Dismantling the Deep Earth: Geochemical Constraints from Hotspot Lavas for the Origin and Length scales of Mantle Heterogeneity

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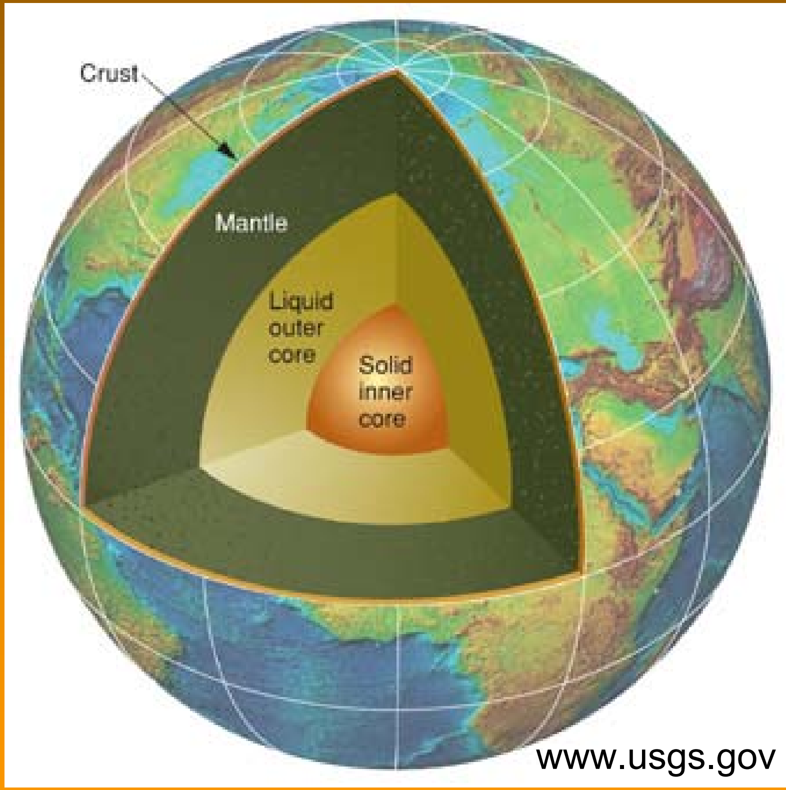
Composition and Evolution of the Earth's Mantle

- Earth's radius = 6370 km
- Earth's mantle = 2900 km (LA to Chicago)
- Continental crust = 35 km
- Oceanic crust = 6 km
- AGE = 4.567 Billion Years



Formidable depths and ages

First, a *caveat.*

In God's kitchen

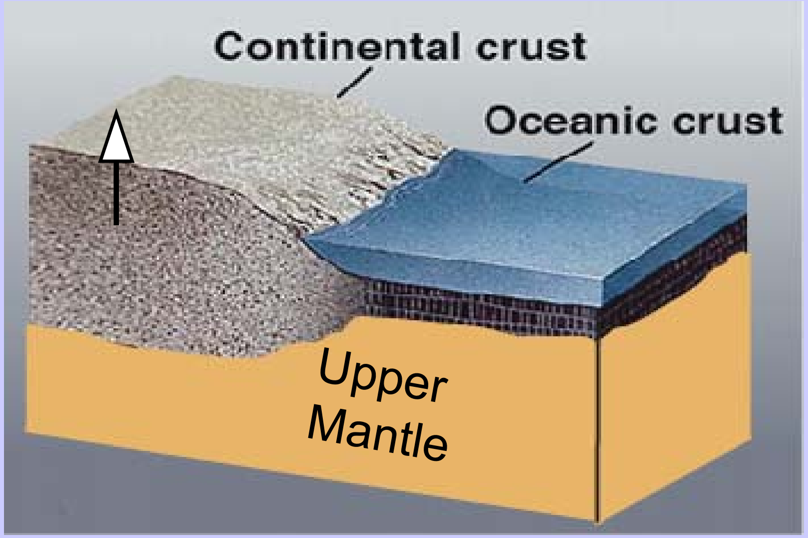
- We have little idea about the composition of the inside of the earth. ***We know almost NOTHING.***
- Why? Because it's really hard to dig deep holes.

"Indeed, what *can* be proved in the Earth Sciences?"

-C. Allègre
Phil. Trans. R. Soc. Lond. A
vol. 360, 2002

Scratching the surface, inferring (guessing) what's beneath!

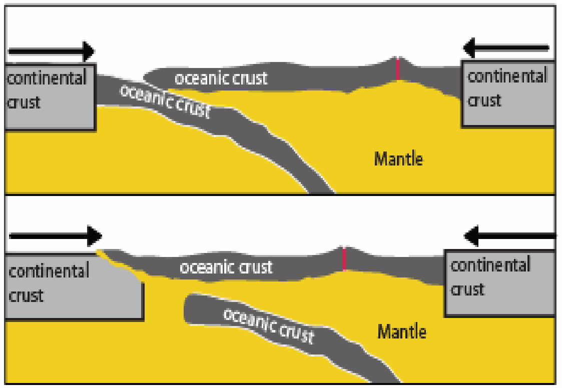
- The Soviet "Kola" drill hole
- ~12.3 km deep
- Drilled from 1970-1992
- Drilled continental crust.
- They got nowhere near mantle depths.



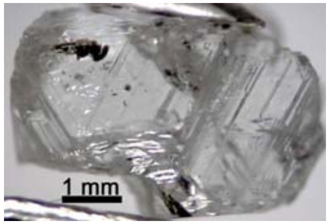
How do we know the mantle’s composition?

- **Xenoliths:** Pieces of the mantle can be entrained in magmas and brought to the surface.

- **Ophiolites:** Part of oceanic plate thrust onto continental margins.

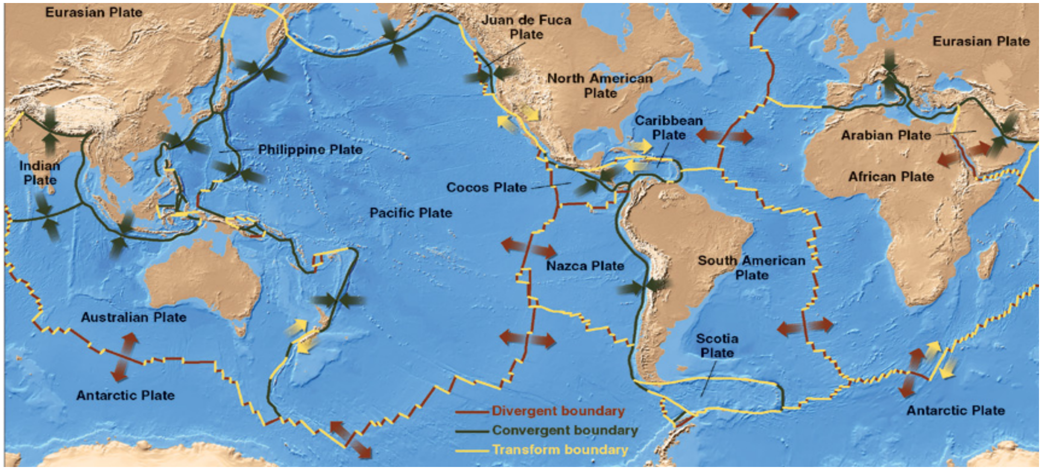


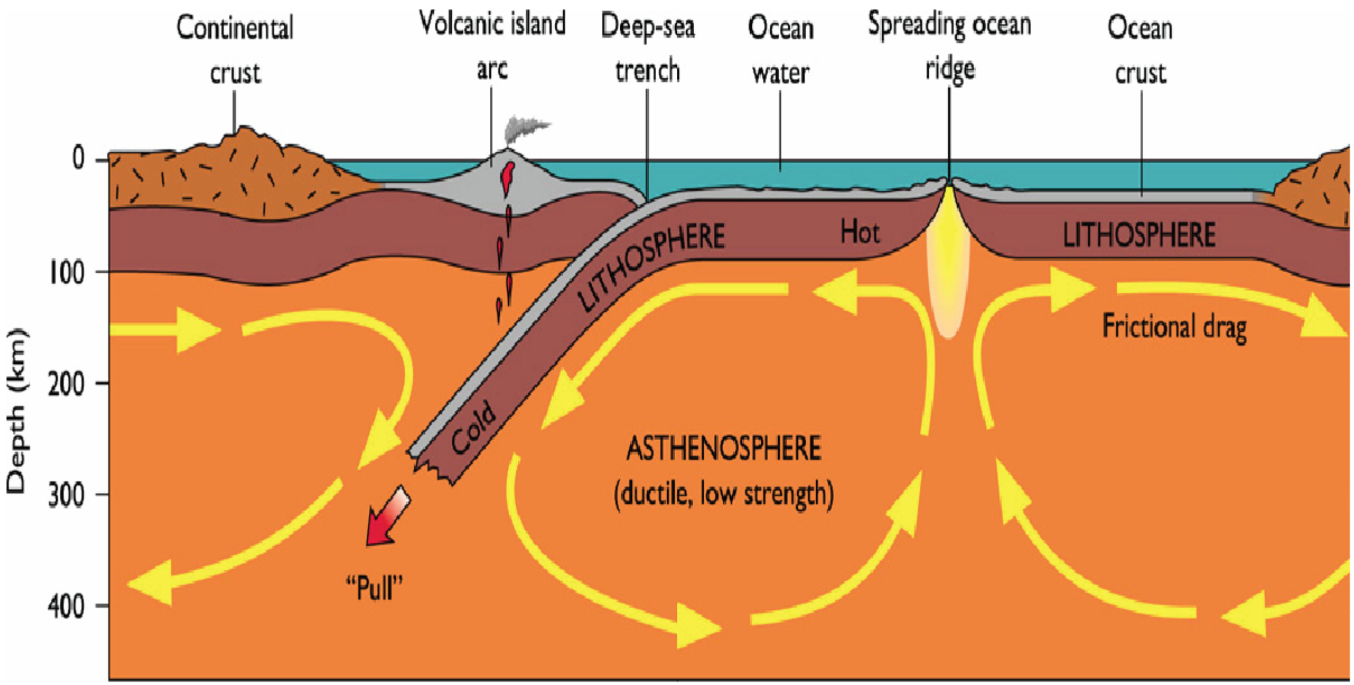
- **Diamonds:** Form at great depth. Inclusions in diamonds host “trapped” mantle.



- **Lavas:** Melts of the mantle. Calculate the unmelted mantle composition by examining compositions of lavas.

A Dynamic Earth

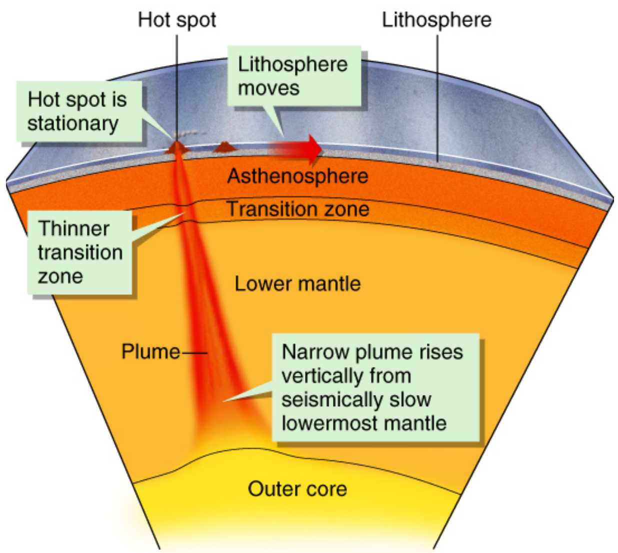


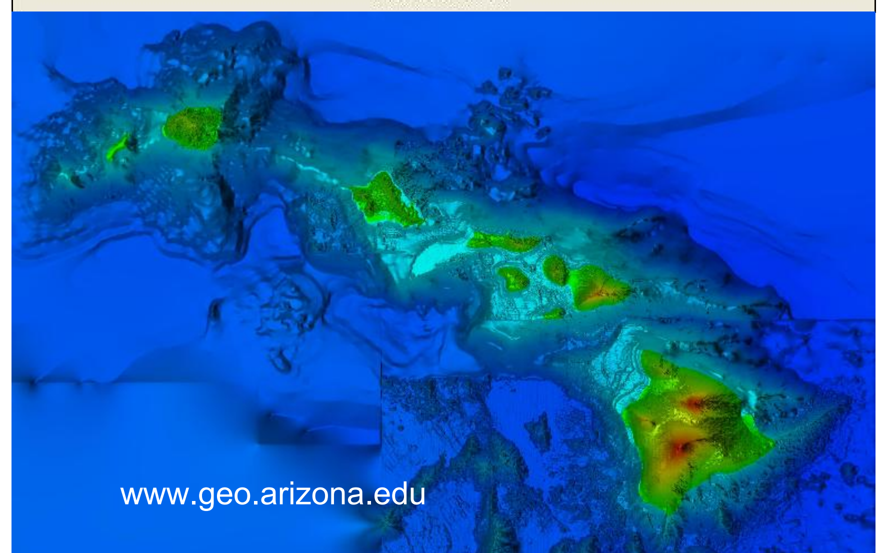


What happens to plates after they are subducted?

One hypothesis is that subducted plates are "recycled" and upwell in mantle plumes and melt beneath hotspots!

Hotspot lavas fed by upwelling mantle





- **Upwelling plumes sample the deepest domains of the mantle.**
- **Upwelling plumes melt beneath hotspots.**
- **Thus, hotspot lavas tell us about the composition of the deepest earth.**

The mantle is chemically and isotopically heterogeneous

-Radiogenic isotopes (e.g., $^{87}Sr/^{86}Sr$) and some trace element ratios (e.g., Nb/U) are little changed between solid and melt.

-Lavas erupted at hotspots reveal significant isotopic and trace element heterogeneity. Therefore:

the solid mantle sources of these lavas are heterogeneous.

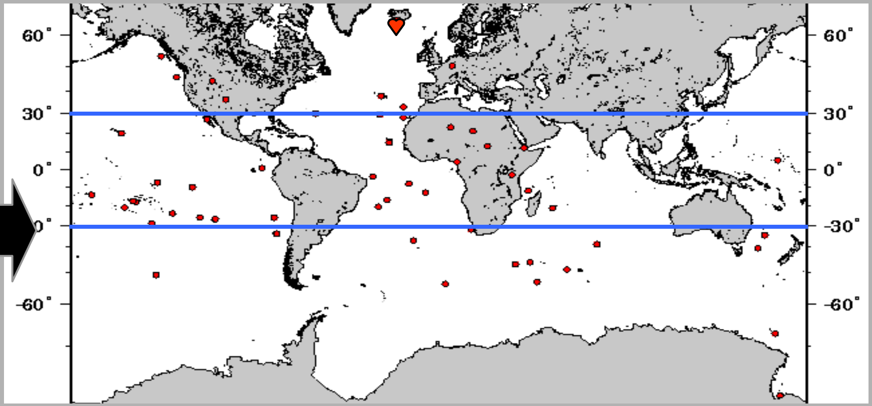
$^{87}Sr/^{86}Sr$ solid mantle = $^{87}Sr/^{86}Sr$ melt (lava)

Who cares about the mantle's composition?

The observation that the mantle is heterogeneous leads to some of the most important questions in the study of the deep Earth:

1. How did the mantle become heterogeneous—how are the heterogeneities formed?
2. How old are the heterogeneities—how long do they survive?
3. At what length scales do the heterogeneities exist—how big (or small) are they? How are they distributed?

Global hotspot distribution



R. Workman

Four Data Chapters

- Ch 1: Strontium isotopes in melt inclusions from Samoan basalts: Implications for heterogeneity in the Samoan plume.

  Earth Planet. Sci. Lett., v. 245, pp. 260-277, 2006.

- Ch 2: The return of subducted continental crust in Samoan lavas.

  Nature, v. 448, pp. 684-687, 2007.

- Ch 3: New Samoan lavas from Ofu Island reveal a hemispherically heterogeneous high $^3He/^4He$ mantle

  Earth Planet. Sci. Lett., 2007, in press.

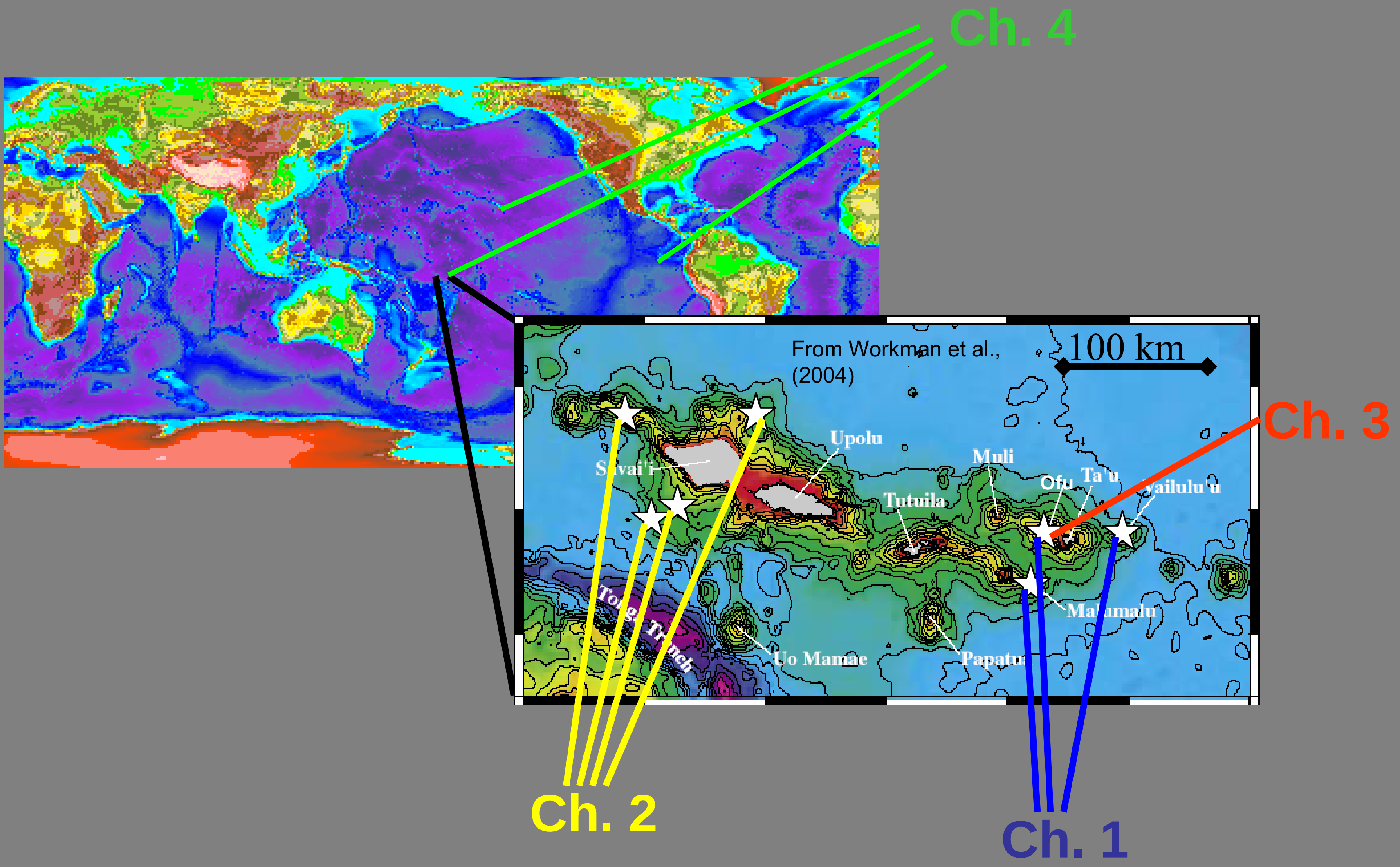
- Ch 4: High $^3He/^4He$ hotspot lavas expose the Earth's "missing" titanium, tantalum and niobium (TITAN): The missing link between continental crust and depleted mantle found?

  Geochem., Geophys., Geosyst., 2007, submitted manuscript.

Origins of heterogeneity

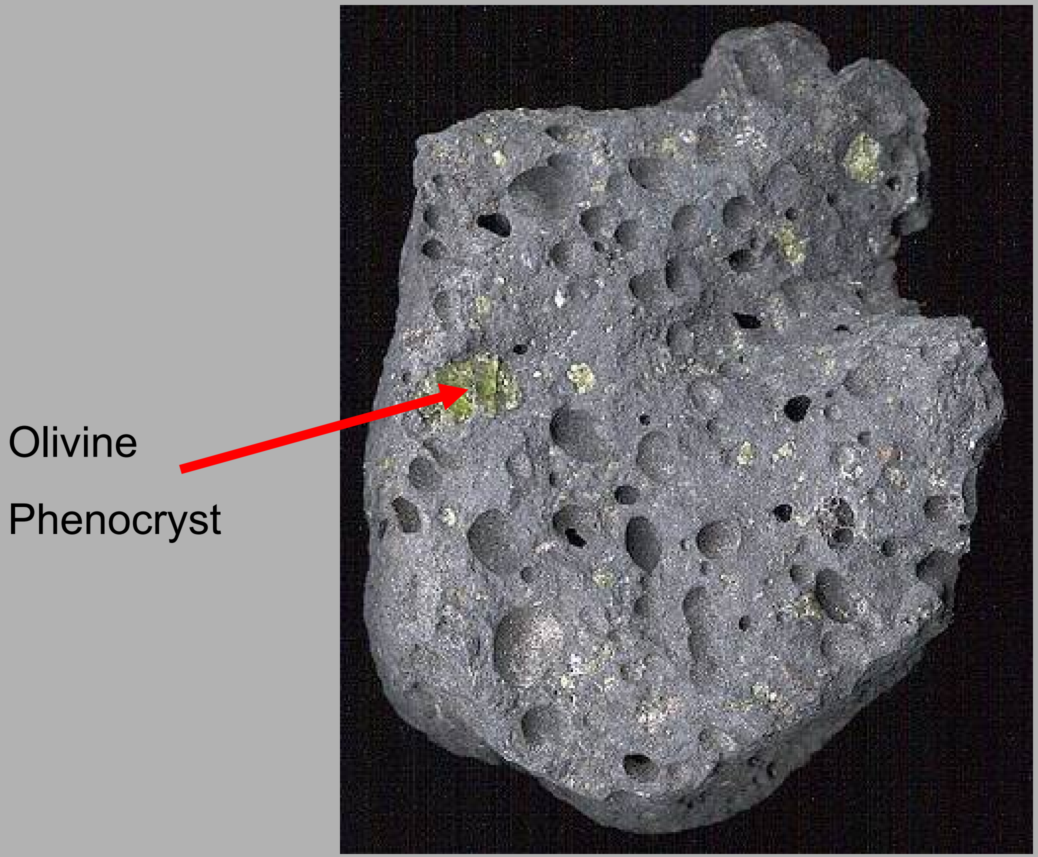
Length scales of heterogeneity

Study Sites



Ch. 4
From Workman et al., (2004)
100 km
Ch. 3
Upolu
Muli
Ofu
Ta'u
Tutuila
Papatua
Uo Mamae
Ch. 2
Ch. 1

Chapter 1: Sr-isotopes in melt inclusions from Samoan basalts



Grind up rocks and measure major & trace elements and isotopes.

But what about individual phenocrysts?

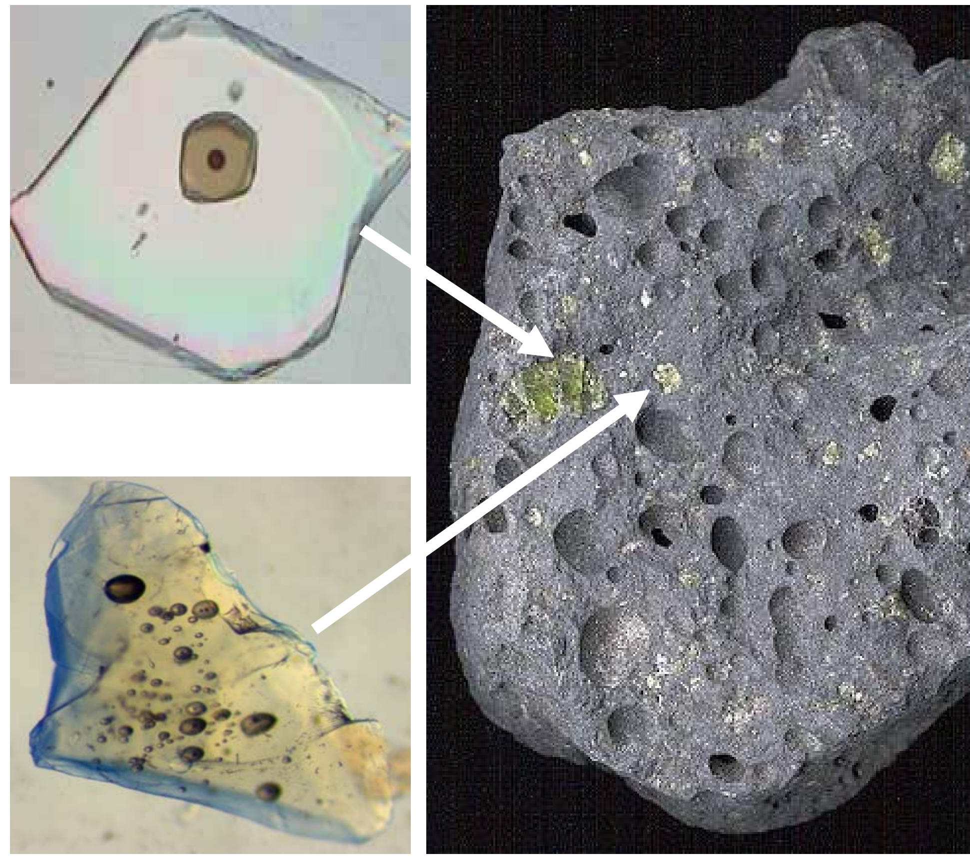
……or melts trapped in phenocrysts?

Melt inclusions

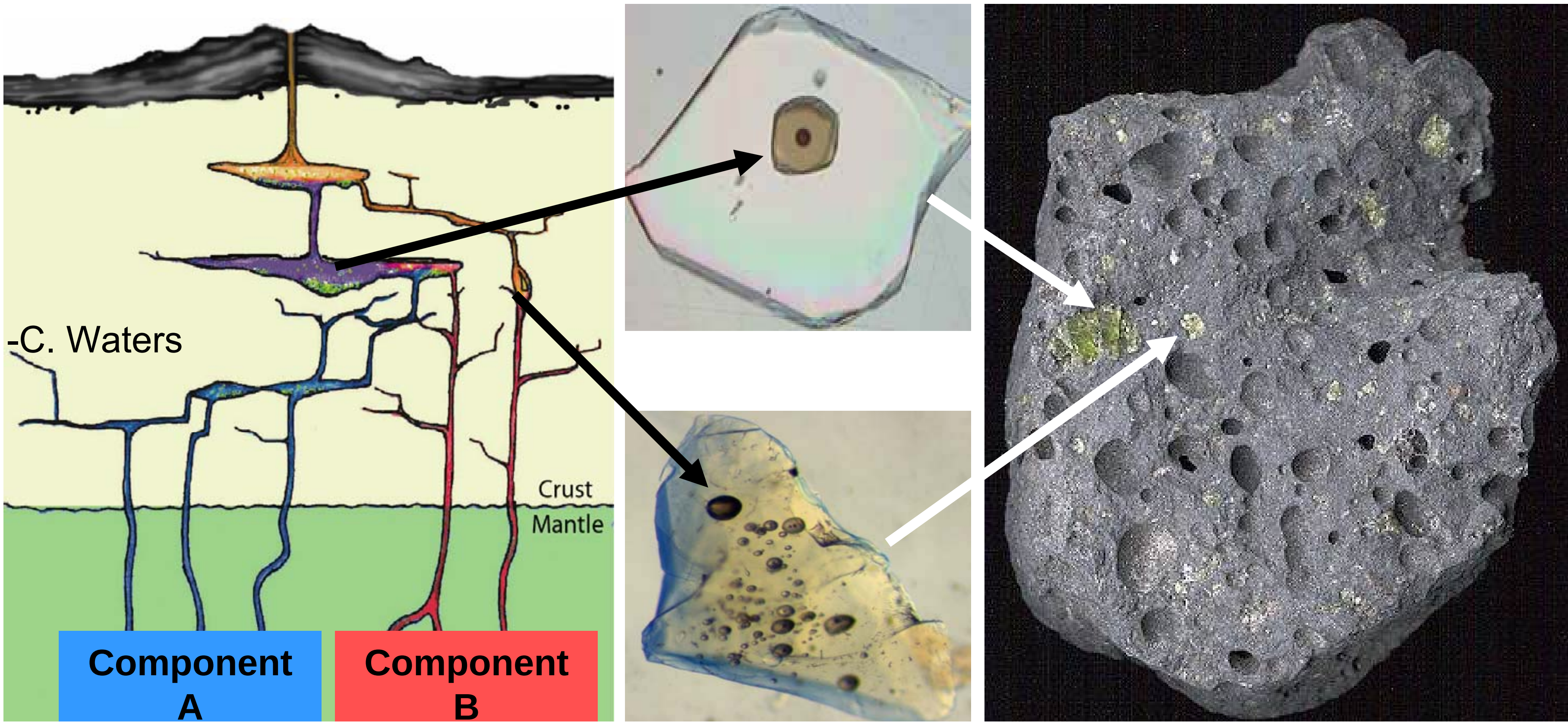
- **Melt inclusions:**

1. Small volumes of melt trapped in growing crystals at depth.

2. Melt inclusions record “snapshots” of intermediate mixing steps in magmas.

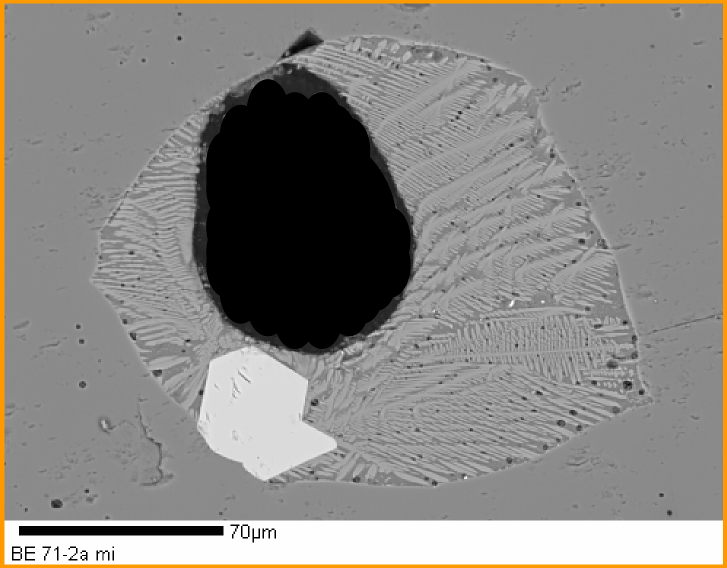


Do melt inclusions sample more heterogeneity in the mantle than seen in whole rocks?



--Hypothesis: If the mantle source sampled by a lava is heterogeneous, then melt inclusions contained in the lava will be heterogeneous.
--To test this hypothesis, we measured $^{87}Sr/^{86}Sr$ in melt inclusions and compared the results to the $^{87}Sr/^{86}Sr$ of the whole rock.

In situ Sr-isotopes on basaltic melt inclusions

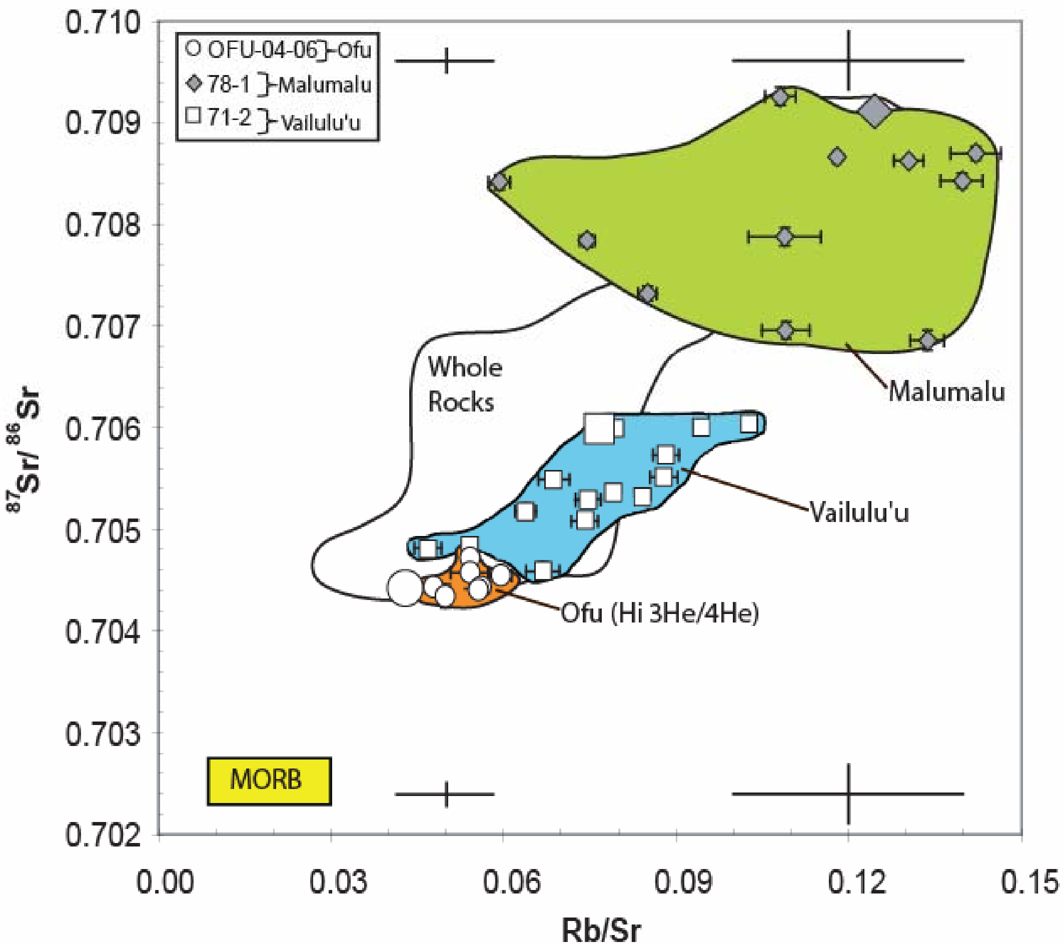


- Measure $^{87}Sr/^{86}Sr$ *in situ* on basaltic melt inclusions by laser ablation. Introduce lased material directly into plasma of a multi-collection ICP-MS.

- Analytically challenging:
  1. Sample limited…melt inclusions are miniscule!
  2. Rb and Kr interferences. Nobody had done this successfully before….

- **GOAL:** Measure $^{87}Sr/^{86}Sr$ very precisely (0.35 per mil, 2σ ext. prec.) in extremely small quantities of basaltic glass (1-10 nanograms Sr).

Results: Melt inclusions preserve more of the mantle source heterogeneity not seen in basalts

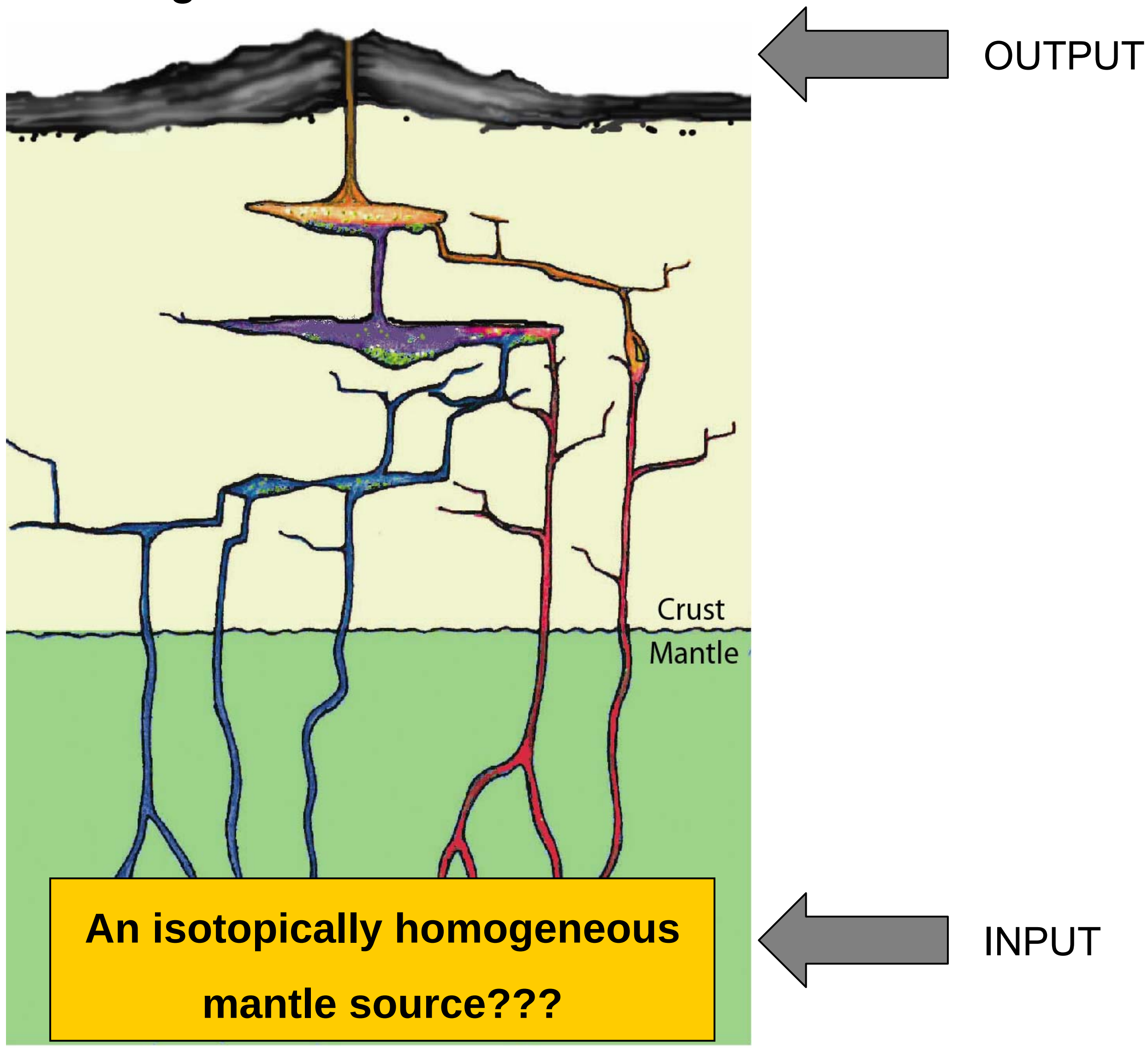


-Melt inclusions from two basalts are heterogeneous.

-Melt inclusions in the 3rd basalt are homogeneous.

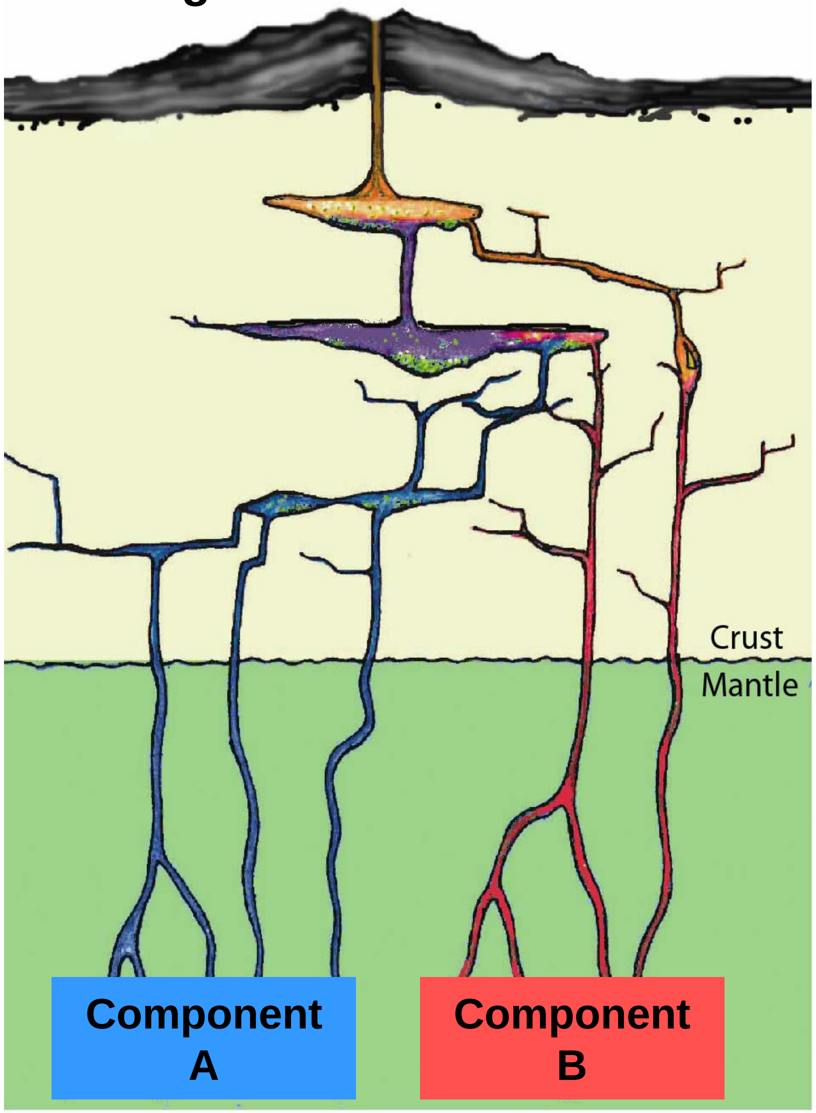
Conceptual Model for Melting & Mixing

Basalts hosting isotopically heterogeneous melt inclusions



Conceptual Model for Melting & Mixing

Basalts hosting isotopically heterogeneous melt inclusions

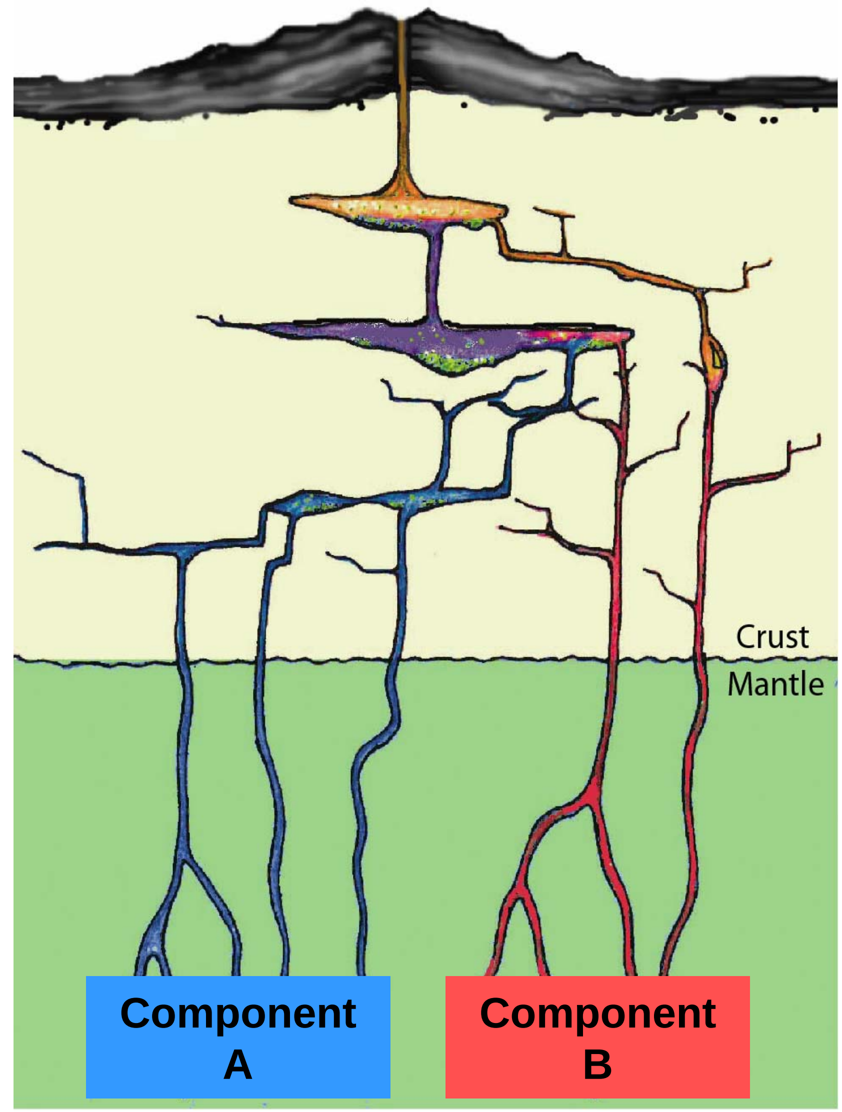


OUTPUT

INPUT

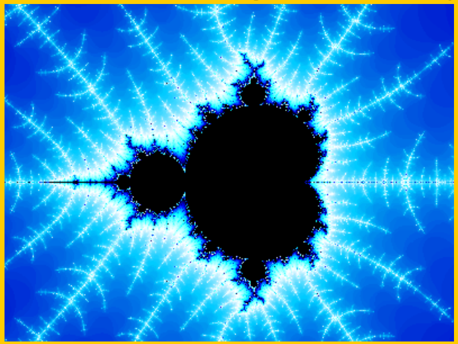
Implications for length scales of mantle heterogeneity

- The mantle heterogeneities beneath a volcano must be smaller than the widths of the melting zones (10’s of km).
- Otherwise, we wouldn’t see $^{87}Sr/^{86}Sr$ heterogeneity in melt inclusions!



Ch. 1 Summary

- Melt inclusions in phenocrysts from a single lava often exhibit heterogeneity.



- This heterogeneity requires that the mantle contributing melts to a single lava is heterogeneous.
- Therefore, the mantle must be heterogeneous at length scales that are smaller than the melting zone (10’s of km).

Ch. 3: Hemispherically heterogeneous high $^3He/^4He$ mantle

- Helium in the Earth's mantle:
  - -Two isotopes: ^3He and ^4He
  - -U and Th decay to Pb via alpha decay (^4He production)
  - -Little ^3He produced in the earth (mostly primordial)
  - -Therefore, $^3He/^4He$ in the earth decreases with time.

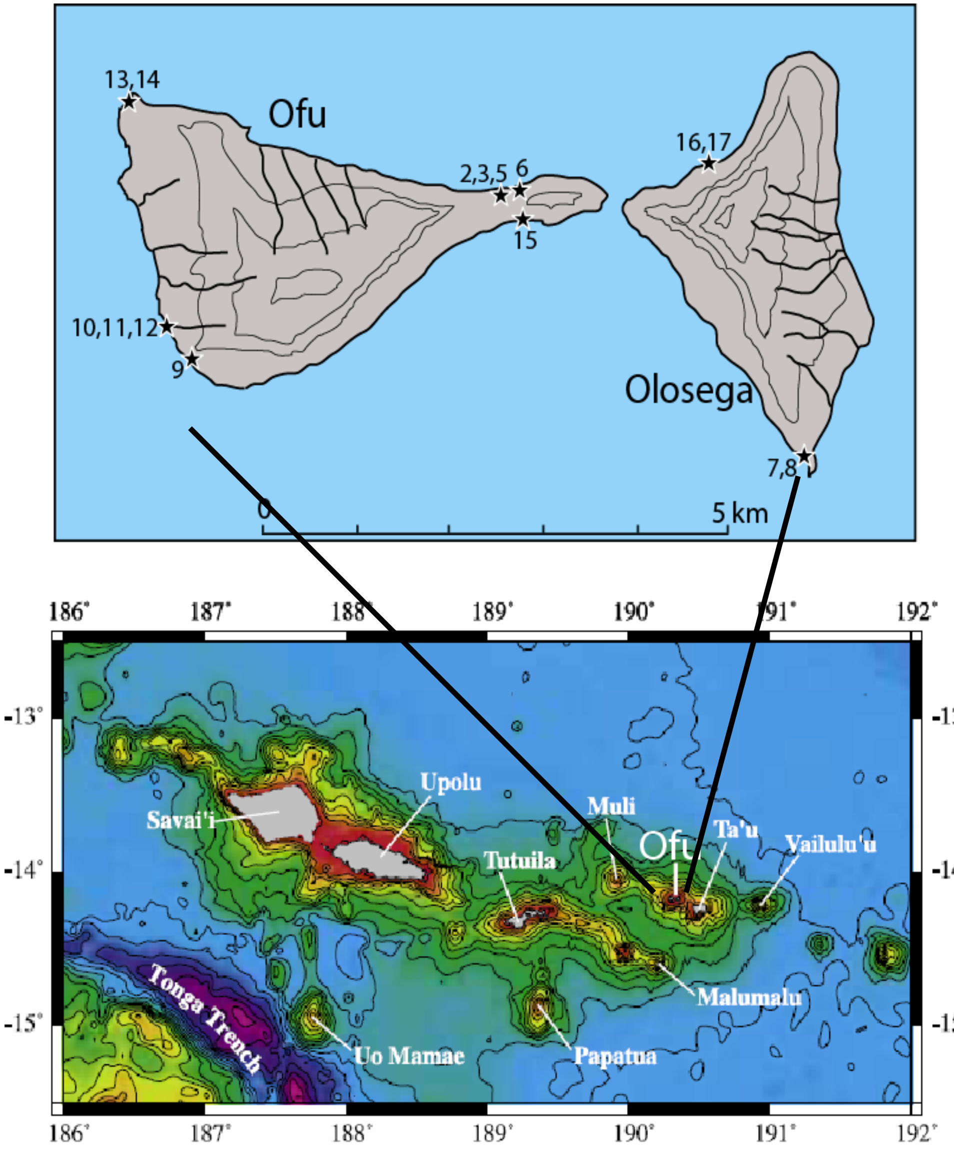
- The sun (solar wind) and the atmosphere of Jupiter have high $^3He/^4He$. High $^3He/^4He$ is thought to be primordial (or at least an ancient signature).

Hotspot lavas with high $^3He/^4He$

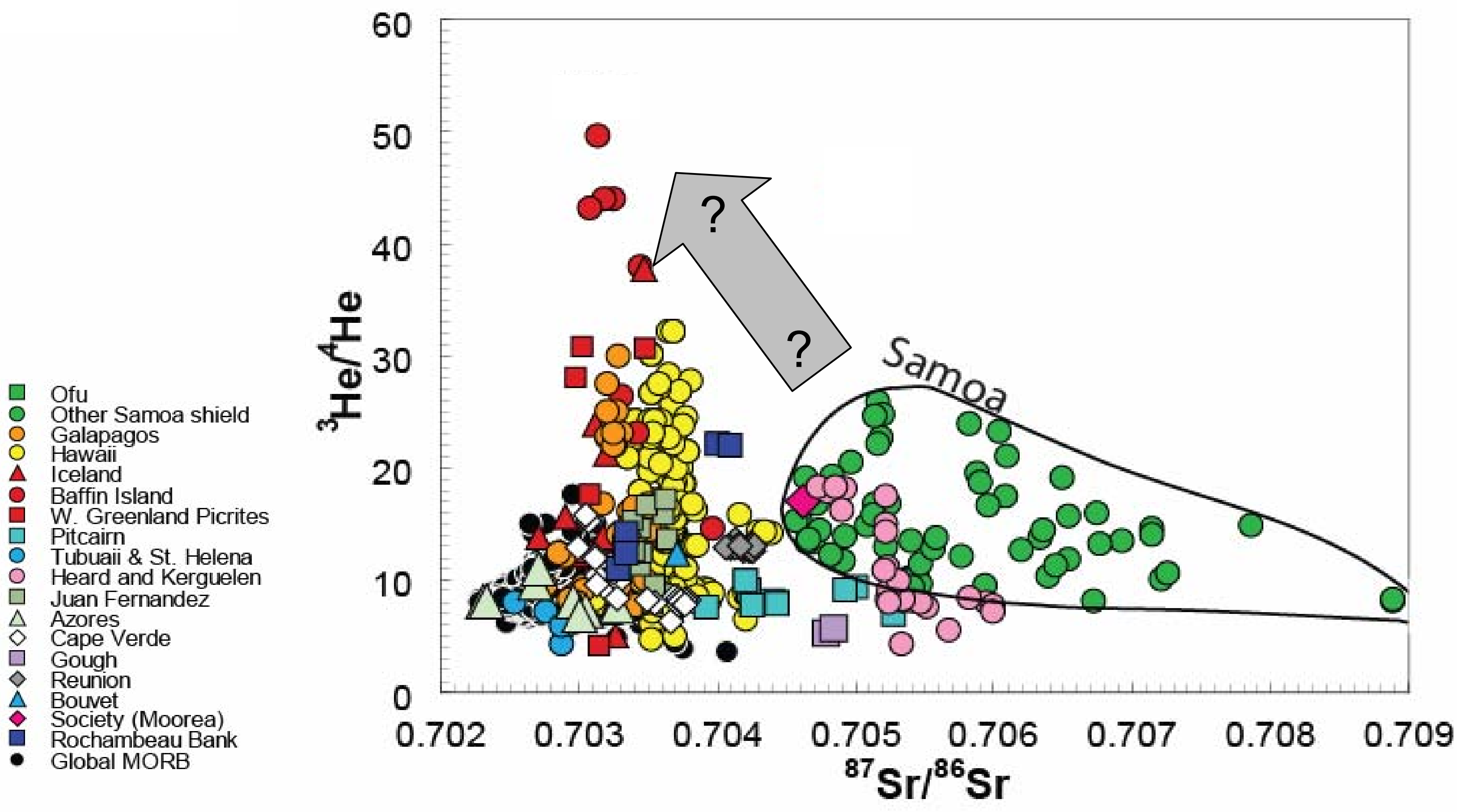
- Hotspot lavas occasionally host high $^3He/^4He$ ratios, and are melts of a mantle reservoir with high $^3He/^4He$.
- High $^3He/^4He$ lavas RARE, so not a lot of data available to describe the high $^3He/^4He$ mantle.
- High $^3He/^4He$ hotspot lavas are the "Holy Grail" of mantle geochemistry.
    1. Sample an ancient component in the earth.
    2. Lavas with high $^3He/^4He$ are thought to sample a common component, called FOZO (Focus Zone).

Discovered high $^3He/^4He$ lavas in Samoa.

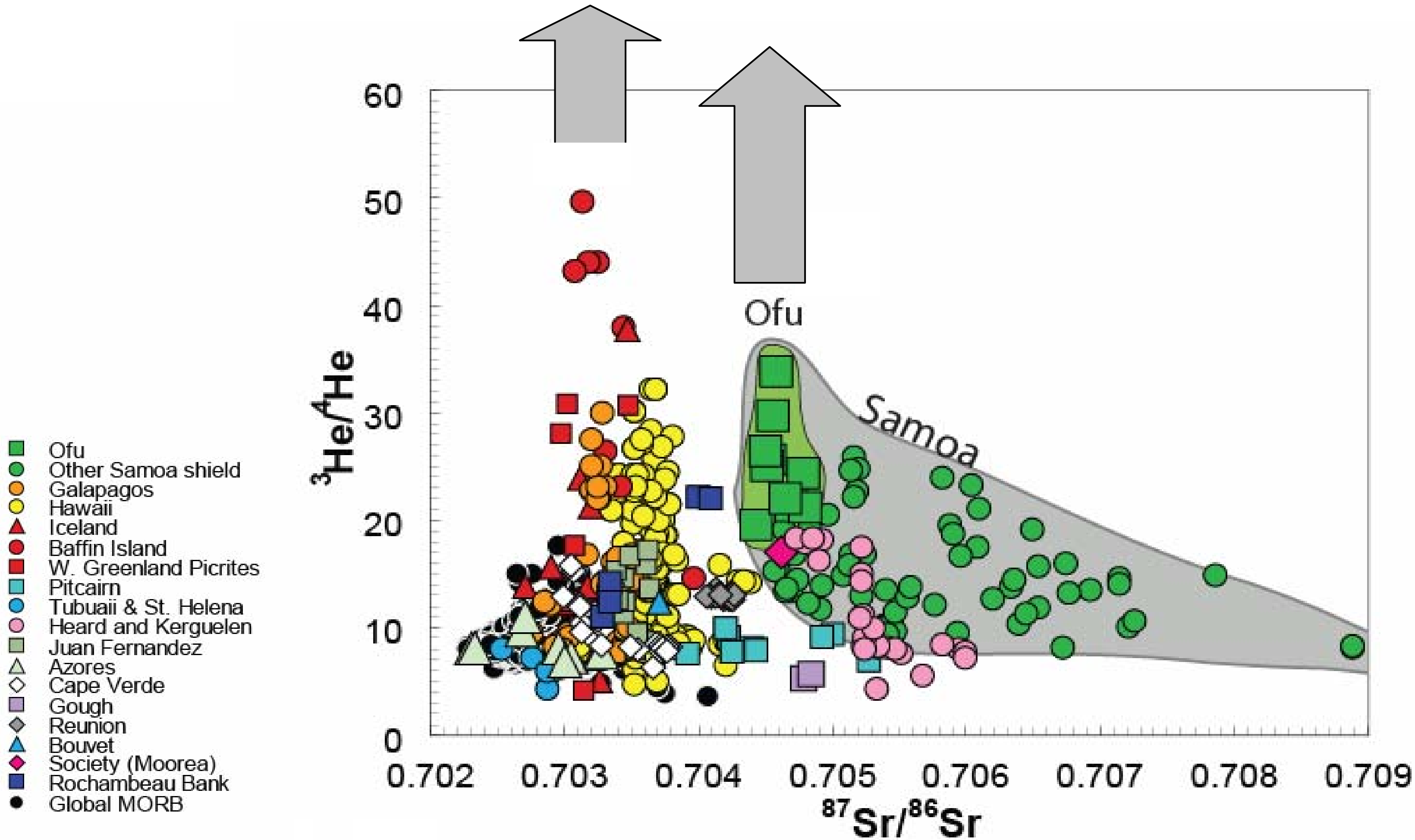
Jungle Geology….



One high $^3He/^4He$ common component?

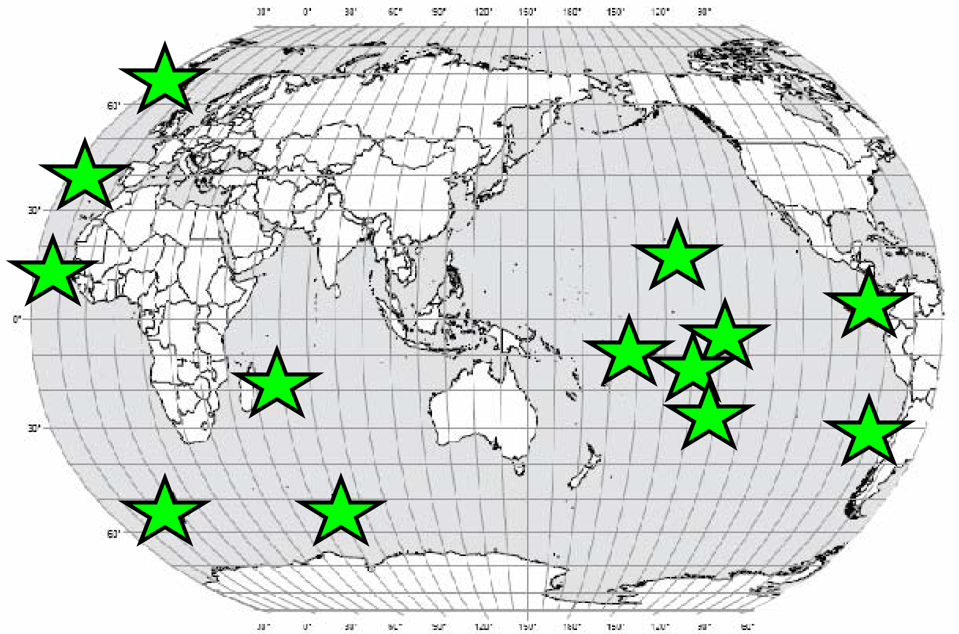


Or Two????



Ofu
Samoa
^{3}He/^{4}He
^{87}Sr/^{86}Sr
60
50
40
30
20
10
0
0.702
0.703
0.704
0.705
0.706
0.707
0.708
0.709
Ofu
Other Samoa shield
Galapagos
Hawaii
Iceland
Baffin Island
W. Greenland Picrites
Pitcairn
Tubuaii & St. Helena
Heard and Kerguelen
Juan Fernandez
Azores
Cape Verde
Gough
Reunion
Bouvet
Society (Moorea)
Rochambeau Bank
Global MORB

Define the $^{87}Sr/^{86}Sr$ (and Nd,Pb) of the high $^{3}He/^{4}He$ mantle domain



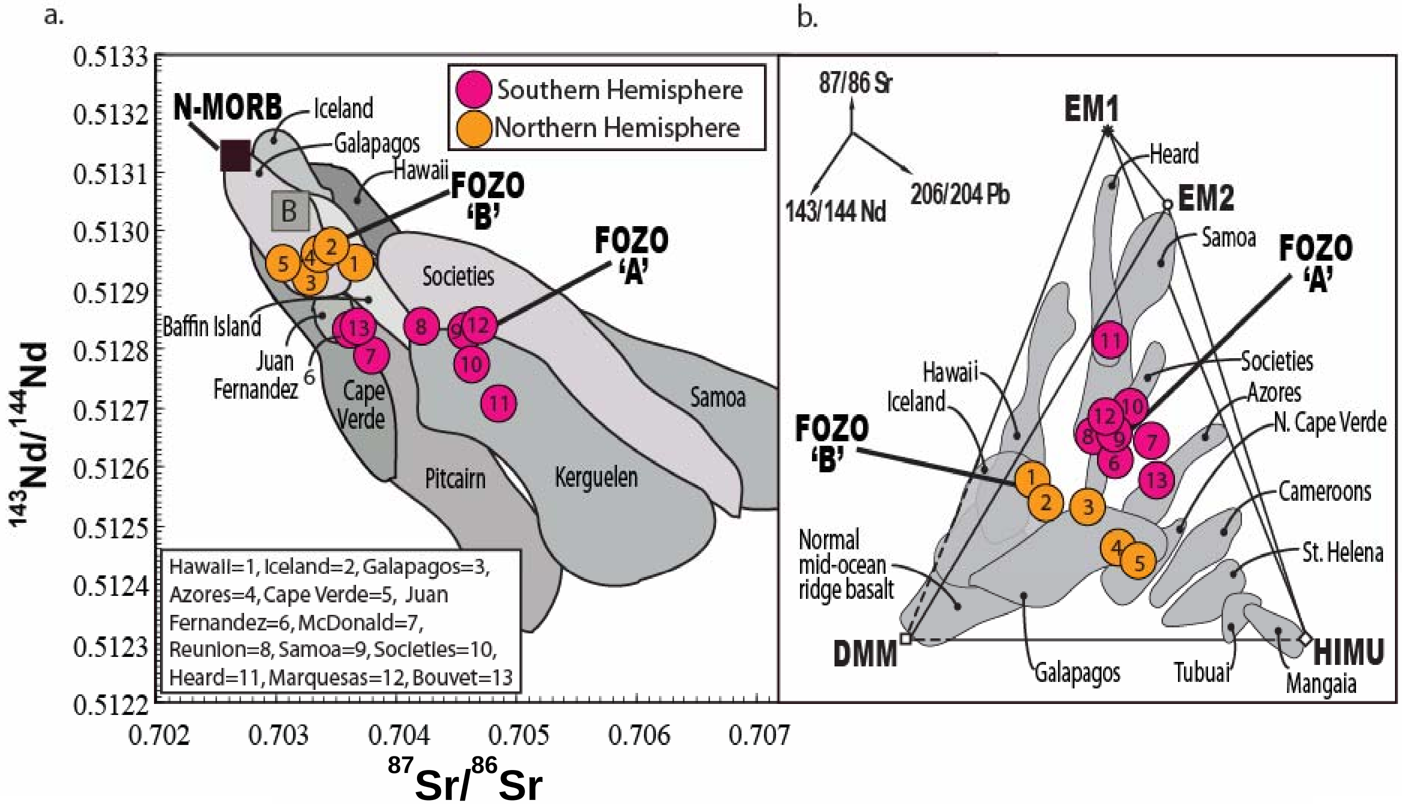
Large dataset, so filter it to include only samples that best represent the high $^{3}He/^{4}He$ mantle:

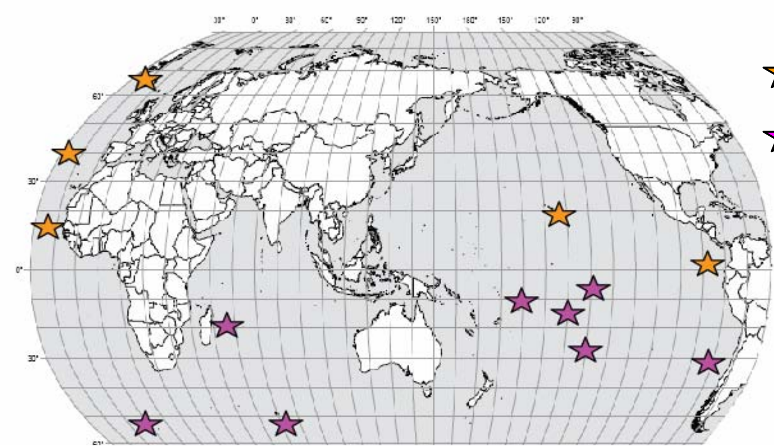
A.) Interested in the $^{87}Sr/^{86}Sr$ (and Nd, Pb) of only the high $^{3}He/^{4}He$ mantle, so examine only the lavas with the highest $^{3}He/^{4}He$ from hotspots that have high $^{3}He/^{4}He$.

B.) High $^{3}He/^{4}He$ lavas from some environments may be contaminated by shallow reservoirs and their $^{87}Sr/^{86}Sr$ (and Nd, Pb) may not represent the high $^{3}He/^{4}He$ mantle:

1.) Continental settings, 2.) submarine MORB settings, and 3.) island arc settings

High $^3He/^4He$ mantle is heterogeneous.



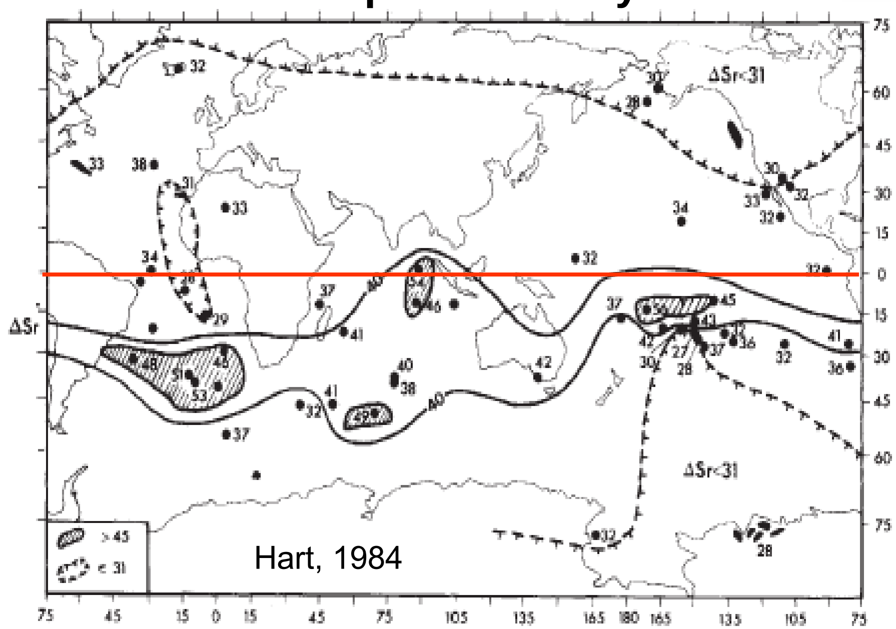


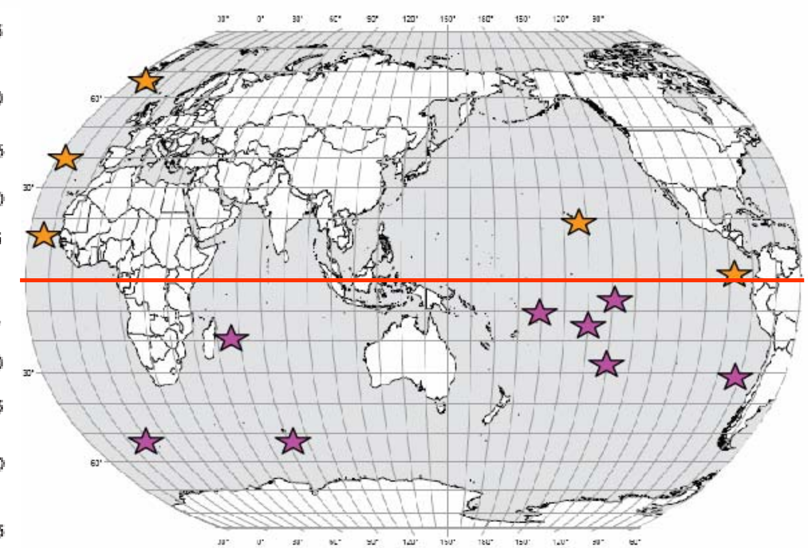
N. Hemisphere (boreal)

S. Hemisphere (austral)

Hemispheric heterogeneity not unknown to mantle geochemists…

"Dupal" Anomaly





Southern hemisphere hotspot lavas exhibit generally higher $^{87}Sr/^{86}Sr$ than their Northern hemisphere counterparts.

High $^{3}He/^{4}He$ lavas in the Southern hemisphere have generally higher $^{87}Sr/^{86}Sr$ than their Northern hemisphere counterparts.

How to preserve hemispheric heterogeneity?

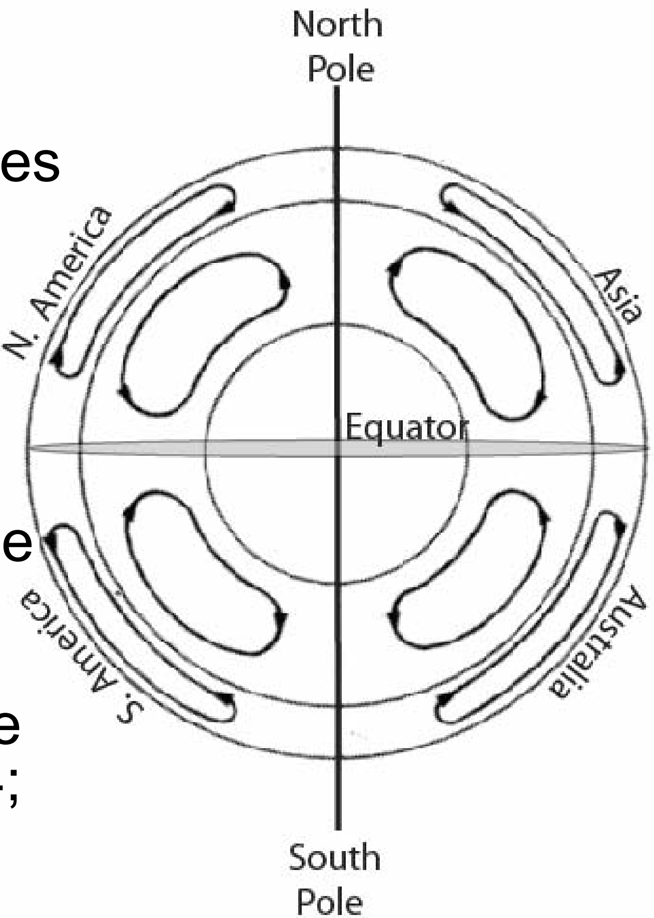
- **Implications for mantle dynamics:**

  A. The mantle is a dynamic, convecting environment that attenuates heterogeneities on (geologically) short timescales.

  B. So, how did the old (>10^9 years), high $^3He/^4He$ reservoir survive mantle convection to preserve hemispheric heterogeneity?

  C. Convective cells organized between the two hemispheres?

  D. Hypothetical "quadrupolar convection" regime that is nearly axisymmetric with the earth's spin axis (Busse, 1983; Hart, 1984; Allègre, 2002)?



Adapted from Busse, 1983

How to generate hemispheric heterogeneity in the first place?

Focused subduction around the perimeter of a supercontinent?

"Indeed, what *can* be proved in the Earth Sciences?"

-C. Allègre
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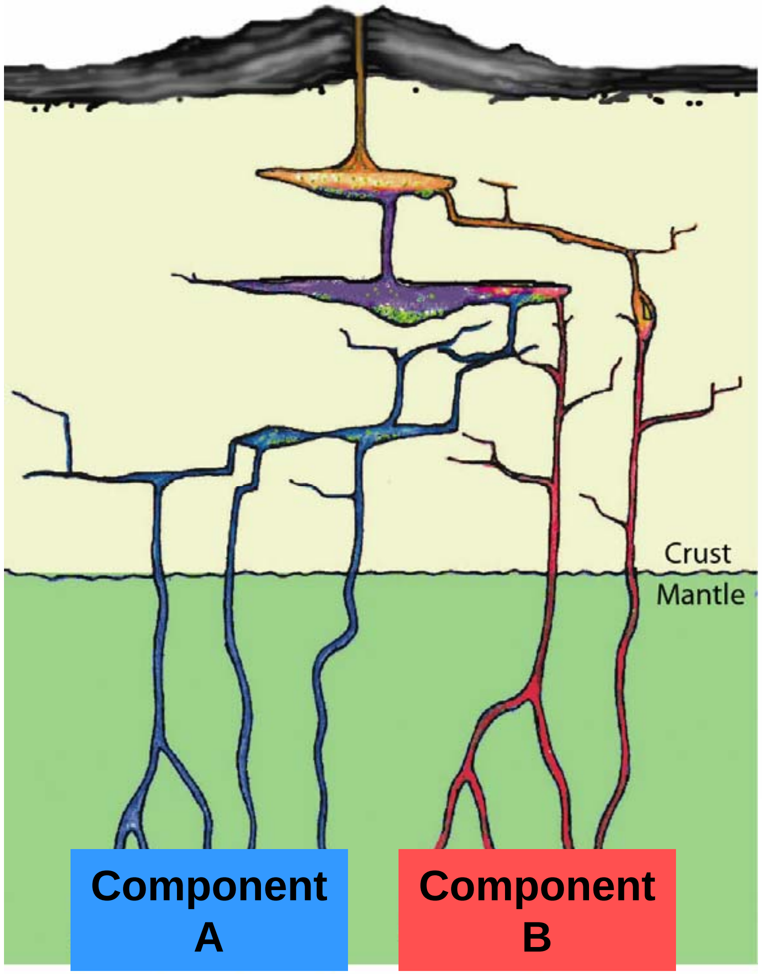
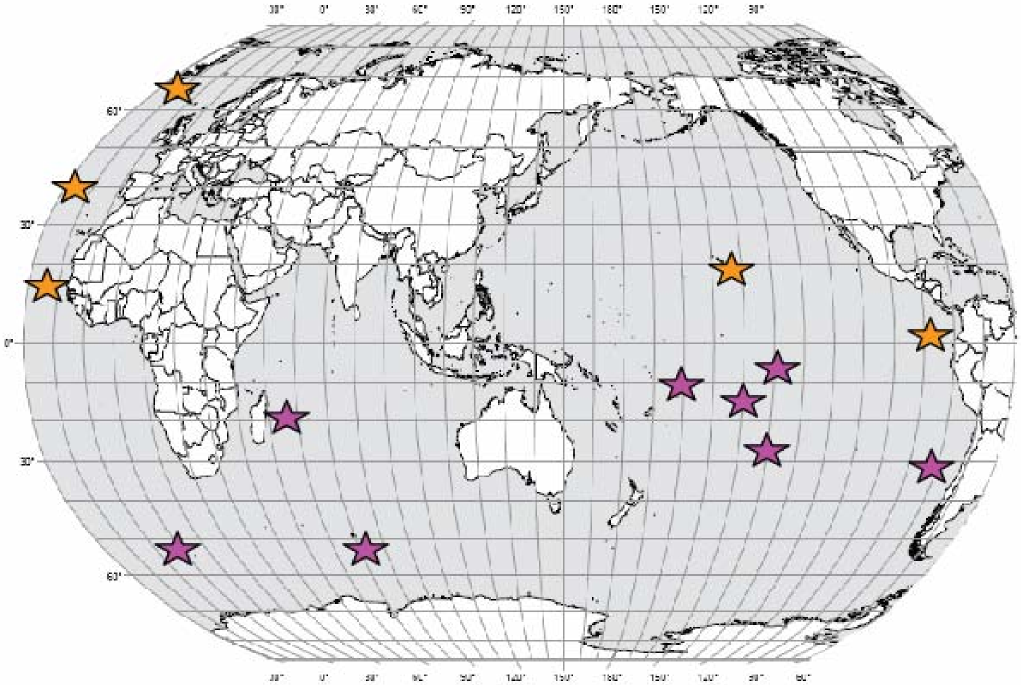
Two scales of mantle heterogeneity

Ch. 1: $^{87}Sr/^{86}Sr$ in melt inclusions: 10's of km



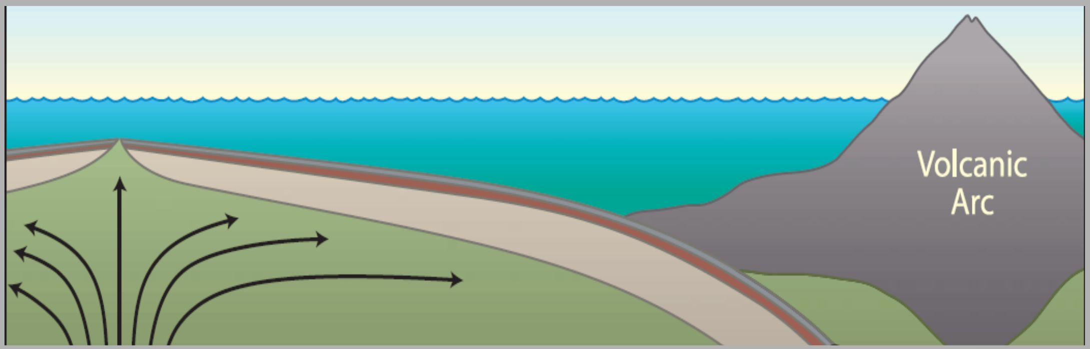
Ch. 3: $^{3}He/^{4}He$ in lavas: Hemispheric



How to generate mantle heterogeneities?

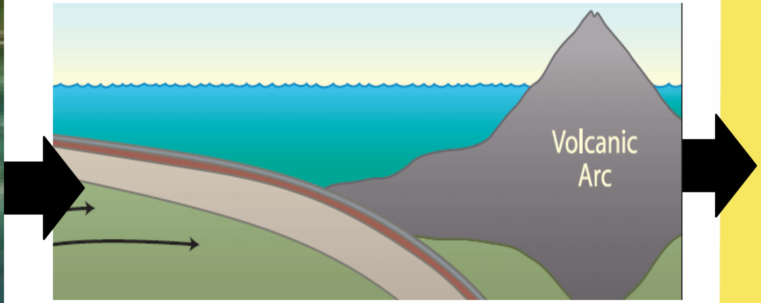
- We've discussed the different length scales at which heterogeneities exist in the mantle.
- But how were they made in the first place?
- Common hypothesis for the formation of mantle heterogeneity = subduction injection of oceanic plates:

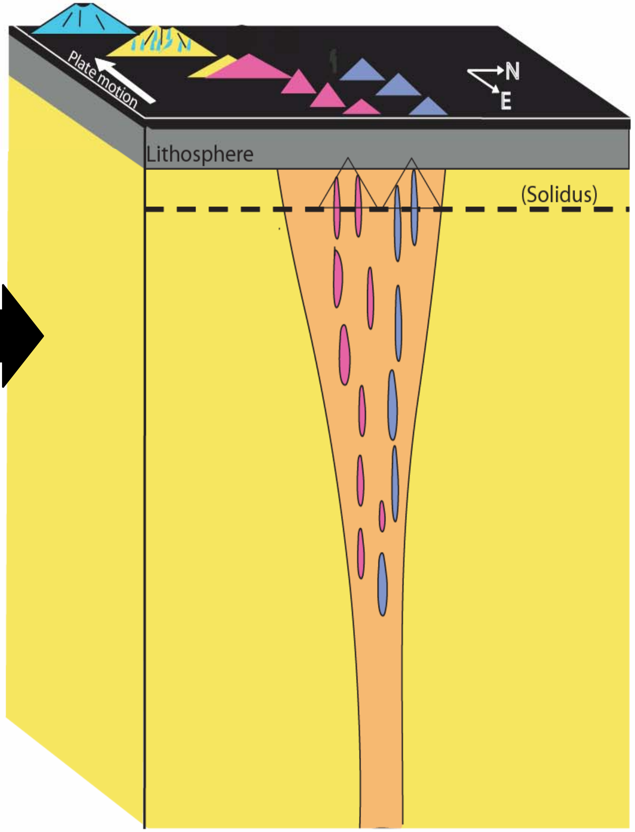
1. Sediment (**Ch. 2**)
2. Oceanic crust and mantle lithosphere (**Ch. 4**)



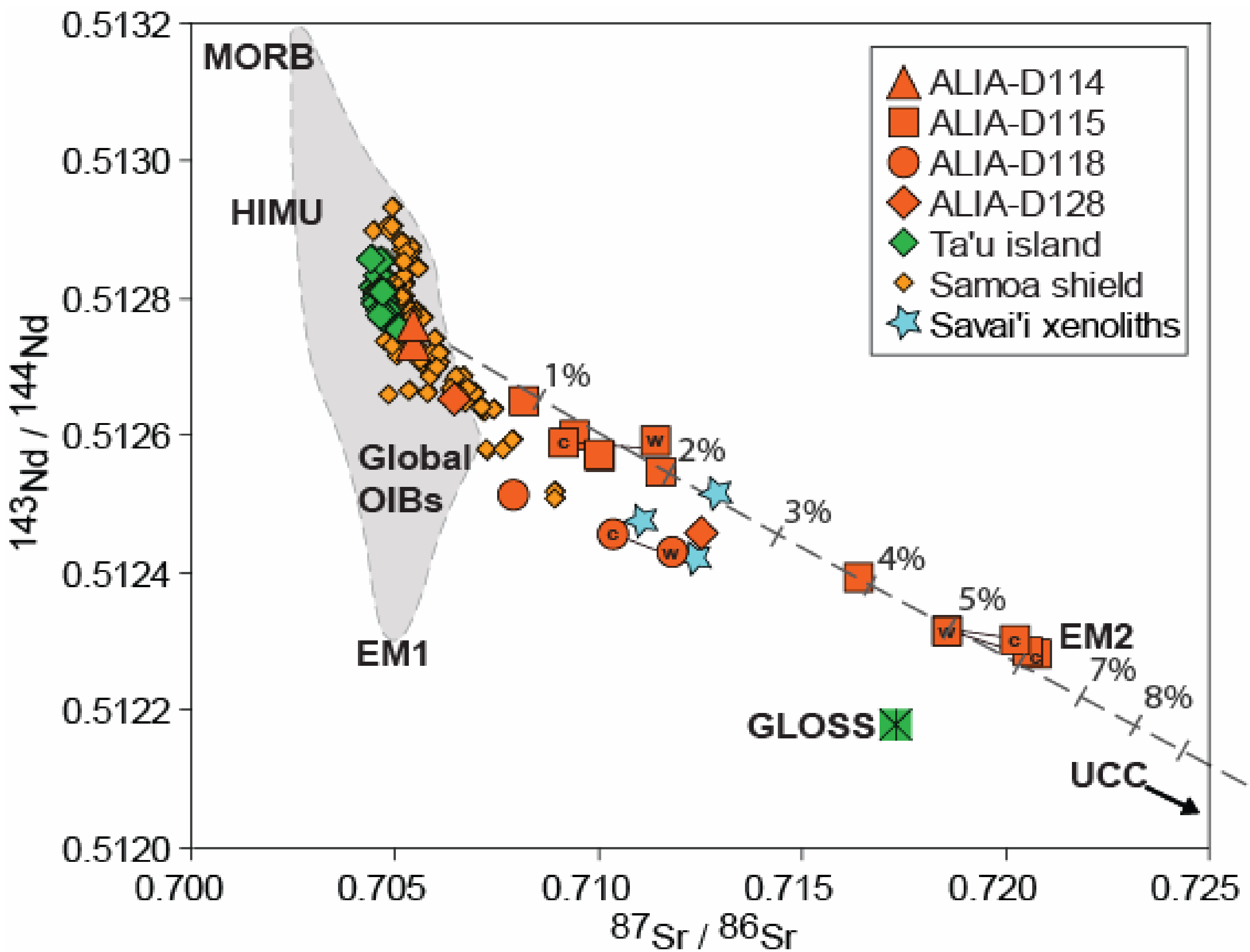
Chapter 2: The return of continental crust in Samoan lavas

Rivers contribute more than 85% of sediment input into oceans

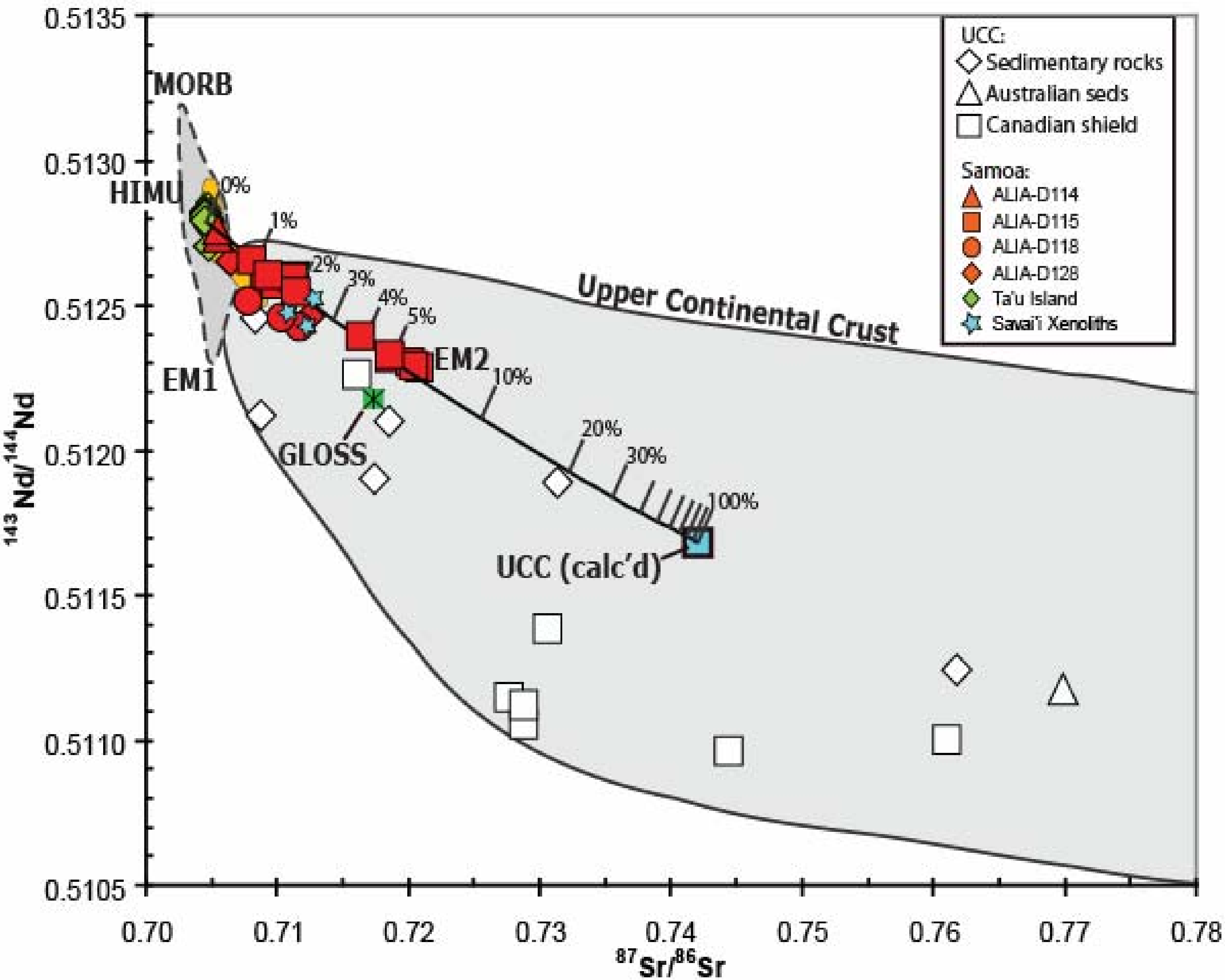




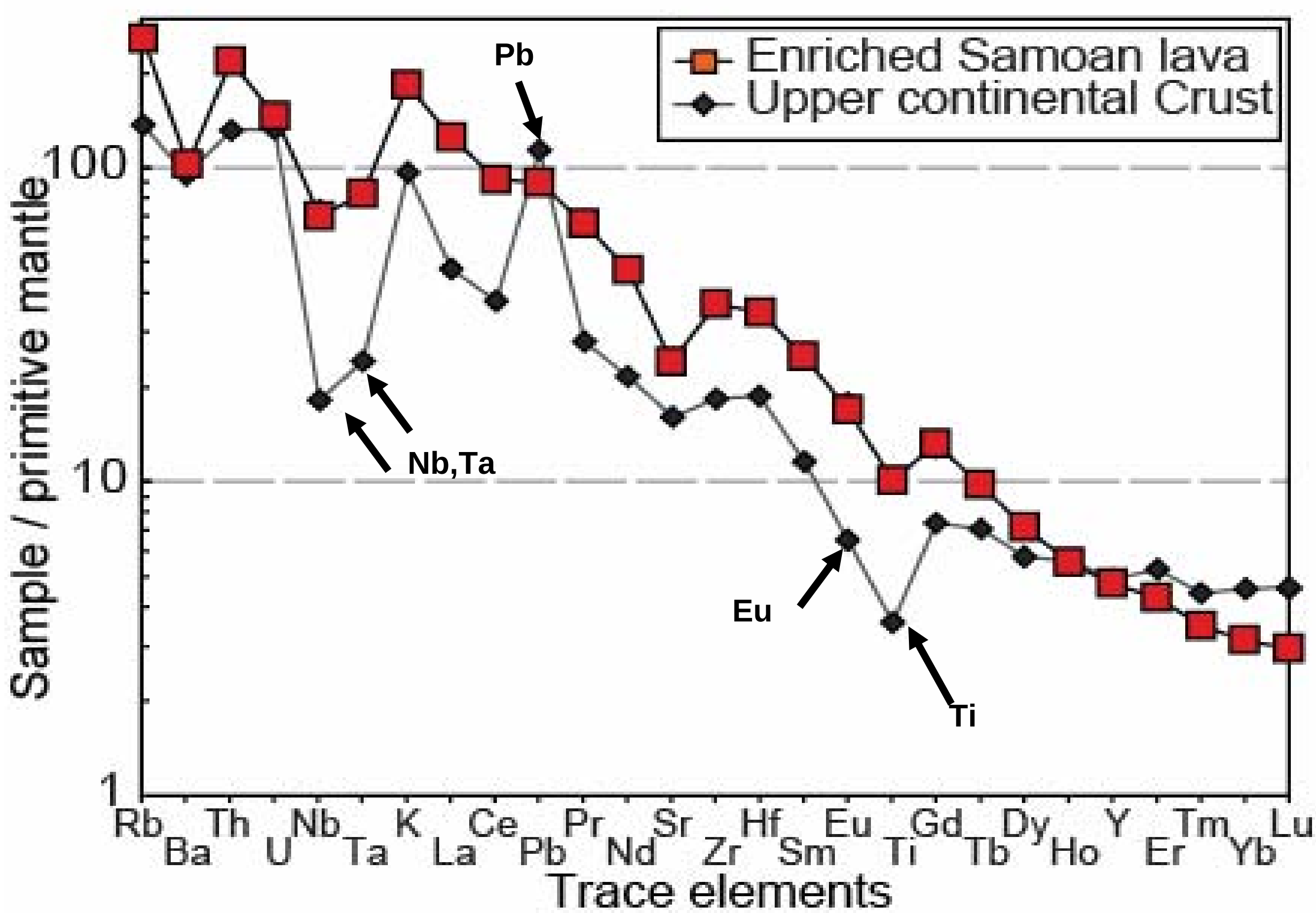
$^{87}Sr/^{86}Sr$ vs $^{143}Nd/^{144}Nd$: Consistent with recycled sediment



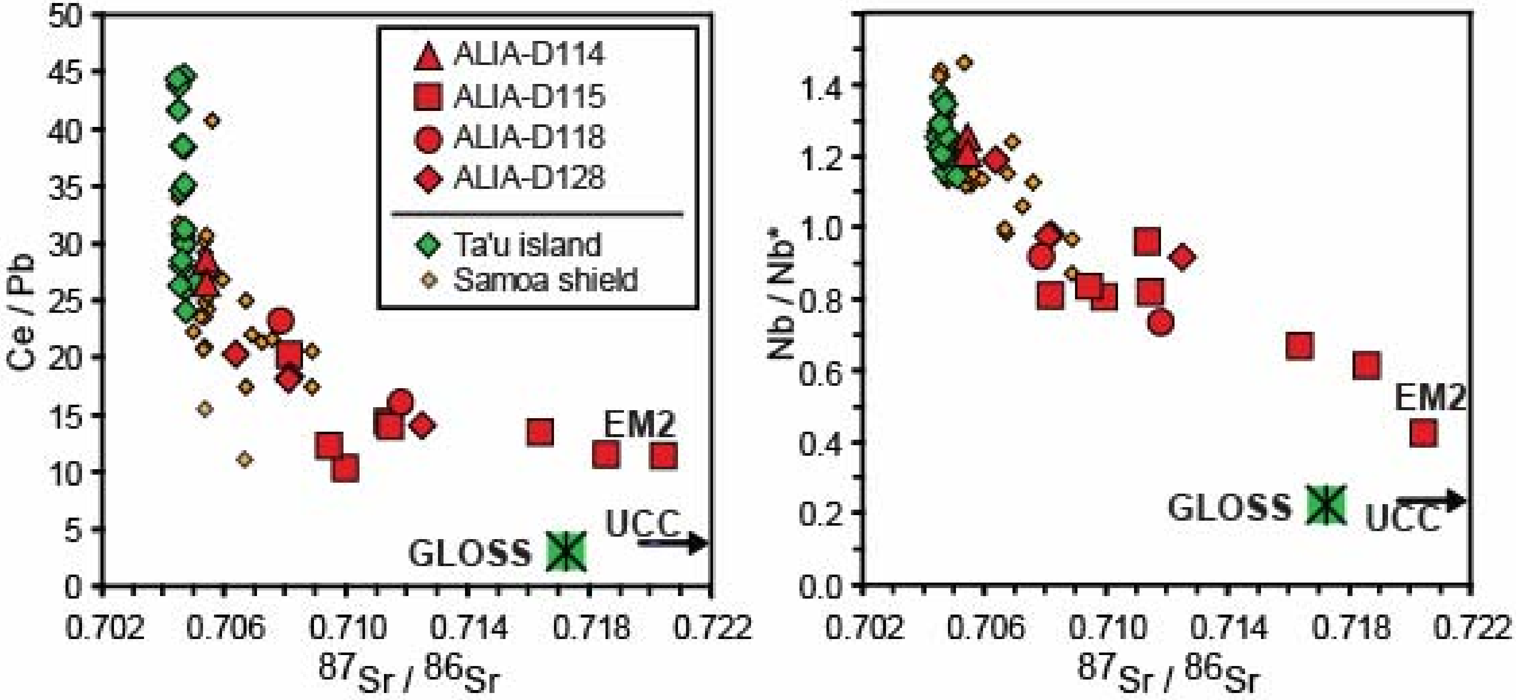
Trending toward continental crust…



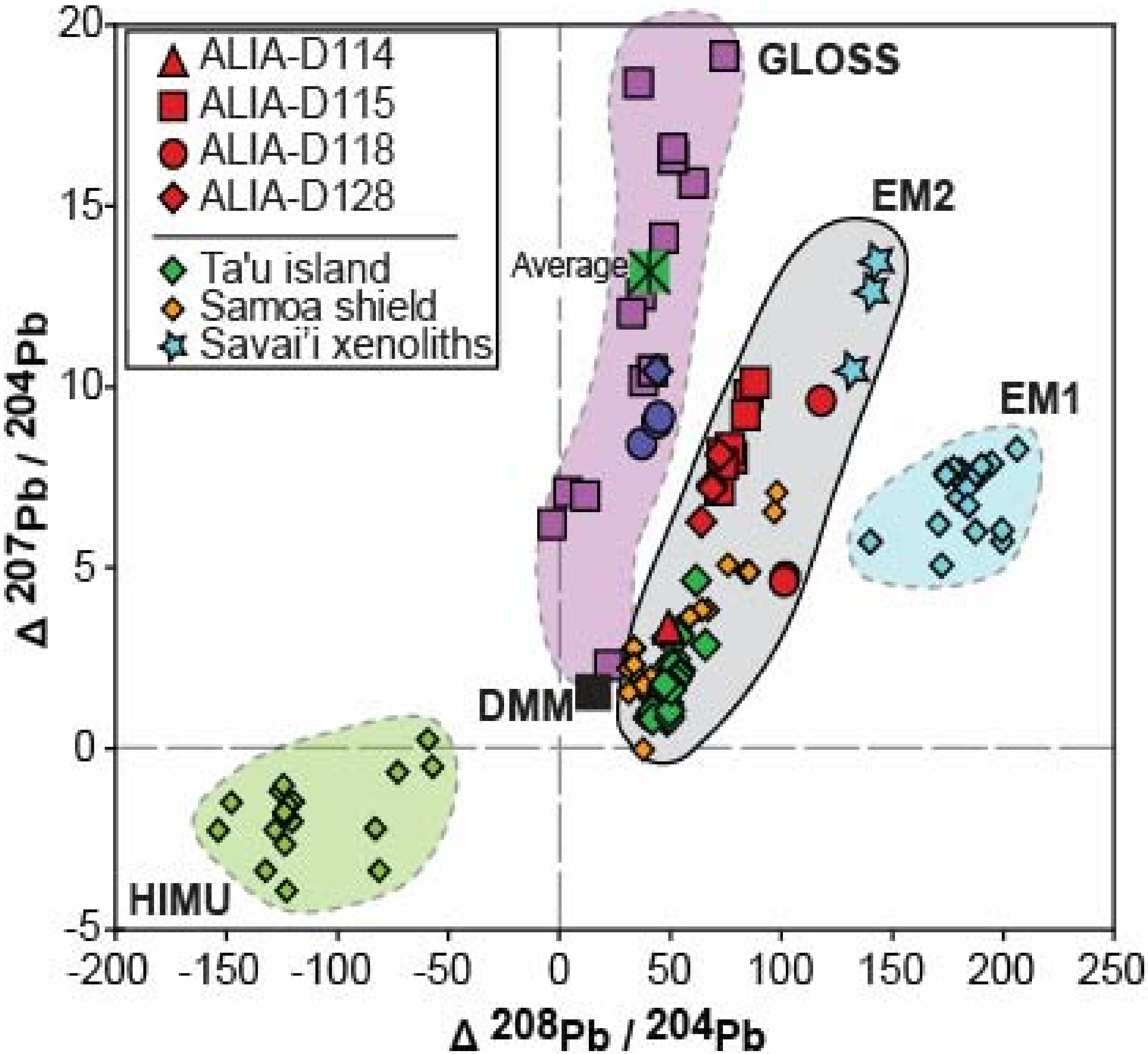
Continental Crust has unique trace element "fingerprints"



Agreement between trace element and isotopic fingerprints



Rule out shallow-level contamination by modern marine sediments



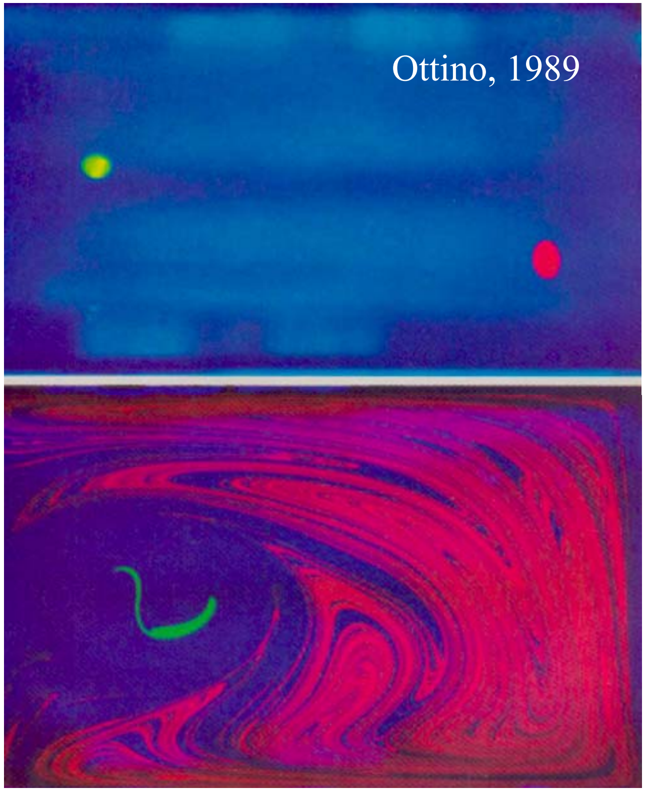
Recycled sediment: An anomalous survivor in a dynamic, chaotically convecting mantle.

- Signatures of recycled sediment are extremely rare in hotspot lavas.

- But 0.5-0.7 km^3 sediment is subducted annually. Over 2.5 Ga, that's a LOT of sediment in the mantle (1/3 of present-day continental mass)!

- What happens to all this sediment? Why don't we see it more often in hotspot lavas?
  - 1. Homogenized by mantle mixing?
  - 2. Never makes it through the subduction zone?
  - 3. Hidden in the deep mantle?

Preservation of subducted sediment in a convecting mantle….



-2 blobs of dye in glycerine.

-Red dye placed in a region of <u>chaotic</u> mixing.

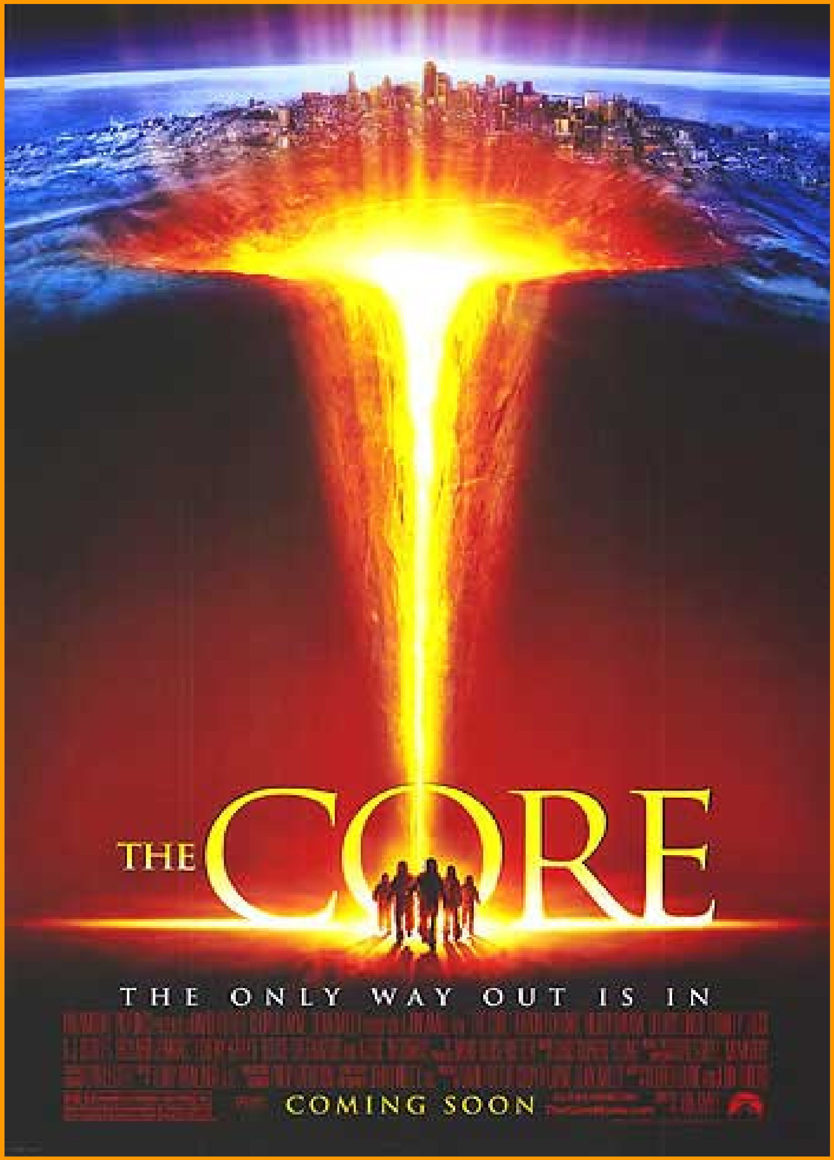
- Green dye placed in an island of <u>non-chaotic</u> mixing.

- Top moved left to right, then bottom moved right to left, 10 cycles.

Some sediment was subducted and survived mantle recycling, and we see it in Samoan lavas (in greatly diluted form)!

Conclusions

- **Ch. 1:** Melt inclusions in Samoan lavas exhibit measurable $^{87}Sr/^{86}Sr$ heterogeneity within a single lava, indicating that the source sampled by an individual lava can be heterogeneous.
- **Ch. 2:** Continental sediment is recycled into the mantle at subduction zones, survives mantle convection, and is returned to the surface and erupted (in diluted form) in Samoan lavas.
- **Ch. 3:** The high $^{3}He/^{4}He$ mantle reservoir is heterogeneous, and there are hints that this heterogeneity is organized between the Earth's Northern and Southern hemispheres.


THE CORE
THE ONLY WAY OUT IS IN
COMING SOON

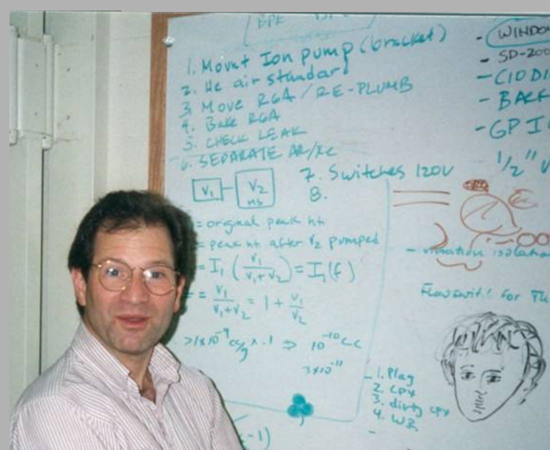
P. Kelemen

J. Collins

N. Shimizu

K. Sims

M. Kurz



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SPECIAL EXPORT LAGER
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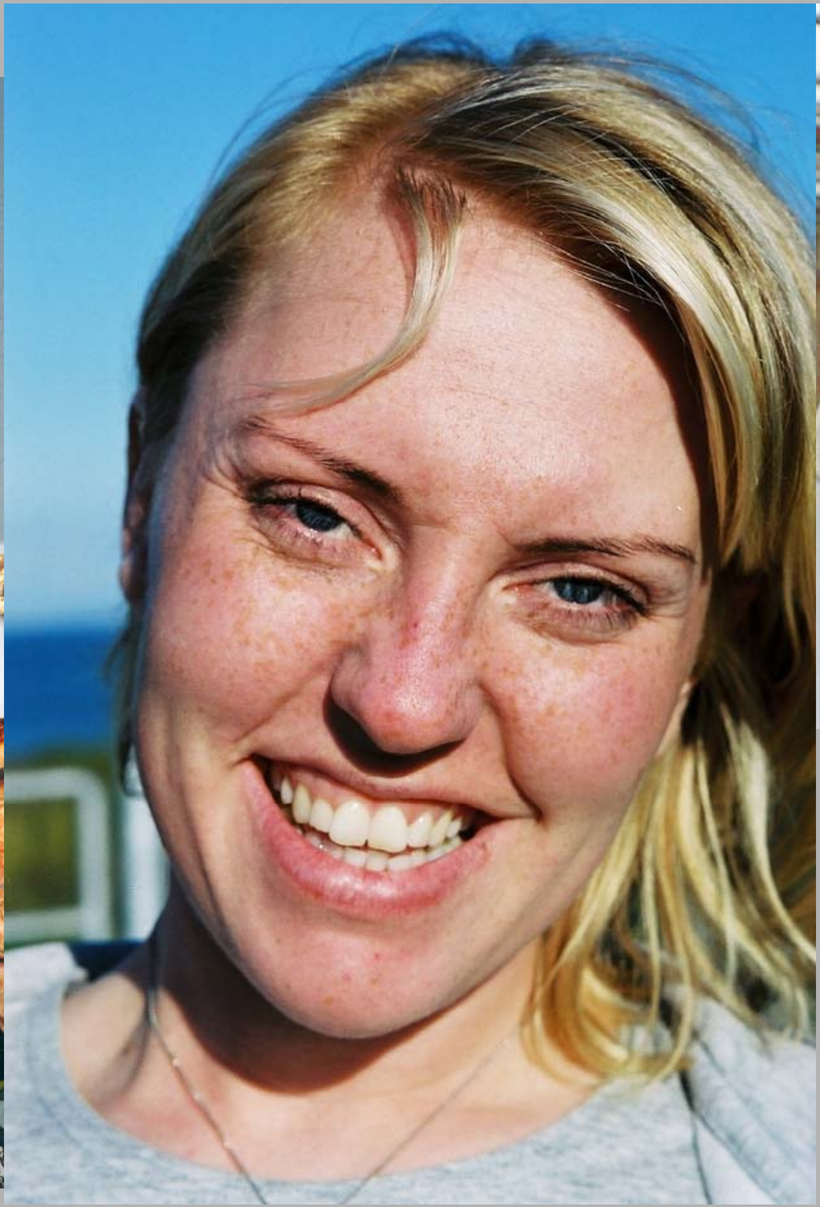


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