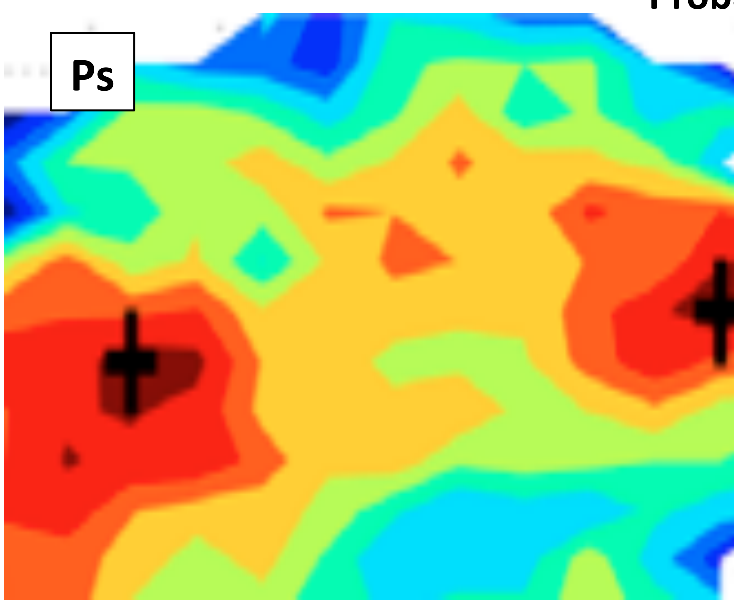
A test of temperature dependence:

1) Sp and Ps west of the Mississippi

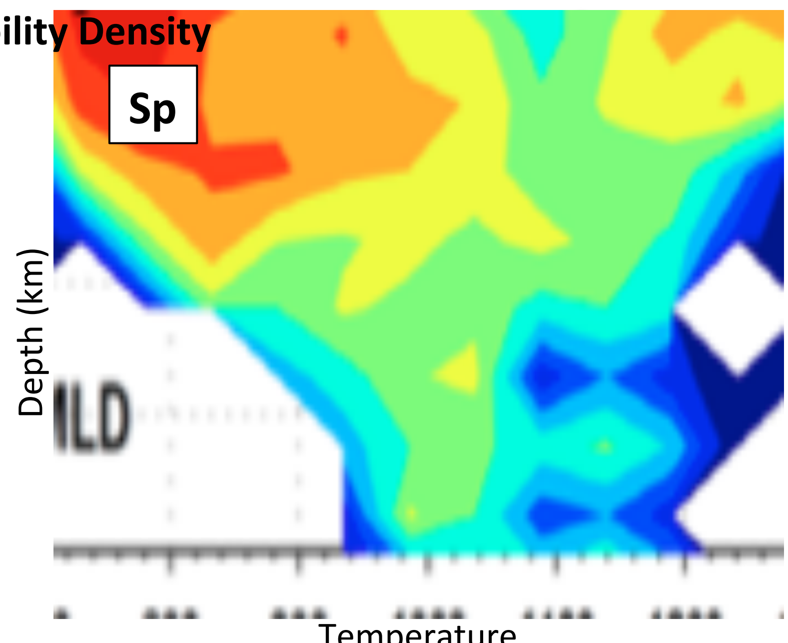
2) Vs from Rayleigh wave tomography
(Shen et al., 2013; Pollitz, 2013)

3) Anelastic Vs→temperature scaling
(Jackson and Faul, 2010)

Probability Density



(Thanks to Steve Hansen, Ken Dueker)

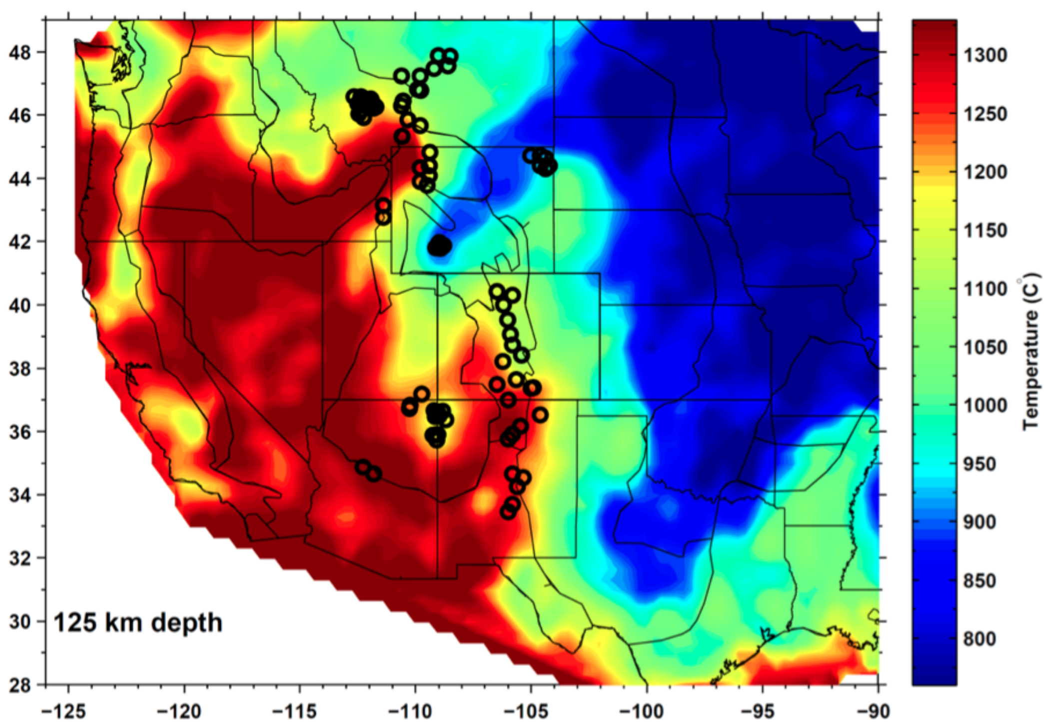


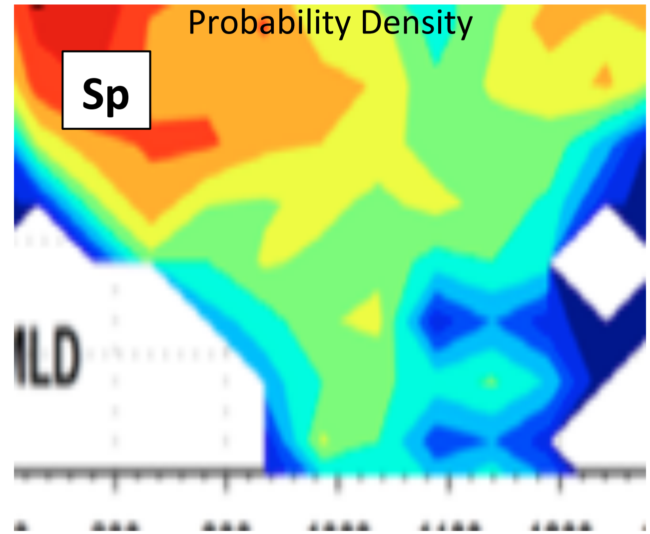
Is the MLD a result of metasomatism?

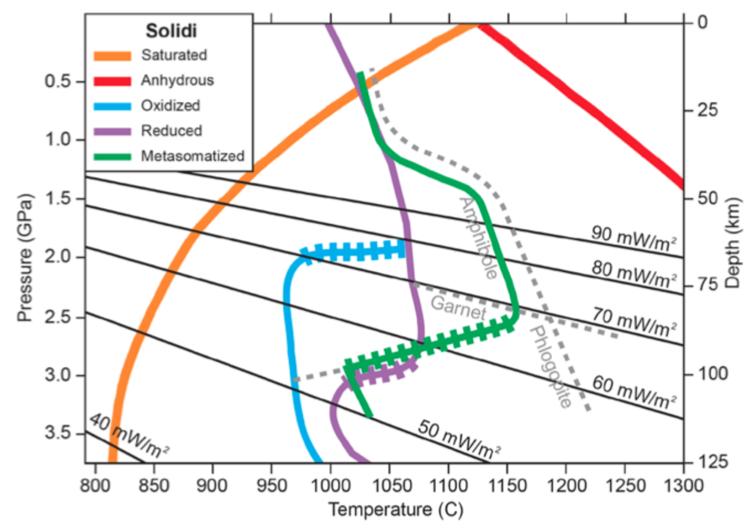
- Infiltration of small melt fraction, volatile-rich melts that freeze within the thick lithosphere

- Consistent with continuity across tectonic boundaries (in NA and Africa [e.g., Savage and Silver, 2008])

- Is the MLD-region the source of alkaline magmas, where thick cold lithosphere has been perturbed (e.g., Pilet et al., 2008)?







Challenges in lithospheric dynamics – Examples motivated by EarthScope

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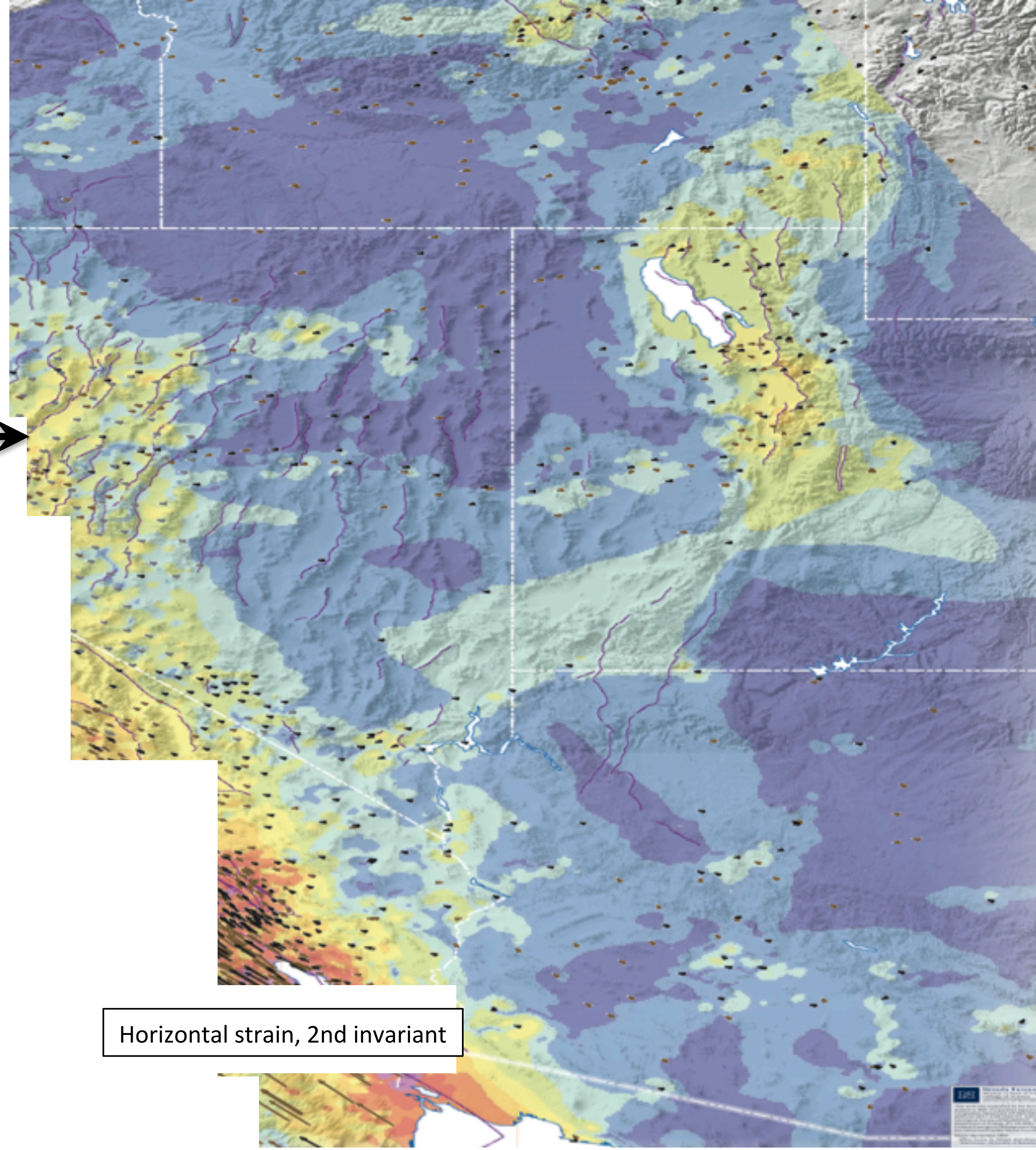
GPS Geodesy

Synoptic scale and increasingly long time-series

Horizontal kinematics have been widely used for a long time, increasingly valuable data in low-strain rate regions

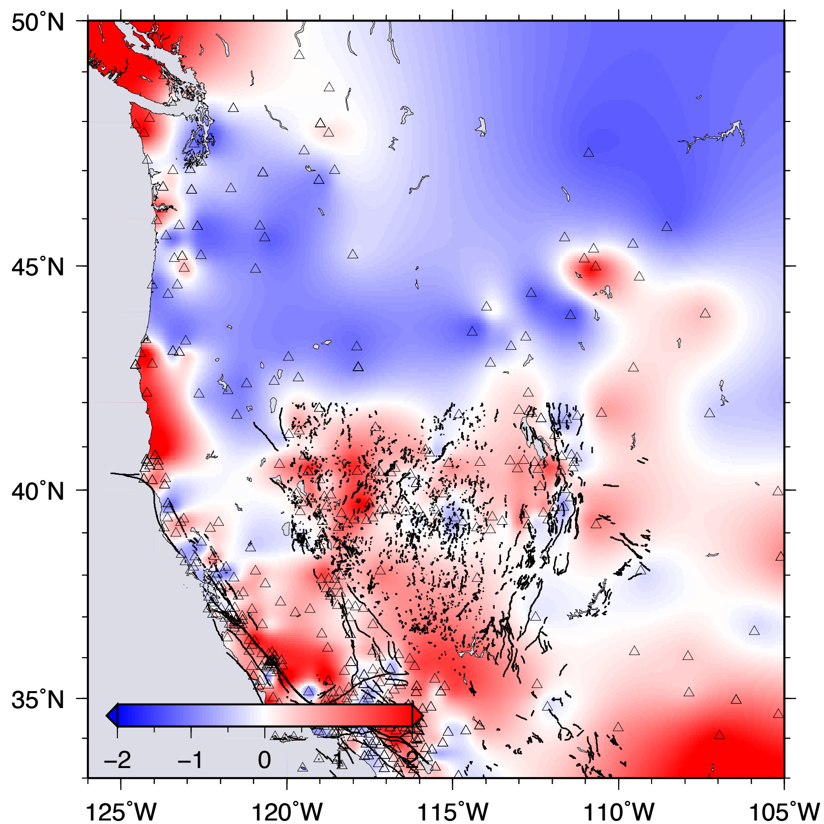
Vertical motions are becoming robust and pose interesting challenges to merging short-term and long motions

(Kreemer et al., 2013)



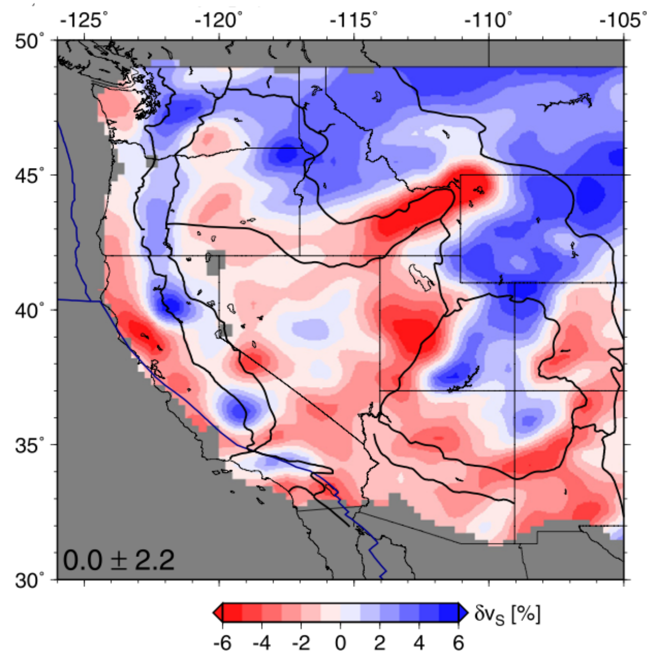
Vertical motions across the western U.S.

Vertical GPS – 100 km smoothing radius



(Thanks to Rick Bennett)

Vs tomography (60 – 160 km)

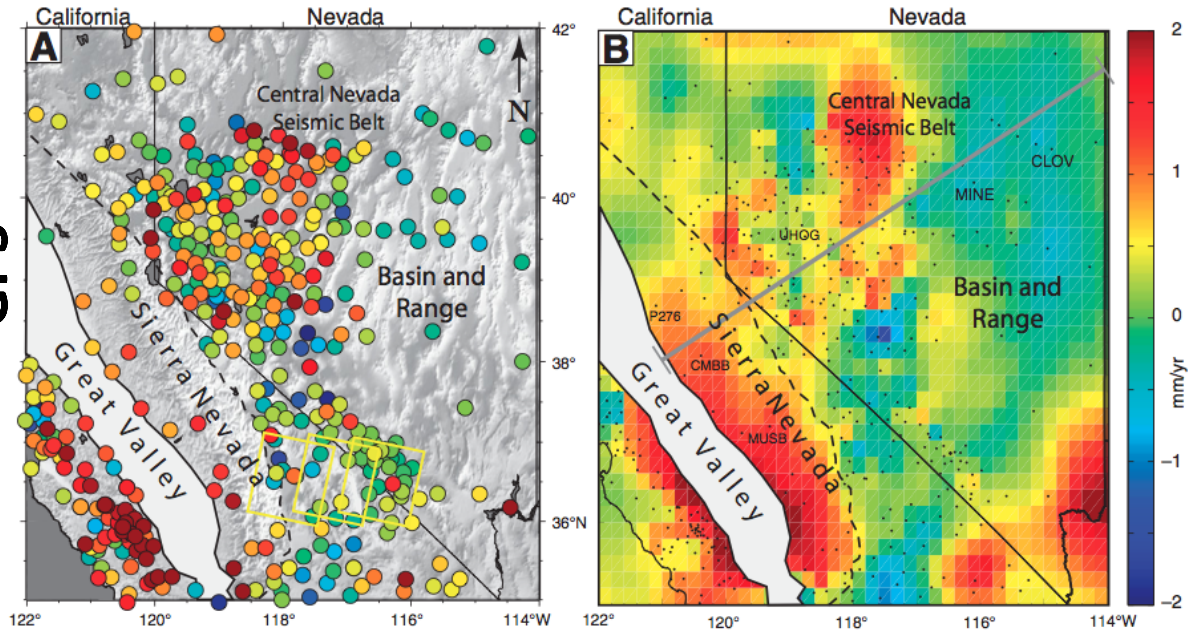


Long-wavelength pattern suggests a potential relationship with mantle structure

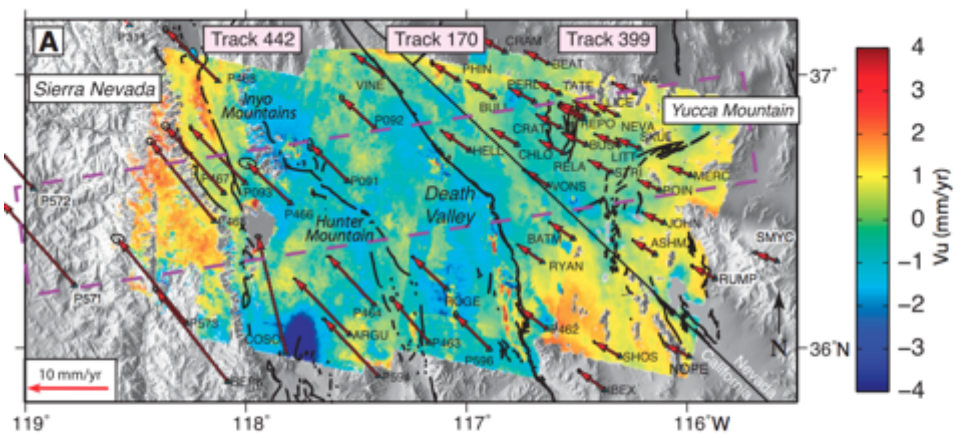
But ~1 mm/yr rates cannot be sustained over million year time-scales?

Sierra Nevada, rapid contemporary uplift

GPS



InSAR



(Hammond et al., 2012 Geology)

~1-2 mm/yr uplift could account for entire elevation of Mt. Whitney during the Quaternary! (Hammond et al., 2012)

What processes are modulating uplift rates in long-term, but not in contemporary measurements?

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5) Deformation in lower crust-uppermost mantle, past and present