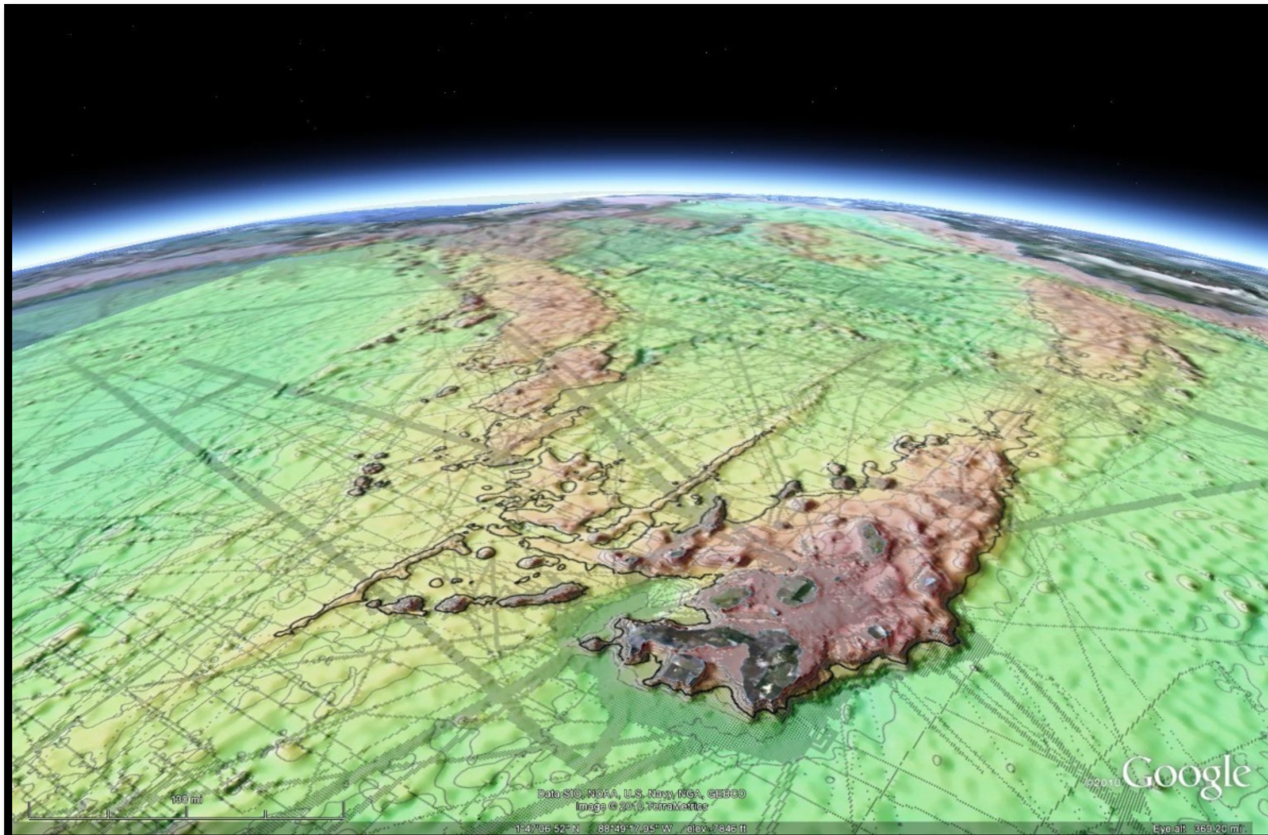
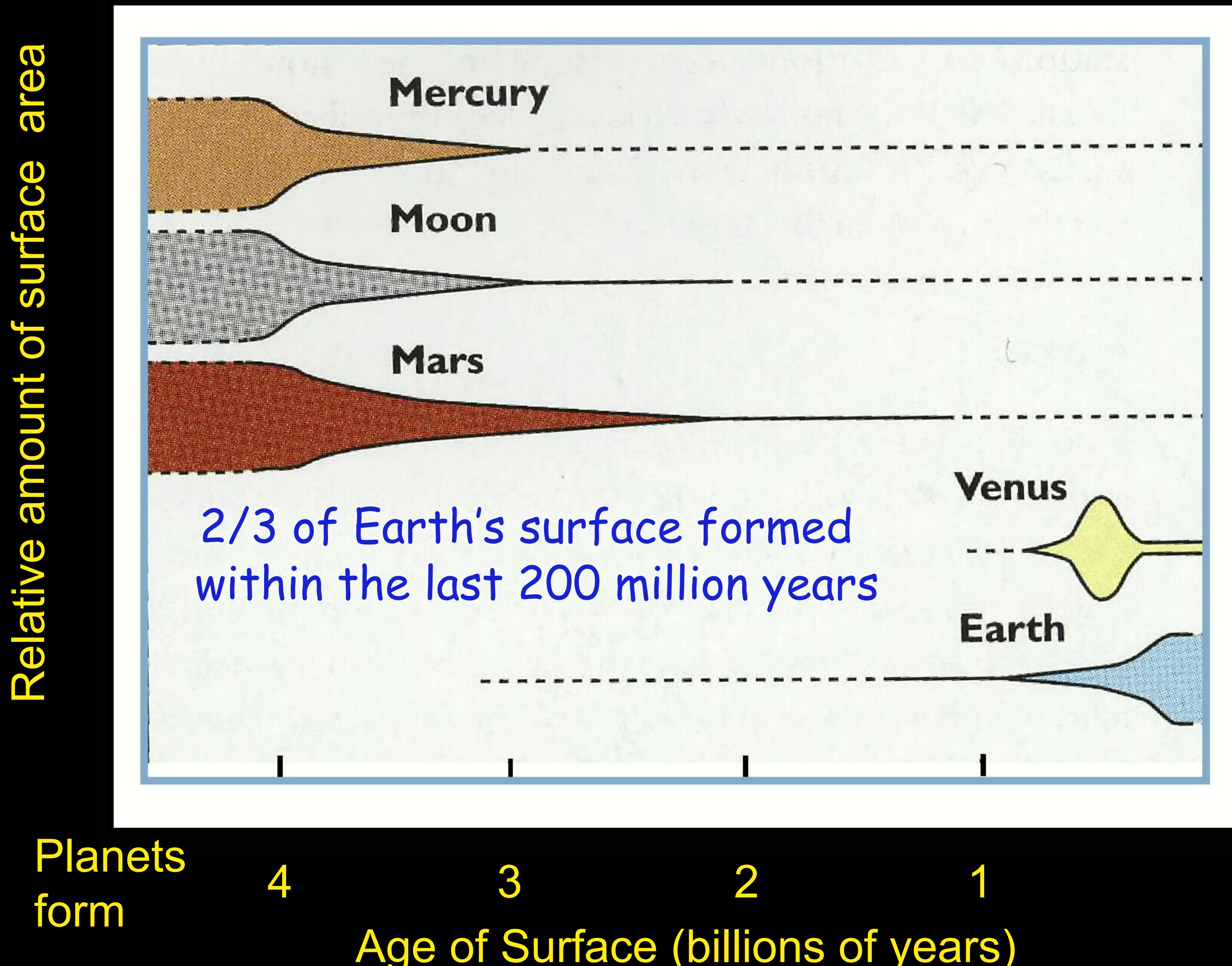
Geophysical Constraints on Mantle Flow, Melting and Plume-Lithosphere-Ridge Interactions in the Galápagos



Darwin Villagómez, Doug Toomey, Emilie Hooft - University of Oregon
Sean Solomon – Carnegie Institution of Washington

(1) Magmatism & Planetary Evolution

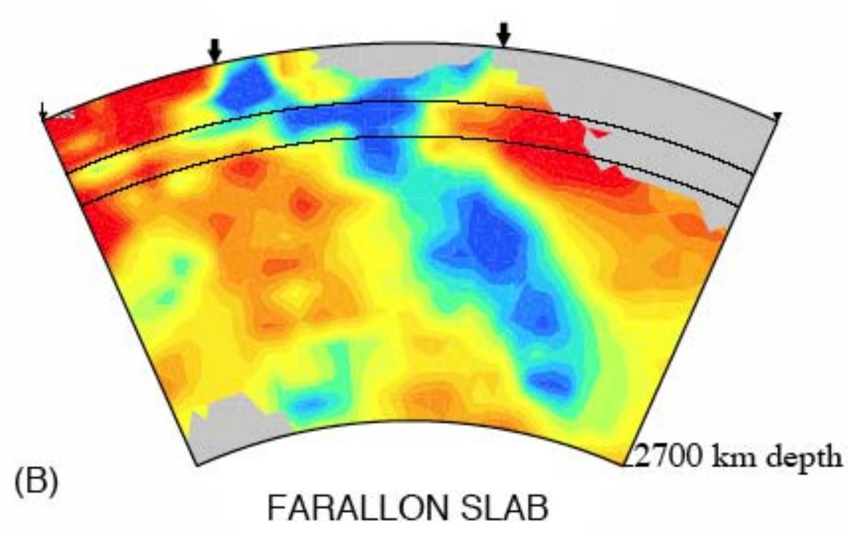


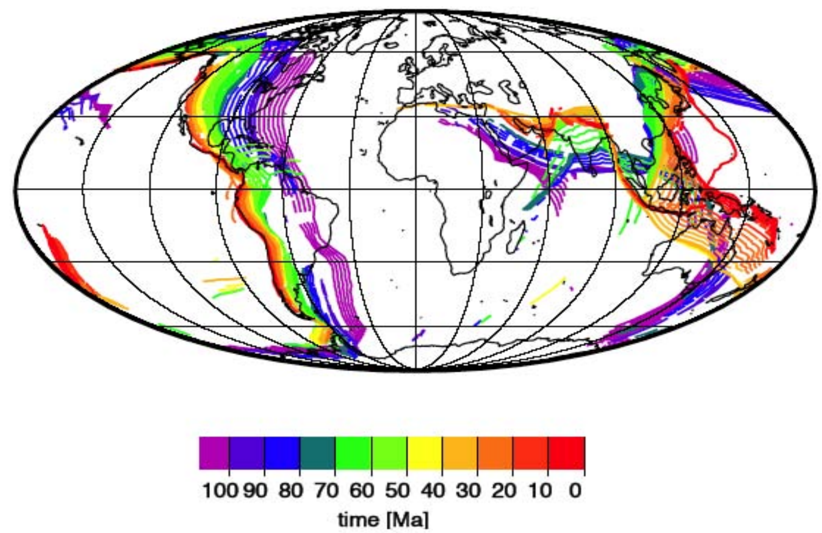
▪

(2) Upwelling is poorly understood

Downwelling

- Large scale downwelling is reasonably well understood
- Both in depth and history
- Input to global convection models
  - Given sinkers and a guess at viscosity, upwelling and return flow predicted. We're done! Veinte cervezas!
- But what if upwelling is not dictated by downwelling alone?
  - Bottom conditions
  - Mantle viscosity
- The near surface expression of upwelling is spreading centers, but how are these connected to deeper flow?





Grand et al., 1997

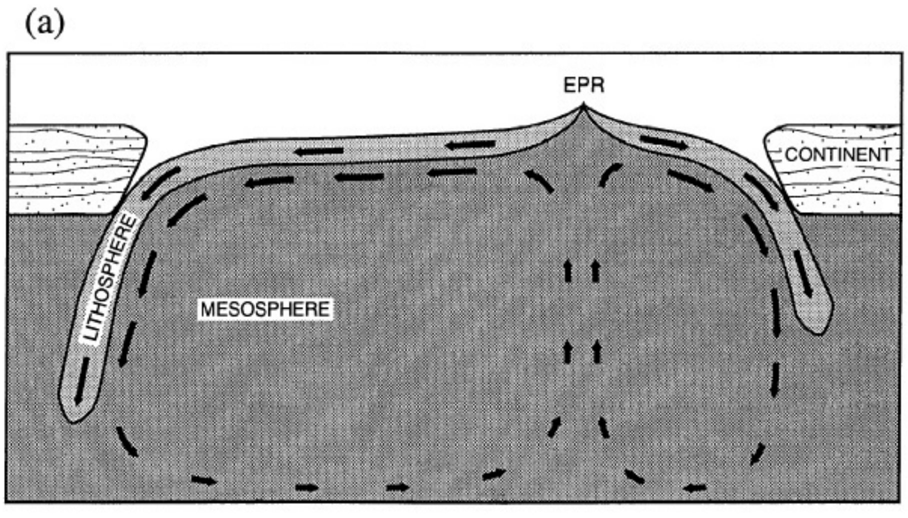
How are plumes and ridges connected to larger scale patterns of mantle flow and upwelling?

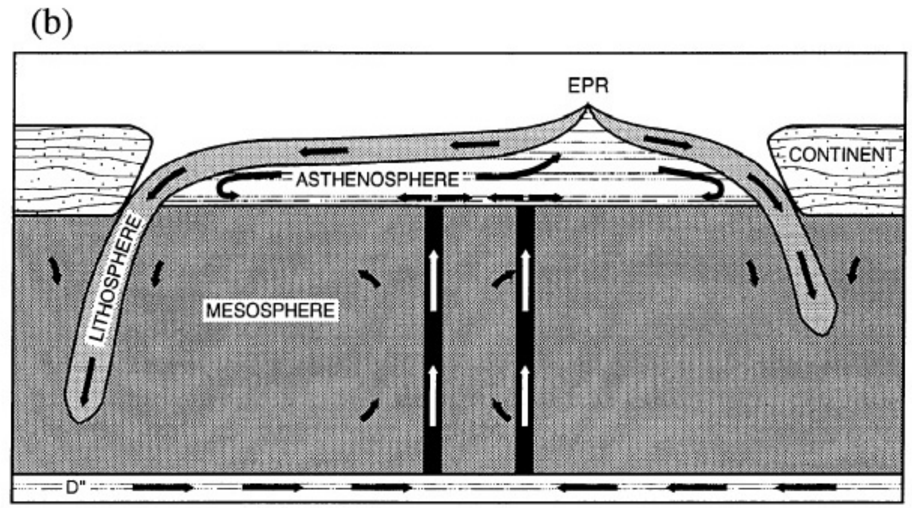
Plate driven flow:

- Convection cells conform to plate motions

Plume fed asthenosphere and Plate Driven Flow

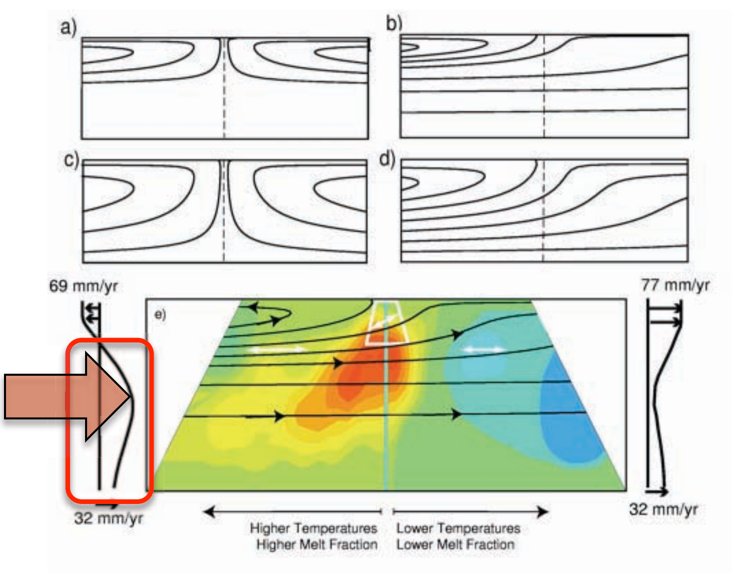
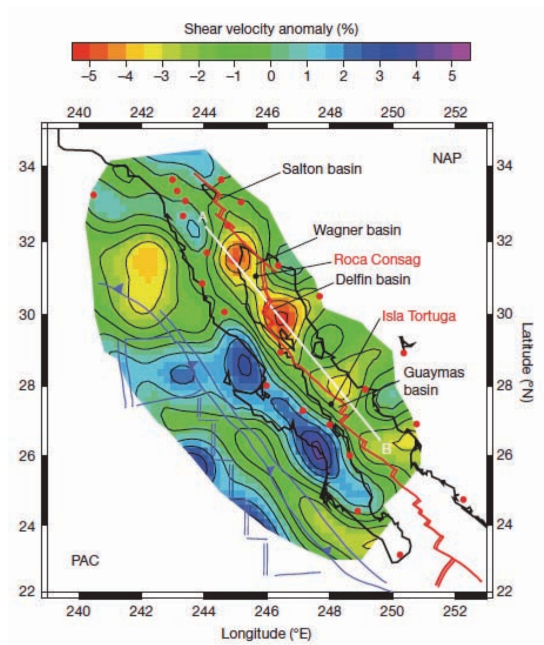
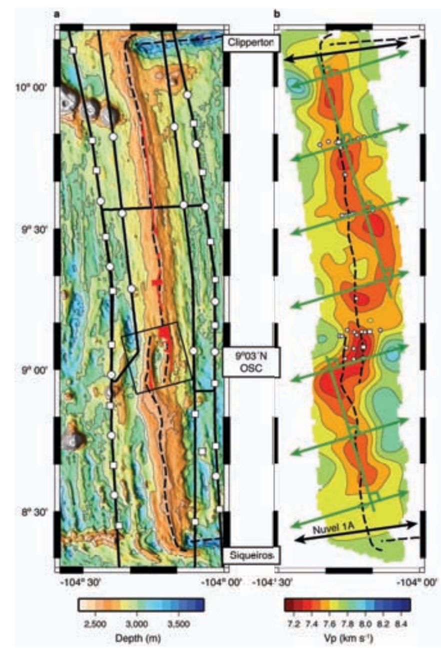
- Convection cells do not conform to plate motions.





Phipps-Morgan et al. [1995]

3) Oceanic asthenosphere is **poorly** understood (and it is behaving badly!)

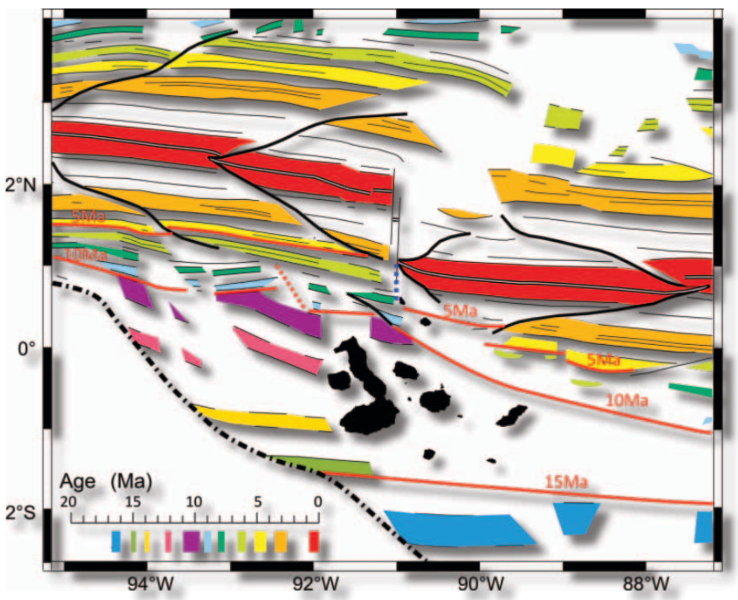
Channeled asthensophere	**Misplaced convective upwellings**	**Skewed mantle divergence**
		
Southern EPR ~100-200 km	Gulf of CA 50-90 km	Northern EPR ~10 km

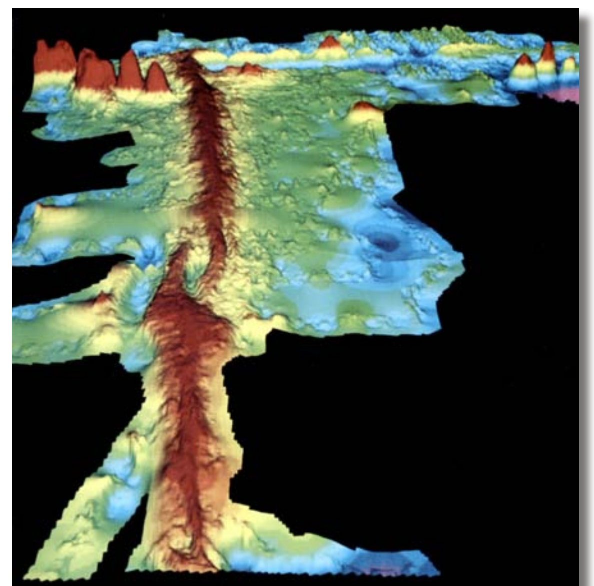
Hammond and Toomey, 2003; Wang et al., 2009; Toomey et al., 2007

4) Lithosphere Plume Interactions: Sites of ocean island formation may be related to ridge crest processes

Oceanic lithosphere is riddled with mechanical and chemical imperfections.

“Small” imperfections (e.g., OSCs) are still ~10 kilometers across and leave continuous wakes of faulted, hydrothermally altered crust and possibly mantle that are weak and seismically active for millions of years

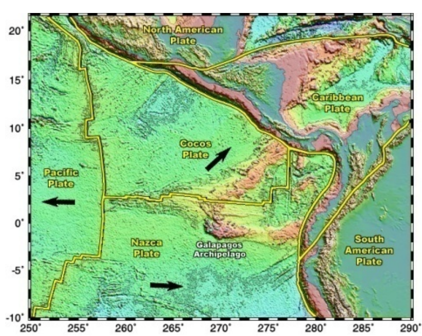


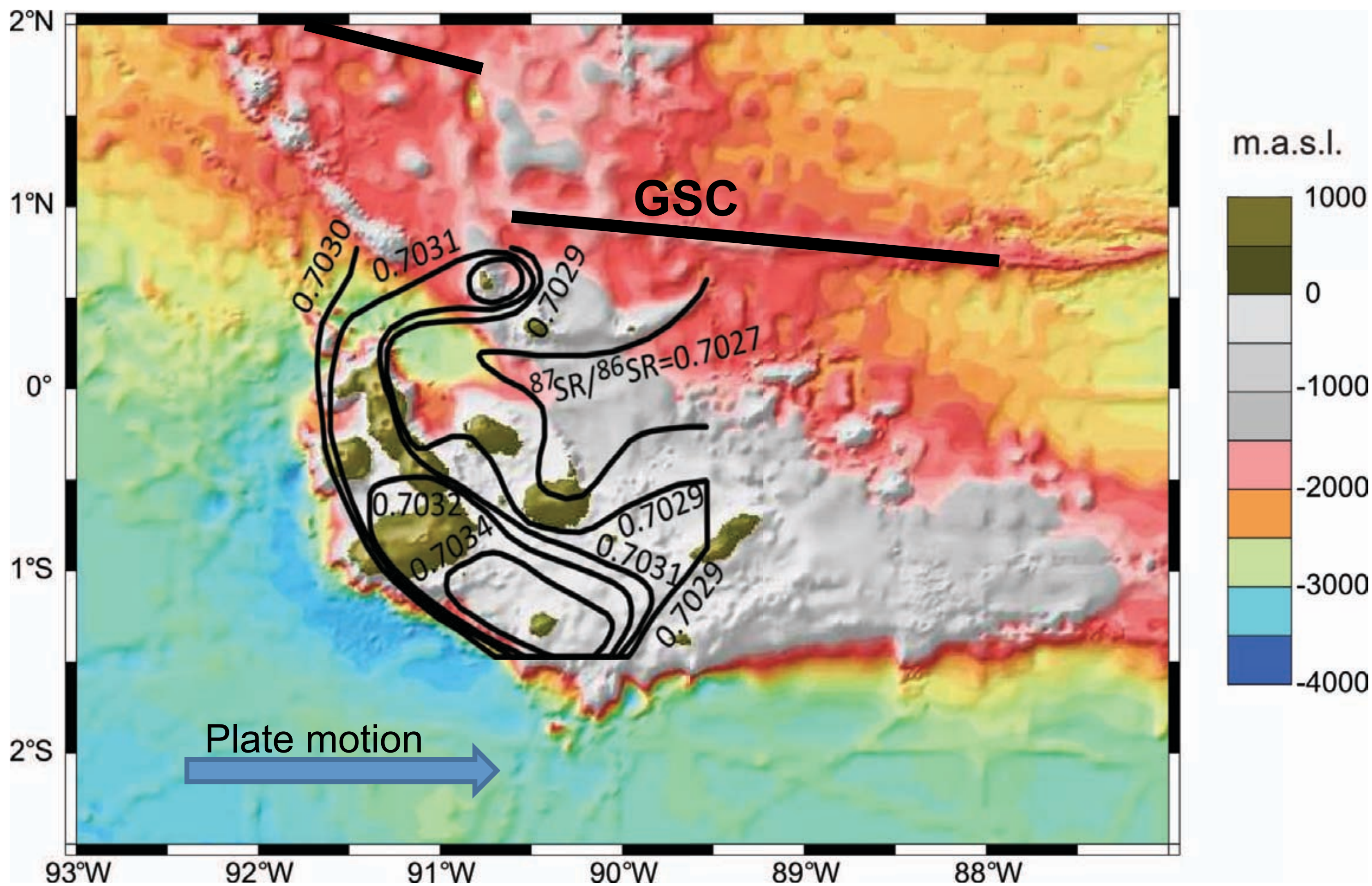


Wilson and Hey, 1995; Meschede and Barckhausen, 2000;

Why is the Galápagos a Natural Laboratory?

- Located 100-200 km south of the Galápagos Spreading Center (GSC)
- Sits on thin and young lithosphere of Nazca Plate (5-20 My old, 30-60 km thick)
- Nazca plate moves eastward with respect to the hotspot
- Lava geochemistry from ocean island basalts (OIB) to mid-ocean ridge basalts (MORB)
    - Distinct geographical pattern [*Geist et al.,* 1988; *White et al*., 1993, *Harpp and White*, 2001].





Galápagos: Some Obvious Questions

- Is the Galápagos hotspot associated with an upwelling mantle plume?
- Where is the center of the hotspot and/or plume located?
- What are the approximate lateral dimensions of the hotspot anomaly in the shallow mantle?
- What causes the spatial variability in lava composition?
- Is asthenospheric flow and hotspot upwelling well coupled to plate motions?
- What is the nature of plume-ridge interaction?

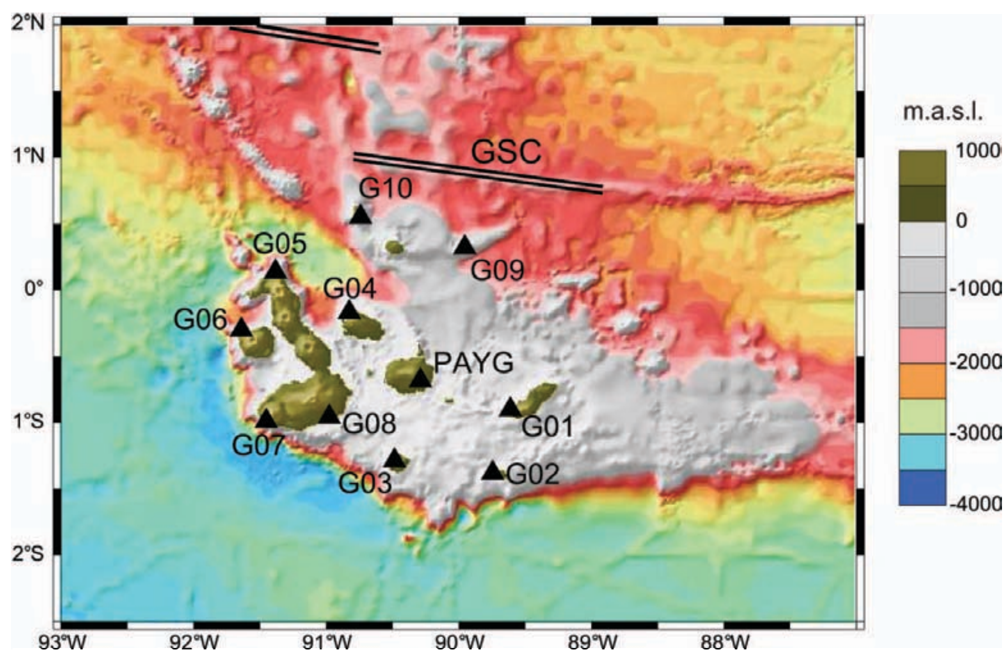
Galápagos Seismic Reconnaissance Array

Types of studies

- Thickness of transition zone
  - Hooft et al. (2003)
- Rayleigh wave tomography
  - Villagomez et al. (2007)
- Ambient noise tomography
  - Villagomez et al. (2011)
- Shear wave splitting
  - Fontaine et al. (2005)
- Joint body-surface wave tomography
  - Villagomez et al. (in prep)

Topics

- Mantle flow
- Mantle melting
- Lithospheric structure
- Plume-lithosphere interactions



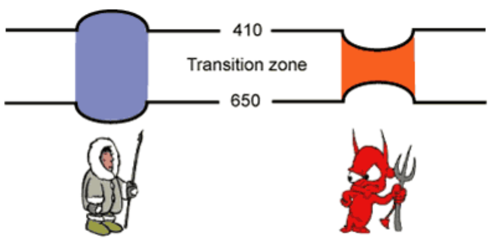

Note: The joint body-surface wave inversions presented here are unpublished. A manuscript is in preparation by Villagomez et al.

RESULTS

Mantle Flow: Main Points

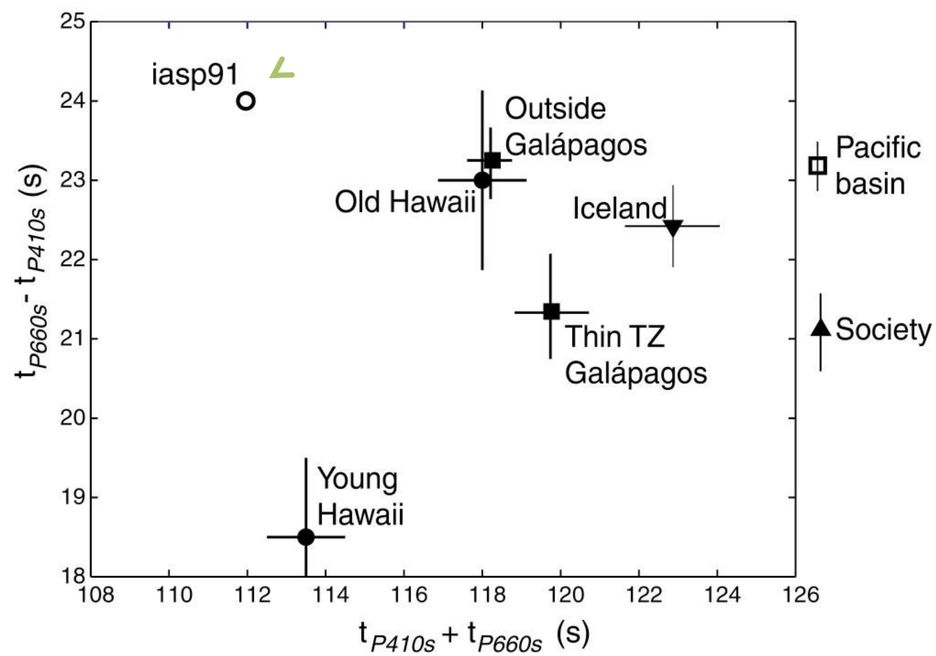
1. Plume vs hotspot
   – Thermal anomaly in the transition zone
2. Upwelling
   – Plume ascent is **not** well coupled to Nazca plate motion, but is affected by plate creation at the GSC
   – Plume is **not** at the leading edge of the Galapagos
3. Flattening
   – Plume upwelling is stalled/deflected by formation of its own residuum. Flattening is **not** obviously asymmetric.
4. Downwelling
   – High velocity anomalies near the leading edge of the Galápagos suggest downwelling & secondary convection

Comparison with other hotspots and Pacific Ocean



Reference

Transition zone thickness



Upper mantle velocities

Hooft et al. (2003)

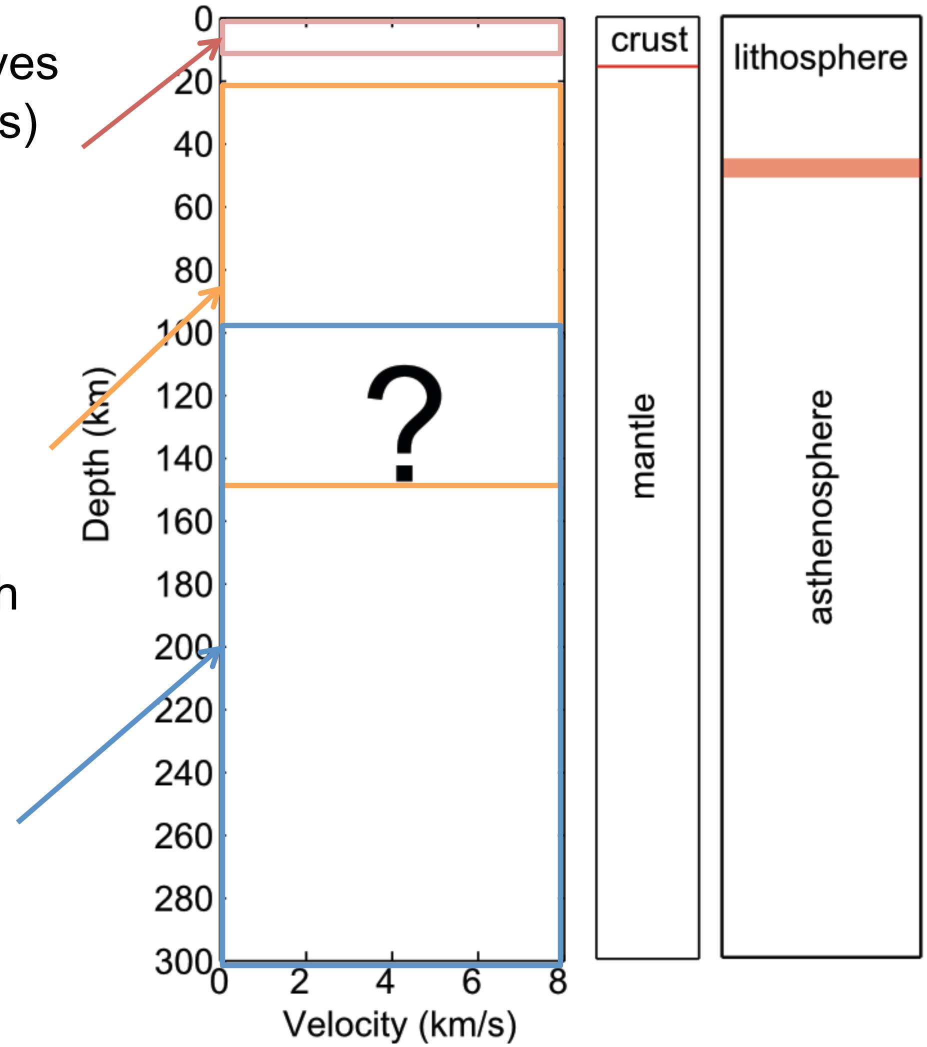
- Galápagos shows a thin mantle transition zone
  - Transition zone: from 410 to 610 km depth. Separates upper and lower mantle.
  - Thinning of transition zone can be caused by increased temperatures
  - Suggests upwelling of a thermal plume at least from 410 km depth (130±60˚K)

Galápagos seismic tomography

1. Ambient noise Rayleigh waves
   Group velocity (period 3-10 s)
   Resolution: 3-13 km depth
   Result: Absolute velocity

2. Surface waves (Rayleigh waves)
   Phase velocity (period 20-120 s)
   Resolution: 20-150 km depth
   Result: Absolute velocity

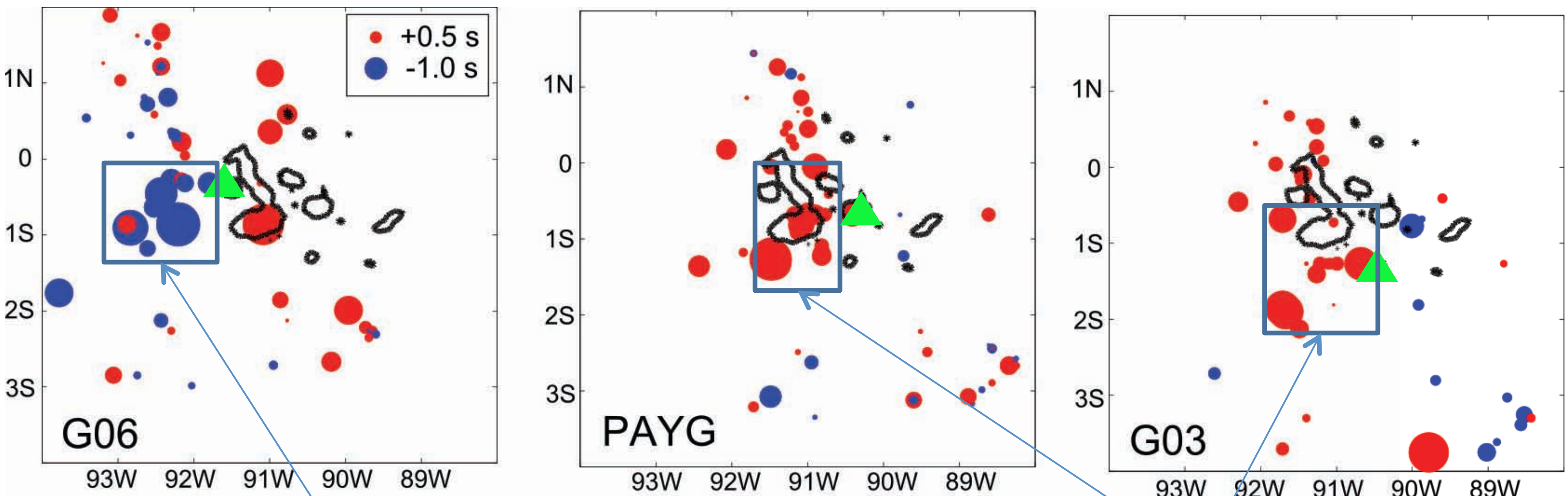
3. Body waves (P and S)
   Resolution: 100-300 km depth
   Result: Velocity variations



Body wave data

- S-wave data indicate there are 2 main regions of anomalous seismic velocity

Piercing point of seismic ray at 400 km depth



Region of anomalously early arrivals

Region of anomalously late arrivals

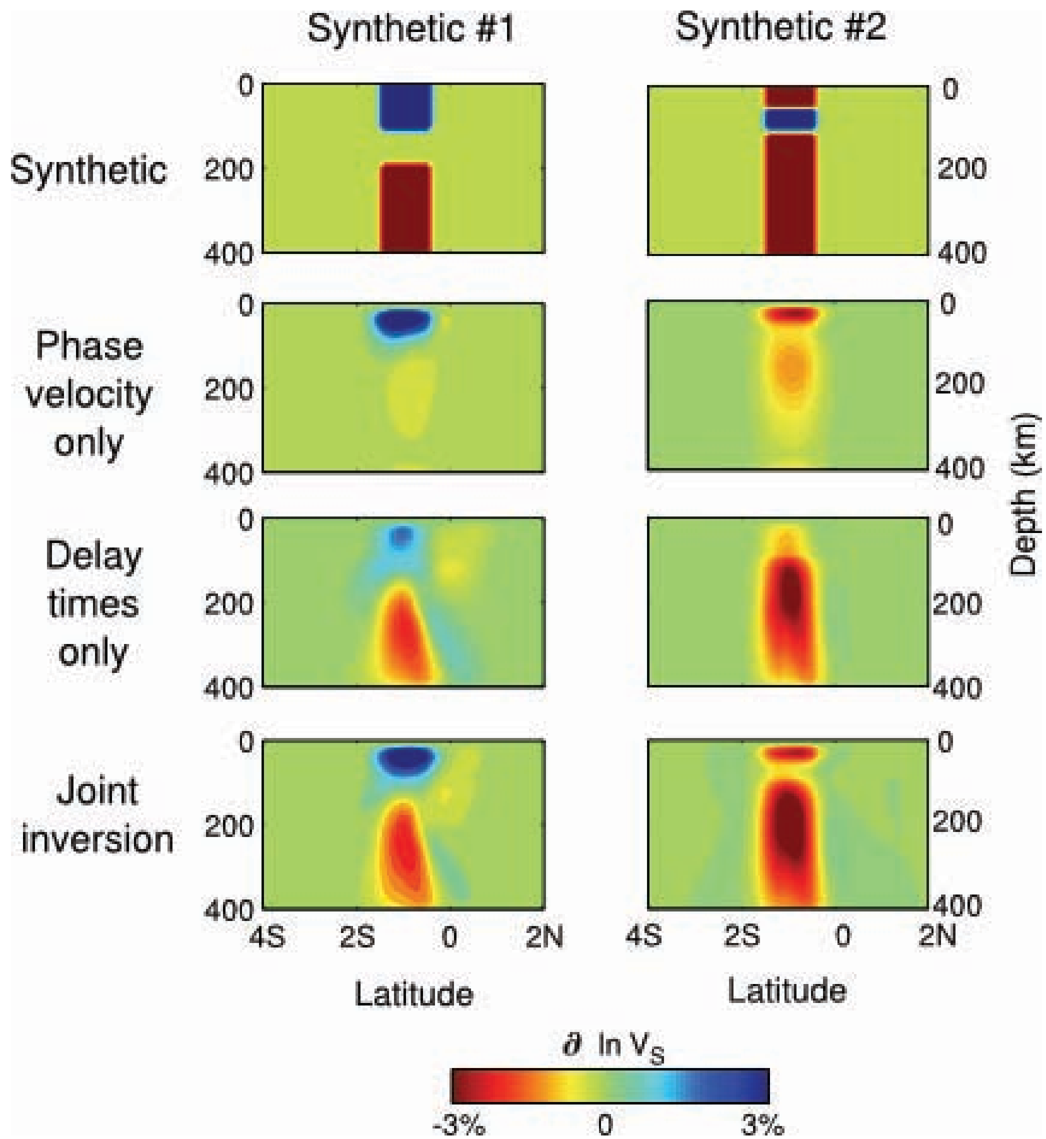
Villagomez et al., in prep.

Joint inversion of surface and body wave data
Synthetic resolution tests

- Depth of resolution of body and surface waves are complementary

- Rayleigh wave phase velocities (20-125 s) best resolve structure shallower than ~150 km depth

- Body waves delay times best resolve structure between ~80 and ~300 km depth



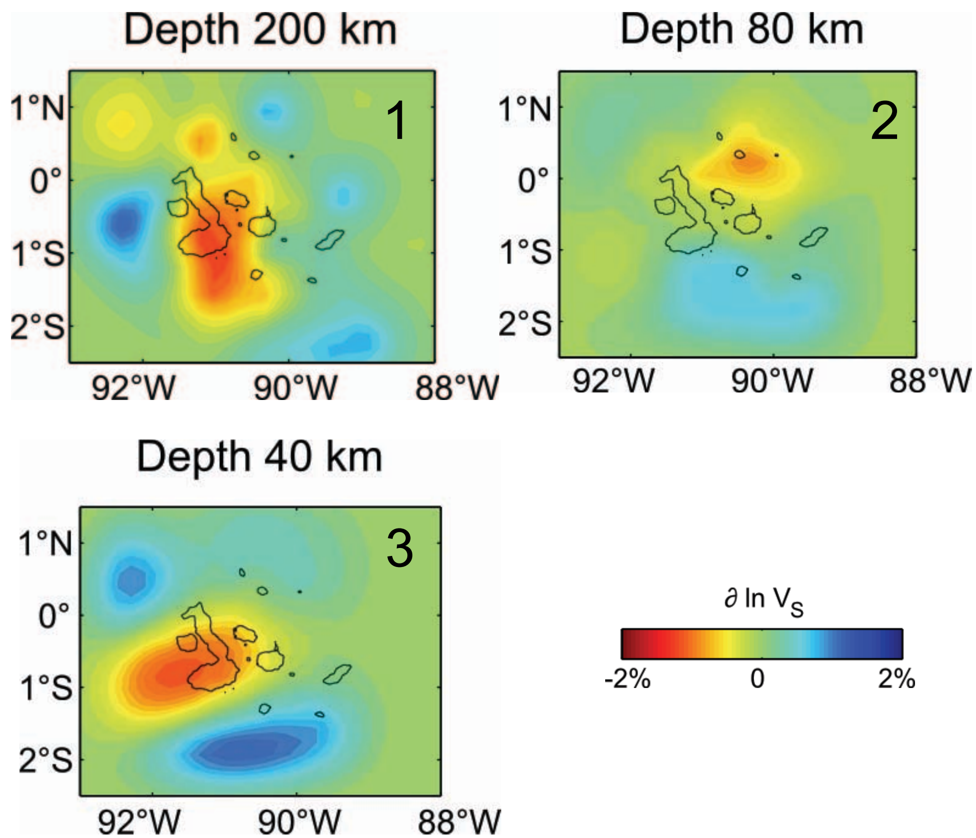
Results of Joint Inversion:
Low velocity anomalies

Three significant anomalies located:

1. South of Isabela at 100-300 km depth
   - Not beneath Fernandina as previously suggested

2. Beneath northeastern part of archipelago at 50-100 km depth
   - Region of depleted MORB lavas

3. Beneath southwestern part of archipelago at 20-50 km depth
   - Region of most active volcanoes
   - Anomaly is underlain by faster material

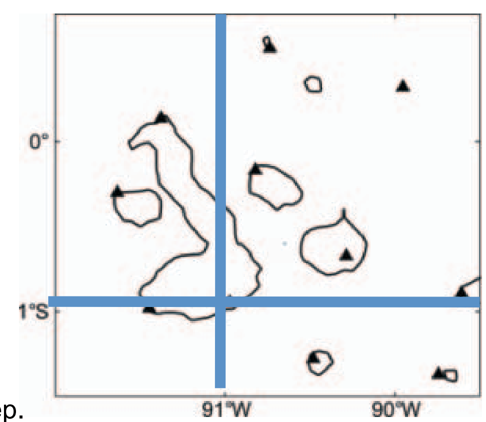


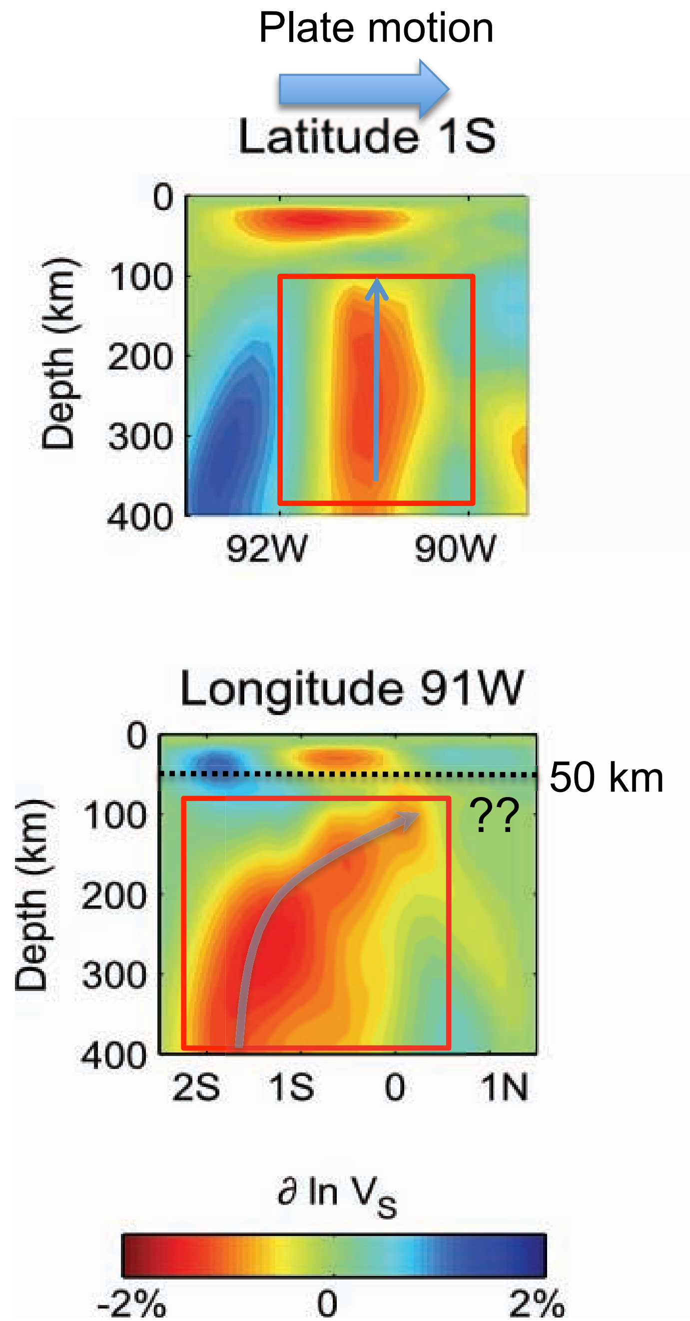
Villagomez et al., in prep.

Results of Joint Inversion:
Low velocity anomalies

Low velocity volume extending from **~300 to ~100 km** depth

- Low velocities at these depths are attributed to melting associated with plume upwelling
- Magnitude of anomaly at ~250 km depth would require ΔT in excess of 150˚K (300˚K)
- Melting is likely in the presence of water and CO_2
- **Plume tilt**
  - No tilt in direction of plate motion
  - Upwelling is from S to N



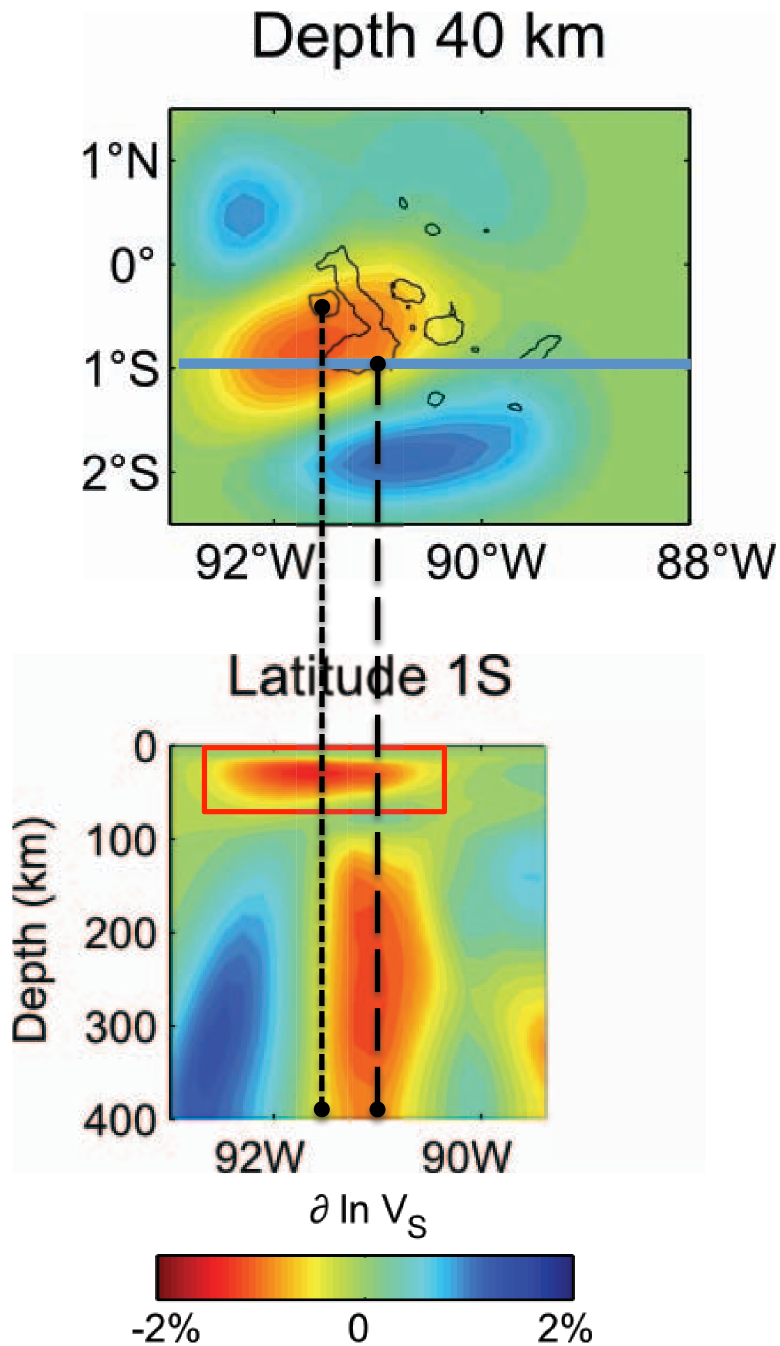


Villagomez et al., in prep.

Results of Joint Inversion: Low velocity anomalies

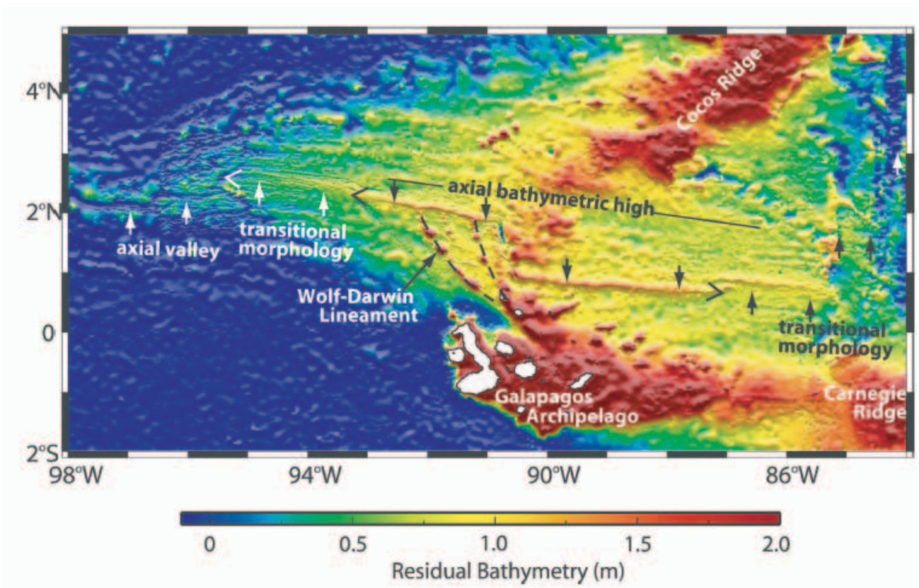
Low-velocity anomaly extending from **20 to 50 km** depth, near base of thermal lithosphere

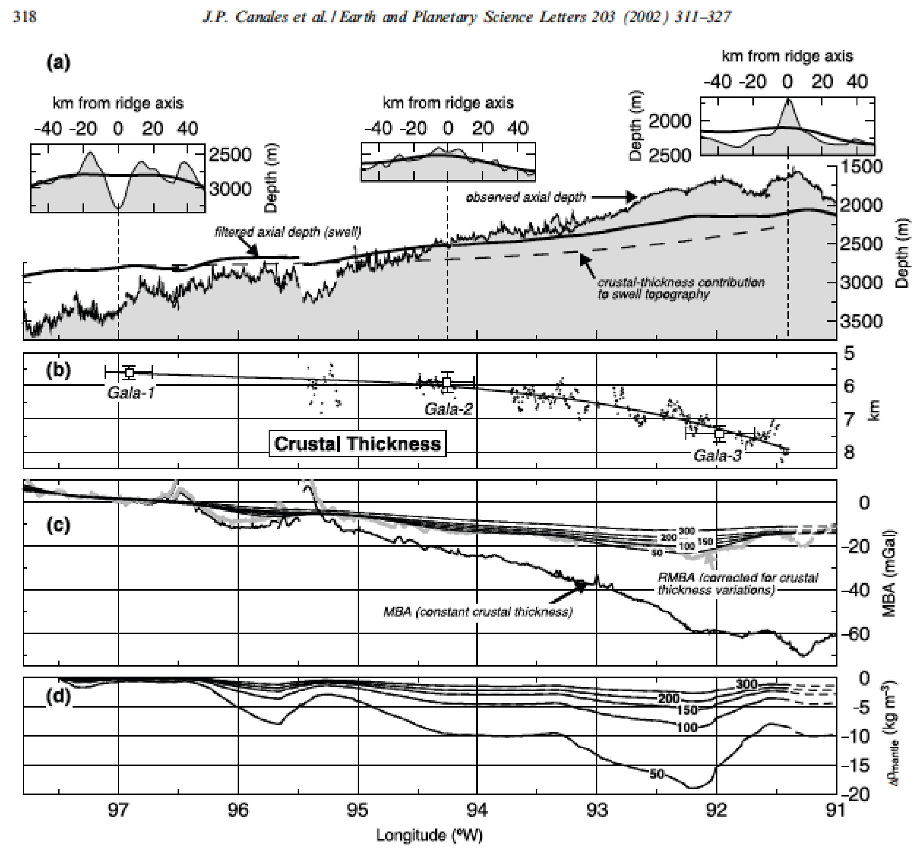
- Anomaly underlies several of the most active volcanoes
- Underlain by faster velocities at 50 to 70 km
- Consistent with a region of accumulation of melts derived from deeper melting
- Alternatively, anhydrous melting
- If decompression melting is occurring at these depths, then upwelling may be driven by either
  - Plume or residuum buoyancies.
  - Or, secondary convection driven by downwelling.
- Western extent of shallow anomalous region is not well defined. Given current data, appears to extend further westward than region of deeper upwelling



Villagomez et al., in prep.

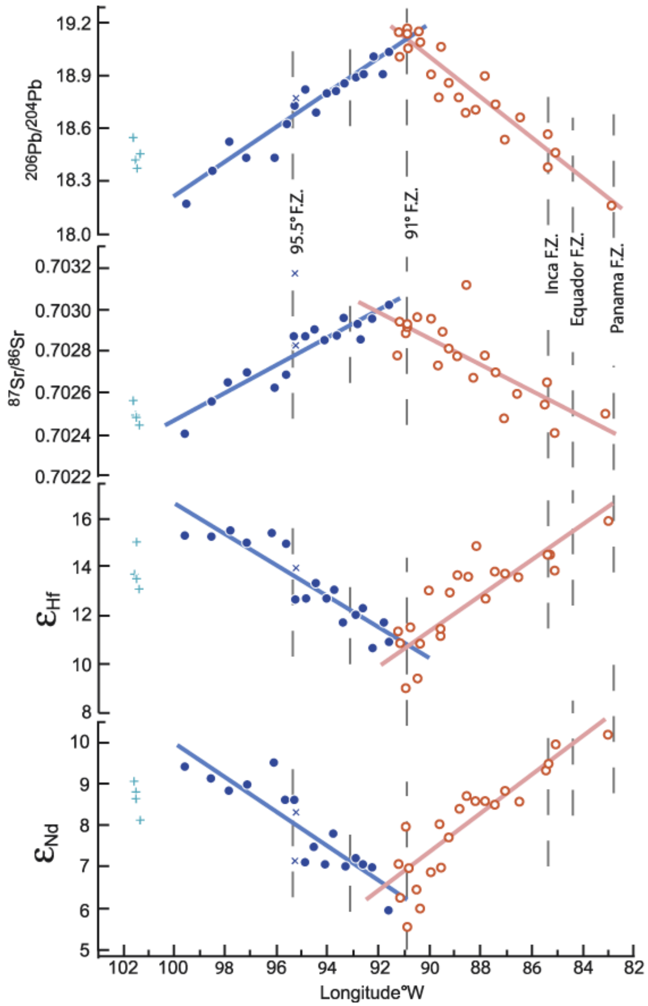
Geophysical signal of plume at the GSC is near 91˚ to 92˚W

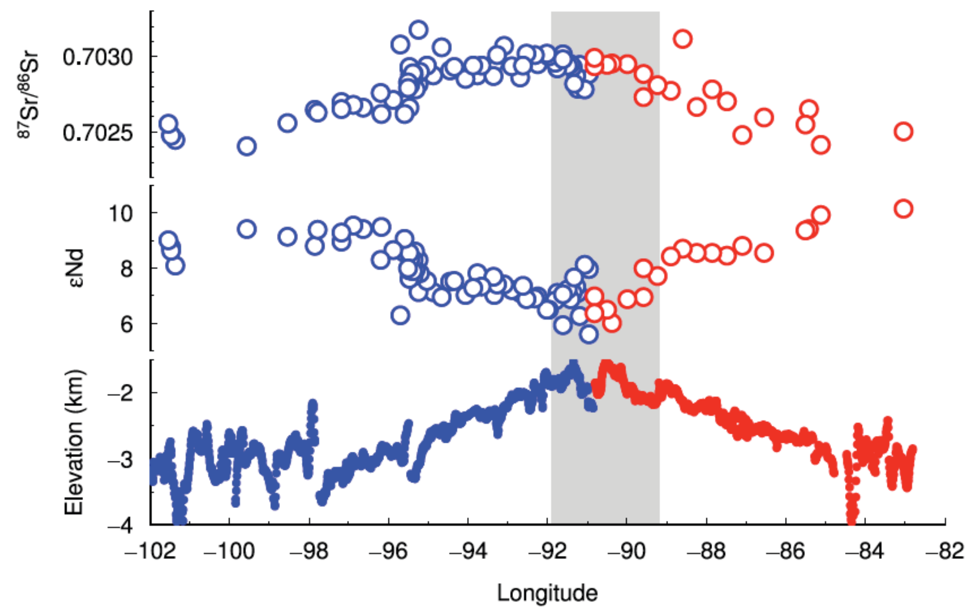


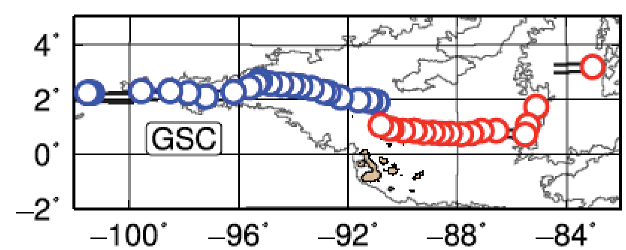


Ito et al, 2001; Canales et al., 2002

Geochemcial signal of plume at the GSC is near 91˚ to 92˚W



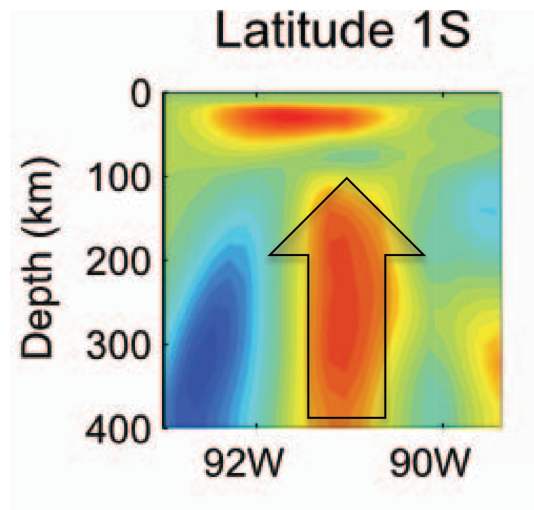


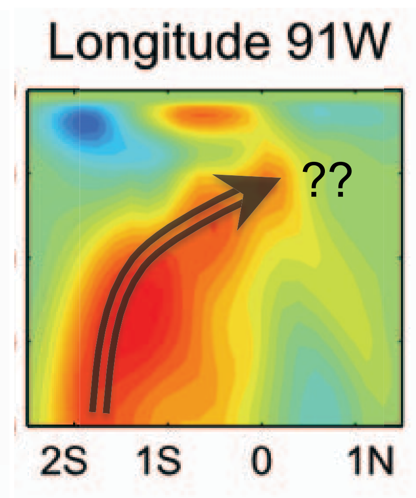


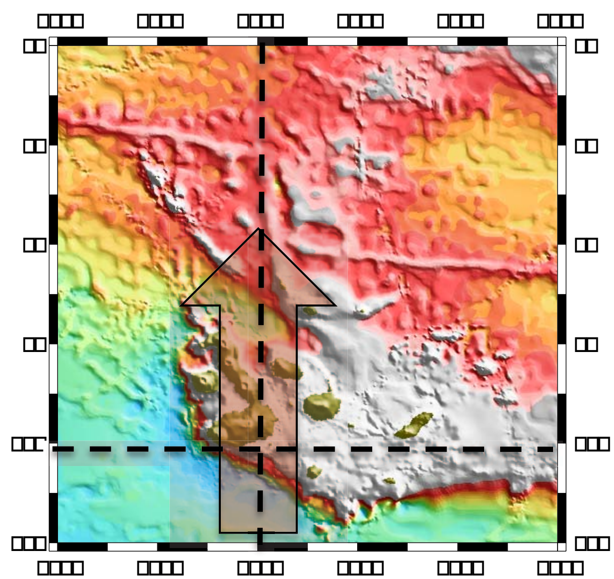
Schilling et al., 2003; Shorttle et al., 2010

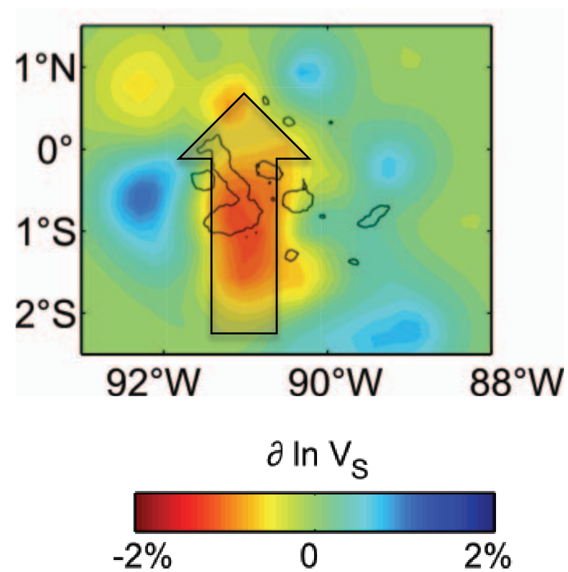
Geophsyical signal of plume upwelling beneath the archipelago is centered near 91˚W

- Plume is <u>not</u> deflected by motion of Nazca plate
- Ascends from south to north
- Ascent in and below asthenosphere is affected by return flow to ridge
- Fernandina is the leading edge of the volcanic chain, but it does **not** directly overlie the plume



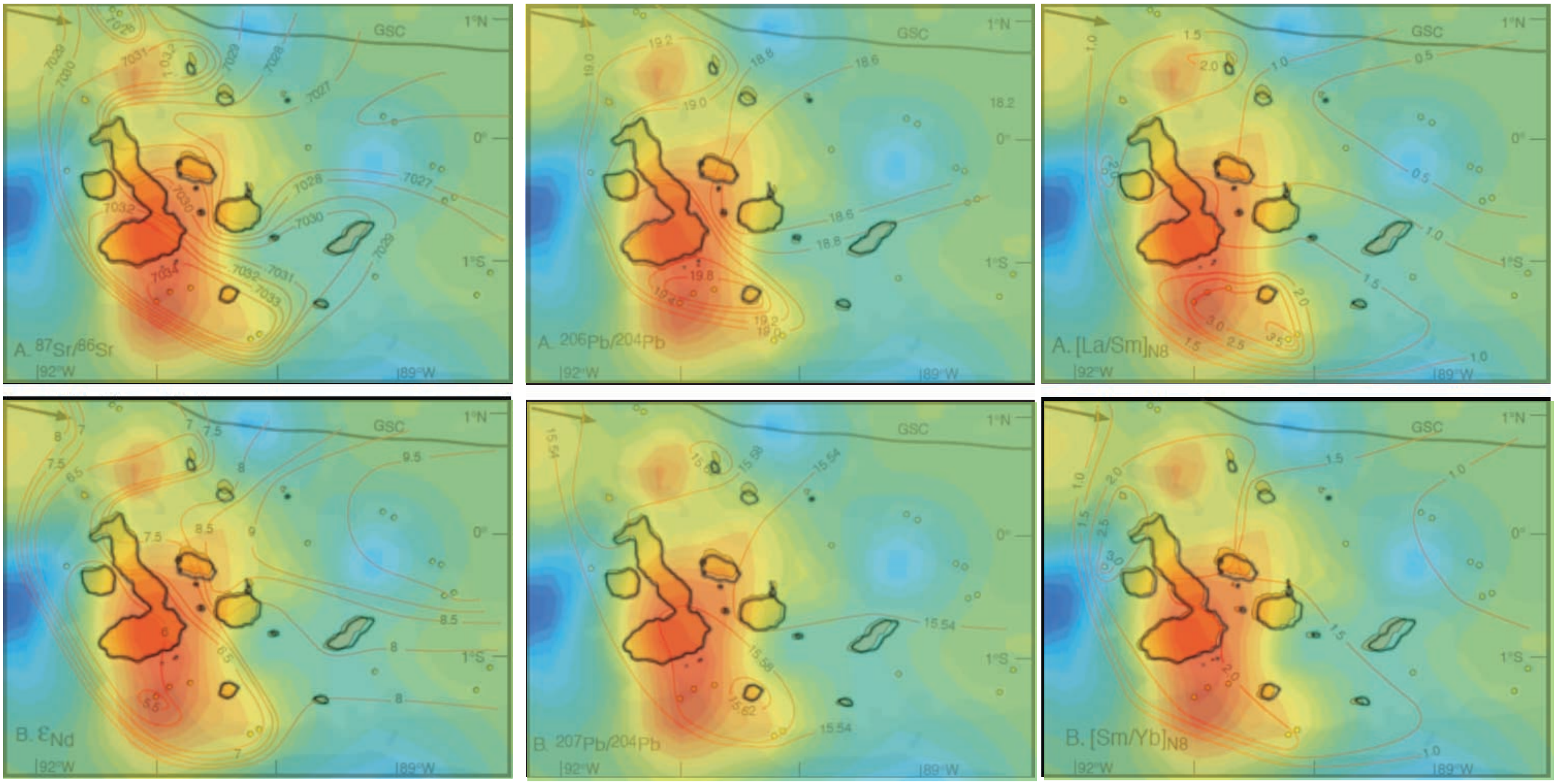






Villagomez et al., in prep.

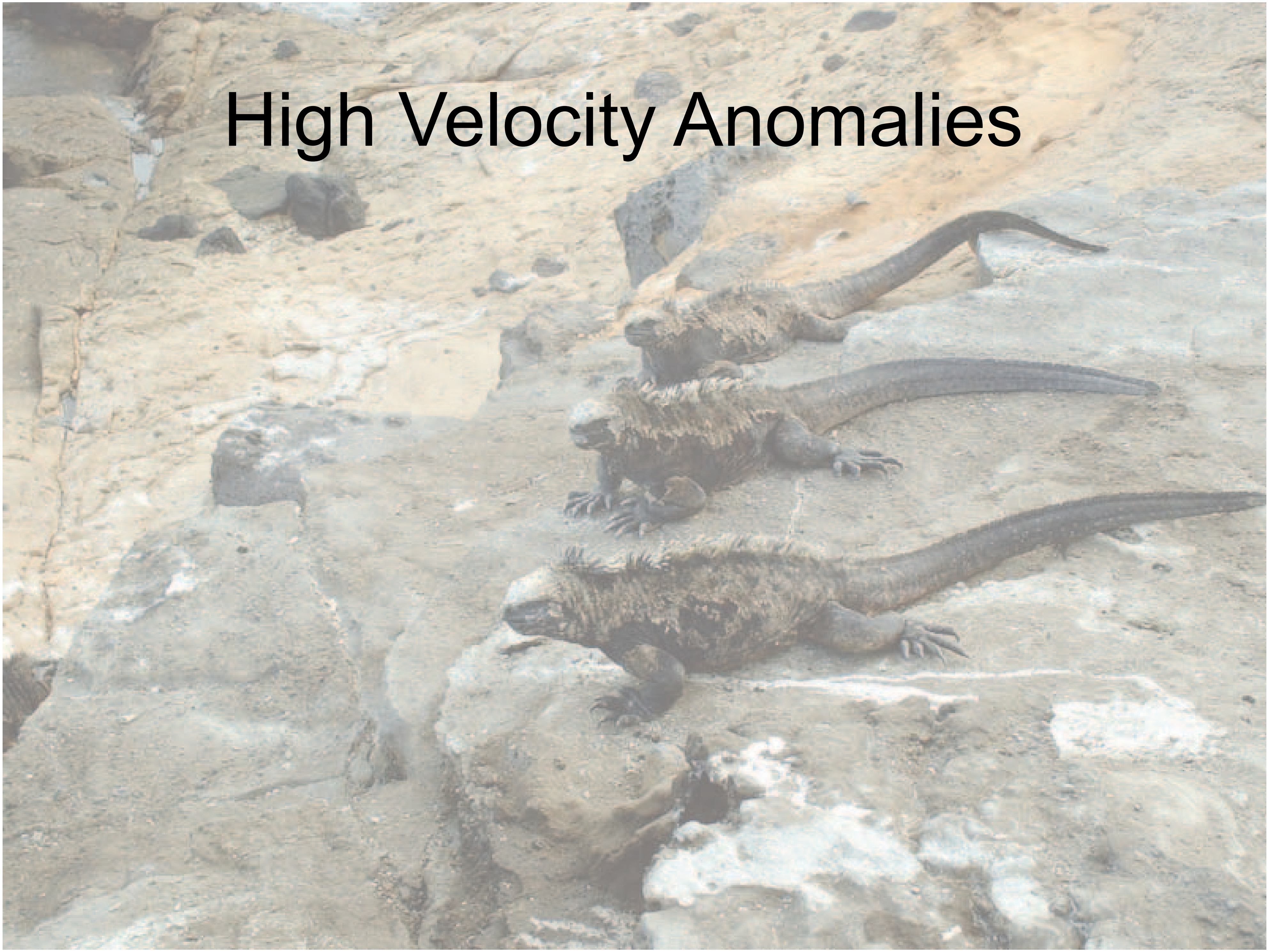
Geophysical and geochemical signatures of plume upwelling in the archipelago



Harpp and White, 2001

Villagomez et al., in prep.

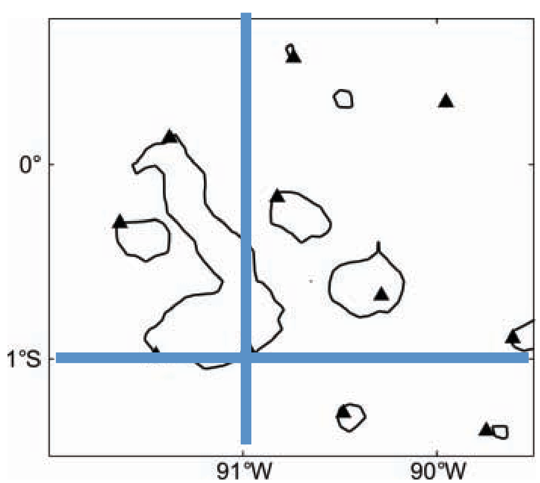
High Velocity Anomalies

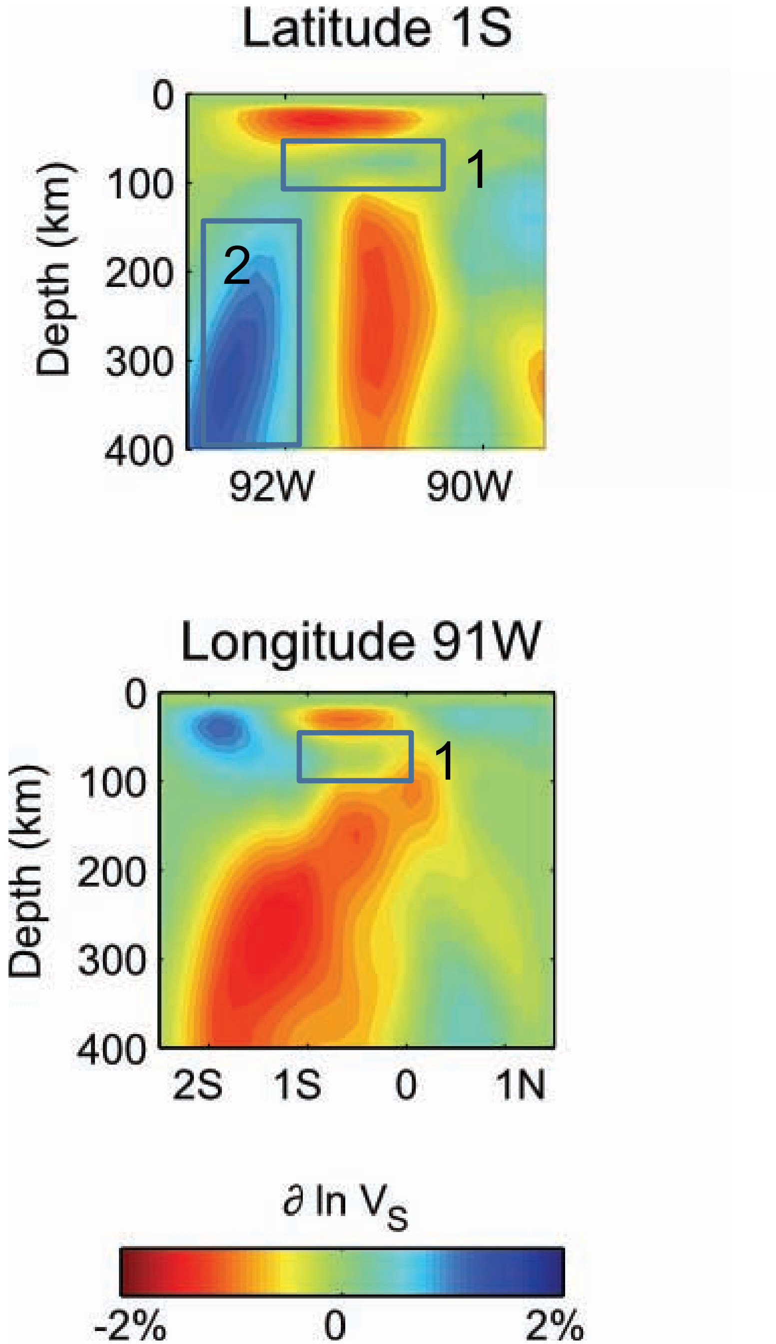


Results of Joint Inversion:
High velocity anomalies

Two significant anomalies detected

1. Higher than normal velocities between 50 and 100 km depth
   - Located above center of mantle upwelling at depths >100 km
2. Higher than normal velocities located to the west of the archipelago
   - Depth range is not well constrained due to reduced number of crossing rays





Villagomez et al., in prep.

Flattening

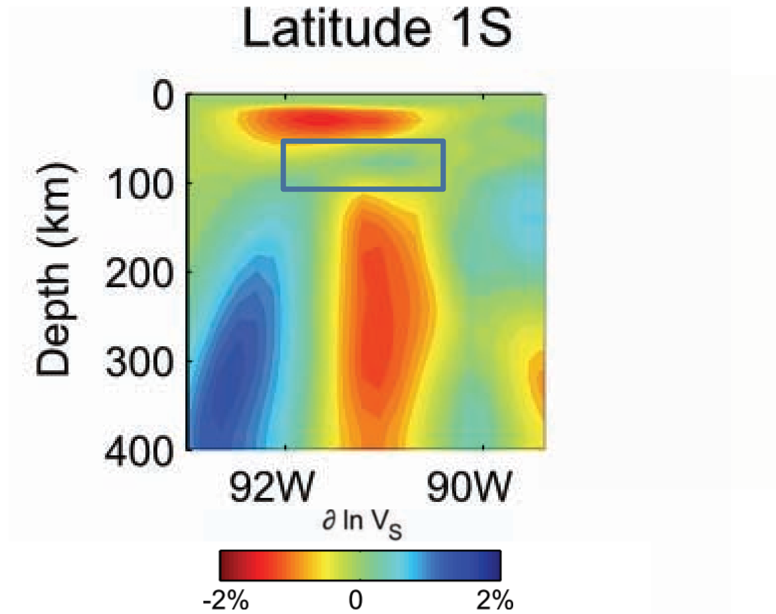
- Upwelling mantle stalls against the residuum of melting
- Variable thickness of thermal and chemical lithosphere affects final depth of melting
- Geophysical and geochemical estimates to depth of top of the melting column are consistent (Gibson and Geist, 2010)

Results of Joint Inversion:
High velocity anomalies

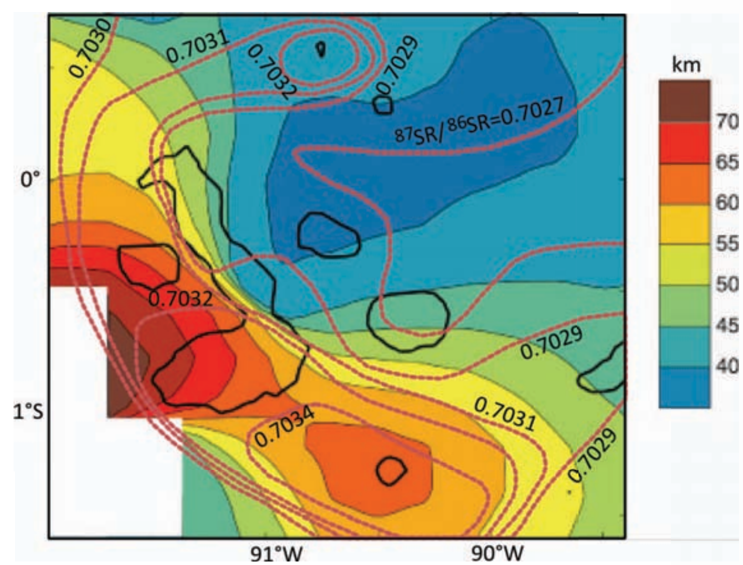
Higher than normal velocities between **50 and 100 km** depth
- Higher than normal velocities attributed to removal of water (e.g. Karato, 1986) – residuum from melting
- We term this region the high velocity lid

- High velocity lid has variable thickness
  - Thicker (50-100 km depth) beneath the southwestern part of the archipelago
  - Thinner (40-50 km depth) beneath the northeastern part of the archipelago

- Thickness correlates well with regional-scale geochemical anomalies



Inferred thickness of lid



Villagomez et al., in prep.

Geophysical and Geochemical Estimates of Lithospheric Thickness

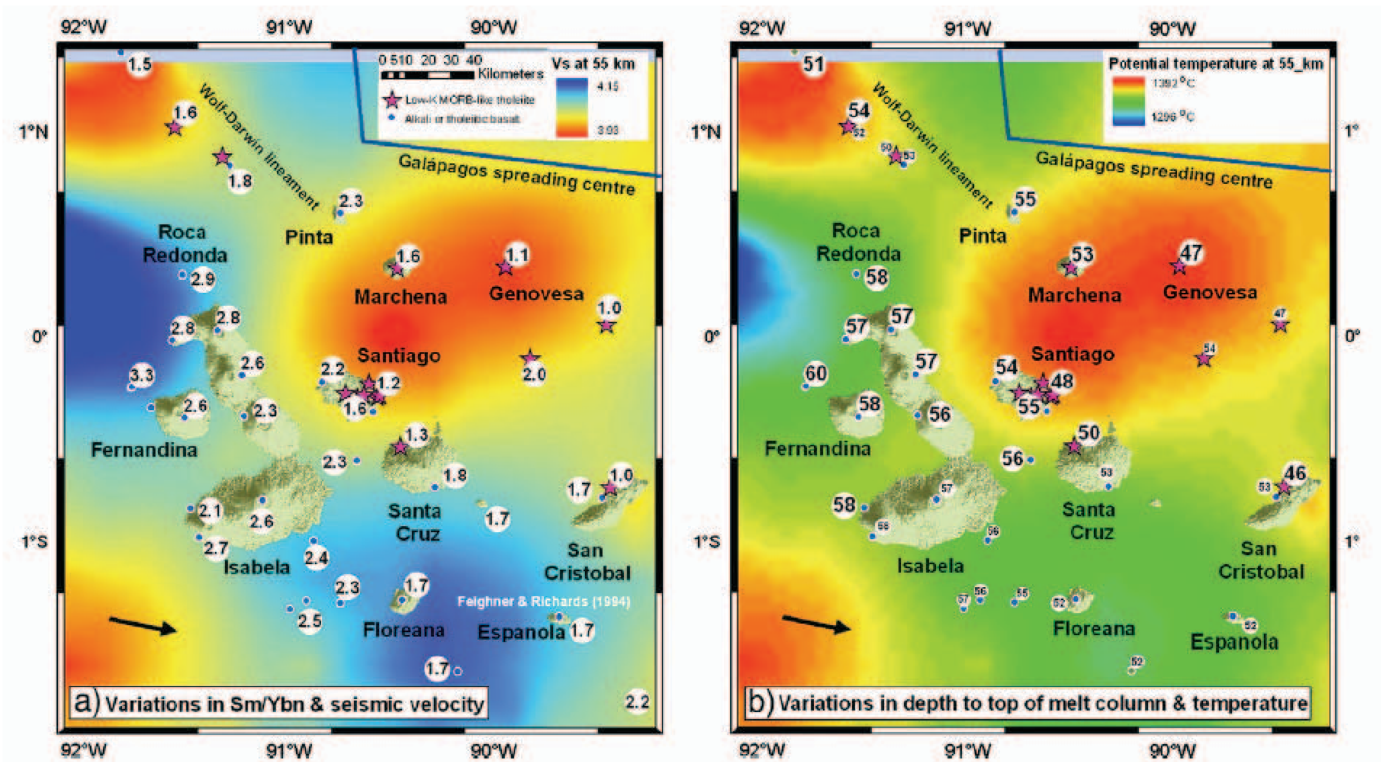


Fig. 8. Depth slice at 55 km below the Galápagos Archipelago showing: (a) Variation of V_s and observed $[Sm/Yb]_n$ ratios. (b) Mantle potential temperature, calculated from the V_s wave dataset of Villagomez et al. (2007) using the equations of Priestley and McKenzie (2006), together with estimates of depths to the top of melt columns (Table 1) predicted from rare-earth-element inversion modelling (numbers in large font) and parameterization of $[Sm/Yb]_n$ ratios (numbers in small font) using Eq. (1) given in the text. Solid black arrow shows the direction of motion of the Nazca plate.

Vs at 55 km depth
Sm/Yb ratios

Potential T &
REE inversion

Gibson and Geist, 2010

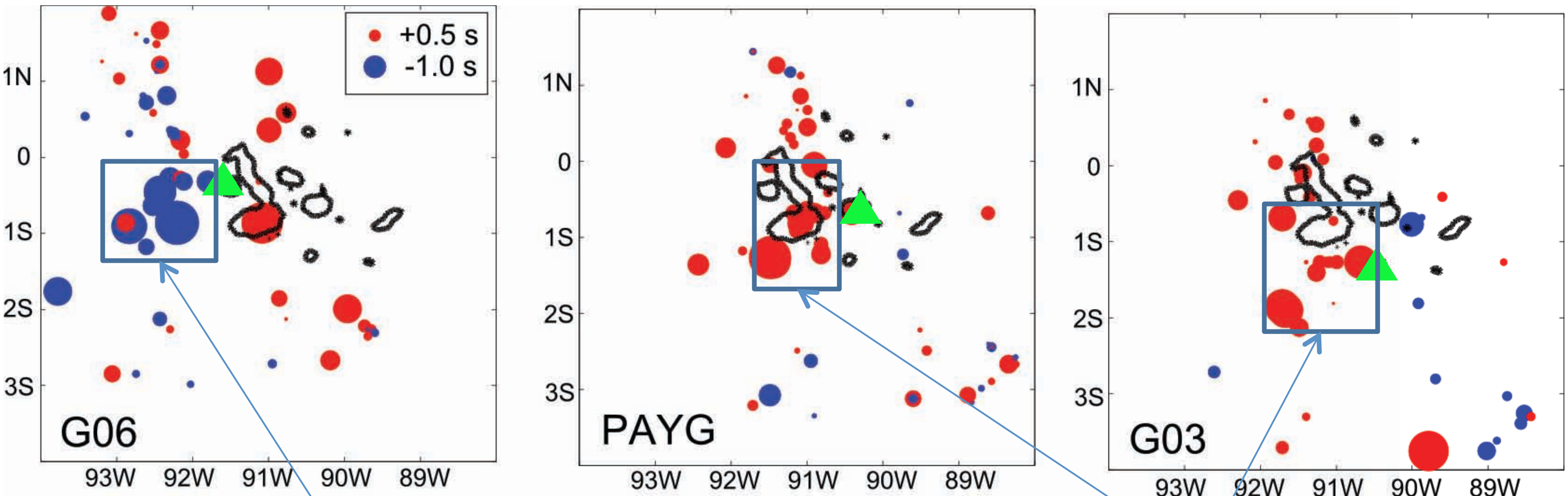
Downwelling

- Downwelling may play a suprising role in western Galapagos
- High velocity anomalies at depths of 100 to 300 km require a sinking thermal and/or compositional anomaly
- Is downwelling around the older margins of the archipelago contributing to secondary convection?
- What are the implications of downwelling for uplift history?

Body wave data

- S-wave data indicate there are 2 main regions of anomalous seismic velocity

Piercing point of seismic ray at 400 km depth



Region of anomalously early arrivals

Region of anomalously late arrivals

Villagomez et al., in prep.

Results of Joint Inversion:
High velocity anomalies

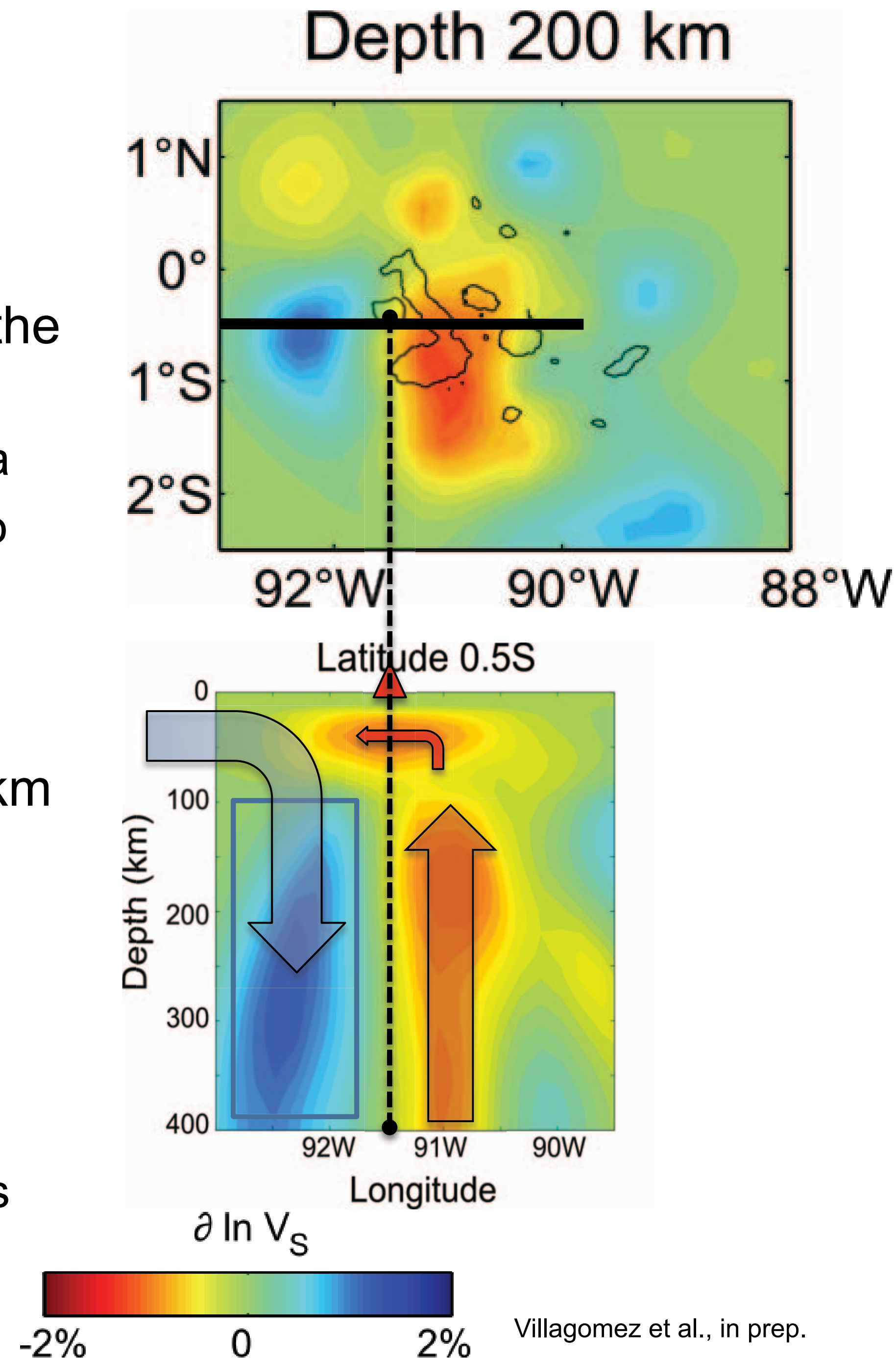
Higher than normal velocities located to the west of the archipelago

- Presence well supported by S-wave data
- Shape/extent not well constrained due to reduced number of crossing rays (future studies)

What increases velocities at 200 to 300 km depth?

- Colder temperatures
- Dehydrated mantle
- Depleted mantle

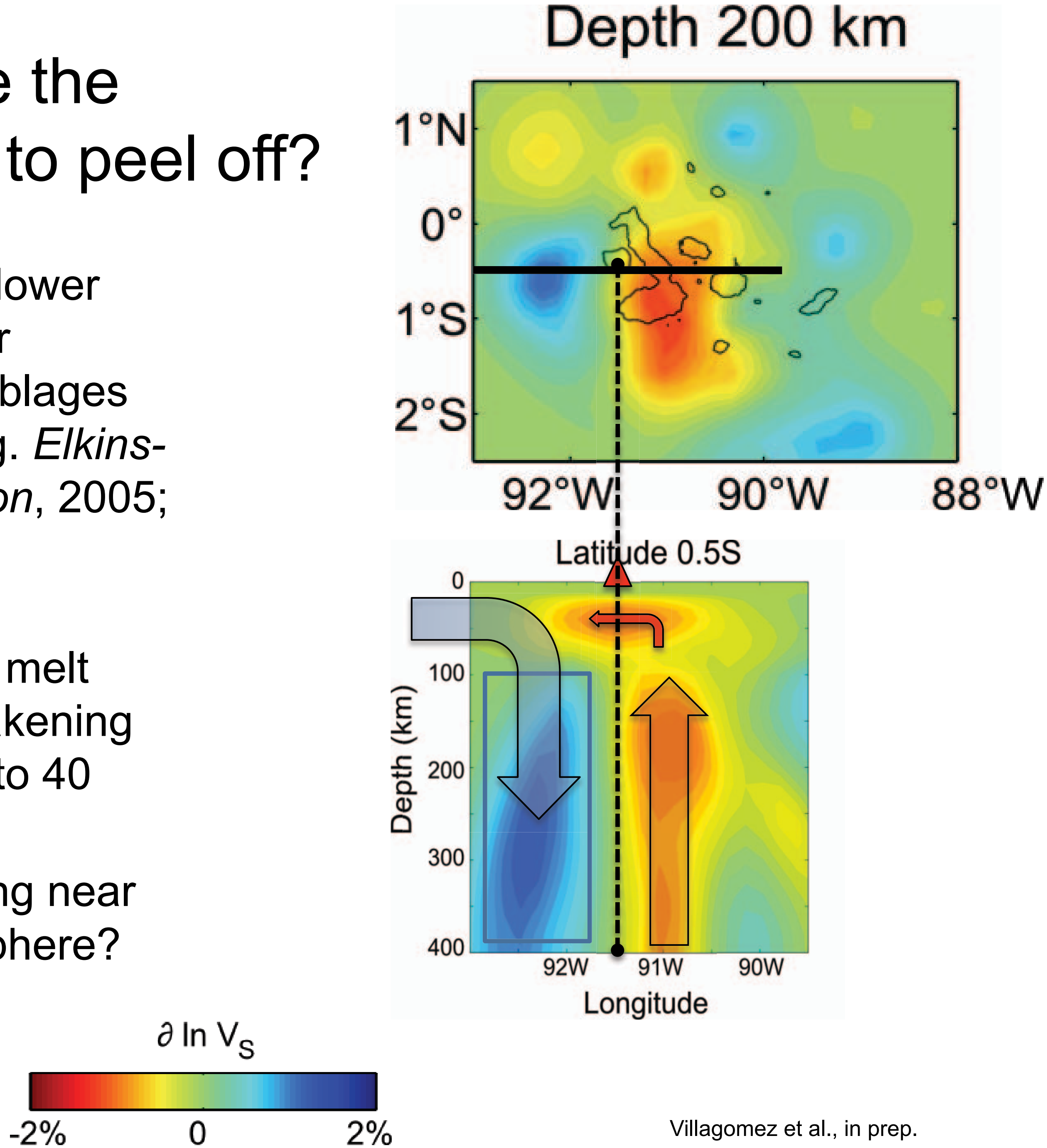
Implication: Lower part of boundary layer has peeled off…



Villagomez et al., in prep.

What could cause the lower lithosphere to peel off?

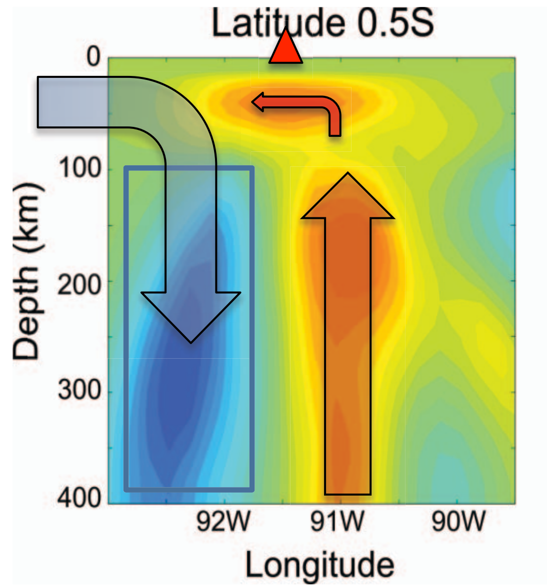
- Transformation of the lower lithosphere into denser eclogitic phase assemblages after melt injection [e.g. *Elkins-Tanton*, 2005; *Anderson*, 2005; *West et al.*, 2009]
- Region of mechanical delamination aided by melt accumulation and weakening at shallow depths (20 to 40 km)
- Does melt accumulating near base of thermal lithosphere?

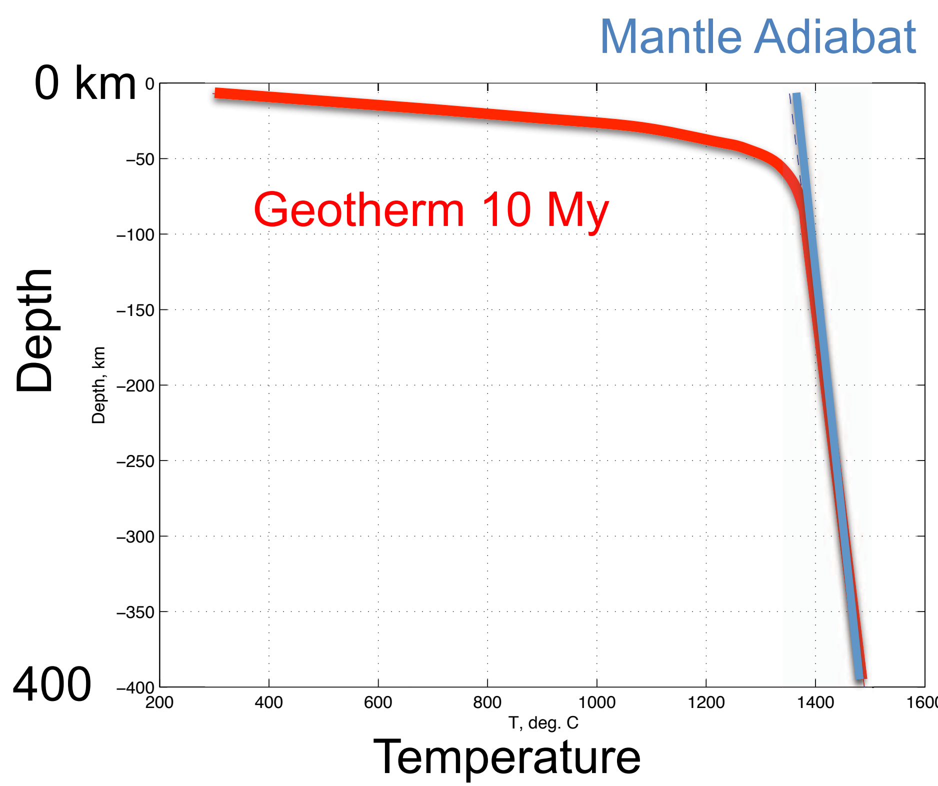


Villagomez et al., in prep.

Why would it sink?

- Lower part of thermal boundary layer is cooler than mantle adiabat (once it begins to sink, it is more dense than surroundings)
- Initiation of sinking could be result of melt impregnation at shallow depths (e.g. 20 to 30 km) and formation of eclogite
- 30 km depth is likely subsolidus
- It's embarrazada!





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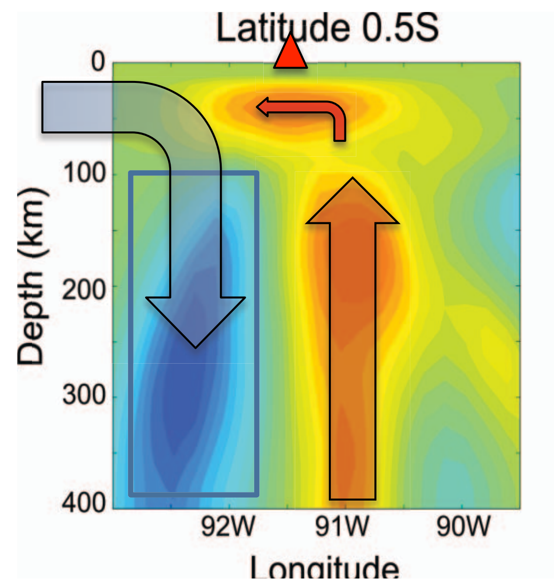
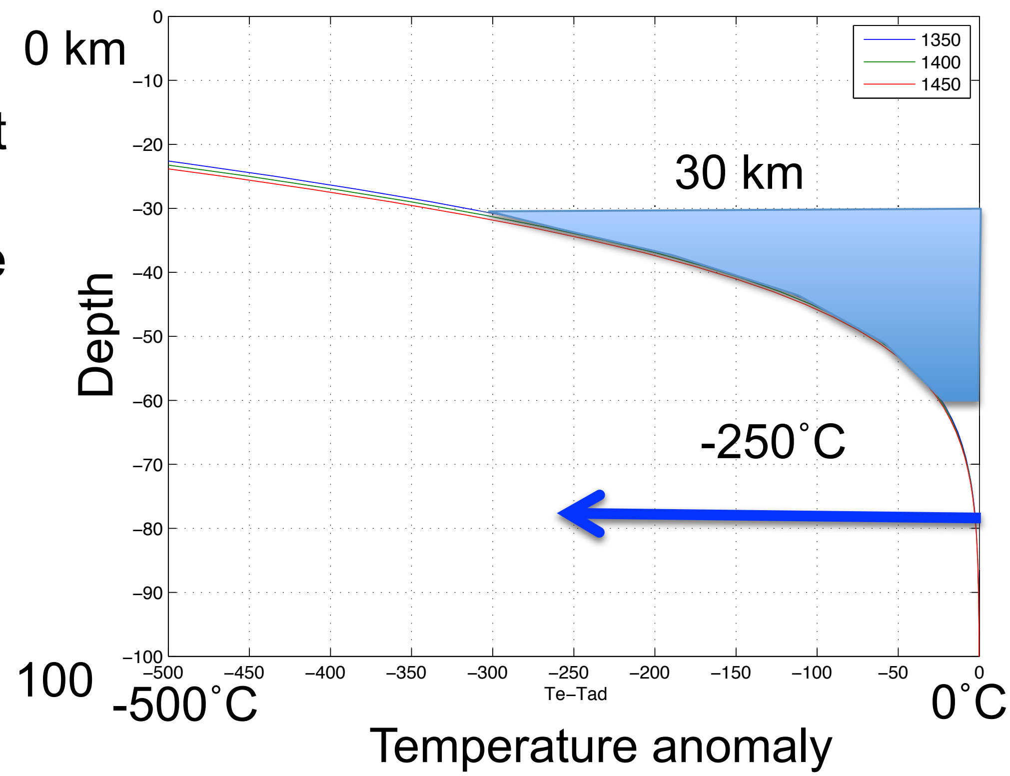
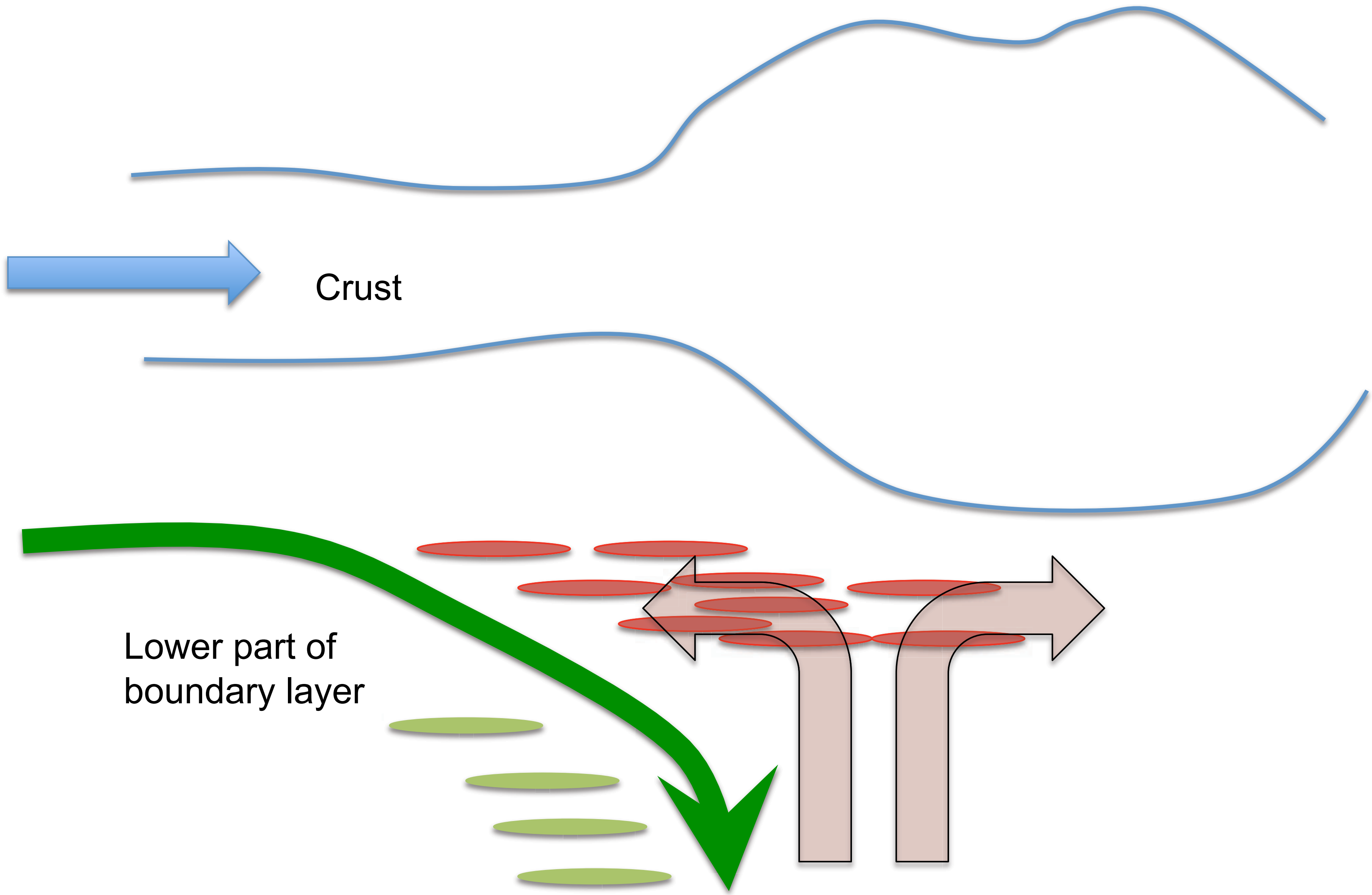




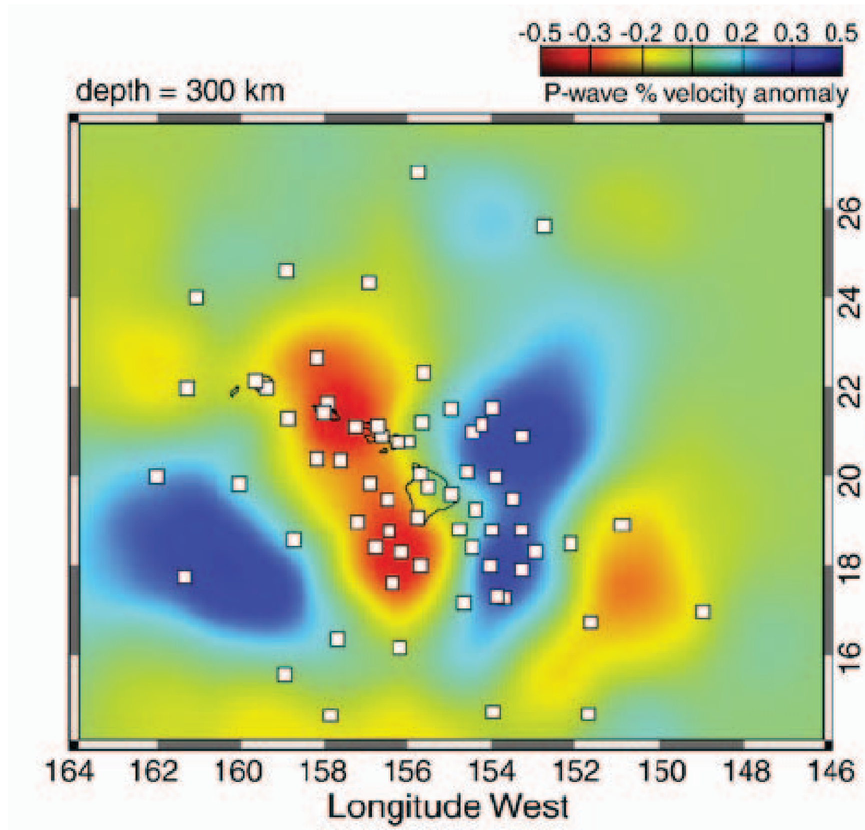
Villagomez et al., in prep.

Is leading edge affected by wedge dynamics?



Hawaii

- A parabola of high velocities has also been observed at 300 km depth
- Inferred to be a curtain of downwelling, possibly mechanically eroded lithosphere



Wolfe et al., 2011

Concluding thoughts

- Future
  - Synthesis
  - Problems of scale
    - relating large to small or coarsely resolved to finely resolved
  - Community Experiments

Synthesis

Observations

- Surface geology
- Geochemical/petrological
- Geophysical

Testing and Refinement

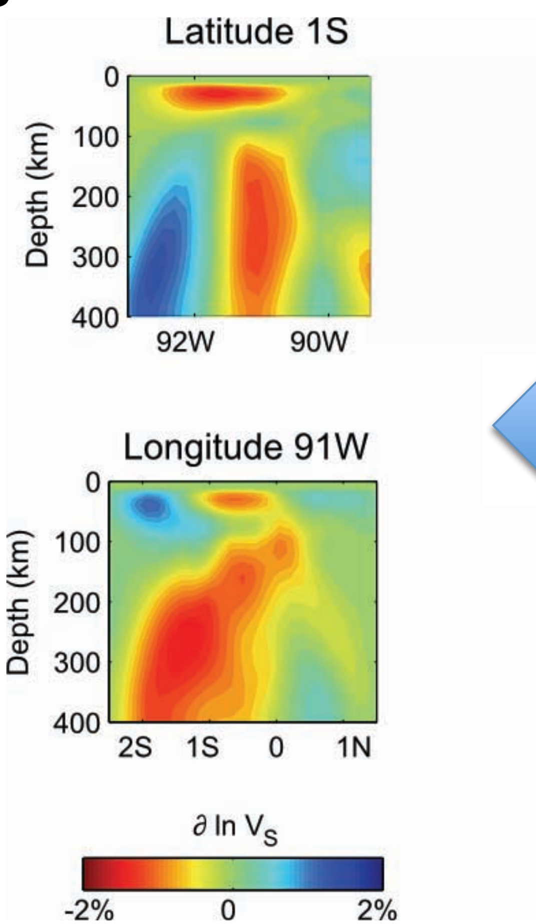
- Geo(petro)dynamic models of mantle flow and melt generation
- Lab based predictions of silicate melting

Some cross-disciplinary topics

- What is the rheology of the asthenophere?
- What is the lithosphere-asthenosphere boundary?
- Which models of mantle flow and melt transport are consistent with the suite of observations?
- Are surface processes affected by upwelling/downwelling (e.g., uplift history)?

Problems of Scale

Larger scale



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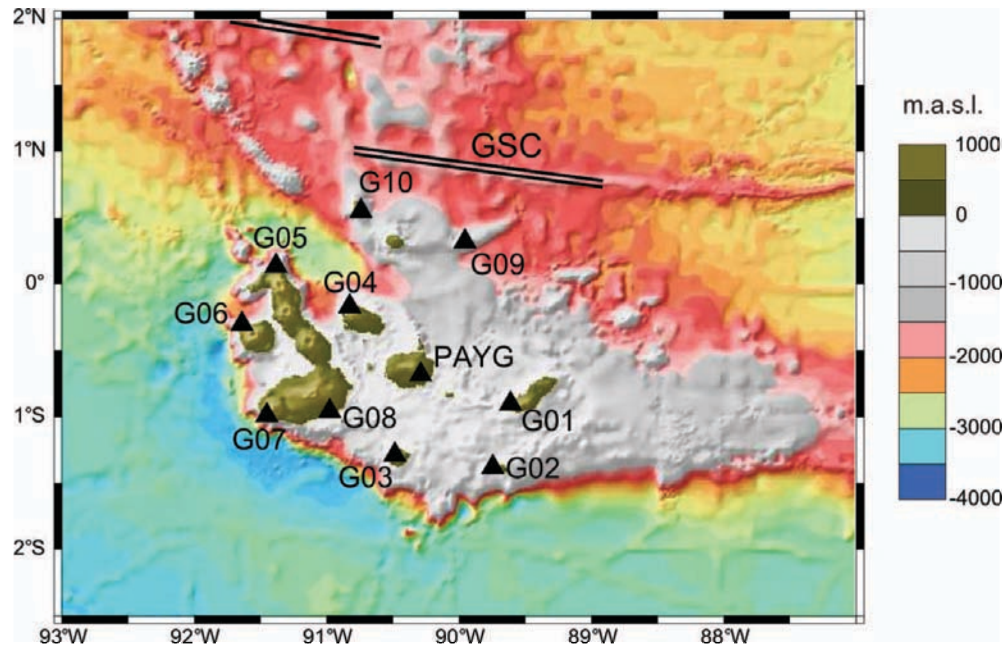
Volcano scale

There is a hidden zone between the upper crustal magma body and 20 km depth

Community Experiments

Missing and crucial data

- Crustal and mantle structure off the archipelago
  - Plume-ridge connection is not constrained geophysically
  - What is the structure of crust and mantle prior to plume?
  - Better constraints on downwelling



Why is the Galápagos a Natural Laboratory?

- Located 100-200 km south of the Galápagos Spreading Center (GSC)
- Sits on thin and young lithosphere of Nazca Plate (5-20 My old, 30-60 km thick)
- Nazca plate moves eastward with respect to the hotspot
- Lava geochemistry from ocean island basalts (OIB) to mid-ocean ridge basalts (MORB)
    - Distinct geographical pattern [*Geist et al.,* 1988; *White et al*., 1993, *Harpp and White*, 2001].