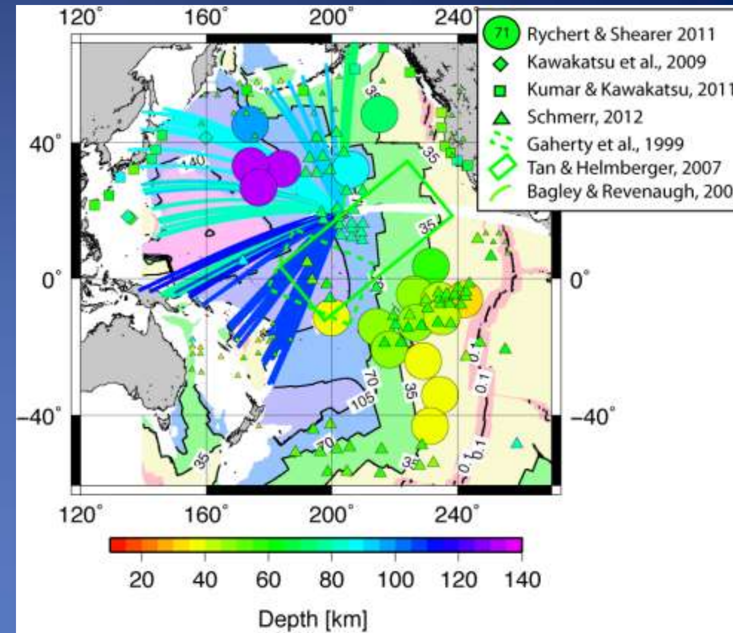
The lithosphere-asthenosphere boundary beneath hotspots

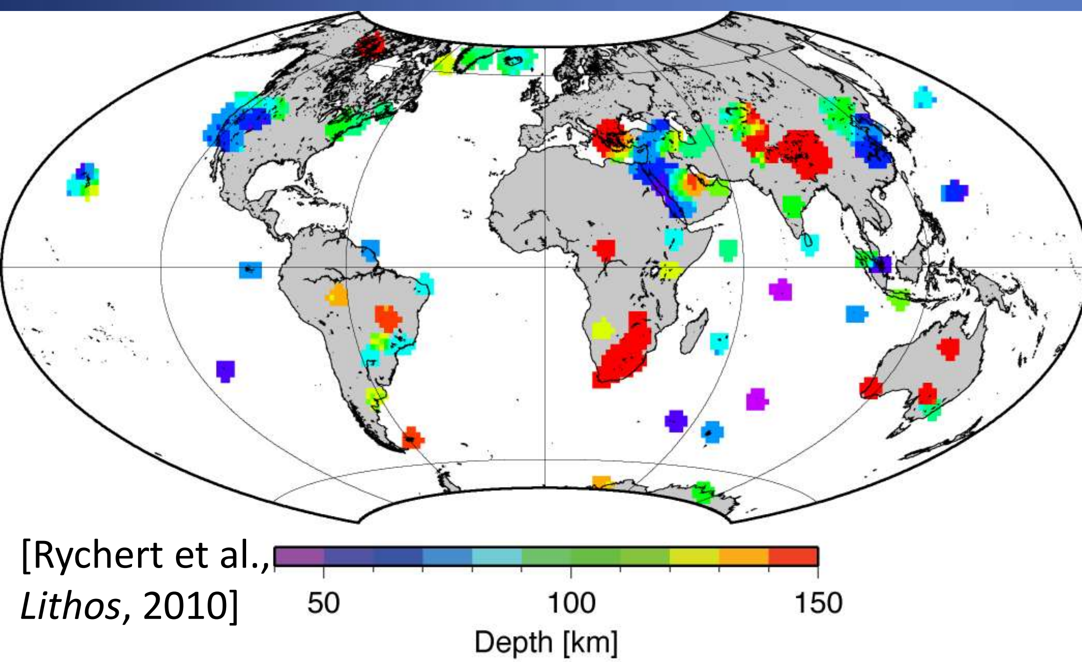
Catherine A. Rychert
University of Southampton

Ocean lithosphere-asthenosphere boundary

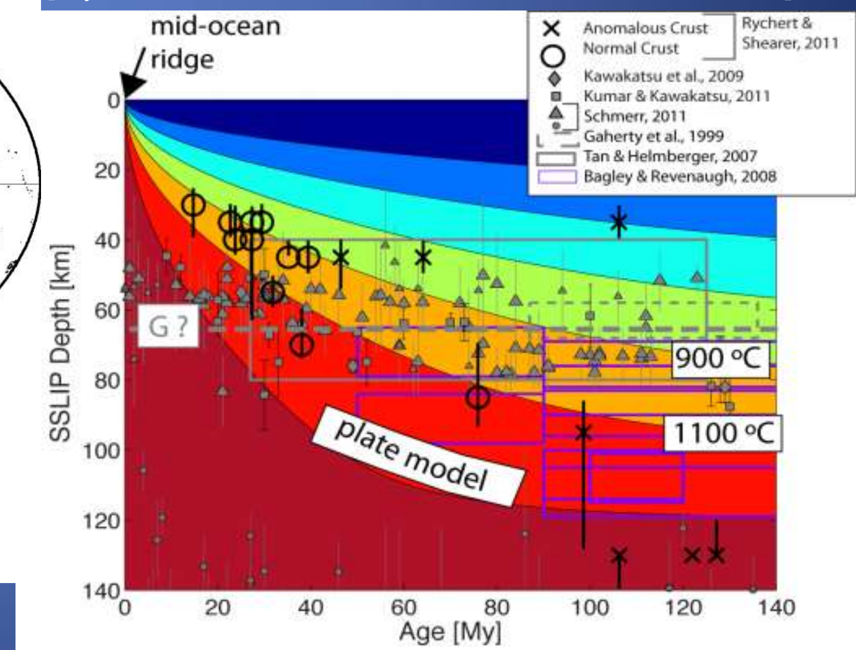
Global receiver functions: most insitu measurements come from ocean island stations



[Rychert, Schmerr, Harmon, *G-cubed, 2012*]



[Rychert et al., *Lithos*, 2010]



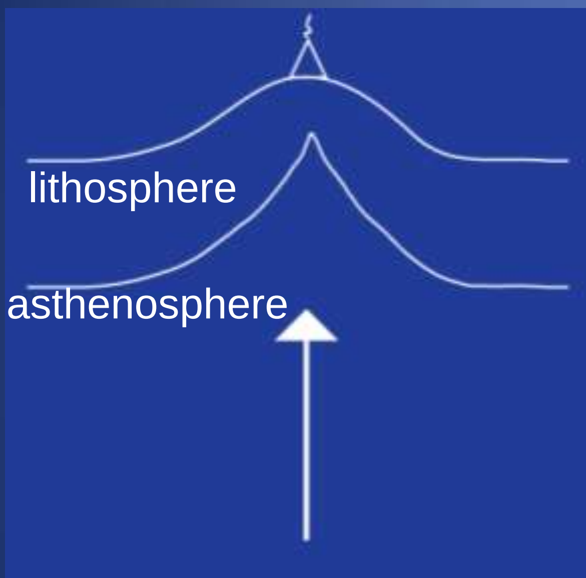
[Fischer et al., *Ann. Rev. Earth Pl. Sci.*, 2010]

[Rychert & Shearer, *Science* 2009]

hotspot – lithosphere interaction

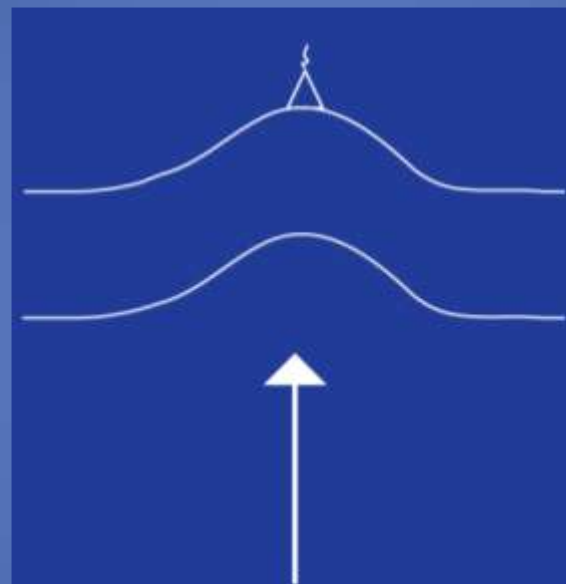
What does it imply about the lithosphere?

heat or thin the lid



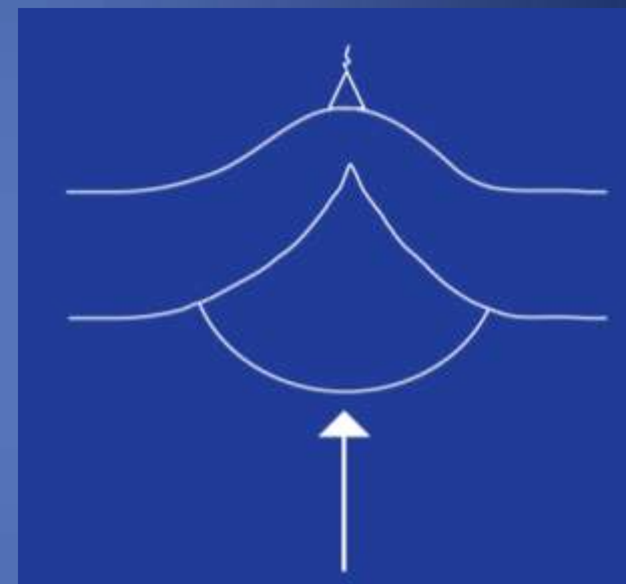
Detrick & Crough, 1978
Li et al., 2004

dynamic support



Sleep, 1990

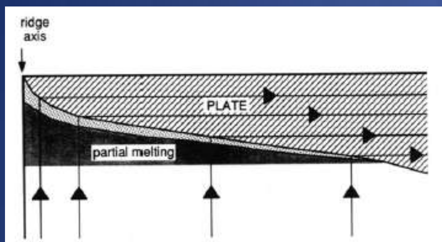
compositional root



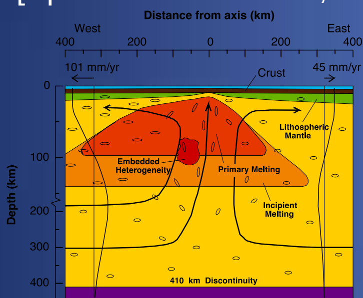
Jordan, 1979
Yamamoto & Phipps Morgan, 2009
Hall & Kincaid, 2003

hotspot – lithosphere interaction

What does it imply about the asthenosphere?

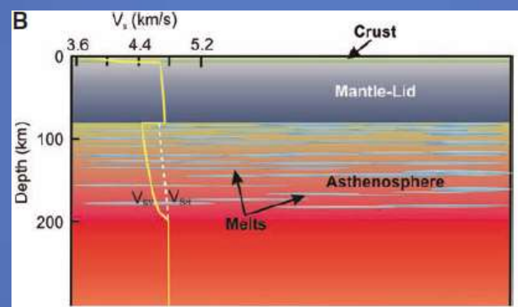


[Sparks & Parmentier, 1991]



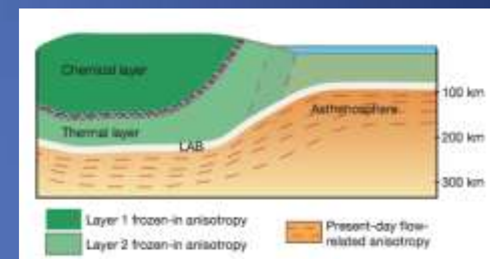
[MELT, 1998]

melt



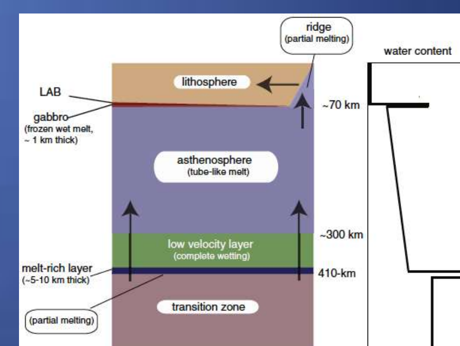
[Kawakatsu et al., 2009]

anisotropy

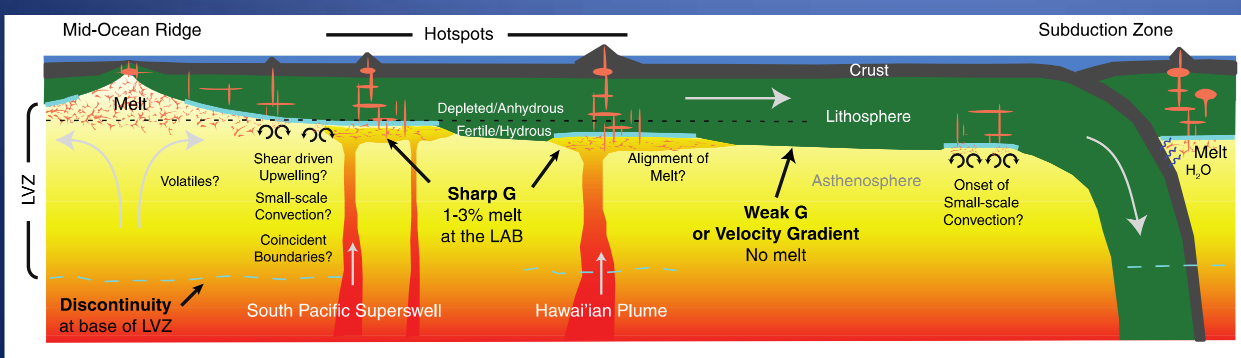


[Yuan & Romanowicz, 2010]

hydration



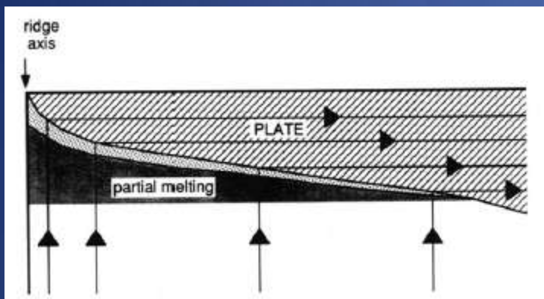
[Karato, 2012]



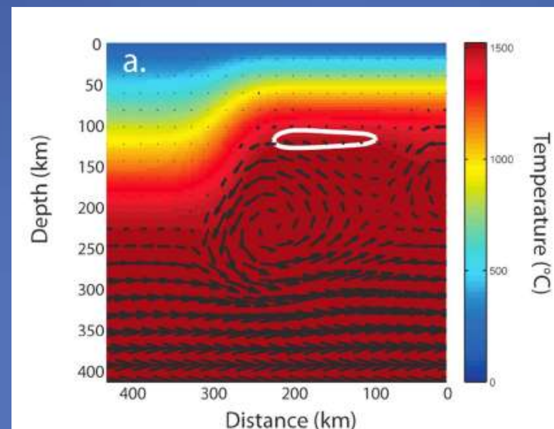
[Schmerr, 2012]

Melt beneath the lithosphere?

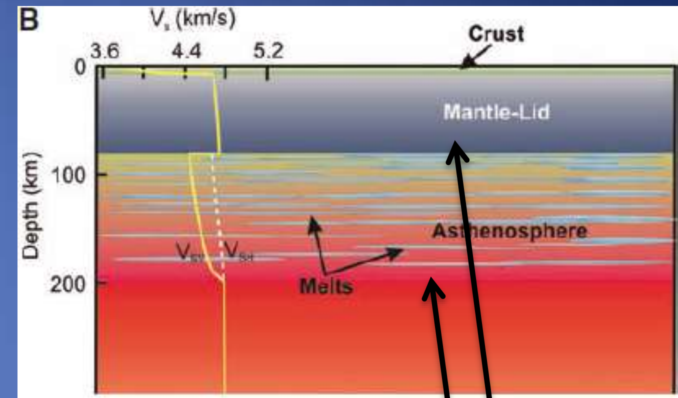
How deep does it extend?



[Sparks & Pamentier, 1991]

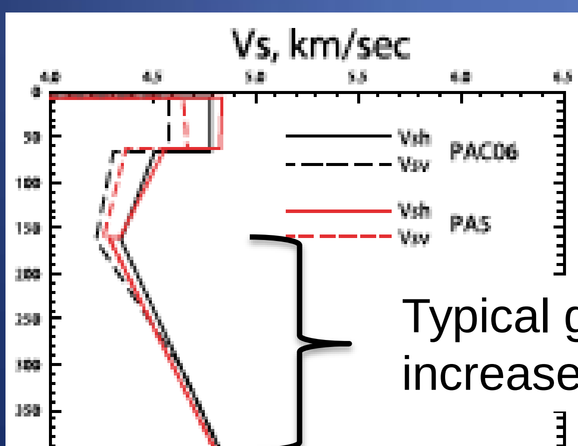


[Till et al., 2010]

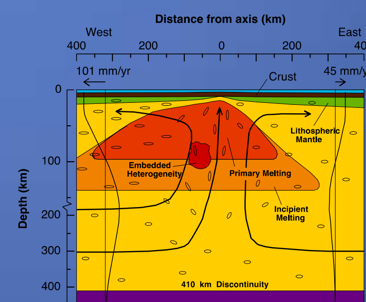


[Kawakatsu et al., 2009]

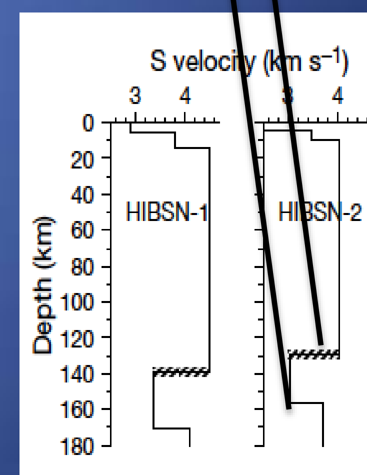
Is there a sharp boundary beneath it?



Typical gradual velocity increase in depth

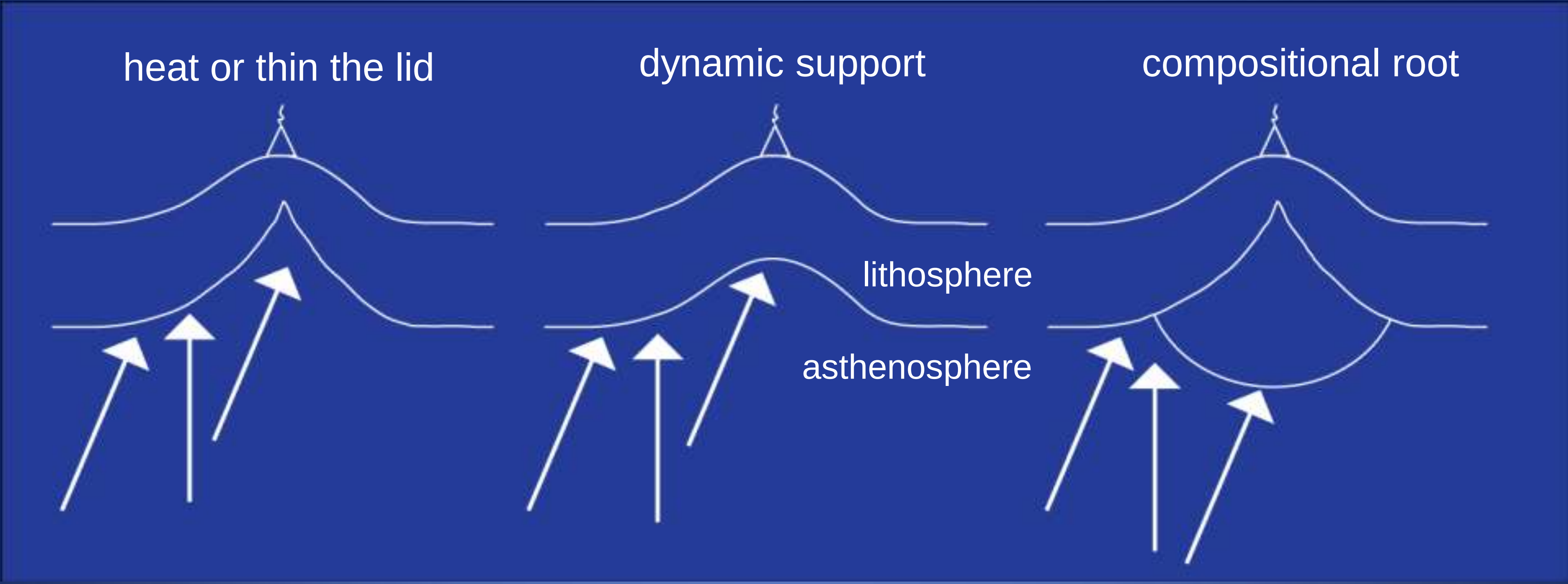


[MELT, 1998]



[Li et al., 2001]

Another important unknown -
Where does the plume impinge on the lithosphere?



Detrick & Crough, 1978
Li et al., 2004

Sleep, 1990

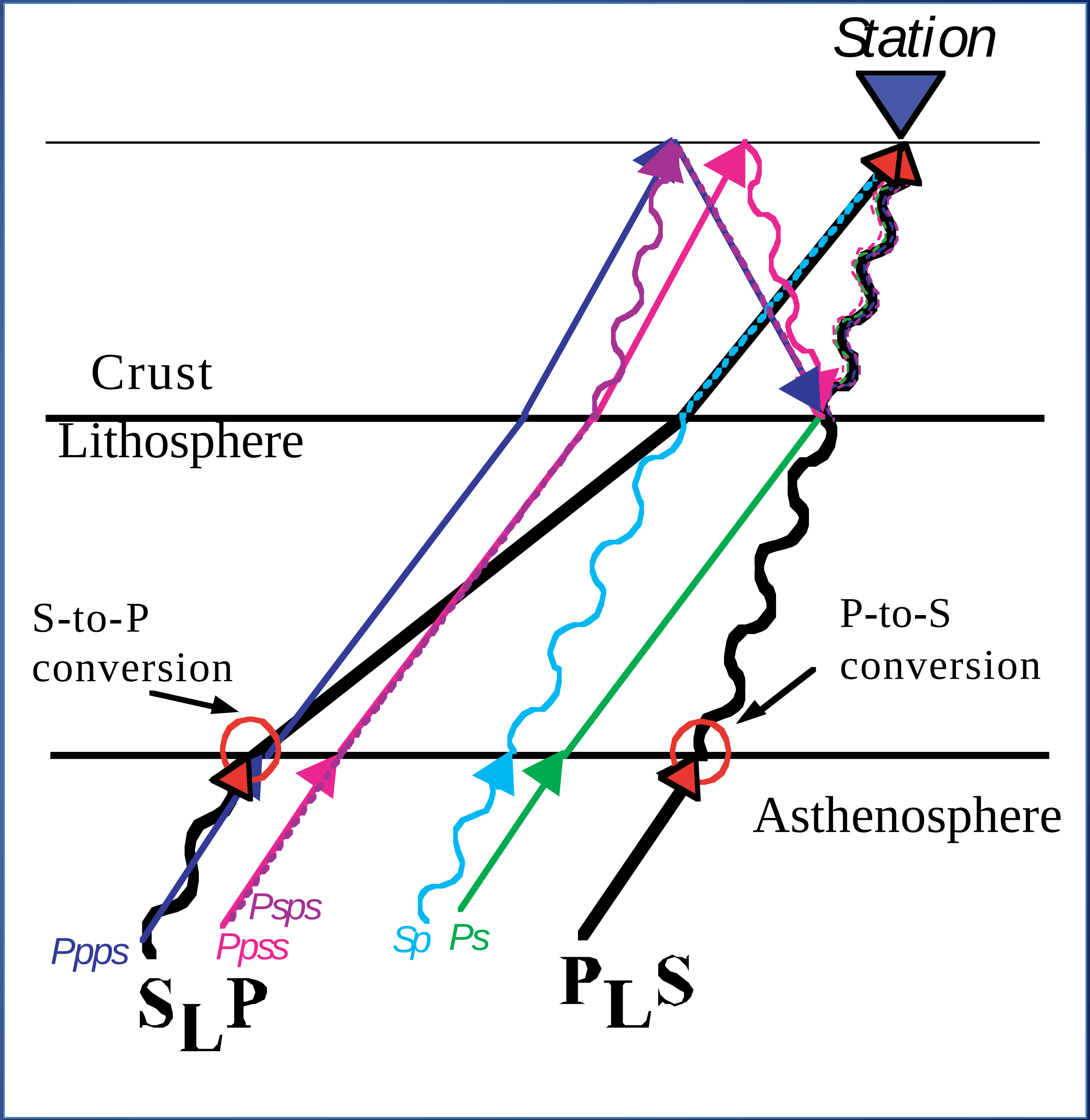
Jordan, 1979
Yamamoto & Phipps Morgan, 2009
Hall & Kincaid, 2003

Method

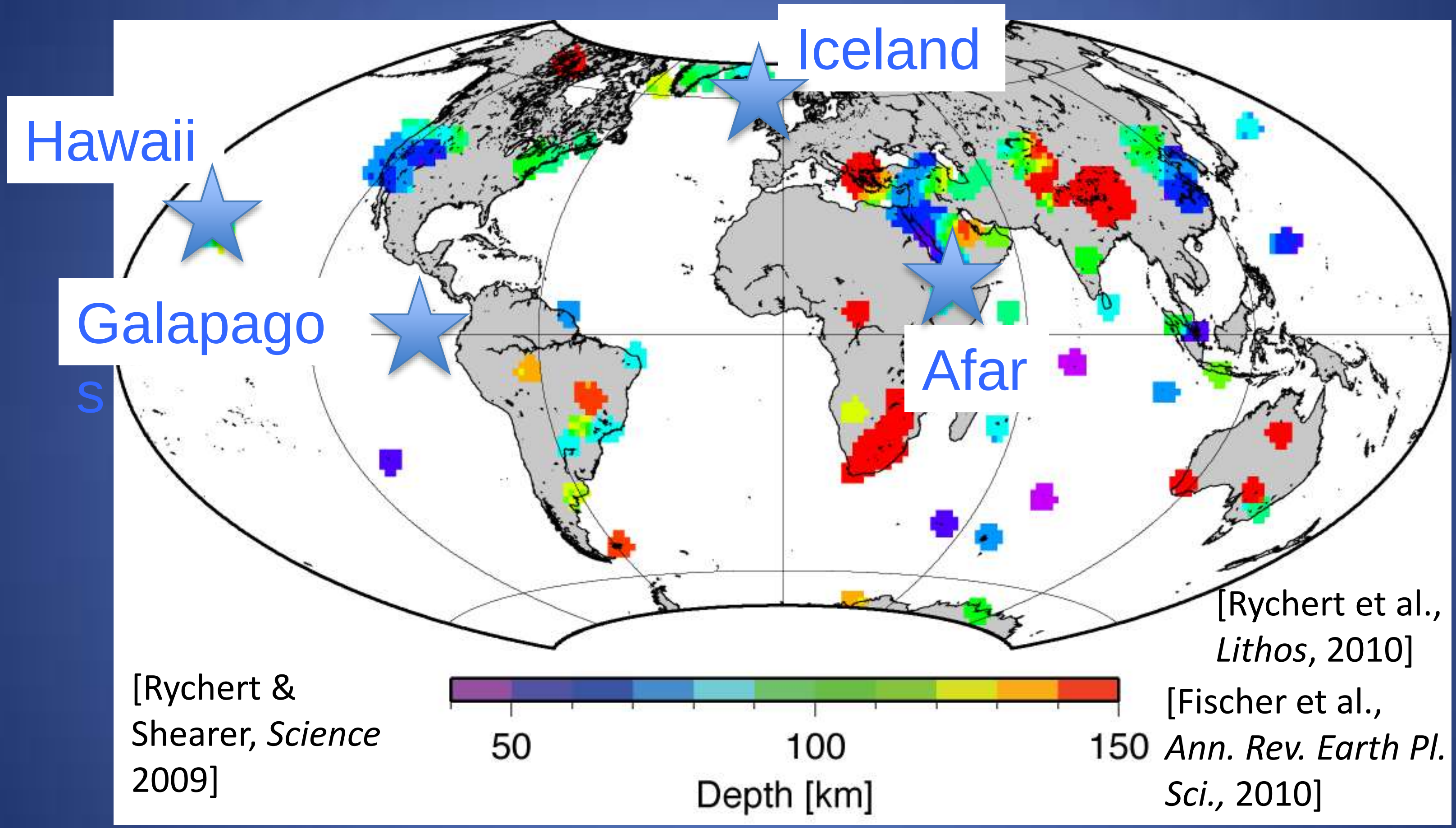
1) Rotate recorded waveform to P and S components.

2a) Bin data by conversion point, simultaneously deconvolve and migrate to depth in 1-D.

2b) Extended multi-taper receiver function technique and 3-D migration.



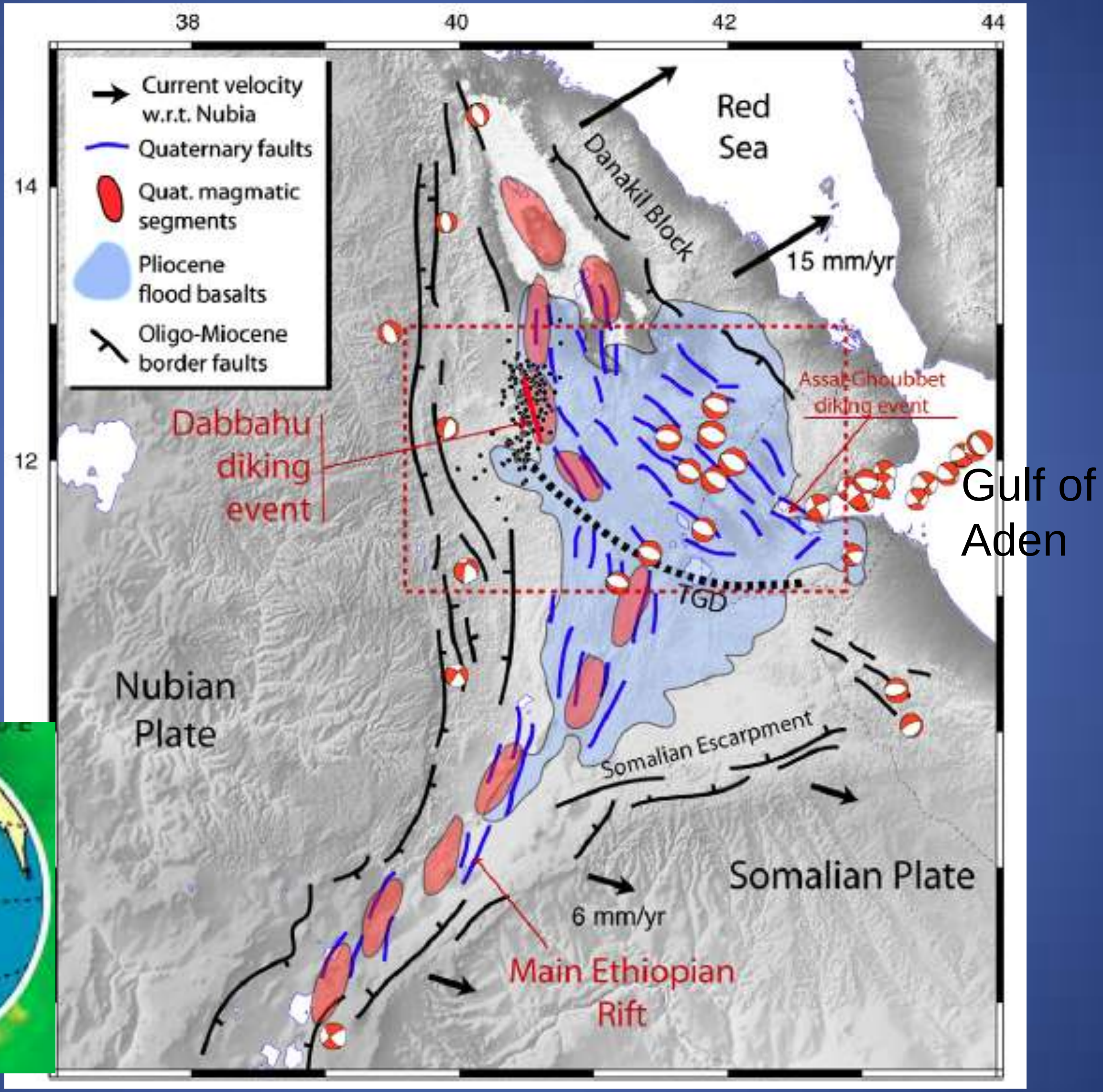
Global compilation of receiver function results. Most insitu measurements come from ocean island stations



Lithosphere-asthenosphere boundary from receiver functions

(Li et al., 2000; Li et al., 2004; Collins et al., 2002; Wolbern et al., 06; Heit et al., 2007; Li et al., 2007; Rychert et al., 2005; Rychert et al., 2007; Snyder, 2008; Kumar et al., 2005; Sodoudi et al., 2006; Ozacar et al., 2008; Angus et al., 2006; Mohsen et al., 2006; Hansen et al., 07; Kumar et al., 2007; Wittlinger and Farra, 2007; Hansen et al., 2009; Sodoudi et al., 2009; Kumar et al., 2005; Oreshin et al., 2002; Kumar et al., 2006; Sodoudi et al., 2006; Chen et al., 2006; Chen et al., 2008; Chen, 2009; Kawakatsu et al., 2009)

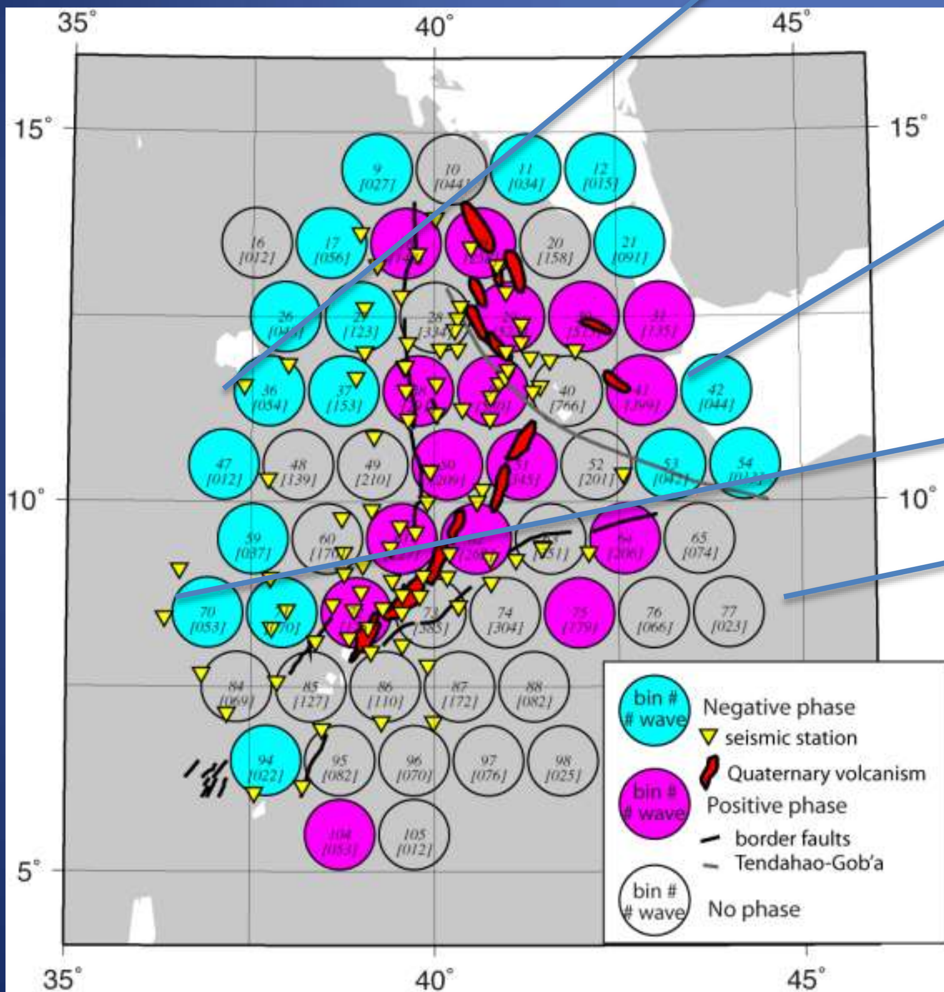
Afar triple junction

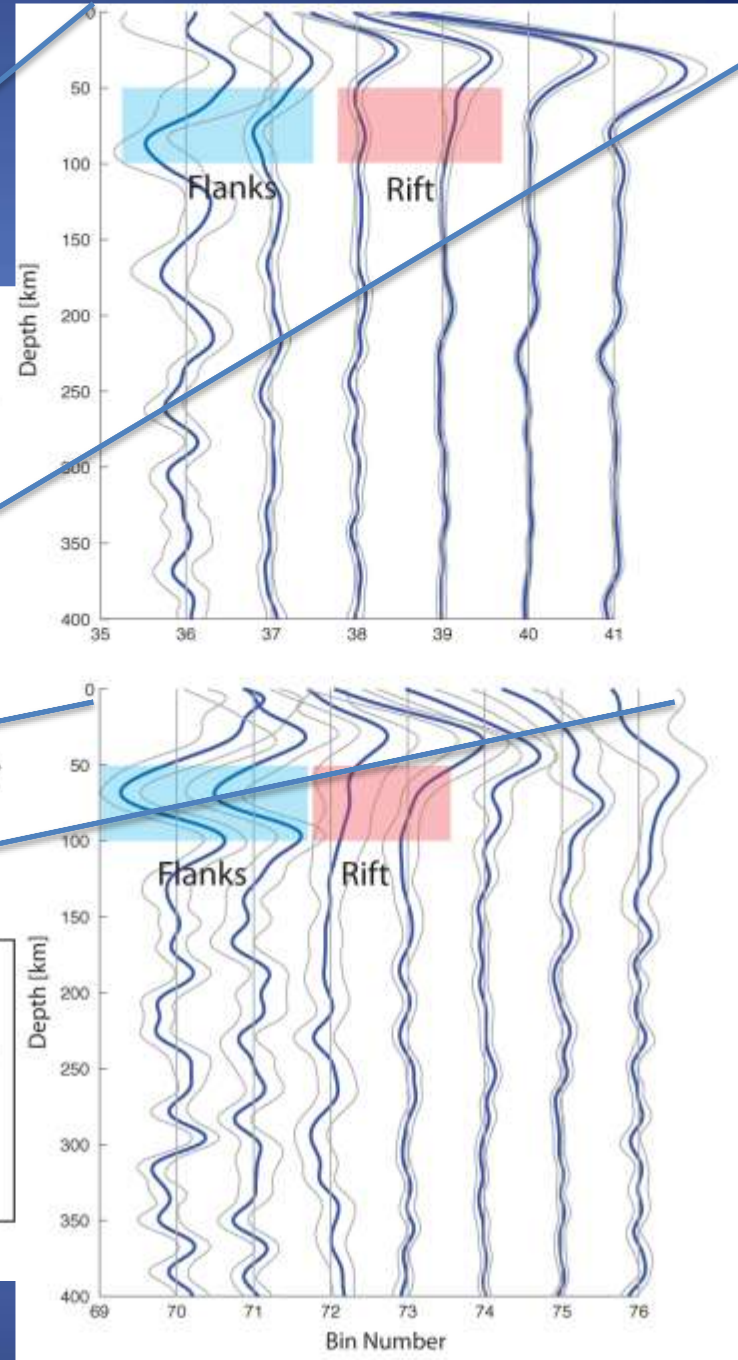


[Beutel et al., 2010]

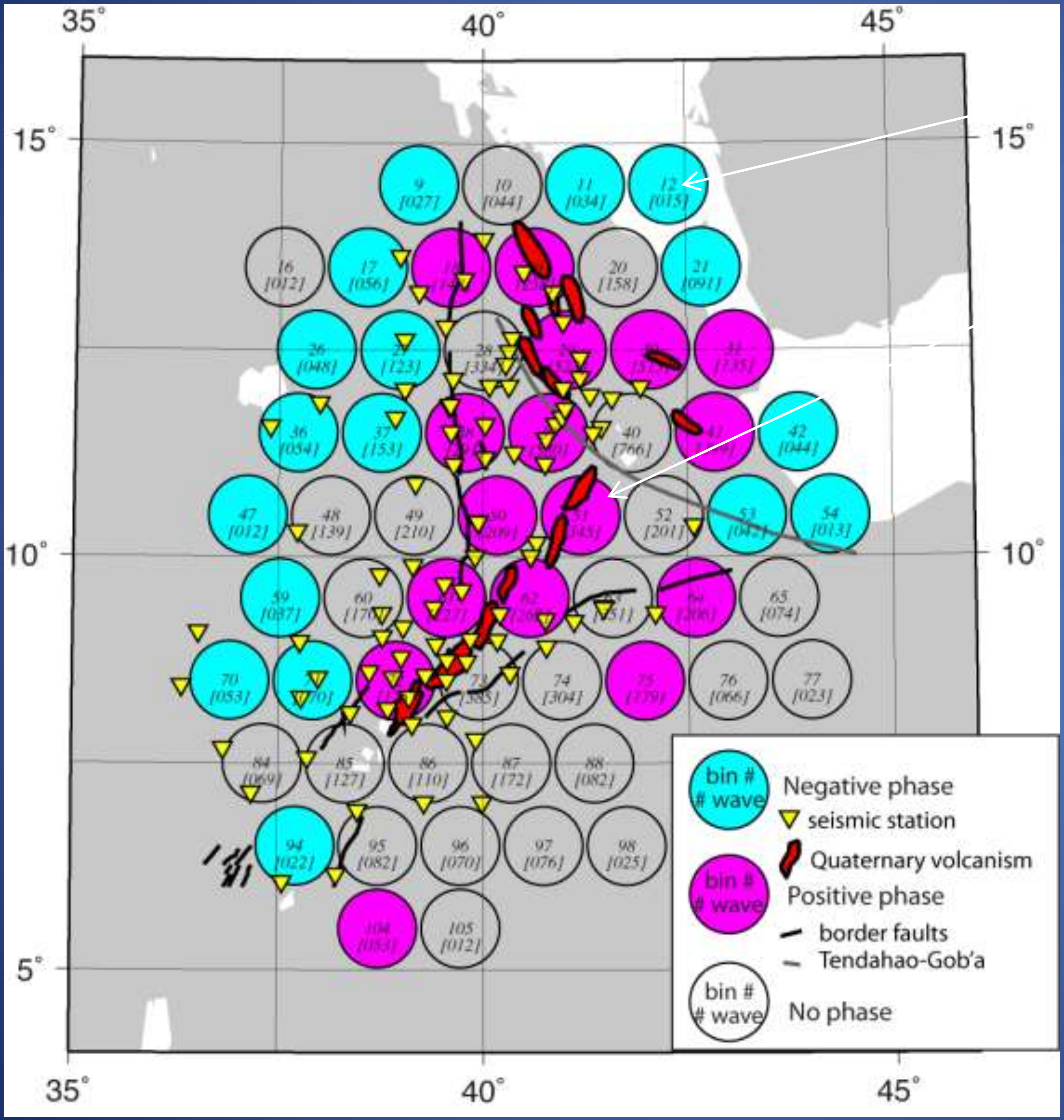
Afar triple junction, 75 km depth

Strong variation in waveform character from flank to rift.





Afar triple junction, 75 km depth

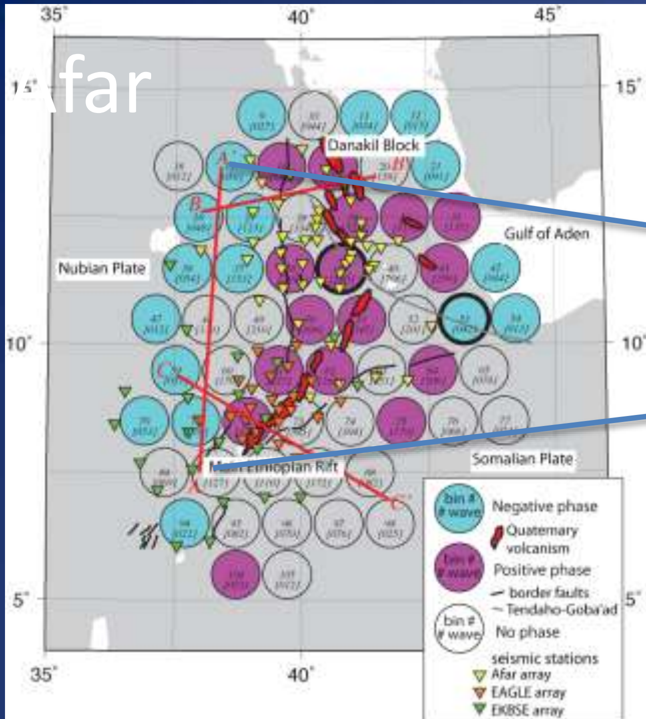


Velocity decreases with depth beneath the flank.

Velocity increases beneath the rift.

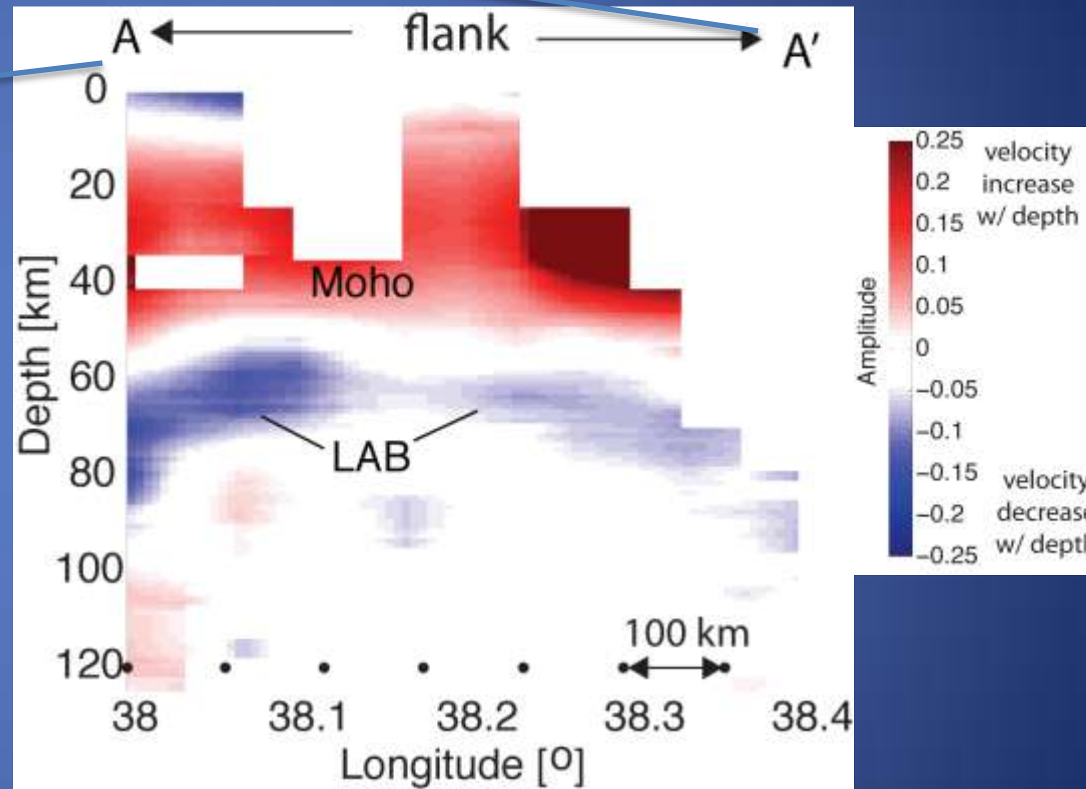
[*Rychert et al., Nature Geo., 2012*]

far



Flank cross section

Results from the migrated extended multitaper method



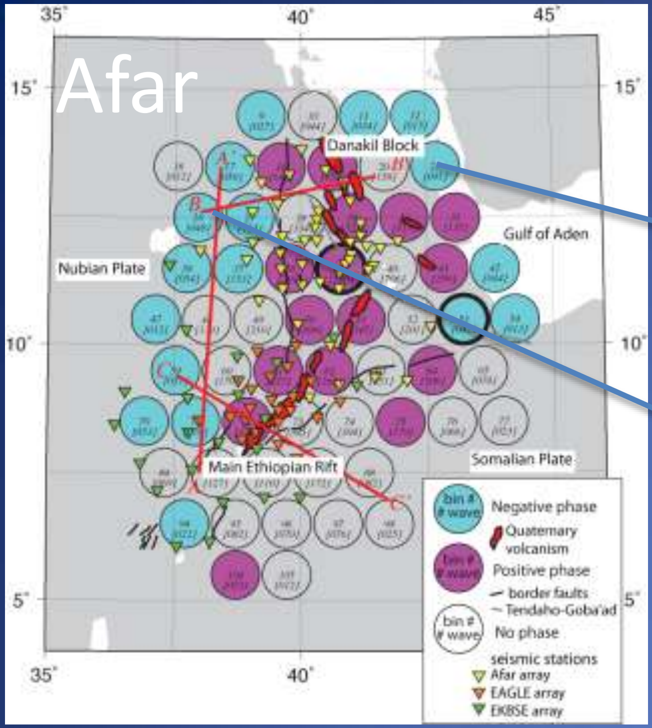
Strong LAB beneath flank, shallows beneath flood basalts

Strong velocity decrease likely requires a mechanism such as melting in the asthenosphere.

[*Rychert et al., Nature Geo., 2012*]

Flank to rift cross section

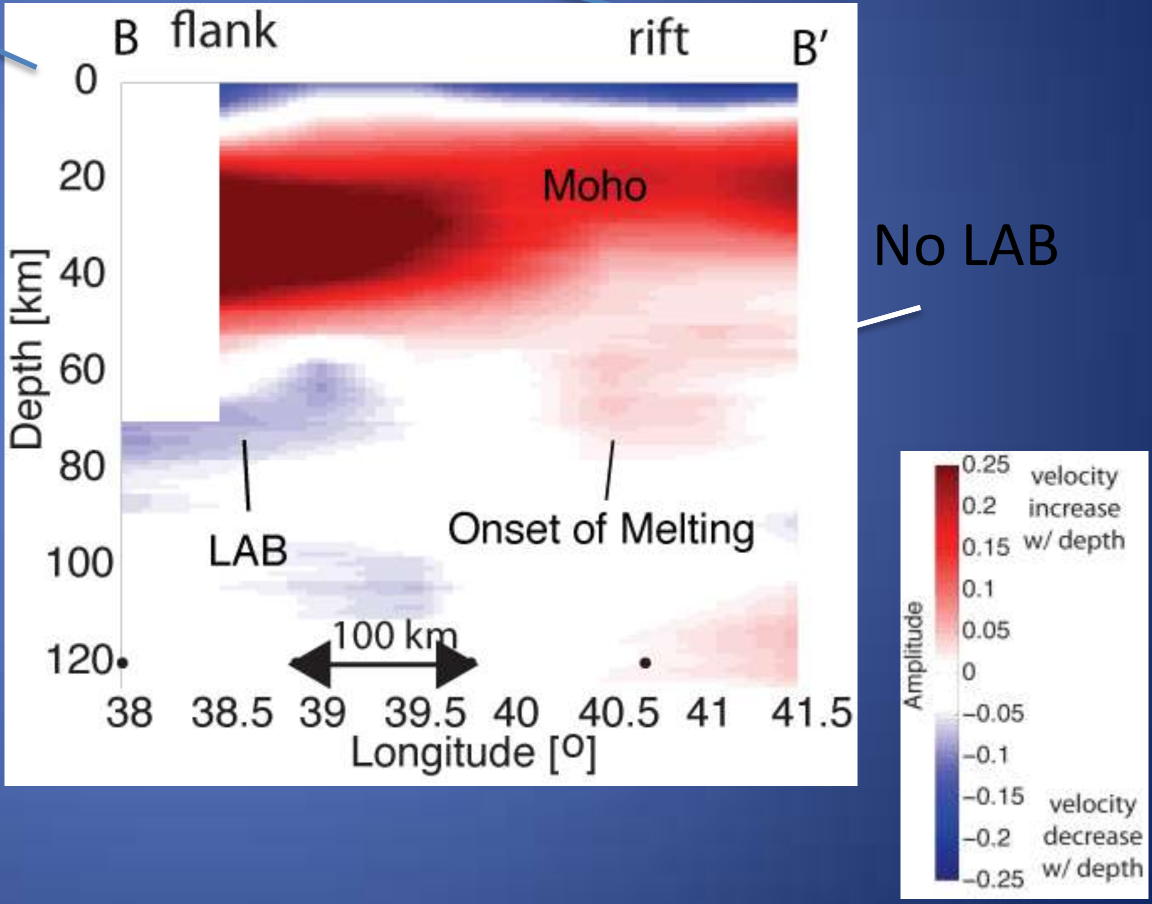
Results from the migrated extended multitaper method



beneath flank.

No LAB beneath rift.

Sharp transition implies rigidity of the lid.

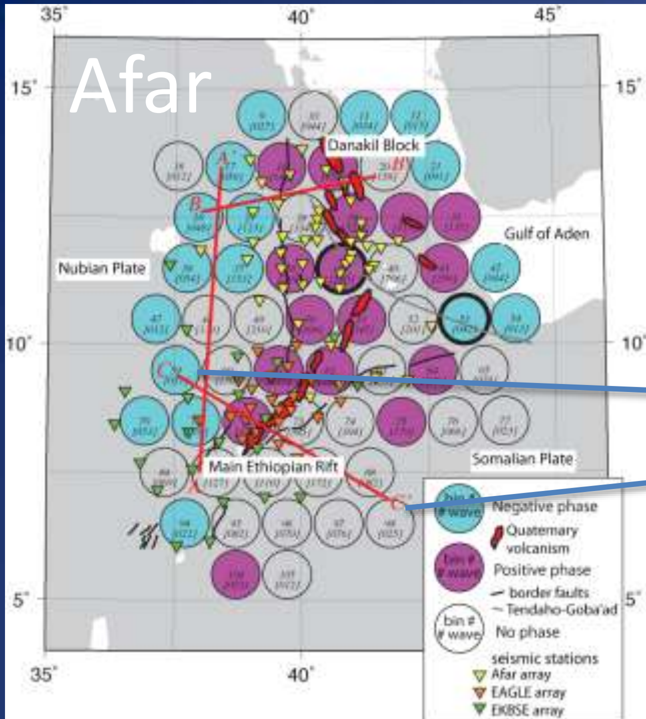


No LAB

[*Rychert et al.,* Nature Geo., 2012]

Flank to rift cross section

Results from the migrated extended multitaper method



beneath flank.

No LAB
beneath rift.

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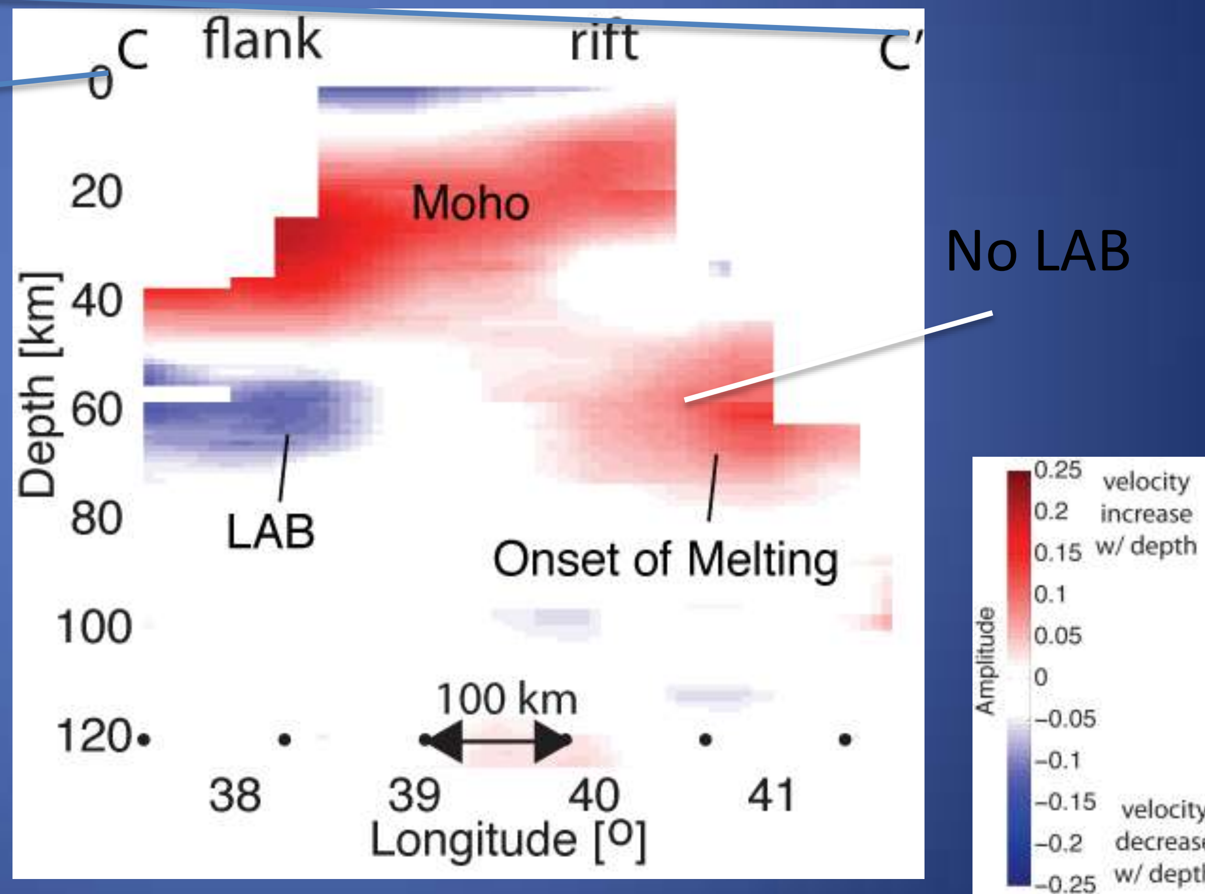


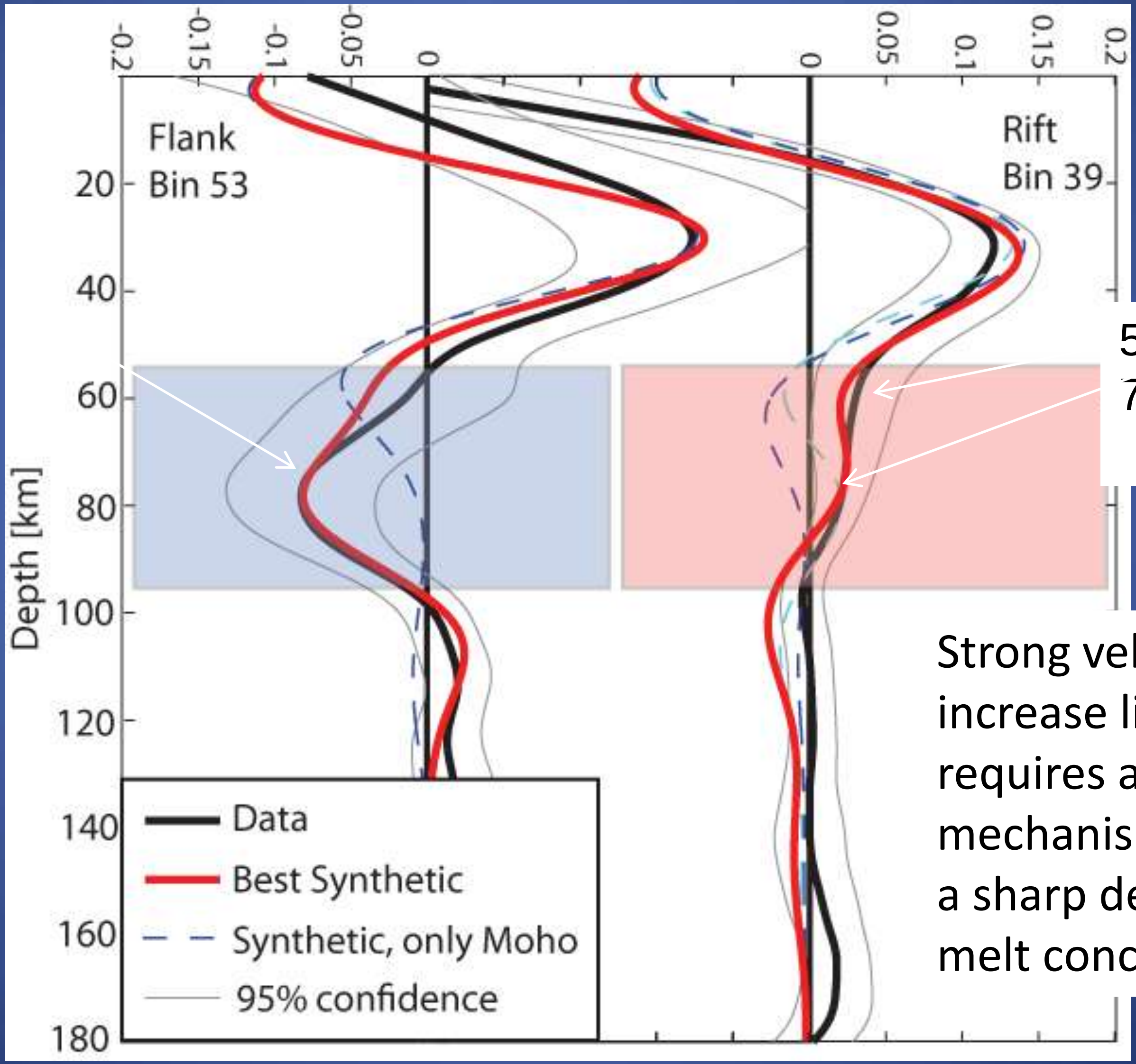
[*Rychert et al.,* Nature Geo., 2012]

Afar

Synthetic Waveform Modeling

11 % ↓ @ 77 km

Strong velocity decrease likely requires a mechanism such as melting in the asthenosphere.

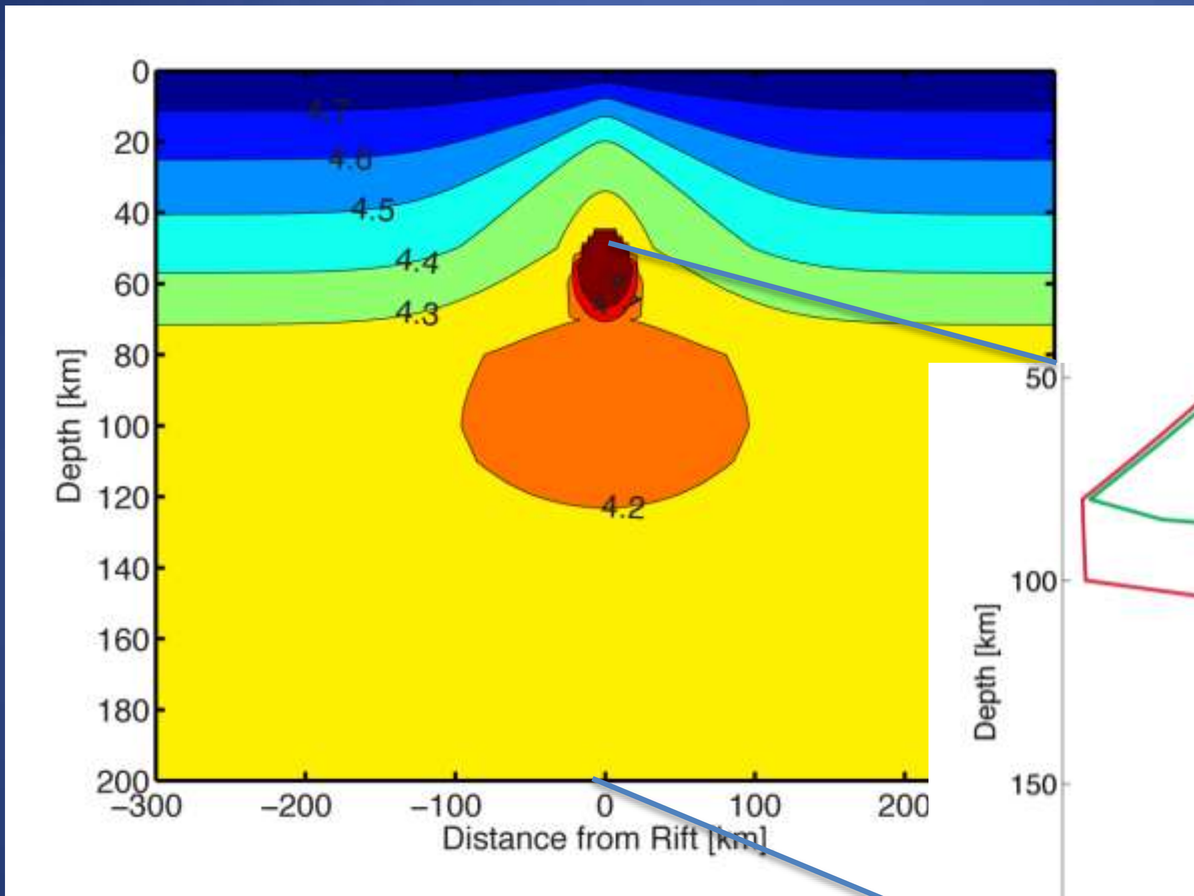


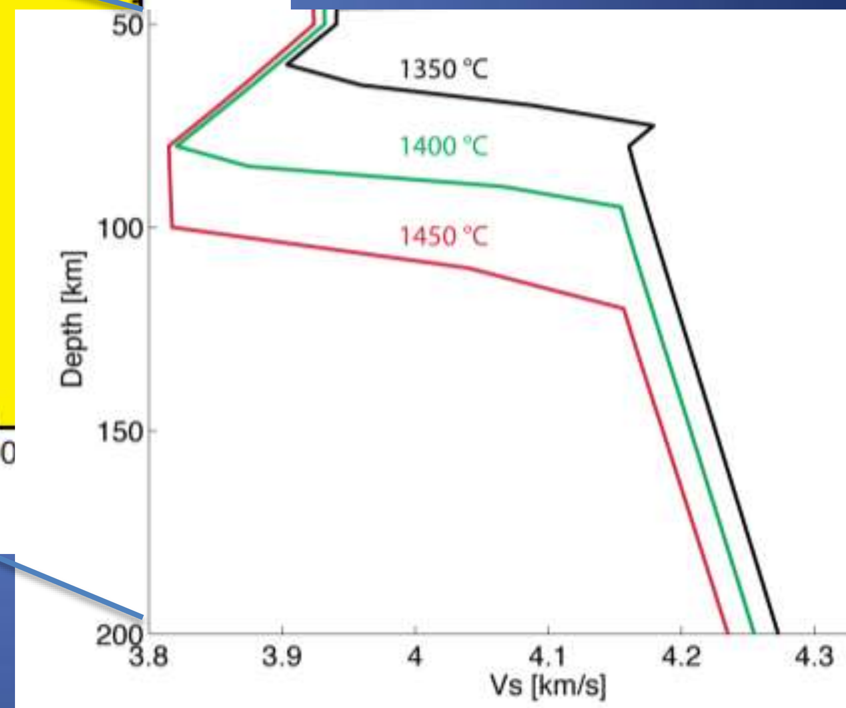
5 % ↑ @ 41 km
7 % ↑ @ 62 km

Strong velocity increase likely requires a mechanism such as a sharp decrease in melt concentration.

[*Rychert et al.,* Nature Geo., 2012]

Afar





Plume potential temperatures (>= 1450˚ C) give velocity increase at > 100 km depth, outside error bars for depth of the seismic discontinuity.

[*Rychert et al.,* Nature Geo., 2012]

Afar

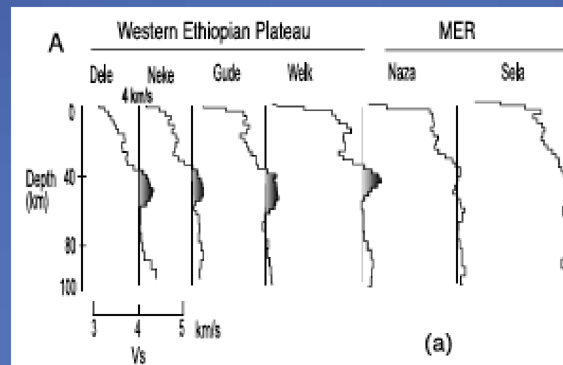
30 km or possibly 100 km

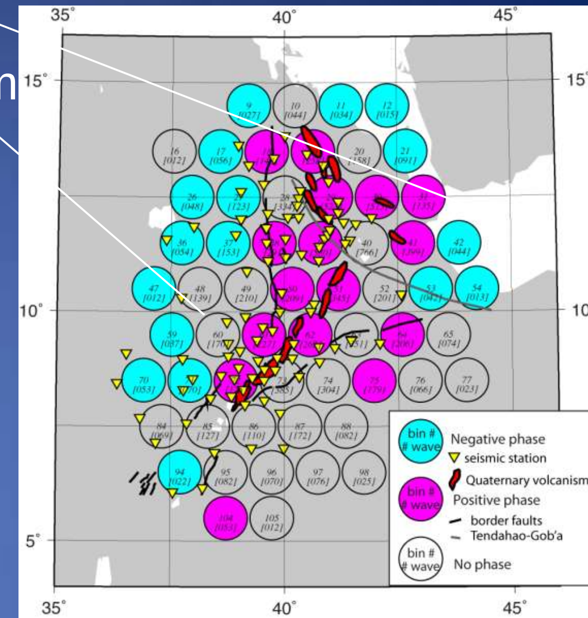
80 km

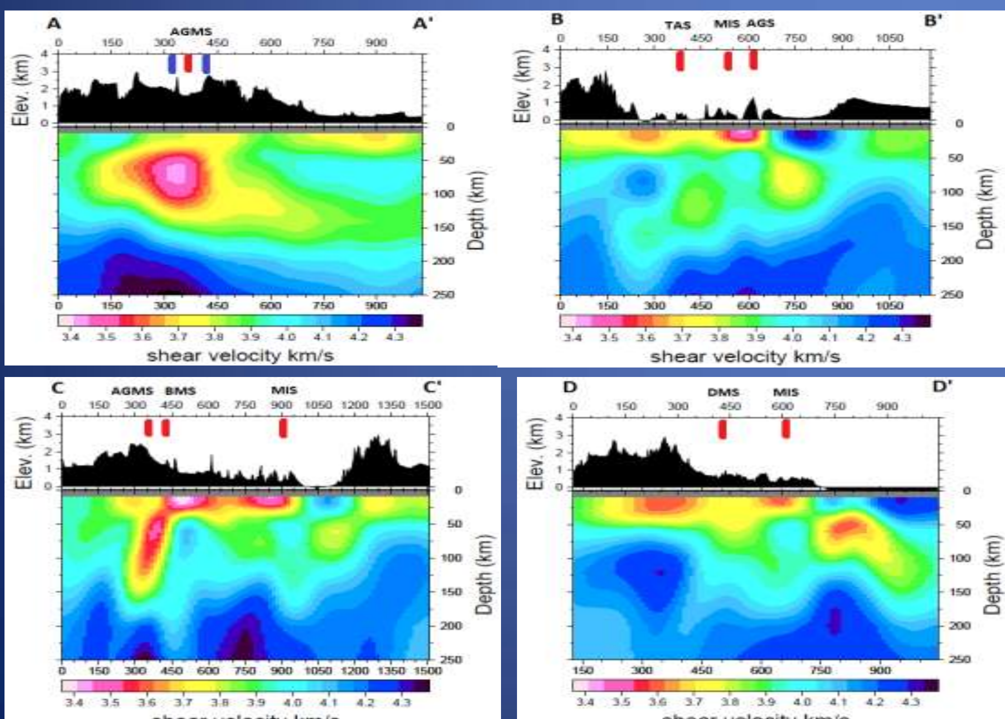
Good agreement with previous/new seismic results.

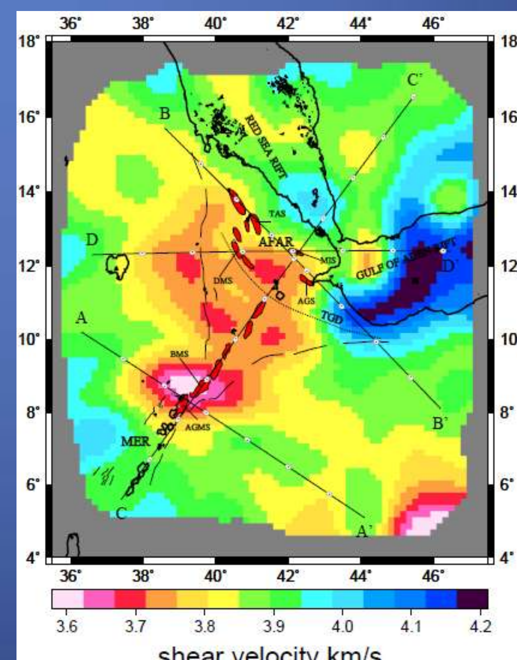
Sp receiver functions [Hansen et al., 2009]

Joint Ps receiver function – surface waves 70-80 km thick lid vs. no lid beneath rift [Dugda et al., 2007].





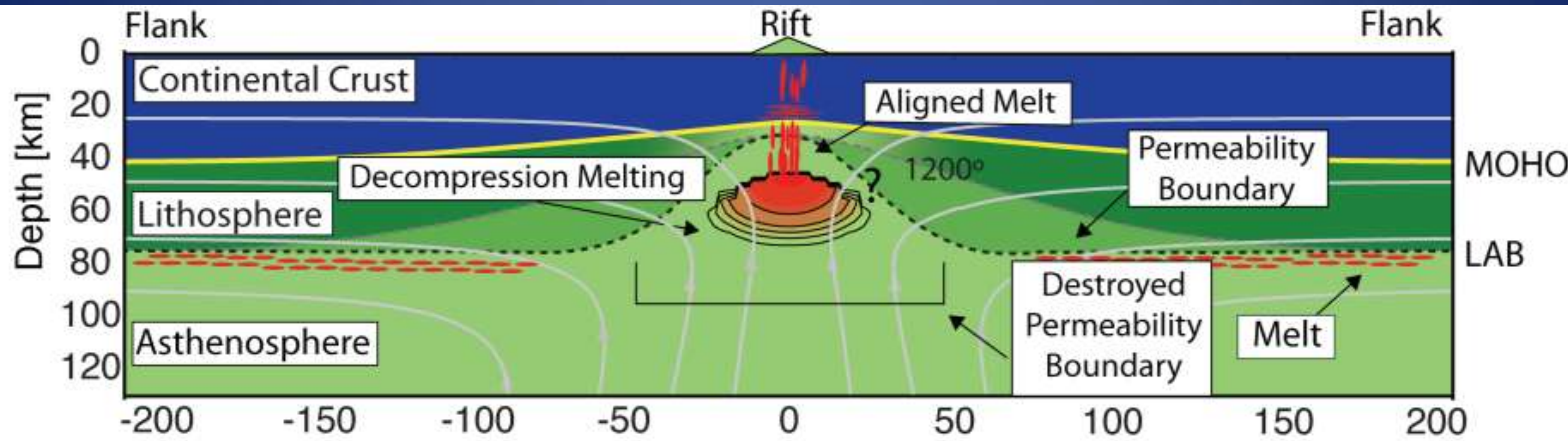




surface waves [Gallagher et al., 2013] see poster!

0 – 60 km

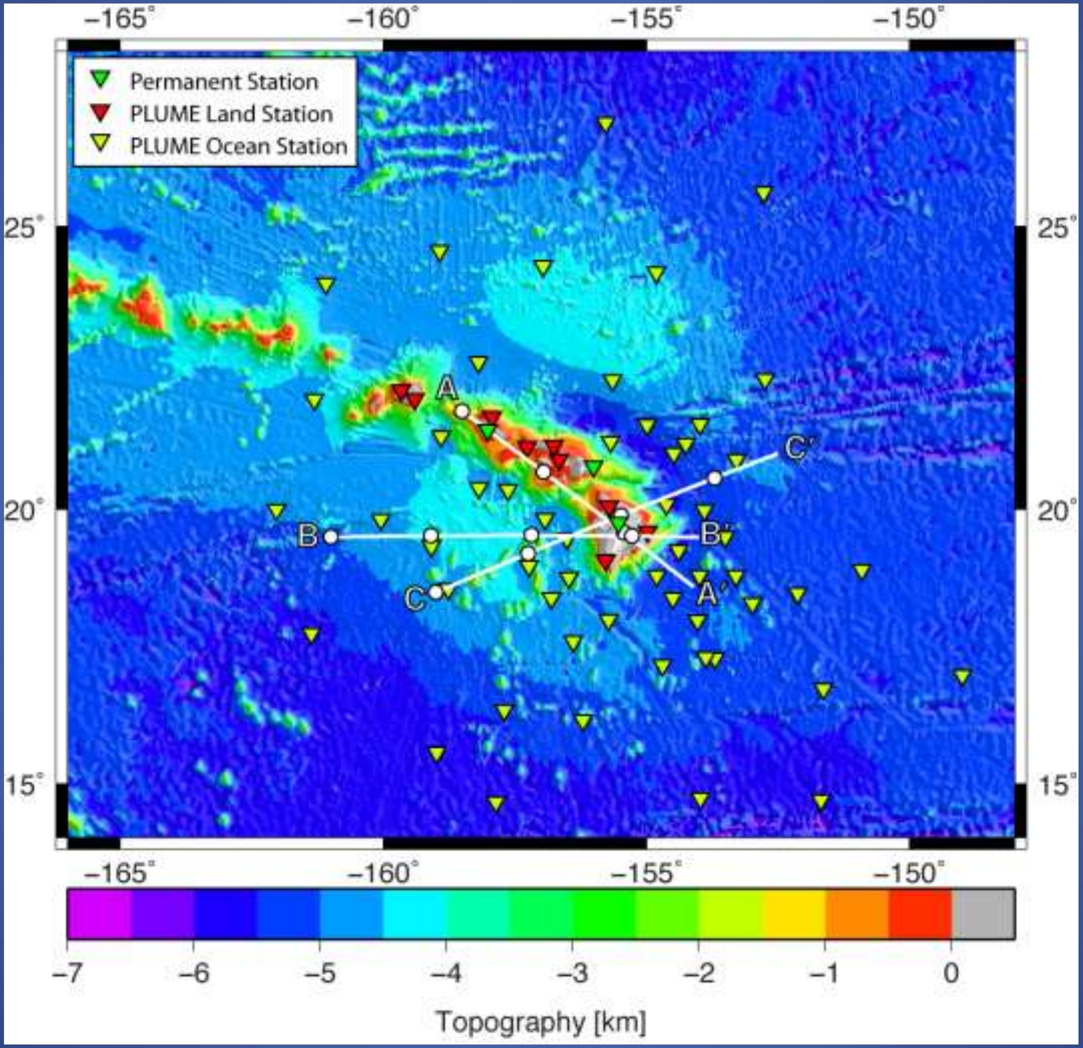
Afar



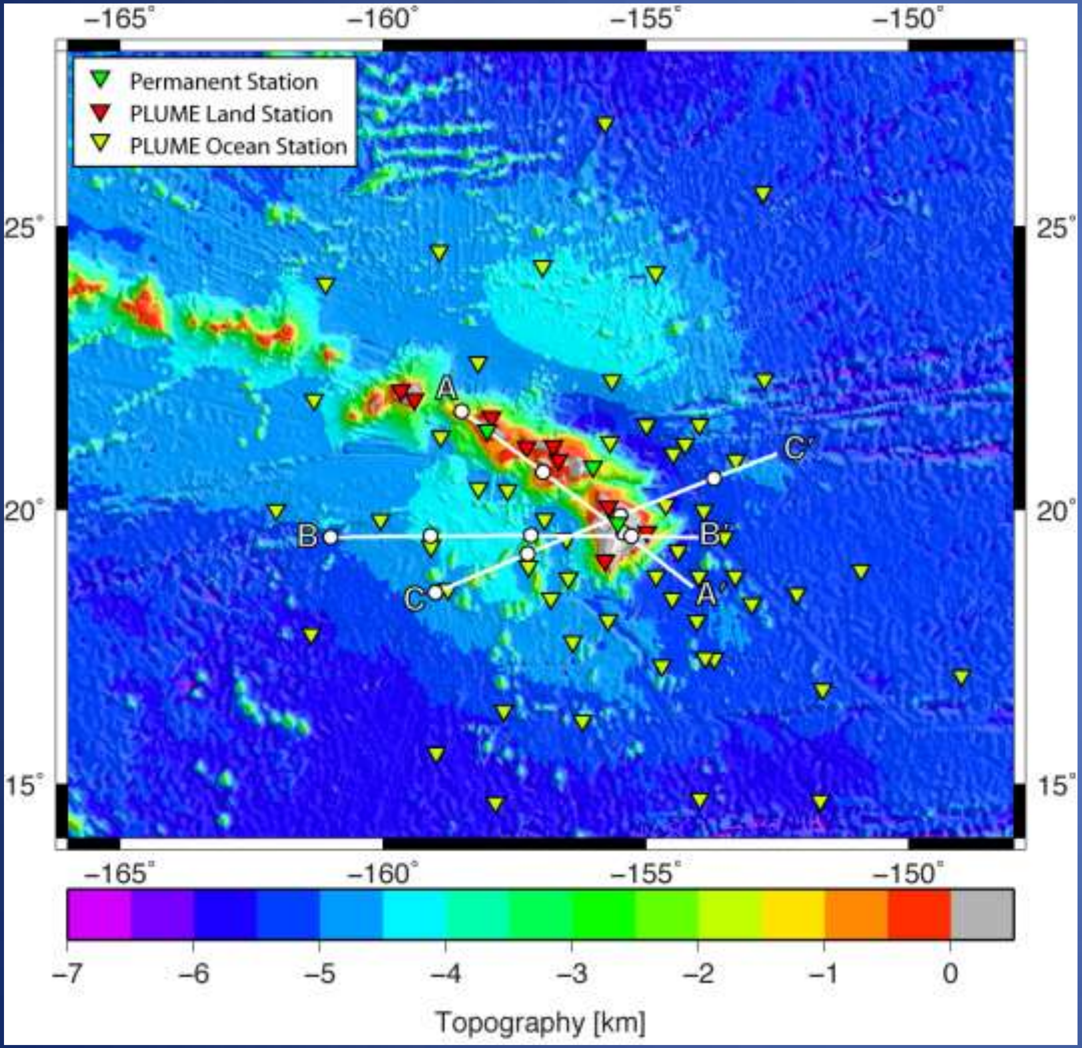
- A sharp rigid lid is imaged on the flank of the Afar rift at ~75 km depth. The transition from flank to rift is abrupt.
- The sub-crustal lithosphere beneath the rift has been destroyed.
- A significant velocity increase imaged beneath the rift is consistent with geodynamic predictions for the onset of decompression melting.
- Its depth is shallow, indicating no significant plume influence today.

[*Rychert et al.,* Nature Geo., 2012]

Hawaii – where a mantle plume likely exists.



Hawaii



PLUME experiment: nearly 70 seafloor sites and 10 land stations, as well as permanent island stations.

2 phases 2005 – 2006 & 2006 – 2007

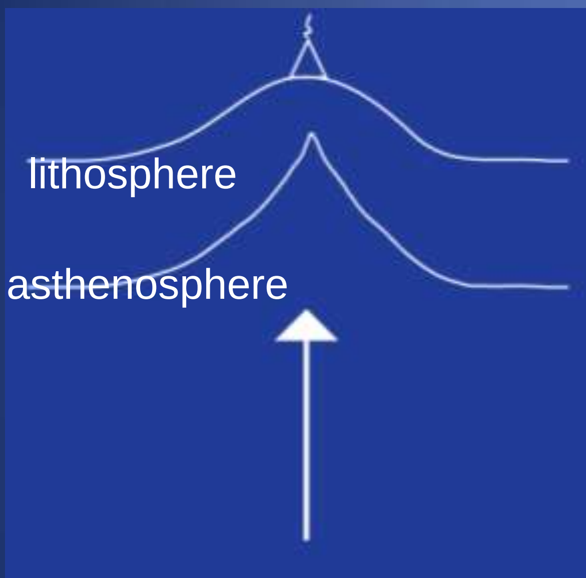
Classic hotspot volcanism

plate motion over fixed plume

~1000 km wide topographic swell

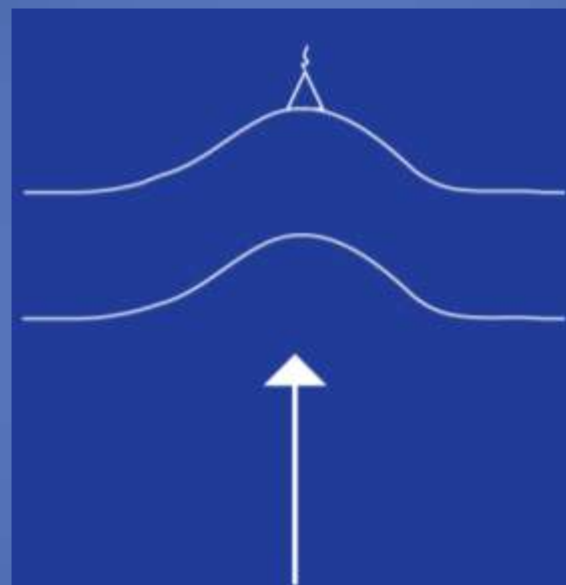
Models to explain Hawaiian Swell

heat or thin the lid



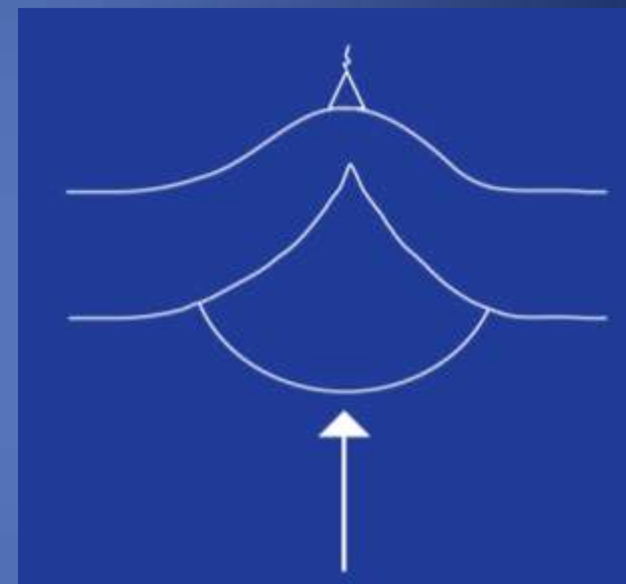
Detrick & Crough, 1978
Li et al., 2004

dynamic support



Sleep, 1990

compositional root



Jordan, 1979
Yamamoto & Phipps Morgan, 2009
Hall & Kincaid, 2003

Models to explain Hawaiian Swell

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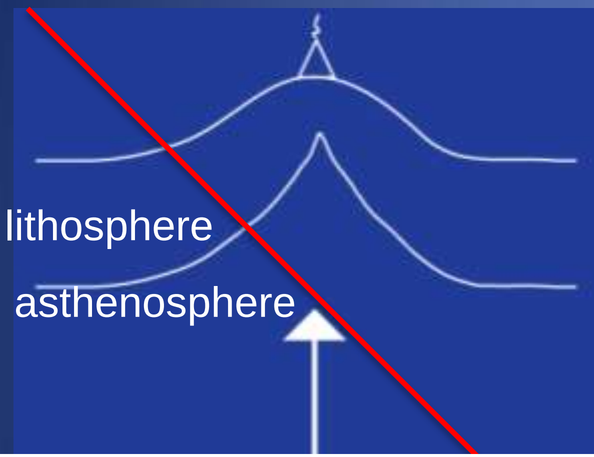
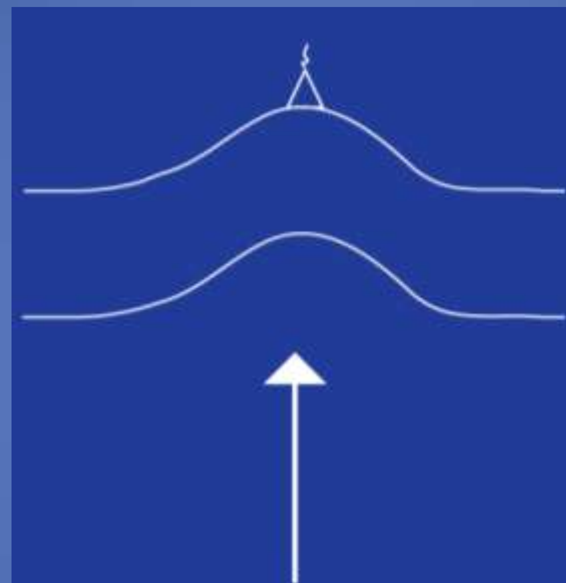


heat flow too low
[Von Herzen, et al., 1989]

Detrick & Crough, 1978
Li et al., 2004

dynamic support



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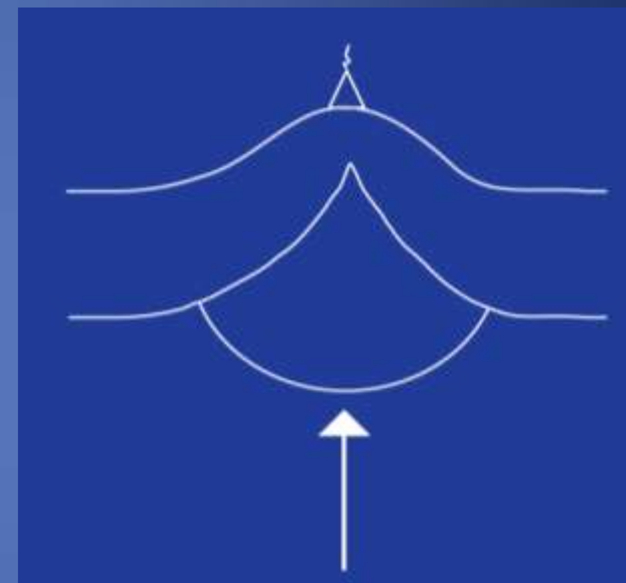


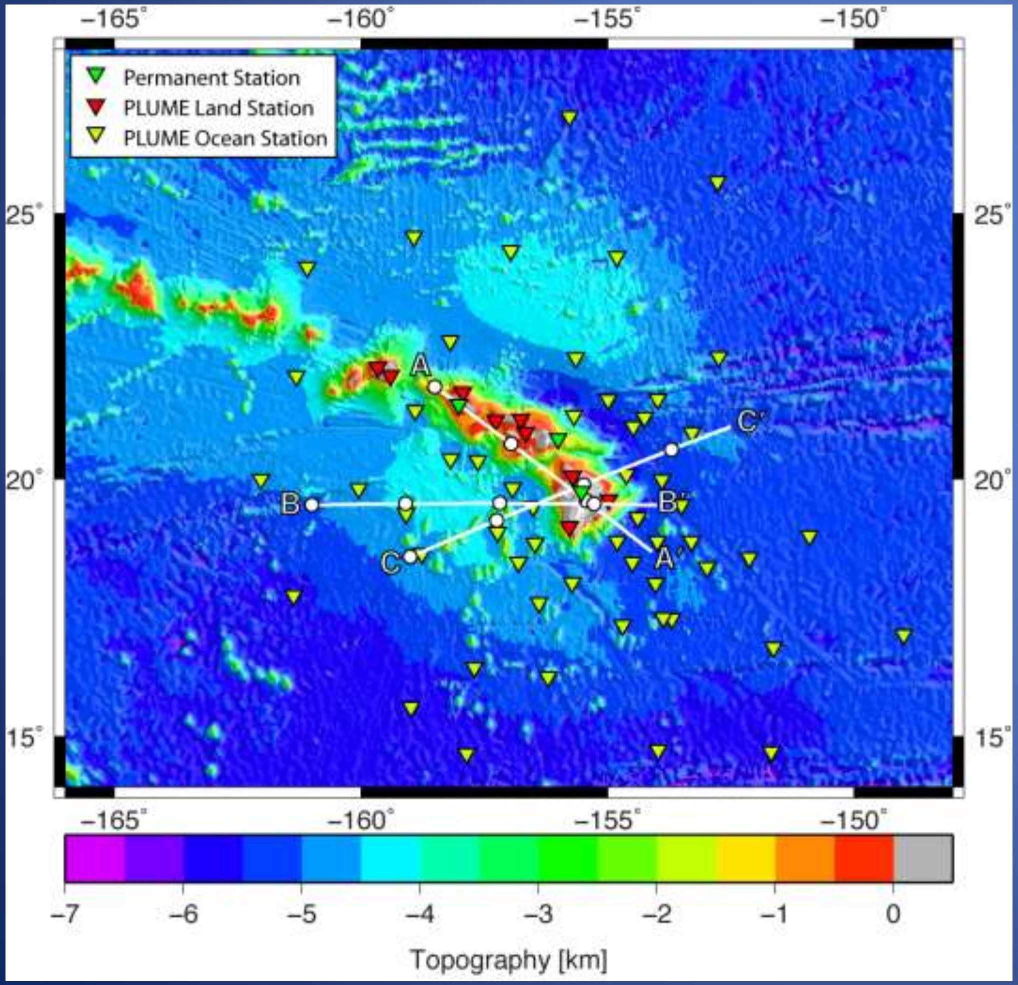
Jordan, 1979
Yamamoto & Phipps Morgan, 2009
Hall & Kincaid, 2003

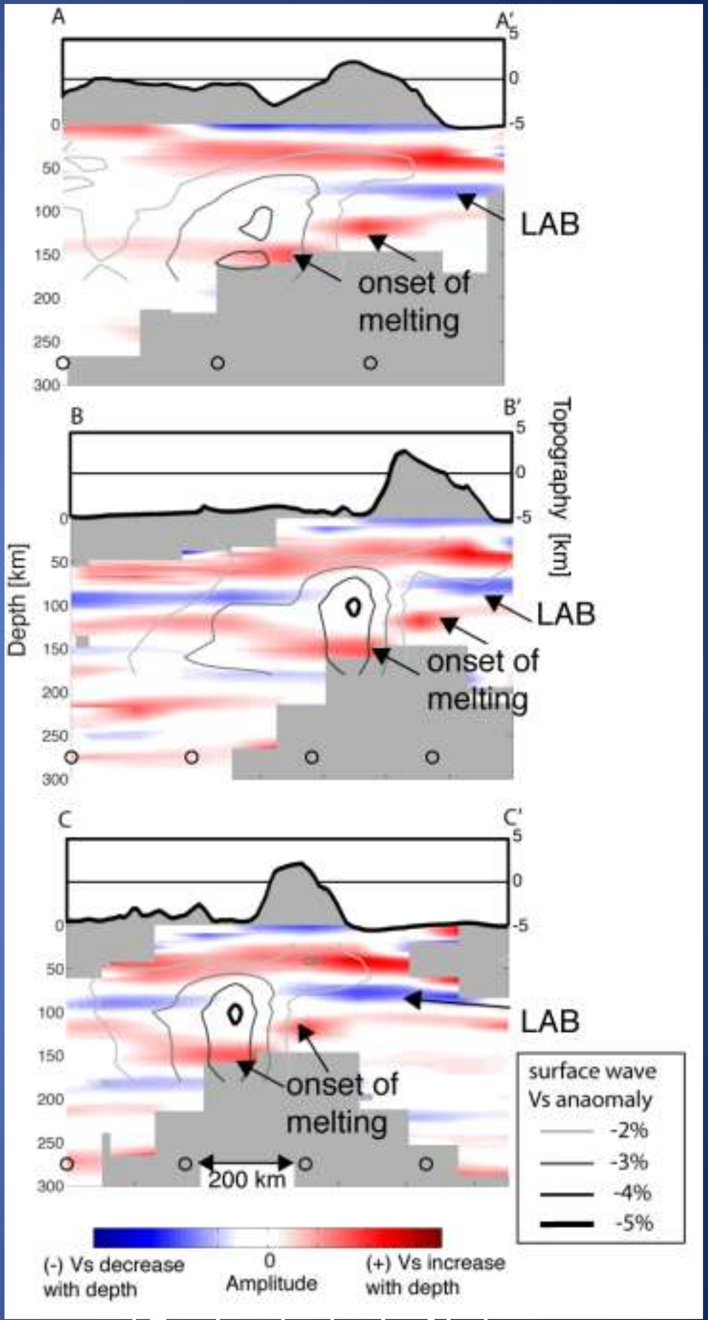
Hawaii - Results

Lithosphere-asthenosphere: 100 km depth, shallowing to 80 km beneath Island of Hawaii.

Also -

Velocity increase with depth: deepens from 110 to 150 km, 100 km west of Hawaii.



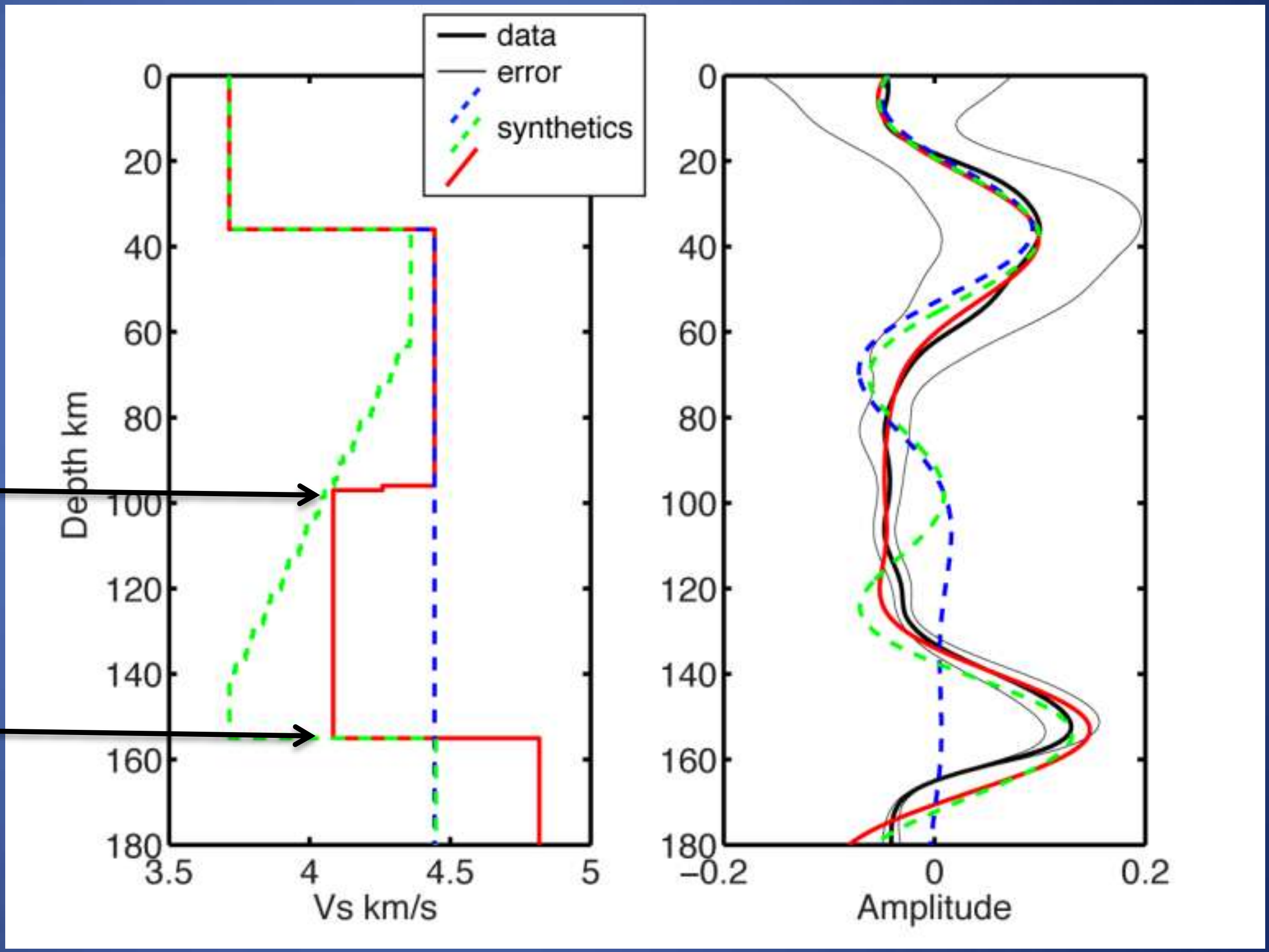


[Rychert et al., Nature Geo., 2013]

Hawaii
Waveform modeling, inferred plume axis

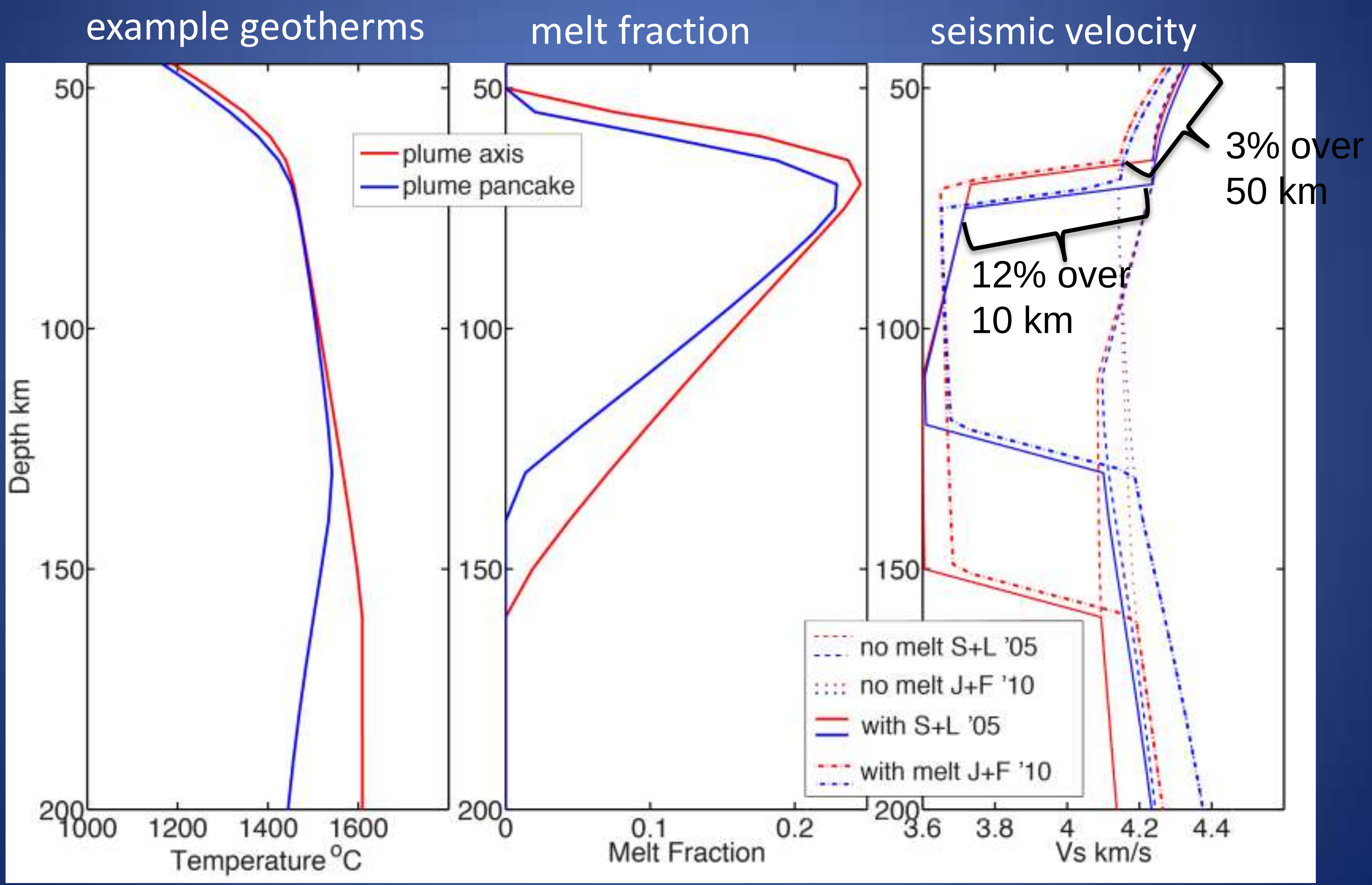
8 +/- 4 %
drop in Vs

18 +/-4 %
increase in Vs
`



[*Rychert et al., Nature Geo., 2013*]

Hawaii
Geophysical modeling – temperature, water, melt?



Hawaii – Discussion

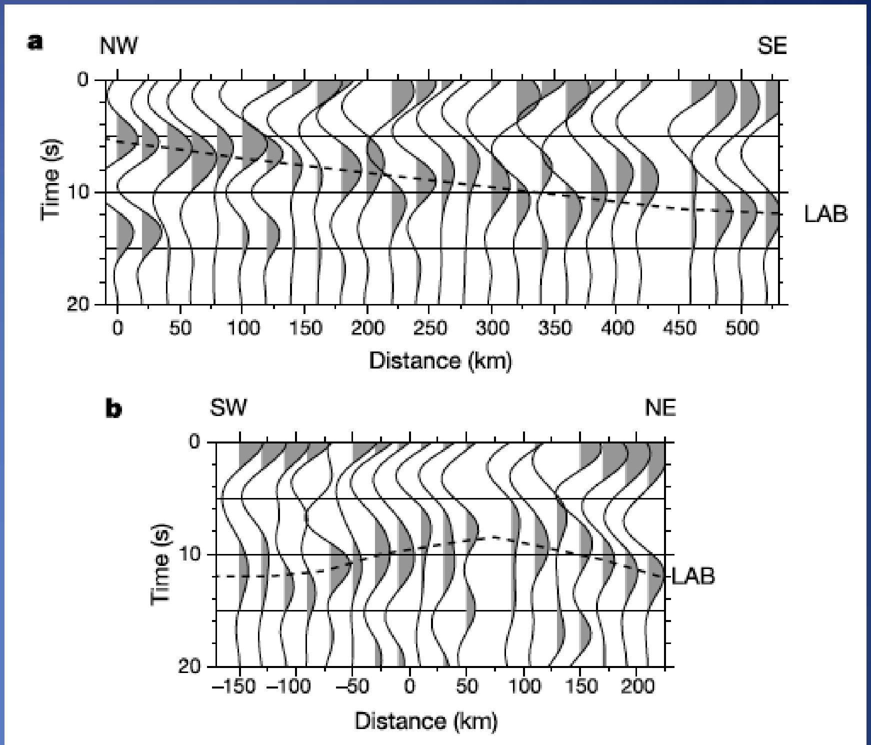
77 – 93 km this study

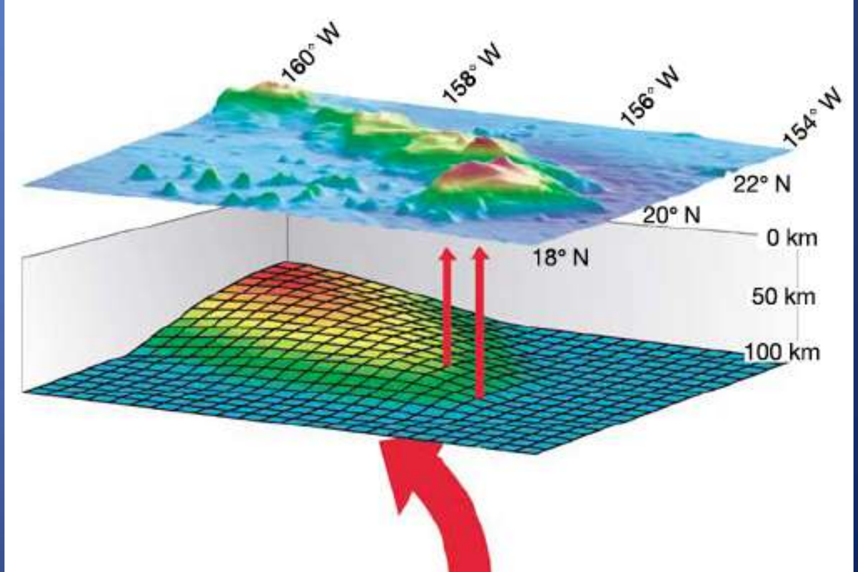
Previous LAB results beneath Hawaii

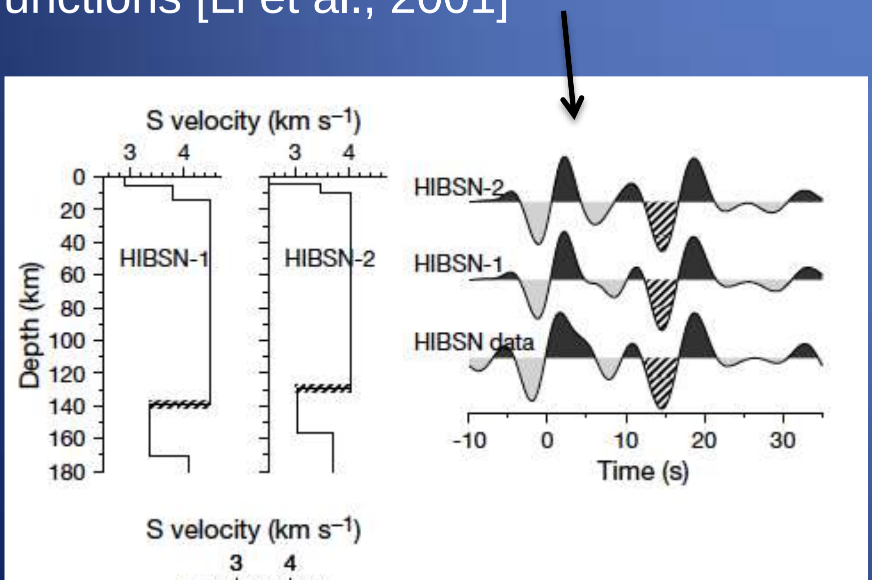
95 km below sea level, previous S-to-P receiver functions [Li et al., 2004]

76 – 81 km below sea level, SS precursors [Schmerr et al., 2012]

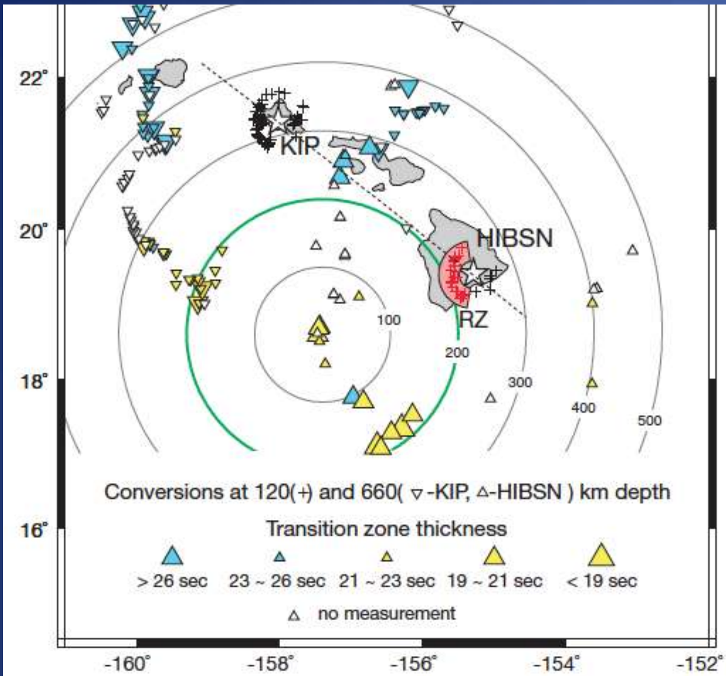
Also, Velocity increase with depth at 130 – 140 km, previous S-to-P receiver functions [Li et al., 2001]







Hawaii - Where is plume at depth?

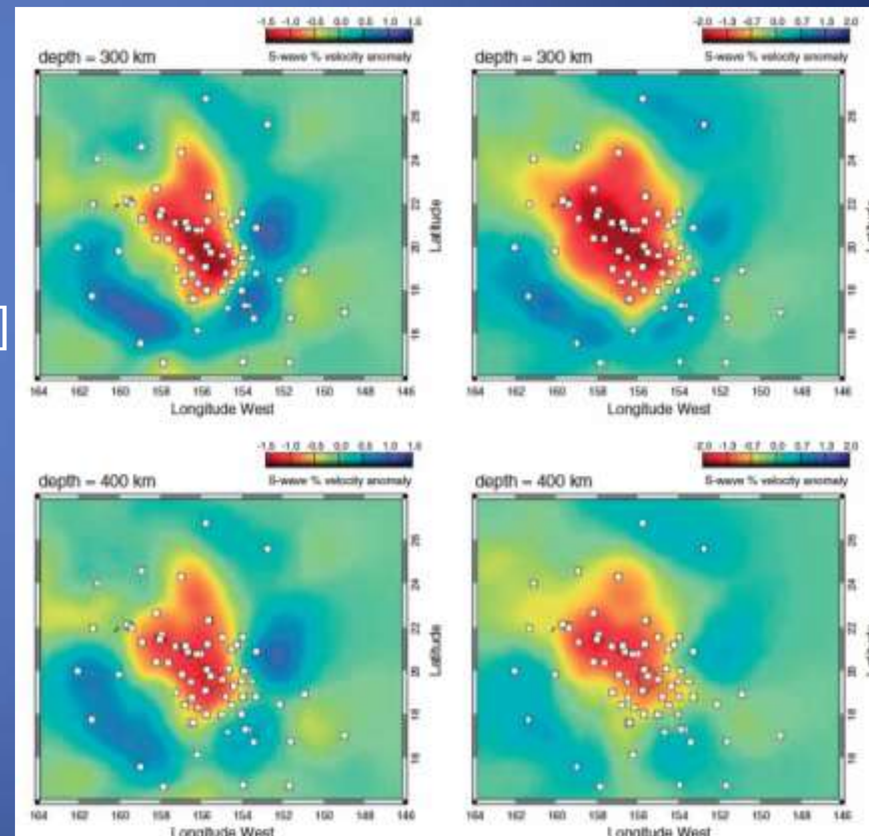


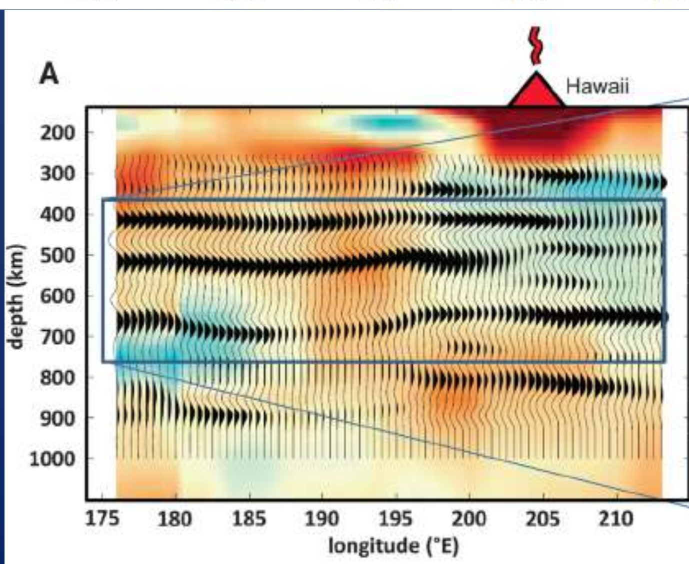
200 km SW

[Li *et al.*, 2000]

directly beneath Hawaii

[*Wolfe et al.*, 2009]

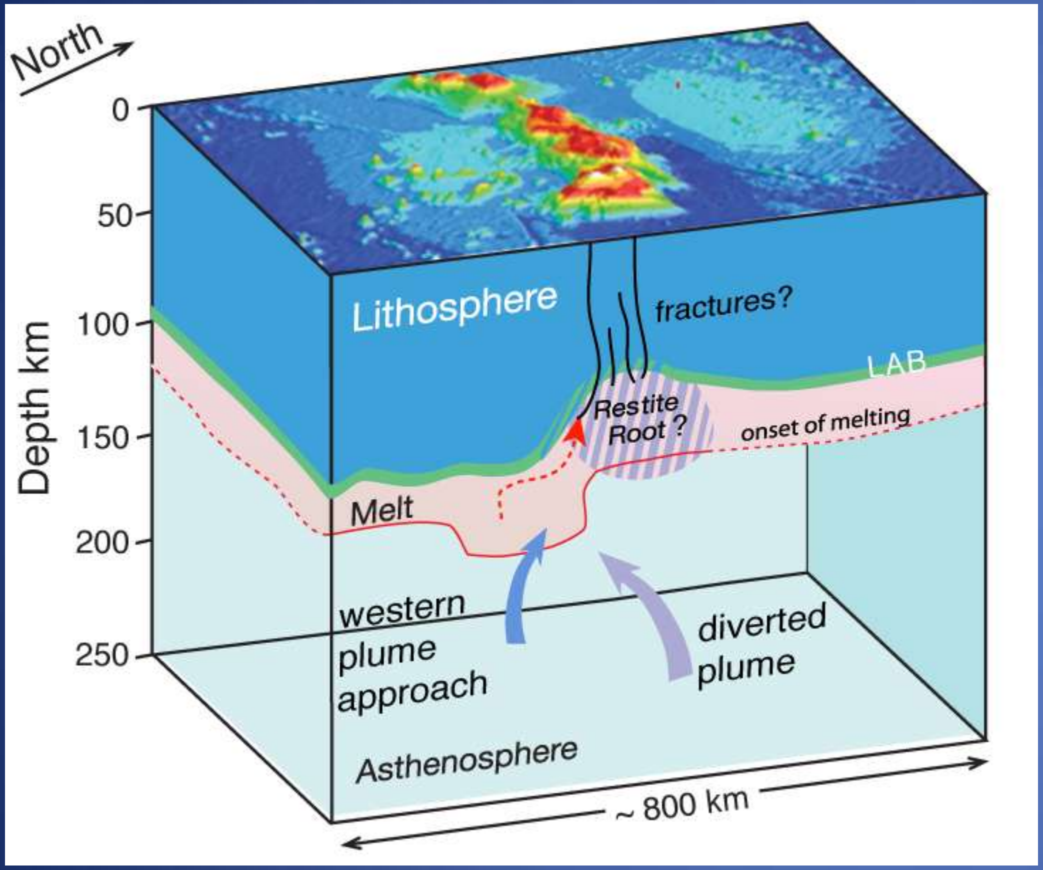




> 700 km W

[*Cao et al.*, 2011]

Hawaii - Conclusions



[*Rychert et al., Nature Geo., 2013*]

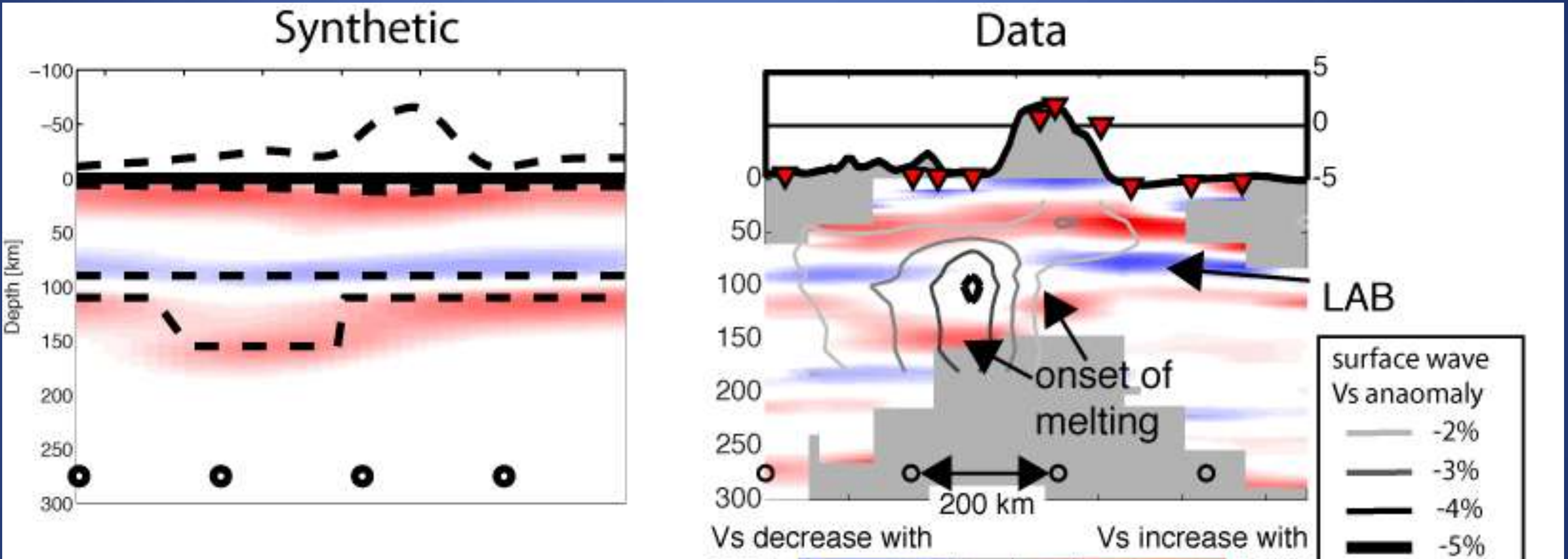
Onset of melting Increases from 110 km depth to 150 km depth

- Hawaiian plume impingement 100 km west of Hawaii
- Either approaches from west or deflected, possibly from a restite root
- Melt transport toward Hawaii along the gently sloping LAB permeability barrier and or/ via pre-existing lithospheric fracturing [Hieronymus & Bercovici, 1999]

Hawaii – What's next?

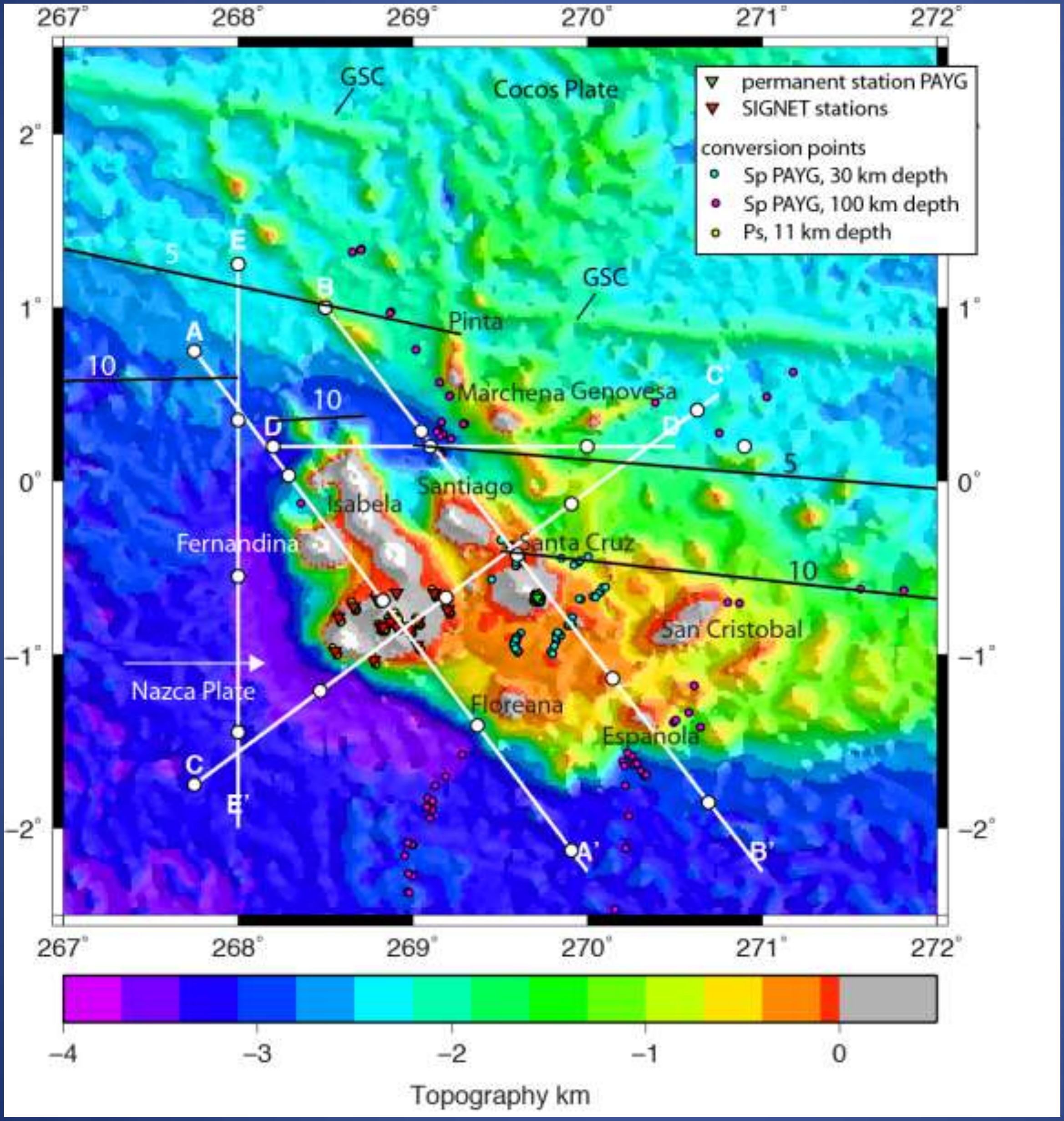
Full waveform modeling

confirms imaging.
Also, some predicted focusing/defocusing.



[*Rychert et al., in prep*]

Galapagos



Data –

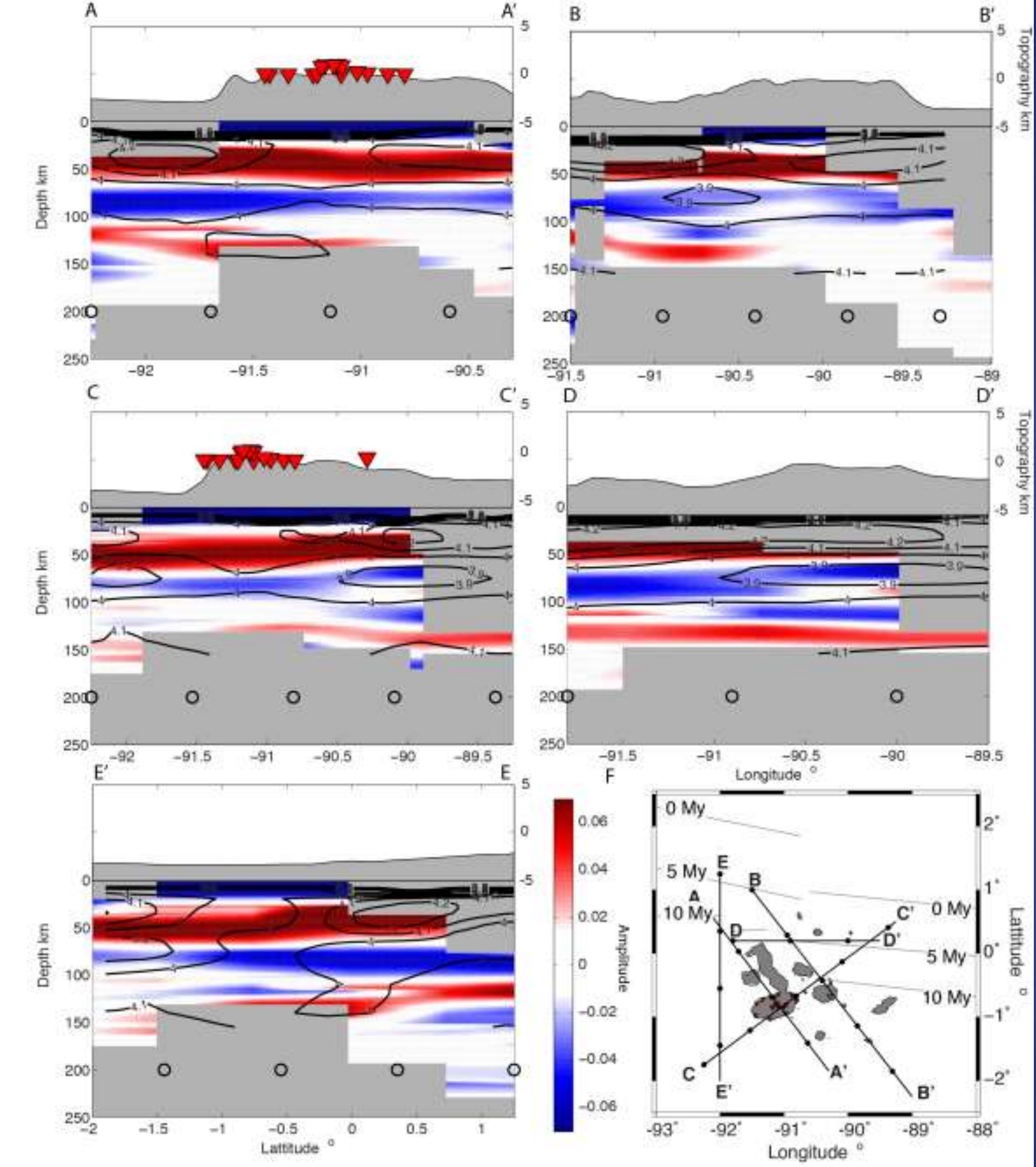
SIGNET array October 2009 – June 2011

Permanent station PAYG 1998 – 2011

Young oceanic lithosphere

Hotspot-ridge interaction

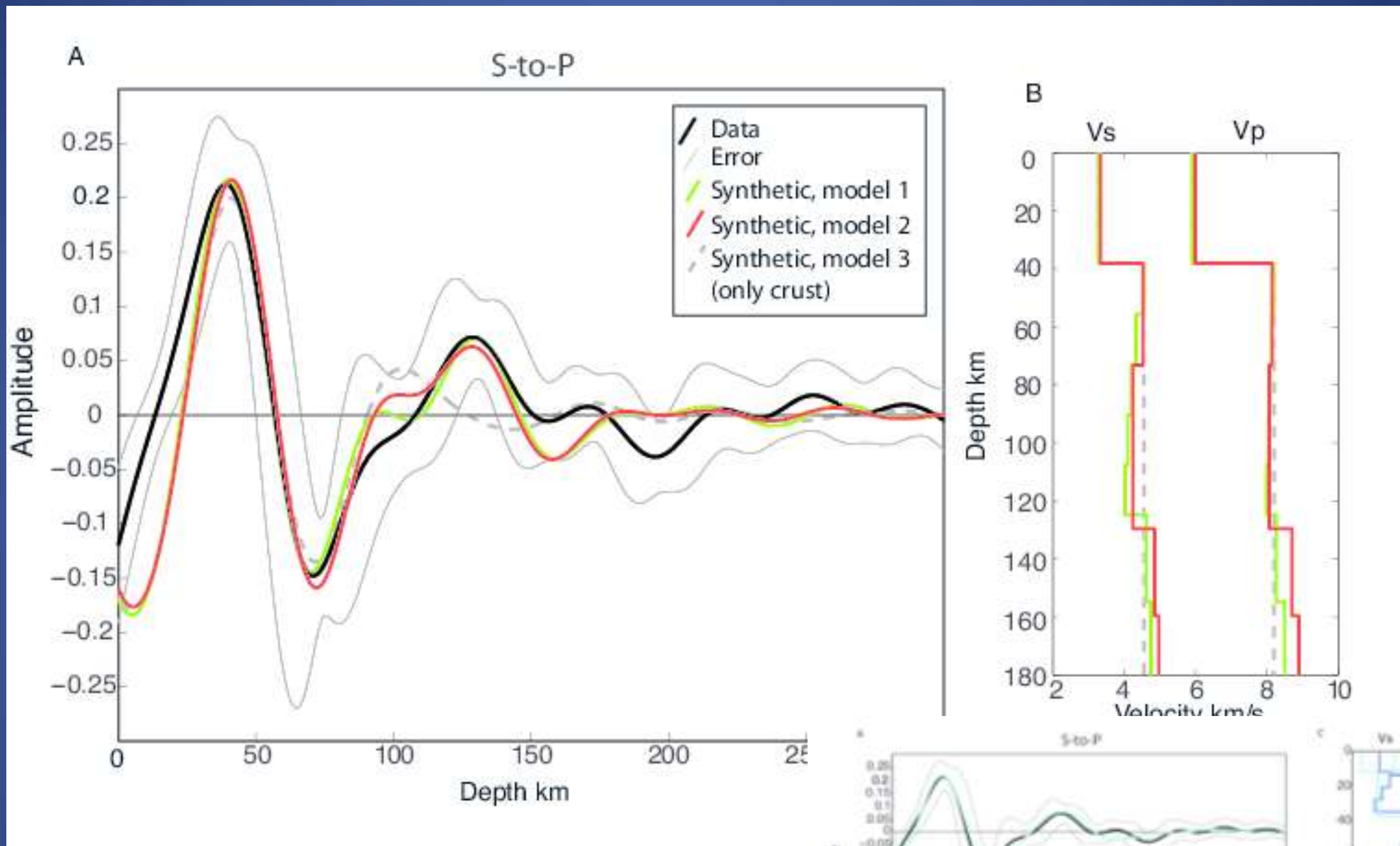
Galapagos

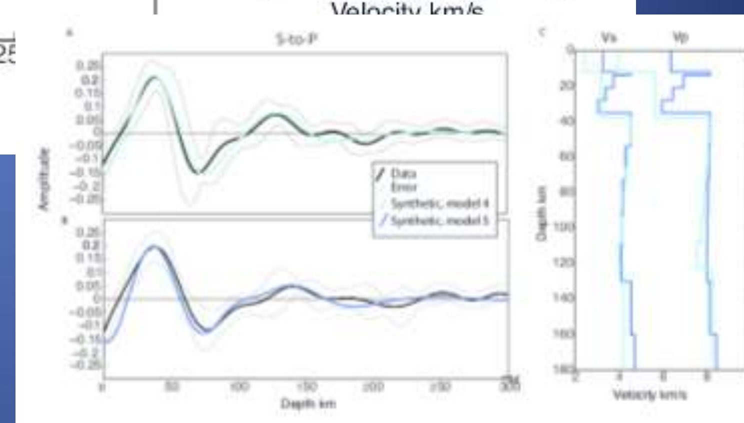


[*Rychert et al., EPSL., 2013*]

Galapagos

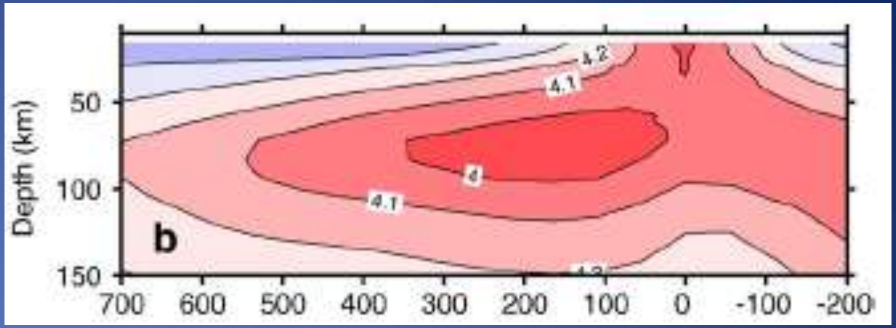
Station PAYG



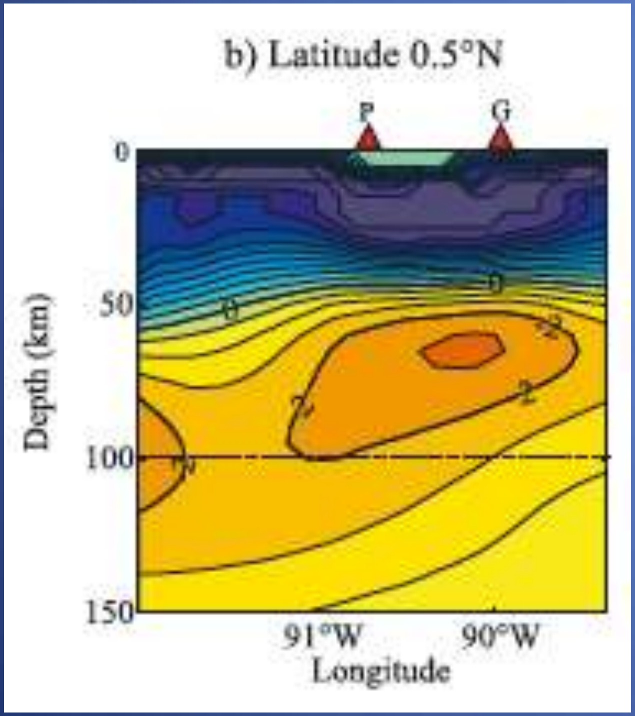


[*Rychert et al., EPSL., 2013*]

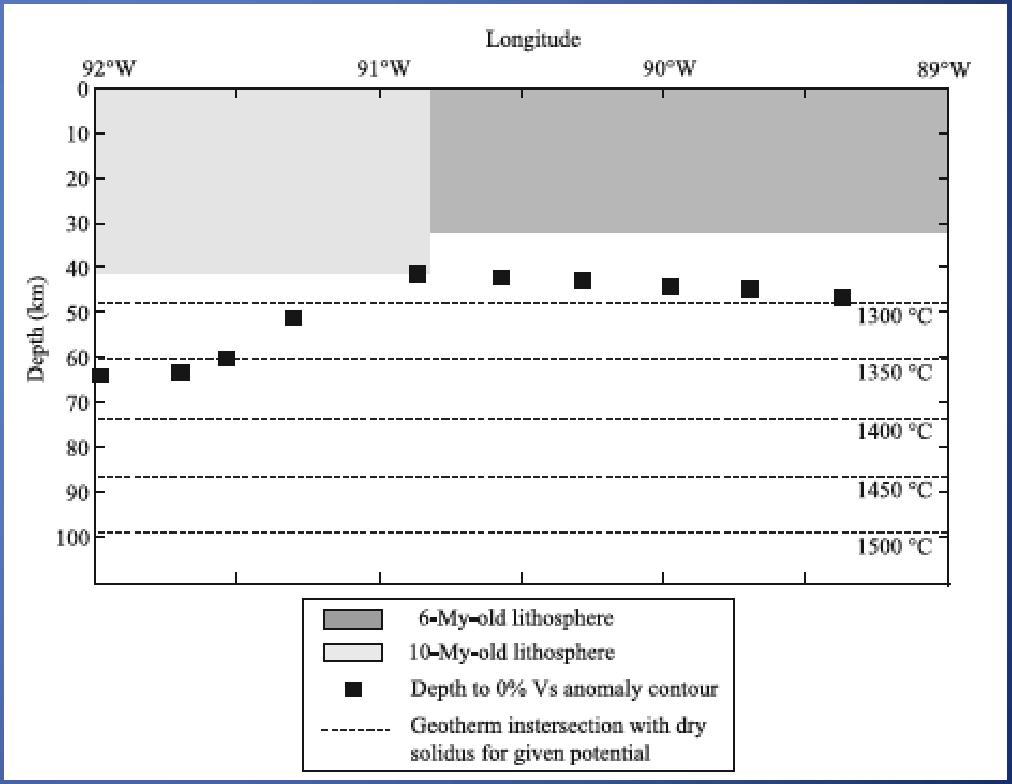
Galapagos



[*Harmon et al., 2009*]

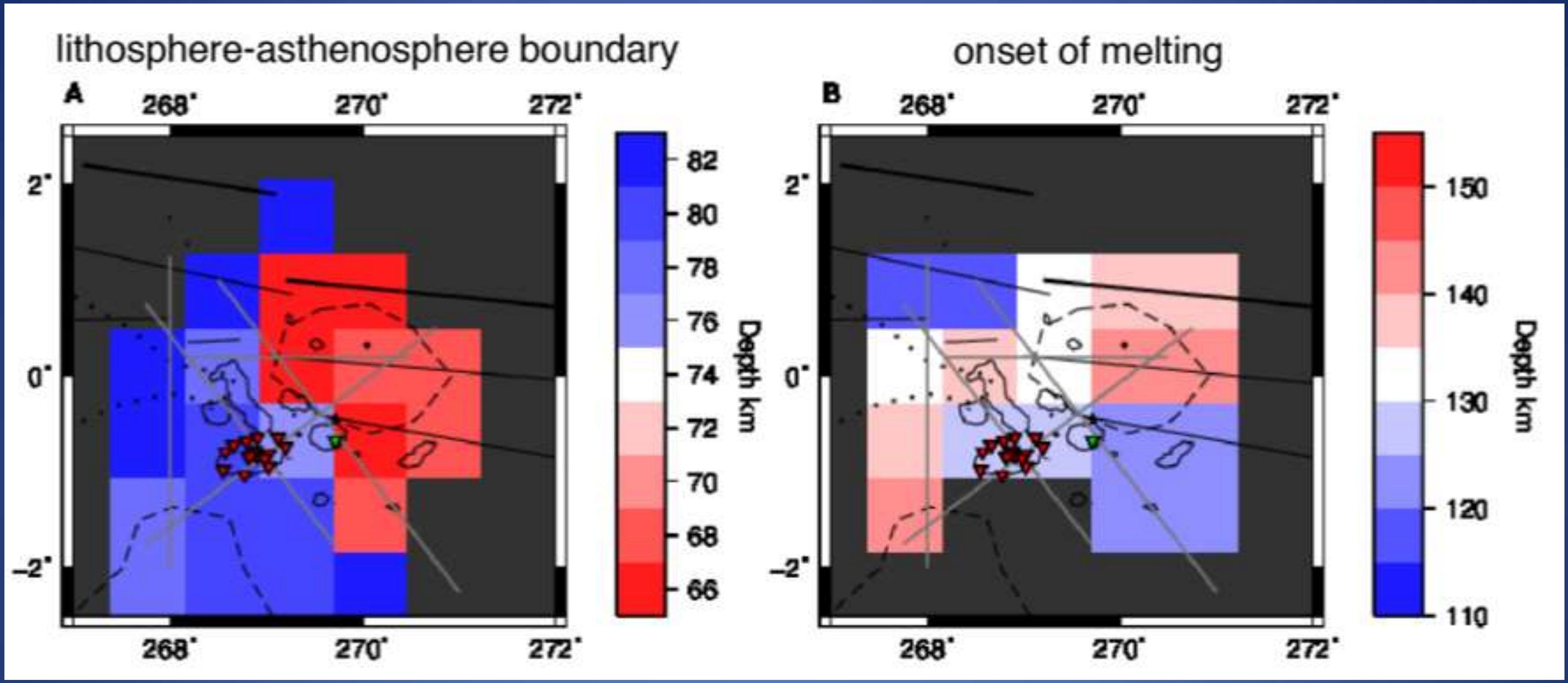


[*Rychert et al., EPSL., 2013*]



[*Villagomez et al., 2007*]

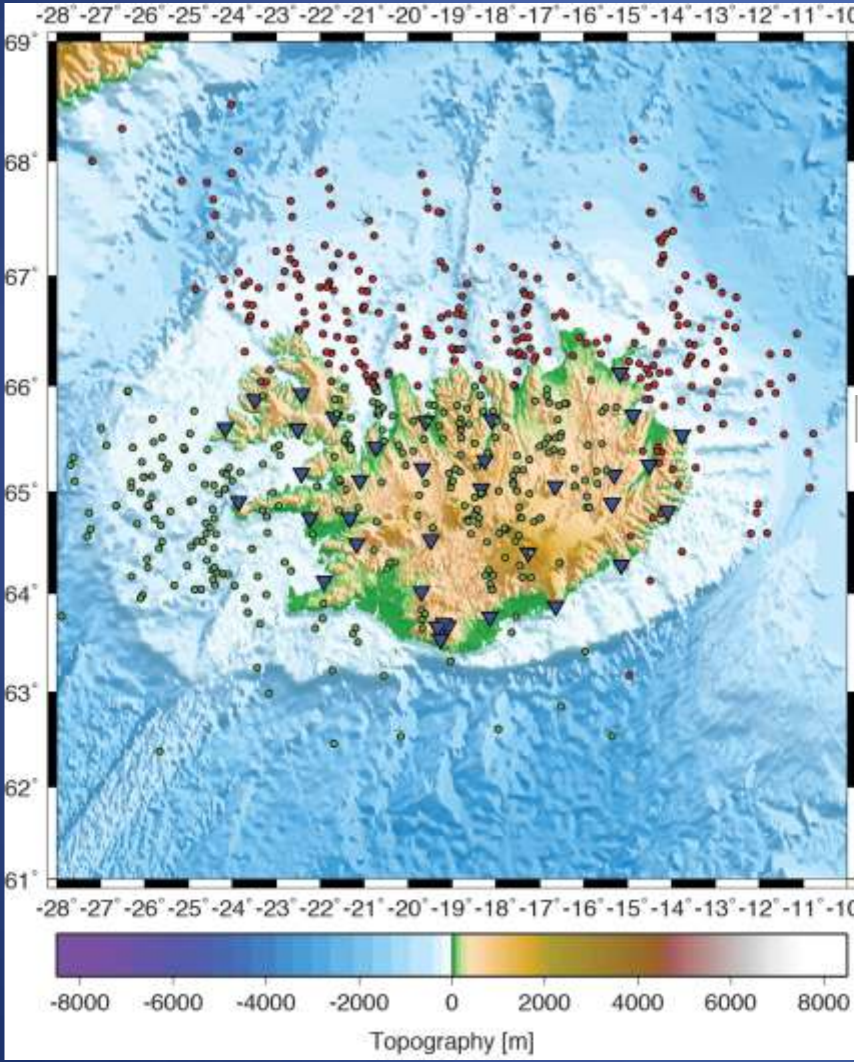
Galapagos

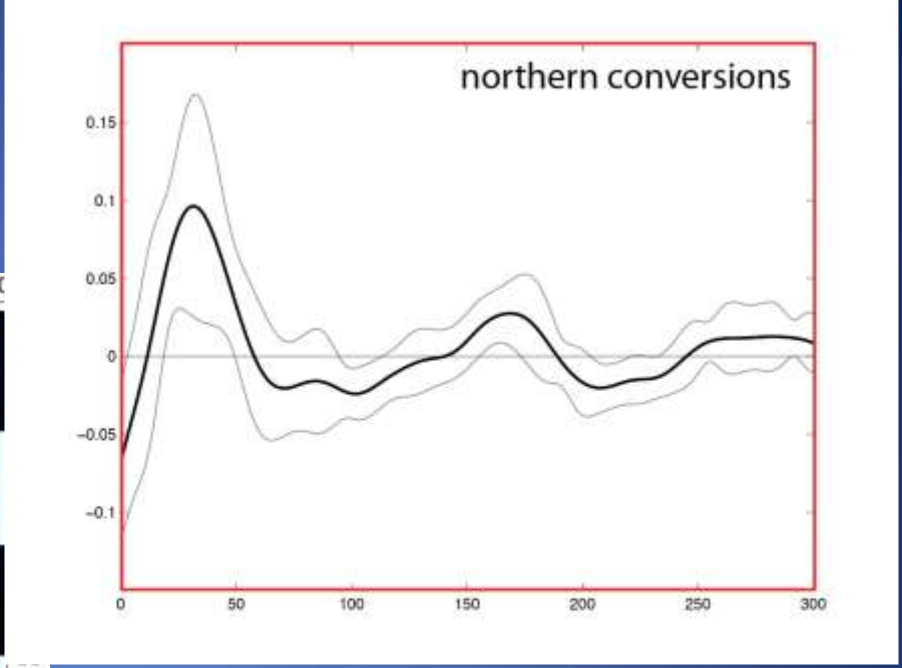


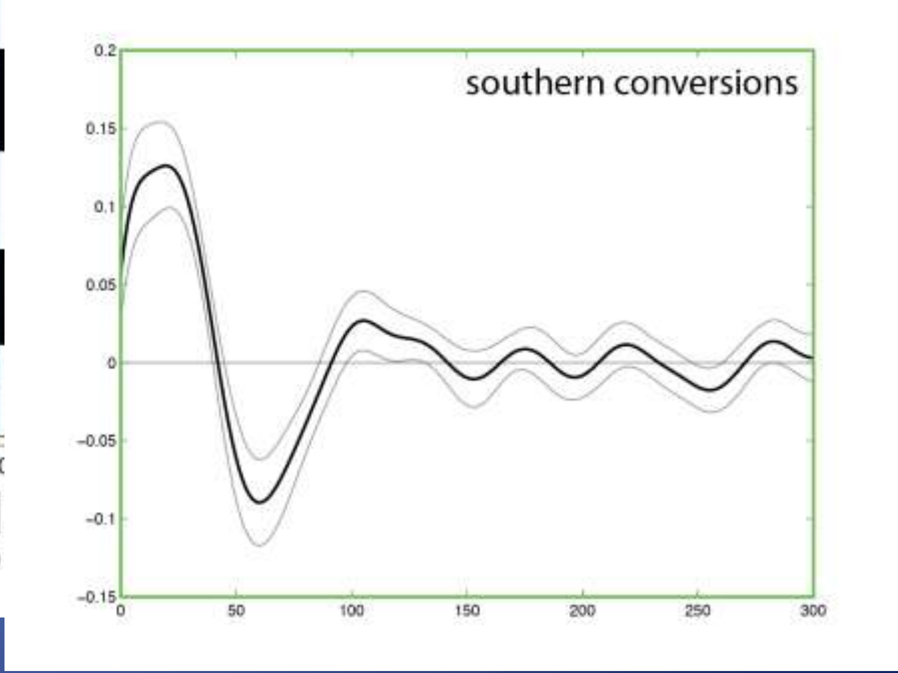
- LAB deeper near hypothesized plume location [Hooft et al., 2003]
- Onset of melting deeper in locations of surface wave anomalies.
- Multiple regions of deepened melting may indicate plume diversions and complex interactions with the ridge.

[*Rychert et al., EPSL., 2013*]

Iceland

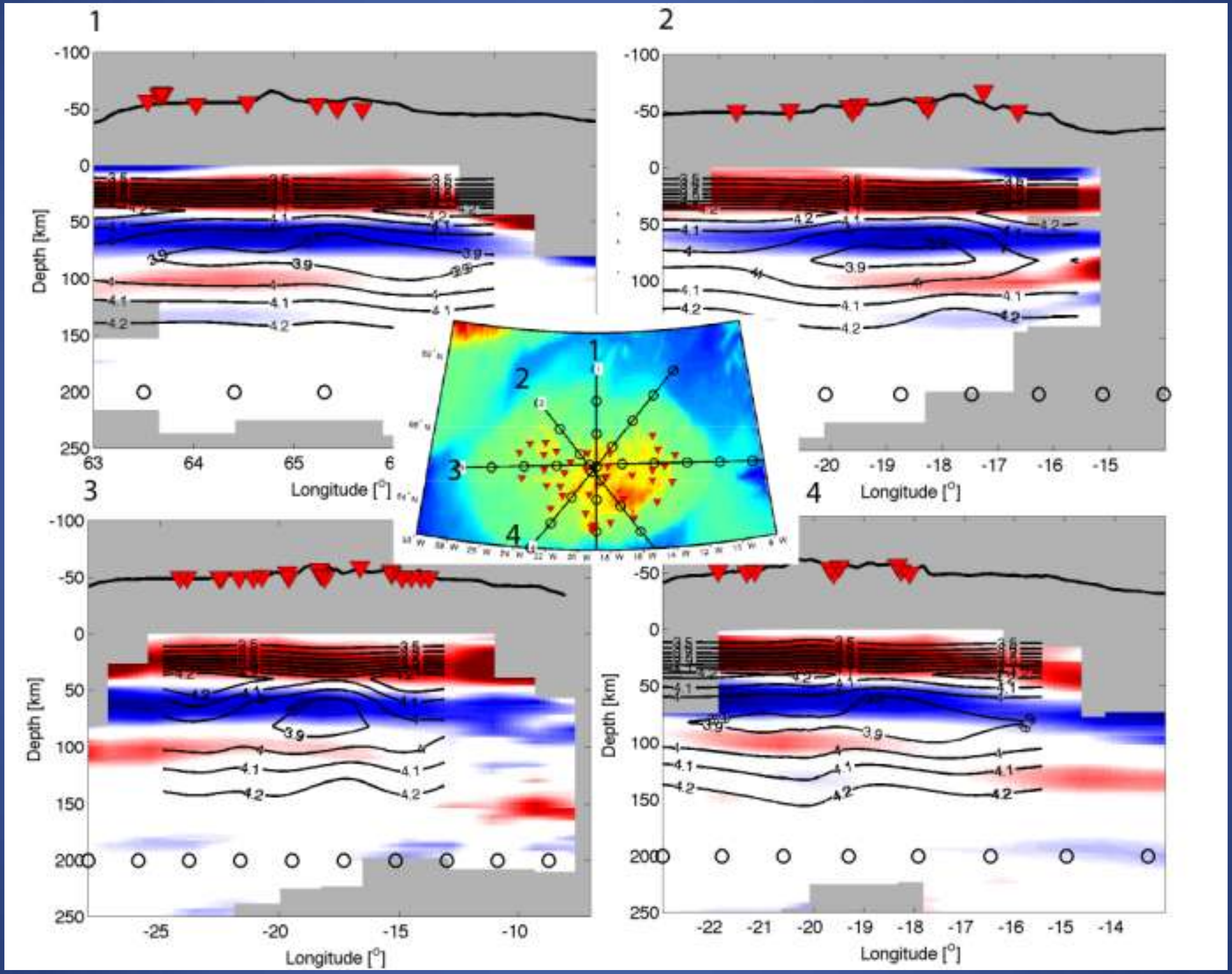






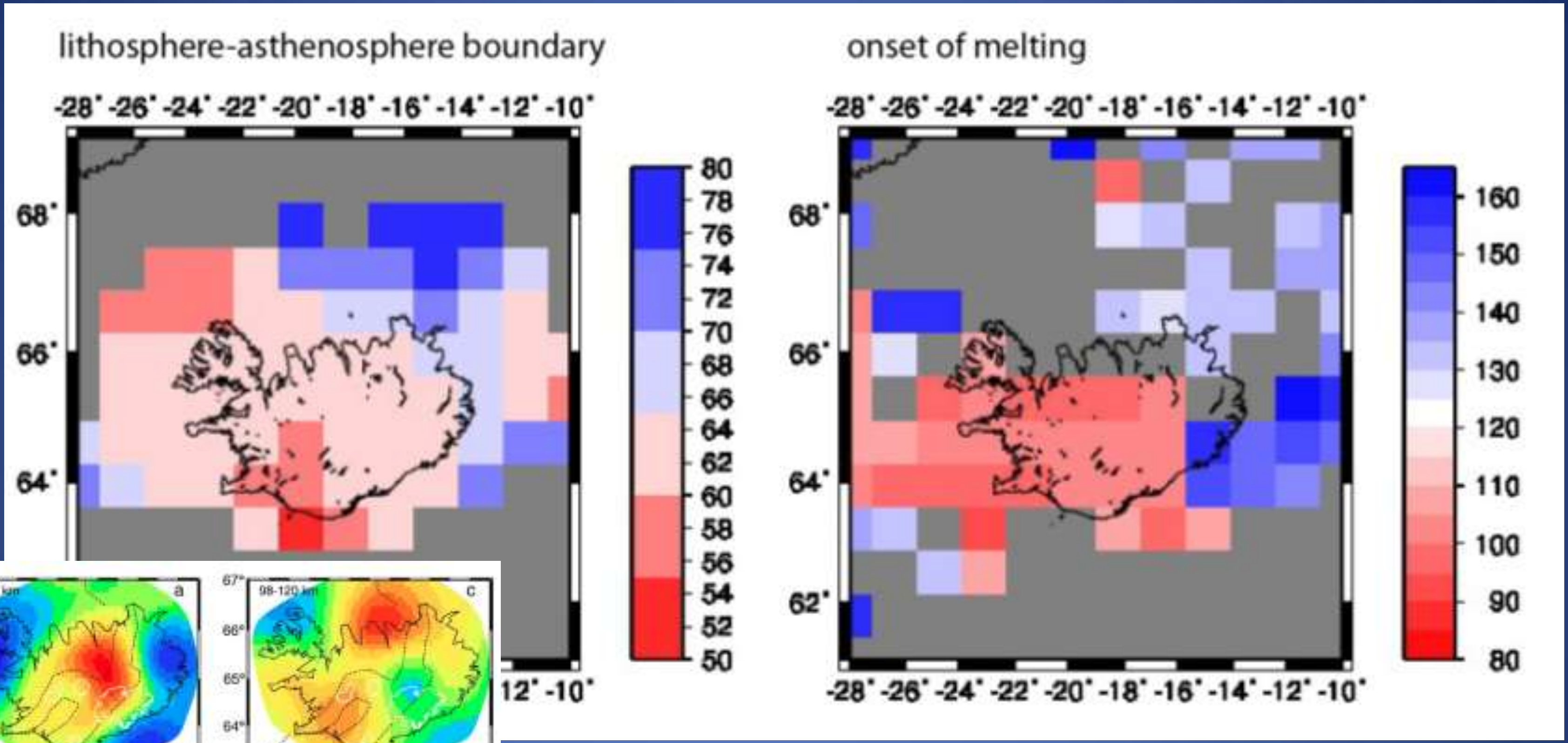
[*Rychert et al., in prep.*]

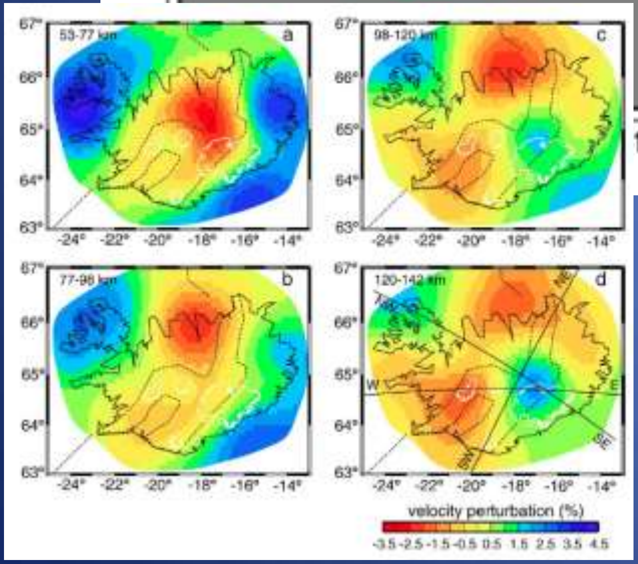
Iceland



[*Rychert et al., in prep.*]

Iceland

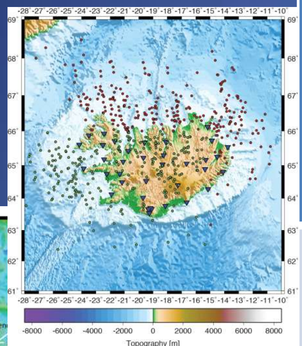


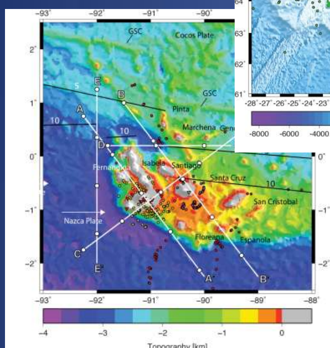


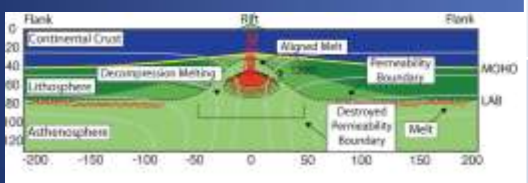
- LAB deeper near hypothesized plume, NE
- Onset of melting deeper in NE

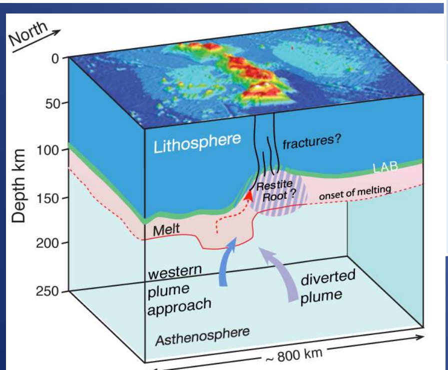
[Li & Detrick, 2006]

Comparison





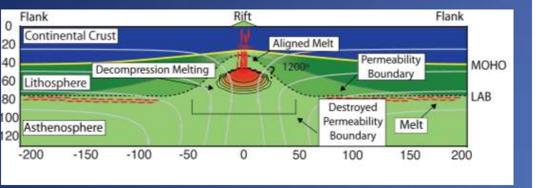




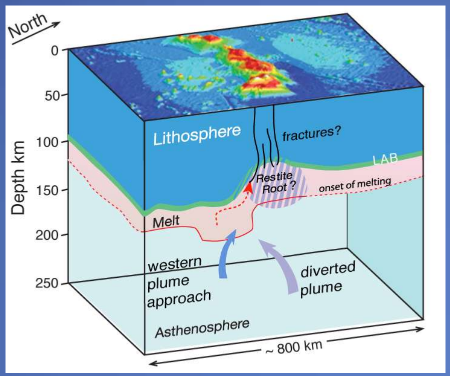
	Age Ma	LAB Depth km	LAB sharpness km	Onset of Melting km
Iceland	0	~60 50-80 (NE)	Not modeled yet	90-160
Galapagos	0	~75 66(NE) - 82 (SW)	Unconstrained, lateral variation?	125-145
Afar	0	60-80 none in rift	~15 km depth (off axis)	66-75
Hawaii	95	~80 75 (E) - 93 (W)	~10 km depth (west of Hawaii)	125-155

Summary

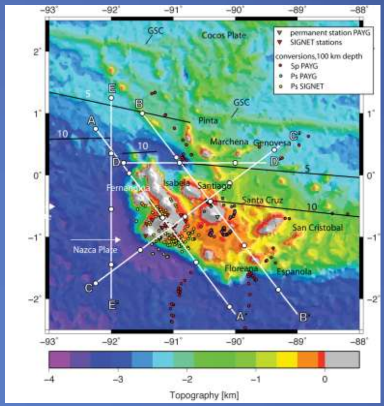
Afar



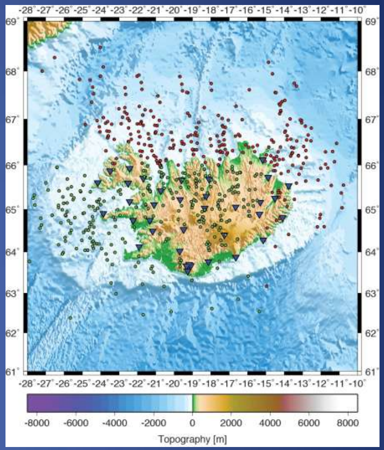
Hawaii



Galapagos



Iceland



- destroyed mantle lithosphere

- Plume located off axis
- LAB thicker near plume

[Rychert et al., Nature Geo., 2012]

[Rychert et al., Nature Geo., 2013]

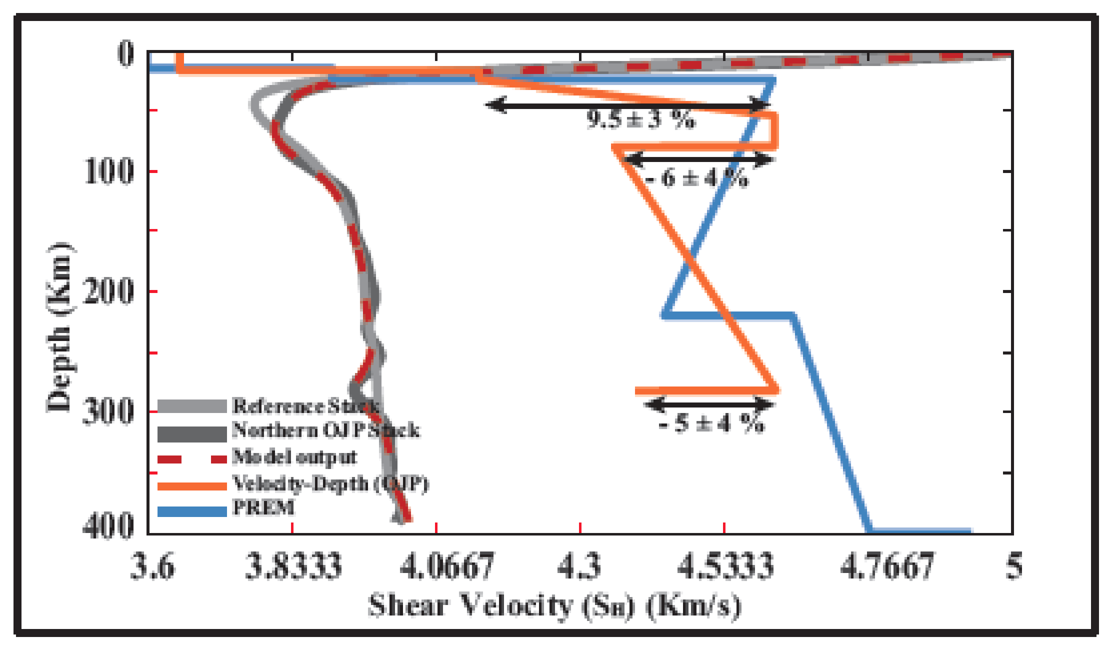
[Rychert et al., EPSL, 2013]

[Rychert et al., in prep.]

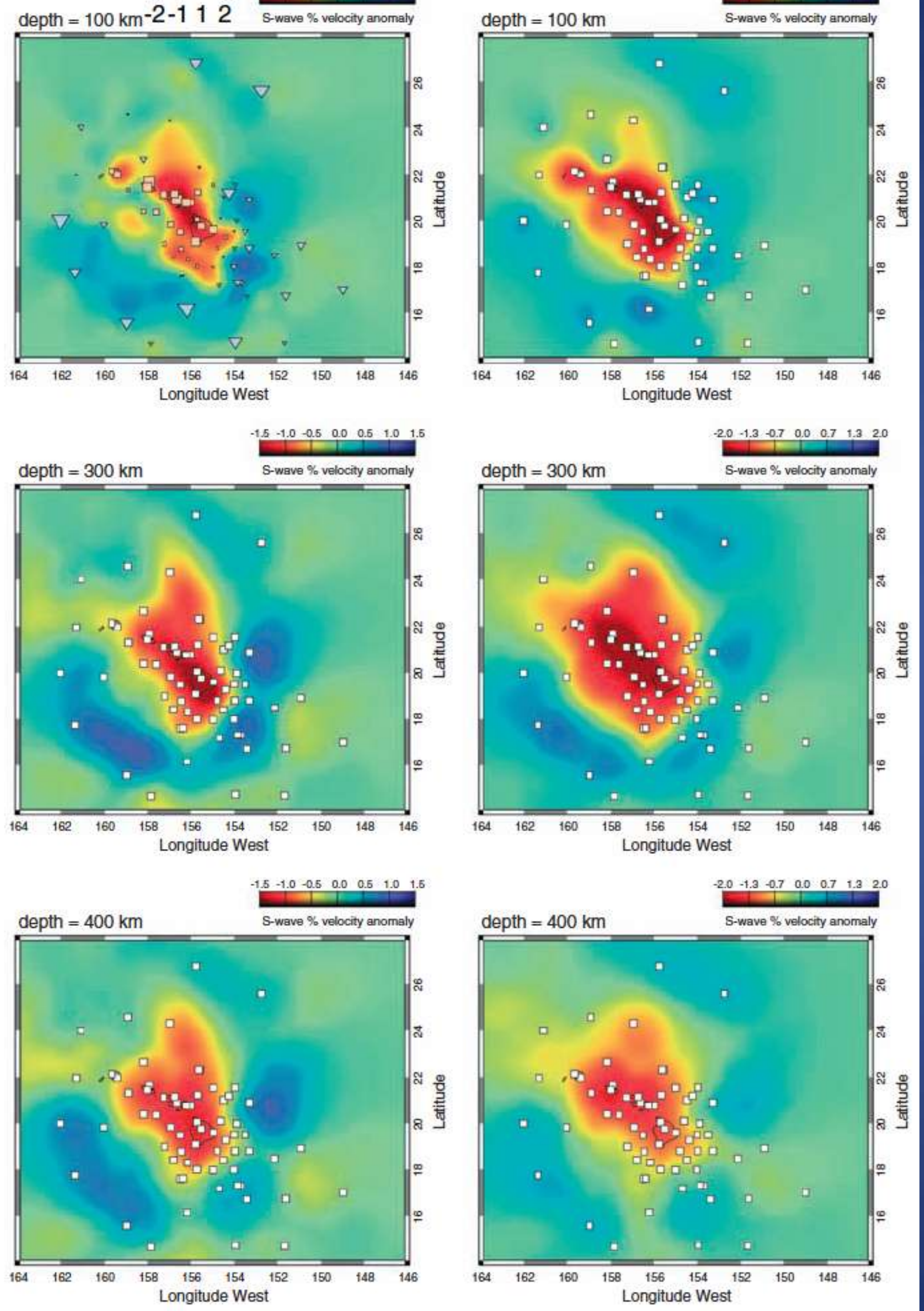
Conclusions

- A sharp rigid lid is imaged on the flank of the Afar rift. No mantle lid exists beneath the rift, rather a discontinuity at the onset of decompression melting, without a strong plume influence.
- The base of a melt rich layer beneath Hawaii, Galapagos, and Iceland increases in depth where the plume impinges on the lithosphere.
- Plume is located off-axis beneath Hawaii, Galapagos, Iceland
- The LAB is deeper near the region of plume impingement, consistent with compositional definition.
- Melt may be guided toward axis of volcanism via pre-existing structures.
- Suggests melt is retained in the asthenosphere beneath areas of active volcanism in sufficient quantities and over significant depth ranges to be observed seismically.

Ontaong Java Plateau: a modern day analogue for the formation of the continents?



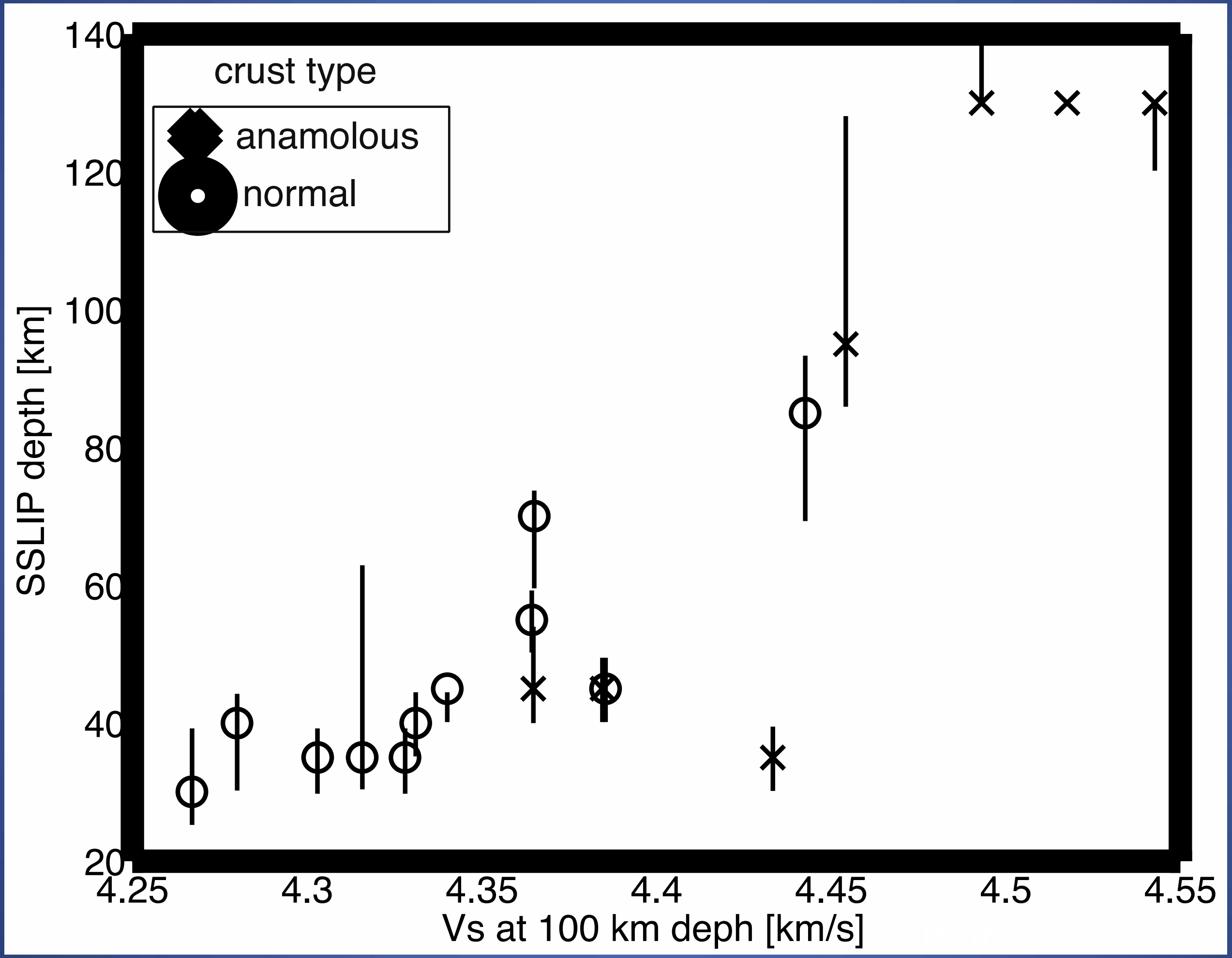
Saikiran Tharimena, see poster!



[*Wolfe et al.,* 2009]

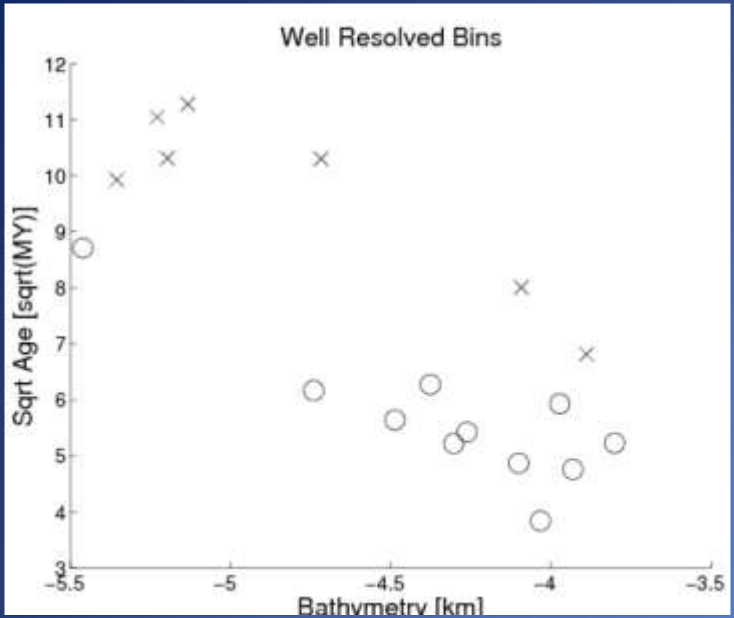
SSLIP – SS Lithospheric Interface Profiling

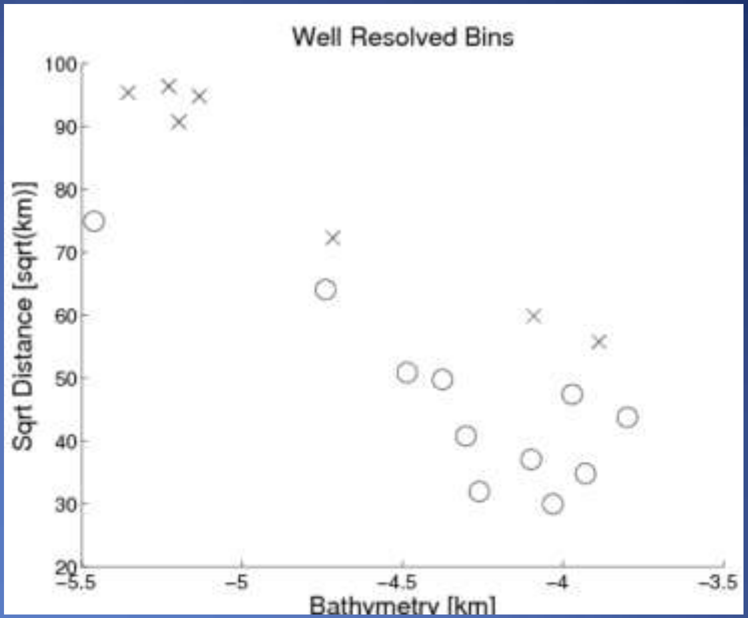
Comparison to previous work

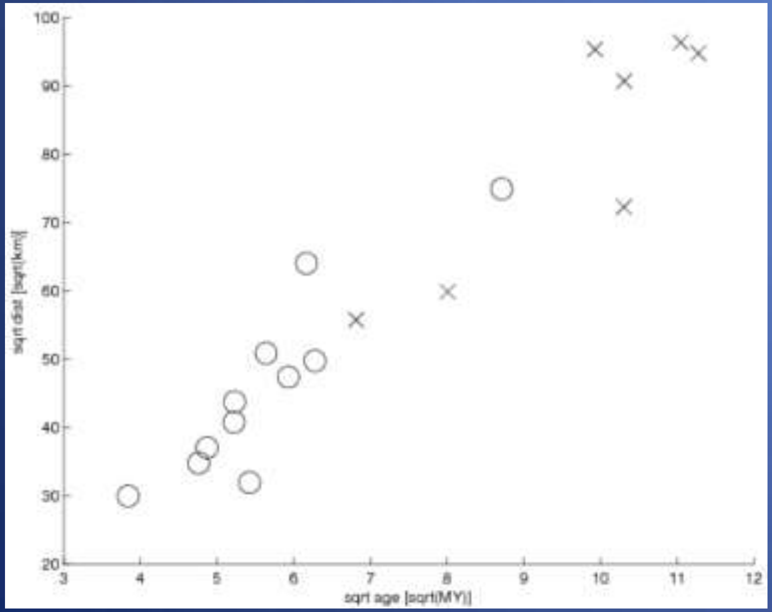


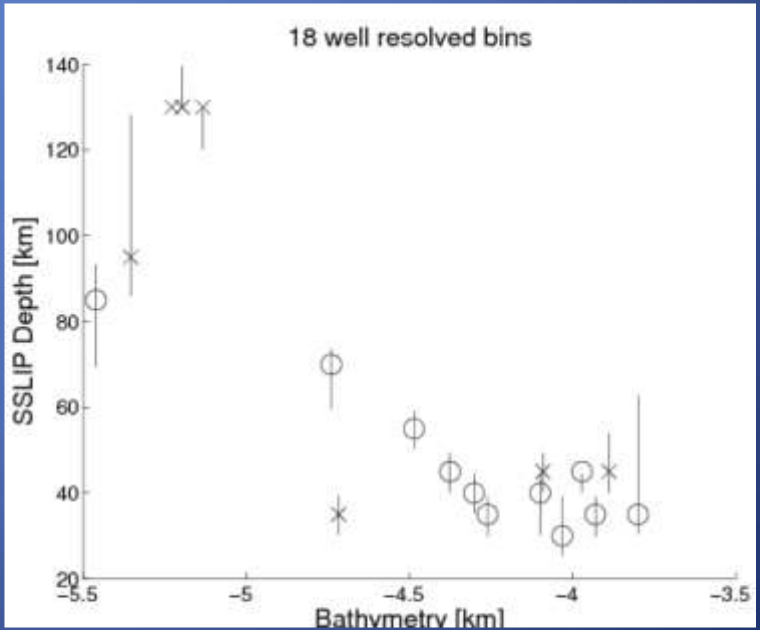
[*Nettles & Dziewonski*, 2008]

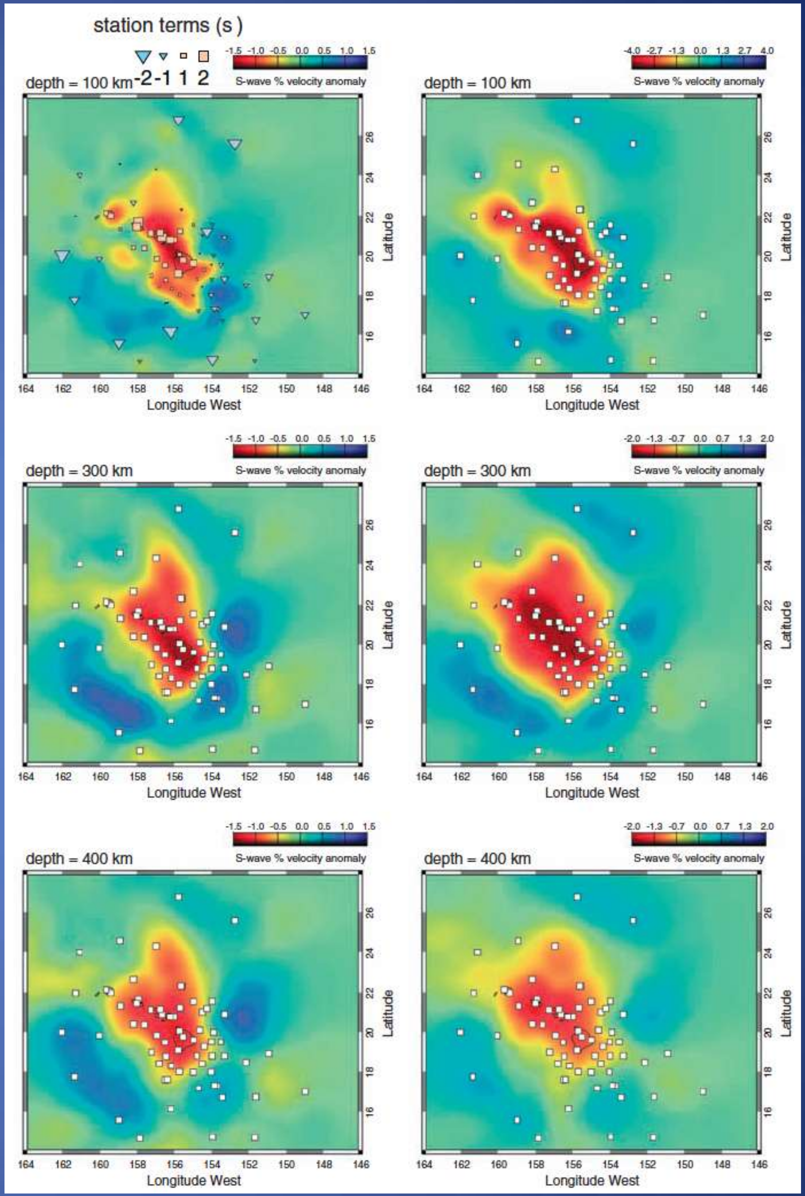
SSLIP
[*Rychert & Shearer, JGR*, 2011]


Well Resolved Bins
Sqrt Age [sqrt(MY)]
Bathymetry [km]
12
11
10
9
8
7
6
5
4
3
-5.5
-5
-4.5
-4
-3.5

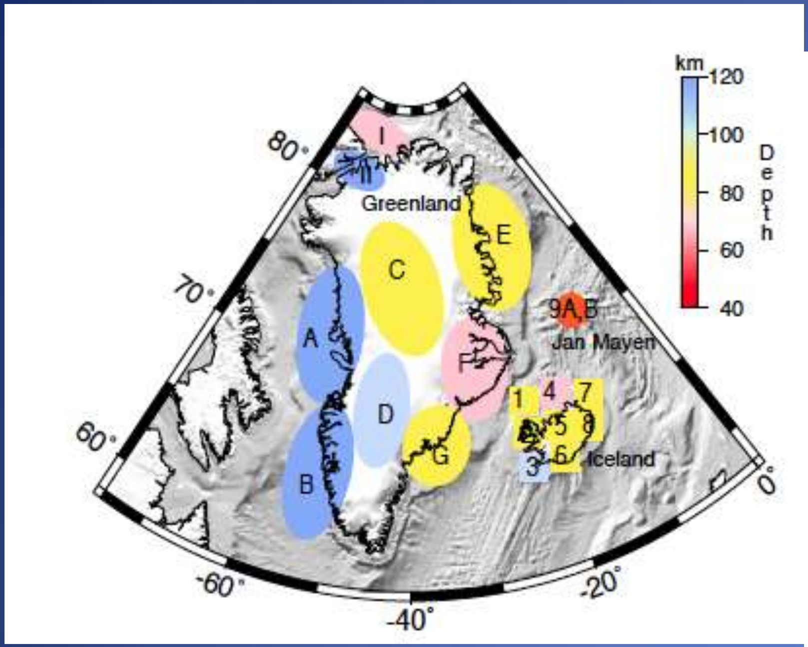

Well Resolved Bins
Sqrt Distance [sqrt(km)]
Bathymetry [km]
100
90
80
70
60
50
40
30
20
-5.5
-5
-4.5
-4
-3.5

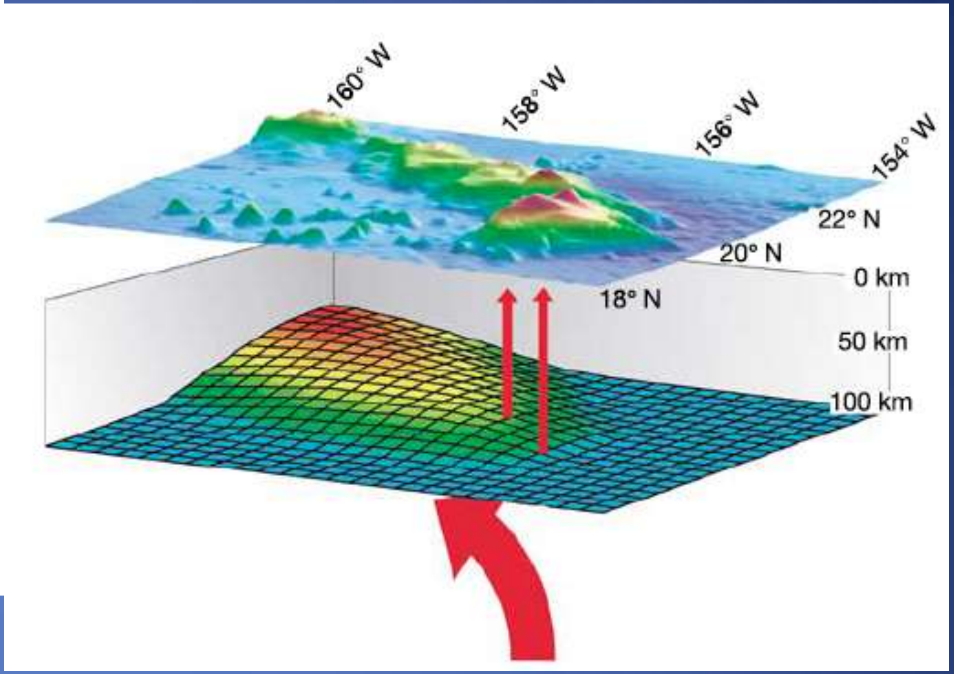

sqrt dist [sqrt(km)]
sqrt age [sqrt(MY)]
100
90
80
70
60
50
40
30
20
3
4
5
6
7
8
9
10
11
12


18 well resolved bins
SSLIP Depth [km]
Bathymetry [km]
140
120
100
80
60
40
20
-5.5
-5
-4.5
-4
-3.5



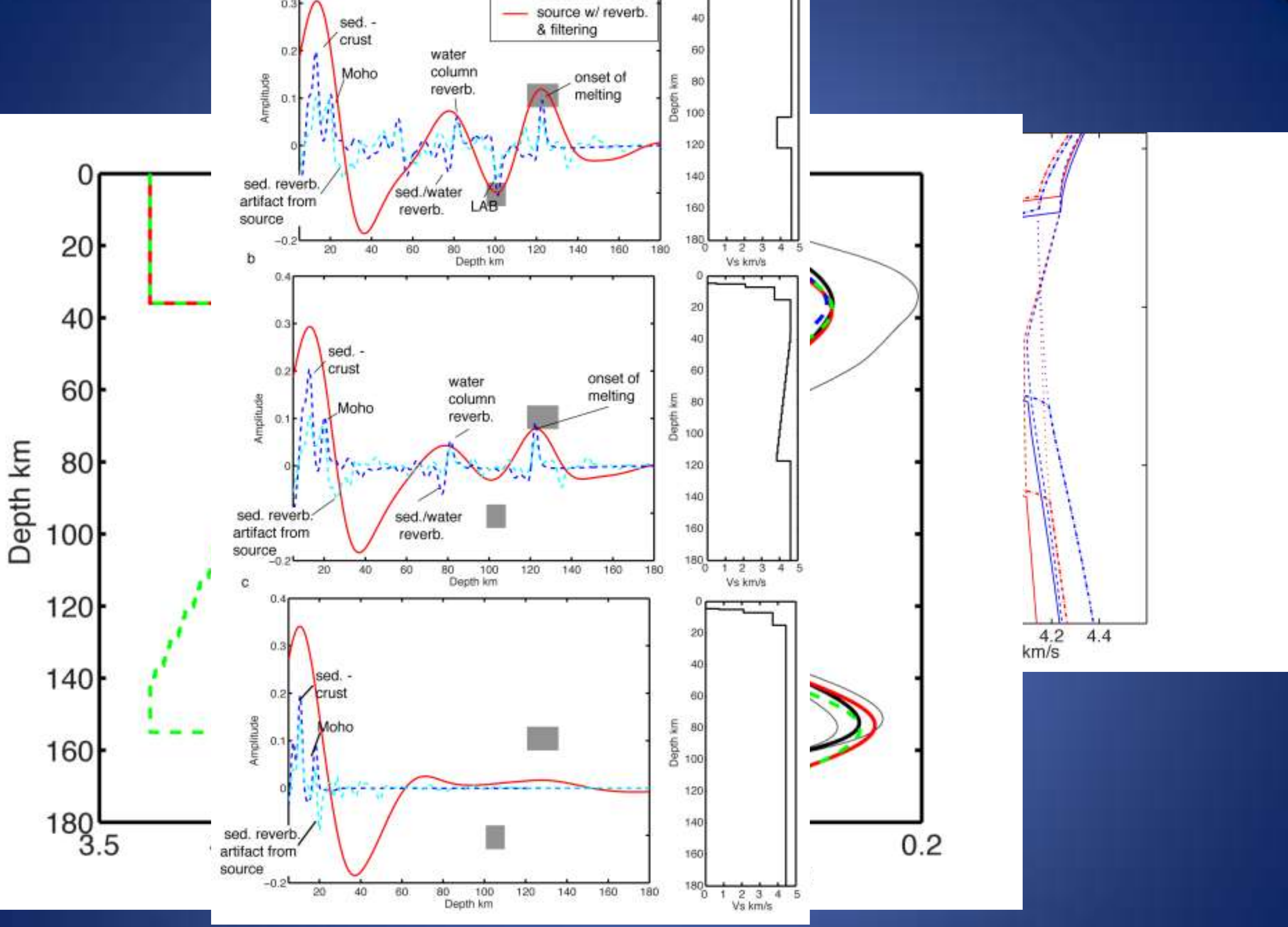
[*Wolfe et al.*, 2009]





70 – 110 km

100-110 km thins to 50-60 km



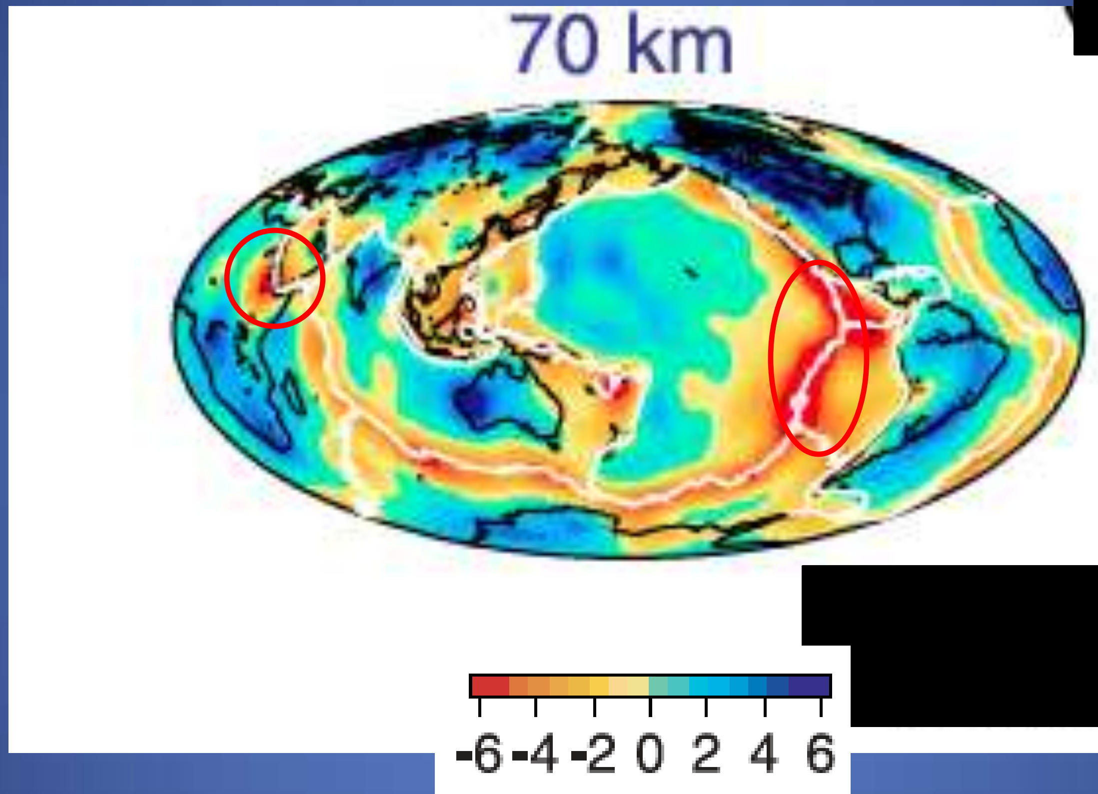
source w/ reverb.
& filtering
sed. -
crust
Moho
water
column
reverb.
onset of
melting
sed. reverb.
artifact from
source
sed./water
reverb.
LAB
Amplitude
Depth km
Vs km/s
b
c
km/s
0.2
3.5

temperatures from geochemistry (1370 - 1490°C)[Rooney et al., 2011] agrees with our predicted range (1350 – 1400°C), i.e., not significantly hotter than normal mantle.

2) 3) Indeed, petrologic estimates for the depth of melting in Afar (70 - 90 km) [Furman, 2007] agree with the depth of our observed seismic discontinuity.

3) 5) Afar rift is likely seismically slow in comparison to surrounding regions from down to ~200 km depth due channelized flow from a low viscosity asthenospehre, which provides slightly warmer material, but certainly no plume. Such a model has been used to explain similar seismic structure and low mantle potential temperatures beneath the East Pacific Rise [Toomey et al., 2002]. Lateral asthenospheric flow has also been invoked to explain diachronous volcanism and geochemical variations beneath Afar [Ebinger & Sleep, 1998].4) No plume directly beneath Afar in recent

Afar looks like the EPR @ 70 km depth



[redacted]

[Kustowski et al., 2008]

No significant plume influence is required!

Conclusions

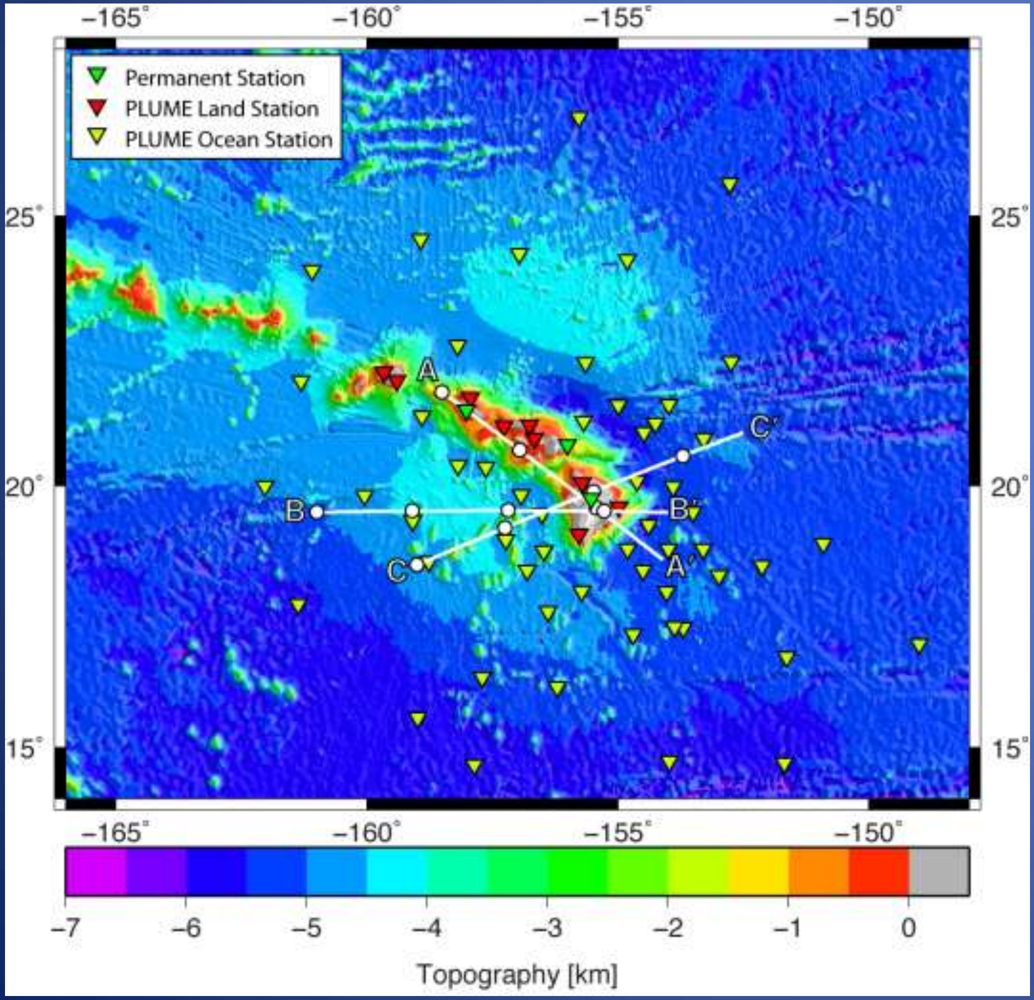
- A sharp rigid lid is imaged on the flank of the Afar rift at ~75 km depth. The transition from flank to rift is abrupt.
- The sub-crustal lithosphere beneath the rift has been destroyed.
- A significant velocity increase imaged beneath the rift is consistent with geodynamic predictions for the onset of decompression melting.
- Its depth is shallow, indicating no significant plume influence today.

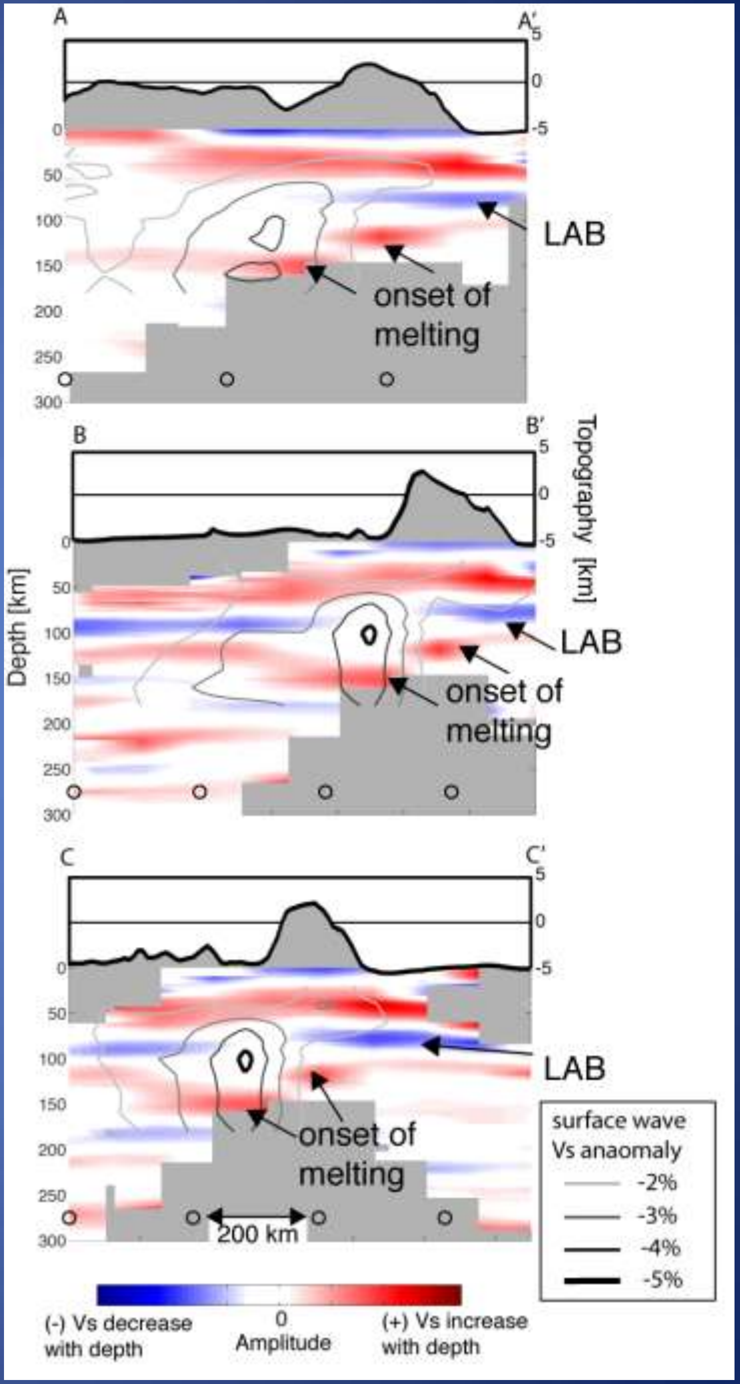
Hawaii –

Image plume pancake and conduit

[*Rychert et al., submitted*]

Onset of melting increases in depth 100 km west of Hawaii, in location of plume conduit





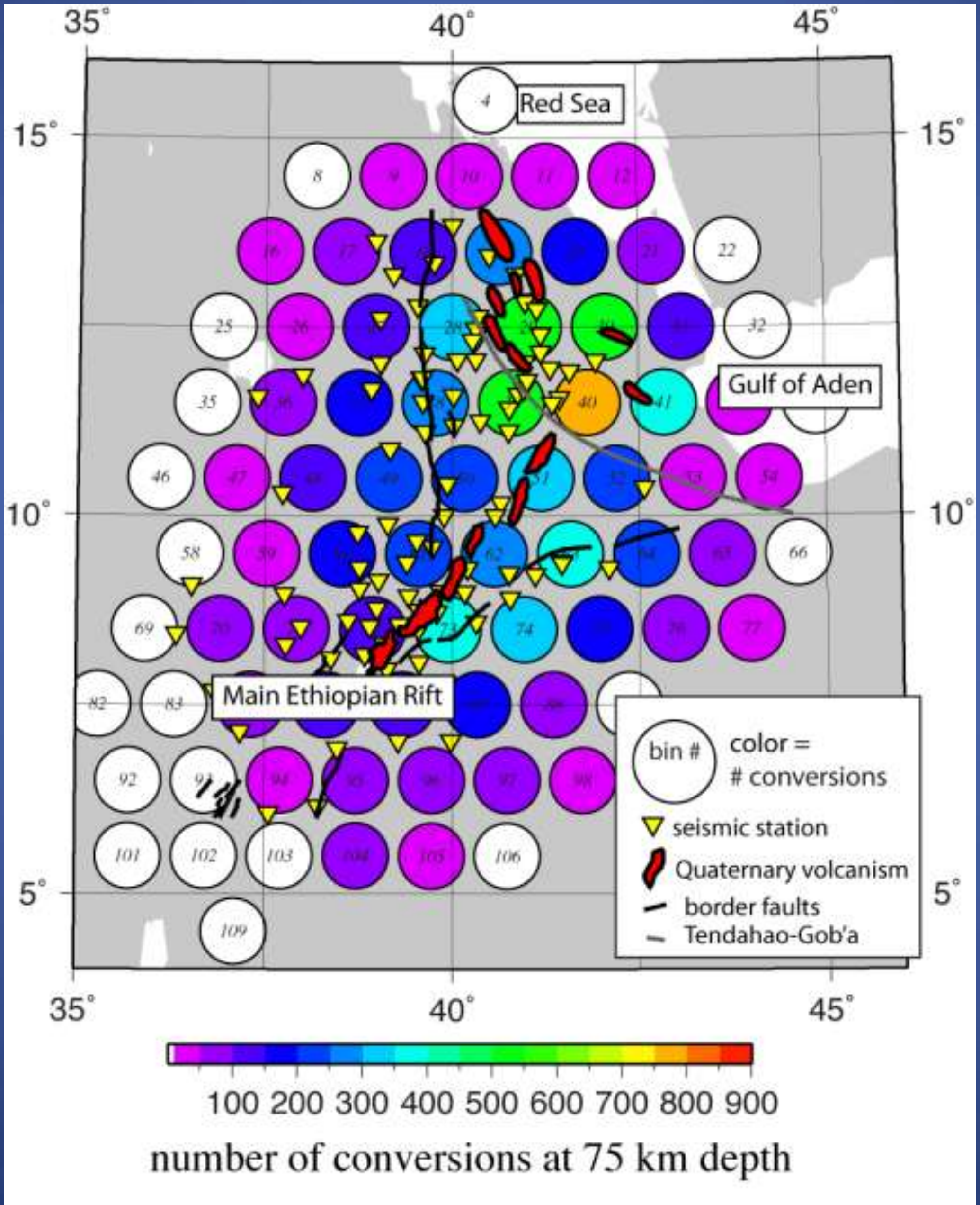
Hawaii – Discussion

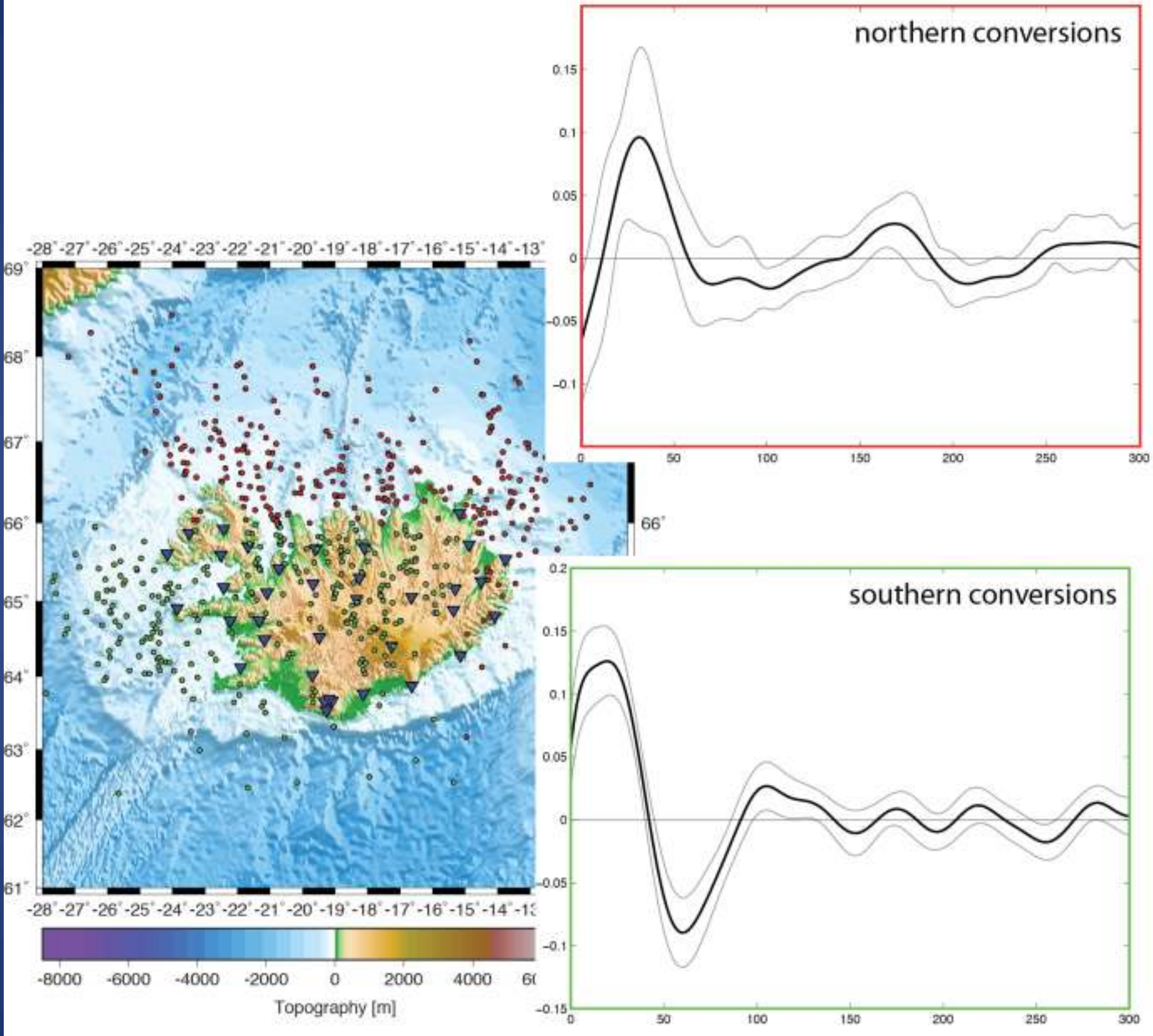
Melt and compositional buoyancy may provide support for Hawaiian Swell without producing a large heat flow anomaly.

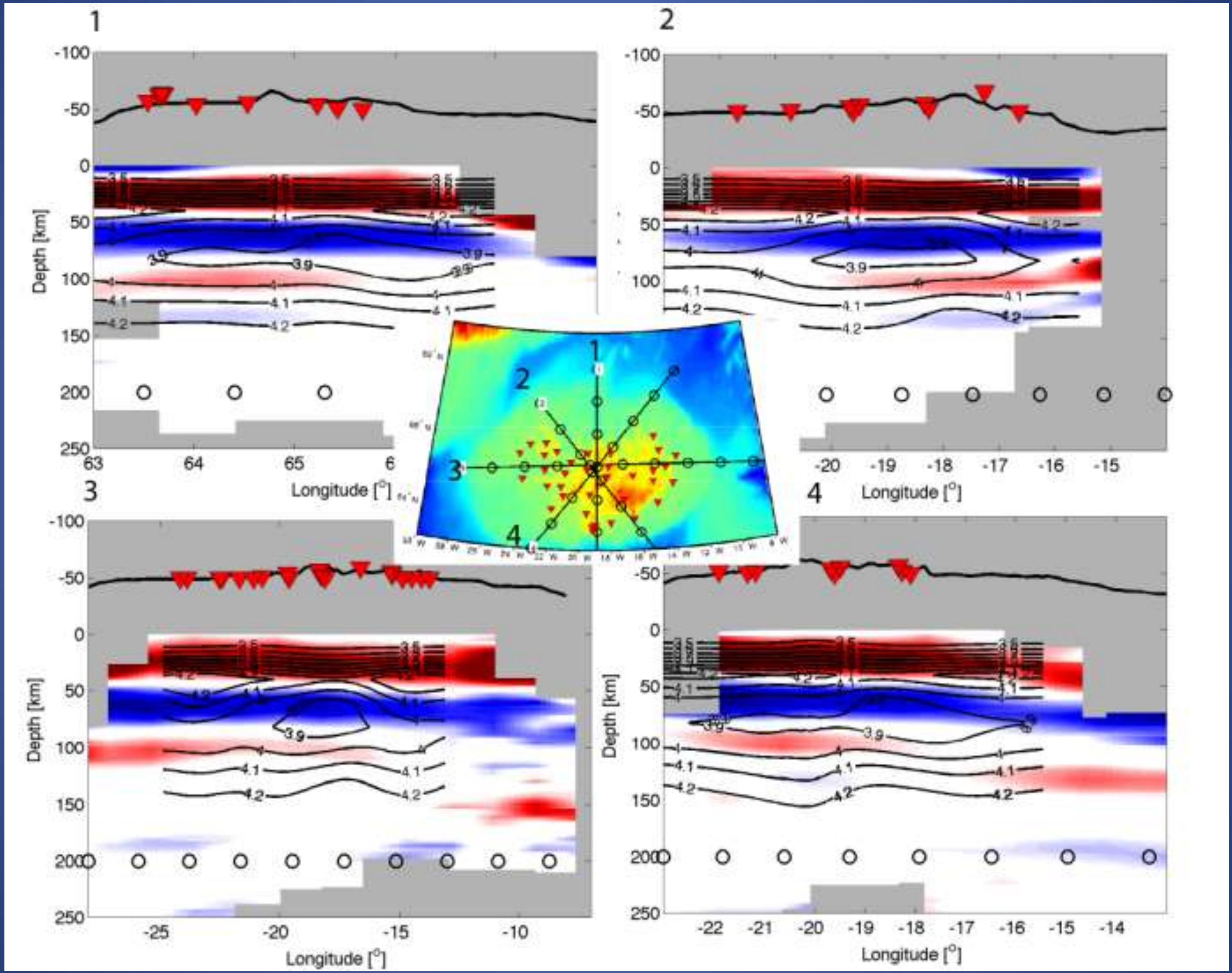
Western plume may explain high topography there in comparison to east.

Bin by conversion point.

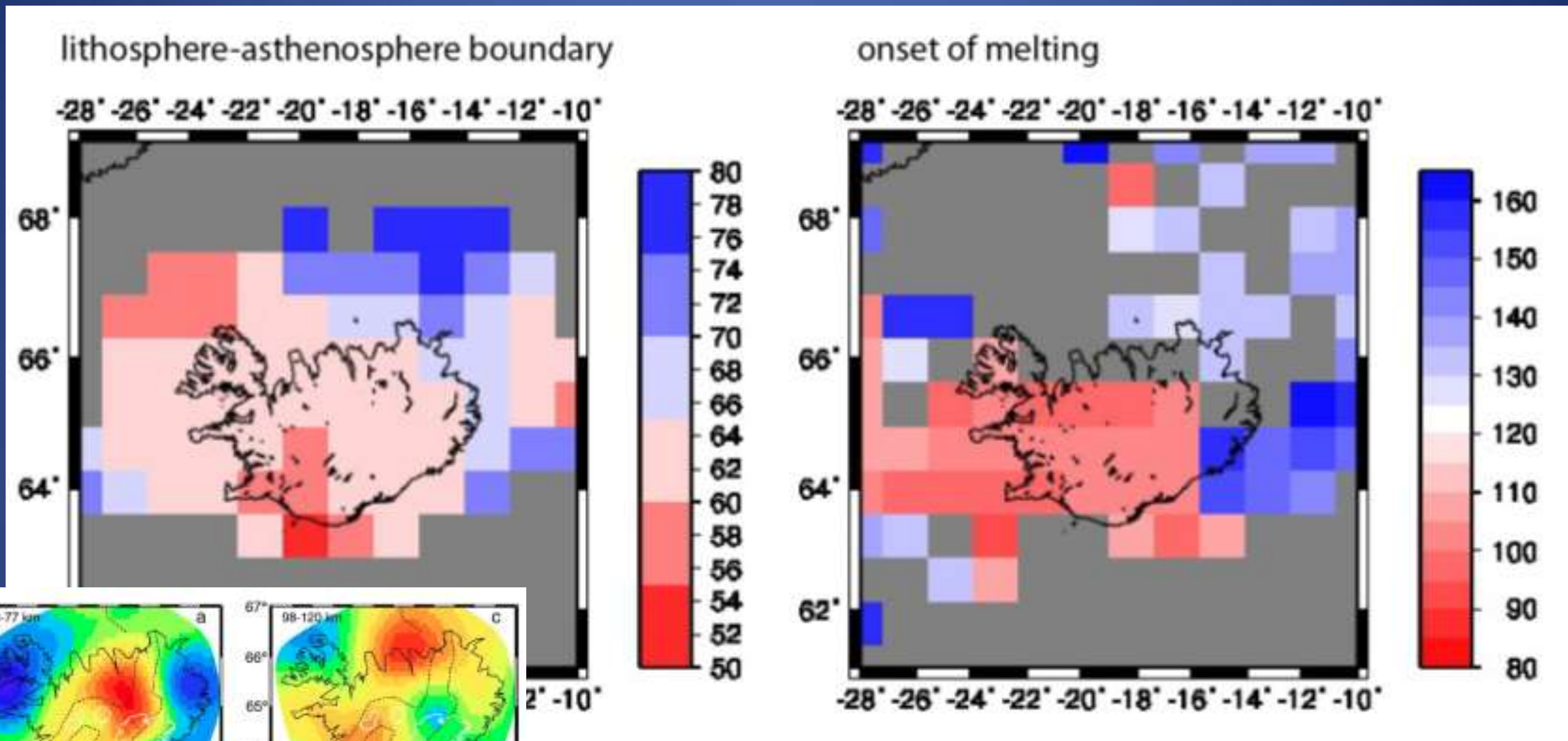
Bin radius = ¾ degree, 75 km depth.

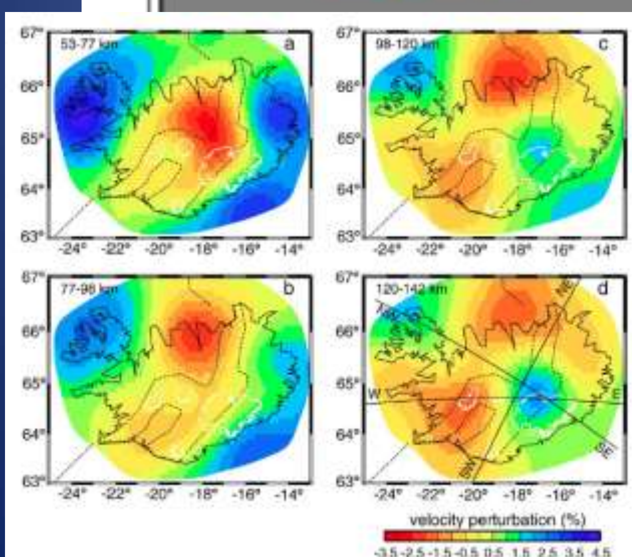



northern conversions
southern conversions
Topography [m]

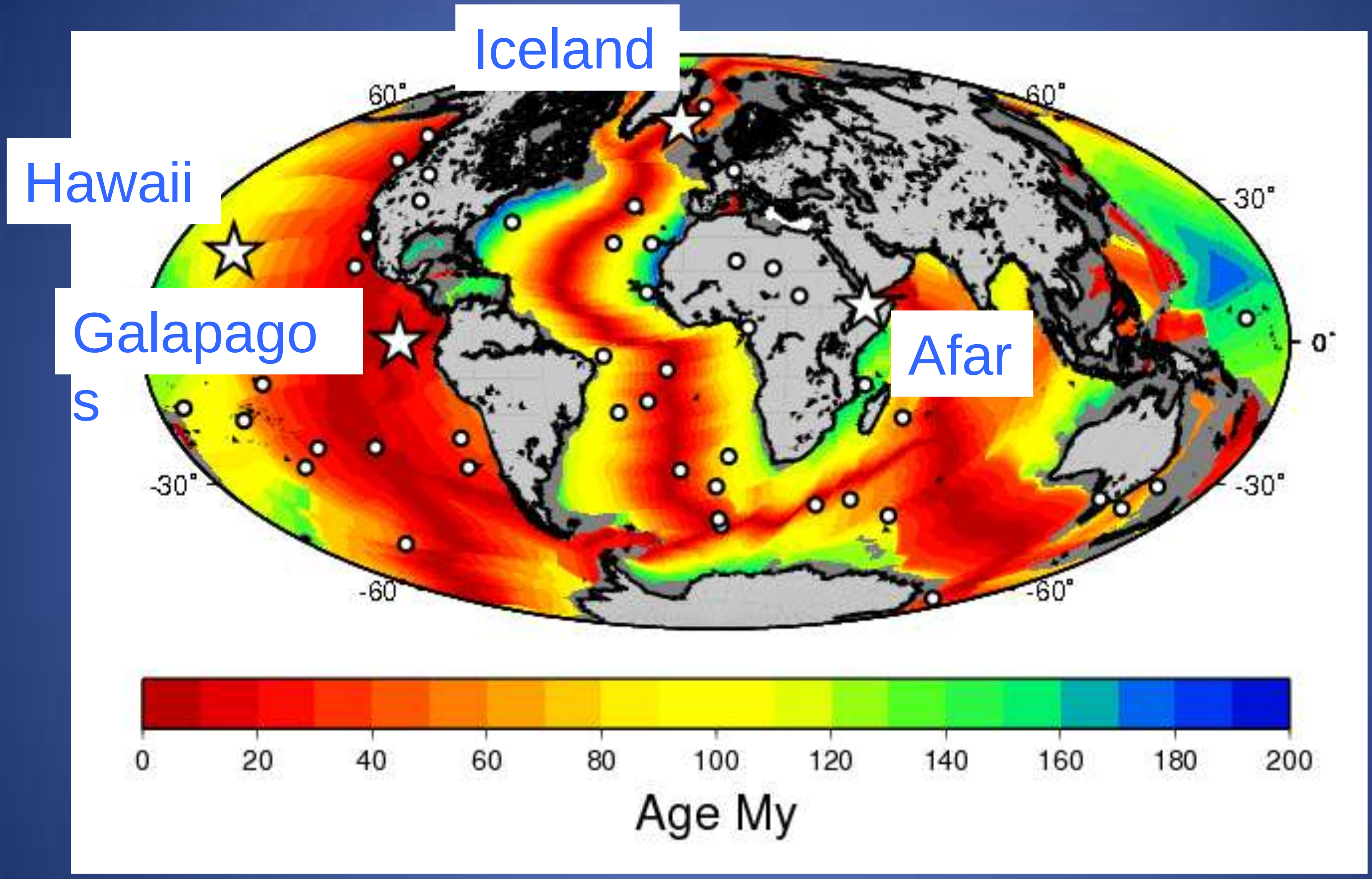


1
2
3
4
Depth [km]
Longitude [°]

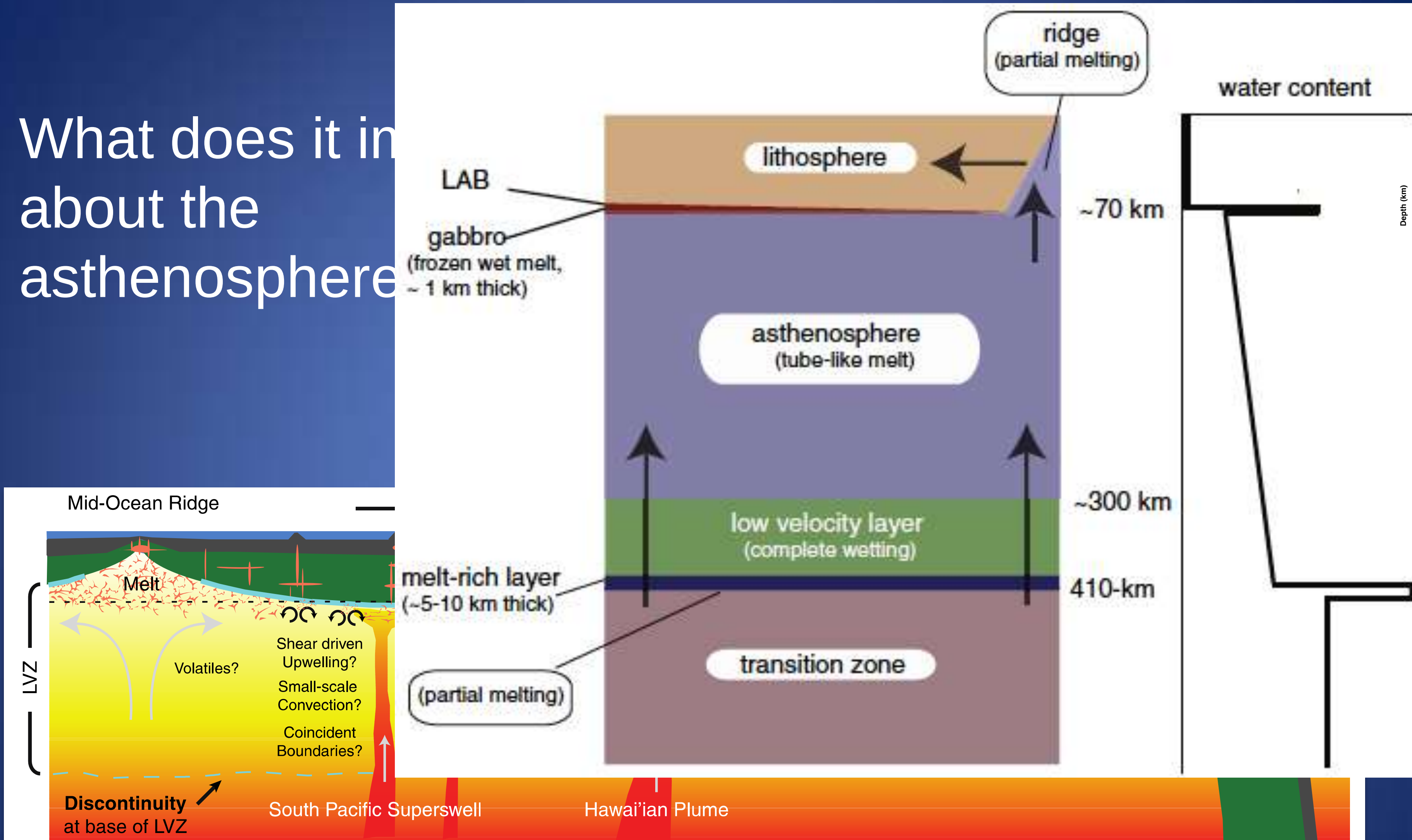




Li & Detrick, 2006]


Iceland
Hawaii
Galapagos
Afar
60°
60°
30°
0°
-30°
-30°
-60
-60°
0
20
40
60
80
100
120
140
160
180
200
Age My

What does it in about the asthenosphere

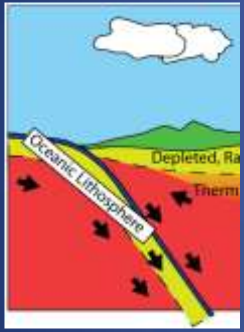


[Schmerr, 2012]

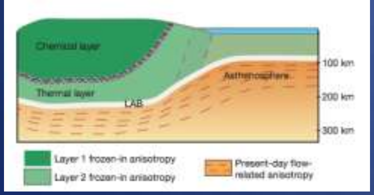
Lithosphere-asthenosphere boundary at tectonic transitions.

What does it imply about the lithosphere?

subduction

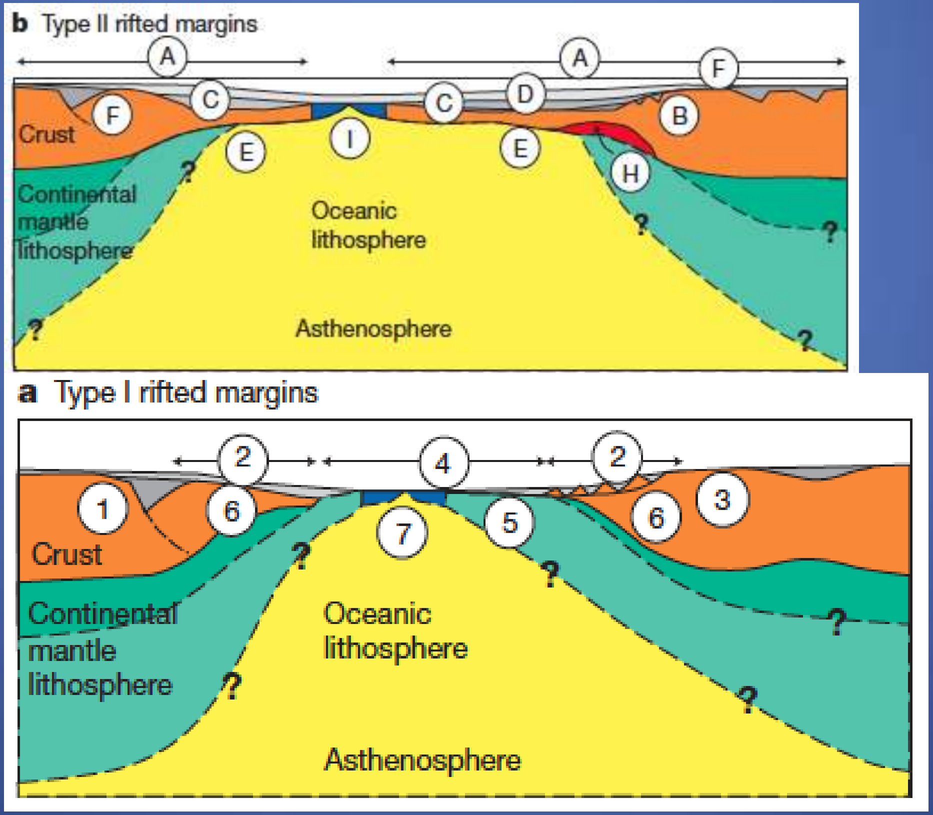


continent-ocean



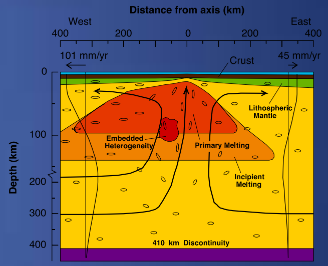
[Yuan & Romanowicz, 2010]

rift



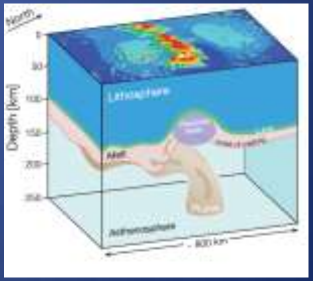
[Huismans & Beaumont, 2011]

ridge



[MELT seismic team, 1998]

hotspot



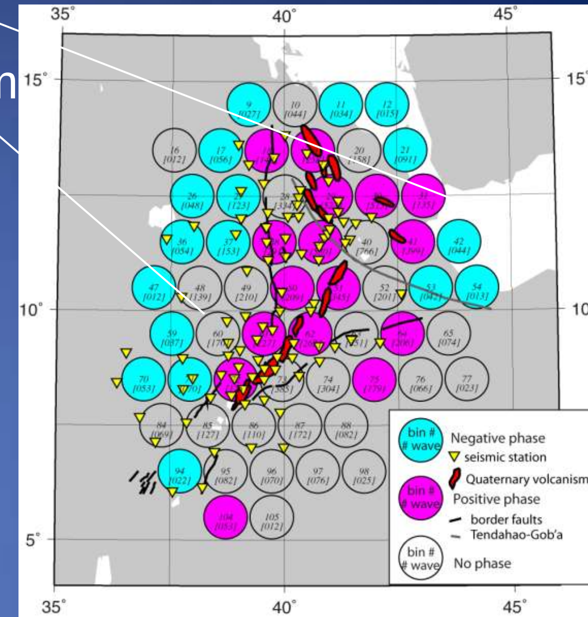
[Rychert et al., 2013]

Good agreement with previous seismic results.

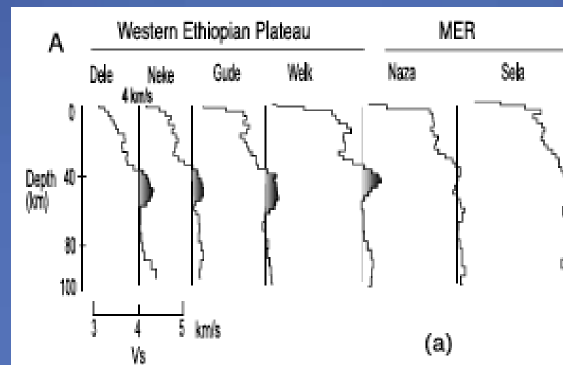
30 km or possibly 100 km

Sp receiver functions [Hansen et al., 2009]

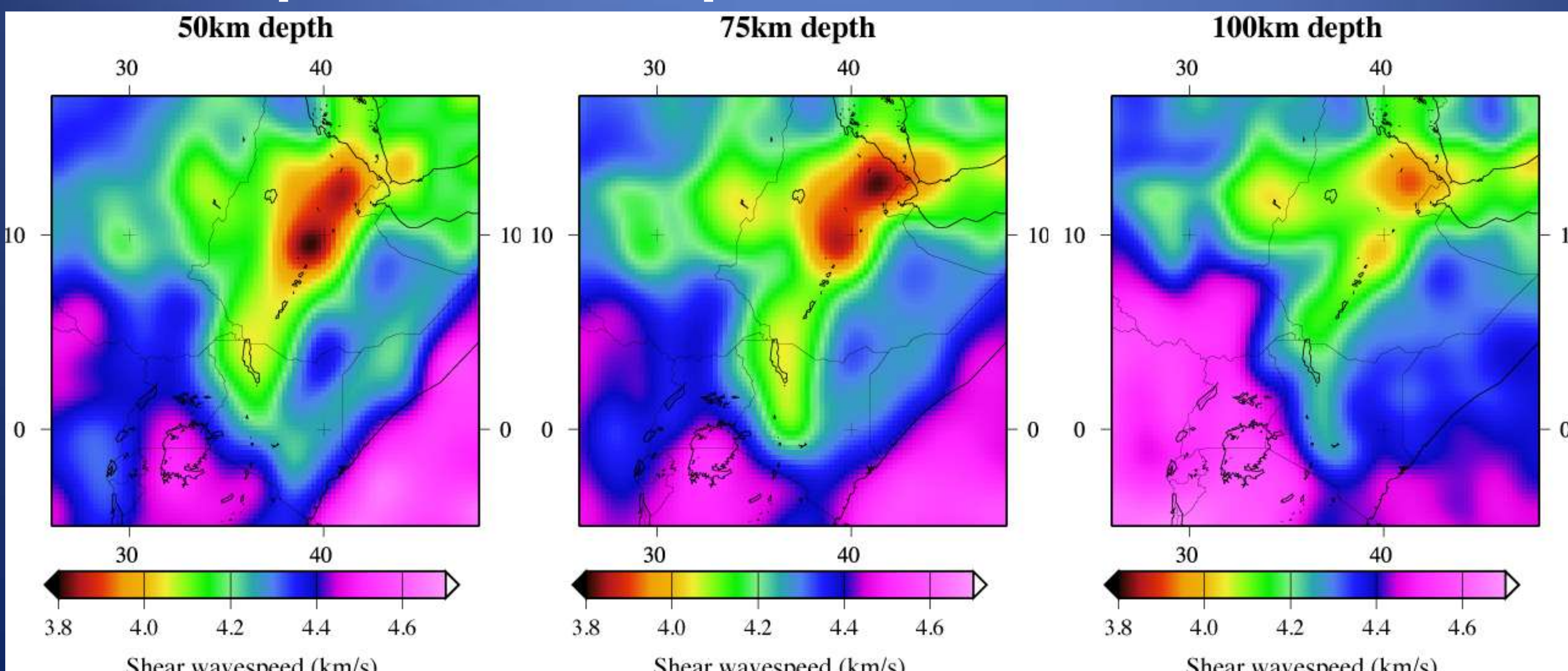
80 km

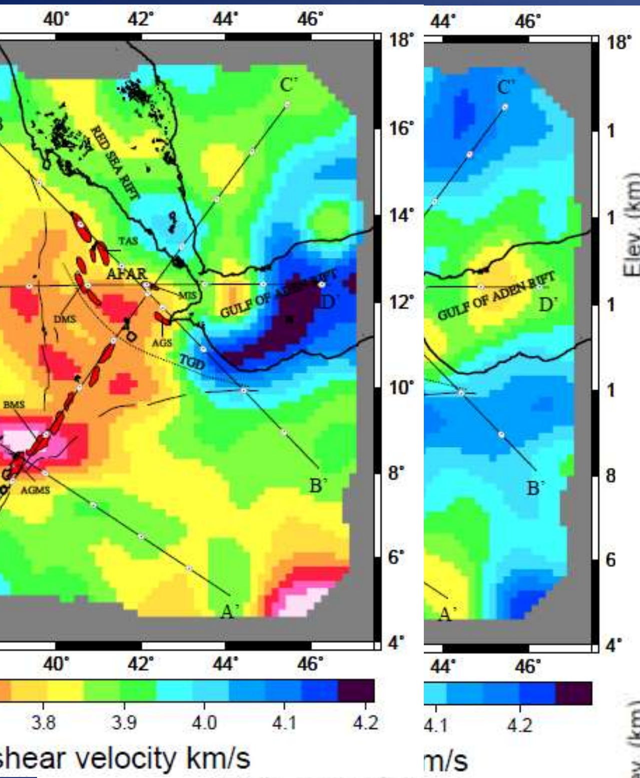


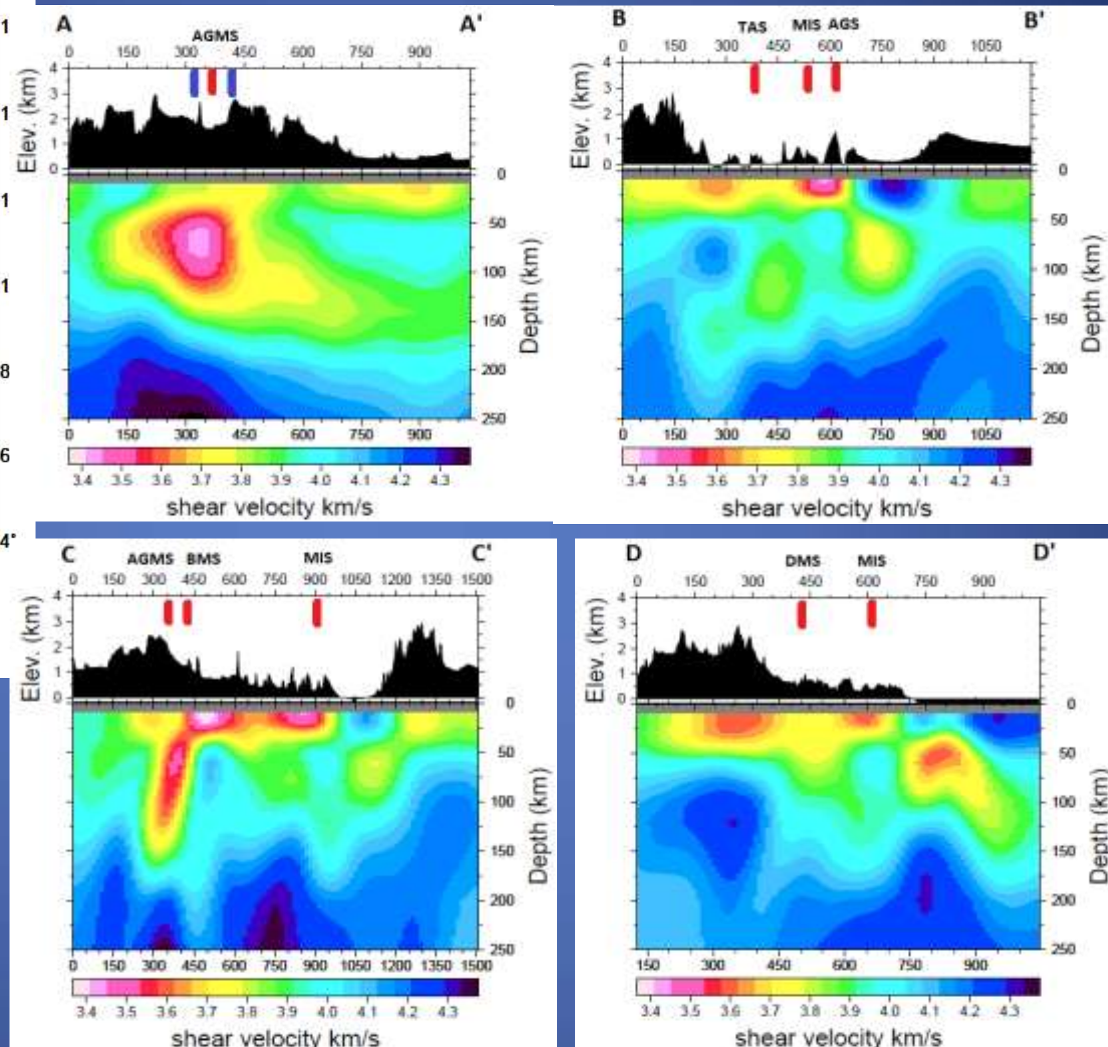
Joint Ps receiver function – surface waves 70-80 km thick lid vs. no lid beneath rift [Dugda et al., 2007].



Surface waves [Fishwick et al., 2010].







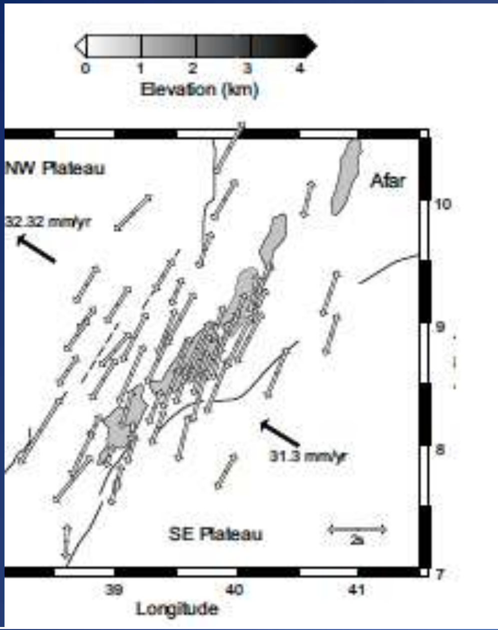
0 – 60 km

60 – 160 km

surface waves [Gallagher et al., 2013]

see poster!

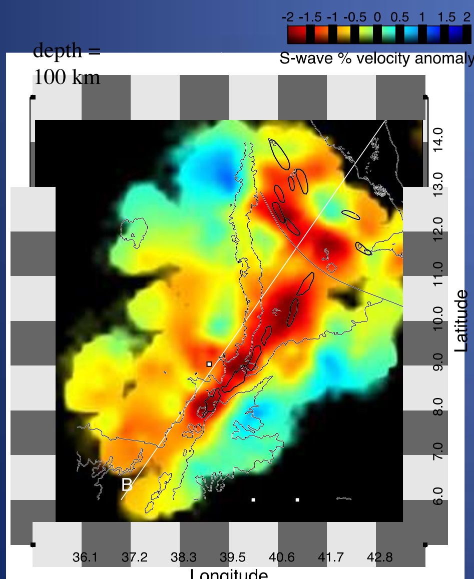
Previous seismic results

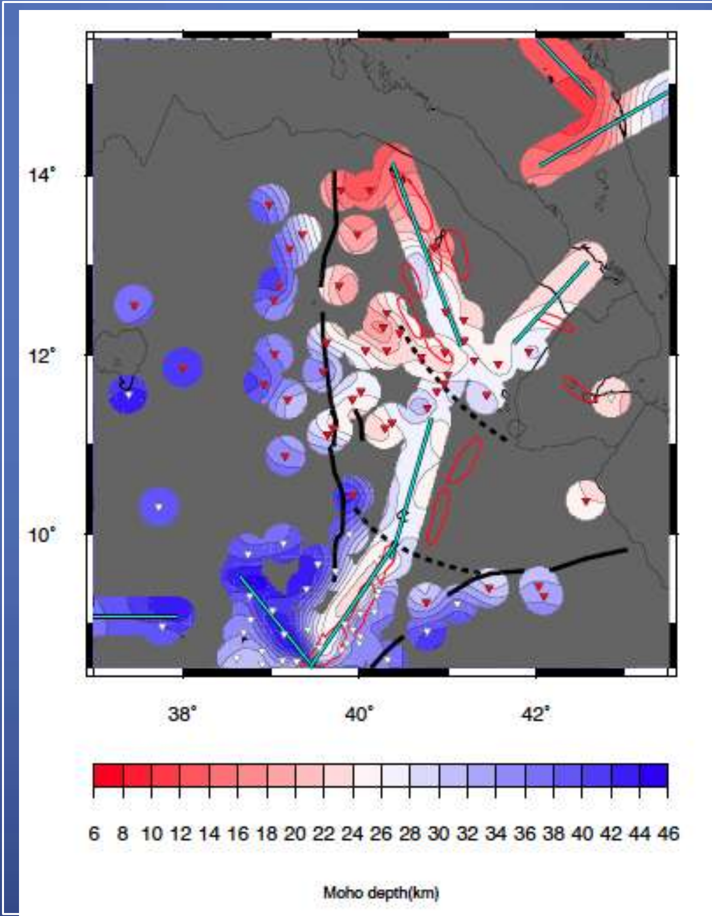


SKS & surface waves – aligned melting in upper 75 km.

[Kendall et al., 2005; Bastow et al,. 2010]

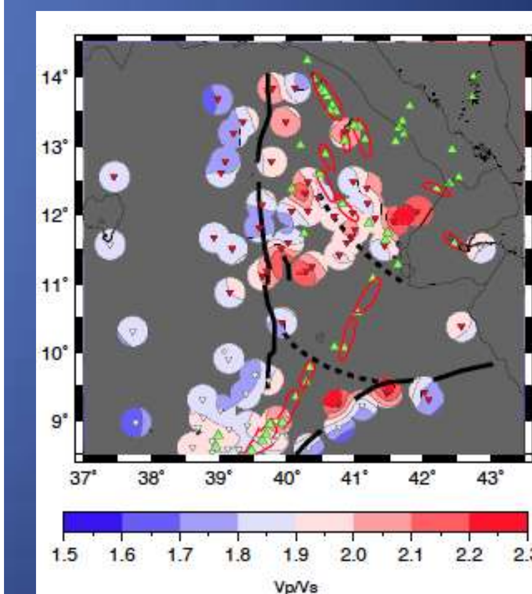
Body wave velocity anomalies beneath rift



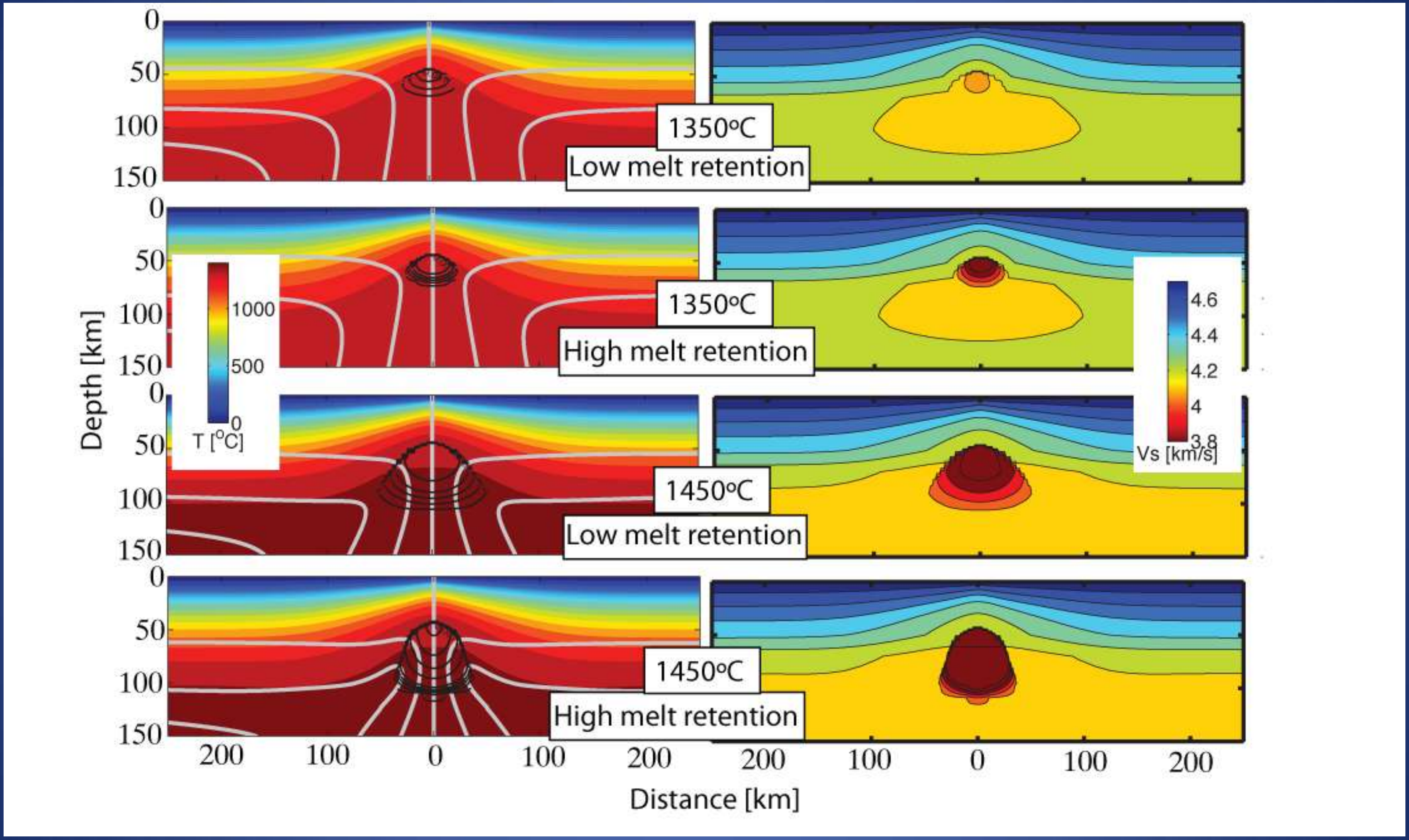


P-to-S: Moho shallows, Vp/Vs high beneath rift

[Hammond et al., 2011]

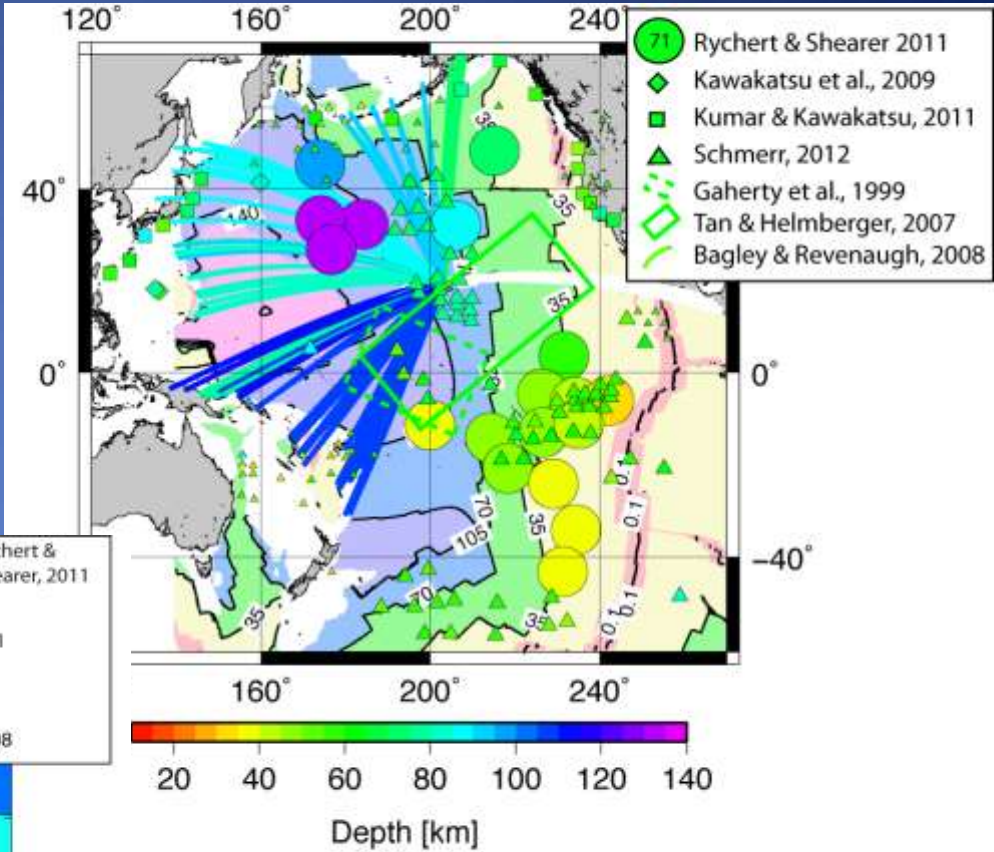


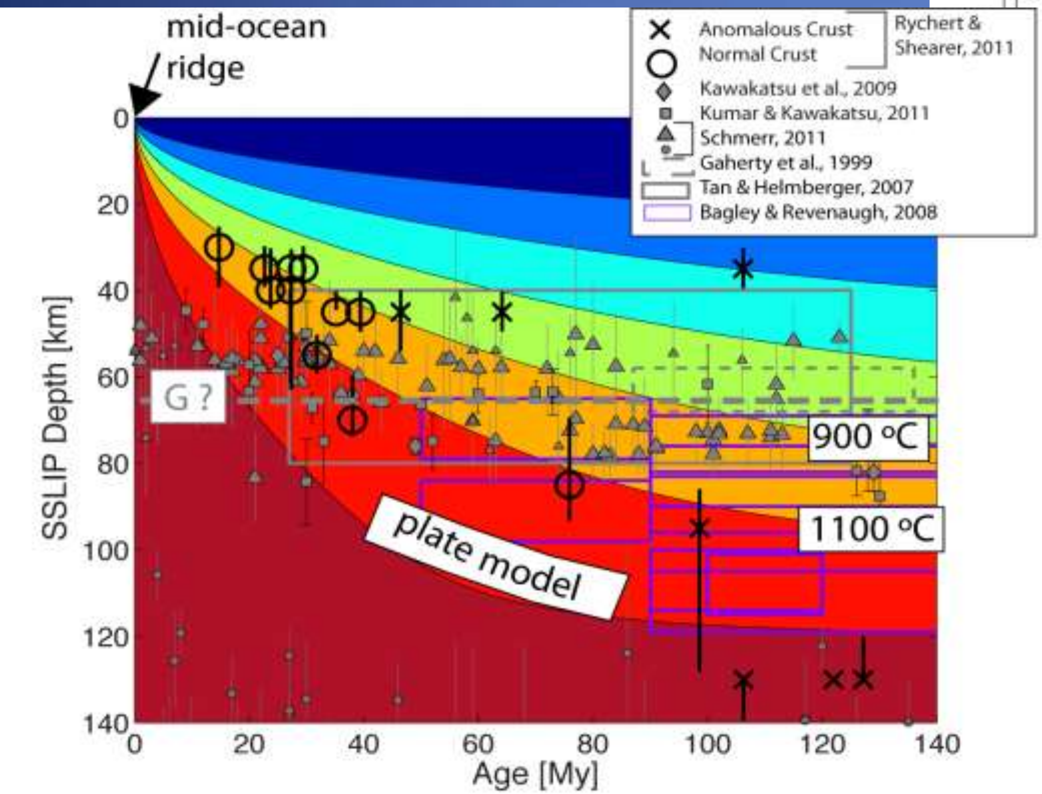
Geodynamic Modeling



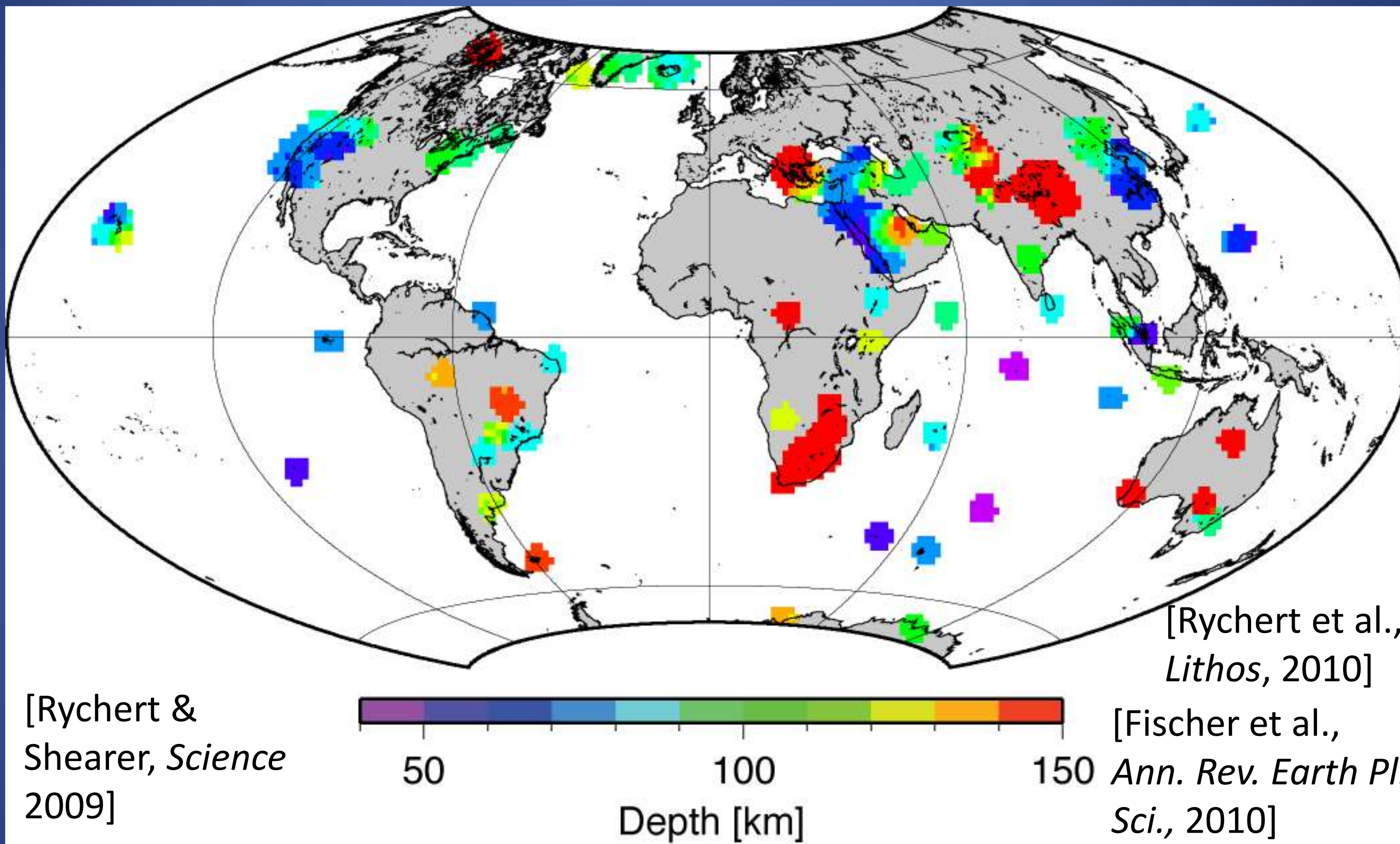
Ocean lithosphere-asthenosphere boundary

[Rychert, Schmerr, Harmon, *G-cubed, 2012*]





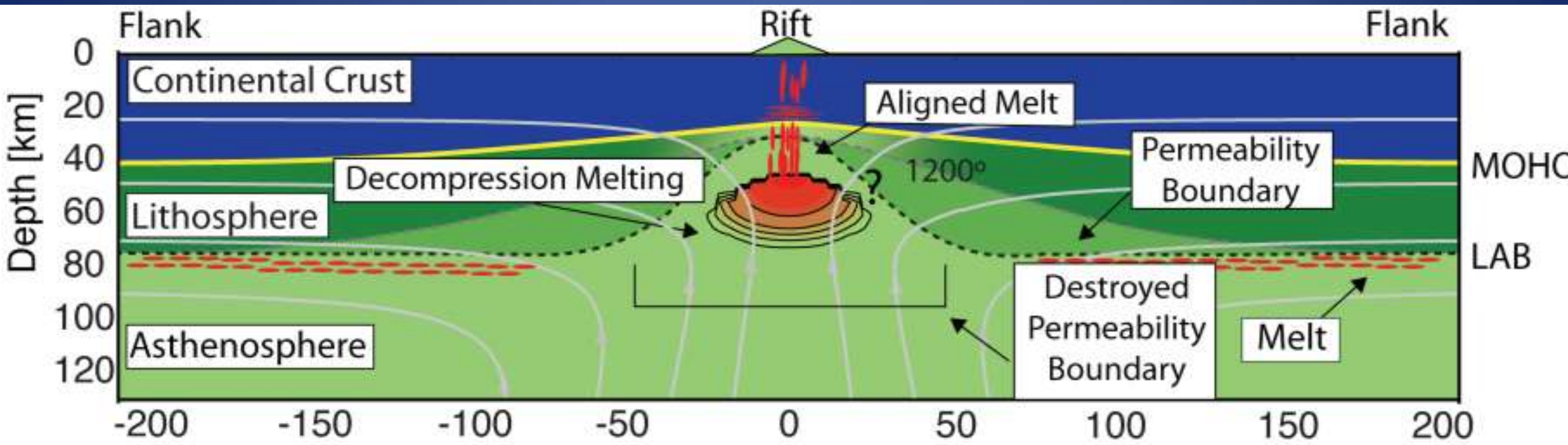
Global compilation of receiver function results. Most insitu measurements come from ocean island stations



Lithosphere-asthenosphere boundary from receiver functions

(Li et al., 2000; Li et al., 2004; Collins et al., 2002; Wolbern et al., 06; Heit et al., 2007; Li et al., 2007; Rychert et al., 2005; Rychert et al., 2007; Snyder, 2008; Kumar et al., 2005; Sodoudi et al., 2006; Ozacar et al., 2008; Angus et al., 2006; Mohsen et al., 2006; Hansen et al., 07; Kumar et al., 2007; Wittlinger and Farra, 2007; Hansen et al., 2009; Sodoudi et al., 2009; Kumar et al., 2005; Oreshin et al., 2002; Kumar et al., 2006; Sodoudi et al., 2006; Chen et al., 2006; Chen et al., 2008; Chen, 2009; Kawakatsu et al., 2009)

Conclusions



- A sharp rigid lid is imaged on the flank of the Afar rift at ~75 km depth. The transition from flank to rift is abrupt.
- The sub-crustal lithosphere beneath the rift has been destroyed.
- A significant velocity increase imaged beneath the rift is consistent with geodynamic predictions for the onset of decompression melting.
- Its depth is shallow, indicating no significant plume influence today.

Hawaii –

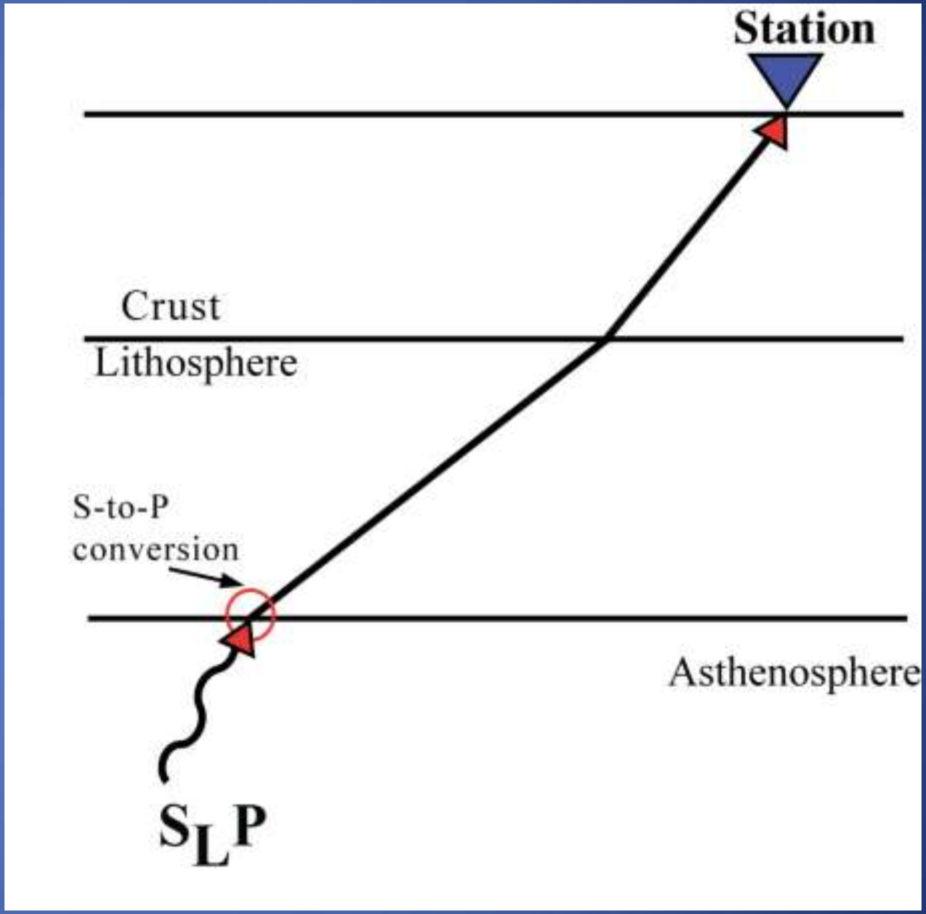
Method - Receiver Functions

1) Orient OBS data using Rayleigh waves.

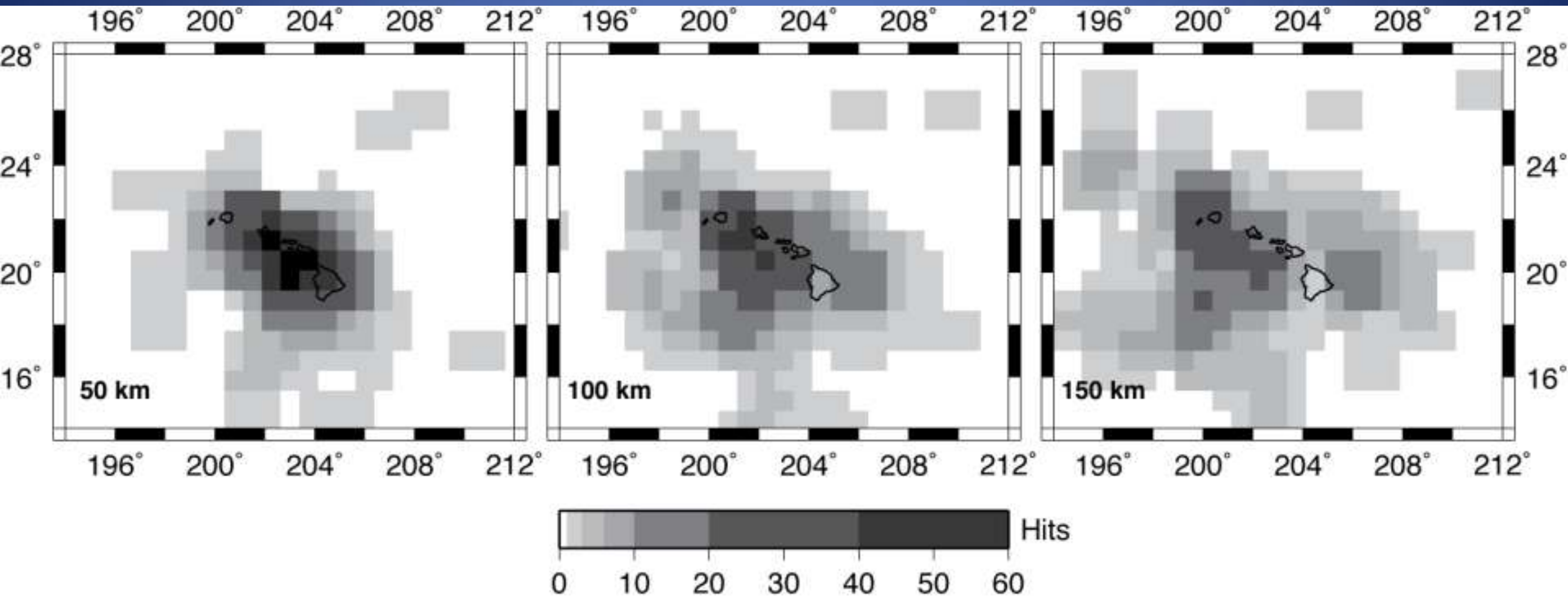
2) Rotate waveform to P and SV components.

3) Deconvolve with extended multitaper [Helffrich, 2006].
Filter 0.05 – 0.14 Hz

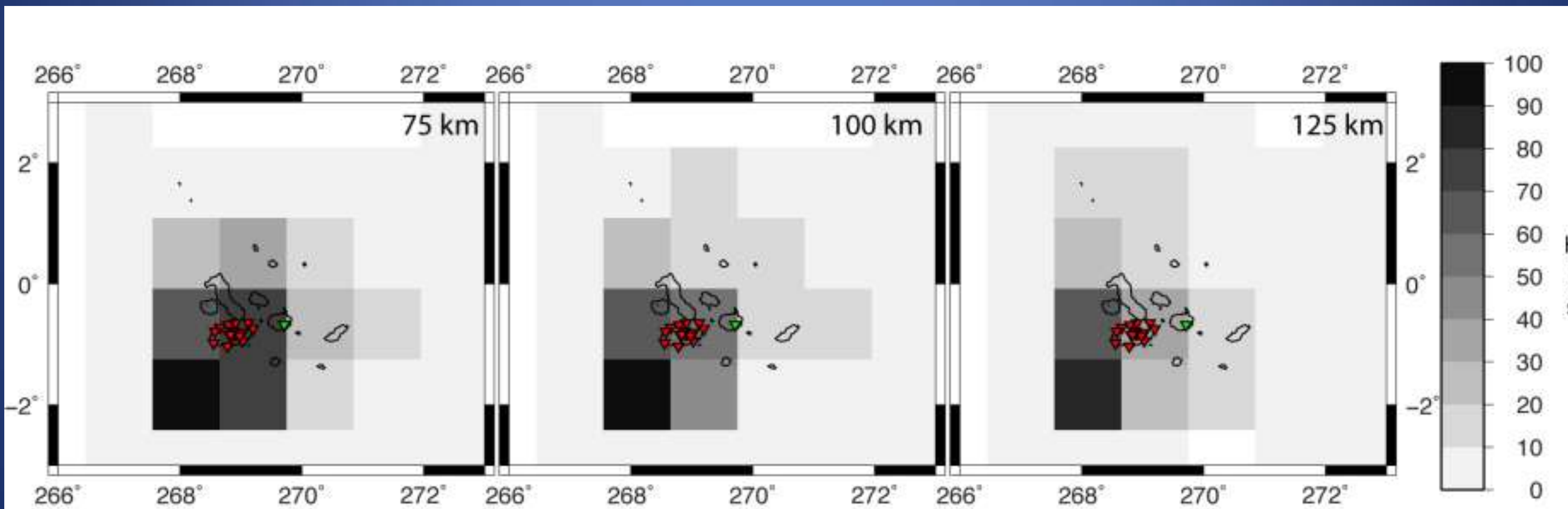
4) Migrate to depth [Angus et al., 2009].
Weight by SNR.
Grid ¾° by ¾°, 1 km depth
Migration model from P-to-S receiver functions (crust) [Leahy et al., 2010] and surface waves (mantle) [Laske et al., 2011].
Smooth based on Fresnel zone



Hawaii – hitcount map



Galapagos – hitcount map

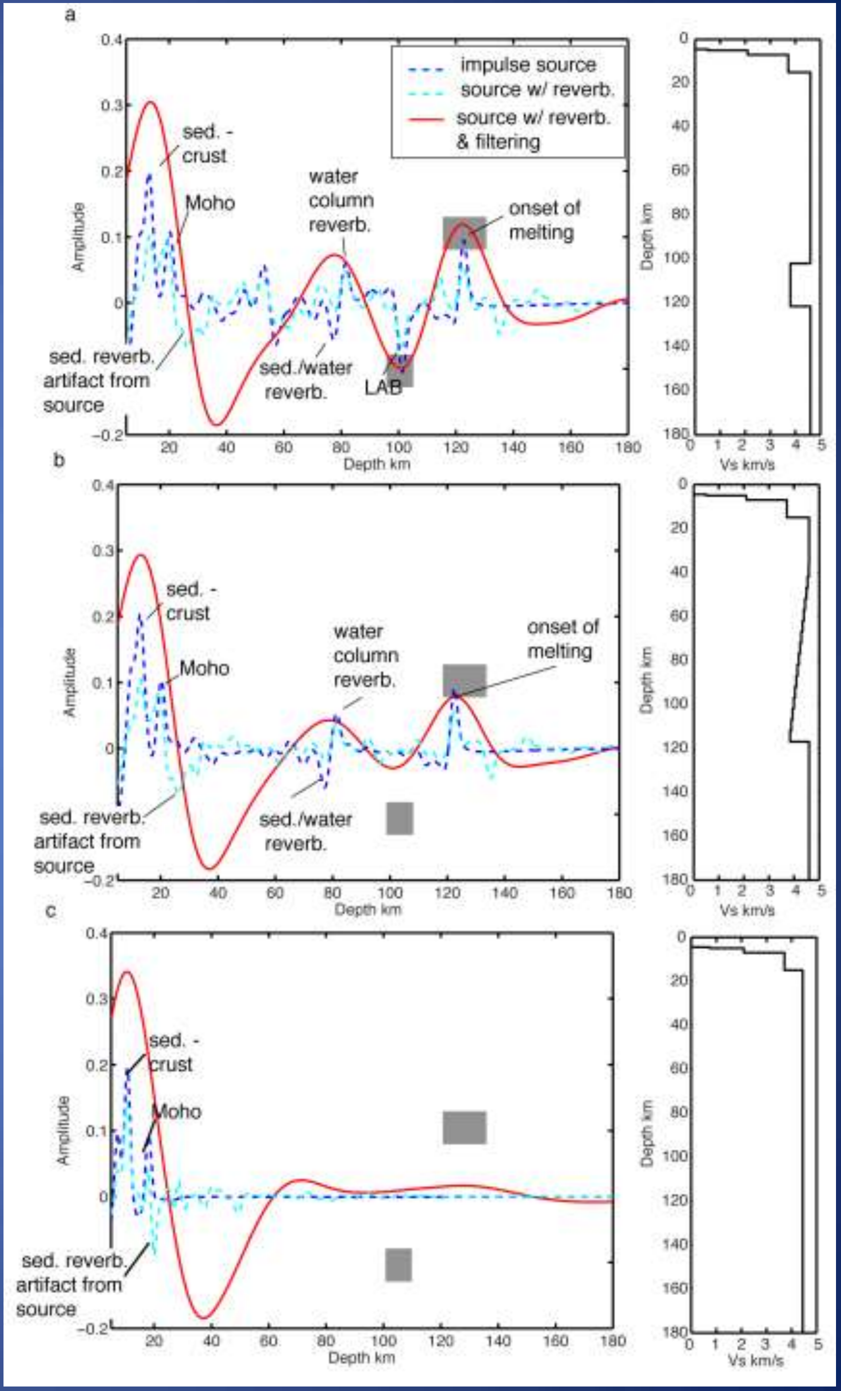


Waveform modeling

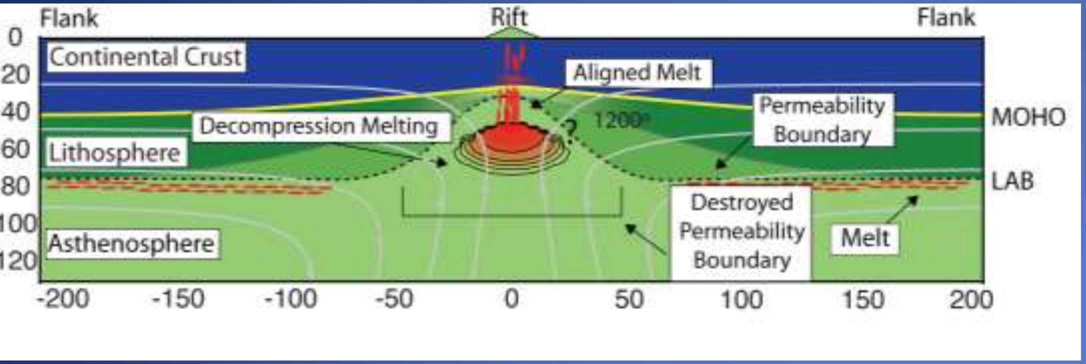
station on seafloor.

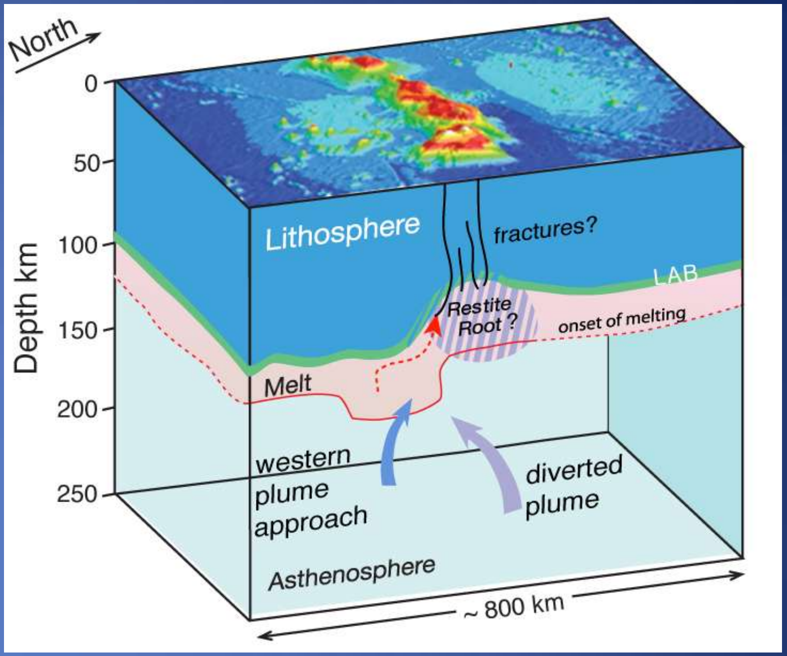
consider range of amplitudes in data.

LAB and onset of melting: 8-20% ΔVs over < 15 km depth.



Afar vs. Hawaii





- destroyed mantle lithosphere
- onset of melting ~75 km depth
- potential temperatures ~1350° - ~1400°
- No strong plume influence

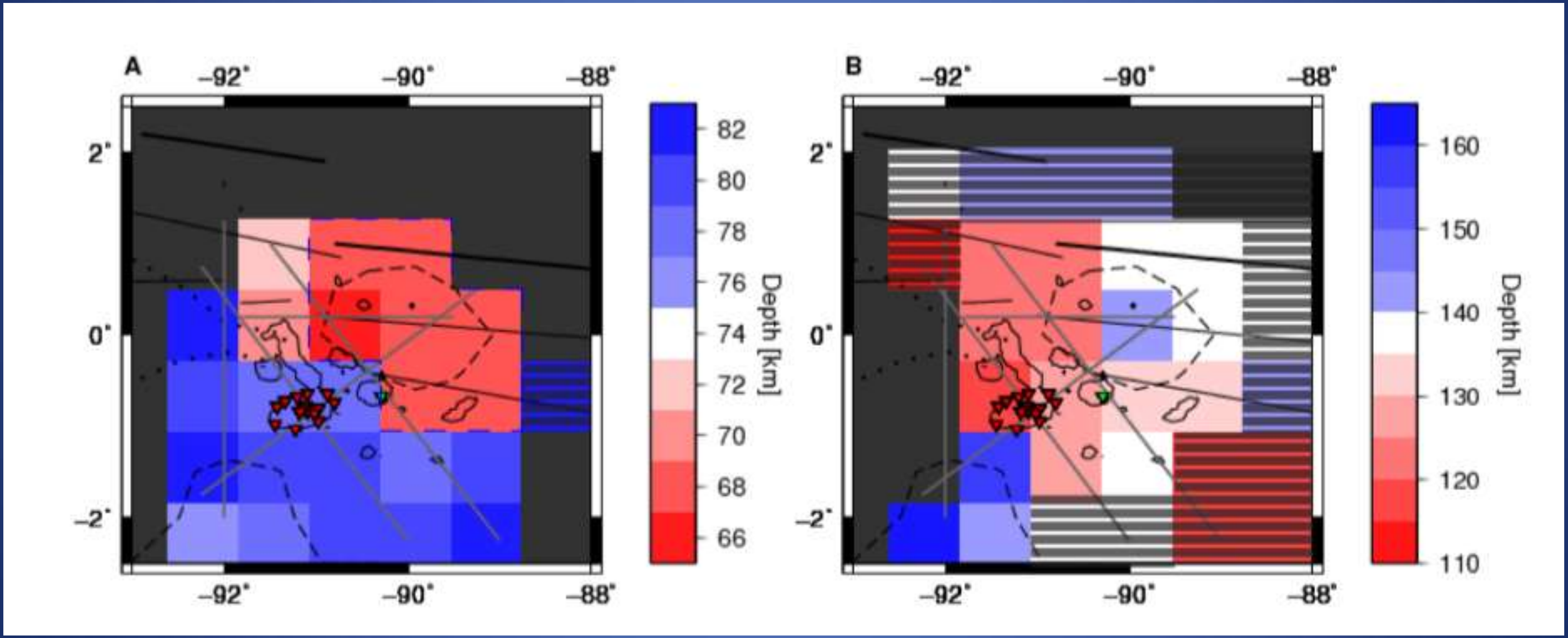
[*Rychert et al., Nature Geo.*, 2012]

[*Rychert et al., Nature Geo., in revision*]

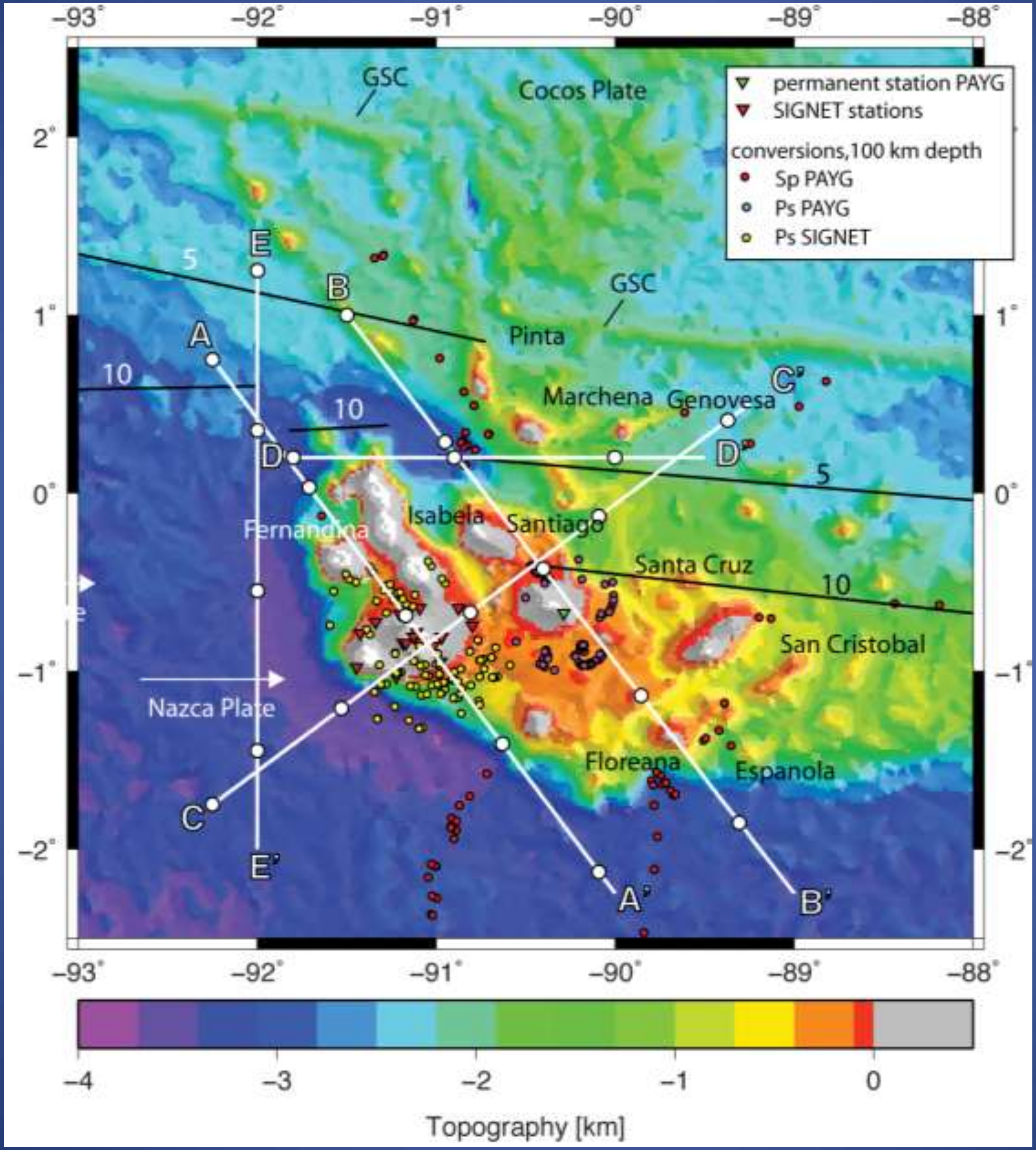
- possibly subtly thinned lithosphere
- onset of melting ~150 km depth
- potential temperature increase from ~1450° to ~1550°
- Hawaiian plume impingement 100 km west of Hawaii
- Deflection, possibly by a restite root

Galapagos –

lithosphere-asthenosphere onset of melting

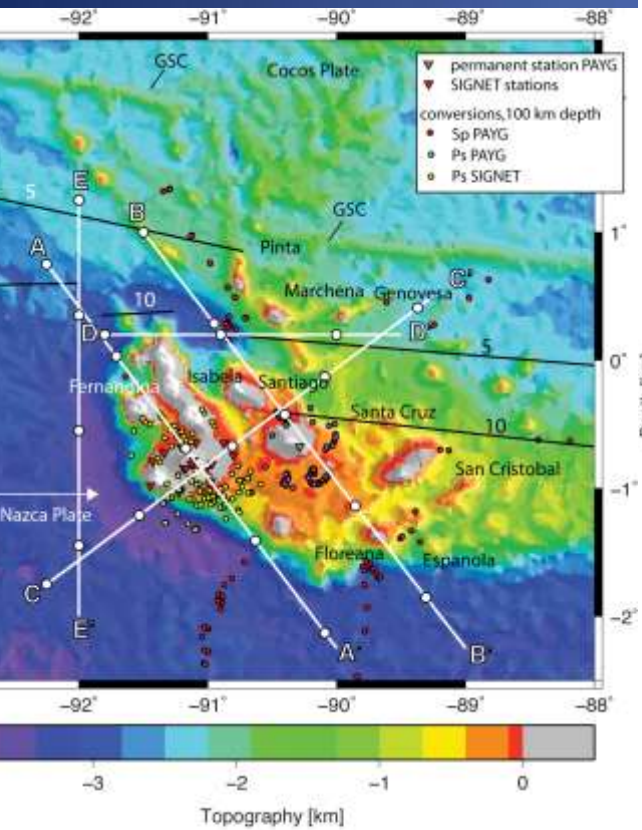


Galapagos

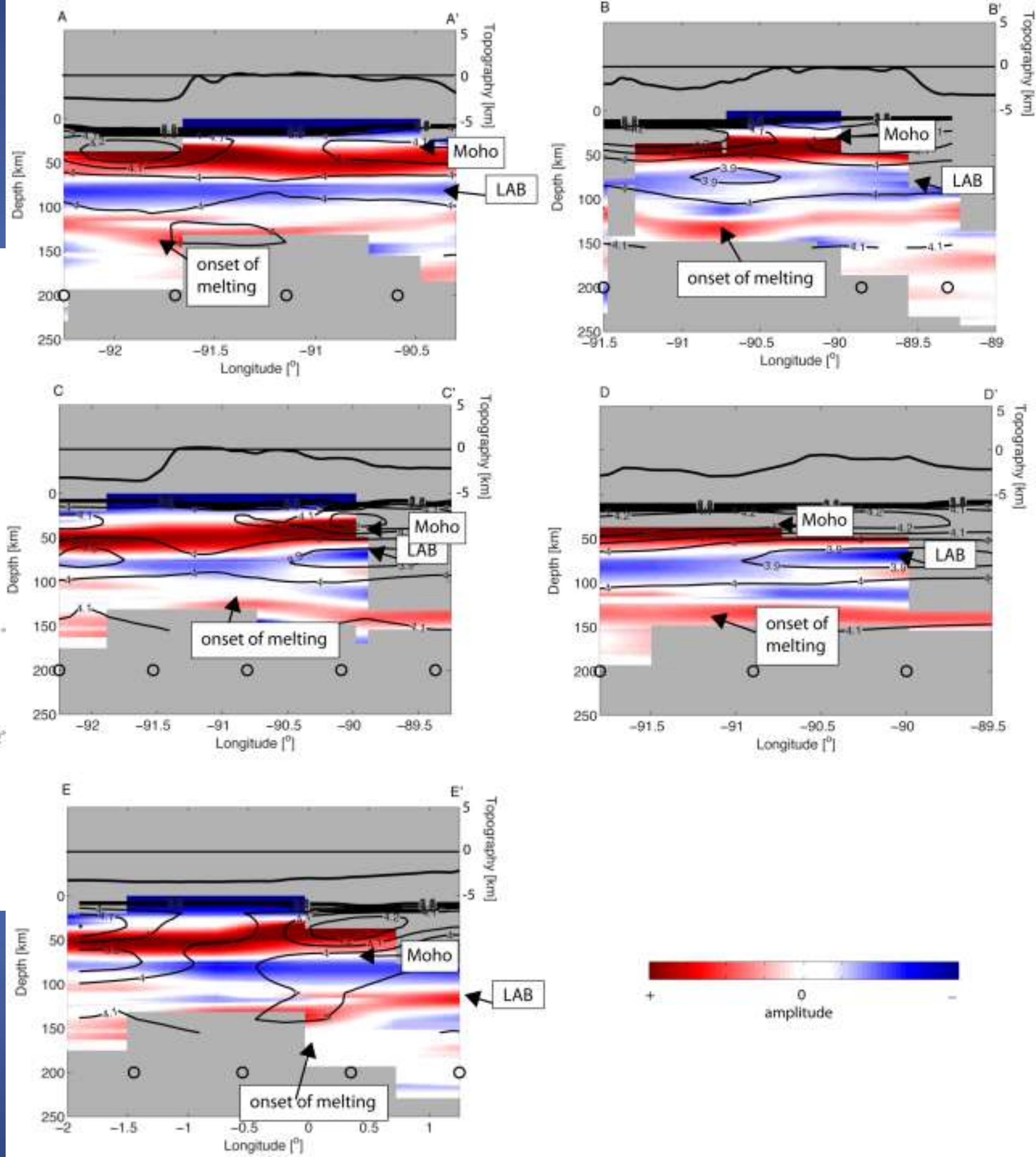


-93°
-92°
-91°
-90°
-89°
-88°
2°
1°
0°
-1°
-2°
GSC
Cocos Plate
permanent station PAYG
SIGNET stations
conversions,100 km depth
Sp PAYG
Ps PAYG
Ps SIGNET
GSC
Pinta
Marchena
Genovesa
5
10
10
5
10
E
B
A
C'
D
D'
Isabela
Santiago
Fernandina
Santa Cruz
San Cristobal
Nazca Plate
Floreana
Espanola
C
E'
A'
B'
-4
-3
-2
-1
0
Topography [km]

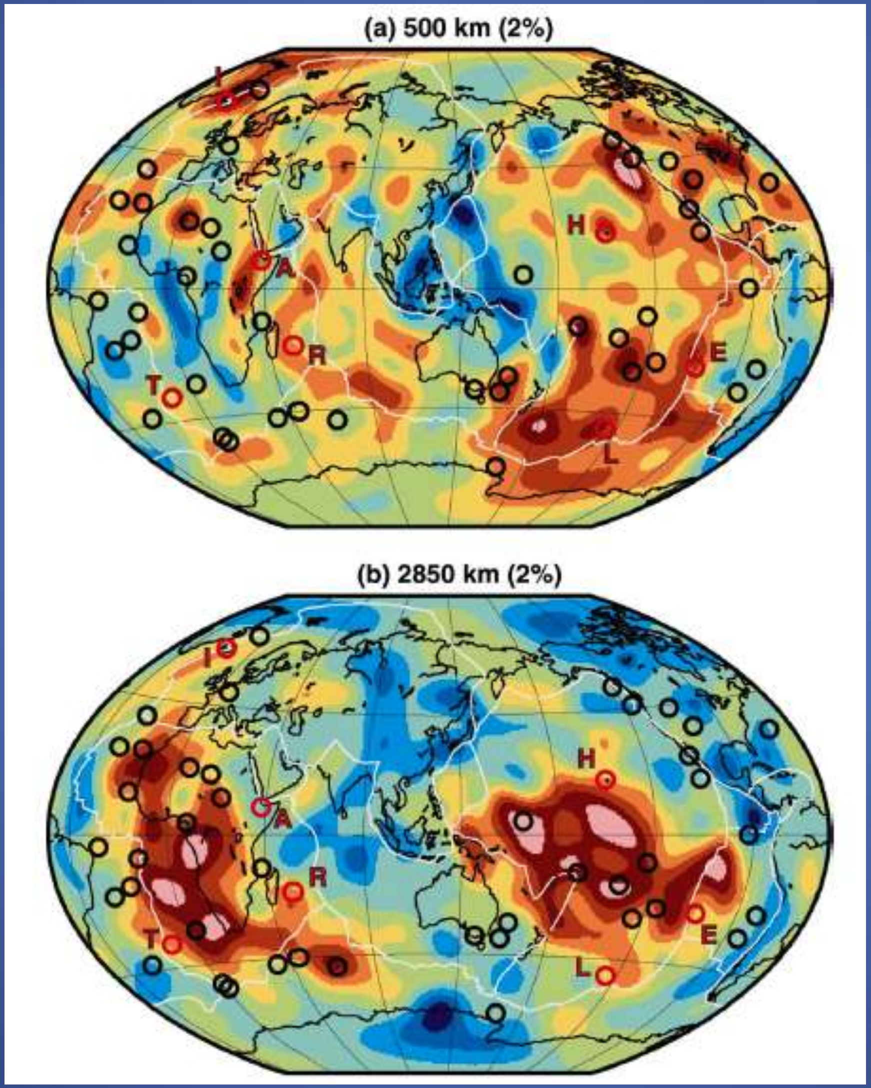
Galapagos –



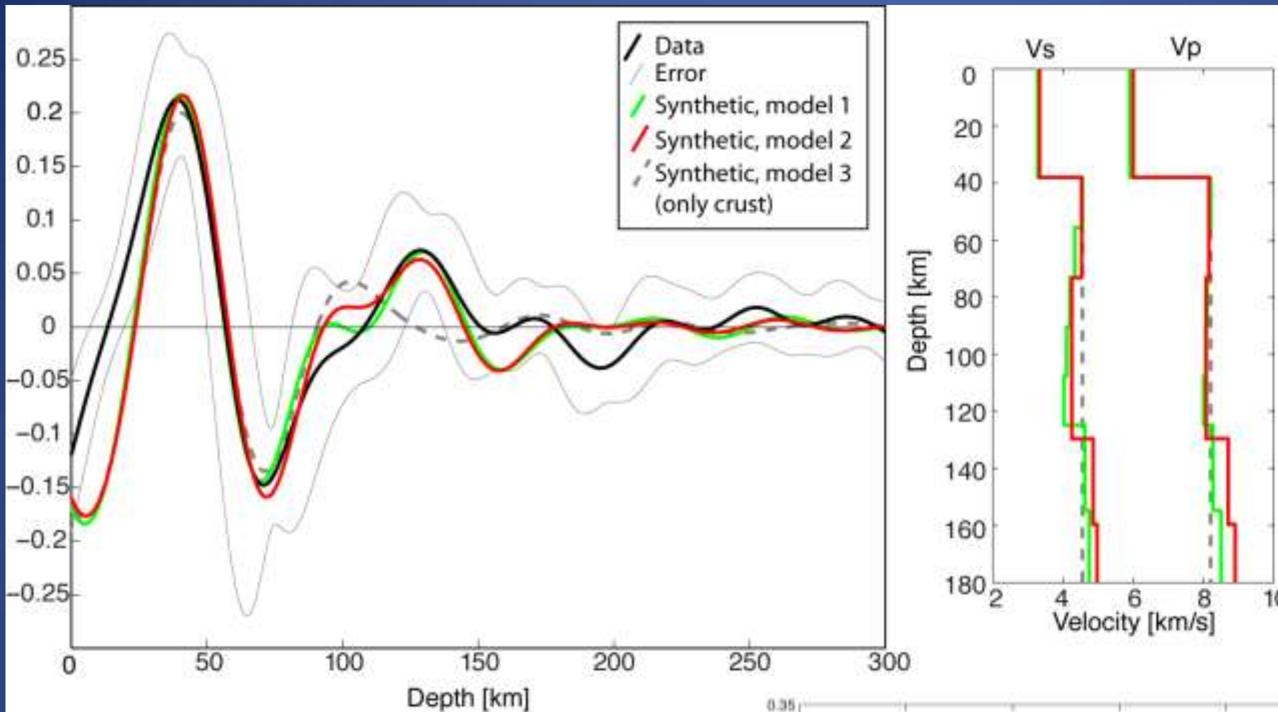
-92° -91° -90° -89° -88°
permanent station PAYG
SIGNET stations
conversions,100 km depth
Sp PAYG
Ps PAYG
Ps SIGNET
GSC
Cocos Plate
Pinta
Marchena
Genovesa
Isabela
Fernandina
Santiago
Santa Cruz
San Cristobal
Floreana
Espanola
Nazca Plate
A A' B B' C C' D D' E E'
5 10
1° 0° -1° -2°
-3 -2 -1 0
Topography [km]



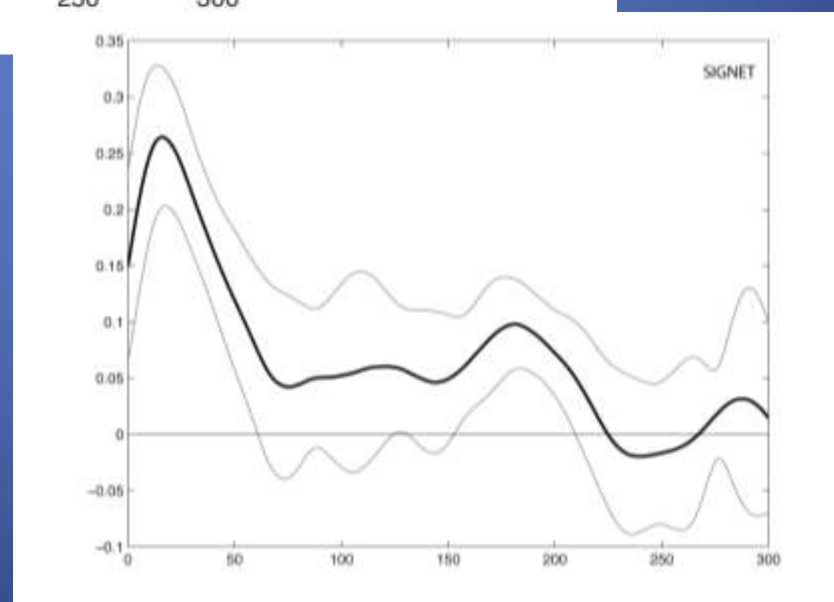
A A'
B B'
C C'
D D'
E E'
Moho
LAB
onset of melting
Depth [km]
Topography [km]
Longitude [°]
amplitude
+ 0 -


(a) 500 km (2%)
I
A
R
T
H
E
L
(b) 2850 km (2%)
I
A
R
T
H
E
L

S-to-p modeling data from station PAYG

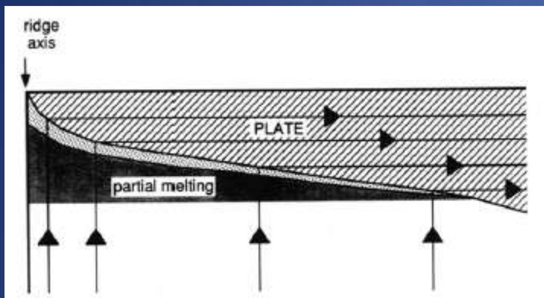


P-to-s Signet Array

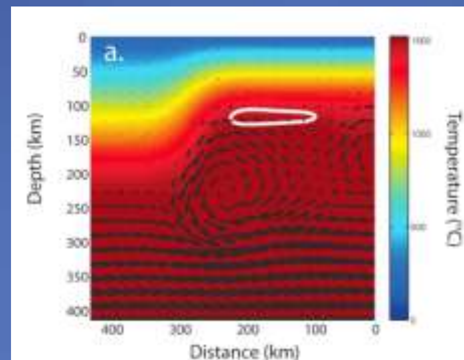


hotspot – lithosphere interaction

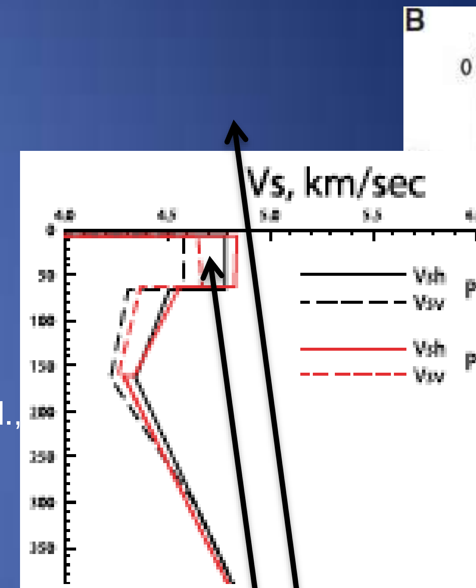
What does it imply about the asthenosphere?



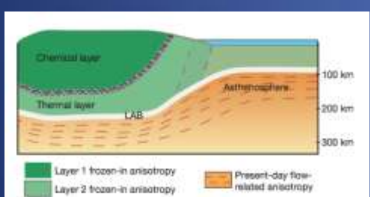
[Sparks & Pamentier, 1991]



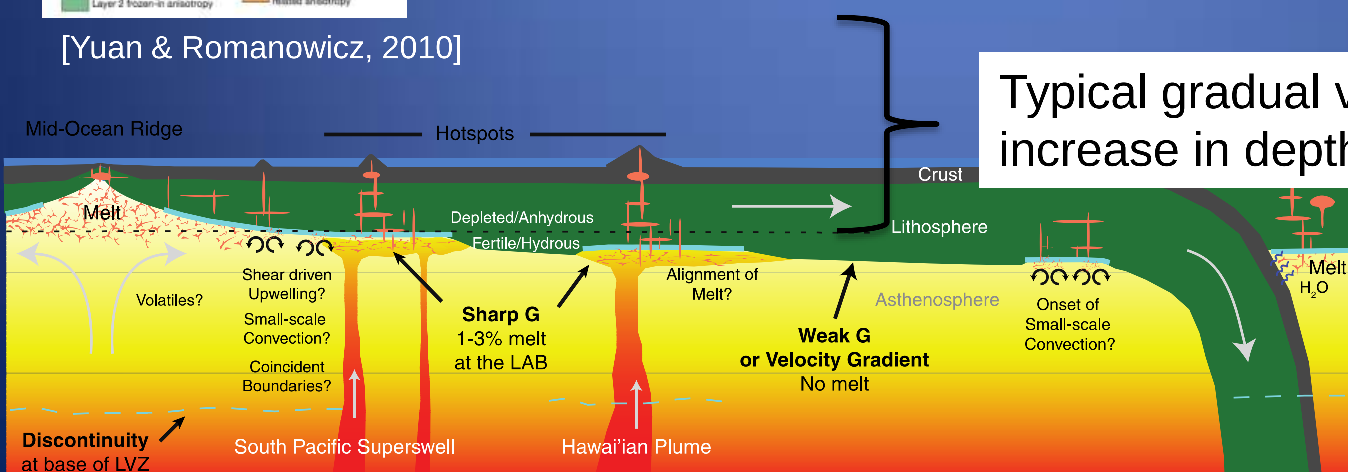
[Till et al., 2010]



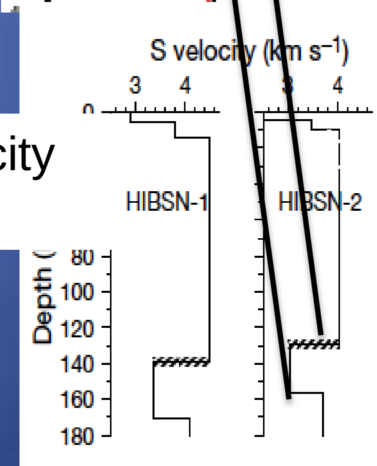
[Kawakatsu et al.,



[Yuan & Romanowicz, 2010]



Typical gradual velocity increase in depth

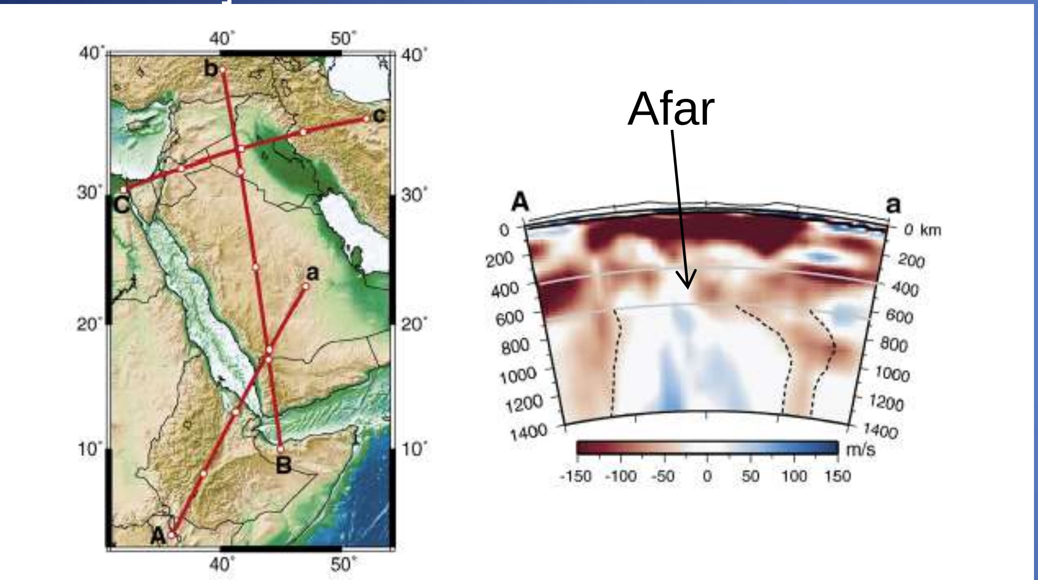


[Li et al., 2001]

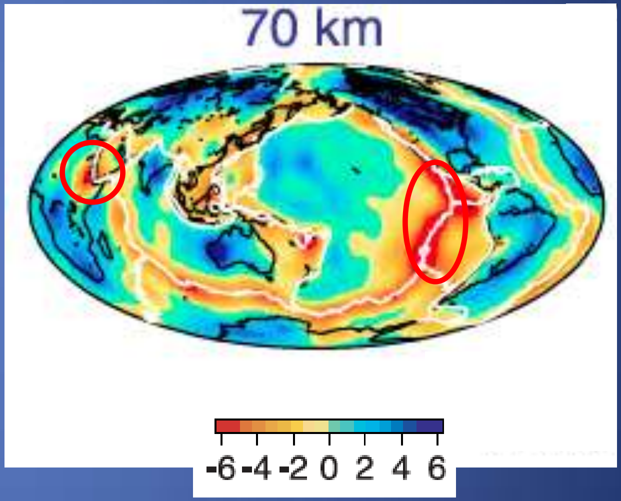
ther
und

Other Supporting Evidence

- Africa has moved ~700 km away from the location where a plume caused flood basalt volcanism ~35 Ma [Silver et al., 1998].
- Although interpreted as a thermal anomaly, the range of potential temperatures from geochemistry (1370 - 1490° C)[Rooney et al., 2011] agrees with our predicted range (1350 – 1400° C), i.e., not significantly hotter than normal mantle.
- Depth of melting consistent with geochemical estimates (70 – 90 km) [Furman, 2007].



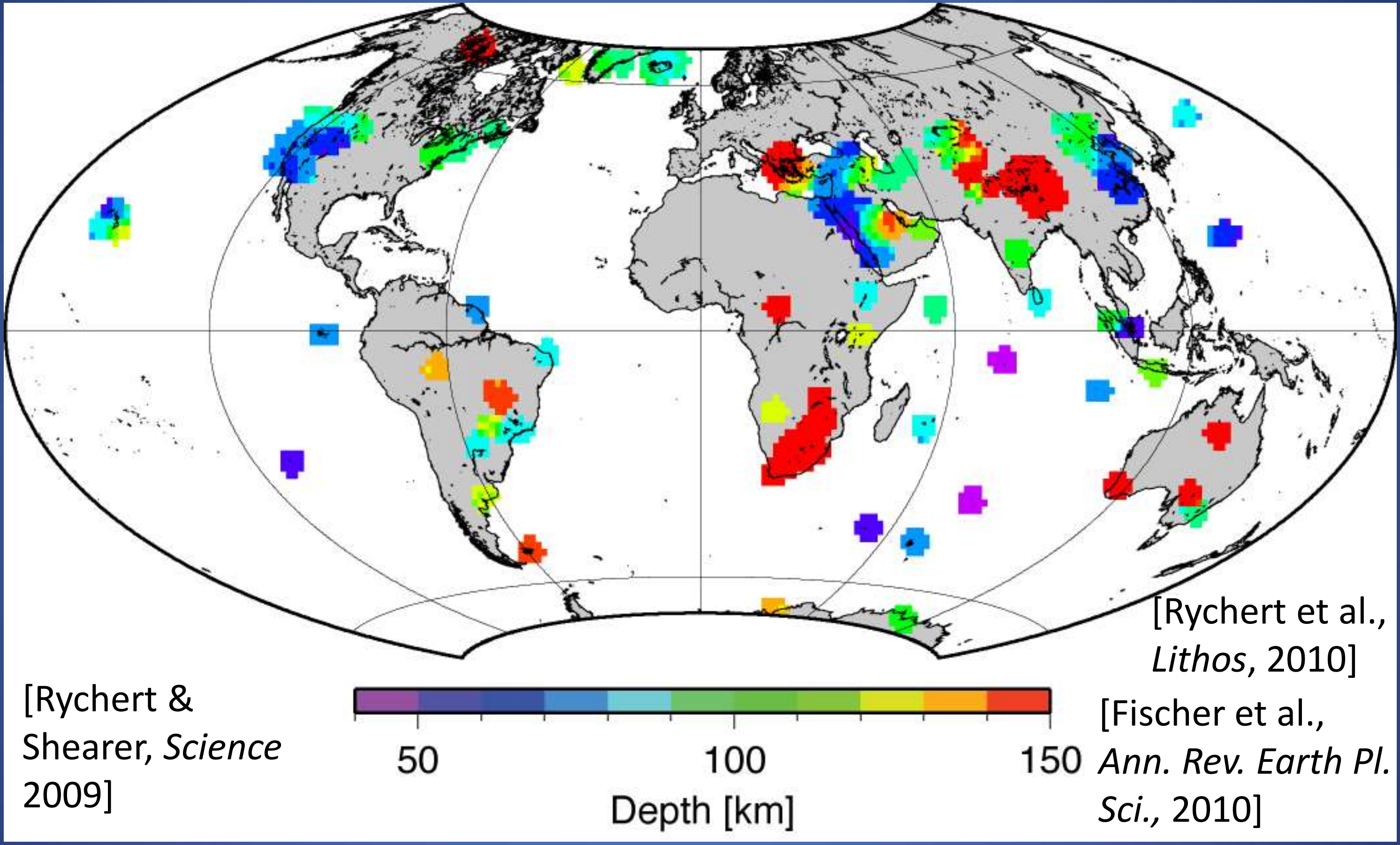
[Chang & van der Lee, 2011]



[Kustowski et al., 2008]

- No plume visible beneath Afar in joint body wave surface wave tomography.
- Channelized flow from a low viscosity asthenosphere may provide slightly warmer material, but certainly no plume [Toomey et al., 2002; Ebinger & Sleep 1998].

Global compilation of receiver function results. Most insitu measurements come from ocean island stations



Lithosphere-asthenosphere boundary from receiver functions

(Li et al., 2000; Li et al., 2004; Collins et al., 2002; Wolbern et al., 06; Heit et al., 2007; Li et al., 2007; Rychert et al., 2005; Rychert et al., 2007; Snyder, 2008; Kumar et al., 2005; Sodoudi et al., 2006; Ozacar et al., 2008; Angus et al., 2006; Mohsen et al., 2006; Hansen et al., 07; Kumar et al., 2007; Wittlinger and Farra, 2007; Hansen et al., 2009; Sodoudi et al., 2009; Kumar et al., 2005; Oreshin et al., 2002; Kumar et al., 2006; Sodoudi et al., 2006; Chen et al., 2006; Chen et al., 2008; Chen, 2009; Kawakatsu et al., 2009)

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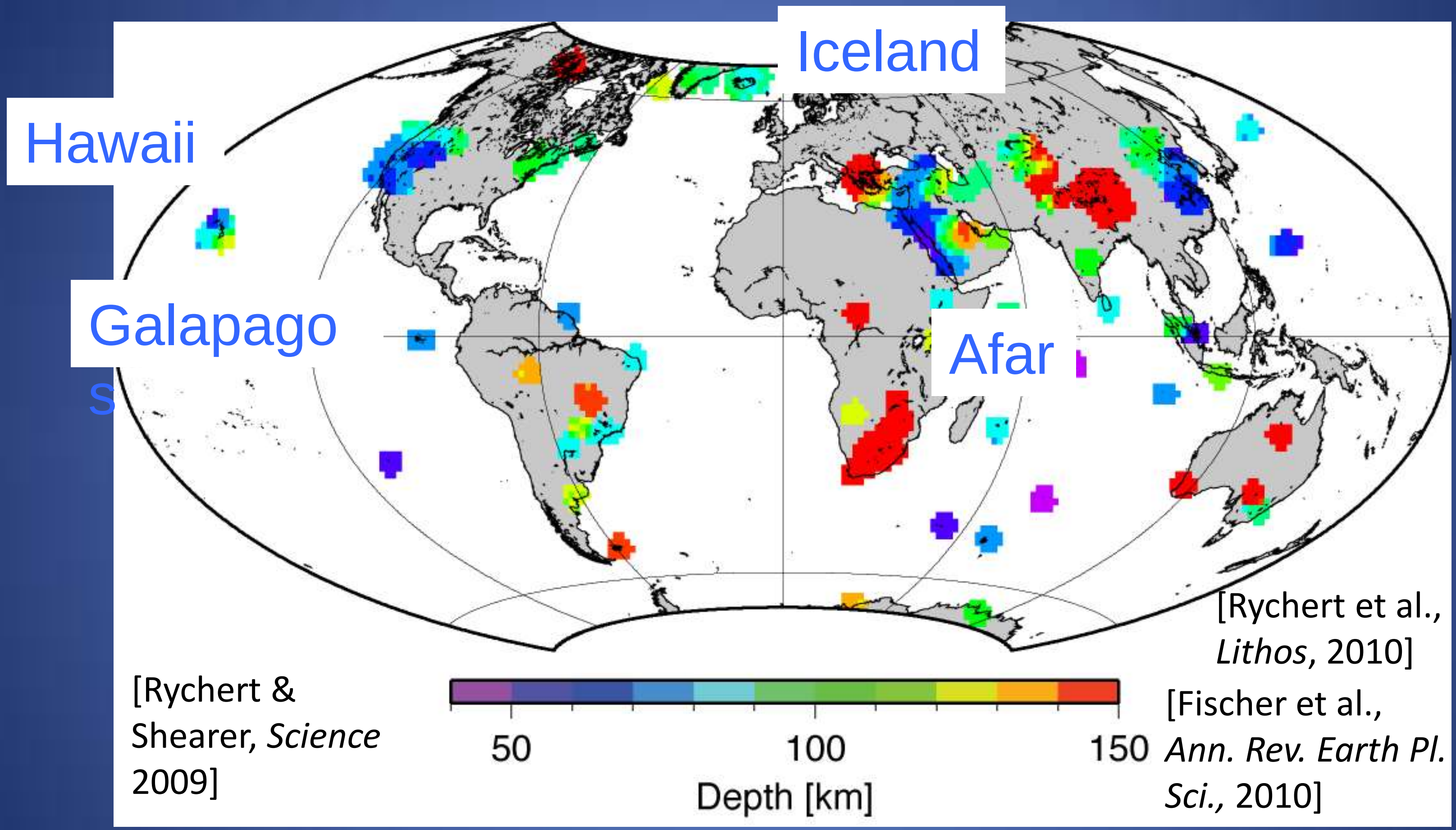

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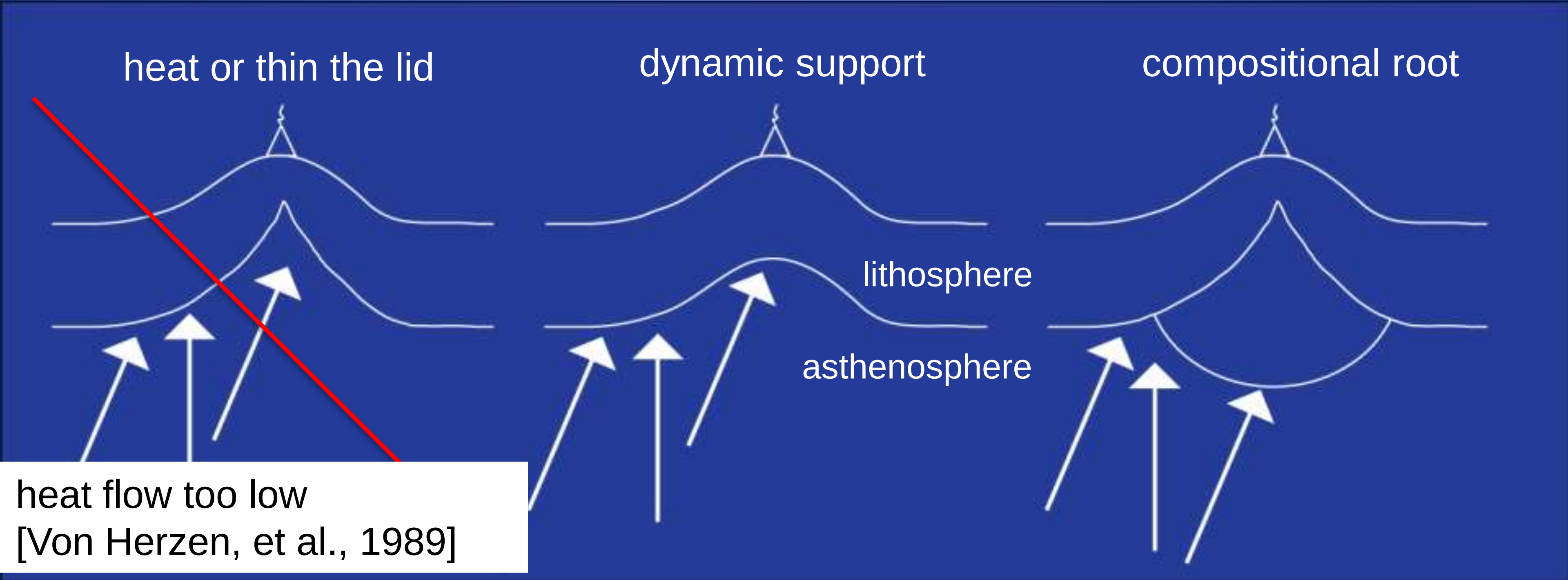
Hawaii -
Another important unknown -
Where does the plume impinge on the lithosphere?



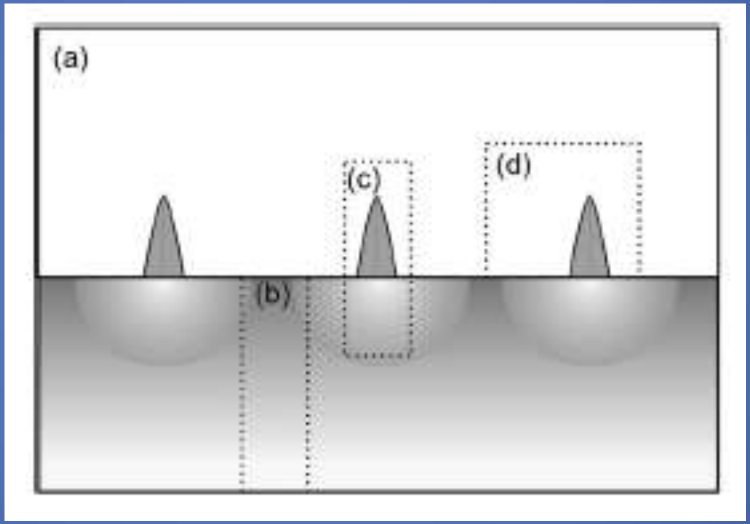
Detrick & Crough, 1978
Li et al., 2004

Sleep, 1990

Jordan, 1979
Yamamoto & Phipps Morgan, 2009
Hall & Kincaid, 2003

Galapagos

Melt ponding beneath lithosphere with dykes



[Havelin et al., 2013]

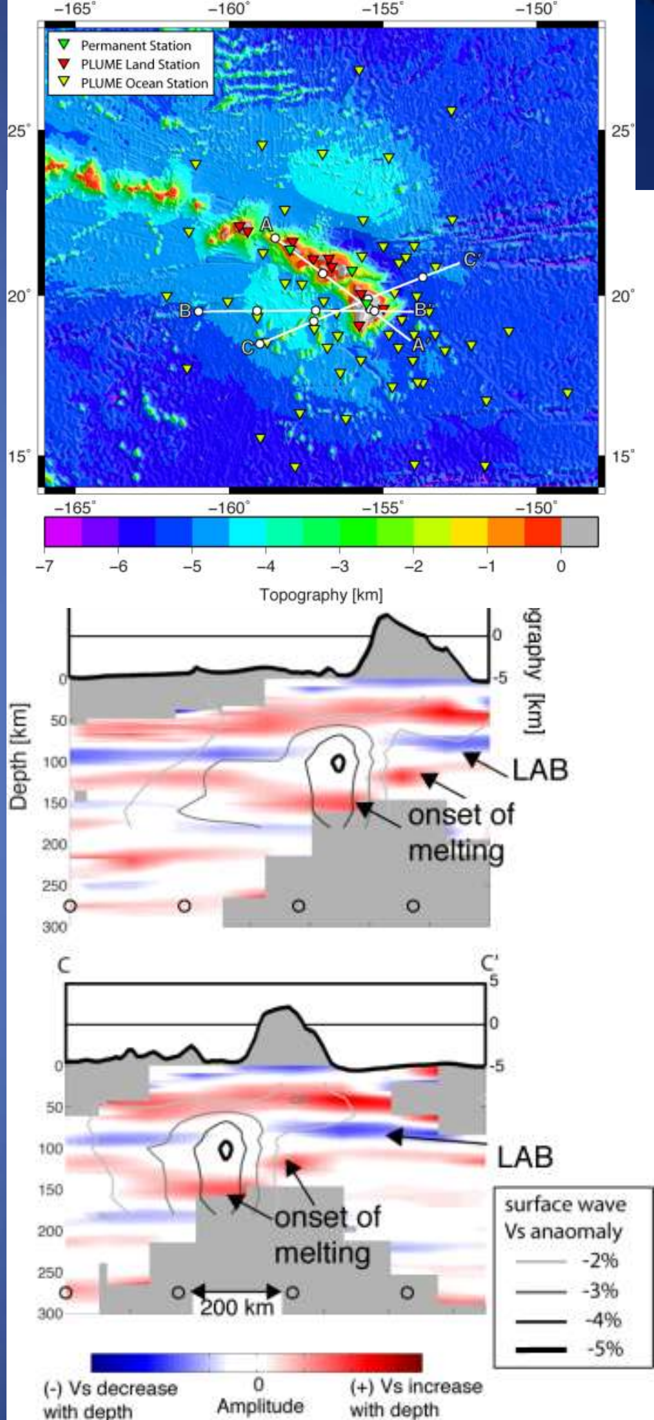
Hawaii – Discussion

Other supporting evidence-
Agreement with geochemical estimates: 1500° – 1600° , 150-180 km [Lee et al., 2009].

Western plume impingement may explain 'Loa' -' Kea' trend (southwest more isotopically enriched than northeast) [Bryce et al., 2005].

Melt and compositional buoyancy may support Hawaiian Swell without a large heat flow anomaly.

Western plume may explain high topography on west in comparison to east.



Hawaii – Discussion

How can we explain plume impingement 100 km to the west?

Has the plume moved? [Tarduno et al., 2009] Sudden plume movement after ~47 My fixity seems too coincidental.

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Angled approach? [Steinberger & Antretter, 2006] Where is plume at depth?

Hawaii – Discussion

How can we explain plume impingement 100 km to the west?

Has the plume moved? [Tarduno et al., 2009]
- Sudden plume movement after ~47 My fixity seems too coincidental.

Angled approach? [Steinberger & Antretter, 2006]
- Possibly…

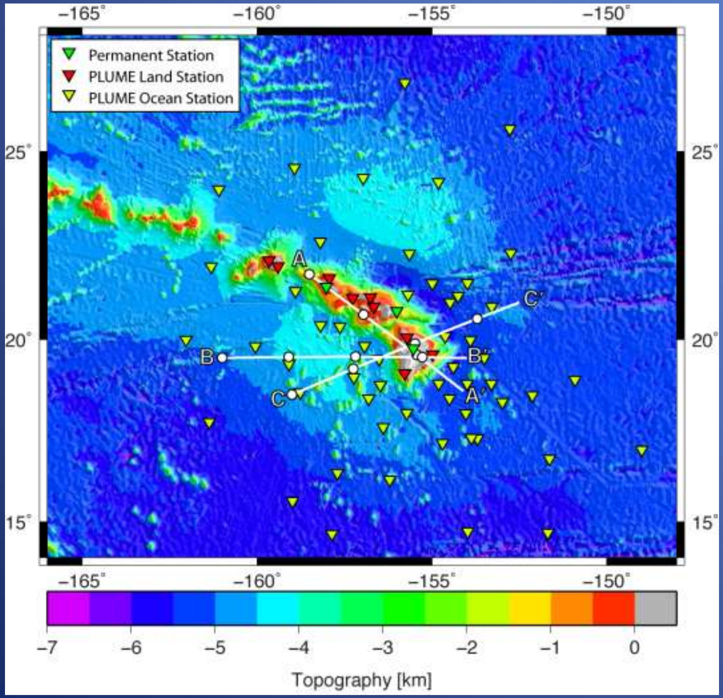
Diverted at shallow depth?
- Restite root.

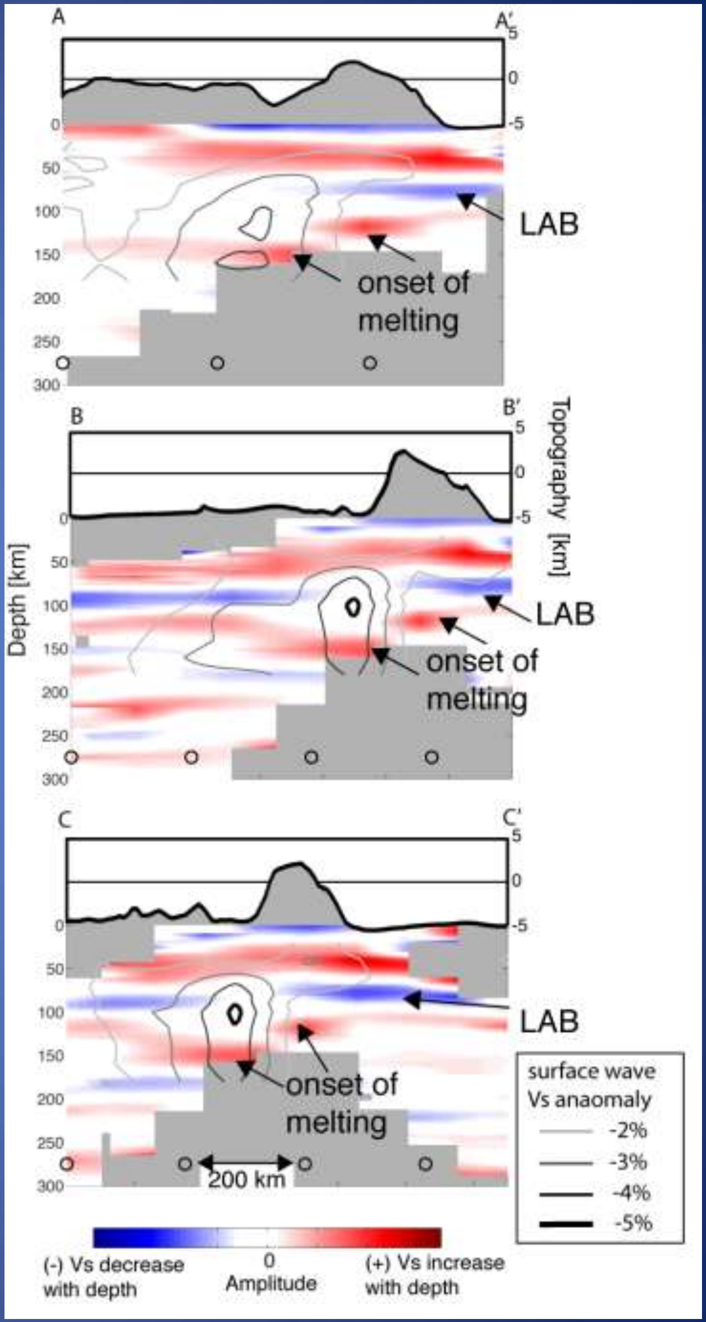
Hawaii - Results

Consistent with base of a melt rich layer, i.e., the onset of melting at 110 – 150 km depth.

Deepest in location of plume impingement, 100 km west of Island of Hawaii. Agrees with surface waves!

Depth of melting corresponds to potential temperatures 1450° – 1550° C [Katz et al., 2003], 100° local anomaly, 200° from ambient mantle.





[*Rychert et al., submitted*]