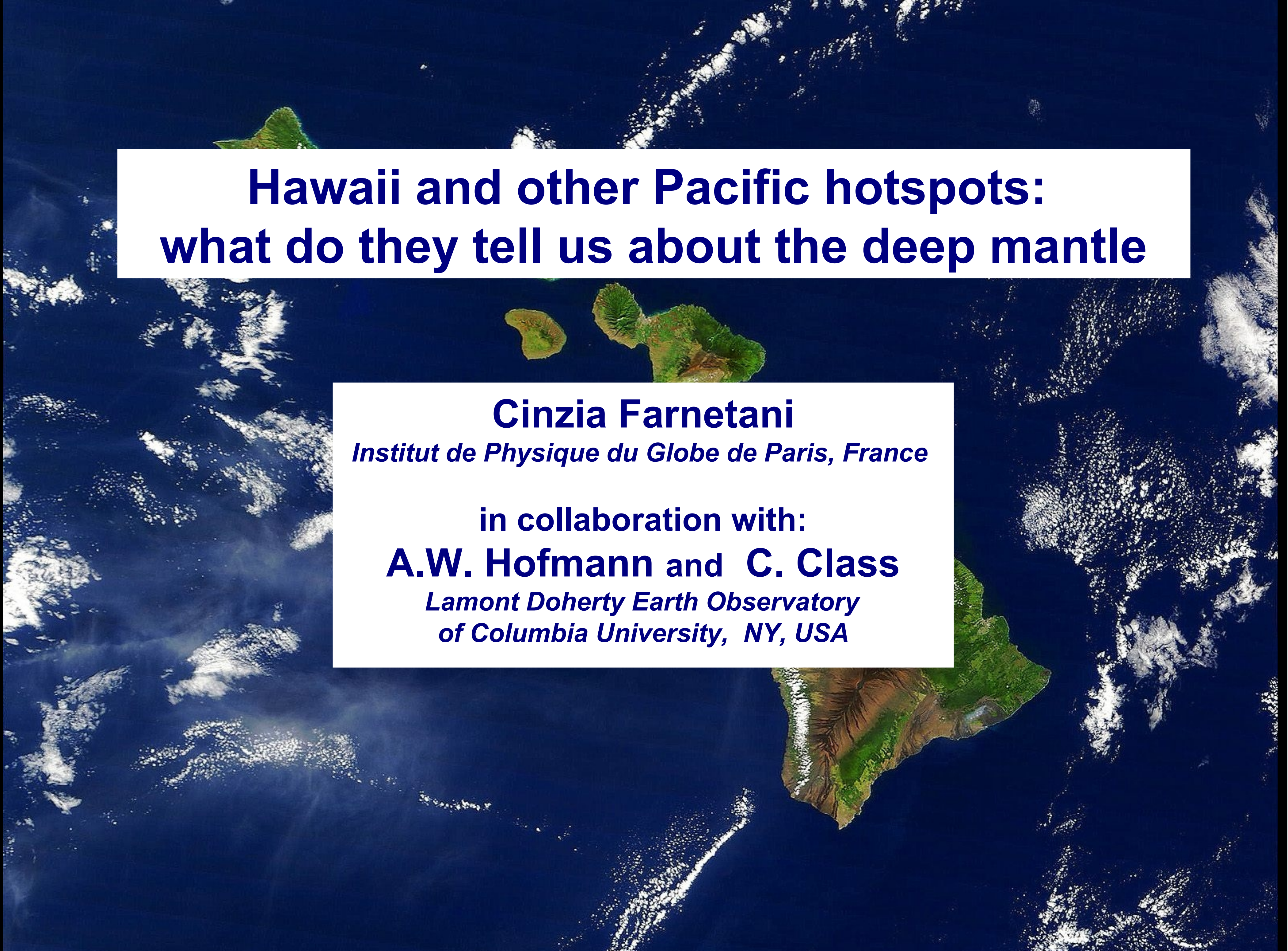


Hawaii and other Pacific hotspots: what do they tell us about the deep mantle

Cinzia Farnetani

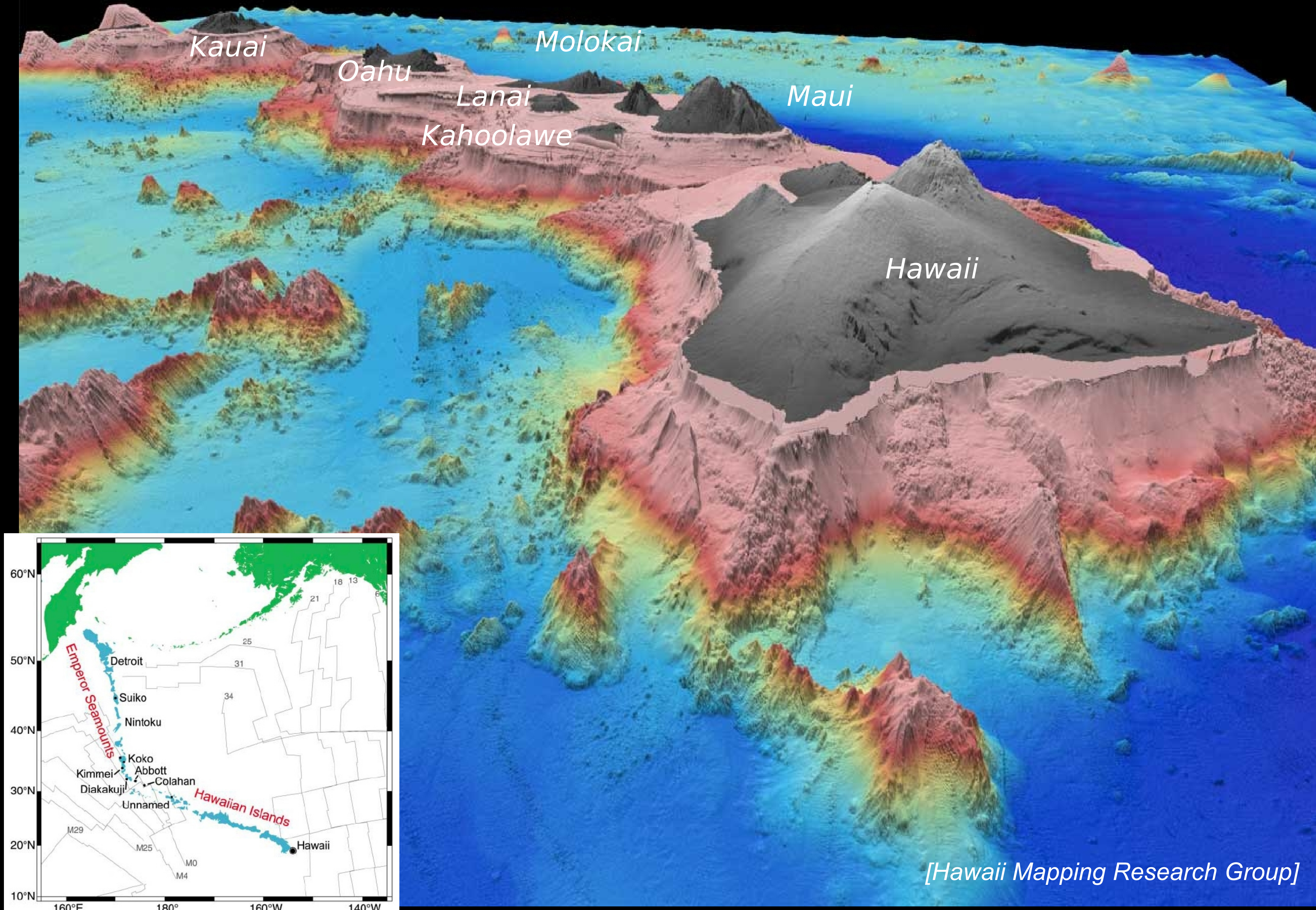
Institut de Physique du Globe de Paris, France

in collaboration with:

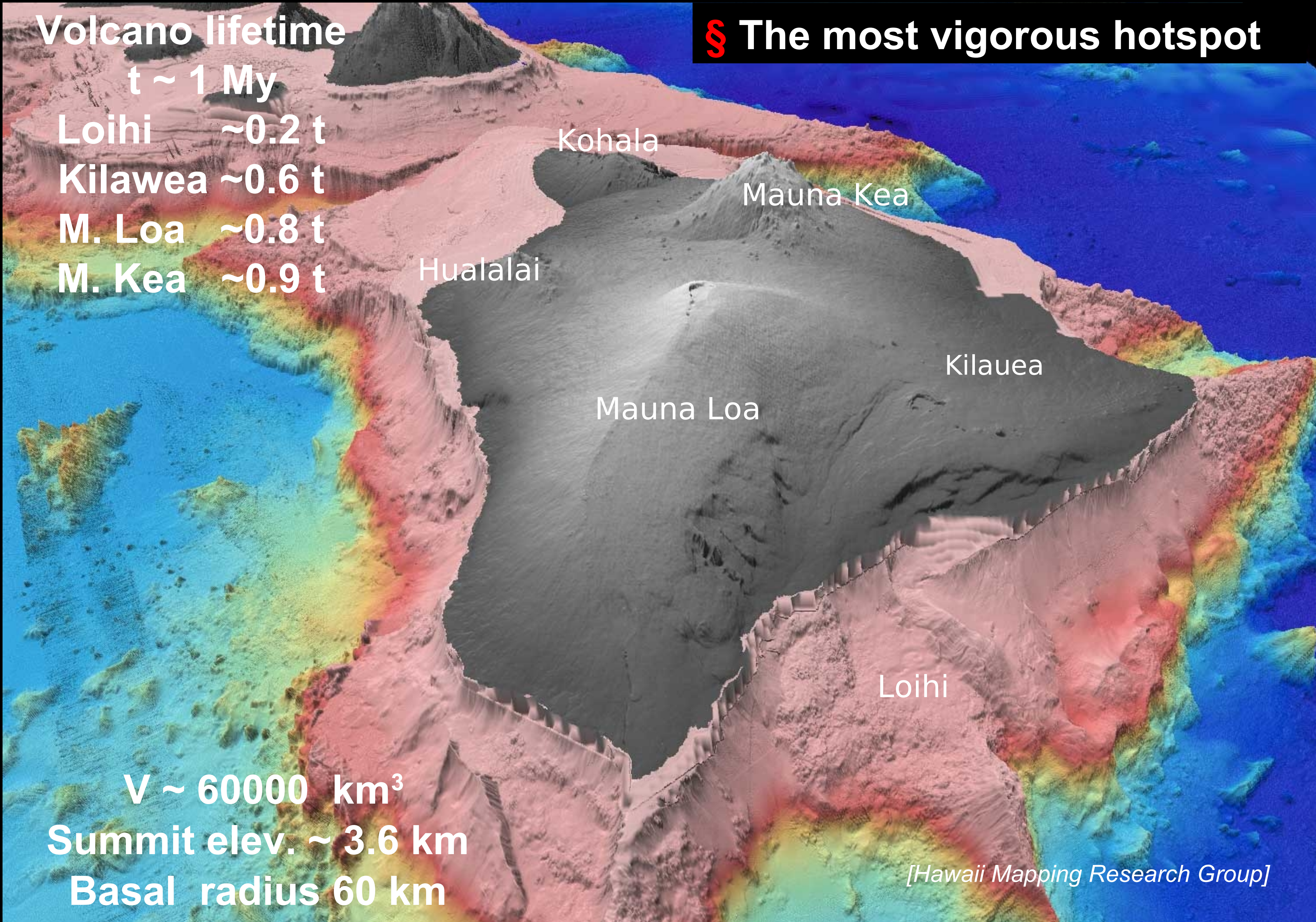
A.W. Hofmann and C. Class

Lamont Doherty Earth Observatory of Columbia University, NY, USA

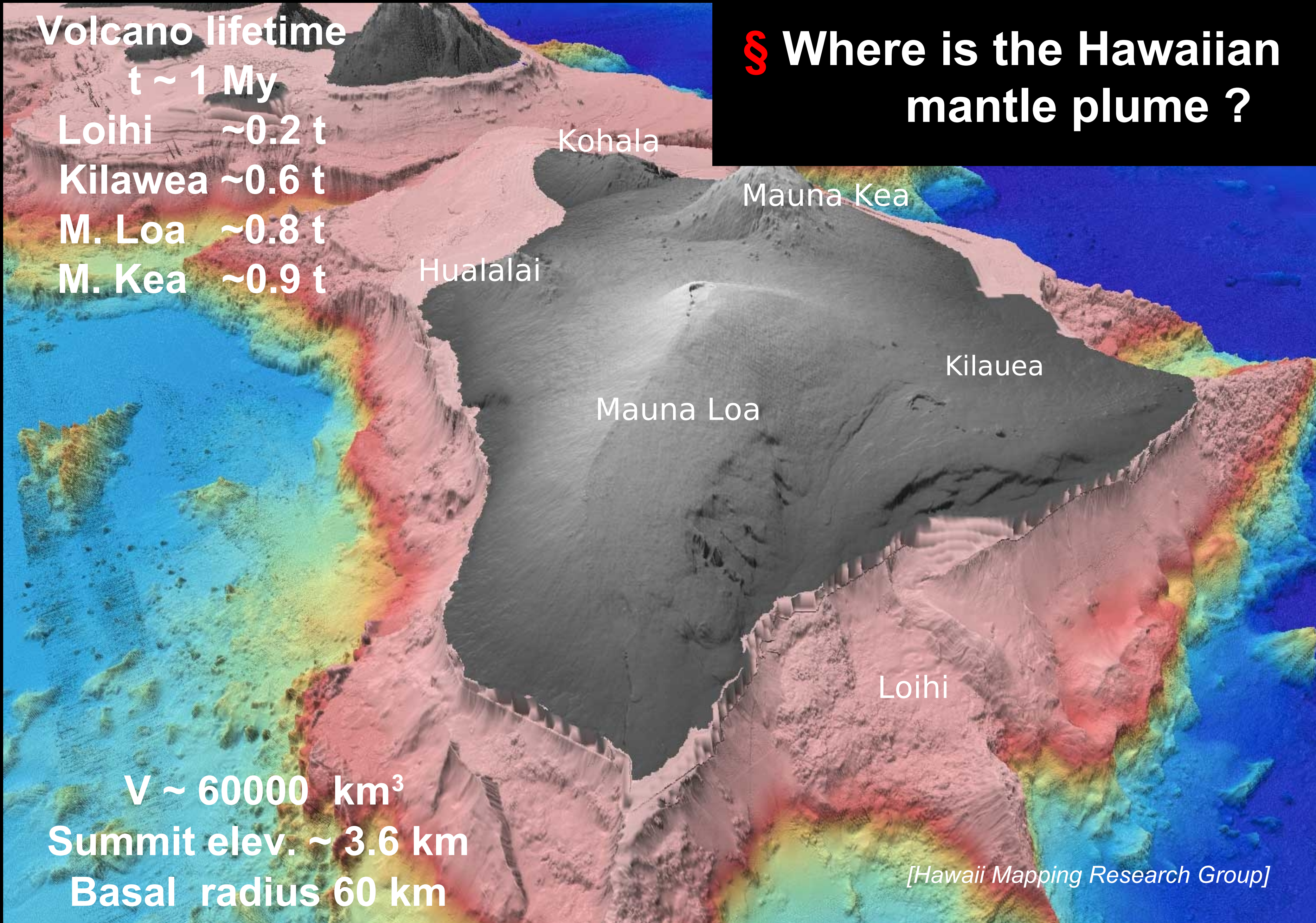
§ The hawaiian hotspot : a long-lasting intraplate magmatism



§ The most vigorous hotspot



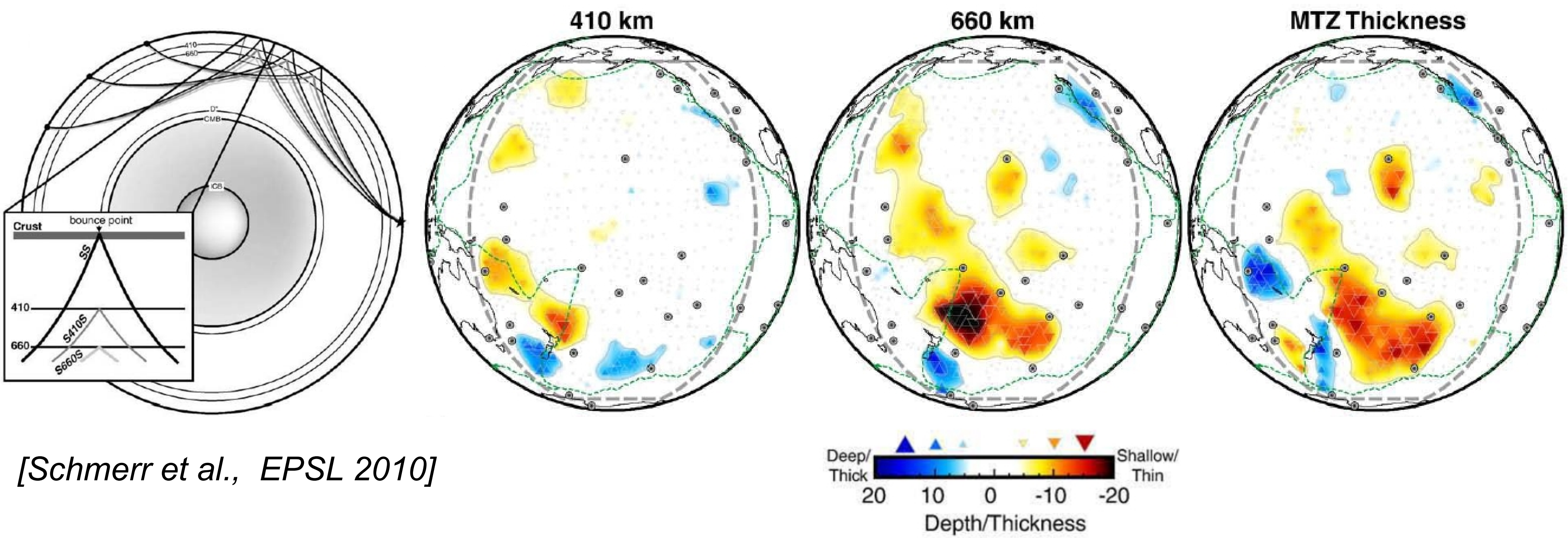
§ Where is the Hawaiian mantle plume ?



Deep mantle plumes and convective upwelling beneath the Pacific Ocean

Nicholas Schmerr [a,b,*], Edward Garnero [b], Allen McNamara [b]

[a] Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Brand Road NW, Washington, DC 20015, USA
[b] School of Earth and Space Exploration, Arizona State University, P.O. Box 874104, Tempe, AZ 85287, USA



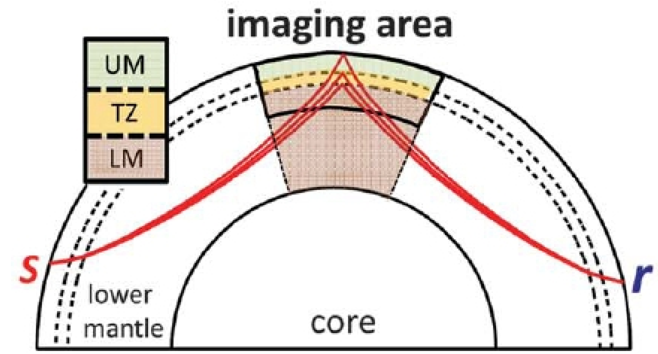
[Schmerr et al., EPSL 2010]

Use SS precursors to map the thickness of the transition zone

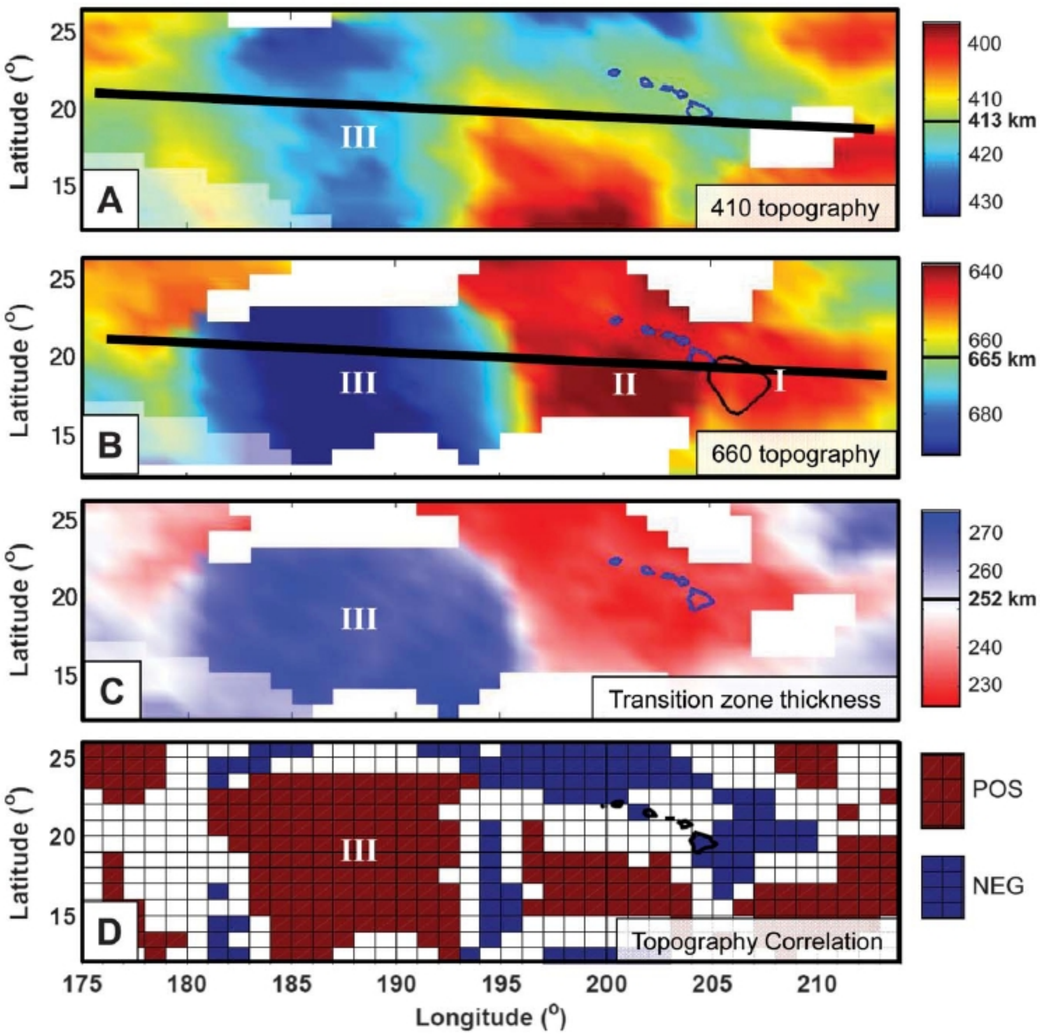
They find a thinned transition zone South of Hawaii

Seismic Imaging of Transition Zone Discontinuities Suggests Hot Mantle West of Hawaii

Q. Cao,[1]* R. D. van der Hilst,[1]* M. V. de Hoop,[2] S.-H. Shim[1]



Underside reflection of SS



[Cao et al., Science, 2011]

In a hot plume we expect:

a deeper 410 (blue)

a shallower 660 (red)

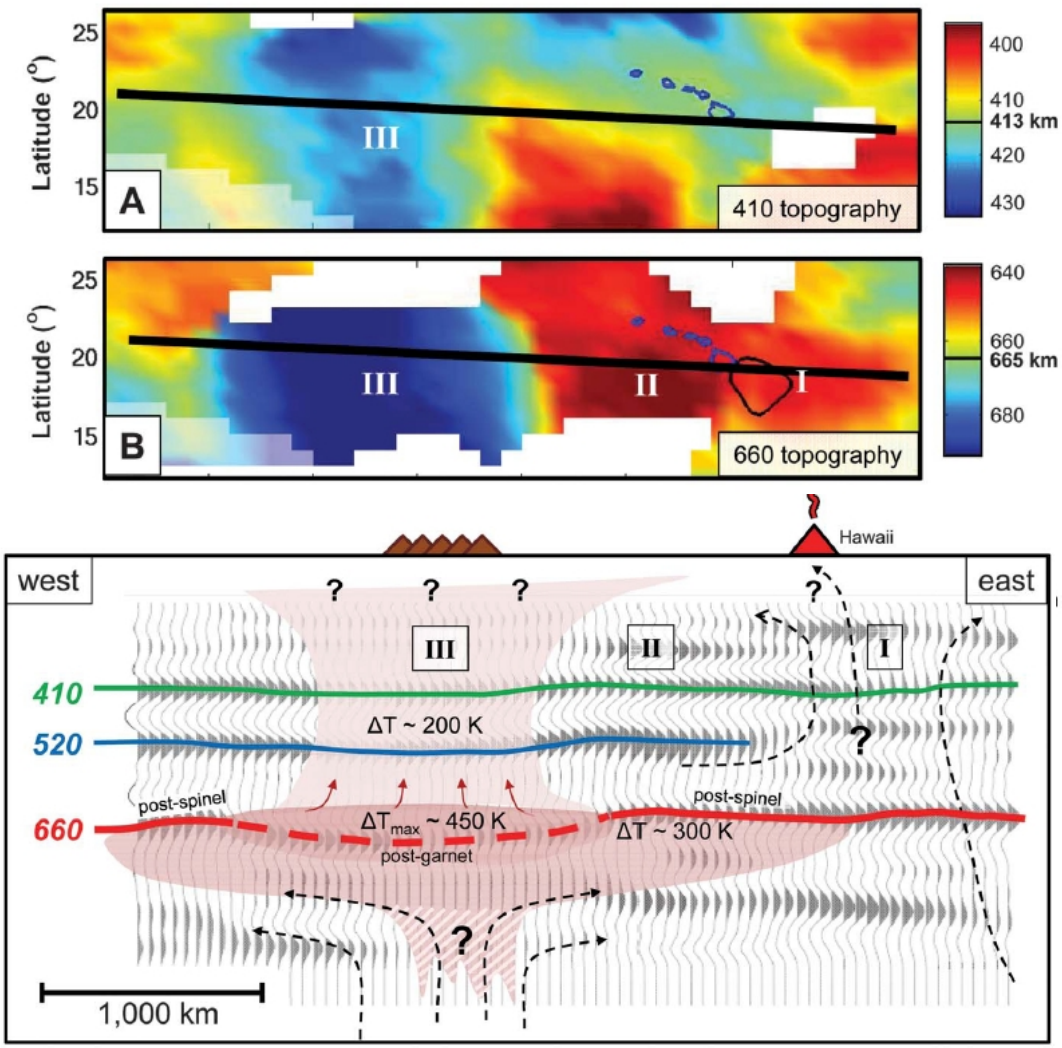
a thin transition zone (red)

a negative correlation

The zone SE of Hawaii satisfies the above criteria.....

Seismic Imaging of Transition Zone Discontinuities Suggests Hot Mantle West of Hawaii

Q. Cao,[1*] R. D. van der Hilst,[1*] M. V. de Hoop,[2] S.-H. Shim[1]



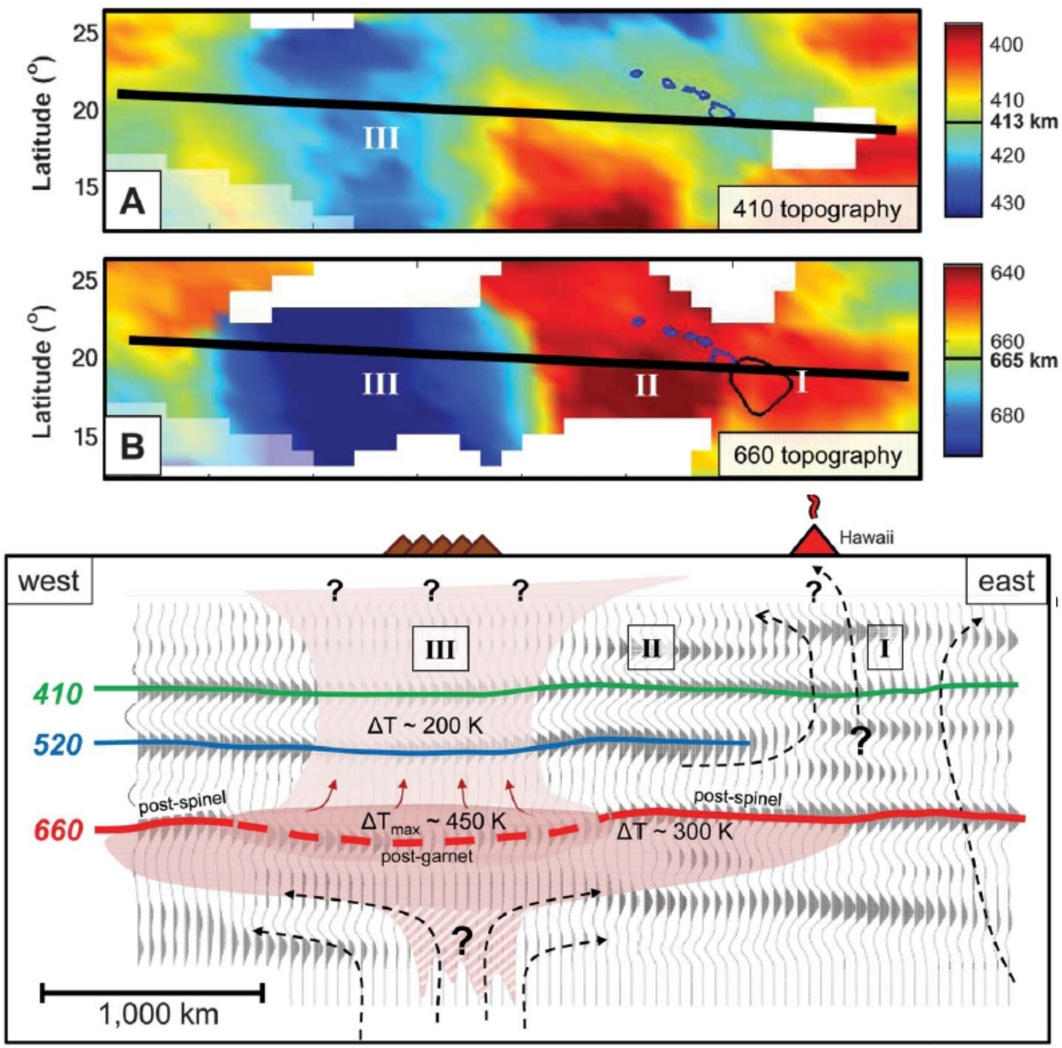
However, according to Cao et al., the 'feeding zone' of the Hawaiian plume is displaced ~1500 km to the West, (i.e., zone III).

The 660km is deeper because of the majorite garnet-perovskite transition.

Surface lavas cannot be used to map geochemical domains in the lower mantle !

Seismic Imaging of Transition Zone Discontinuities Suggests Hot Mantle West of Hawaii

Q. Cao,[1]* R. D. van der Hilst,[1]* M. V. de Hoop,[2] S.-H. Shim[1]



Some warnings :

1) Do seismologists agree with Cao et al. analysis ?

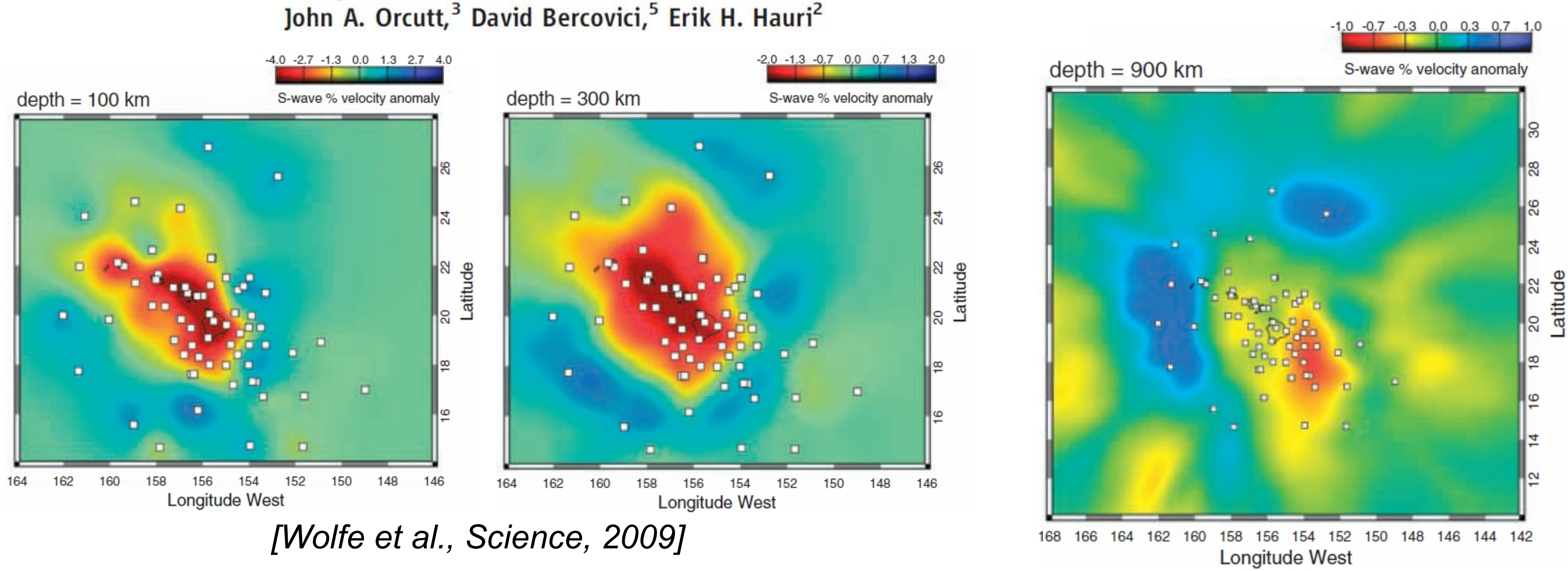
2) The dynamics is missing.

How to physically connect the ponded material to the zone of active volcanism ?

How to explain the high Hawaiian buoyancy flux (B~8000 kg/s) ?

Mantle Shear-Wave Velocity Structure Beneath the Hawaiian Hot Spot

Cecily J. Wolfe,[1]* Sean C. Solomon,[2] Gabi Laske,[3] John A. Collins,[4] Robert S. Detrick,[4] John A. Orcutt,[3] David Bercovici,[5] Erik H. Hauri[2]

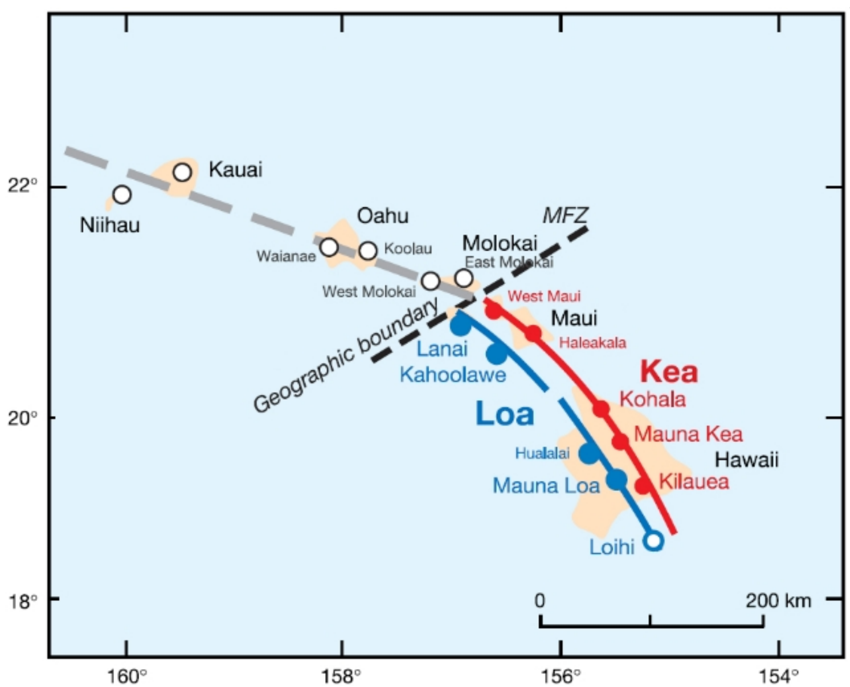


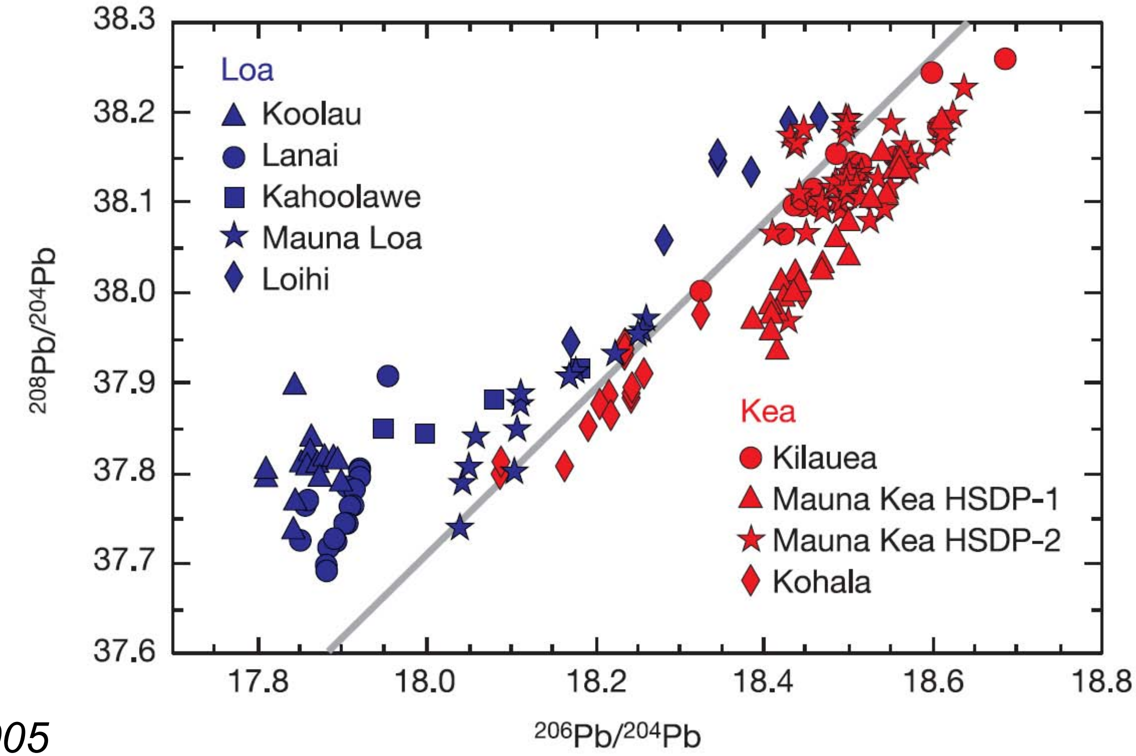
[Wolfe et al., Science, 2009]

- Depth< 400km: low-velocity anomaly elongated in the direction of the island chain
- 400- 660 km: low velocities continue downward
- 900-1500 km : low velocities, over a region several hundred-kilometer-wide, **southeast of Hawaii : a continuous, tilted plume conduit.**

- Conclusions **confirmed by P-wave velocity structure** *[Wolfe et al., EPSL 2011].*

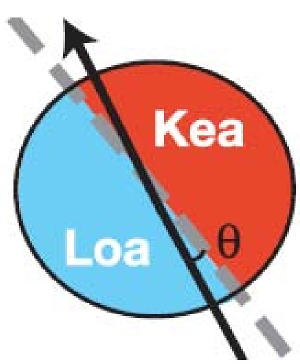
§ The two Hawaiian volcanic chains are geochemically distinct





extracted from: Abouchami et al., Nature, 2005

§ This suggests a 'bilateral' zonation of the plume conduit

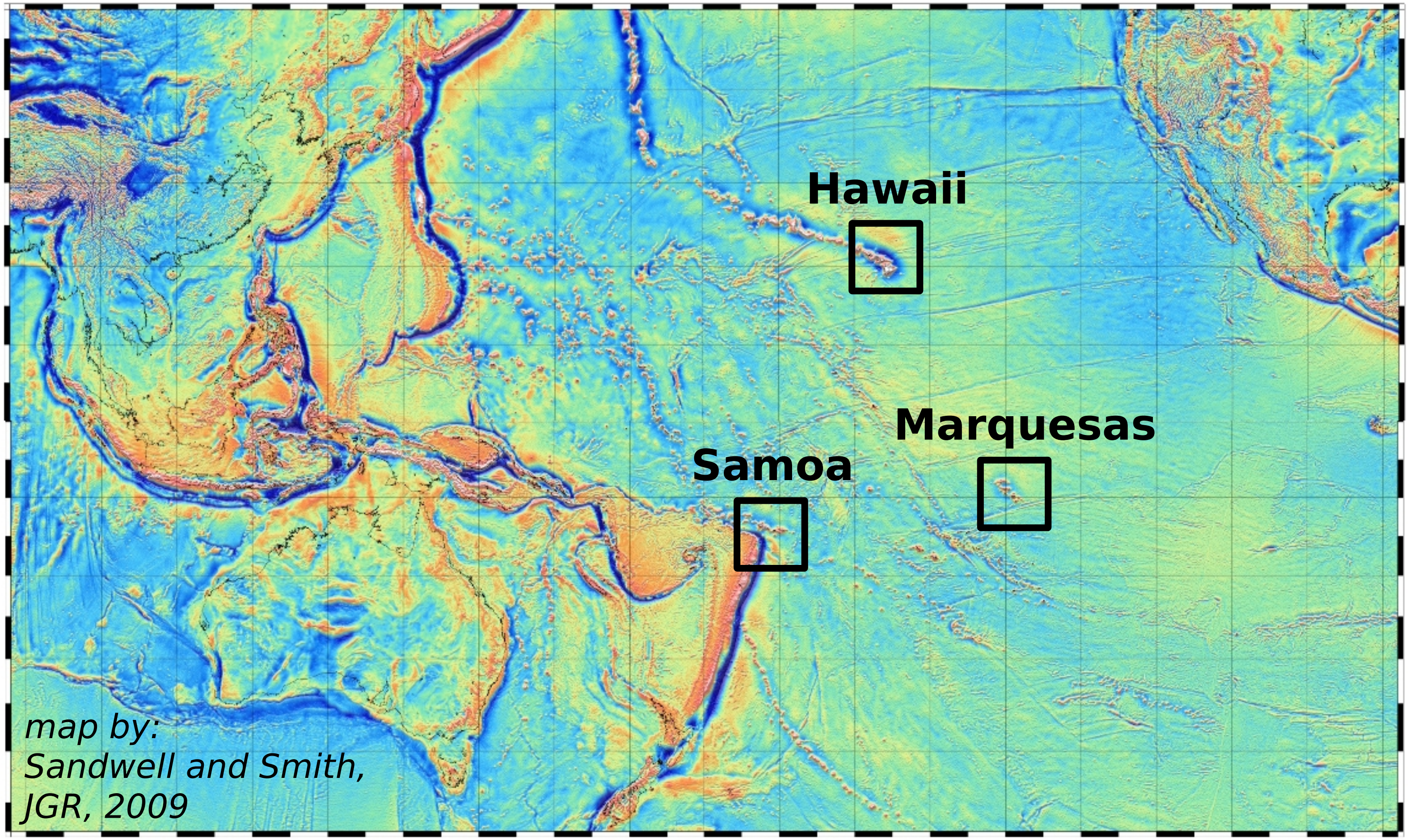


Loa type source: contains recycled crust and sediments

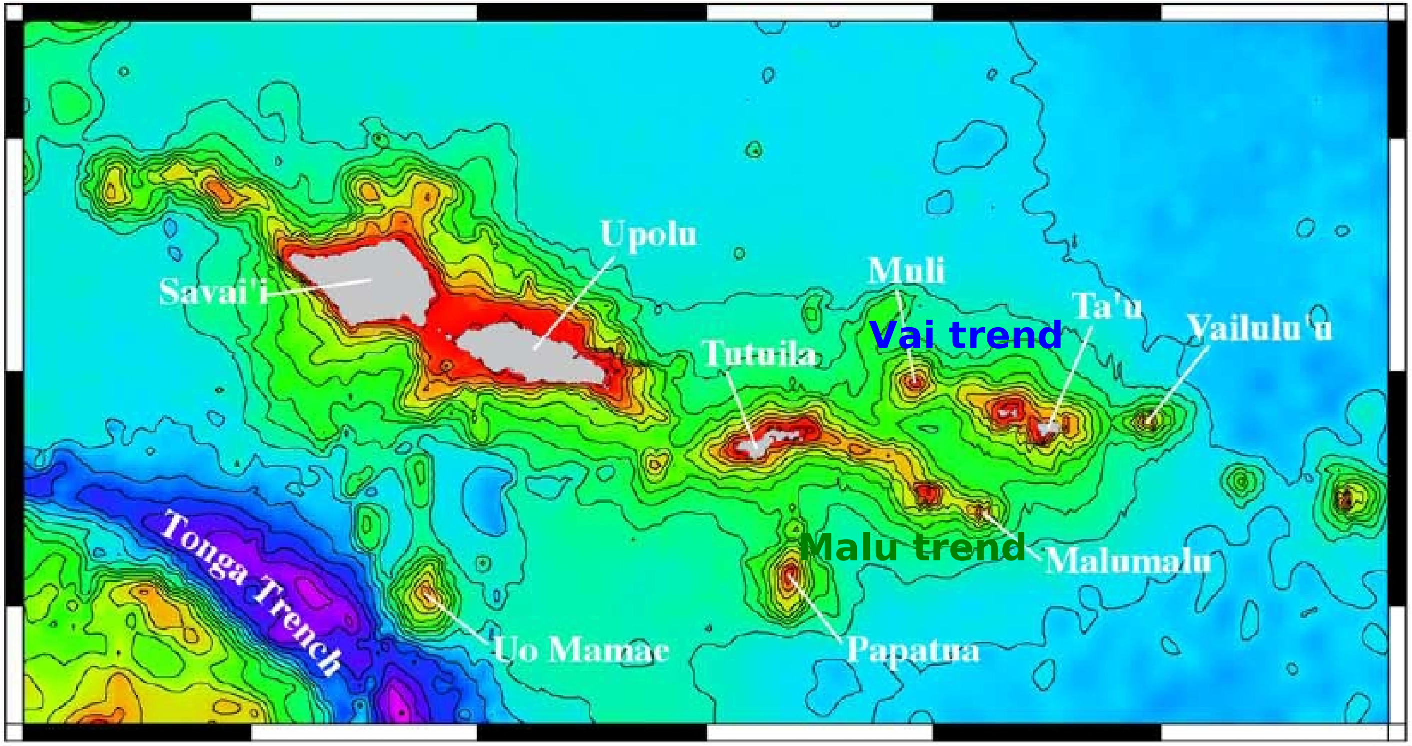
Kea type source: contains recycled lower oceanic crust and lithospheric mantle

§ The 'bilateral' zonation is NOT unique to Hawaii !

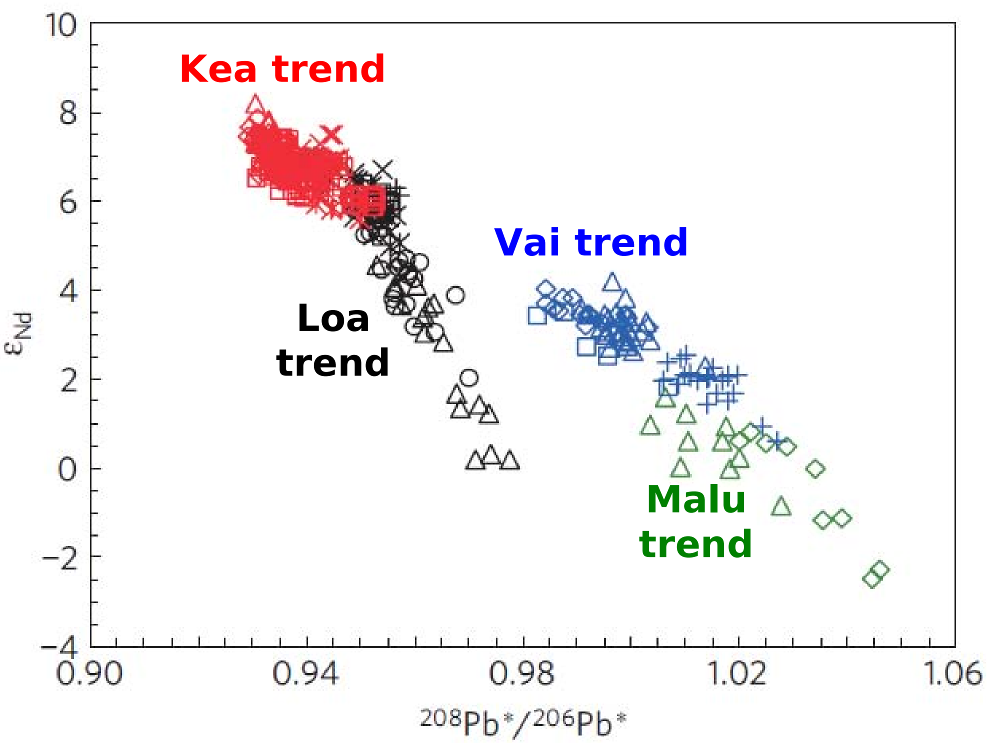
§ It is best revealed by parallel volcanic chains



Huang et al., 2011 **The bilateral zonation may well be a common feature of other Pacific hotspots.**



Hart et al., EPSL, 2004



Huang et al., Nature Geosc. 2011

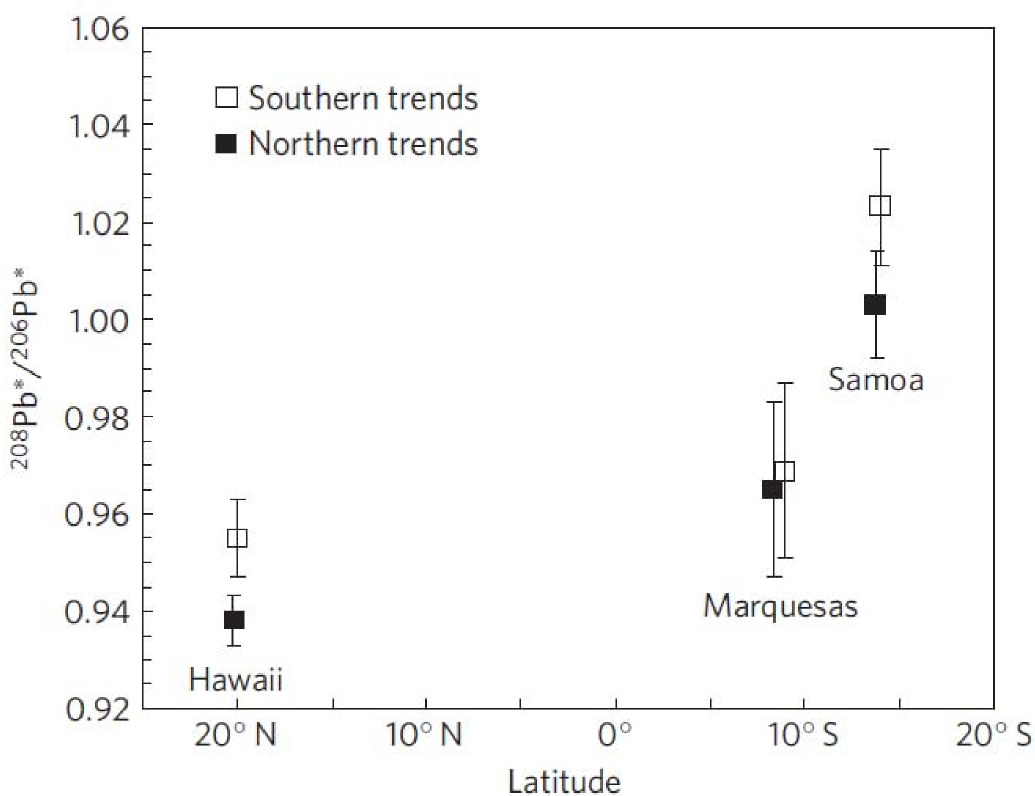
§ First observation :

For Hawaii and Samoa, the volcanic chain to the North (i.e., Kea, and Vai) has lower $^{208}Pb^*/^{206}Pb^*$ than the chain to the South (i.e., Loa, and Malu).

What is the 'radiogenic lead ratio' $^{208}Pb^{*} / ^{206}Pb^{*}$?

$$^{208}\mathrm{Pb}^{\star}/^{206}\mathrm{Pb}^{\star} = \frac{(^{208}\mathrm{Pb}/^{204}\mathrm{Pb})_{\mathrm{sample}} - (^{208}\mathrm{Pb}/^{204}\mathrm{Pb})_{\mathrm{primordial}}}{(^{206}\mathrm{Pb}/^{204}\mathrm{Pb})_{\mathrm{sample}} - (^{206}\mathrm{Pb}/^{204}\mathrm{Pb})_{\mathrm{primordial}}}$$

It reflects the ratio of $^{232}Th/^{238}U$ integrated over the Earth's history.



§ Second observation :

$^{208}Pb^{*}/^{206}Pb^{*}$ increases soutward, from Hawaii to Samoa

Huang et al., Nature Geosc. 2011

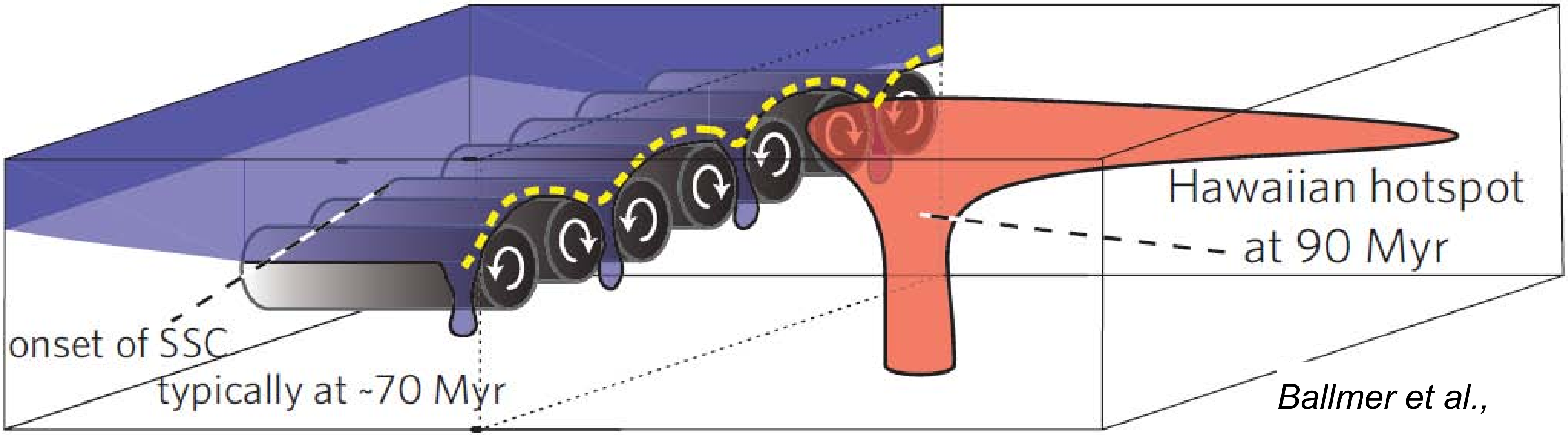
What is the origin of the isotopic difference between parallel volcanic chains ?

Opposing answers:

(i) Because of shallow, sublithospheric, melting processes.

(ii) Because of large-scale heterogeneities in the deep mantle.

'Shallow origin' models

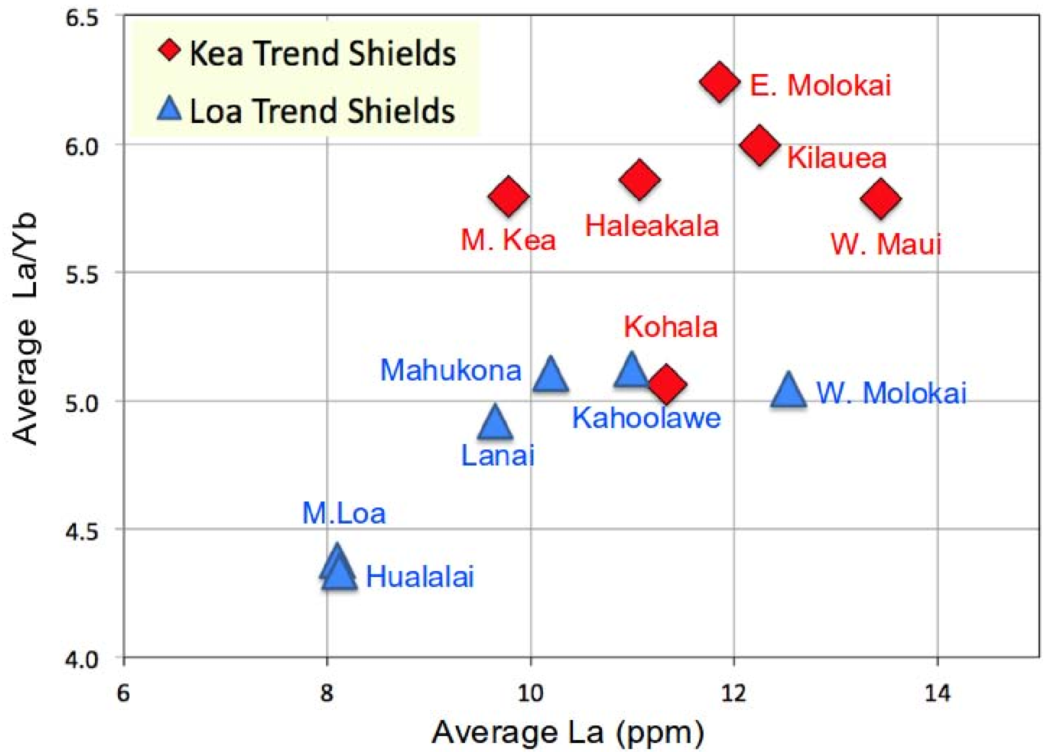


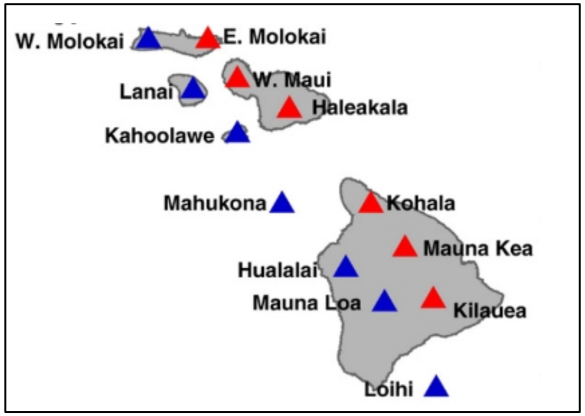
Ballmer et al., Nat. Geosc., 2011

- § The topographic relief at the base of the lithosphere induces differential melting beneath Kea and Loa-track volcanoes.
- § Plume: mixture of peridotite + fertile pyroxenite
- § A thinner lithosphere beneath the Kea-track causes higher melt fractions and more sampling of isotopically depleted peridotite.

Higher melt fraction for Kea-track volcanoes?
No. It is rather the opposite!

Hofmann, in prep. 2012





La *is inversely proportional to the melt fraction (F).*

La/Yb *is not significantly affected by fractional crystallization.*

At a given F, pyroxenite-derived melts should have higher La/Yb *than peridotite-derived melts.*

Kea-track volcanoes

Ballmer's model: thin lithosphere, high melt fractions, more sampling of peridotite.
Expect: low La, low La/Yb

Loa-track volcanoes

Ballmer's model: thick lithosphere, lower melt fractions, more sampling of pyroxenite
Expect: high La, high La/Yb

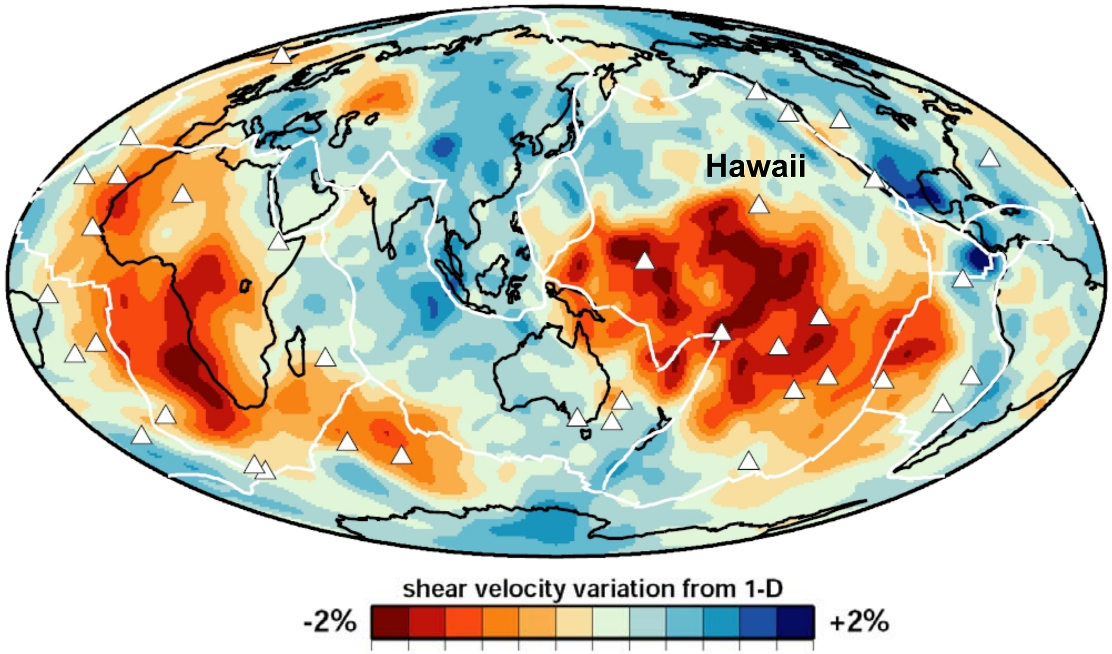
'Deep origin' models

- § **Look at seismic velocity anomalies in the lower mantle**

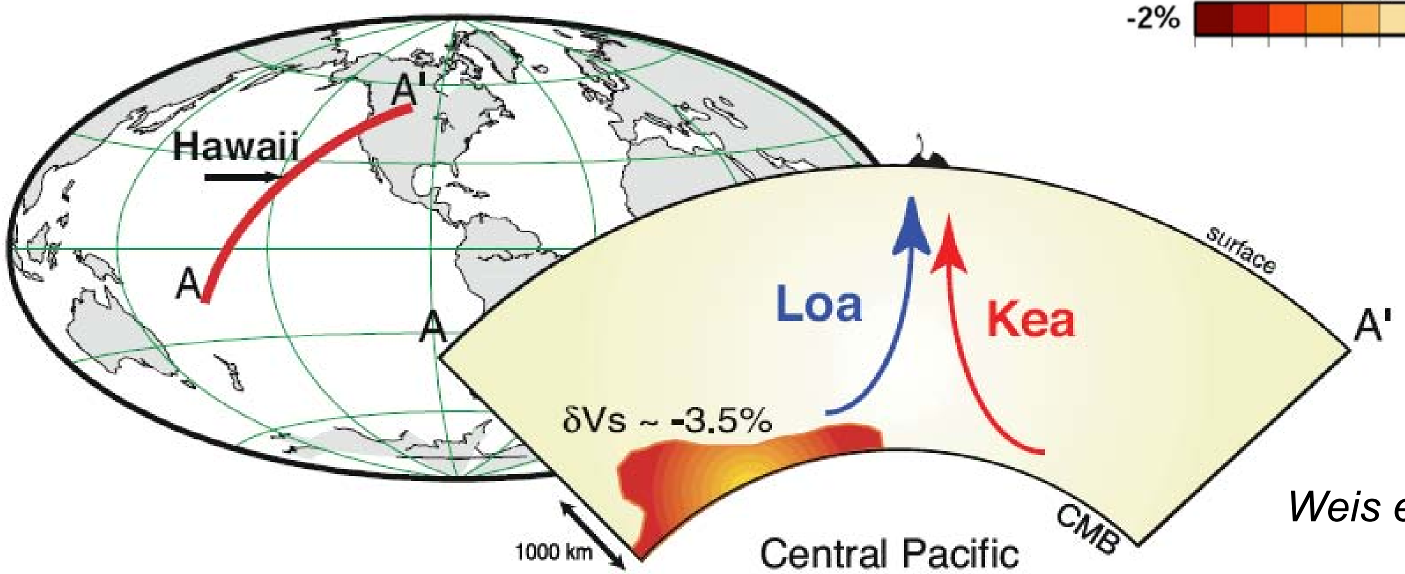
Weis et al., 2011

Loa side samples isotopically enriched material from the edge of the 'Large Low Shear Velocity Province'

At 2800 km depth



Ritsema et al., 2010



Weis et al., Nature Geosc., 2011

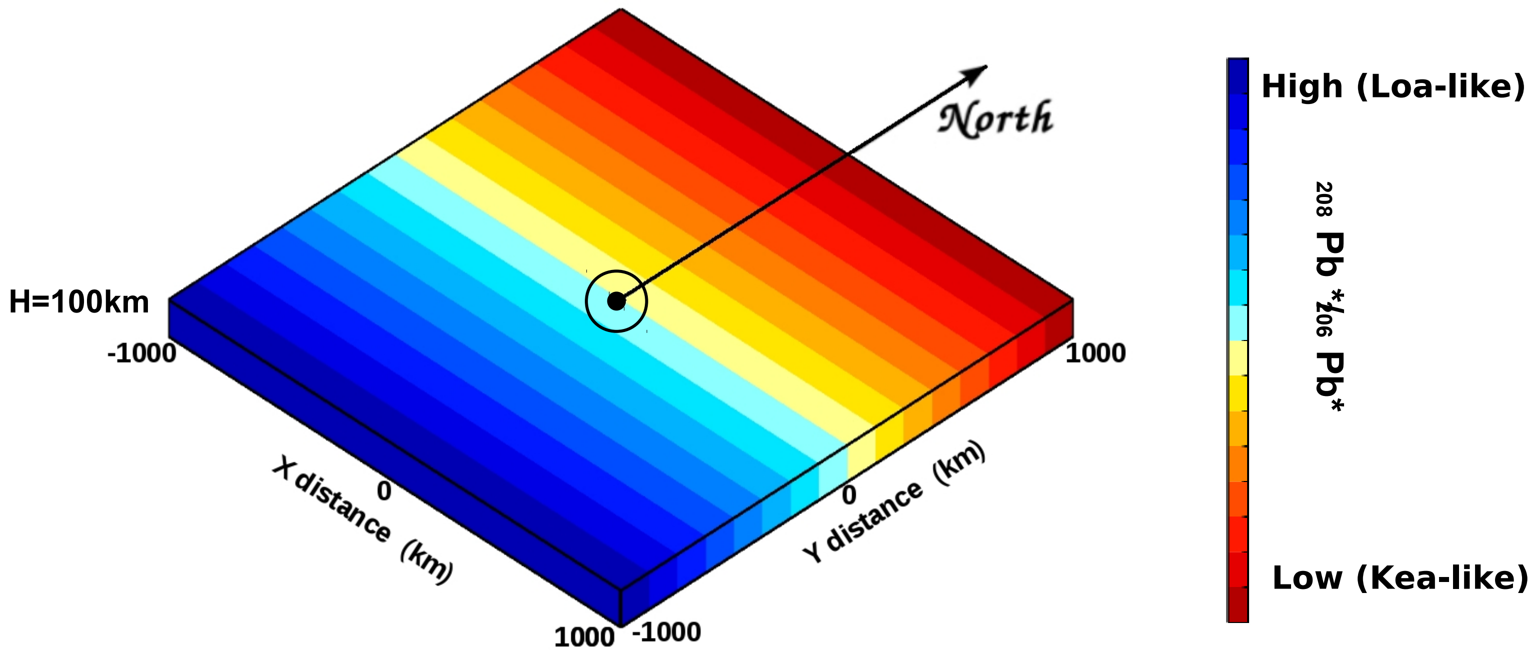
What is the origin of the isotopic difference between parallel volcanic chains ?

- § **Large-scale heterogeneities in the deep mantle.**

- § **The geochemical province known as 'DUPAL anomaly'** ***[Dupré and Allègre, 1983; Hart, 1984]*** **has been correlated with the Large Low Shear Velocity Province** ***[e.g., Castillo, 1988].***

Here we ask the following questions:

- If there is a North-South increase in $^{208}Pb^*/^{206}Pb^*$ across the TBL, what is the resulting plume conduit structure ?
- Can this explain the bilateral nature of the Hawaiian plume ?
- Can we predict the $^{208}Pb^*/^{206}Pb^*$ variability of Hawaiian lavas ?

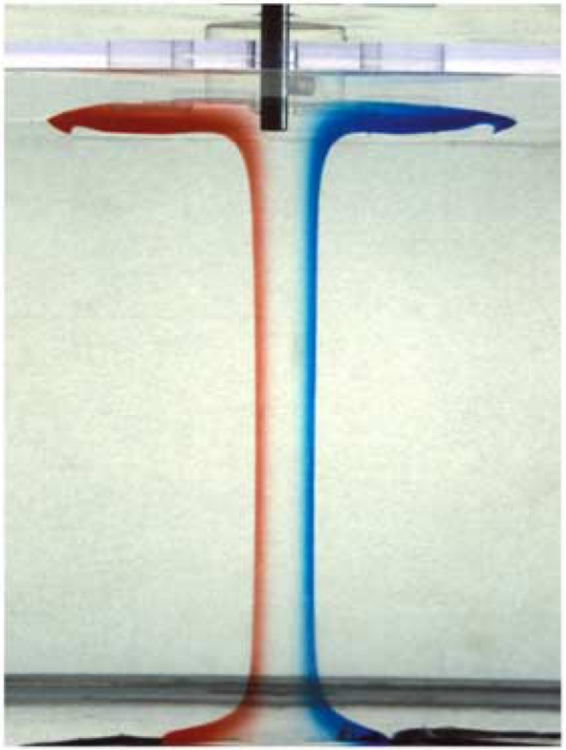


[Farnetani, Hofmann, Classs, in press EPSL, 2012]

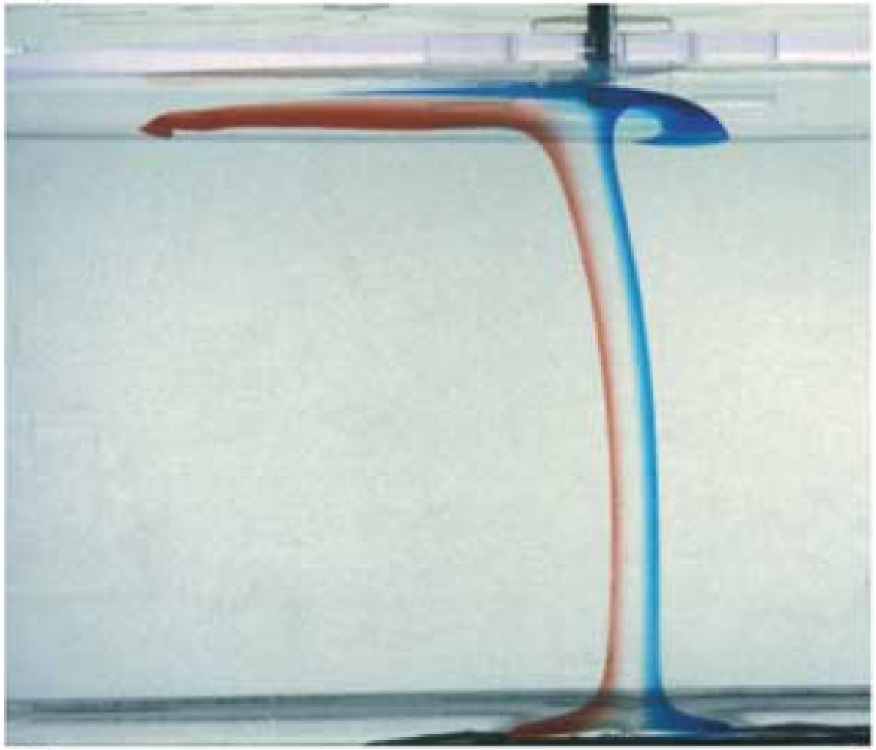
Answering these questions requires some fluid dynamics

§ **Laboratory experiments** *[Kerr and Mériaux, 2004]* **concluded that the Hawaiian plume should be azimuthally zoned**

Without surface shear



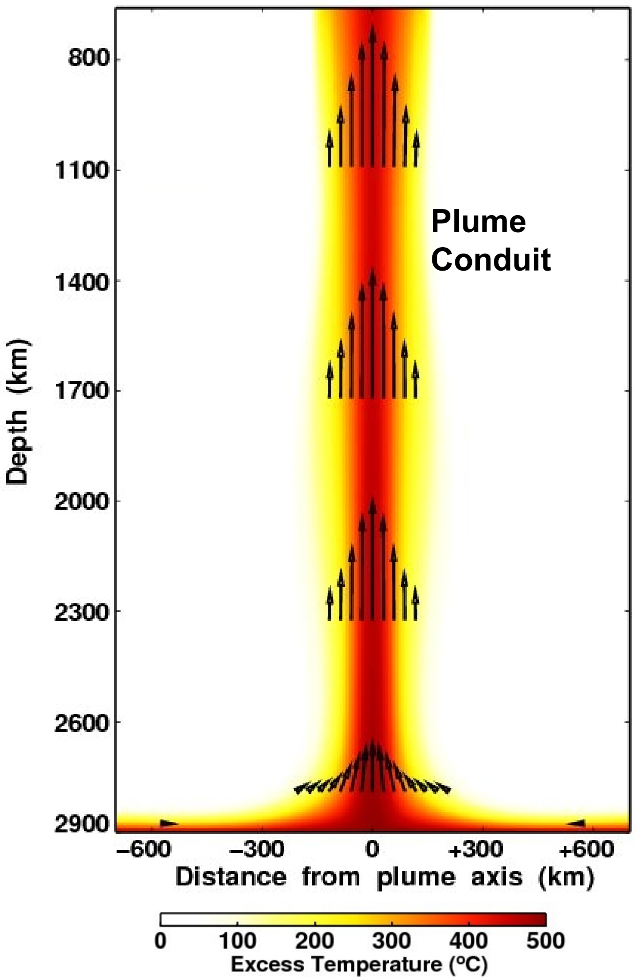
With surface shear

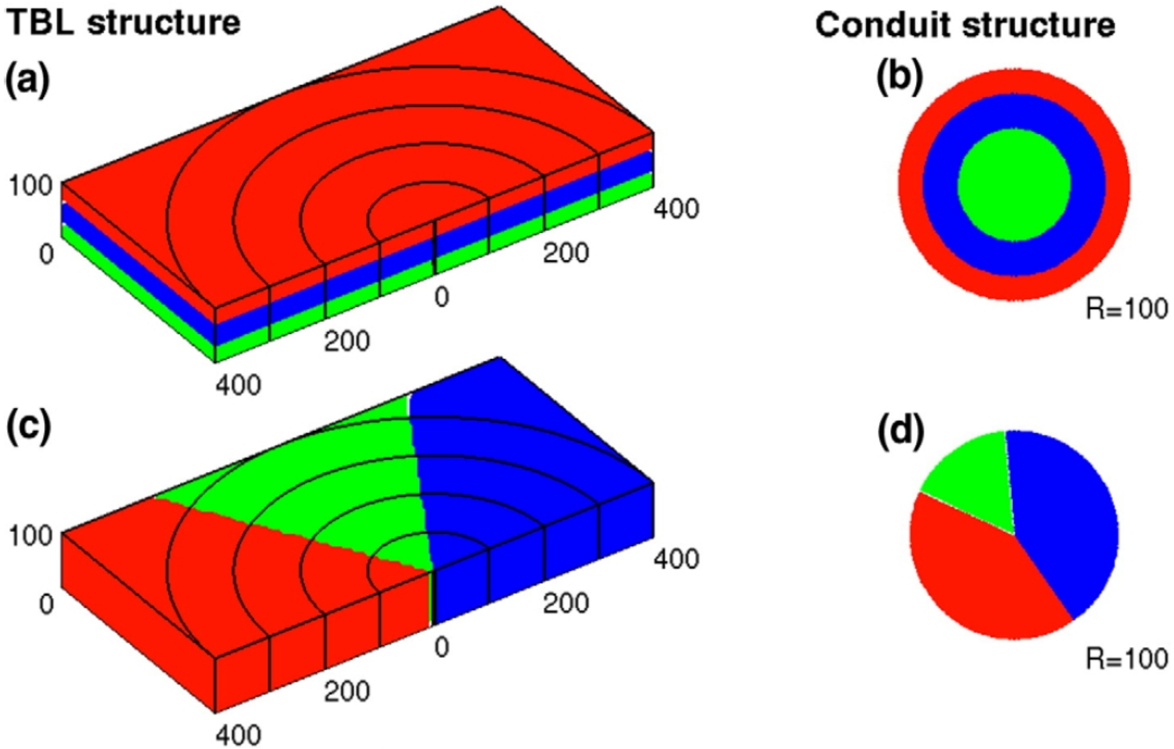


[Kerr and Mériaux, 2004]

Note : colors are intended to represent geochemically distinct material

§ **Numerical simulations** *[Farnetani and Hofmann, 2009]* **explored how simple Thermal Boundary Layer (TBL) zonations map into the plume conduit**



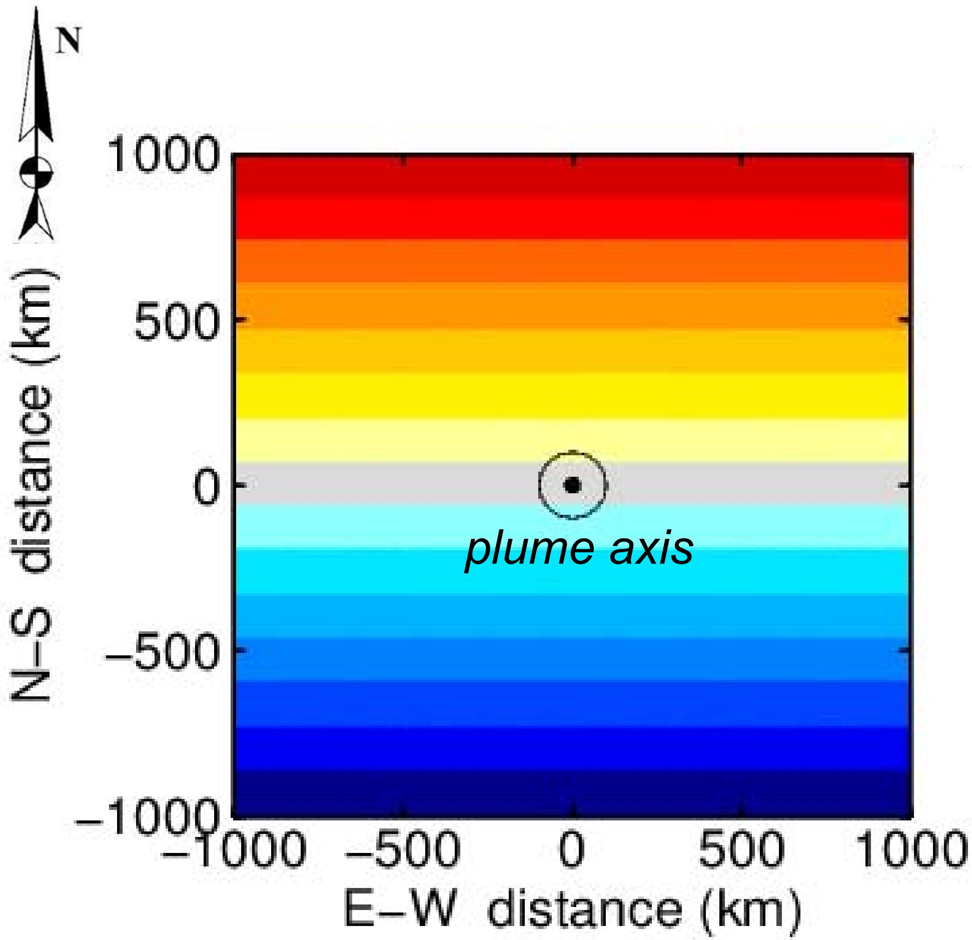


[Farnetani and Hofmann, 2009]

Find: TBL zonation affects the conduit structure.

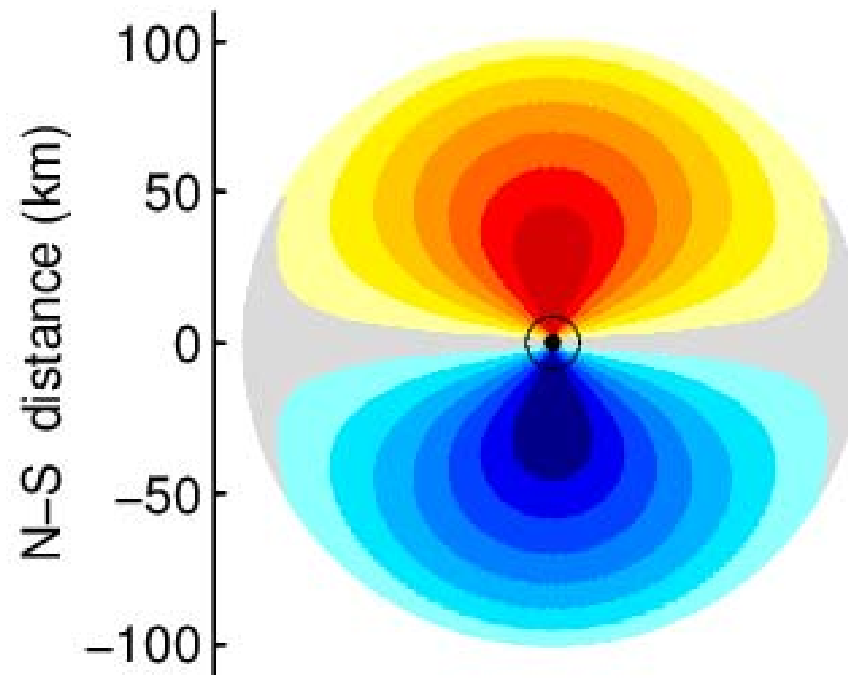
Modelled TBL

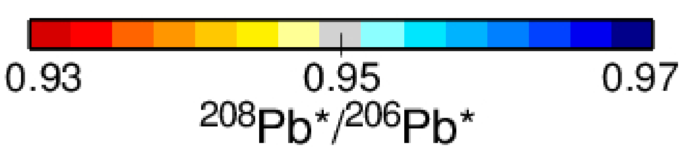
A linear southward increase in ^{208}Pb / $^{206}Pb^*$ generates radial *and* azimuthal variations.



The 'lobate' conduit structure

A novel zonation appears: globally bilateral, but with high $^{208}Pb^*$ / $^{206}Pb^*$ variations in the N-S direction.





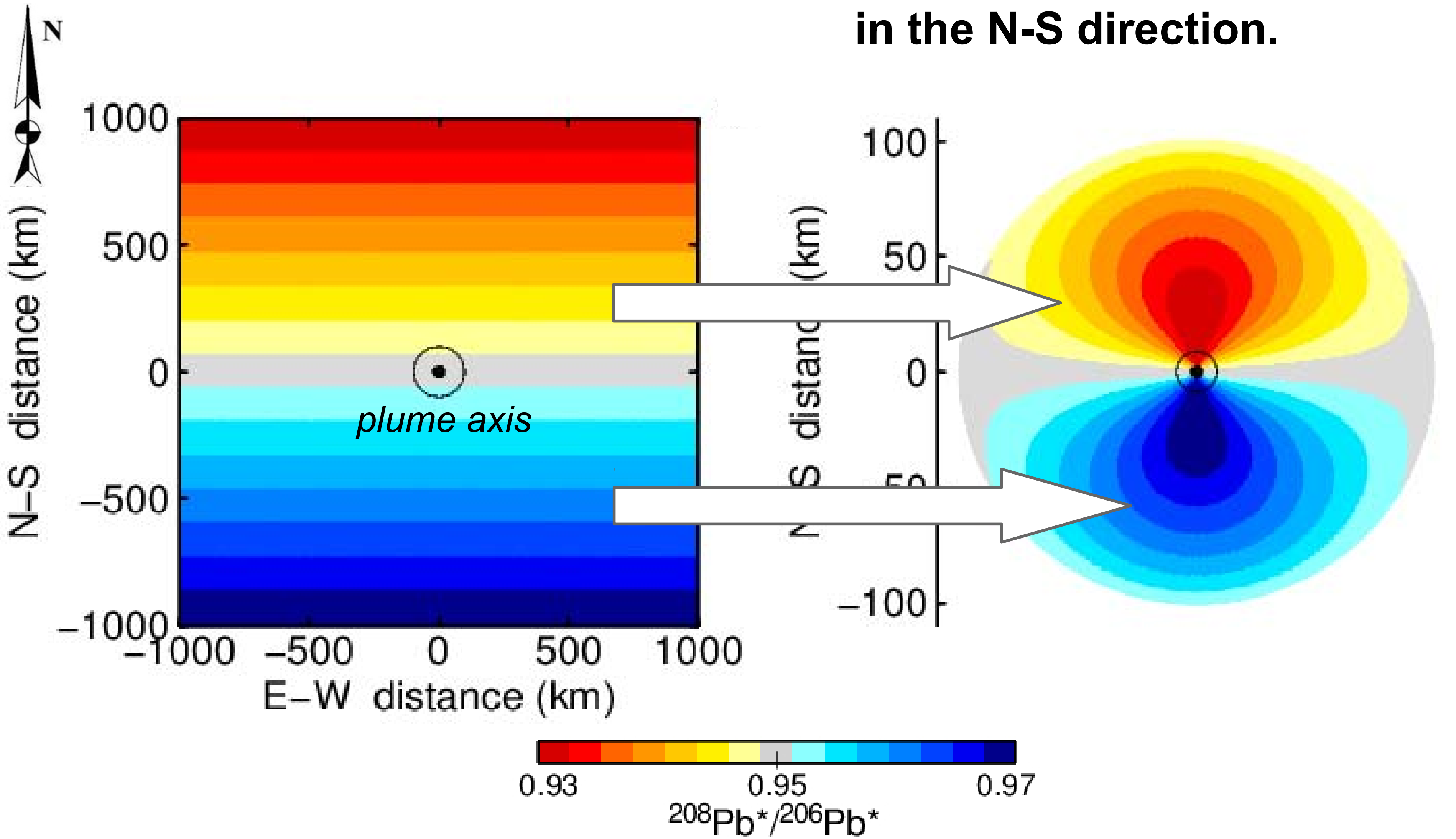
modeled range : 0.95 ± 0.02

Modelled TBL

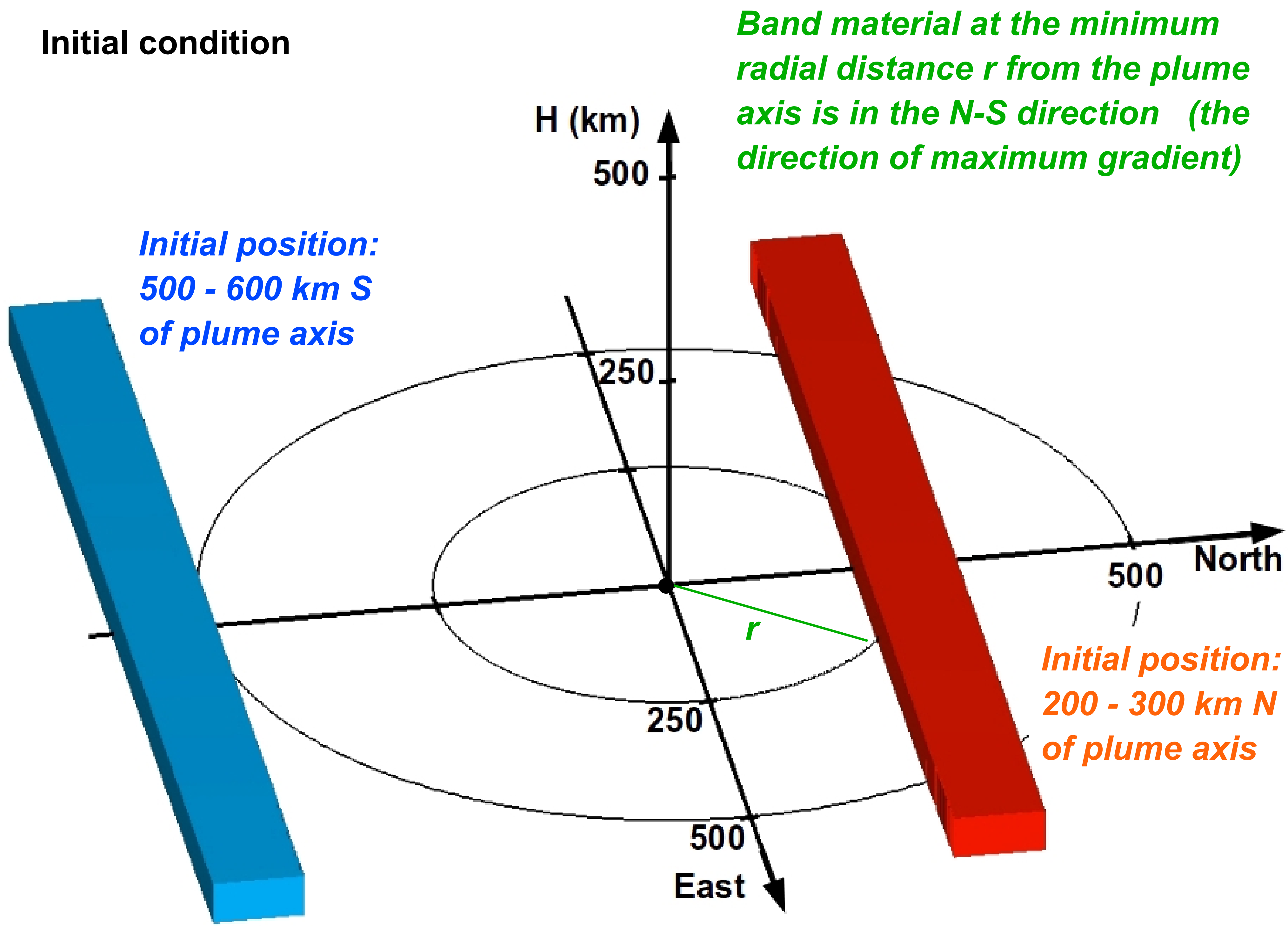
A linear southward increase in $^{208}Pb / ^{206}Pb^*$ generates radial *and* azimuthal variations.

The 'lobate' conduit structure

A novel zonation appears: globally bilateral, but with high $^{208}Pb^* / ^{206}Pb^*$ variations in the N-S direction.

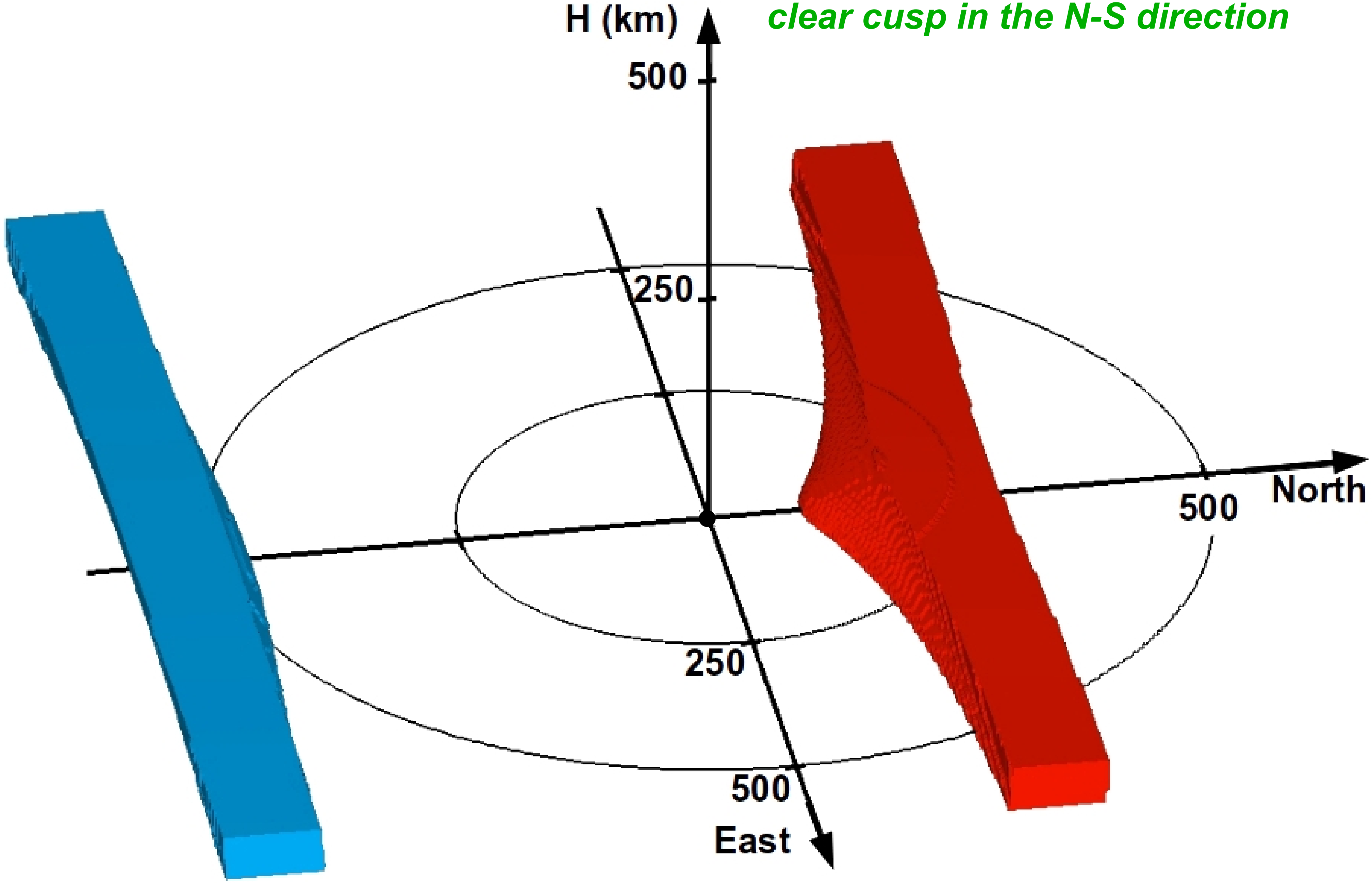


modelled range : 0.95 ± 0.02


Initial condition
Band material at the minimum radial distance r from the plume axis is in the N-S direction (the direction of maximum gradient)
H (km)
500
250
Initial position: 500 - 600 km S of plume axis
r
North
500
250
500
East
Initial position: 200 - 300 km N of plume axis

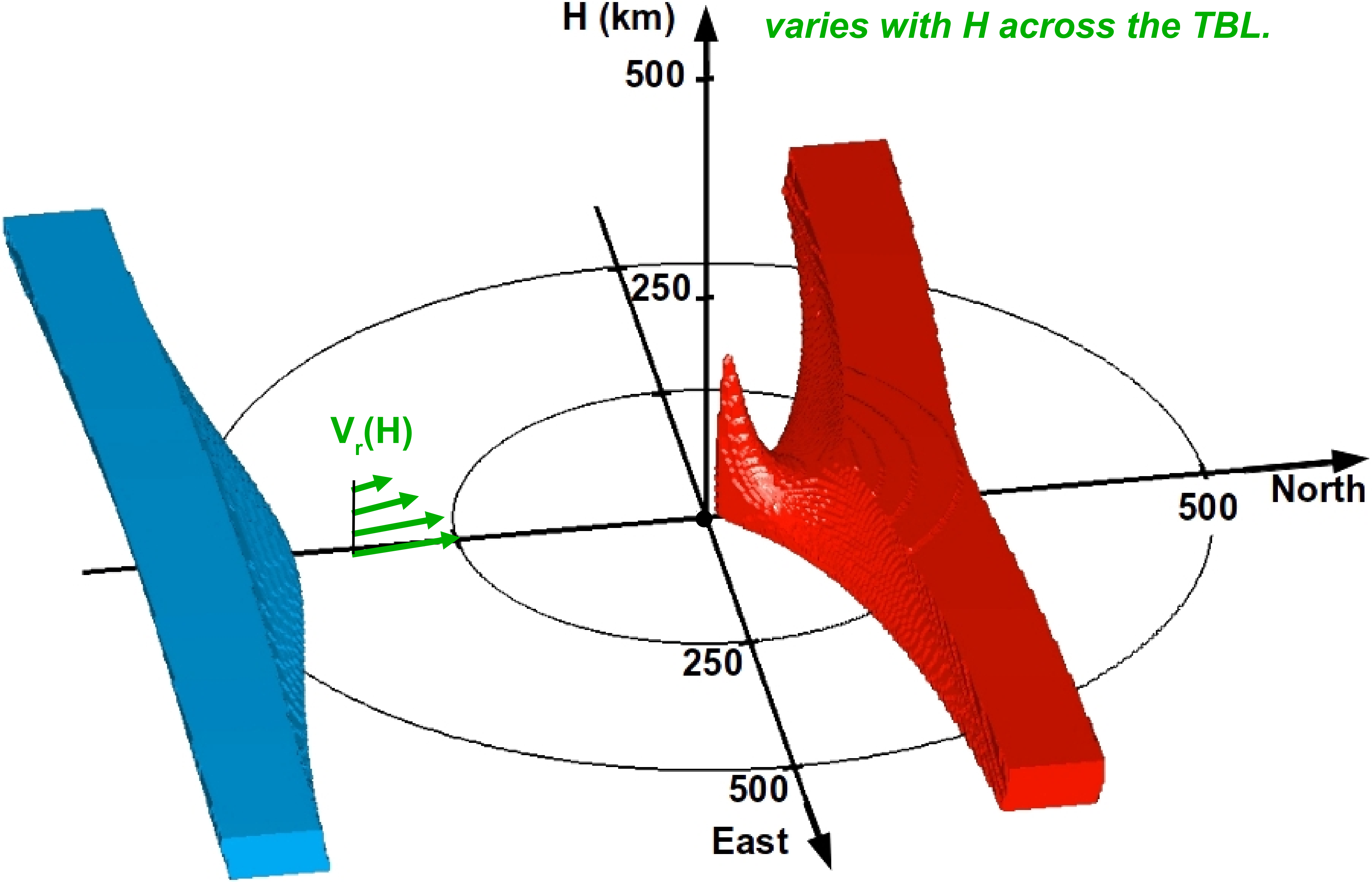
Elapsed time
1.3 Ma

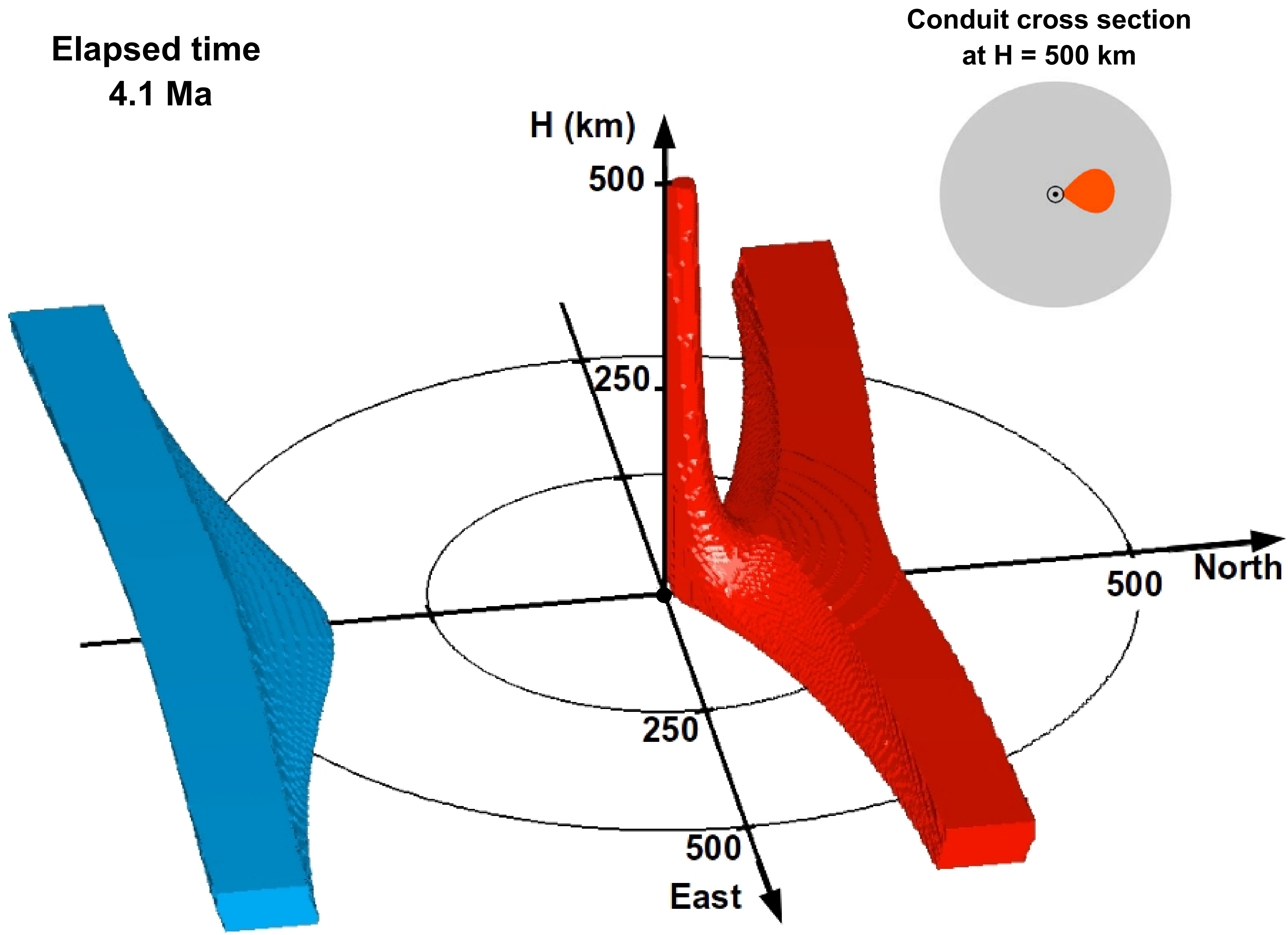
While flowing to the plume axis the band acquires a fan shape with a clear cusp in the N-S direction

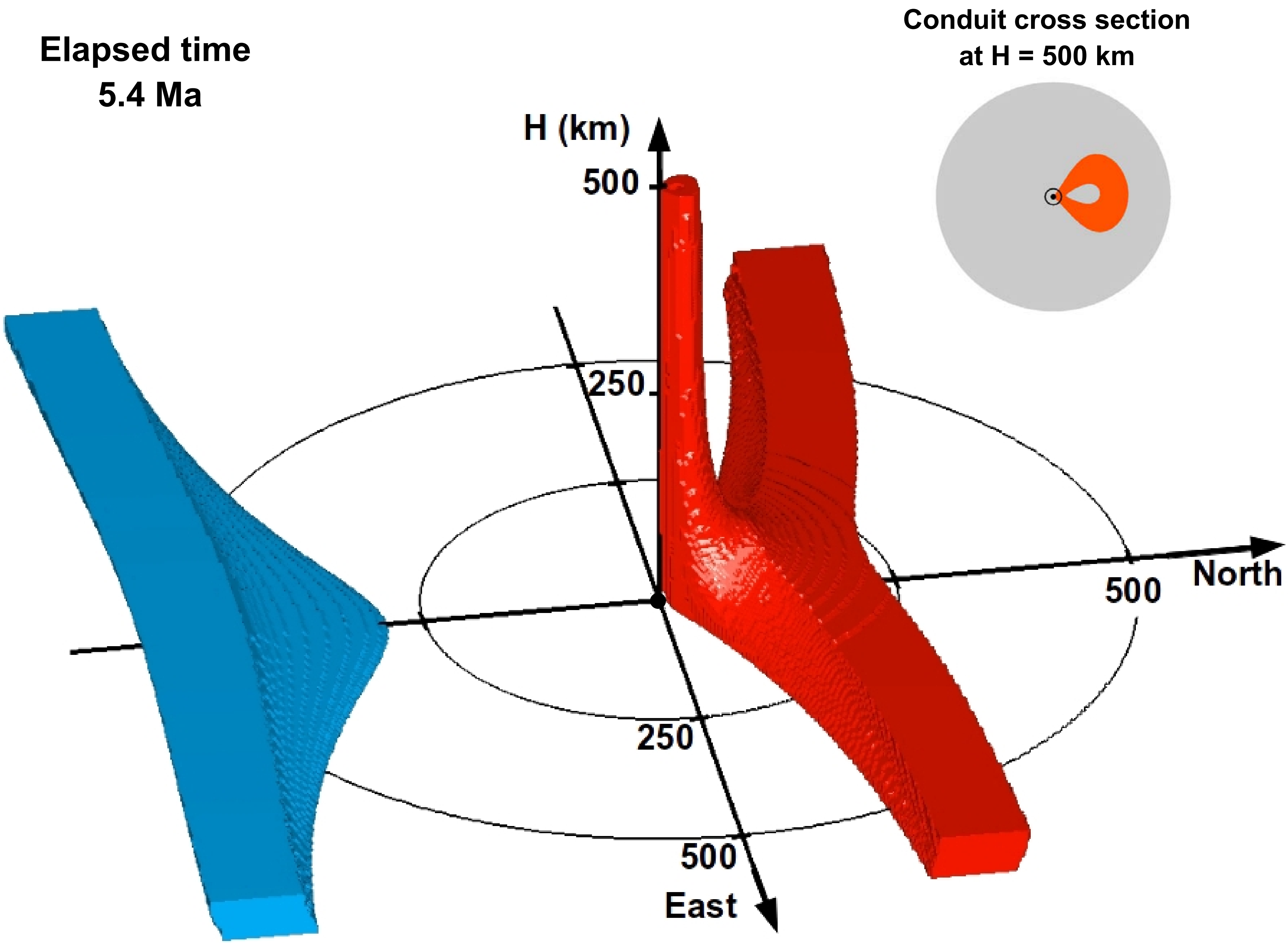


Elapsed time
2.7 Ma

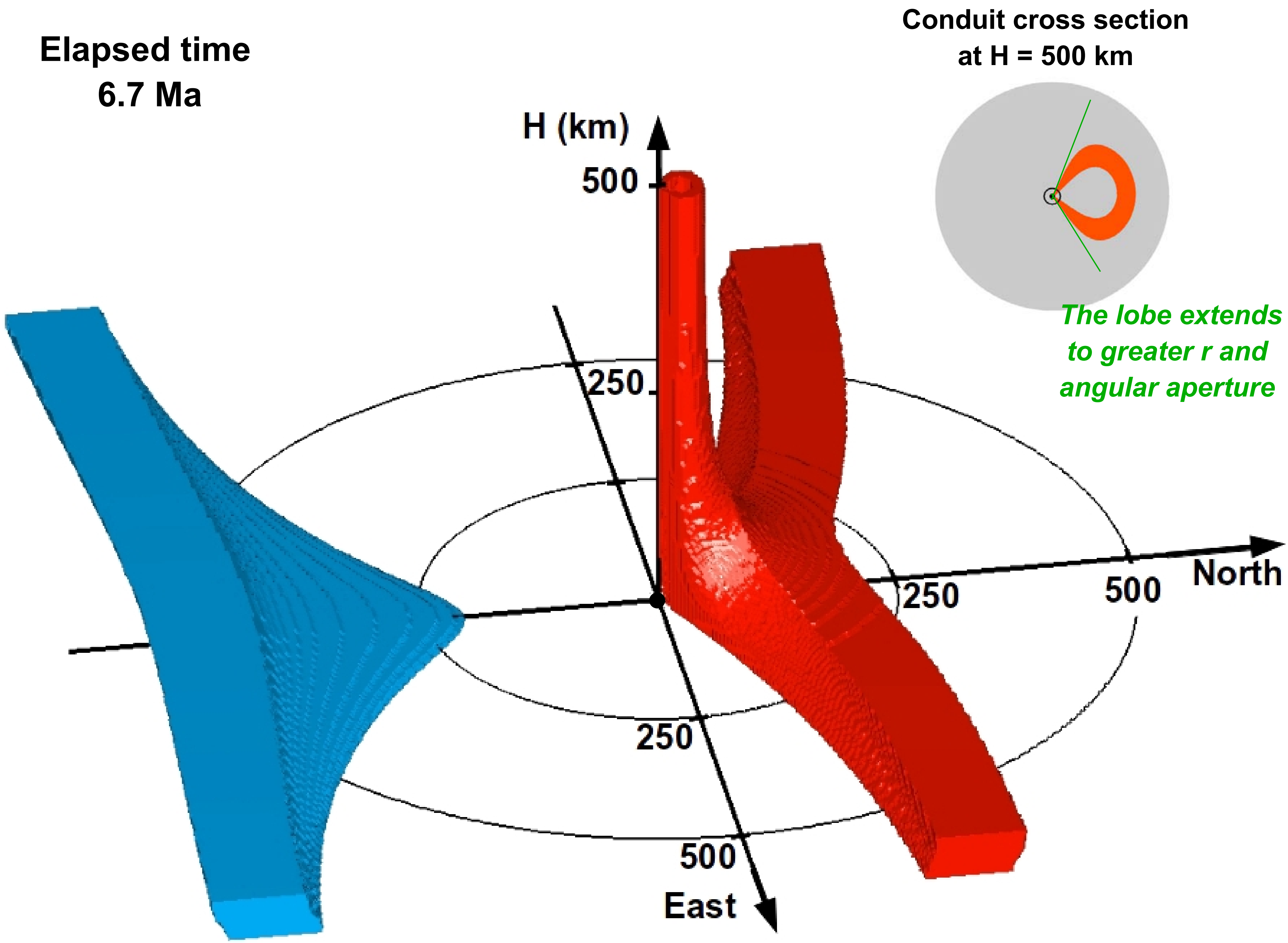
Material flowing to the plume axis undergoes simple shear, since V_r varies with H across the TBL.

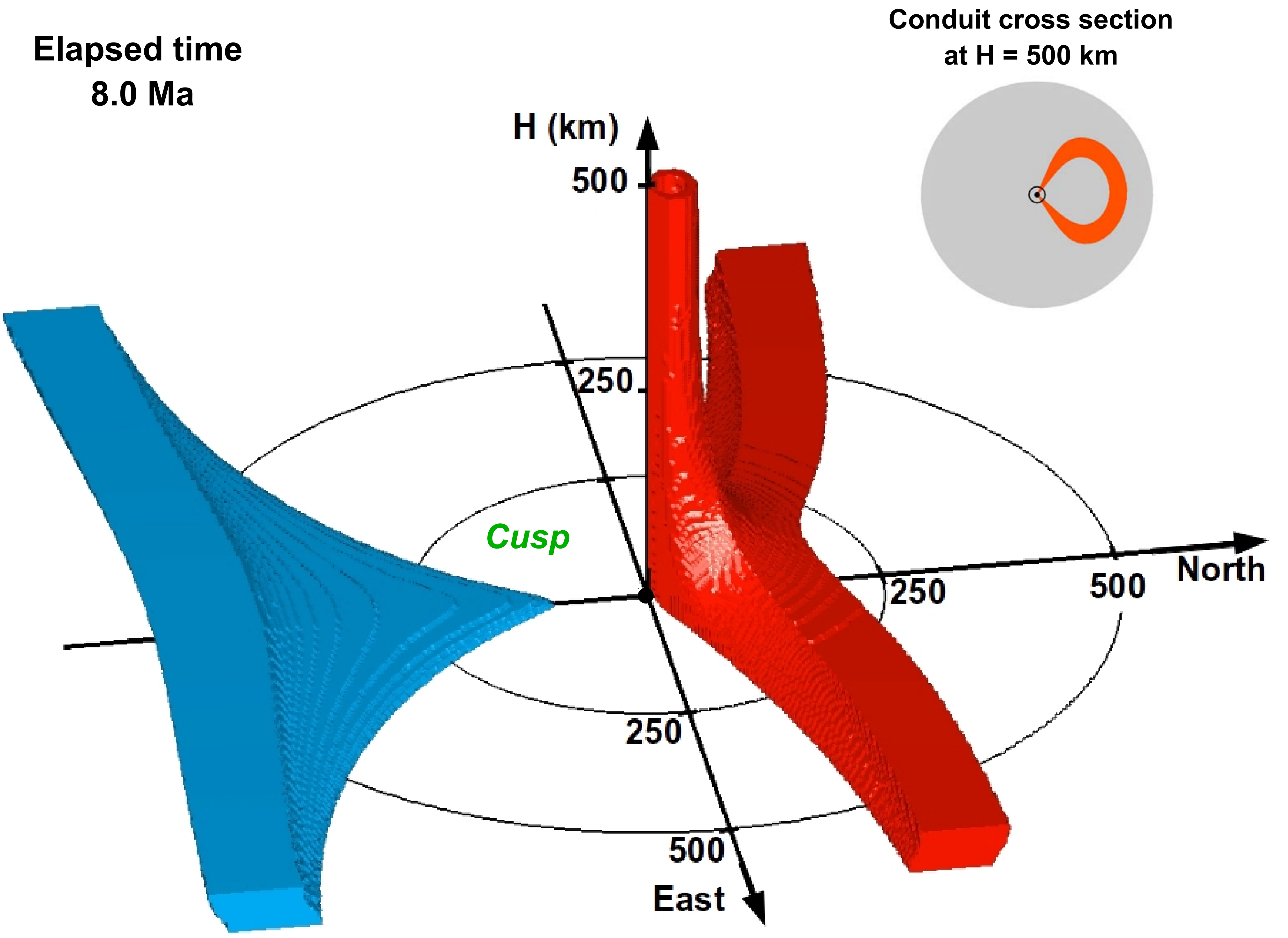


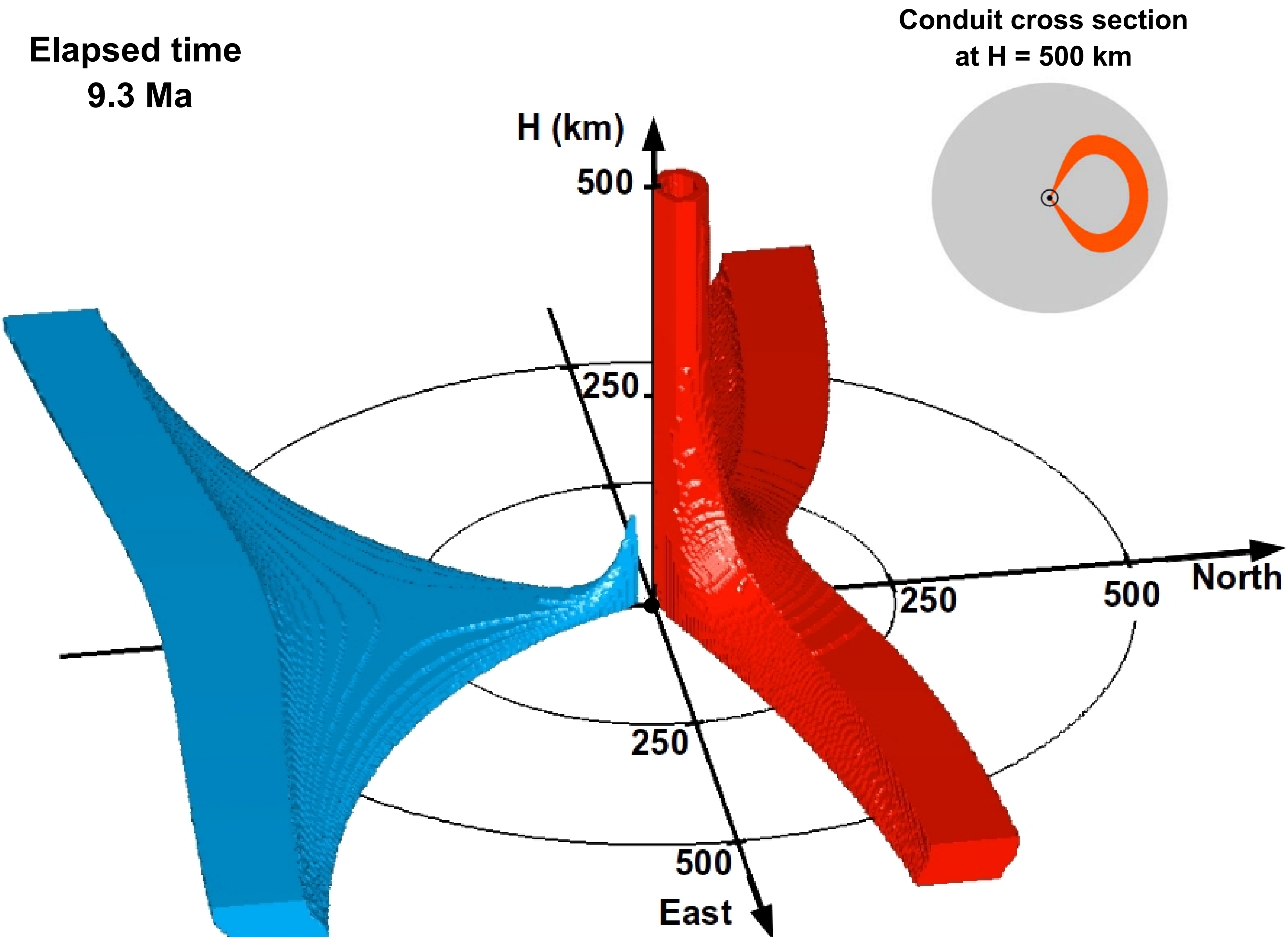

Elapsed time
4.1 Ma
Conduit cross section
at H = 500 km
H (km)
500
250
North
500
250
500
East

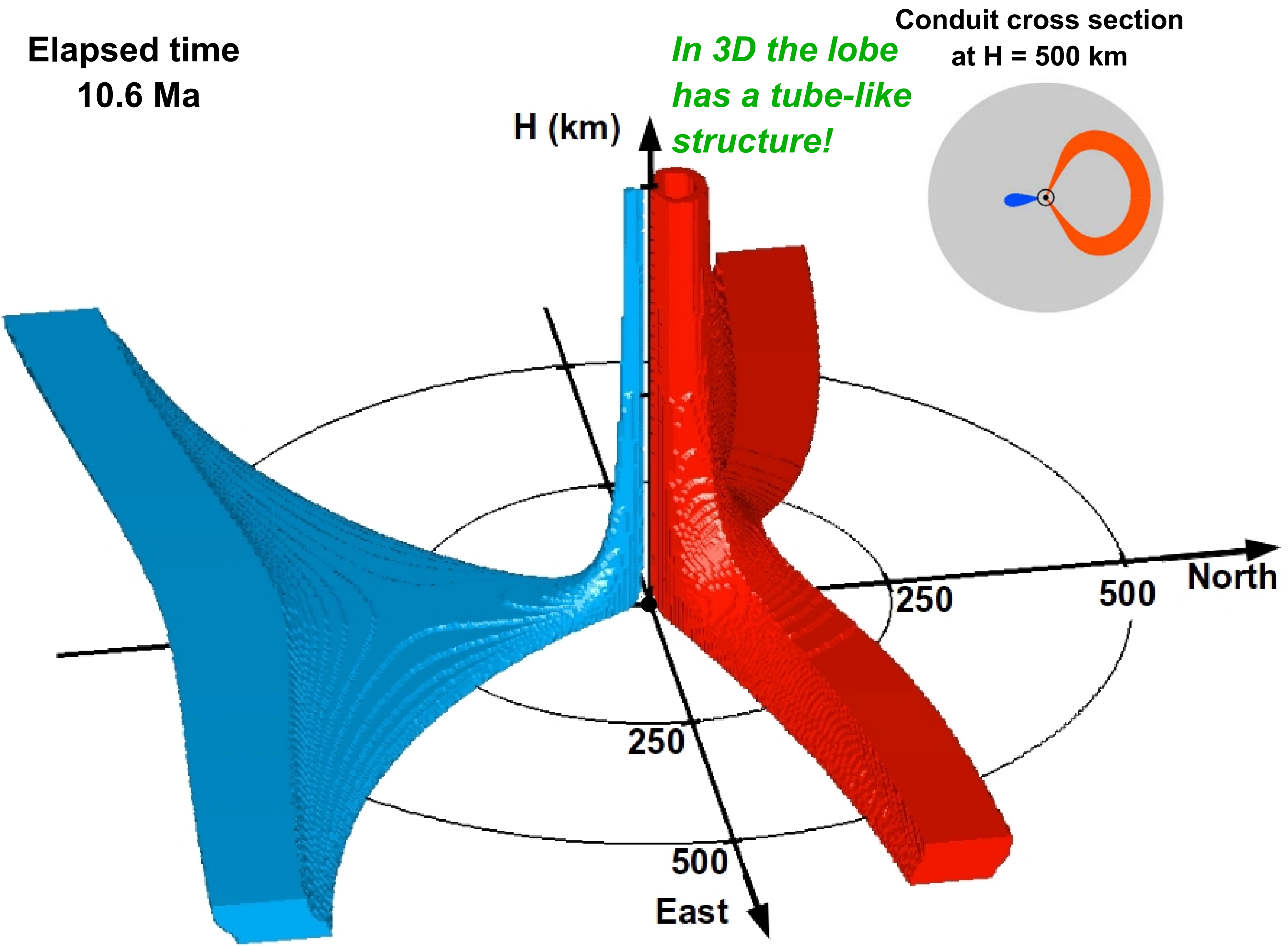


Elapsed time
5.4 Ma
Conduit cross section
at H = 500 km
H (km)
500
250
North
500
250
500
East

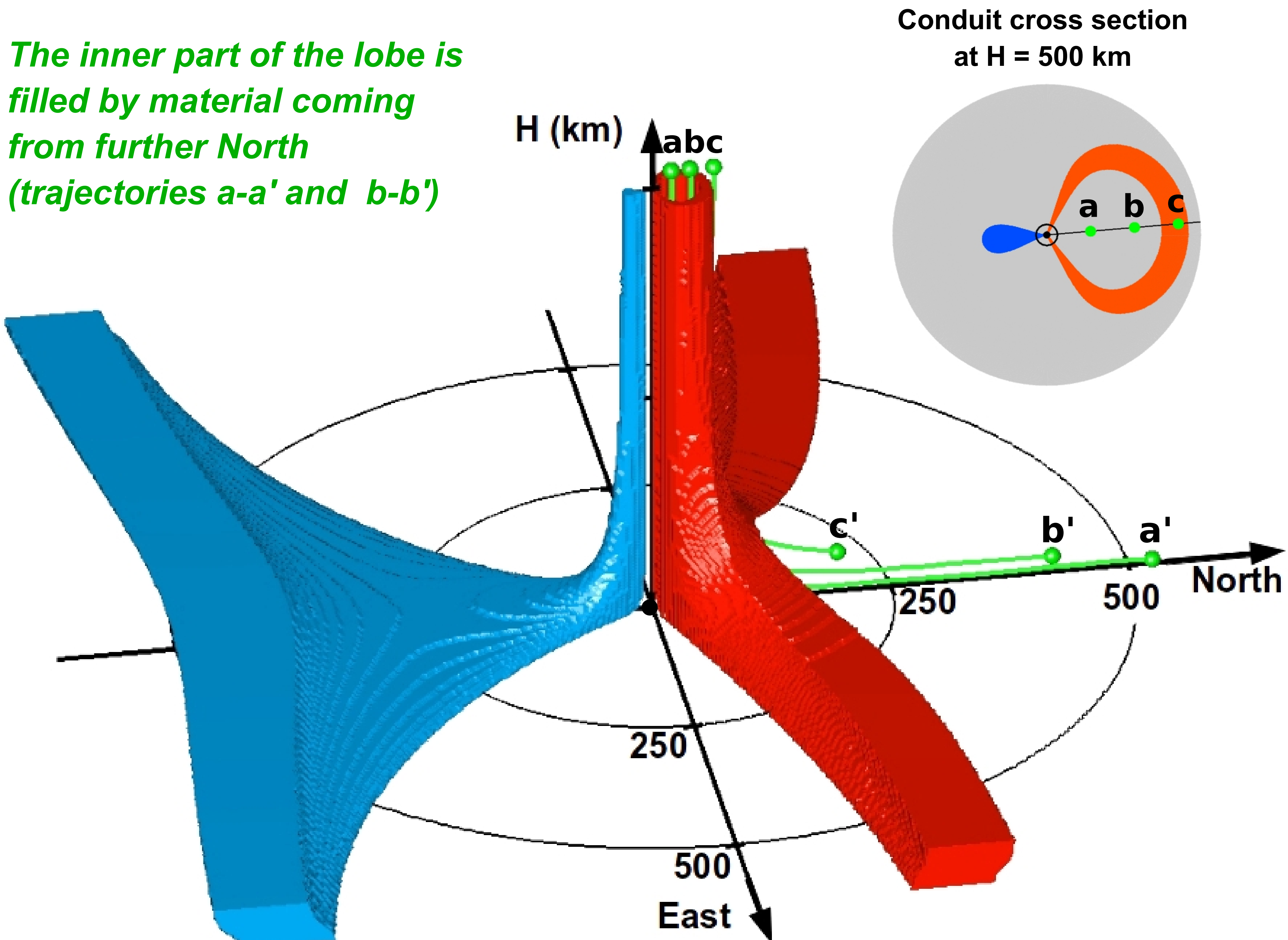

Elapsed time
6.7 Ma
Conduit cross section
at H = 500 km
The lobe extends
to greater r and
angular aperture
H (km)
500
250
North
250
500
250
500
East


Elapsed time
8.0 Ma
Conduit cross section
at H = 500 km
H (km)
500
250
Cusp
250
500
North
250
500
East

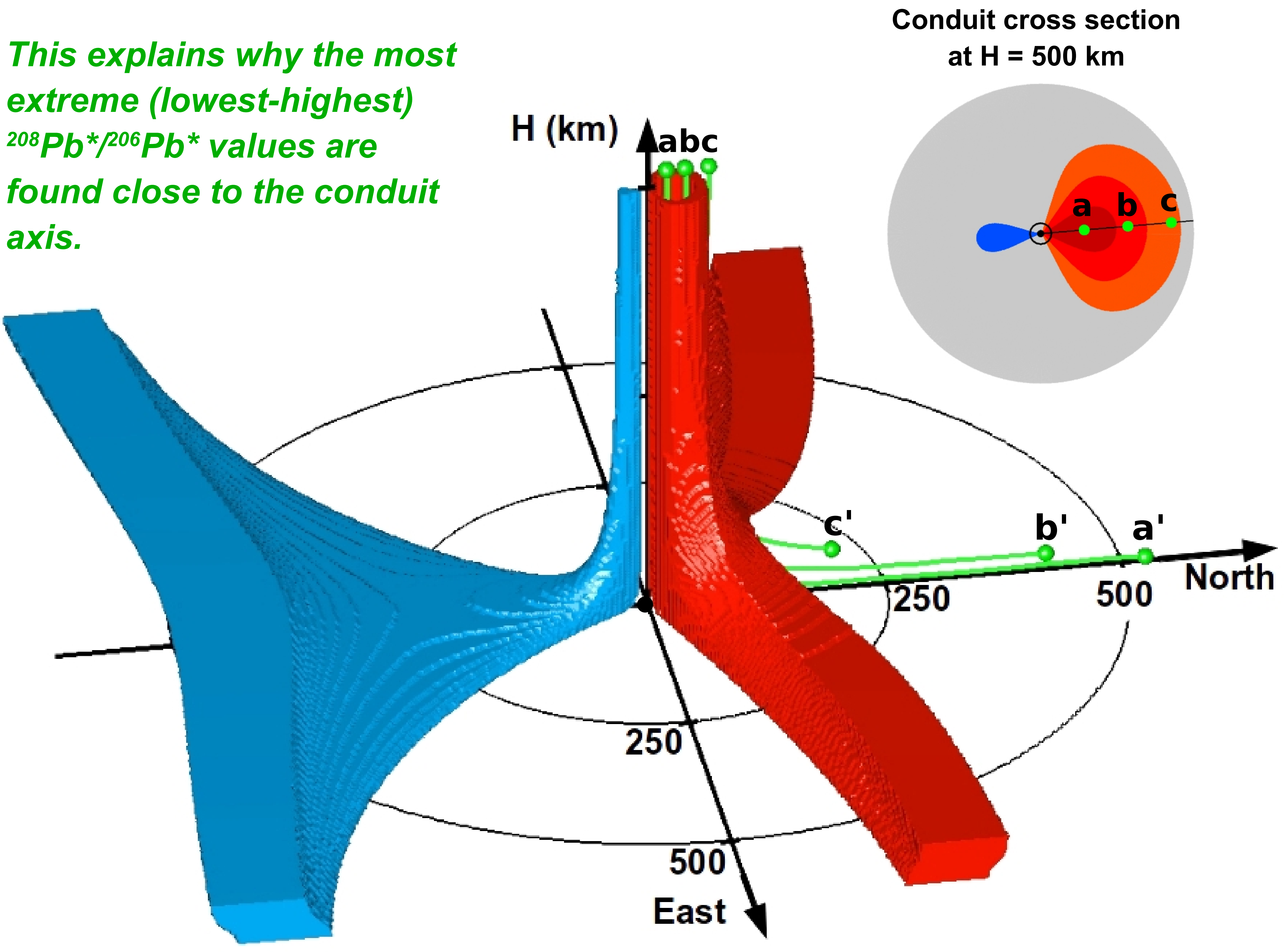

Elapsed time
9.3 Ma
Conduit cross section
at H = 500 km
H (km)
500
250
North
250
500
250
500
East


Elapsed time
10.6 Ma
In 3D the lobe
has a tube-like
structure!
Conduit cross section
at H = 500 km
H (km)
North
250
500
250
500
East

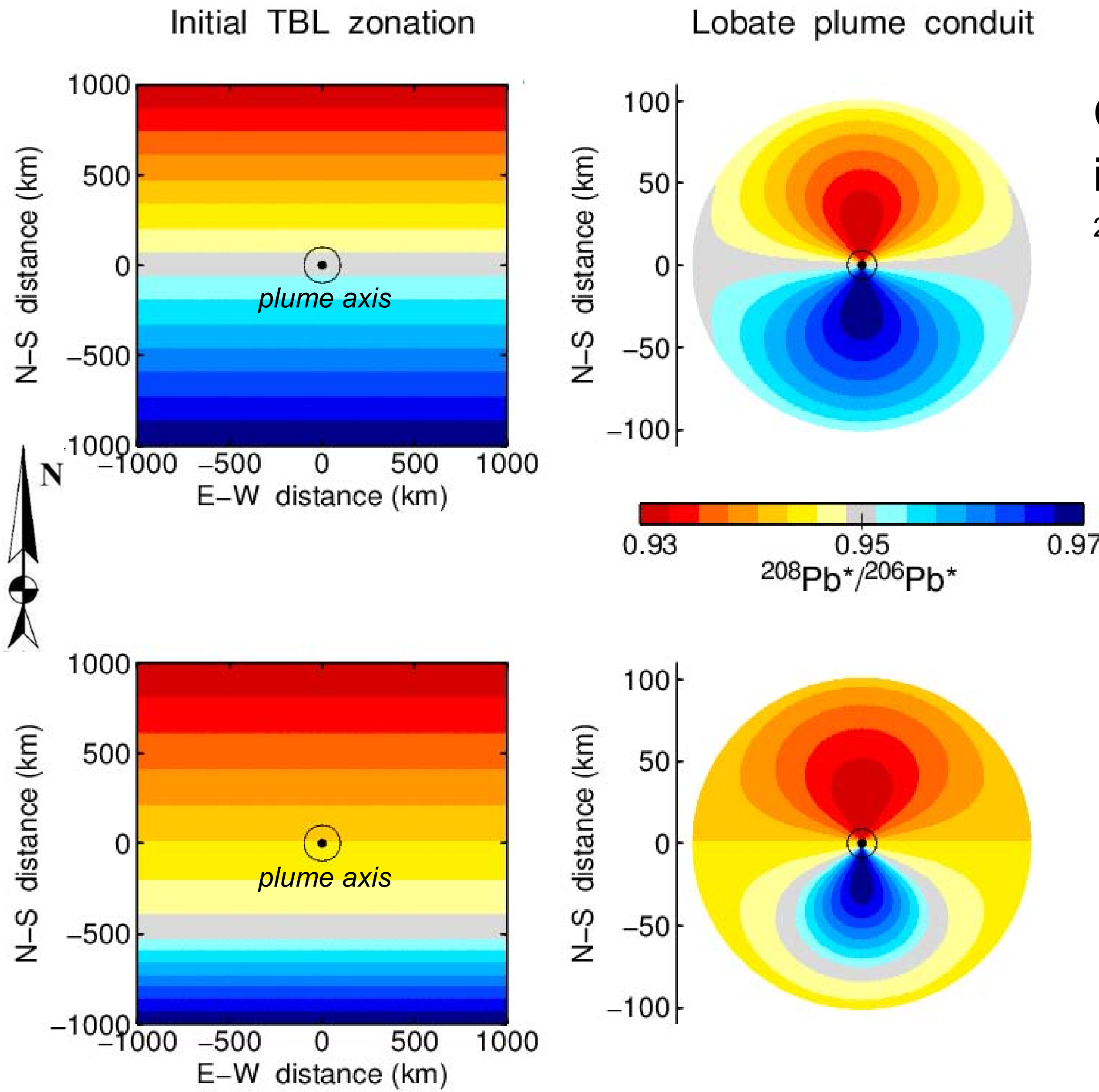
The inner part of the lobe is filled by material coming from further North (trajectories a-a' and b-b')



This explains why the most extreme (lowest-highest) $^{208}Pb^*/^{206}Pb^*$ values are found close to the conduit axis.



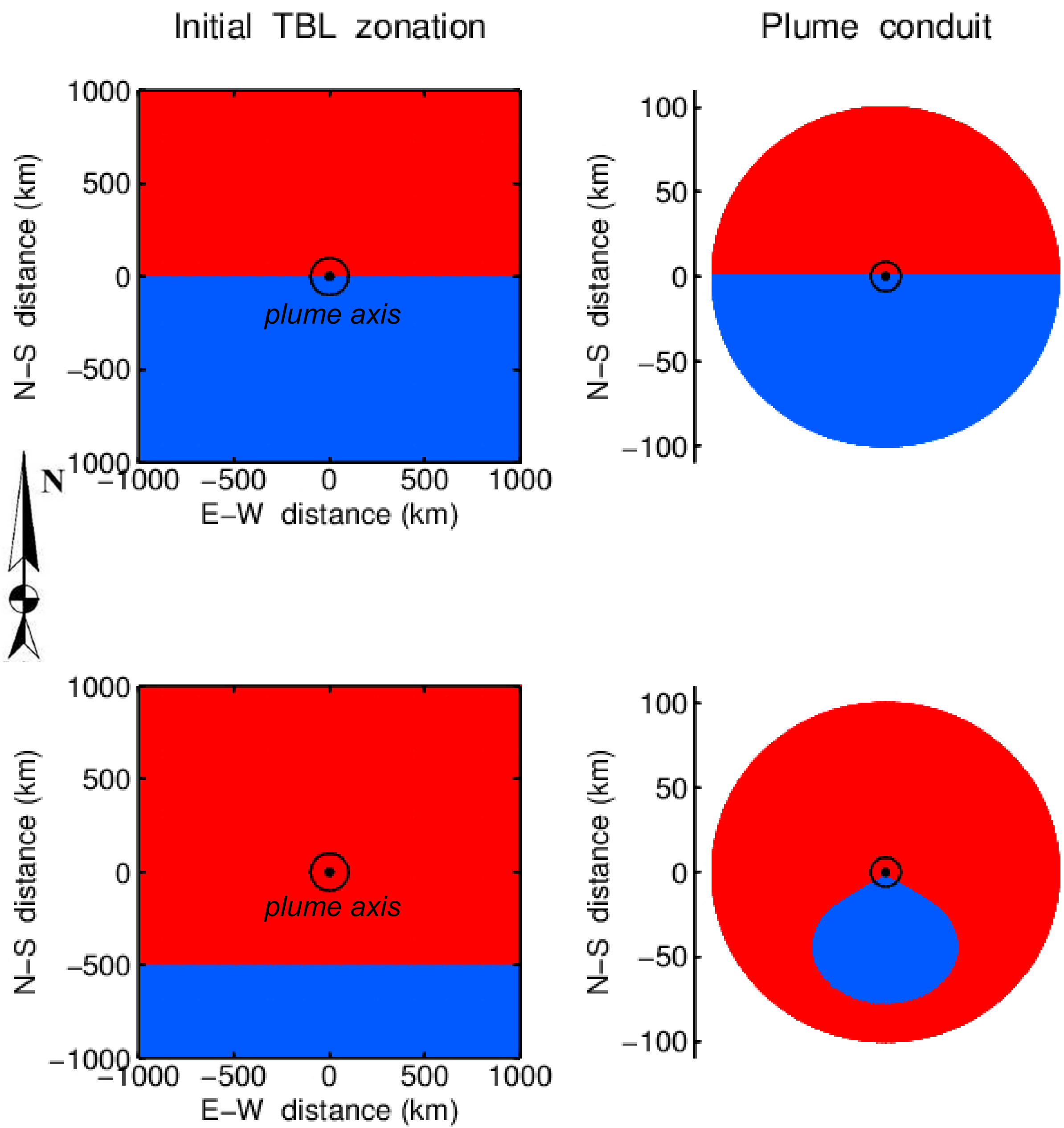
The 'lobate' conduit: is this a robust result?



Case-A : the plume conduit is located above the mean $^{208}Pb^* / ^{206}Pb^*$ value.

Case-B : the plume conduit is displaced 500 km to the north, with respect to the mean $^{208}Pb^* / ^{206}Pb^*$ value.

The 'perfectly' bilateral conduit structure...

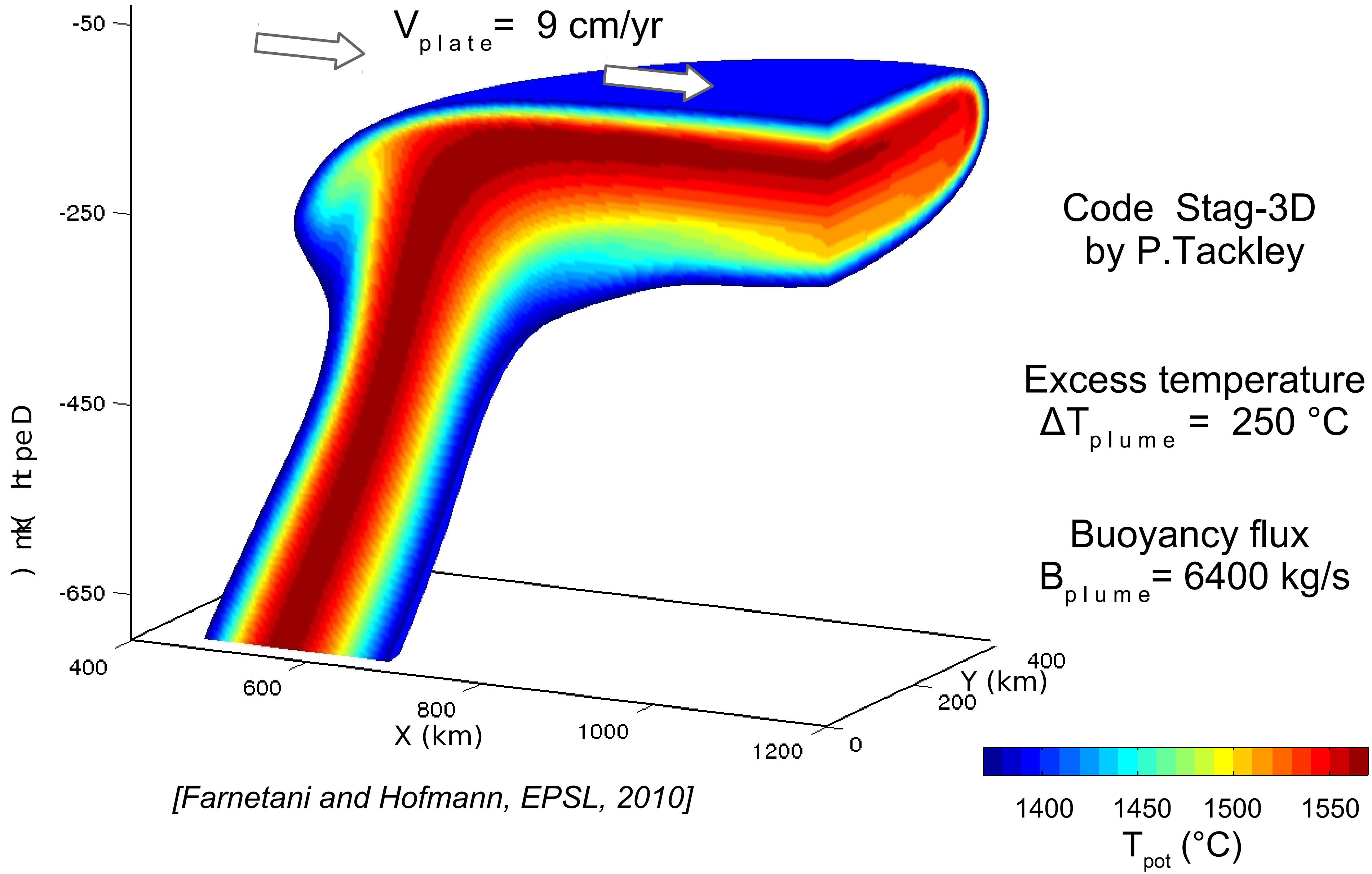


...Is just a special case: when the plume conduit is located above the sharp $^{208}Pb^{*}$ / $^{206}Pb^{*}$ variation in the TBL.

In all other cases the 'lobate' structure appears!

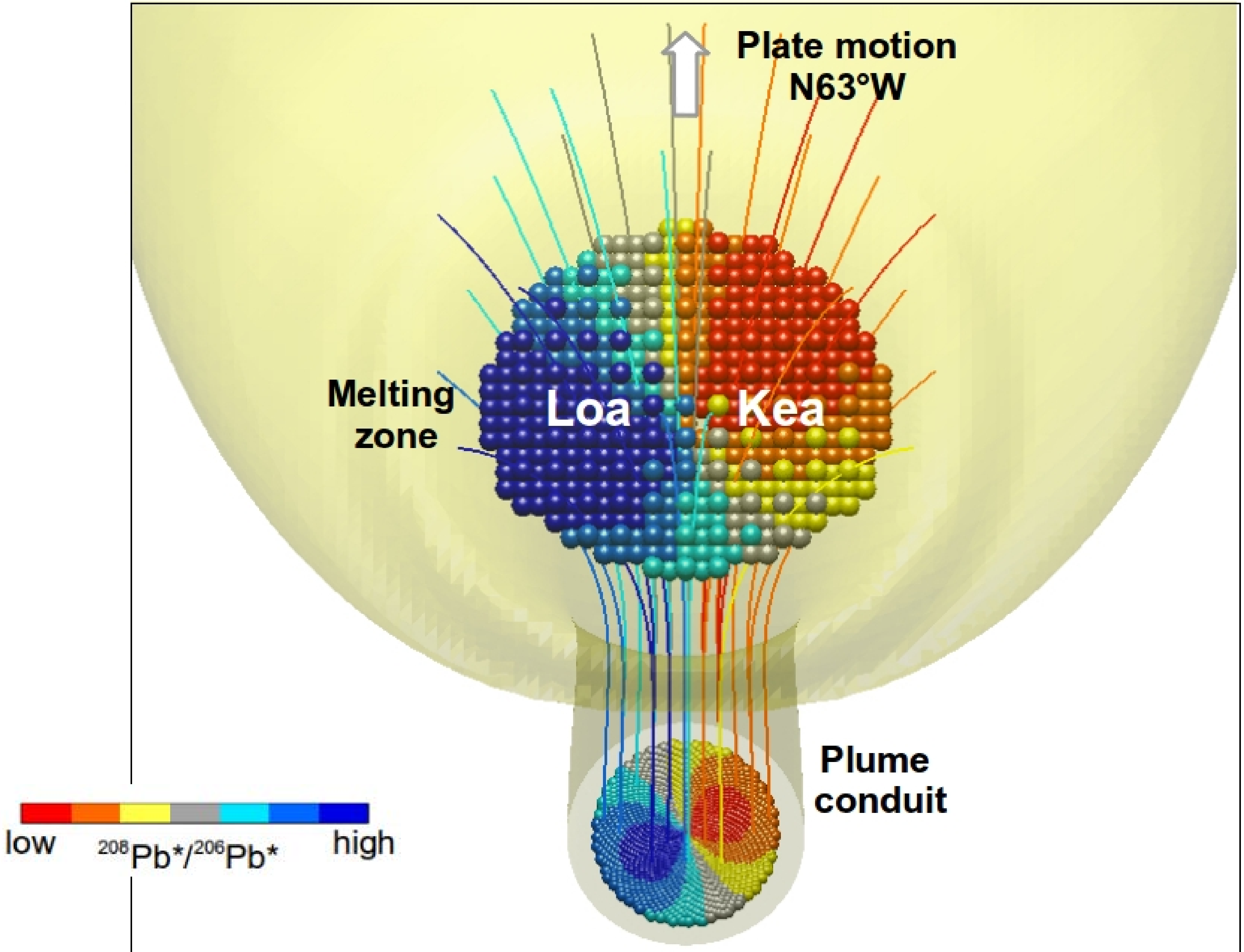
The 'lobate' conduit is a robust result

What is the predicted $^{208}Pb^{*} / ^{206}Pb^{*}$ zonation across the melting zone of the Hawaiian plume?



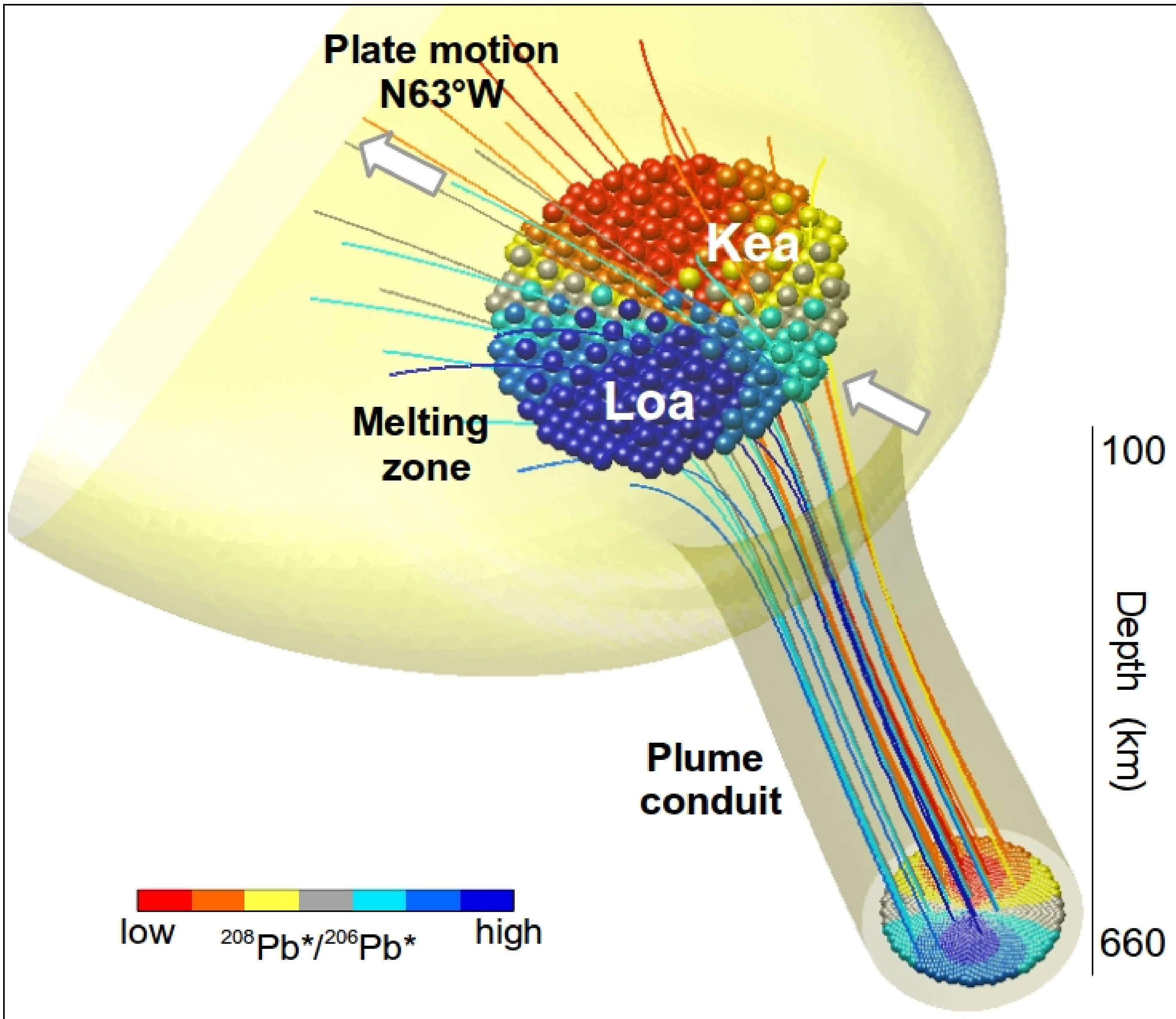
[Farnetani and Hofmann, EPSL, 2010]

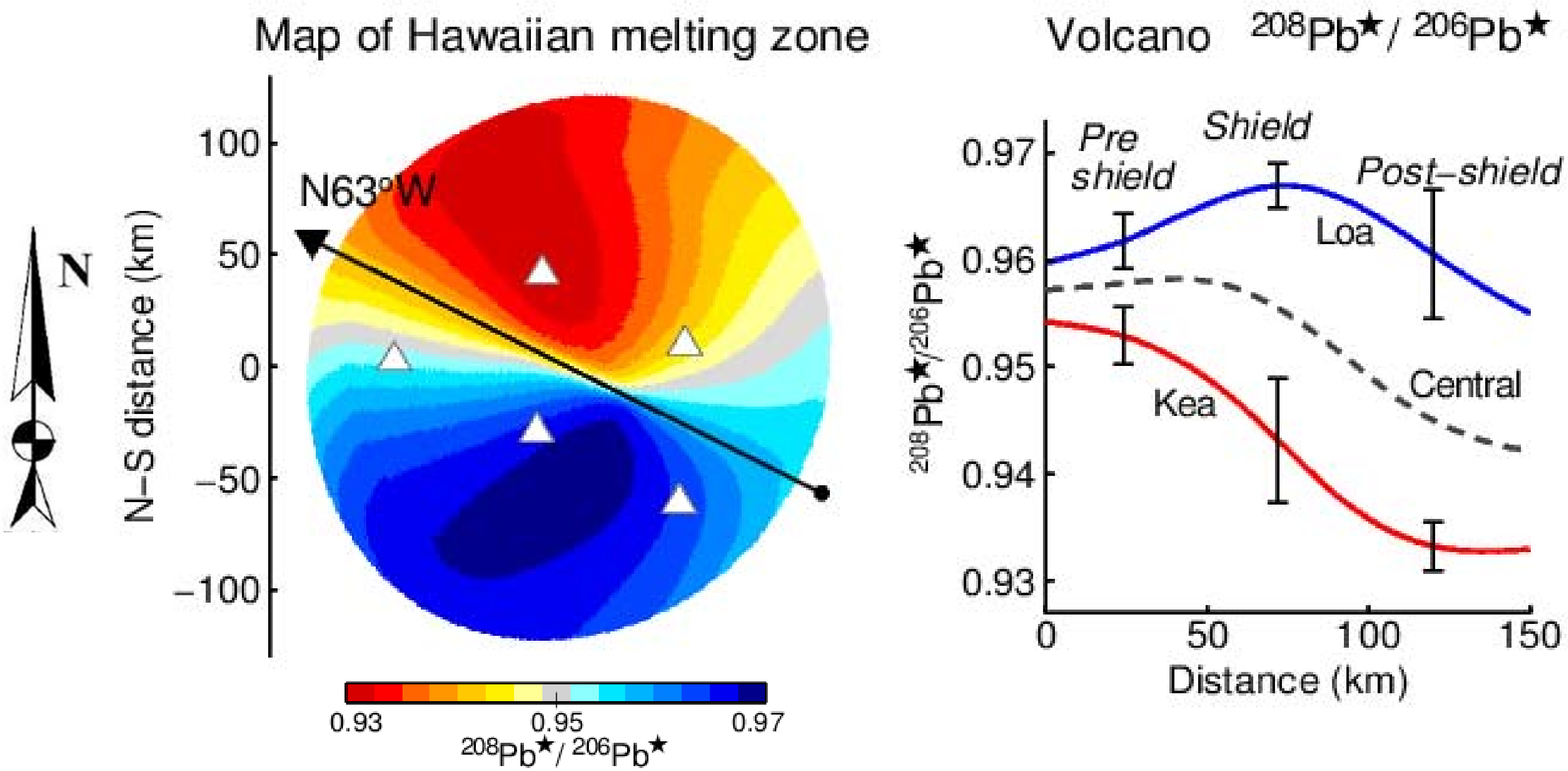
We calculate the trajectories of passive tracers which carry a $^{208}Pb^*/^{206}Pb^*$ value, according to their position in the conduit.



Melting zone: use dry solidus by Katz et al., 2003

We convert the $^{208}Pb^* / ^{206}Pb^*$ distribution inside the three dimensional melting zone into a $^{208}Pb^* / ^{206}Pb^*$ map.

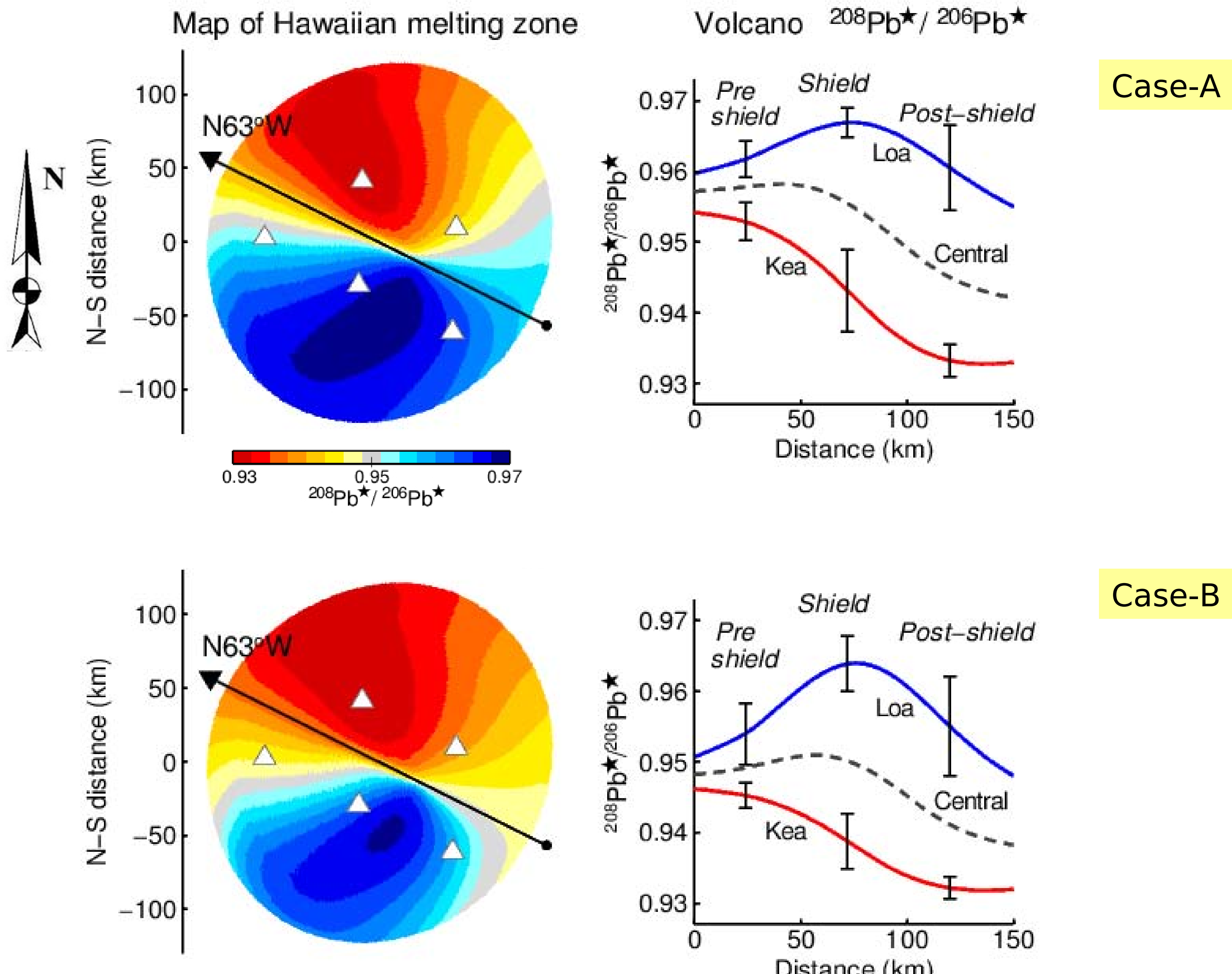




Case-A

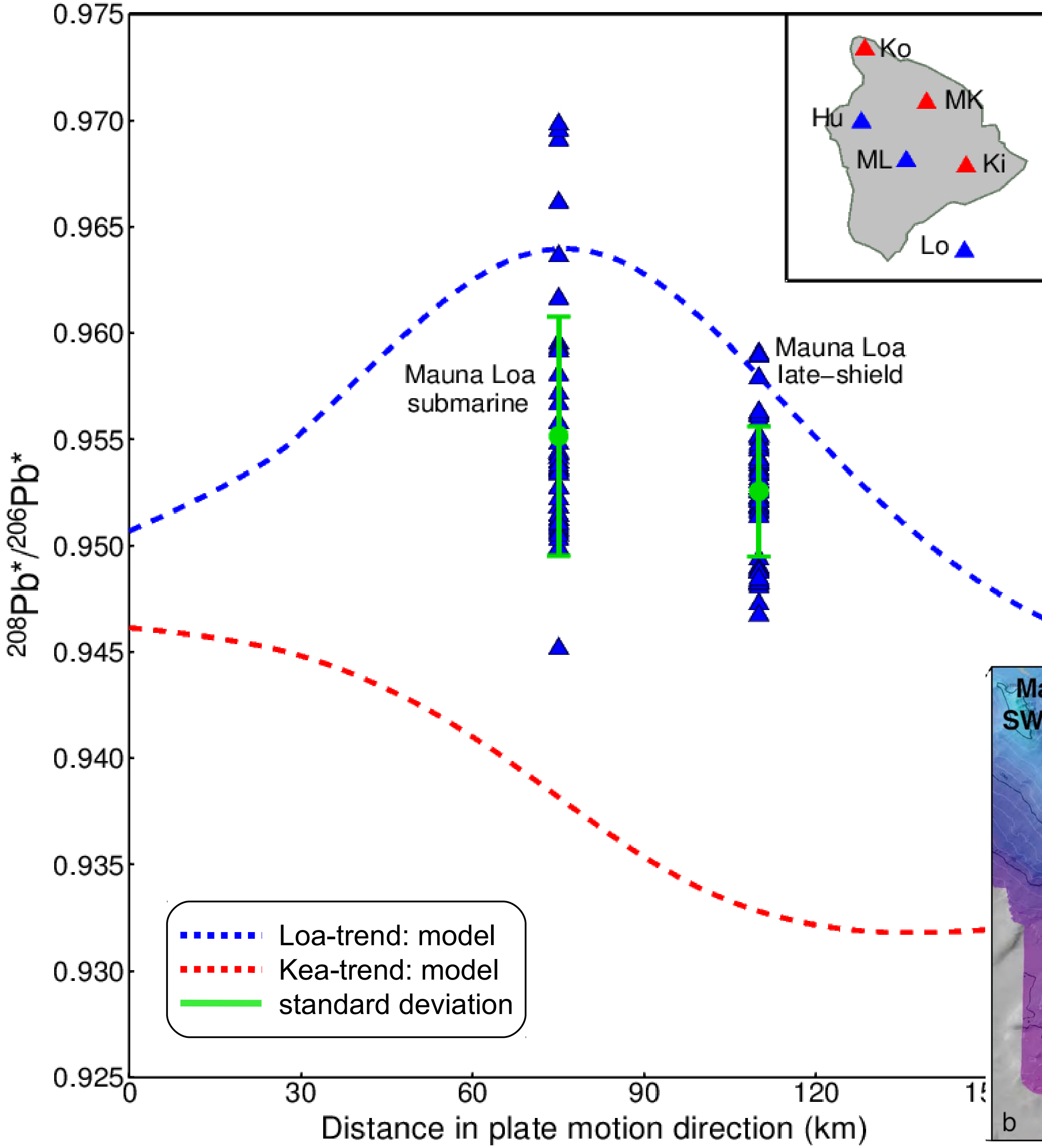
Model predictions:

- **A globally bilateral zonation, with higher $^{208}Pb^*/^{206}Pb^*$ in the Loa-side.**
- **Double-volcanic chains can reveal the isotopic zonation of the melting zone far better than a single, central, volcano.**
- **A complex zonation induces a distinct temporal evolution for Loa and Kea-trend volcanoes.**

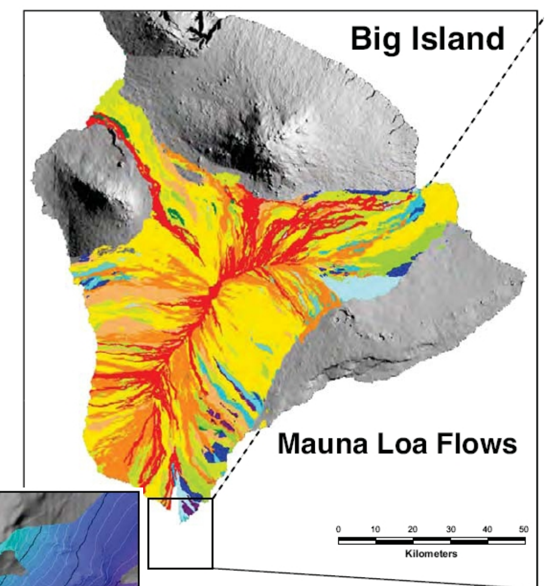


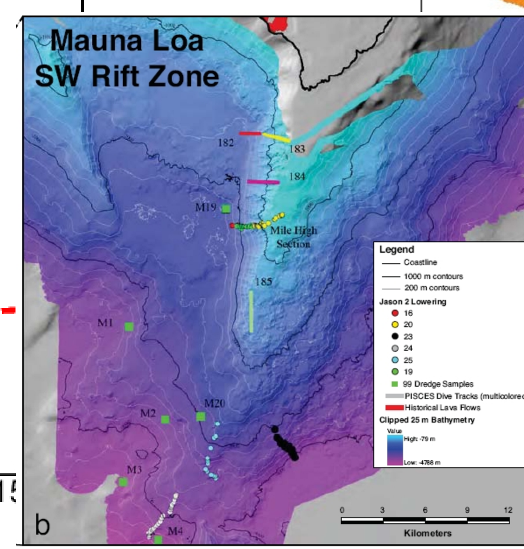
Map of Hawaiian melting zone
Volcano $^{208}Pb^{\star}/^{206}Pb^{\star}$
Case-A
Case-B
N63°W
N
N–S distance (km)
100
50
0
−50
−100
0.93
0.95
0.97
$^{208}Pb^{\star}/^{206}Pb^{\star}$
Pre shield
Shield
Post–shield
Loa
Central
Kea
Distance (km)
0
50
100
150
0.97
0.96
0.95
0.94
0.93

$^{208}Pb^* / ^{206}Pb^*$ model predictions and observations: Mauna Loa



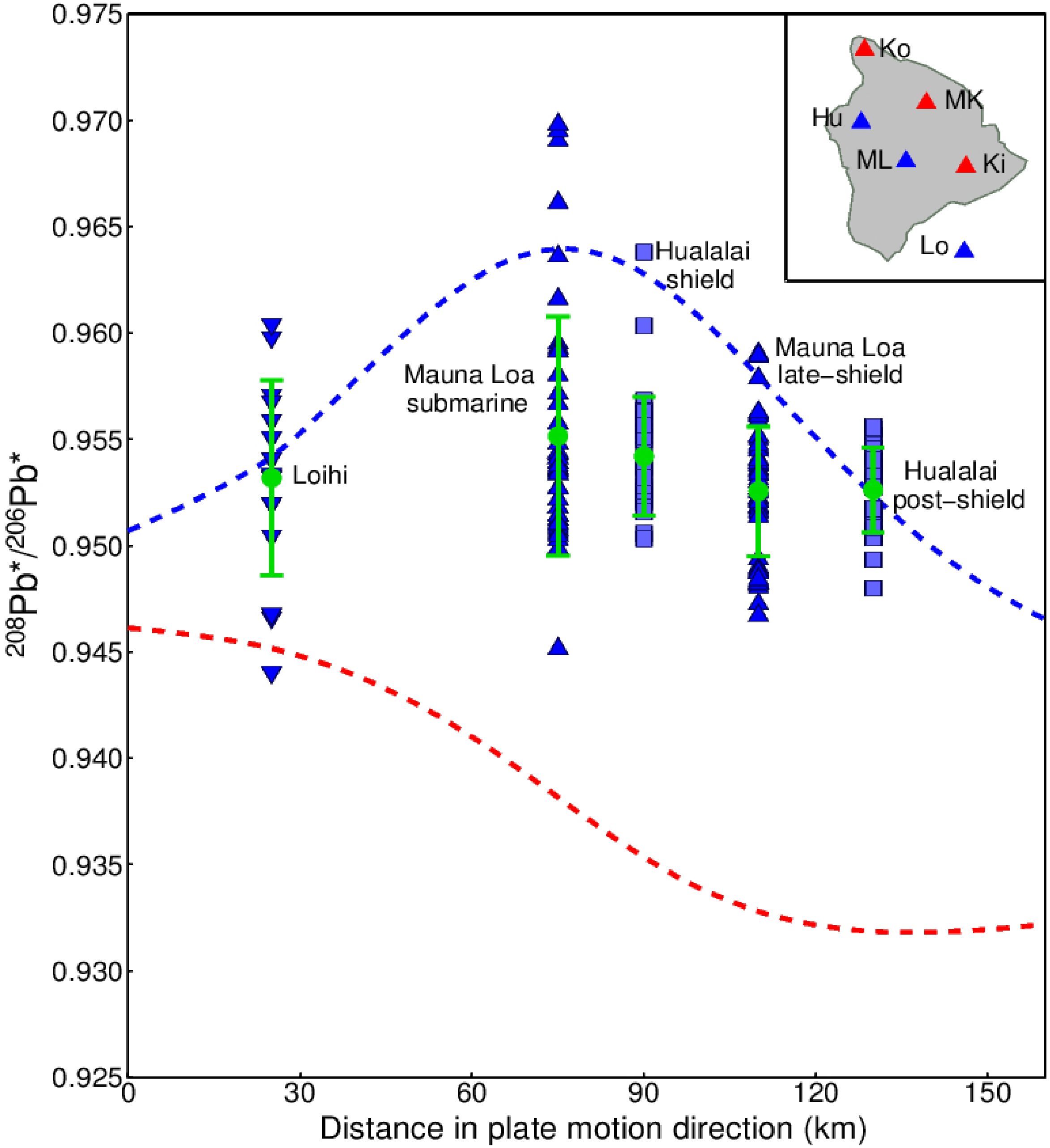
M.Loa shield-stage lavas (submarine) should have higher $^{208}Pb^*/^{206}Pb^*$ than late-shield (subaerial) lavas





[Weis et al., 2011]

$^{208}Pb^*$ / $^{206}Pb^*$ model predictions and observations: Loa-trend



Post-shield lavas (Hualalai) should have lower $^{208}Pb^*/^{206}Pb^*$ than shield lavas.

This is true for both MaunaLoa and Hualalai shield lavas.

Used data:

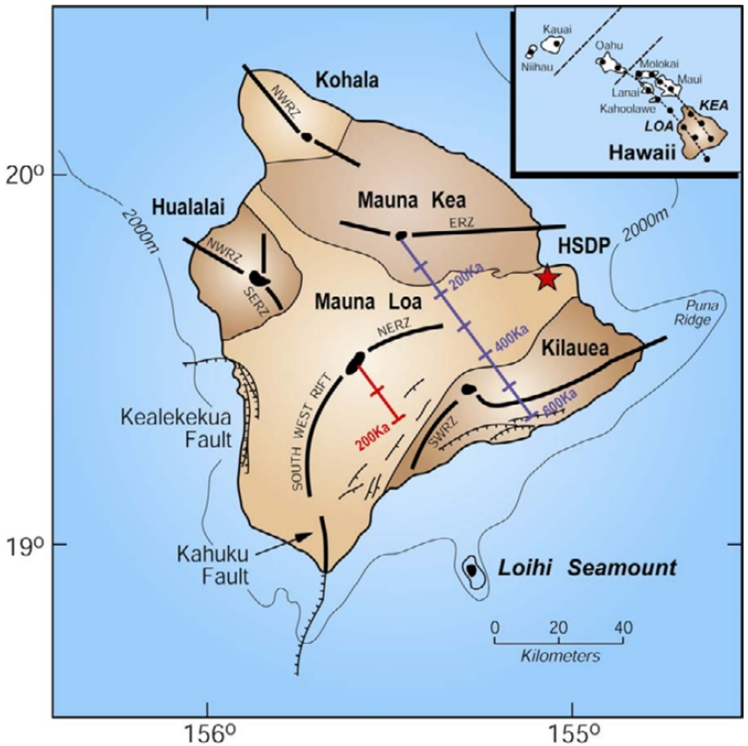
For Loihi, *Abouchami et al., 2005; Ren et al.,2009*. For Mauna Loa submarine, *Weis et al. 2011*.

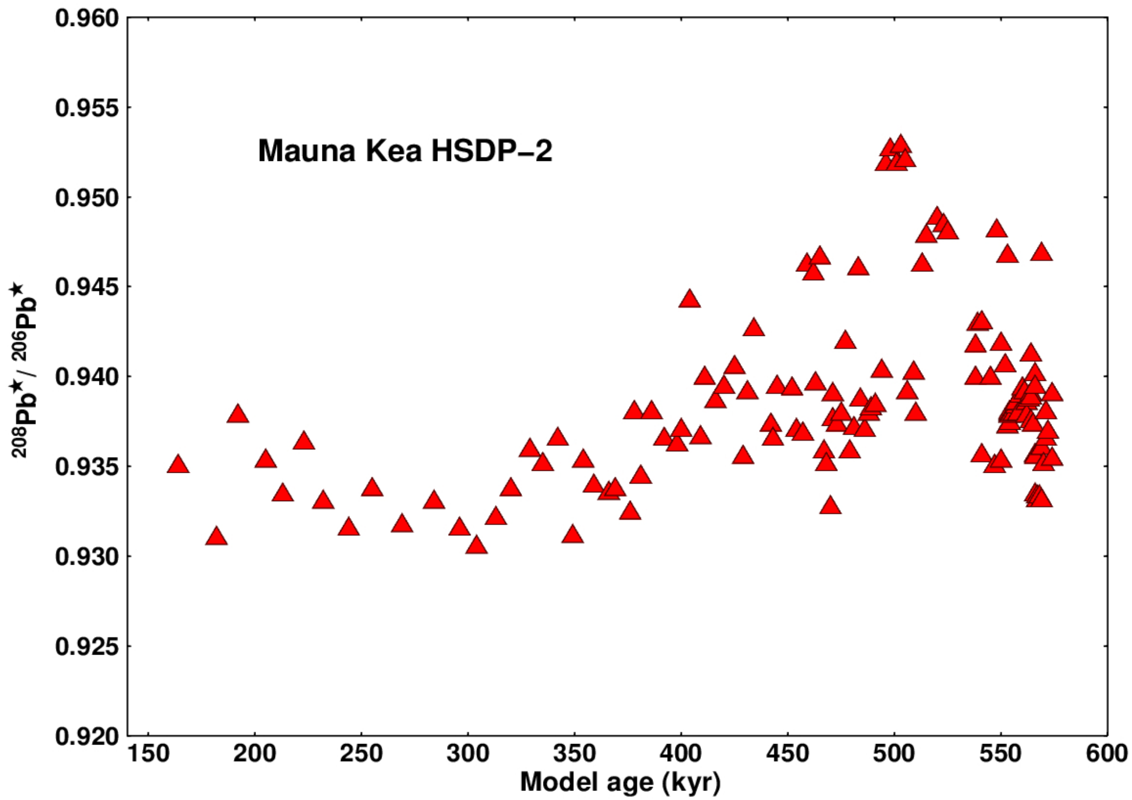
For Mauna Loa late-shield, HSDP *Abouchami et al. 2000*; historic and pre-historic *Weis et al. 2011*.

For Hualalai shield, *Yamasaki et al., 2009*.

For Hualalai post-shield, *Hanano et al., 2010.*

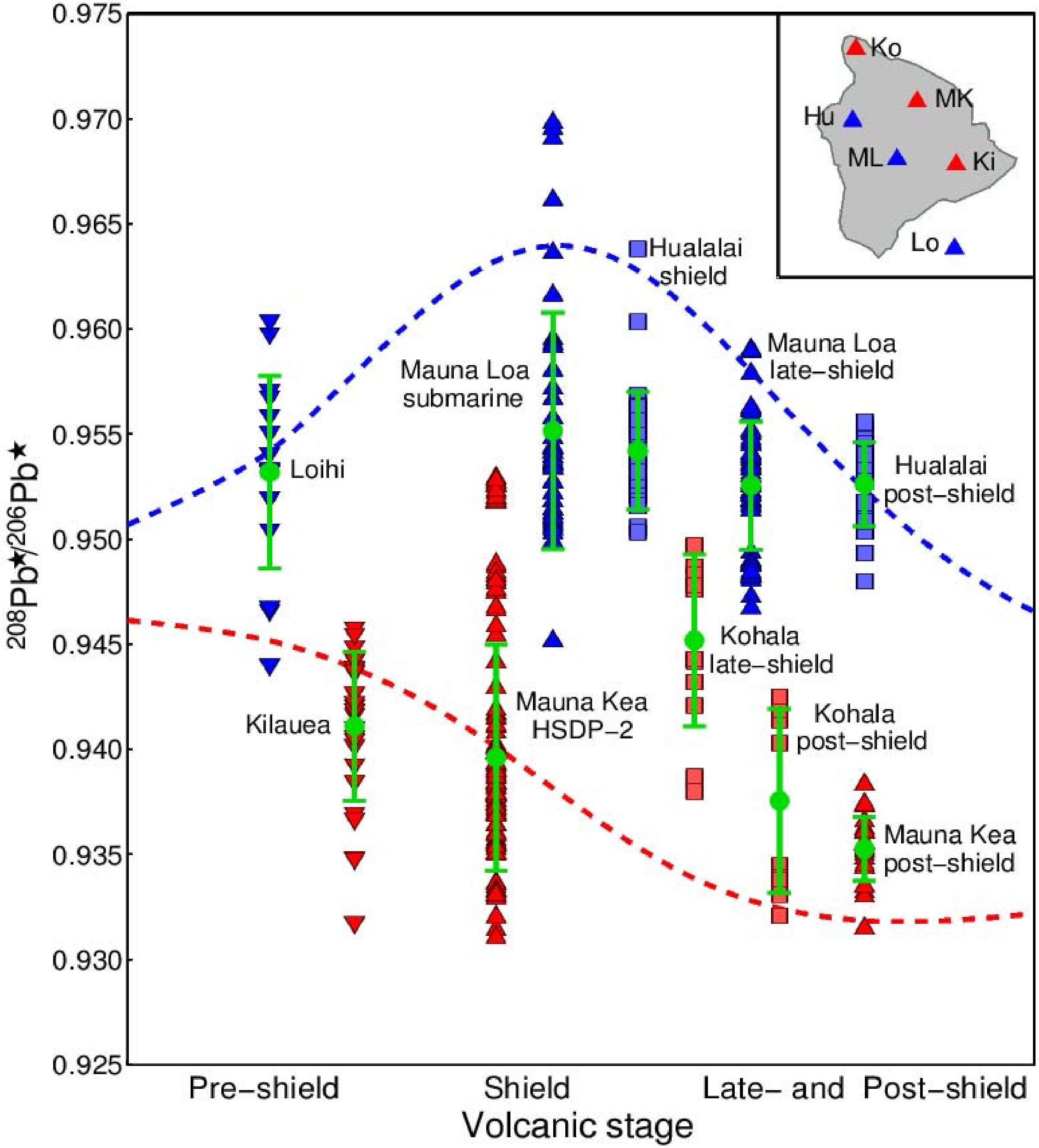
$^{208}Pb^*$ / $^{206}Pb^*$ model predictions and observations: Kea-trend





- Hawaii Scientific Drilling Project (HSDP-2) : provides the isotopic evolution of Mauna Kea over the last 600 kyr.
- Older lavas do have higher $^{208}Pb^*$ / $^{206}Pb^*$, in agreement with model predictions

$^{208}Pb^* / ^{206}Pb^*$ model predictions and observations: Kea-trend



The predicted decreasing trend from shield to post-shield is consistent with observations for Mauna Kea and Kohala.

Our model, with a deep (TBL) southward increase in $^{208}Pb^* / ^{206}Pb^*$ can explain observed trends on long time-scales (> 300 ky) for all six Big Island volcanoes.

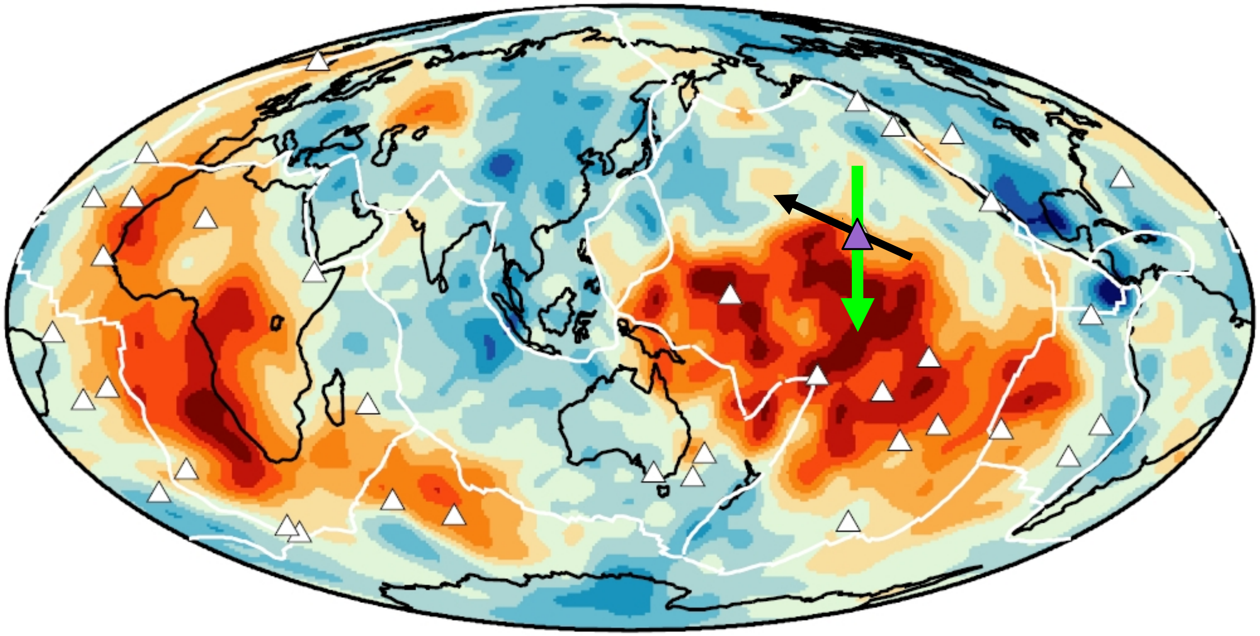
Used data: For Kilauea, *Abouchami et al., 2005; Tanaka and Nakamura, 2005.* For Mauna Kea Shield, *Eisele et al., 2003; Blichert-Toft and Albarède, 2009*. Post-shield *Hanano et al., 2010; Abouchami et al., 2005.*

For Kohala *Hanano et al., 2010; Abouchami et al., 2005.*

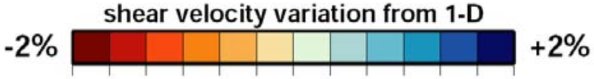
HAWAII

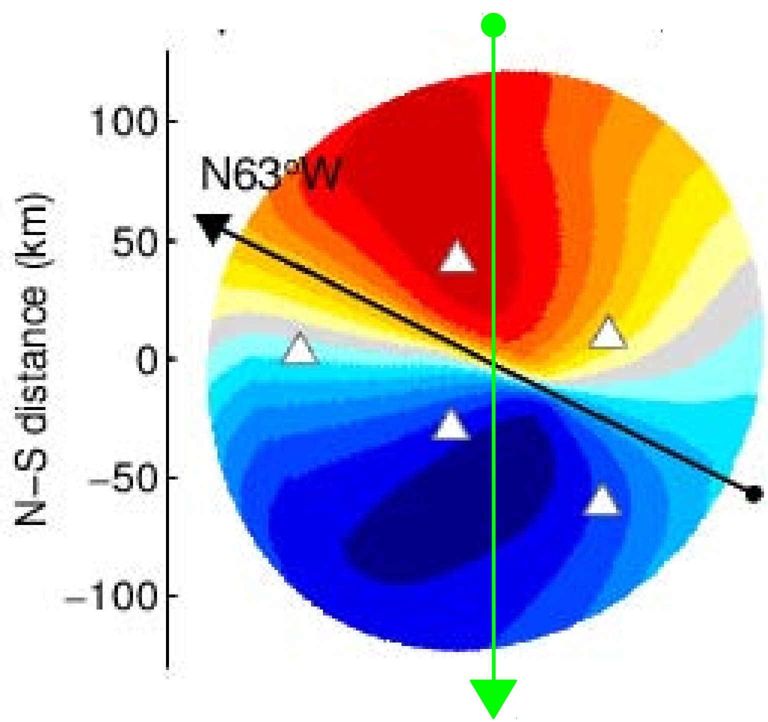
Deep mantle: a southward increase in $^{208}Pb^* / ^{206}Pb^*$ *(green arrow)*

Pacific plate motion: N63W *(black arrow)*

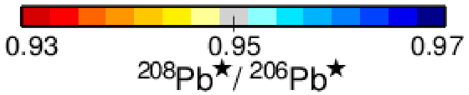


At 2800 km depth, by Ritsema et al., 2010





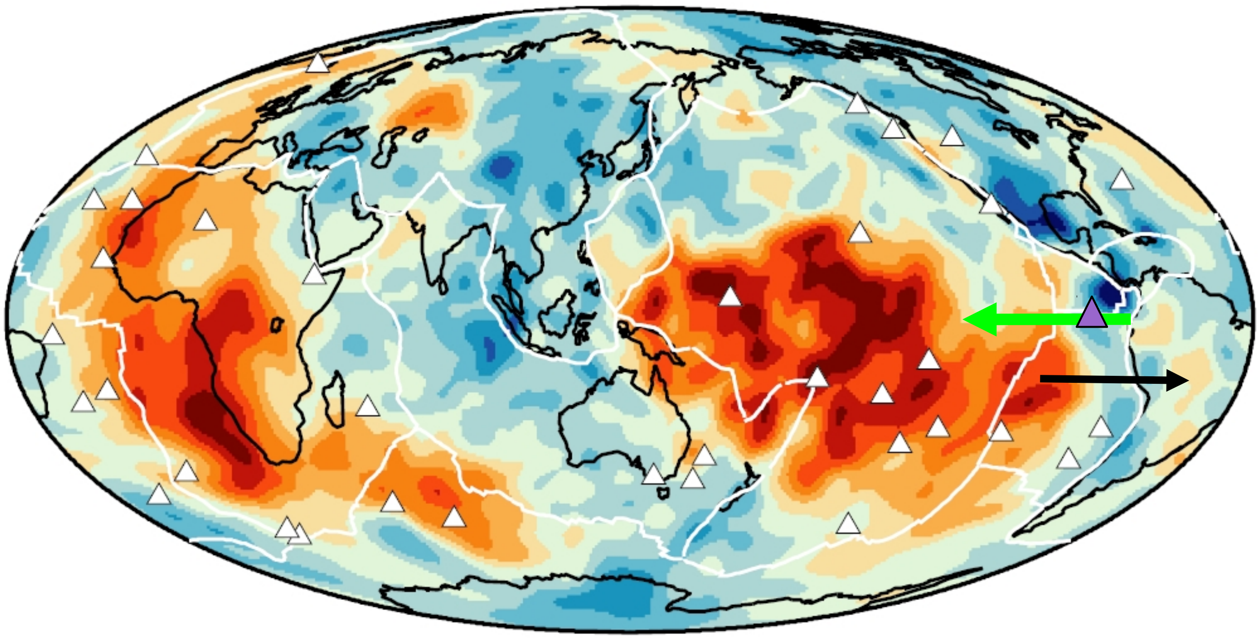
Predicted zonation: the volcanic chain to the south is geochemically enriched.



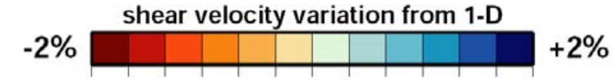
GALAPAGOS

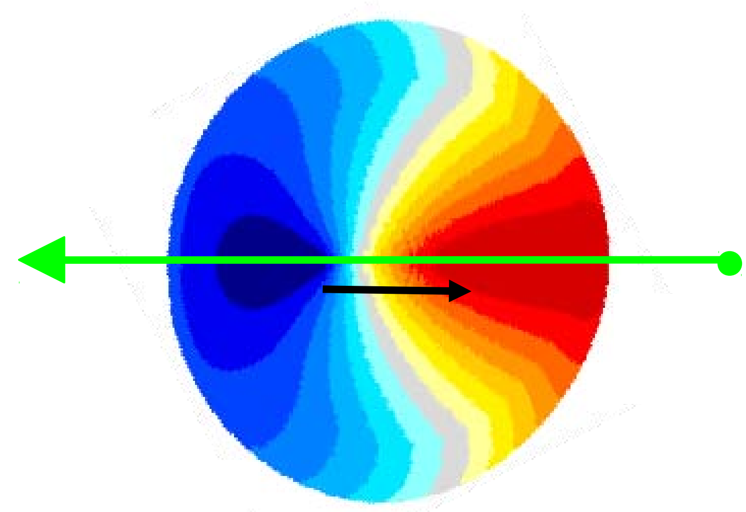
Deep mantle: a westward increase in $^{208}Pb^* / ^{206}Pb^*$ *(green arrow)*

Nazca plate motion: to the East *(black arrow)*

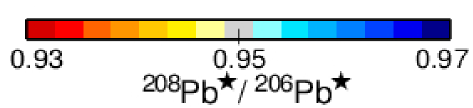


At 2800 km depth,
by Ritsema et al., 2010





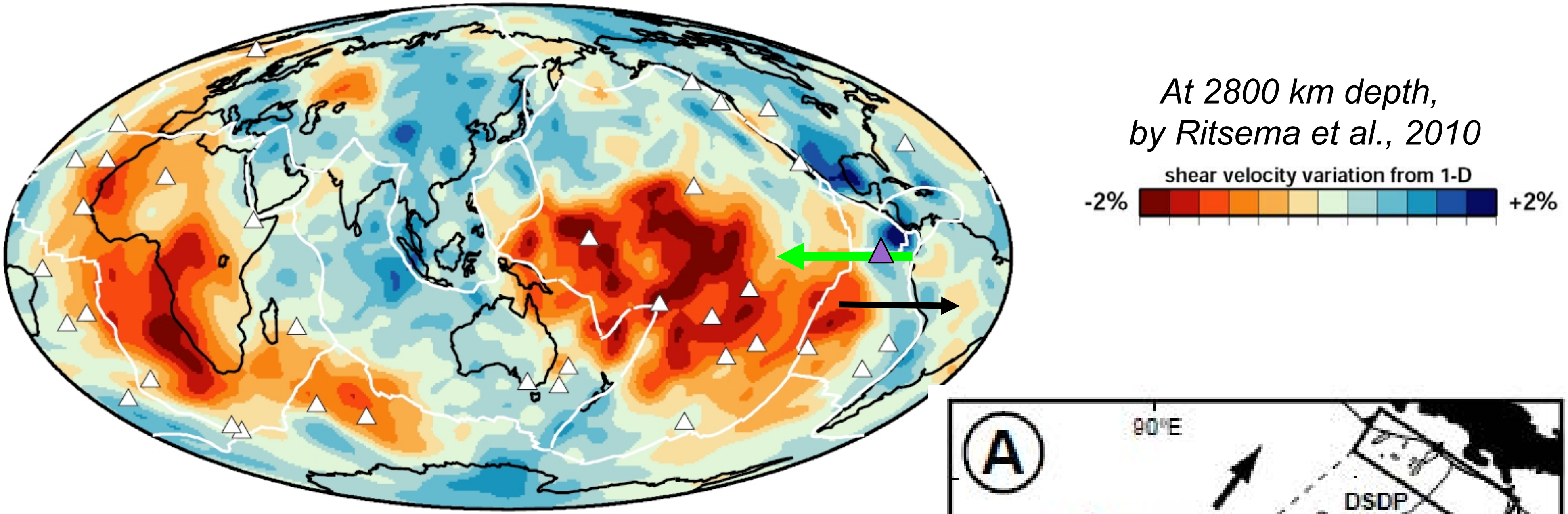
Predicted zonation: remindful of the observed 'horseshoe-shaped' region of enriched material to the west

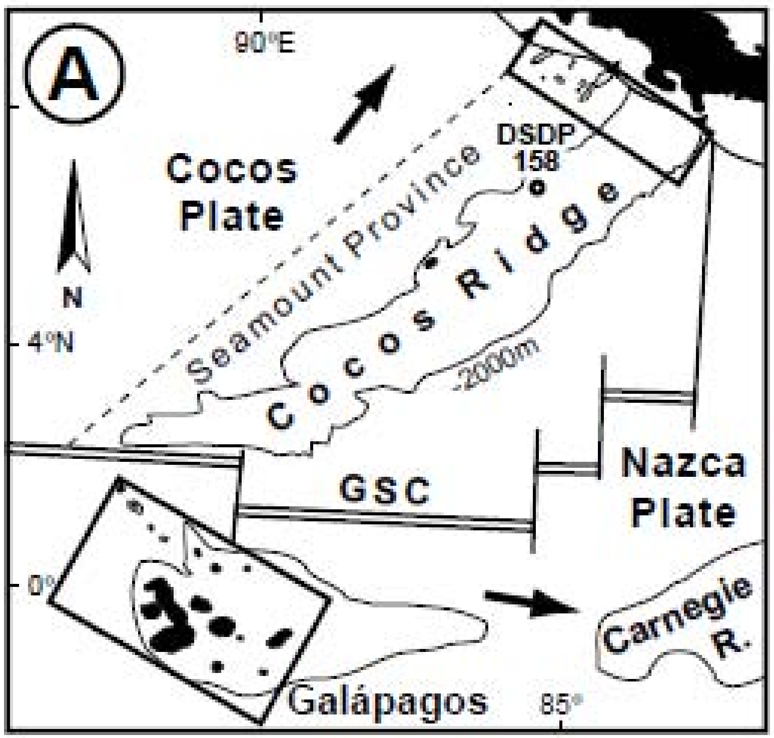


GALAPAGOS

Deep mantle: a westward increase in $^{208}Pb^* / ^{206}Pb^*$ *(green arrow)*

Nazca plate motion: to the East *(black arrow)*





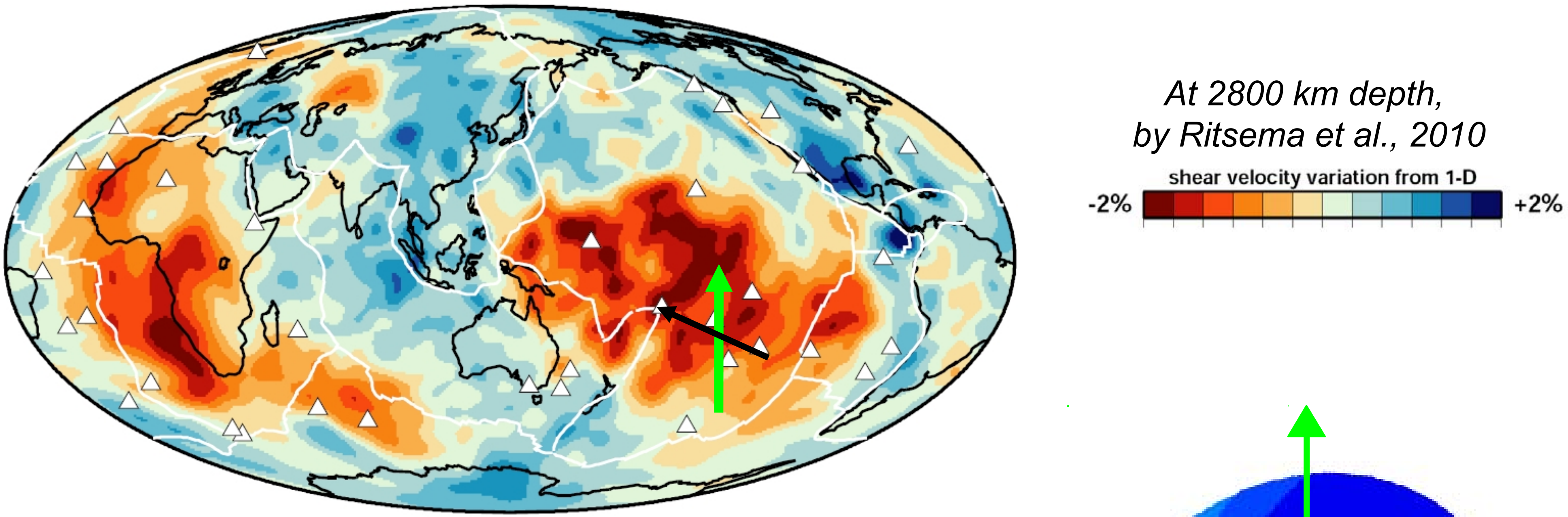
Geochemical zonation of the Galapagos plume for, at least, 14 Myr

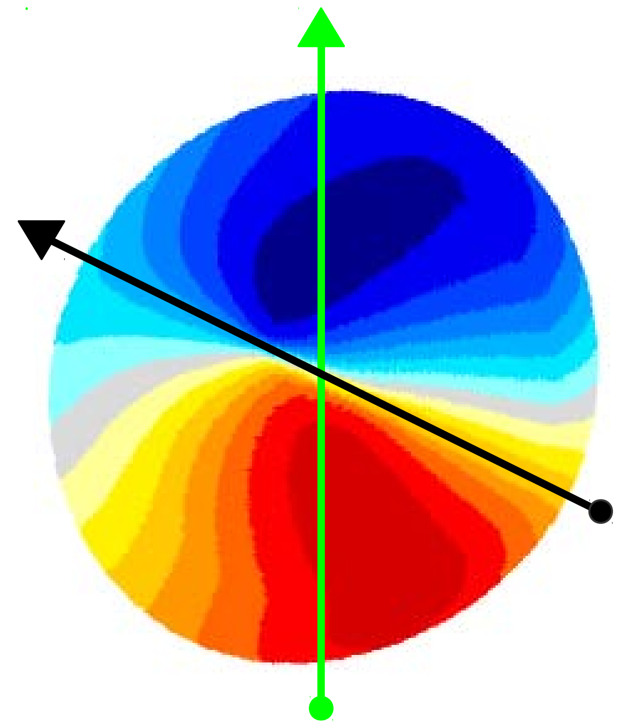
[Hoernle et al, Geology 2000]

SOCIETIES and nearby hotspots

Deep mantle: a northtward increase in $^{208}Pb^* / ^{206}Pb^*$ (green arrow)

Pacific plate motion: N63W *(black arrow)*





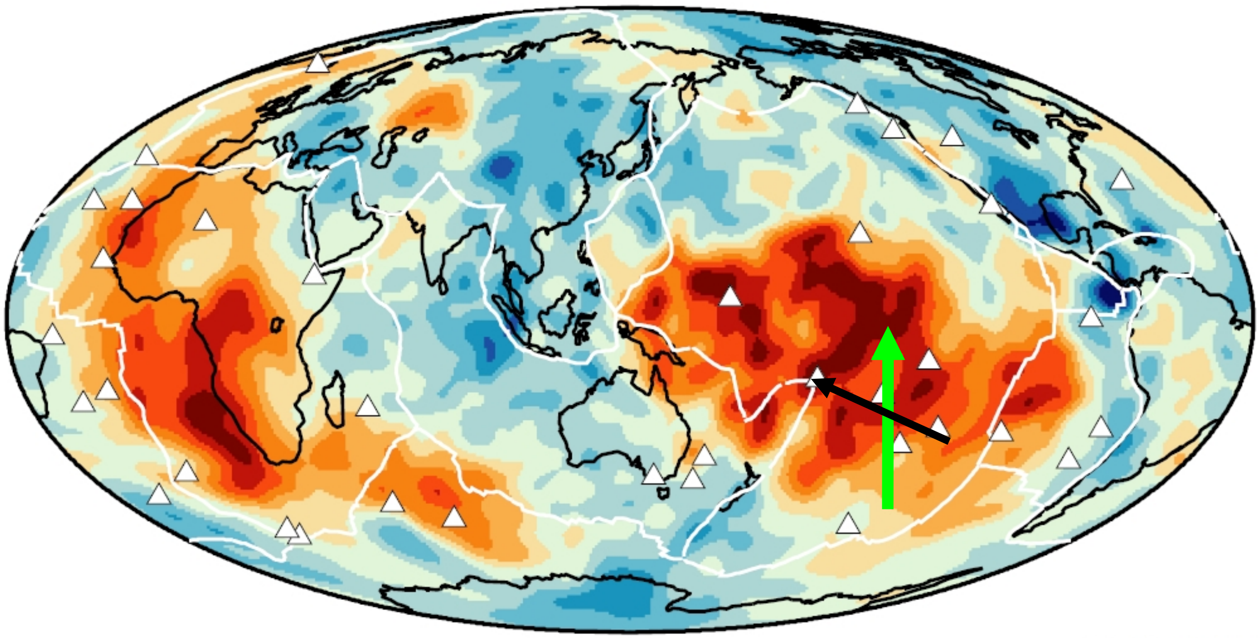
Predicted zonation:
the volcanic chain to the north is geochemically enriched.

in agreement with Payne Jackson, Hall's work on Societies double volcanic chains *[2012, submitted Geology]*.

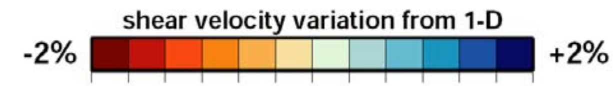
SOCIETIES and nearby hotspots

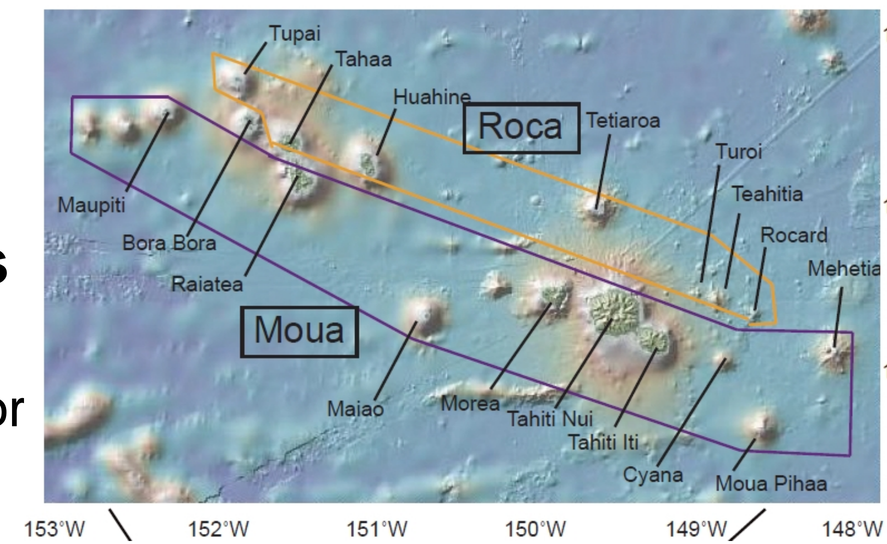
Deep mantle: a northward increase in $^{208}Pb^* / ^{206}Pb^*$ (green arrow)

Pacific plate motion: N63W *(black arrow)*



At 2800 km depth,
by Ritsema et al., 2010





Predicted zonation:
the volcanic chain to the north is geochemically enriched.

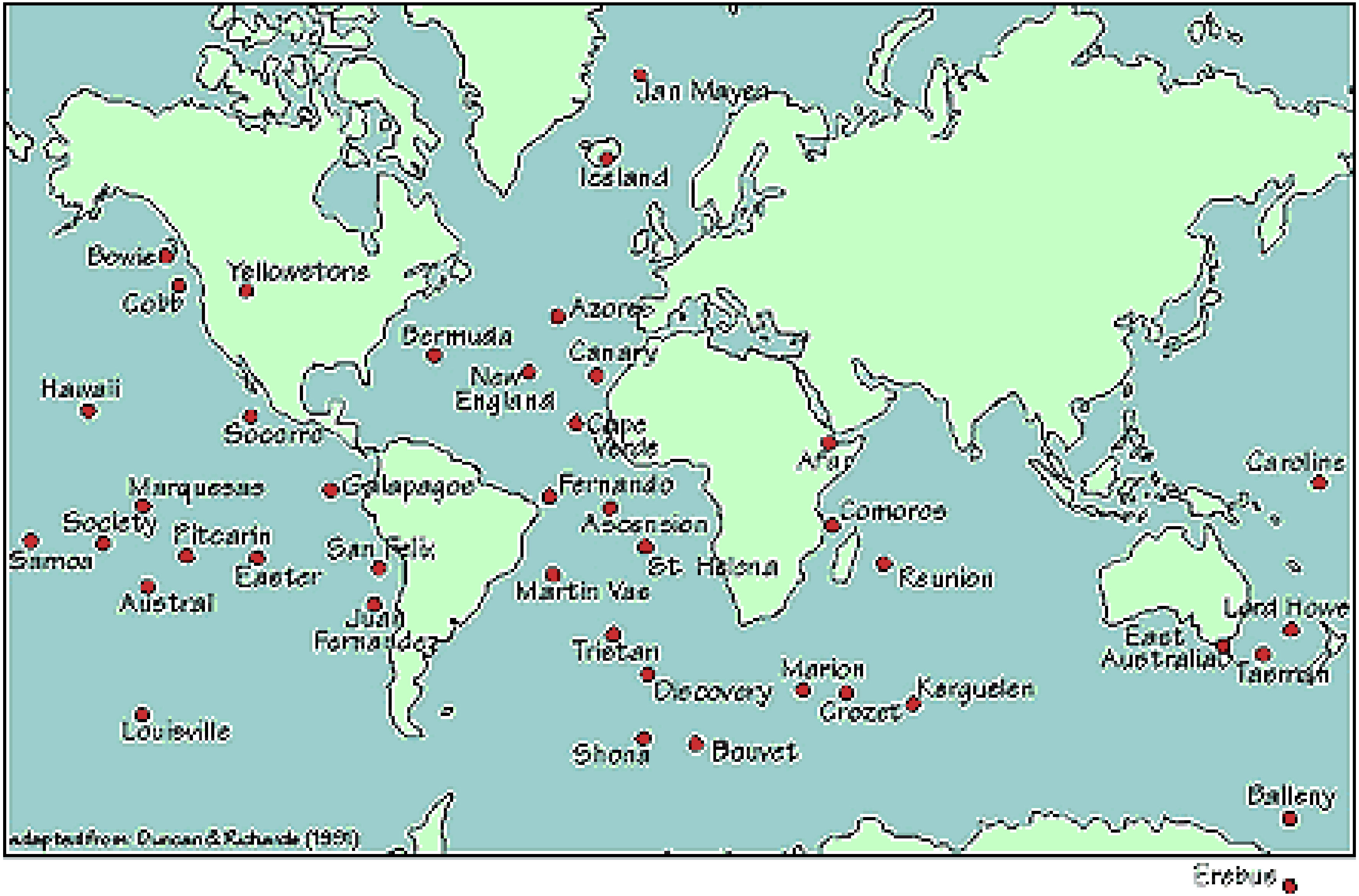
in agreement with Payne Jackson, Hall's wor
on Societies double volcanic chains
[2012, submitted Geology].

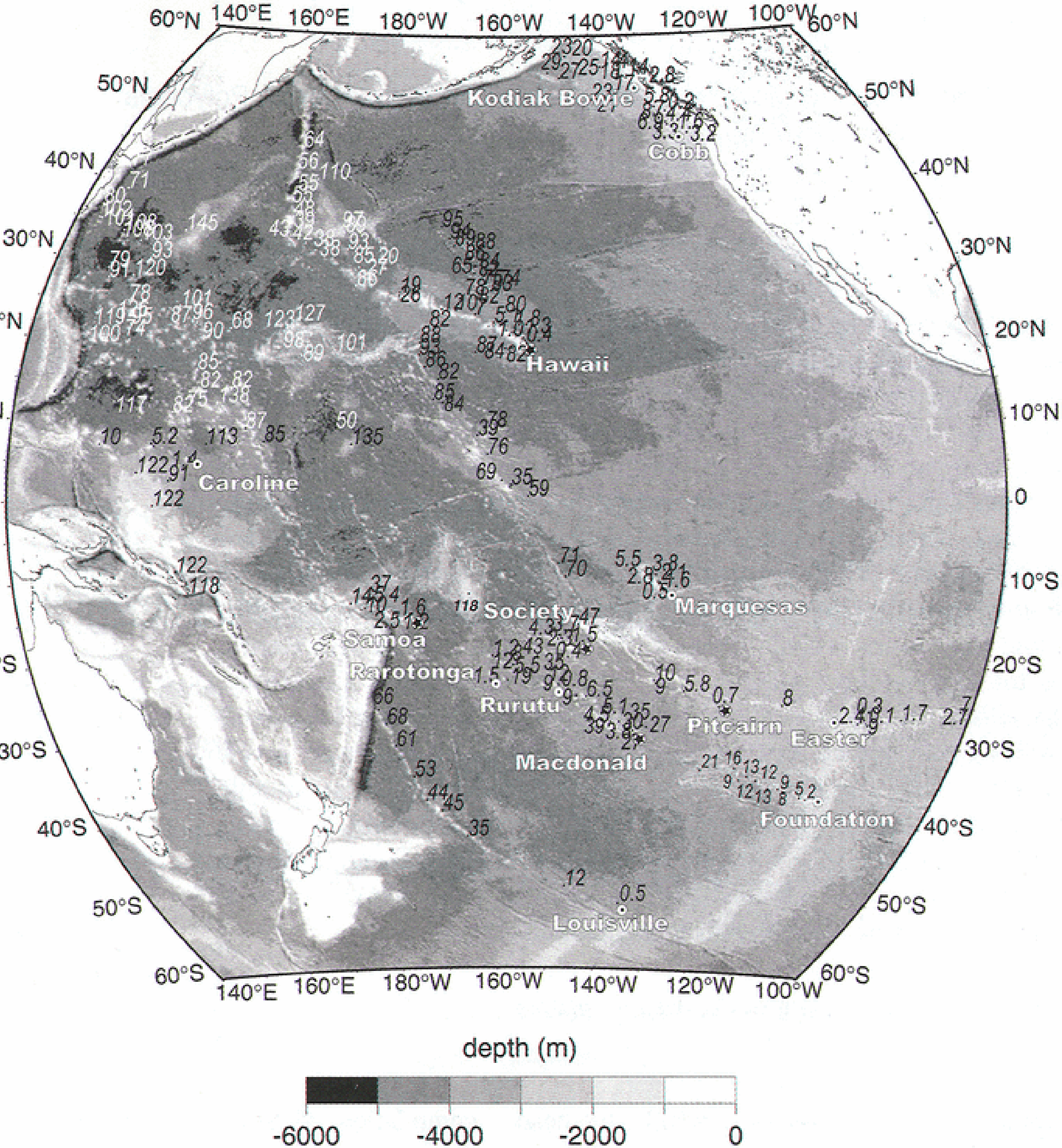
Conclusions

The geochemical zonation observed at Hawaii, and at other Pacific hotspots, reflects large-scale heterogeneities in the deep mantle, source region of plumes.

The modeled large-scale increase of $^{208}Pb^* / ^{206}Pb^*$ in the deep mantle generates: (1) a *'lobate'* zonation of the plume conduit, (2) distinct $^{208}Pb^* / ^{206}Pb^*$ between Kea and Loa-trend volcanoes.

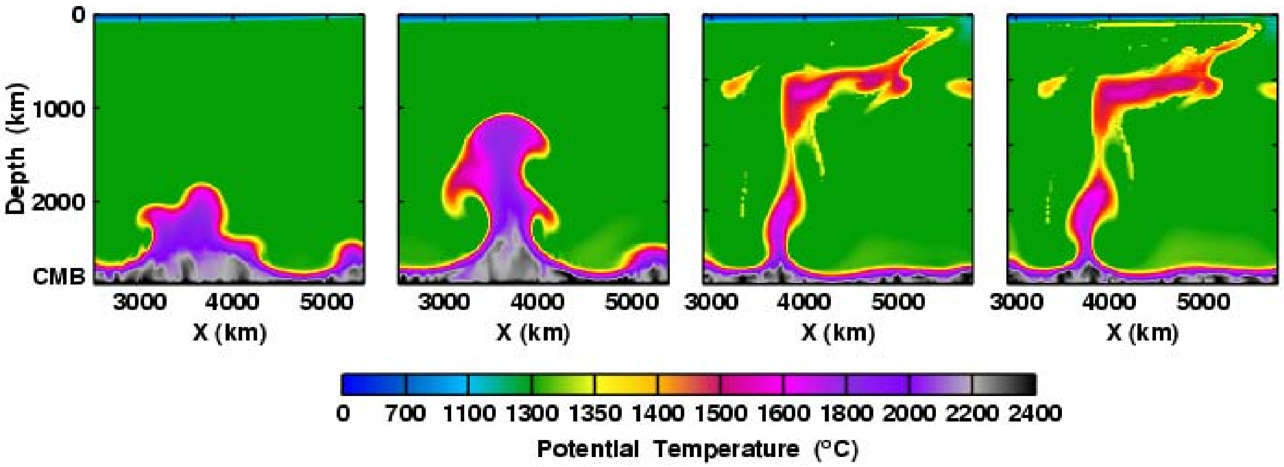
The predicted shield to post-shield evolution of $^{208}Pb^* / ^{206}Pb^*$ agrees with observations for all six Big Island volcanoes.


Jan Mayen
Iceland
Bowie
Yellowstone
Cobb
Azores
Bermuda
Canary
New England
Hawaii
Socorro
Cape Verde
Afar
Caroline
Marquesas
Galapagos
Fernando
Comores
Society
Pitcairn
Ascension
Samoa
San Felix
Easter
St. Helena
Reunion
Austral
Martin Vas
Juan Fernandez
Lord Howe
East Australia
Tasman
Tristan
Marion
Discovery
Kerguelen
Crozet
Louisville
Shona
Bouvet
Balleny
adapted from: Duncan & Richards (1991)
Erebus



Kodiak
Bowie
Cobb
Hawaii
Caroline
Society
Marquesas
Samoa
Rarotonga
Rurutu
Pitcairn
Easter
Macdonald
Foundation
Louisville
60°N
50°N
40°N
30°N
20°N
10°N
0
10°S
20°S
30°S
40°S
50°S
60°S
140°E
160°E
180°W
160°W
140°W
120°W
100°W
depth (m)
-6000
-4000
-2000
0

Plume ponding at 660 km depth ?
Yes, BUT what is the buoyancy flux of the upwelling material ?



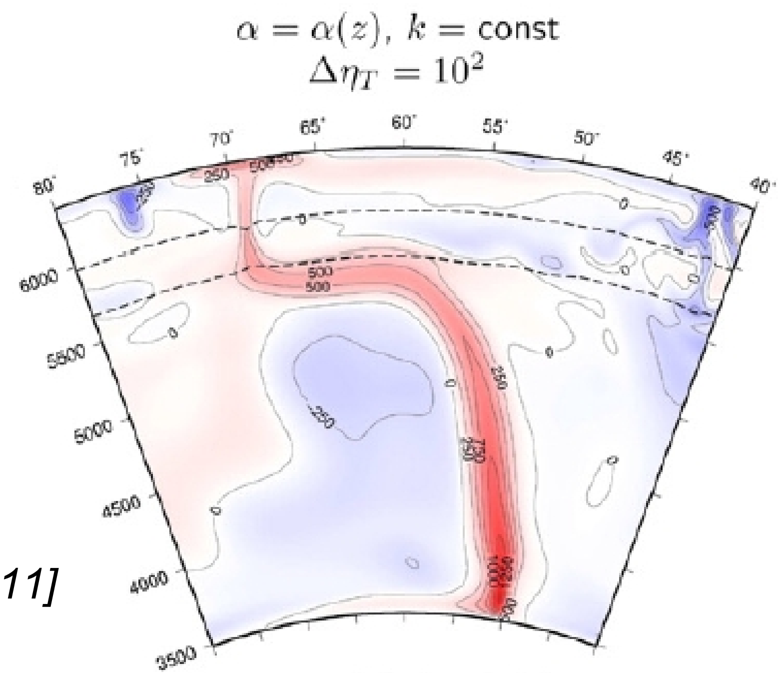
[Farnetani and Samuel, GRL, 2005]

- Our 3D simulations of thermo-chemical plumes show ponding at 660 km.

- However, the tendril's buoyancy flux is 0.1 times the Hawaiian buoyancy flux (6000-8000 kg/s).

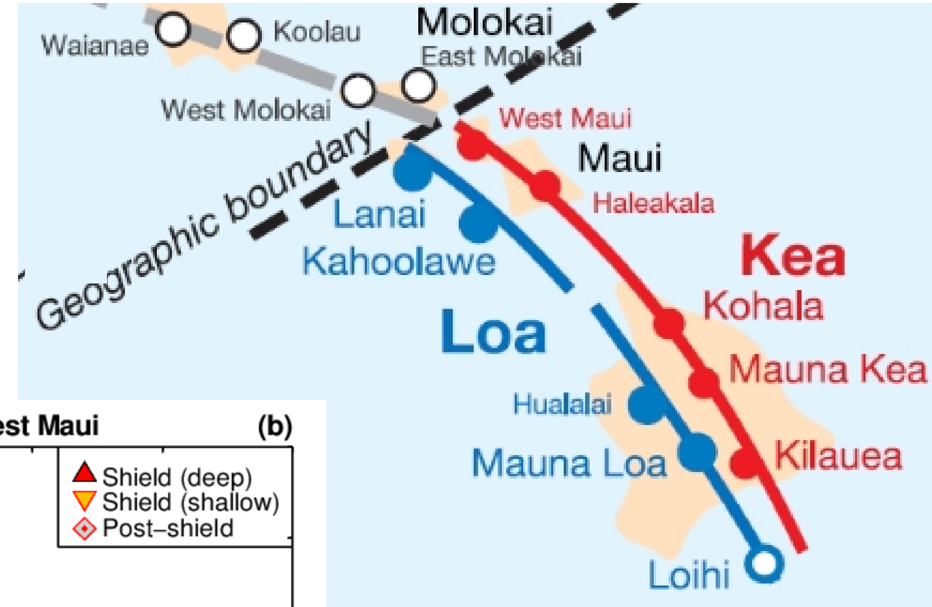
- Recent 2D simulations by *Tosi and Yuen* show that, under specific conditions, also thermal plume can be bent-shaped. Estimated buoyancy flux 1900-4700 kg/s.

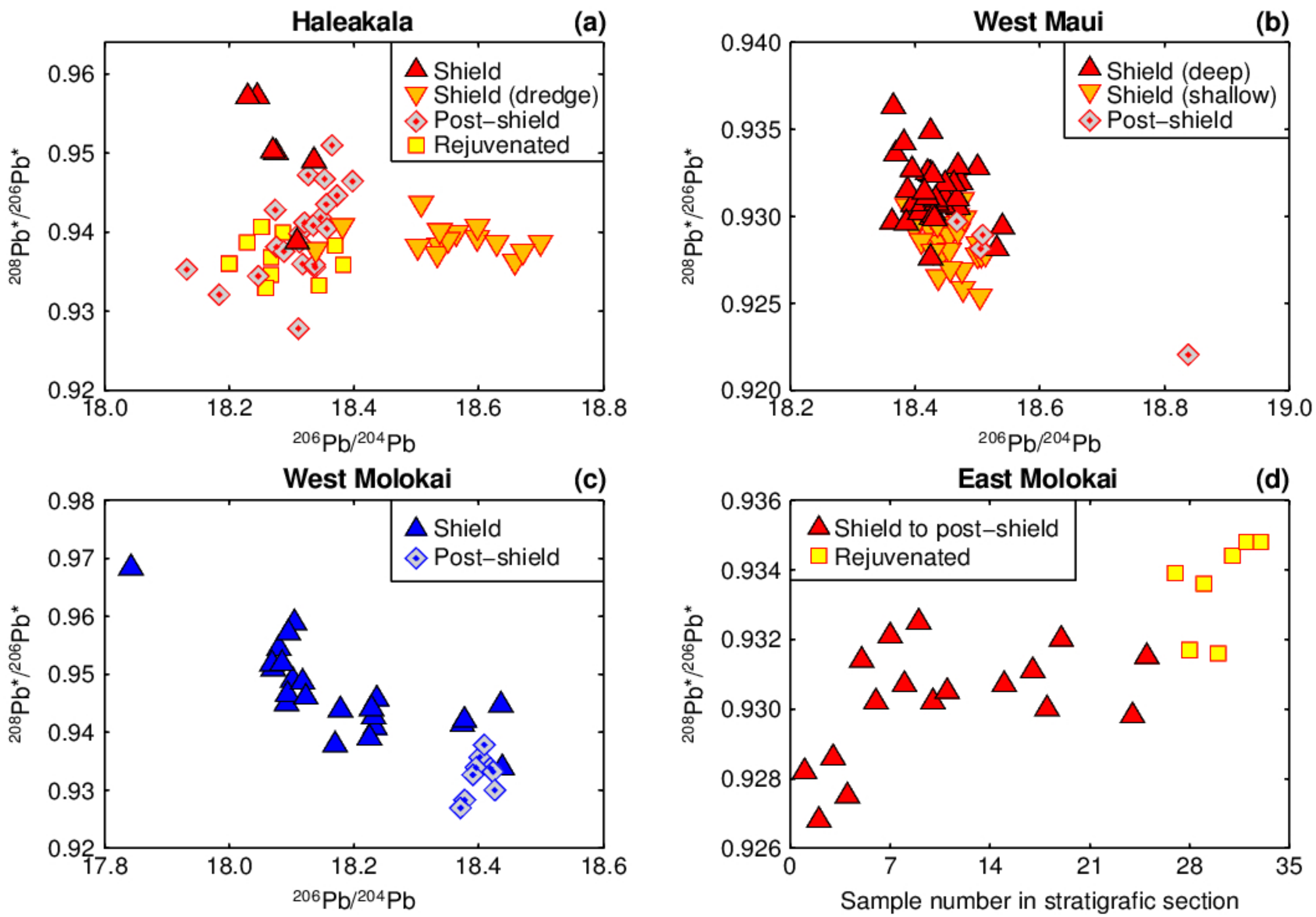
[Tosi and Yuen, EPSL, 2011]



$^{208}Pb^* / ^{206}Pb^*$ for older volcanoes ?

The predicted decreasing trend from shield to post-shield is still observed. Only exception: East Molokai....

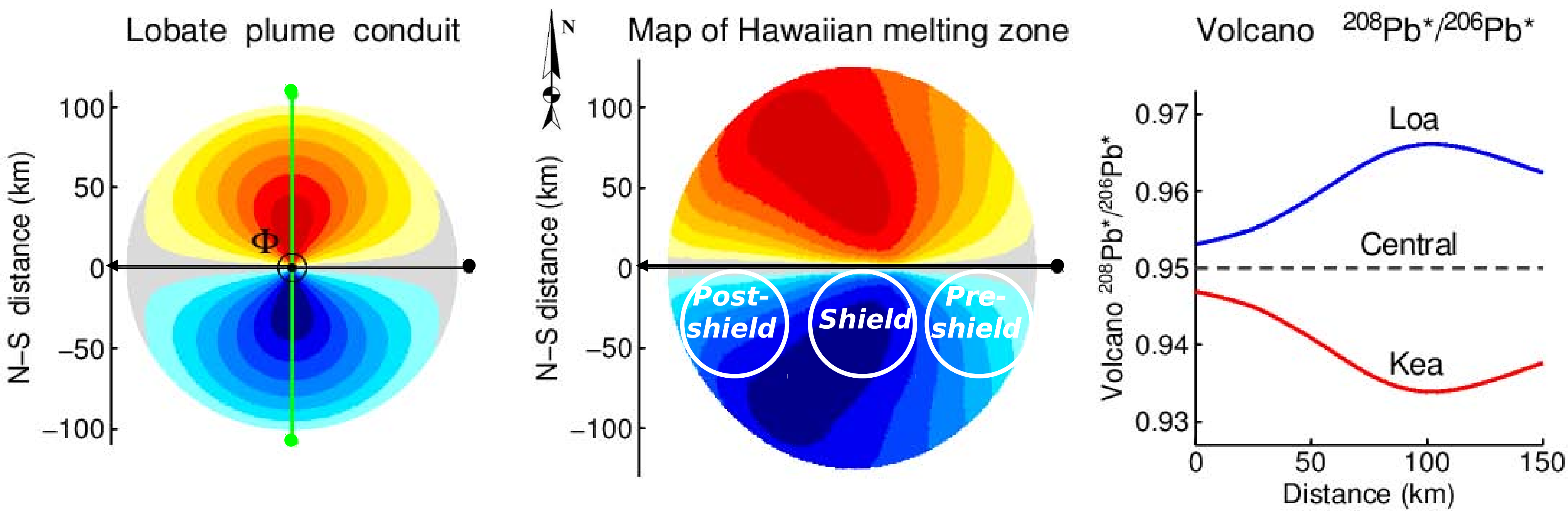




.... caused by a change in absolute plate motion?

For Haleakala: *Chen et al. 1991; Ren et al. 2006; West and Leeman 1987*. For West Maui: *Gaffney et al., 2004*. For West Molokai: *Xu et al., 2007*. For East Molokai: *Xu et al., 2005.*

Testing the effect of a more westerly plate motion direction in the past

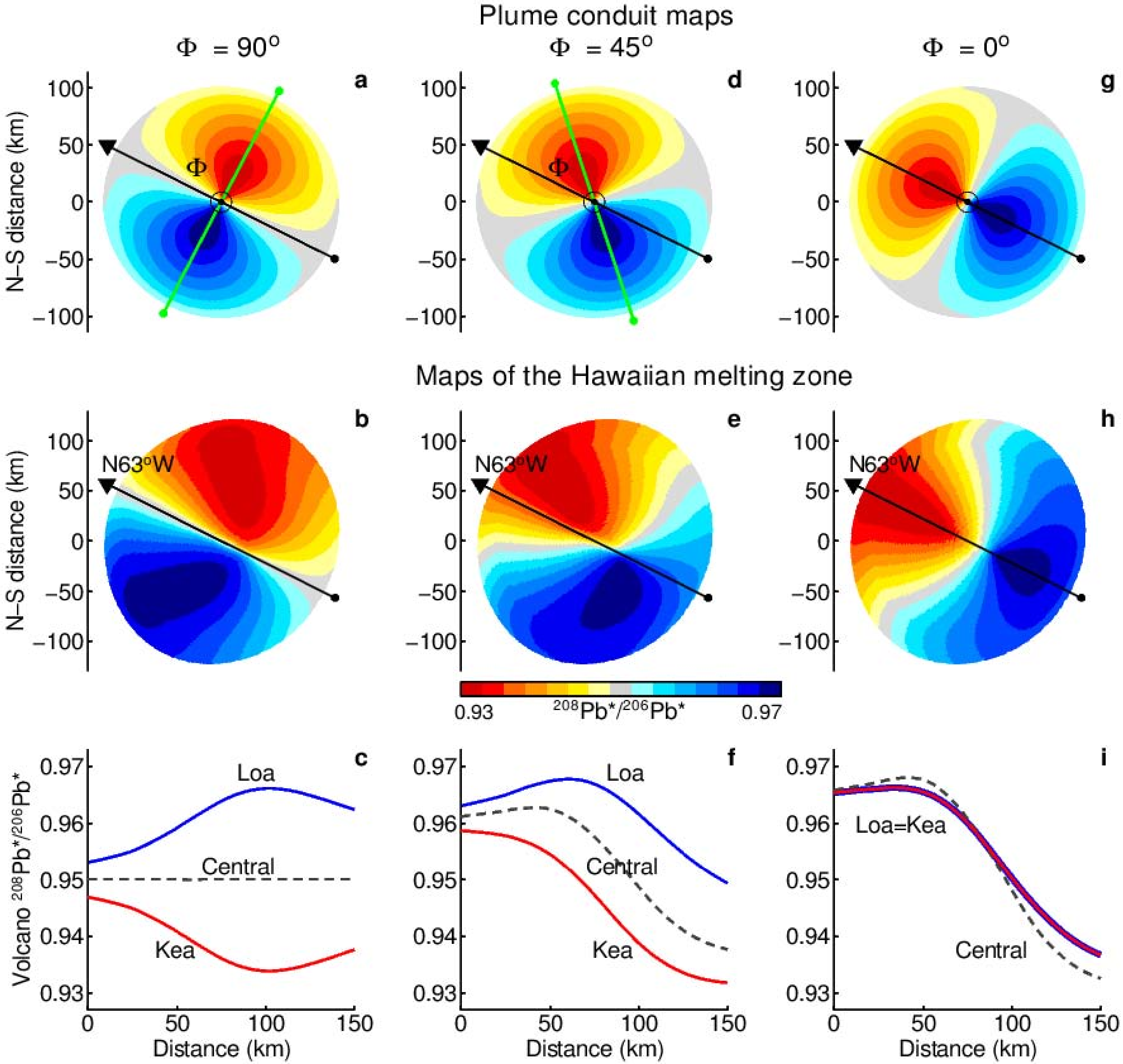


Direction of maximum gradient in the plume conduit (and in the TBL): N-S
Plate motion direction: E-W. Angle Φ = 90°

§ Predict increasing $^{208}Pb^*/^{206}Pb^*$ for post-shield Kea trend volcano.
§ A possible explanation for East Molokai shield to post-shield observations?

Testing the effect of varying Φ

present day plate motion direction (N63°W)



Φ=90° Parallel volcanic chains have opposite $^{208}Pb^* / ^{206}Pb^*$ evolution. A central volcano, equally sampling the two sides, has constant $^{208}Pb^* / ^{206}Pb^*$.

Φ=45° Parallel volcanic chains are still distinct.

Φ=0° A new zonation appears. Parallel volcanic chains are identical.

Therefore, our previous results for Φ=63°, do not depend severely on the assumed N-S direction of maximum gradient.

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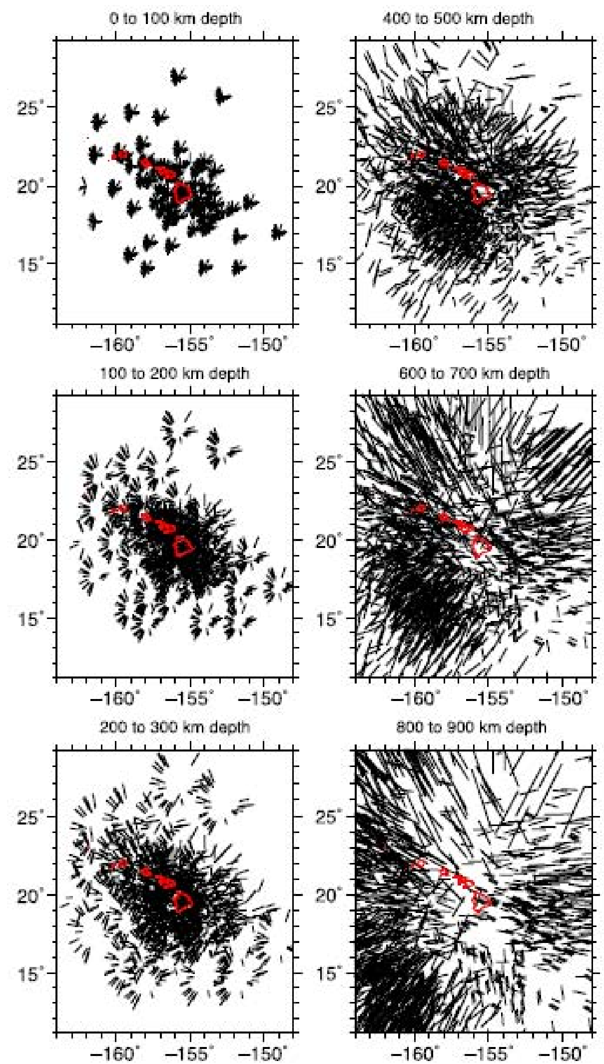
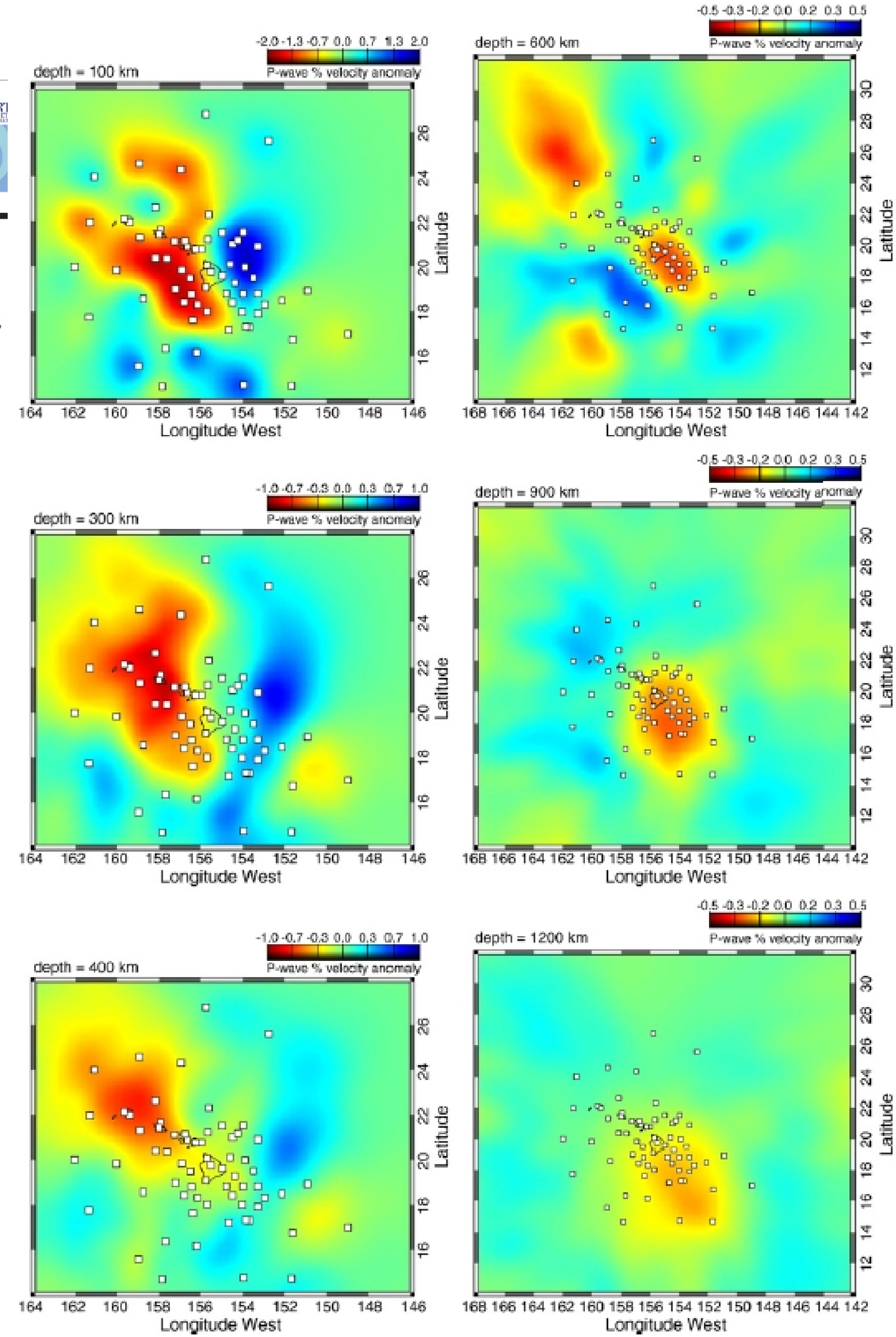
Mantle *P*-wave velocity structure beneath the Hawaiian hotspot

Cecily J. Wolfe [a,*], Sean C. Solomon [b], Gabi Laske [c], John A. Collins [d], Robert S. Detrick [d], John A. Orcutt [c], David Bercovici [e], Erik H. Hauri [b]



3. Wave-path coverage (0.05–0.1-Hz data) at intervals of depth between 0 and 900 km.



Geophysical Journal International

Geophys. J. Int. (2011) **187,** 1725–1742 doi: 10.1111/j.1365-246X.201

Asymmetric shallow mantle structure beneath the Hawaiian Swell—evidence from Rayleigh waves recorded by the PLUME network

Gabi Laske,[1] Amanda Markee,[1] John A. Orcutt,[1] Cecily J. Wolfe,[2] John A. Collins,[3] Sean C. Solomon,[4] Robert S. Detrick,[3] David Bercovici[5] and Erik H. Hauri[4]

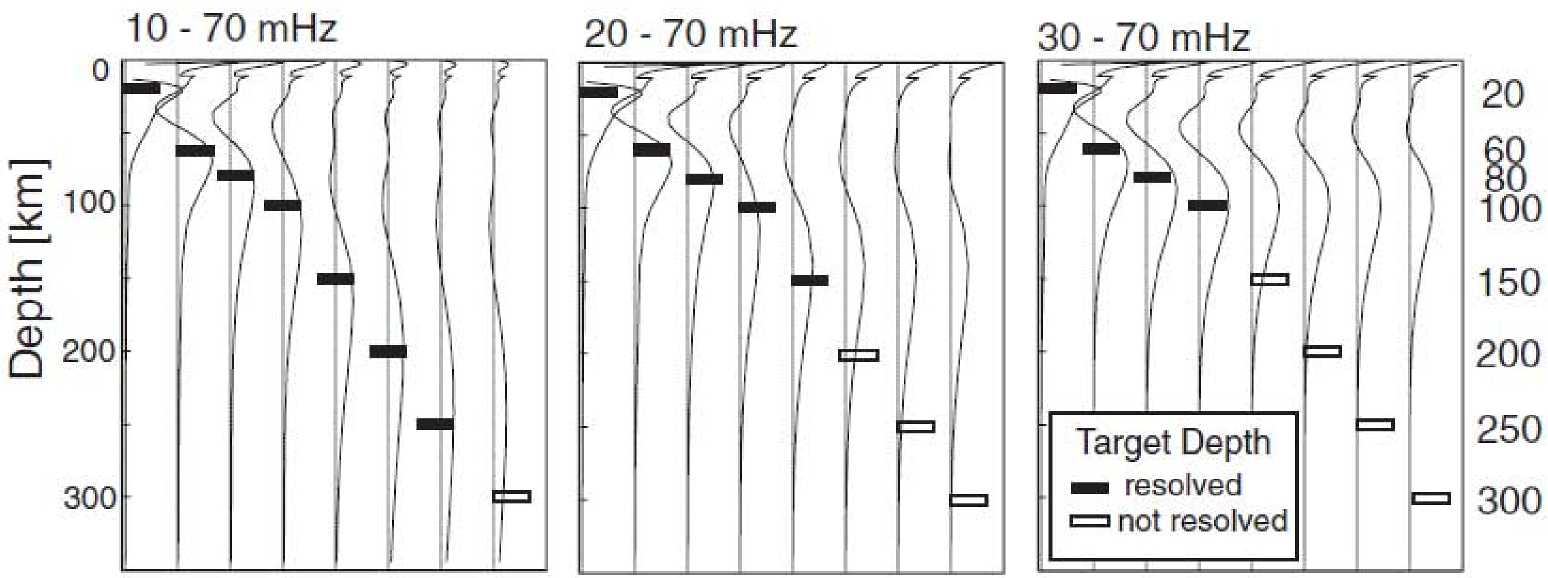


Figure 2. Backus–Gilbert resolving kernels for Rayleigh waves over three frequency ranges and for a given model error of 1 per cent. The eight kernels display the recovery of a δ-function at eight given target depths in kilometres (indicated by the numbers on the right). Rayleigh-wave phase velocity data at frequencies 10 mHz and above are capable of recovering structure down to 250 km depth.

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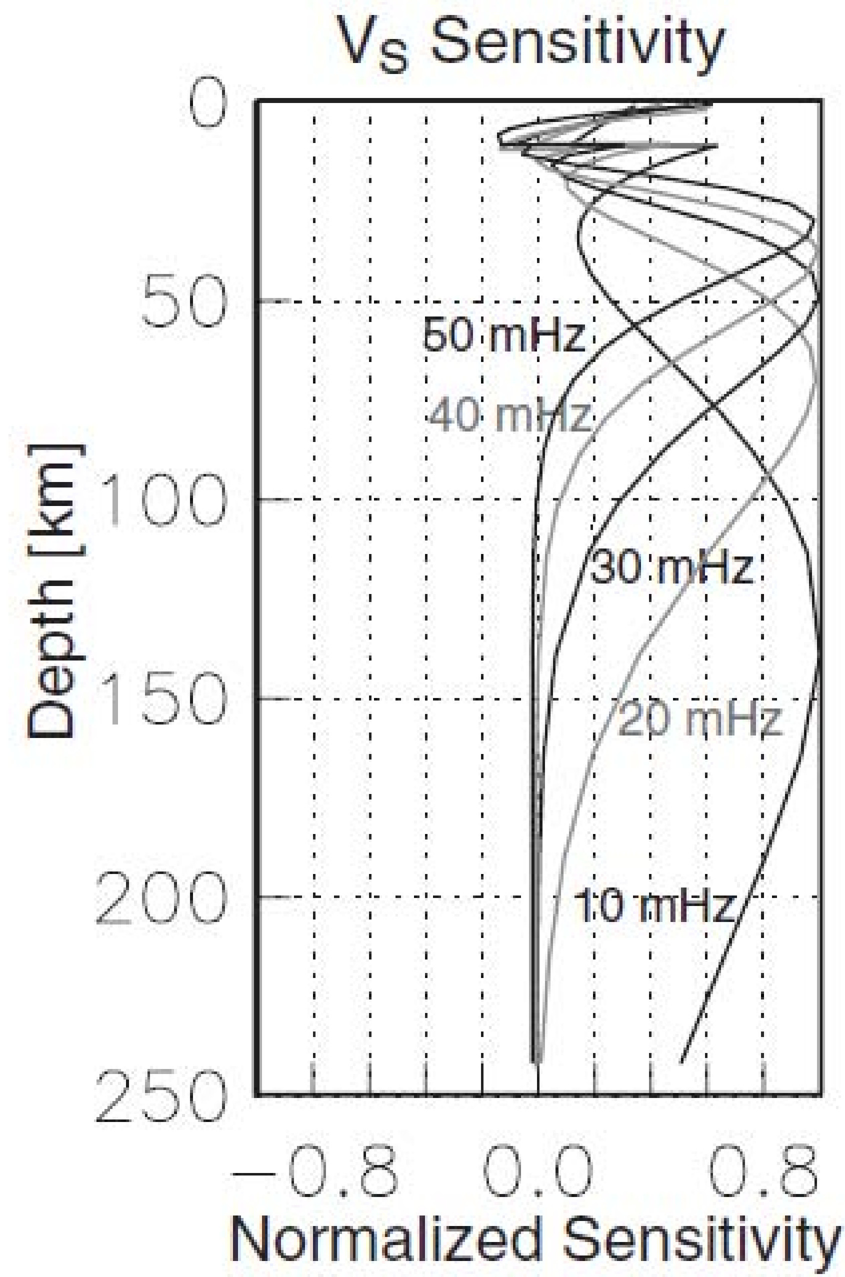

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doi: 10.1111/j.1365-246X.201

Asymm
Swell—
network

Gabi Lask
Sean C. Sc

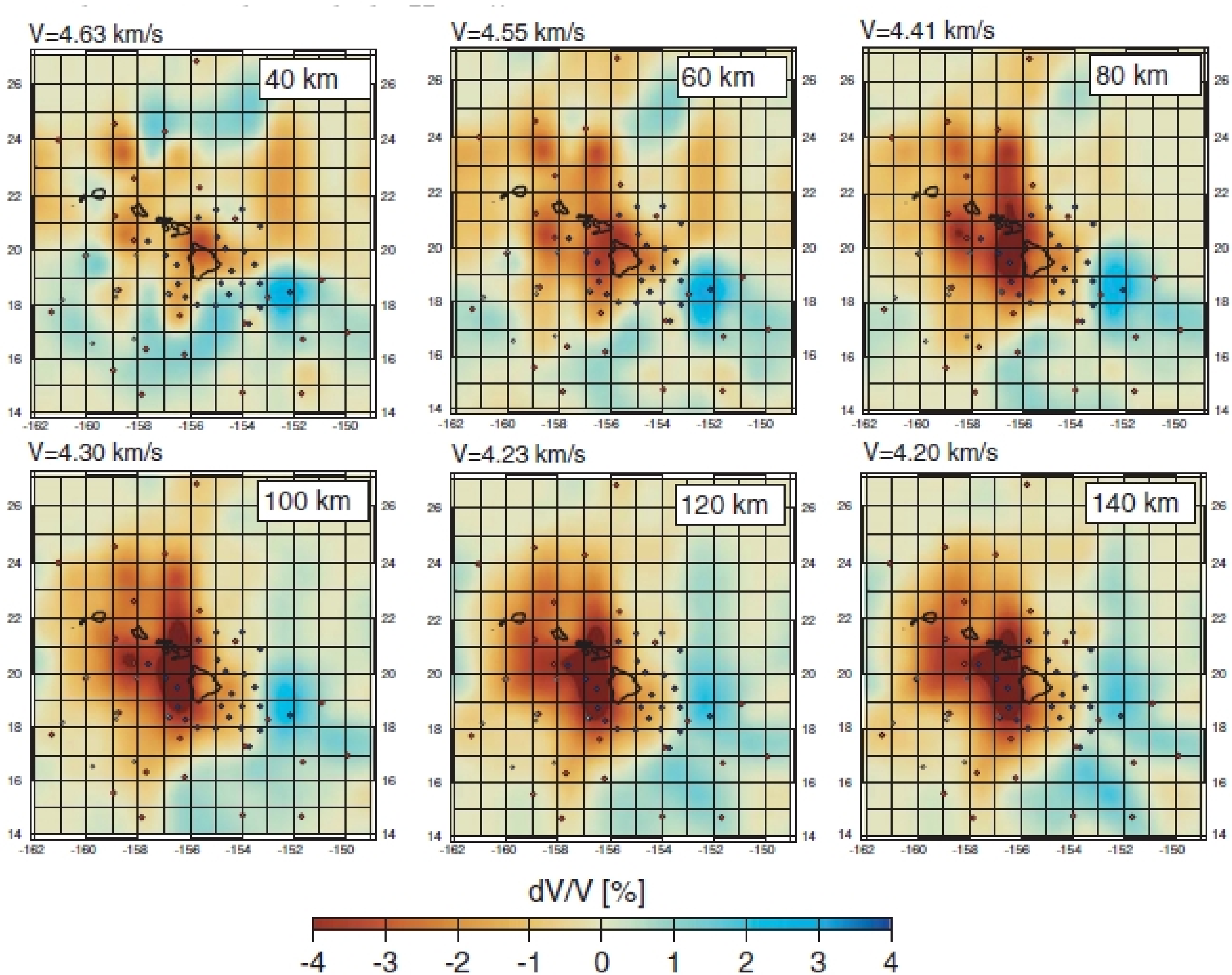
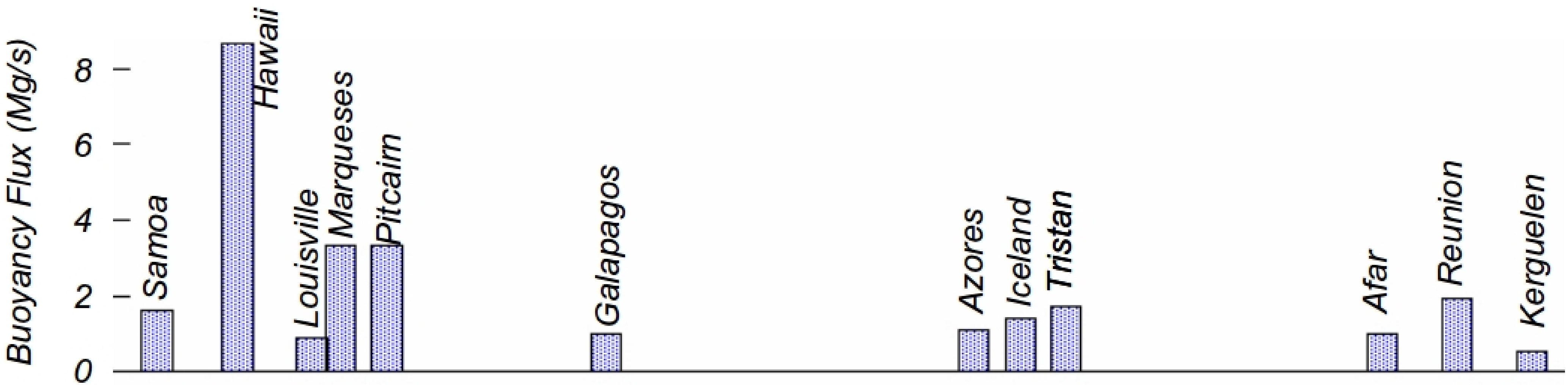


Figure 10. Model of shear velocity anomaly, dV_S/V_S, obtained from the inversion of PLUME data. For clarity in the panels, the subscript is omitted. The six panels show percentage perturbations to the reference model at depths between 40 and 140 km. The reference model is the modified N&F model for 52–100-Myr-old lithosphere (see text for details). The reference velocity at each depth is given above each panel. Different symbols mark the PLUME phase 1 (blue) and phase 2 (red) OBS sites. For reference, the sites of the SWELL pilot experiment are also shown (white). The phase velocity maps were not corrected for effects caused by bathymetry and crustal structure prior to the inversion.



Buoyancy Flux (Mg/s)
0
2
4
6
8
Samoa
Hawaii
Louisville
Marqueses
Pitcairn
Galapagos
Azores
Iceland
Tristan
Afar
Reunion
Kerguelen

$^{208}Pb^* / ^{206}Pb^*$ of Loa and Kea-trend volcanoes