

Using major and trace elements to understand Solid Earth processes and element cycling

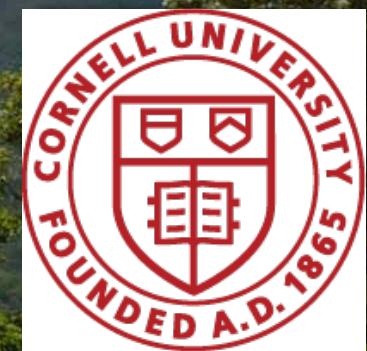
- Presentation focuses on 3 things – i) introduction to mantle melting processes). ii) Element recycling in subduction zones. iii) Evidence of deep element recycling in mantle plumes and other intraplate magmas
- Introduction to melting processes in the mantle in different geodynamic environments (5 slides)
- General petrological and thermodynamically concepts, different compositions (peridotite, pyroxenites, etc) and the role of volatiles
- Mid-ocean ridges (10 slides)
 - Types of ridges (fast, slow, ultraslow) and their petrological and geochemical fingerprints
 - Formation of oceanic crust and development of small scale heterogeneities) and evolution of MORB magmas. Diversity of MOR magmas and their origin (T vs composition)
- Subduction zones, arcs, and generation of continental crust (15 slides)
 - Types of subduction zones (cold vs warm), oceanic arcs vs continental arcs, this will include element recycling, fluid vs melt signatures, and the resulting products.
 - Discussion of improvements and limitations of integration of petrology with geodynamic models
 - Volatiles cycling in subduction zones
 - Implications for the origin of continental crust and different competing geodynamic models.
- Mantle plumes and intraplate magmas (15 slides)
 - Large igneous provinces and OIB magmas: Thermal anomalies vs other processes that trigger intraplate volcanoes. Evidence for thermobarometry for the evidence of mantle plumes
 - Major and trace element evidence of crust recycling (including olivine trace-element systematics). This will include some of my research on the secular evolution of the Galapagos Plume but also all the other work done globally.
- Volatile budgets of intraplate magmas (ongoing work my group is doing in Hawaii, Canary Islands, and LIPs)
- Isotopic evidence for crust recycling (just a couple slides to transition to Dominique's presentation)

Using Major and Trace Elements to Understand Solid Earth Processes and Element Cycling

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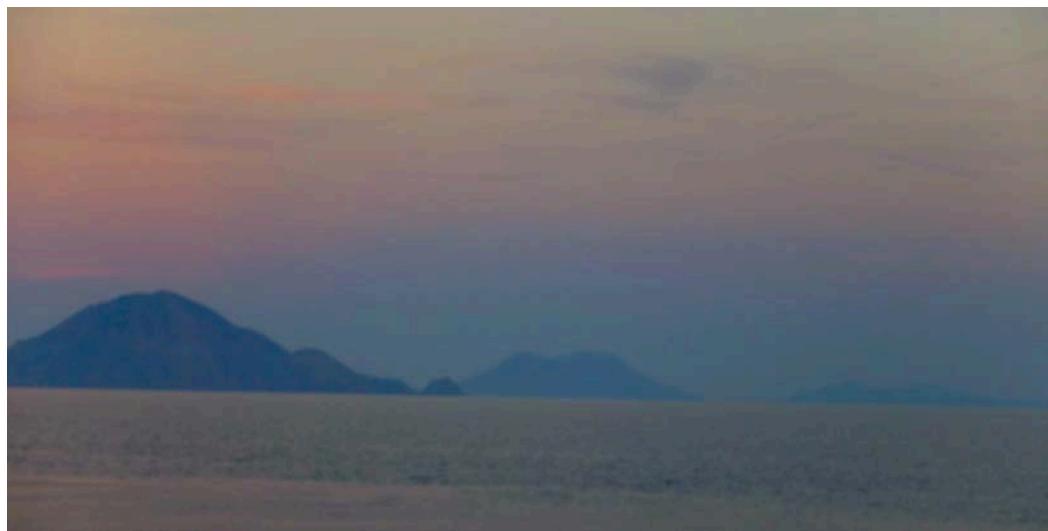
Claude Herzberg
Rutgers



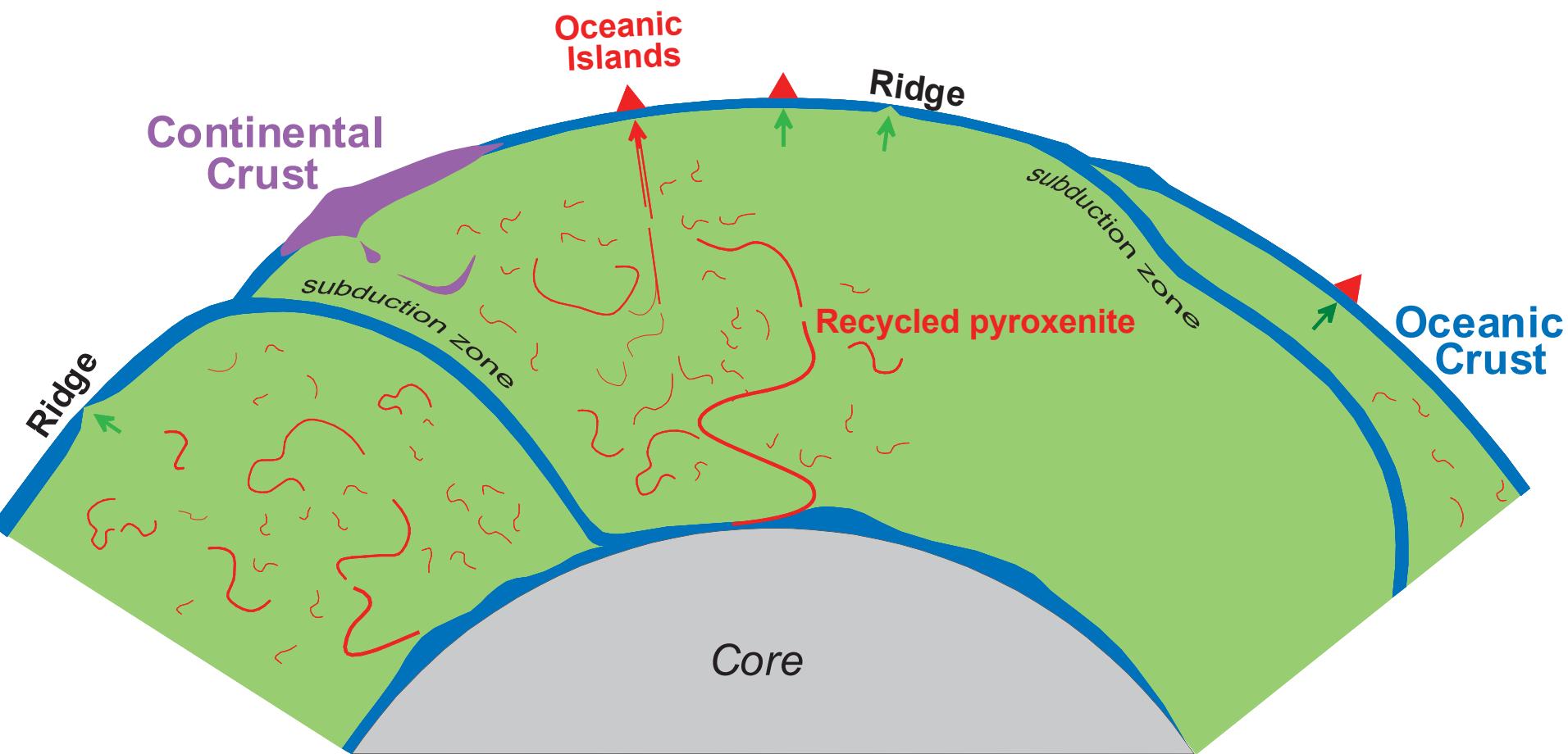


Sunset at Teide, Tenerife, Canary Islands

Volcanoes are probes to the deep Earth



Volcanoes are probes to the deep Earth



Mantle rocks



Peridotite: main component
 $\text{ol} + \text{cpx} + \text{opx} + \text{Al}$ phase (pl, spn, ga)



Pyroxenite:
 $\text{ga} + \text{cpx} + \pm \text{qtz} + \text{rut} \dots =$ recycled oceanic crust
 $\text{ga} + \text{cpx} \pm \text{opx} \pm \text{ol} =$ high-P crystalization

First Molten Rock Experiments

Towards the end of the 19th century, Clarence King and others, determined the geothermal gradient, and thus proved that about 60-80 km there are T and P conditions to melt basalt

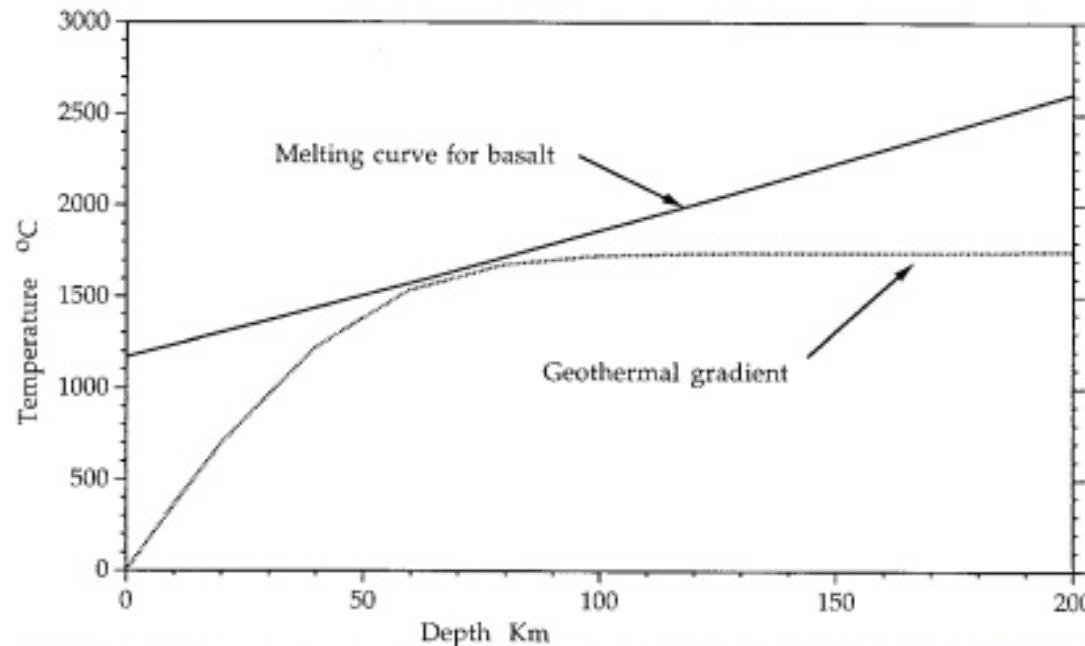


FIGURE 8 At the end of the 19th century, a geotherm had been calculated for the earth by Clarence King and others. The temperature of melting of basalt as a function of pressure had also been determined experimentally by Carl Barus. It was assumed that melting of the Earth's mantle occurred in the depth range where the geothermal gradient approached the basalt melting curve, that is, in the depth range of about 60–80 km below the surface.

Experimental Petrology Instrumentation



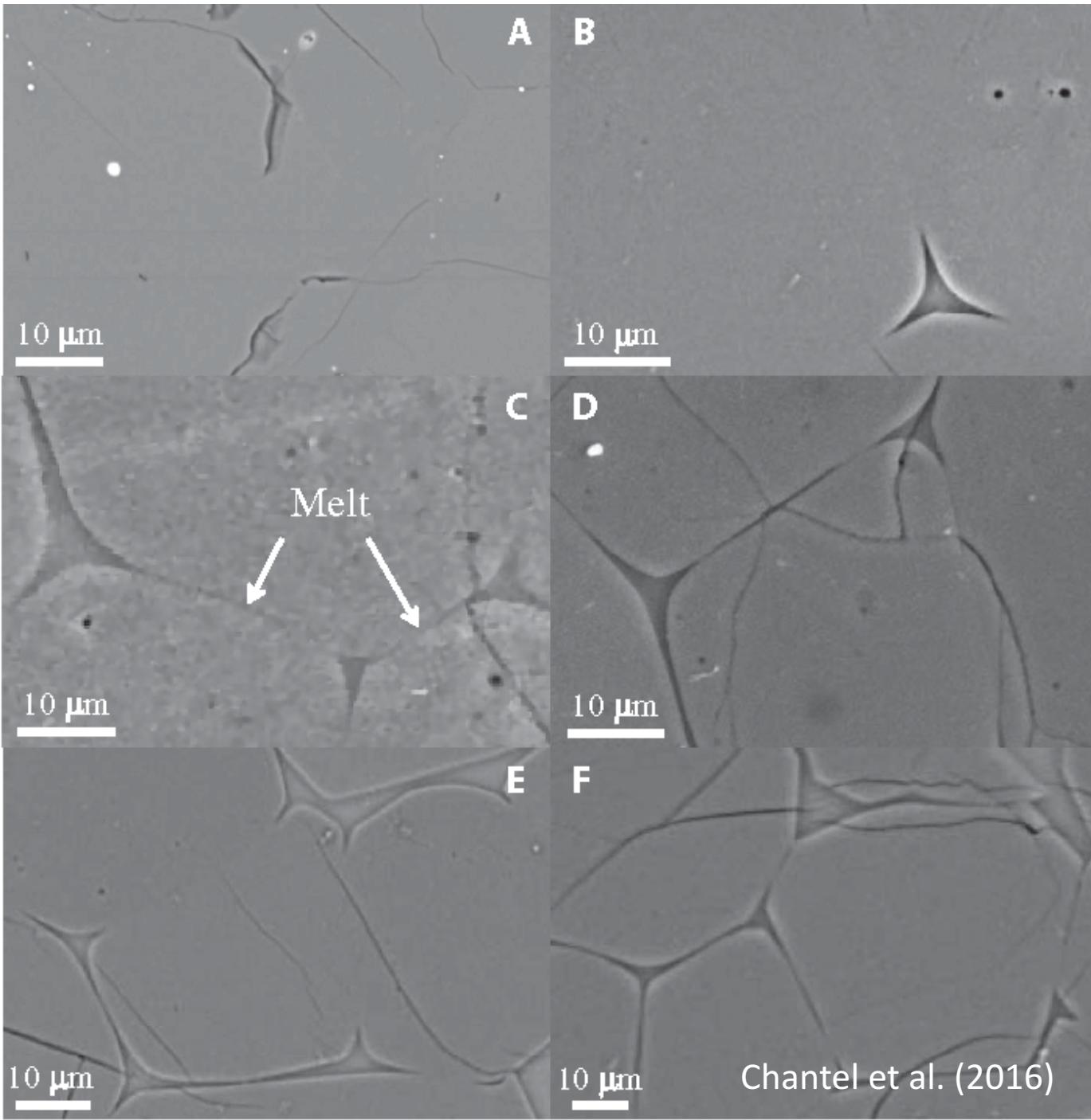
A (BRIEF) TOUR OF EXCITING TOPICS IN EXPERIMENTAL PETROLOGY

Posted 03/24/15 by aguvgp in Education & Outreach Spotlight Uncategorized ,

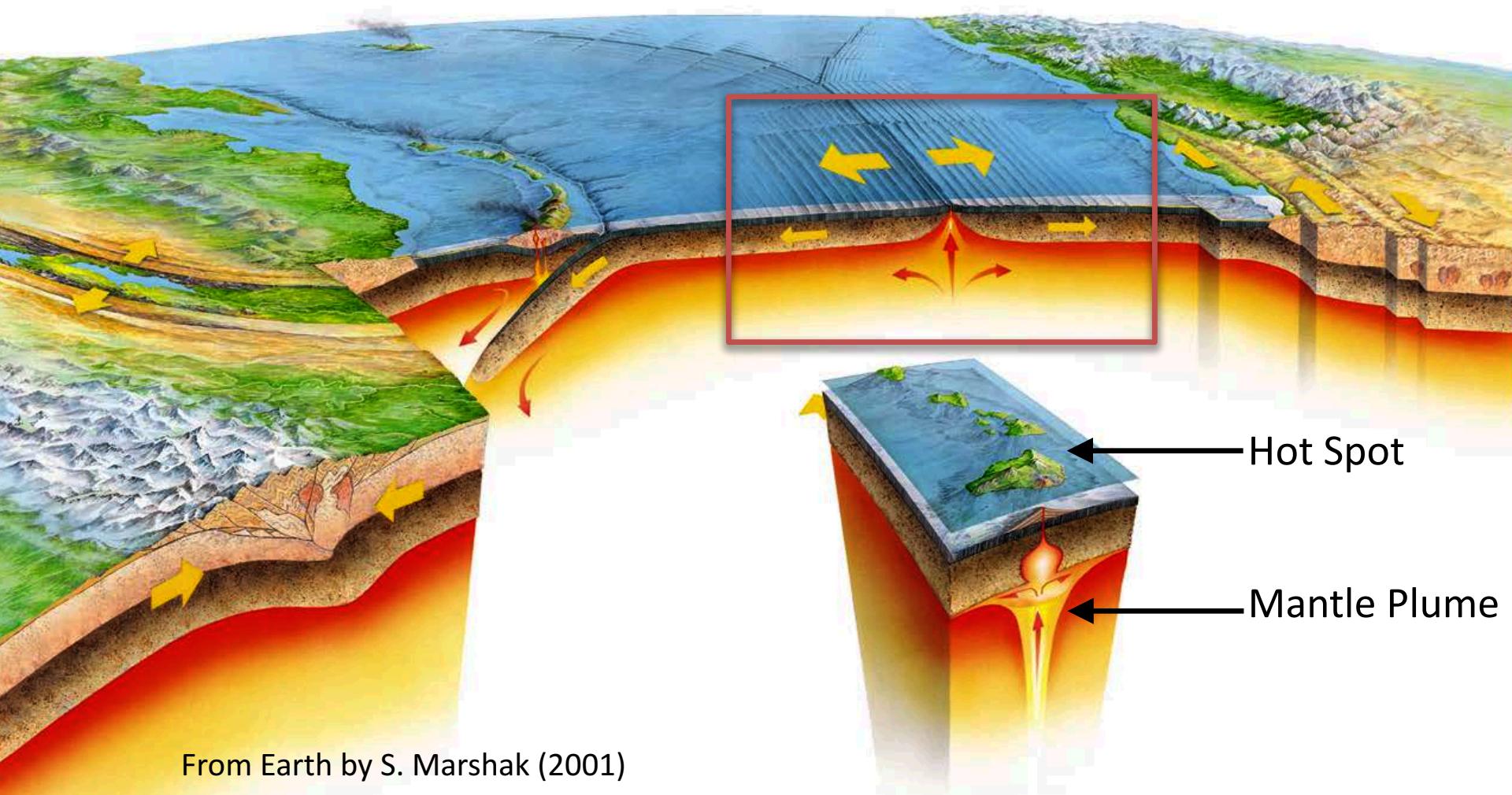
A (Brief) Tour of Exciting Topics in Experimental Petrology

Christy B. Till¹ & Michael Krawczynski²

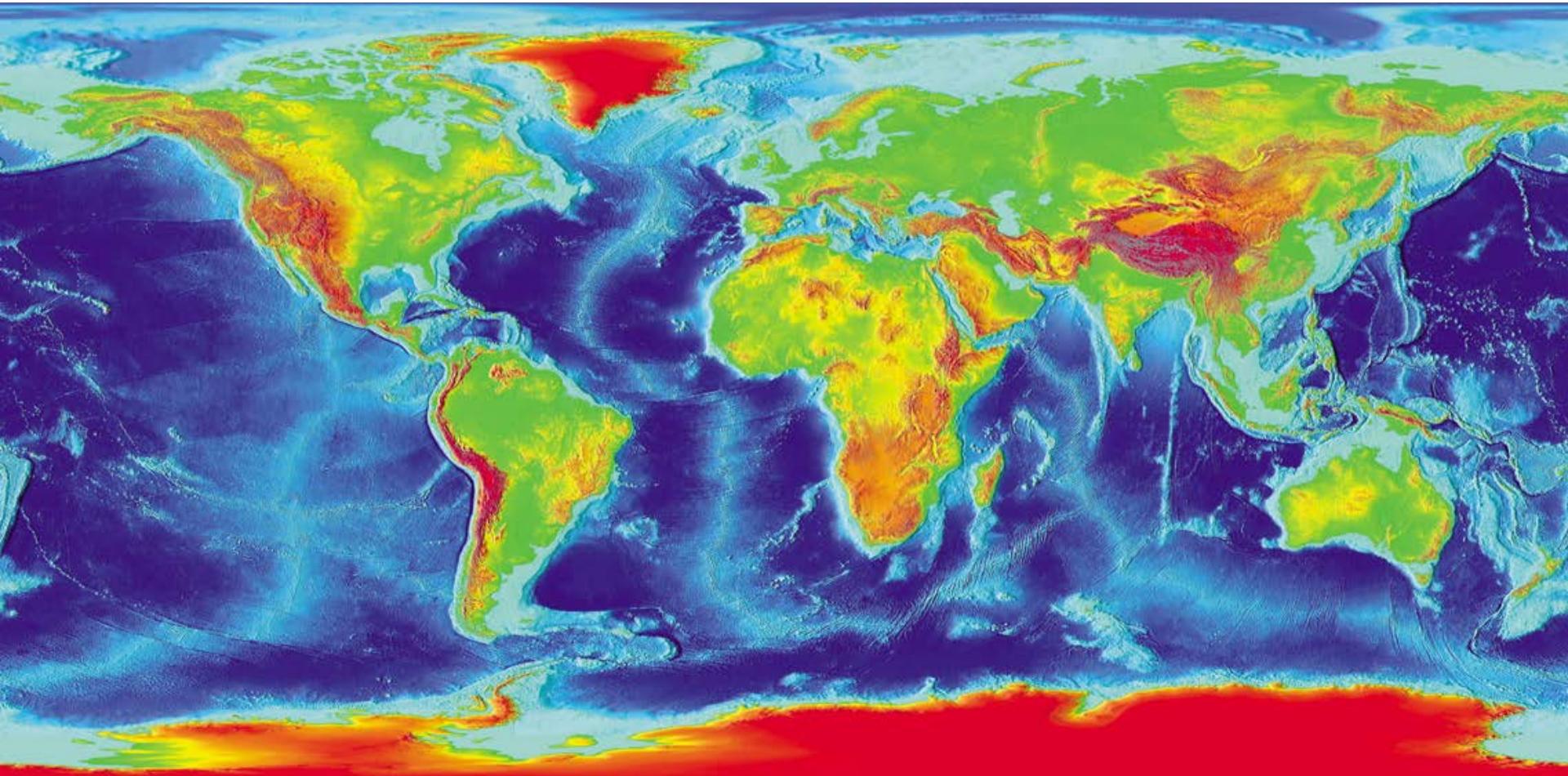




1. Mid Ocean Ridges
2. Subduction Zones
3. Mantle Plumes and Intraplate Magmatism

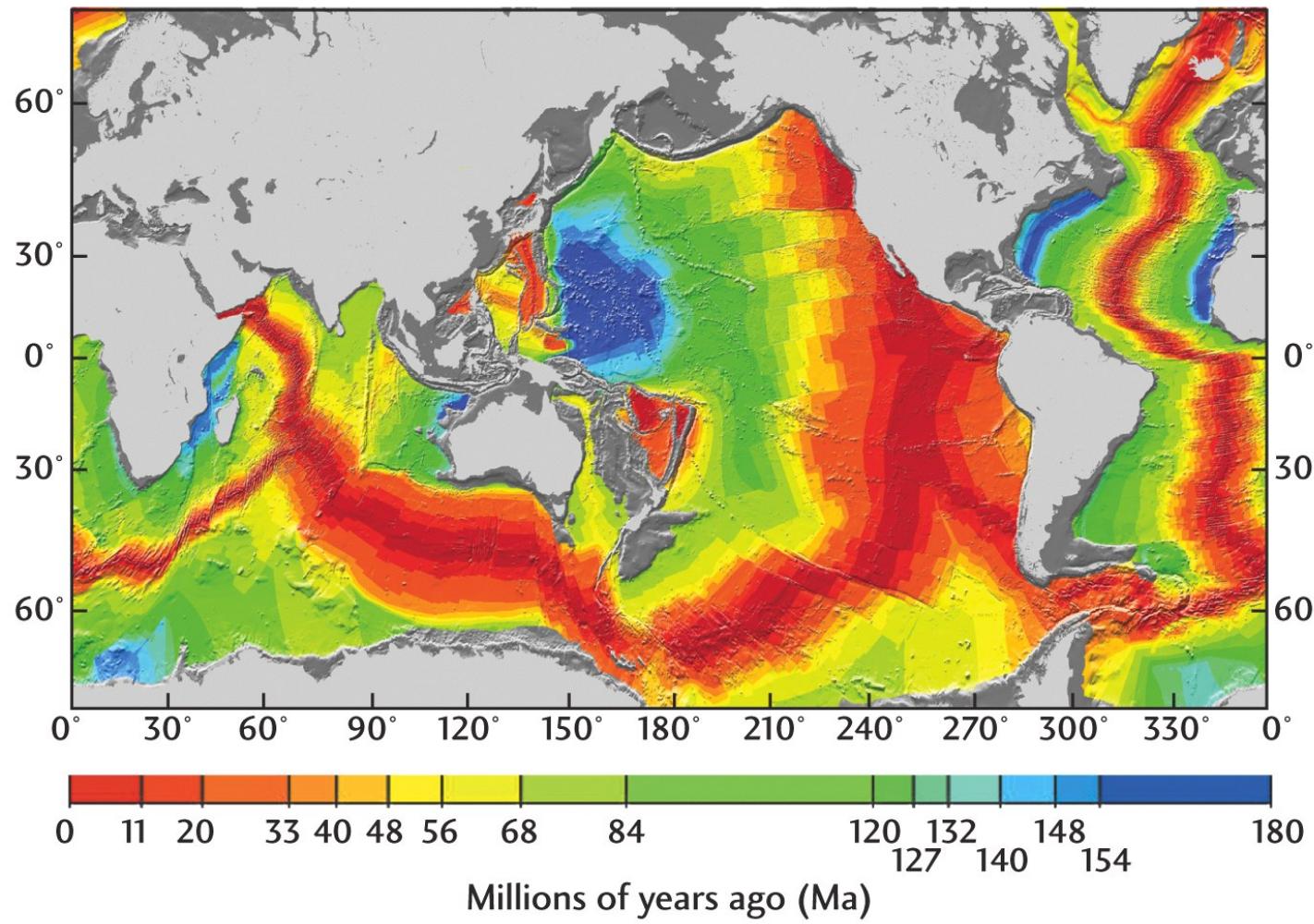


Mid Ocean Ridges



Mid Oceanic ridges:

- divergent lithospheric plate boundary
- 65,000 km length
- MORB = mid-ocean ridge basalts



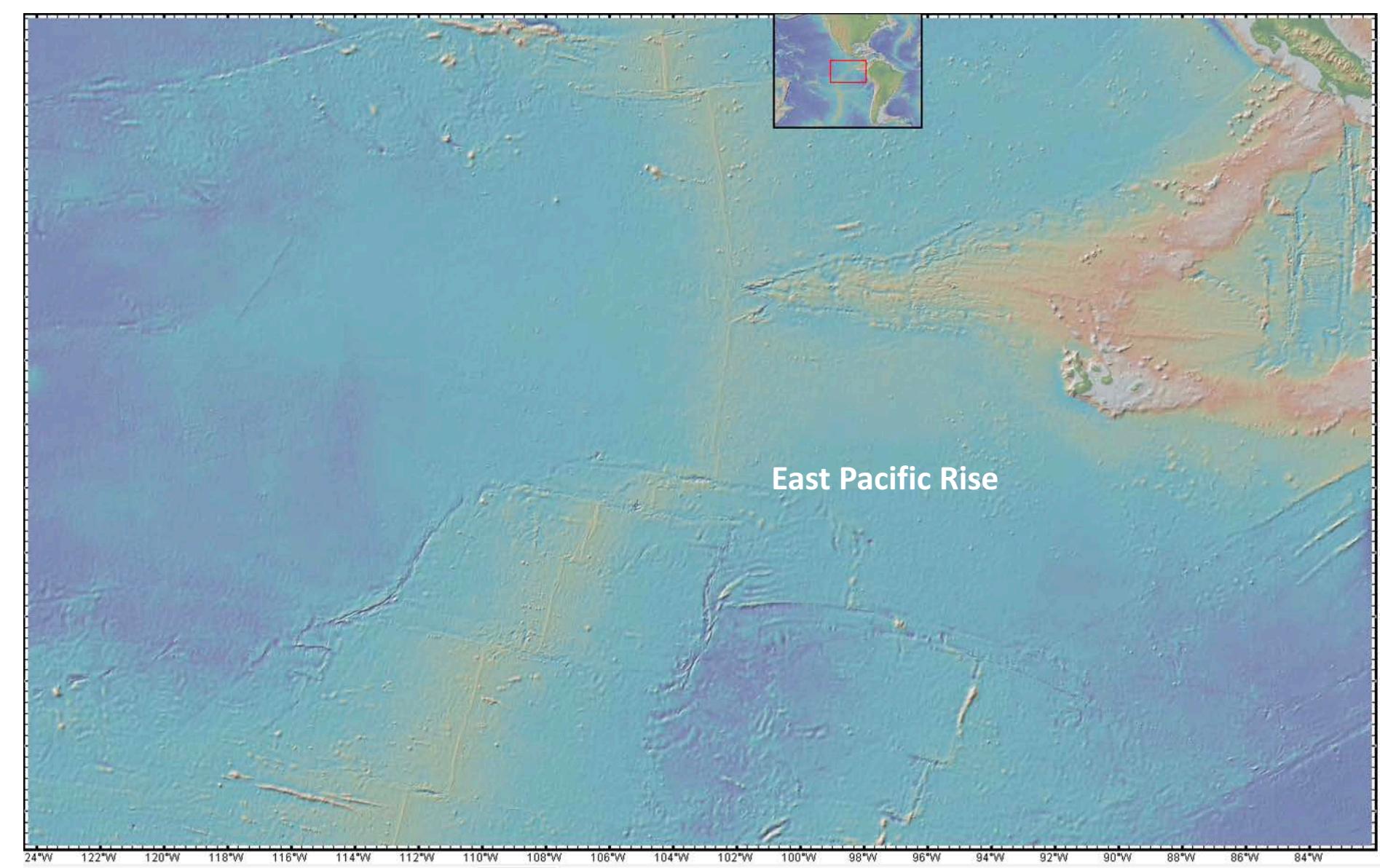
New oceanic crust is formed by sea floor spreading:

Mid-Atlantic Ridge: 2 - 4 cm/yr

East Pacific Rise: 10 - 17 cm/yr

Volume of crust = 18.5 km³/yr

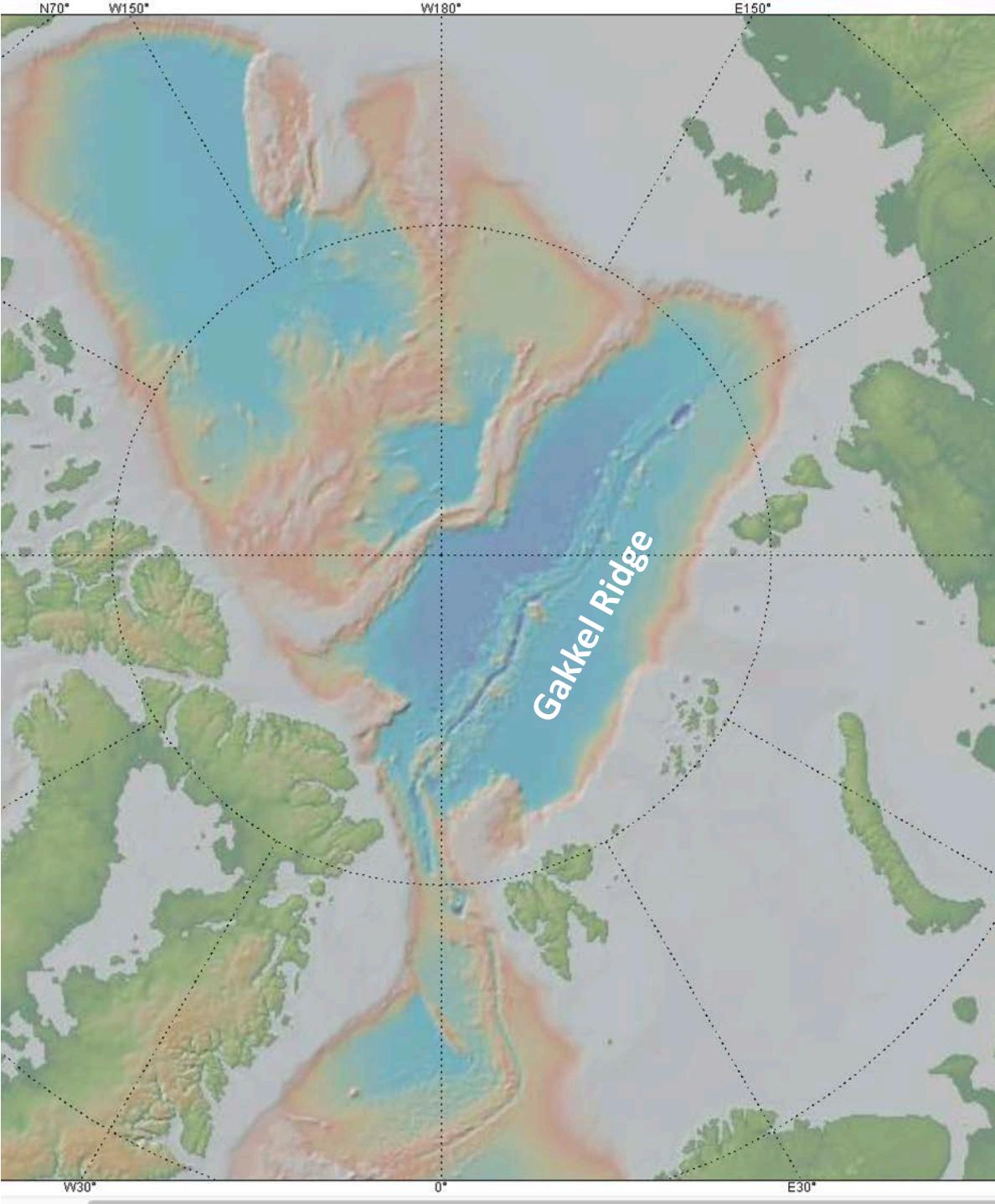
- greater than any other tectonic setting (at the present time)

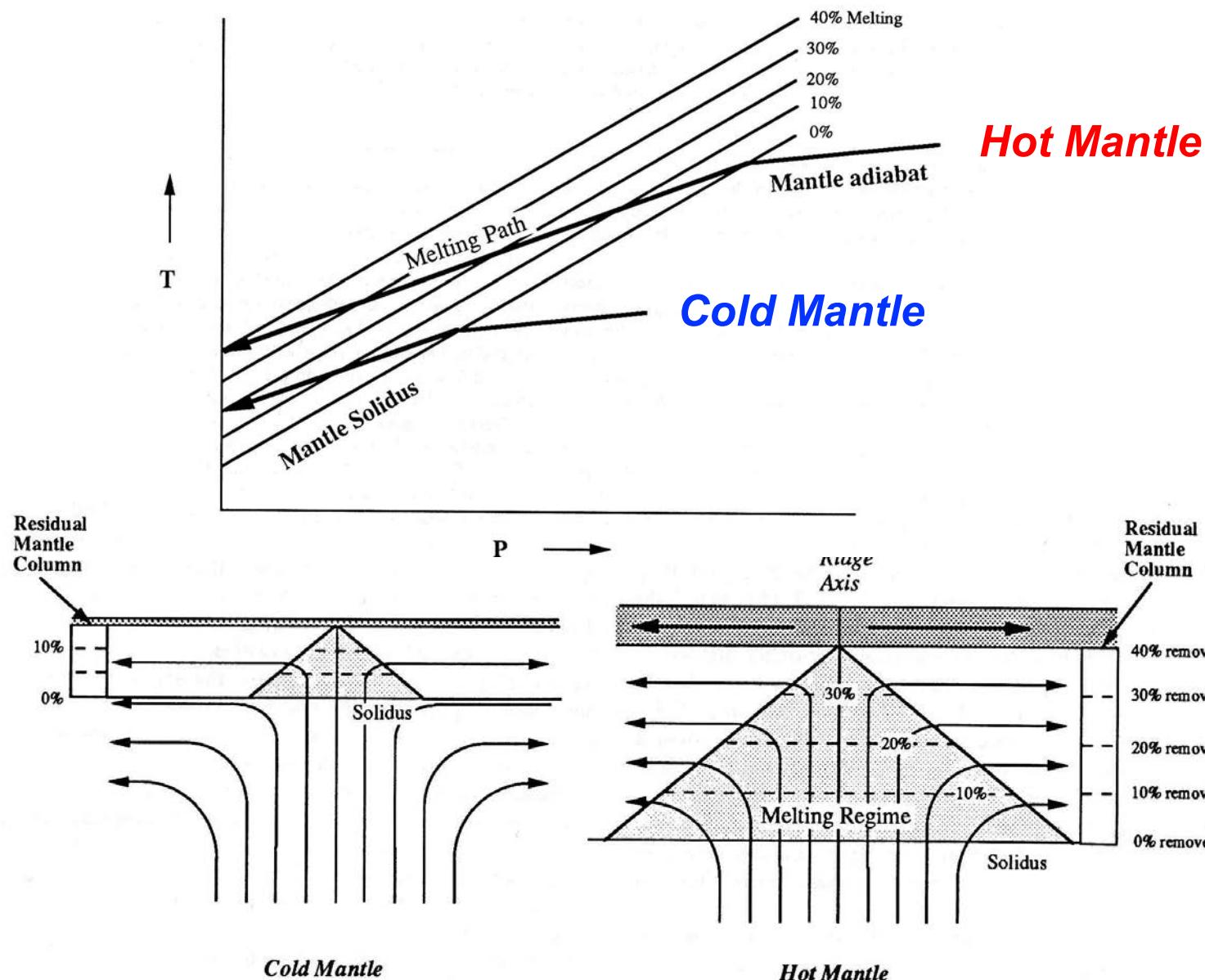


A 3D perspective view of the ocean floor, colored by depth. The Mid Atlantic Ridge runs roughly north-south through the center of the image, appearing as a bright yellow/orange line. To the east, the Carlsberg Ridge branches off towards the southeast. The ocean floor is mostly blue and green, indicating shallower depths. Landmasses are visible as green and brown areas.

Mid Atlantic
Ridge

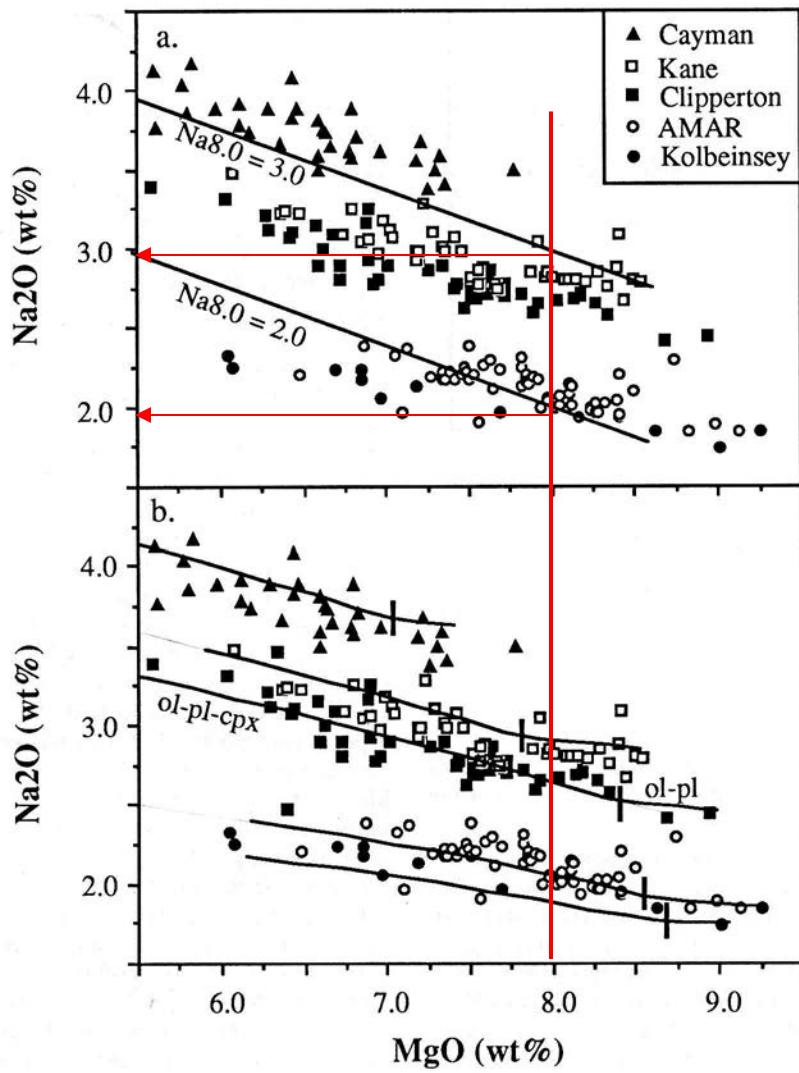
Carlsberg
Ridge





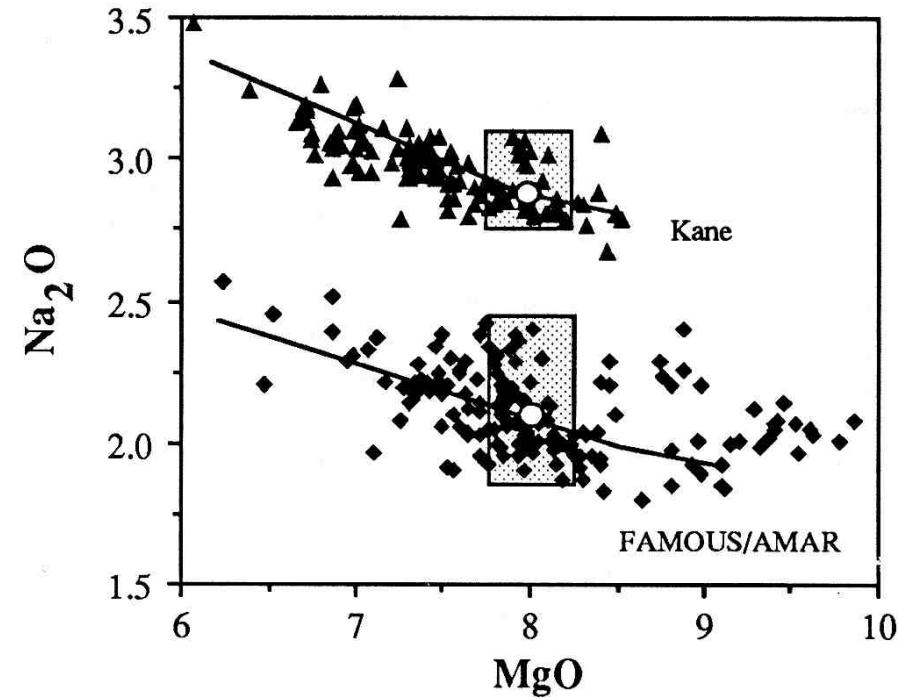
Langmuir, C. H., Klein, E. M., and Plank, T., 1992, Petrological systematics of mid-ocean ridge basalts: Constraints on melt generation beneath ocean ridges: Mantle flow and melt generation at mid-ocean ridges, Geophysical Monograph p. 183-280.

Global trends

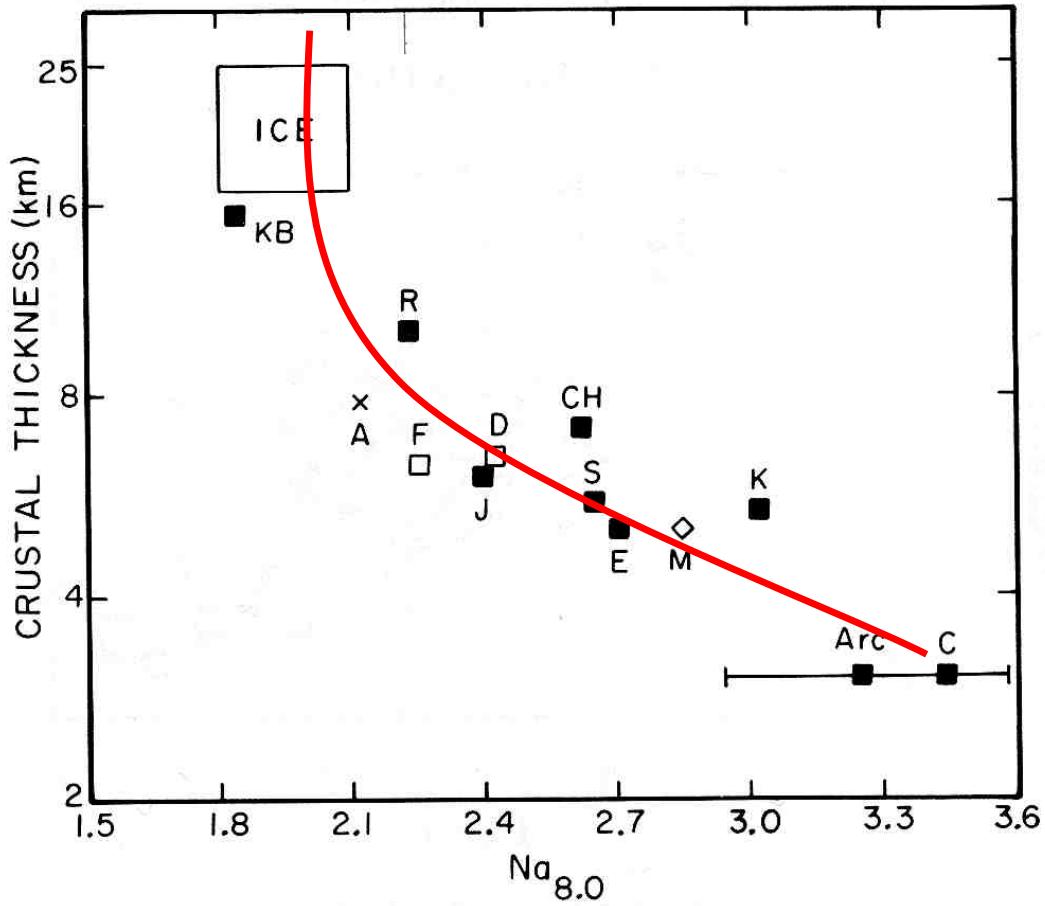


Na_2O at 8% MgO

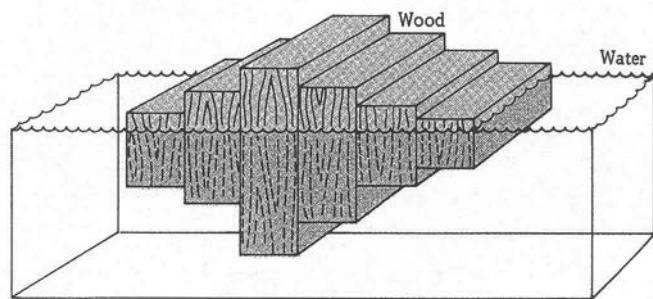
Global & Local trends



Langmuir et al. (1992)



Isostacy:
Ridge axis bathymetry ↑
as the crust thickens.

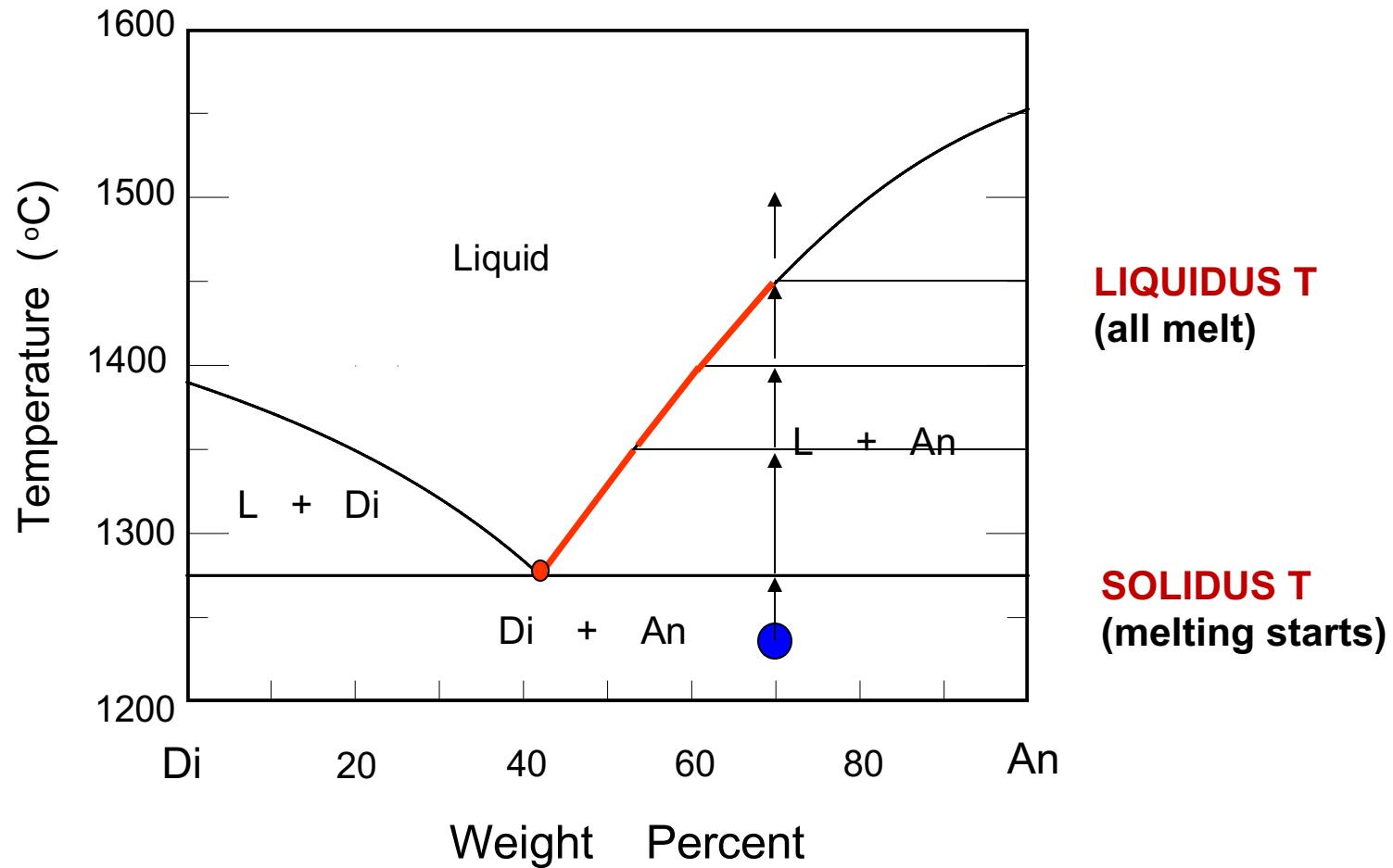


Partial melting

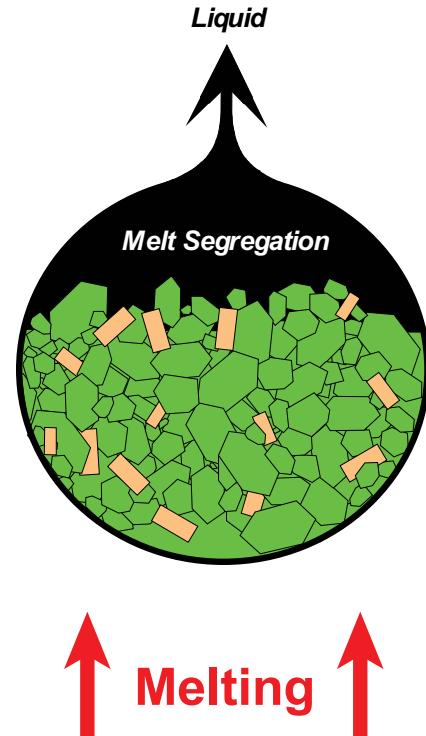
- In the Mid-ocean ridge tectonic environment partial melting produced by **mantle decompression**, this decompression is related with the mantle upwelling (mantle circulation-ridge push and slab pull).
- Melt is produced when the hot material rise and decompress.
- This liquid it is generally more buoyant than the matrix (mantle/crust).
- The type of melting is **aggregated fractional melting**

Isobaric Equilibrium Melting

1 atmosphere

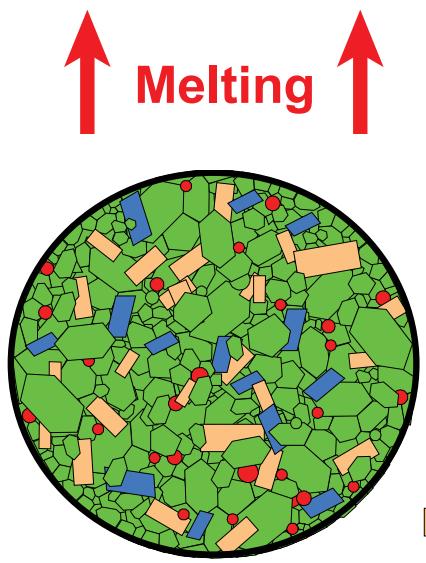


Mid Ocean Ridge Basalts (MORB)

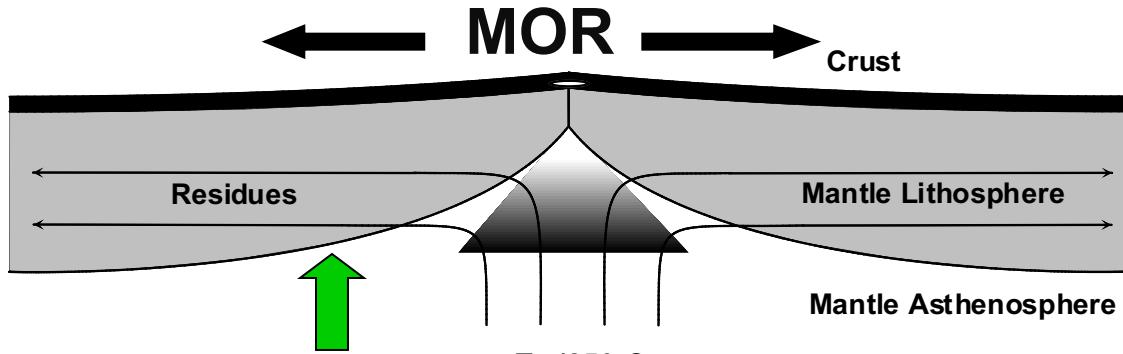
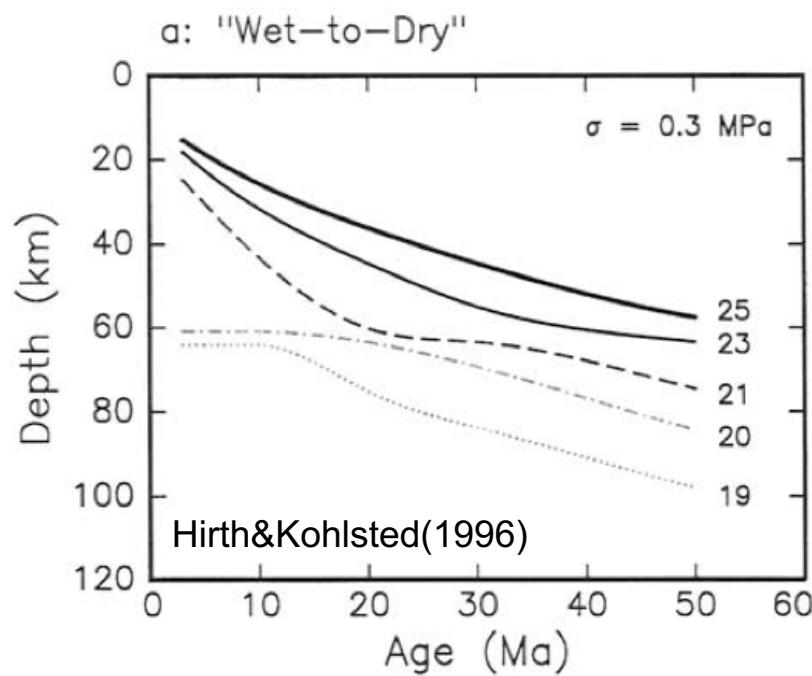


$$FC_L = \text{crust}$$

$$+ (1-F)C_s = \text{residue}$$



Mantle Peridotite



**Abyssal Peridotite
(Lithospheric Residual Mantle)**

Phaseplot Demo_Peridotite Melting

Open the Mac App Store to buy and download apps.



PhasePlot 4+

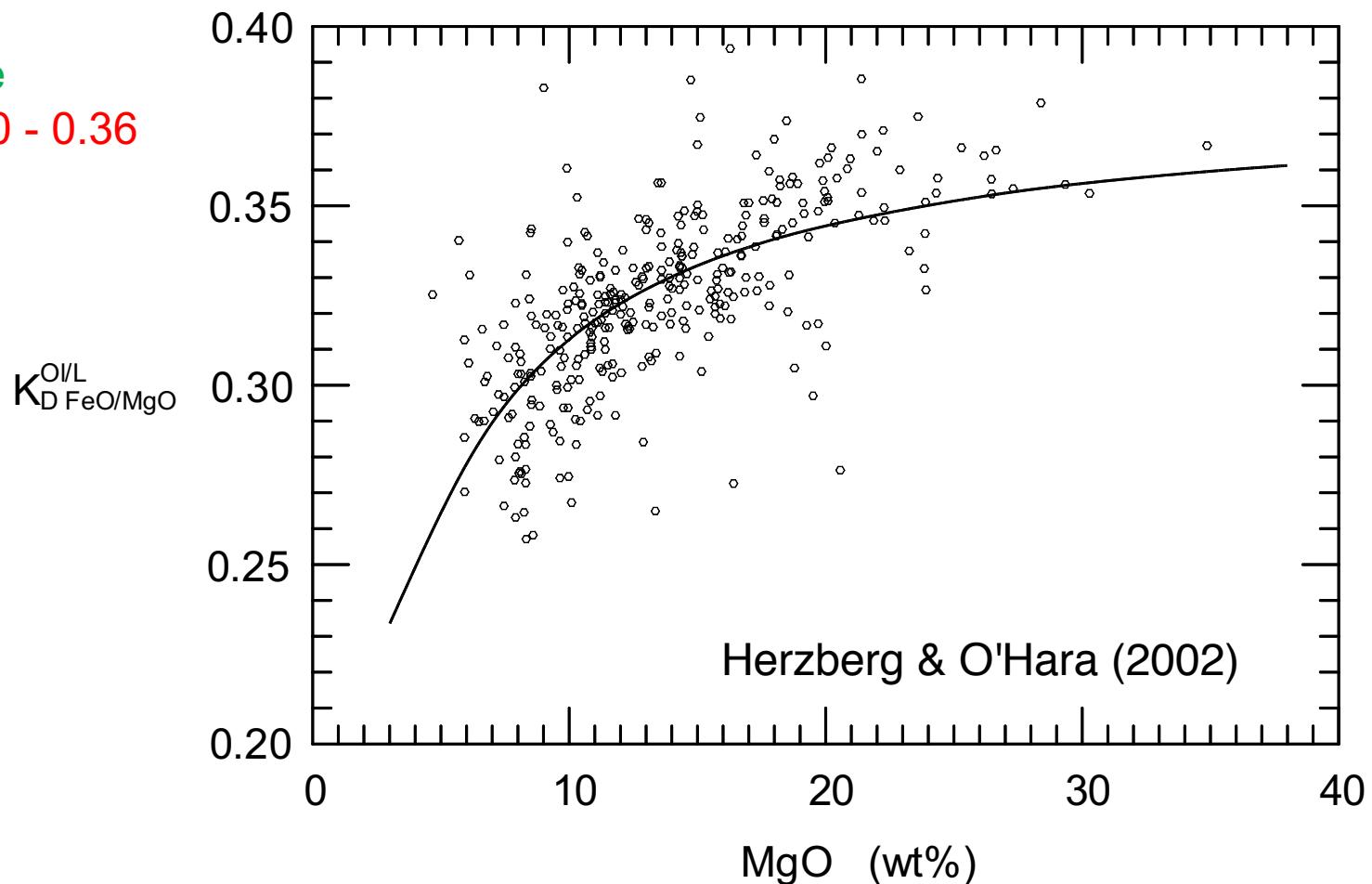
Mark Ghiorso CT Software

Free

[View in Mac App Store ↗](#)

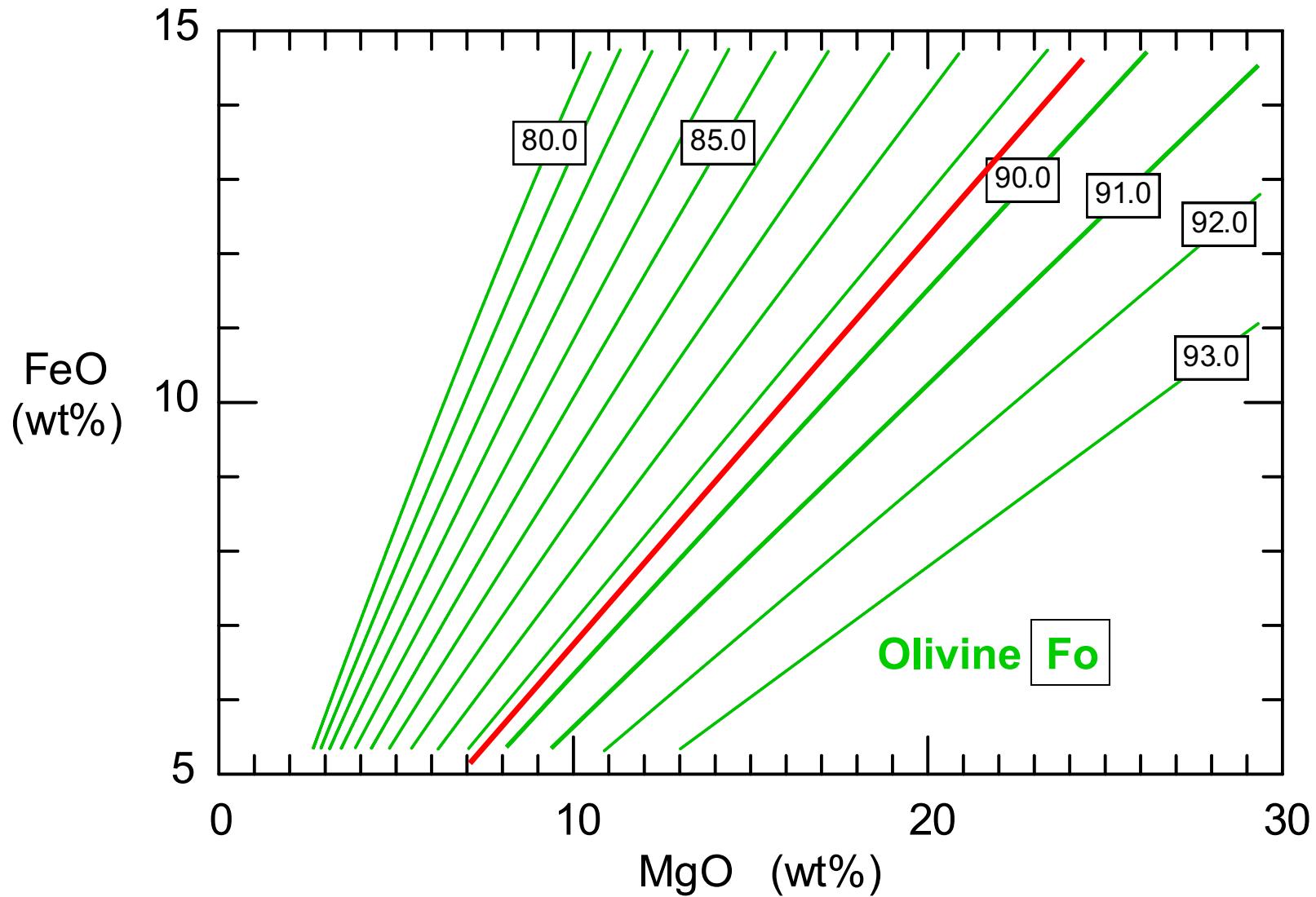
The partitioning of FeO and MgO between Olivine & Liquid is almost constant (Roeder & Emslie, 1970):

$$\frac{\left| \frac{\text{FeO}}{\text{MgO}} \right|_{\text{Olivine}} - 0.30 - 0.36}{\left| \frac{\text{FeO}}{\text{MgO}} \right|_{\text{Melt}}} = 0.30 - 0.36$$



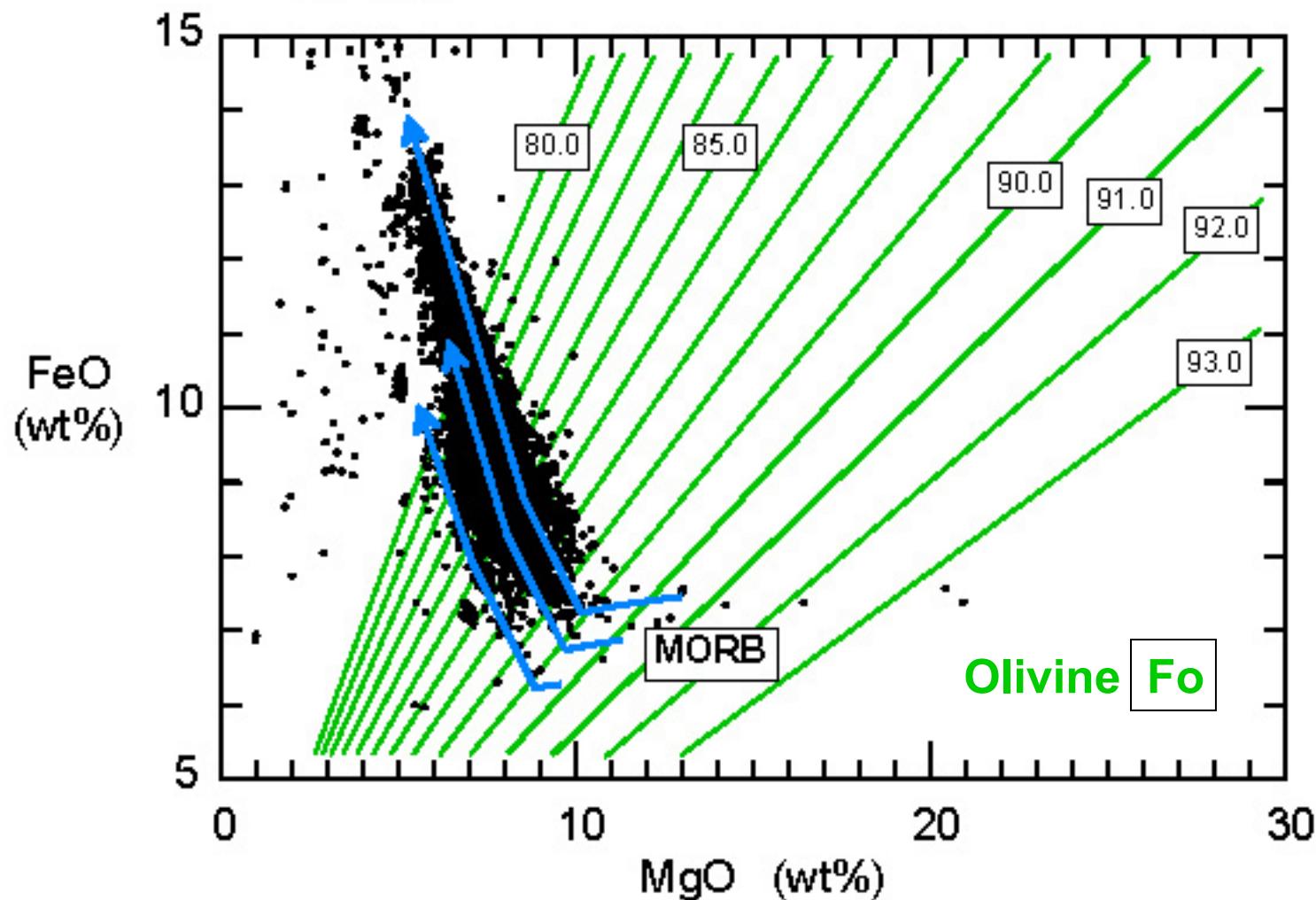
FeO and MgO in Liquids

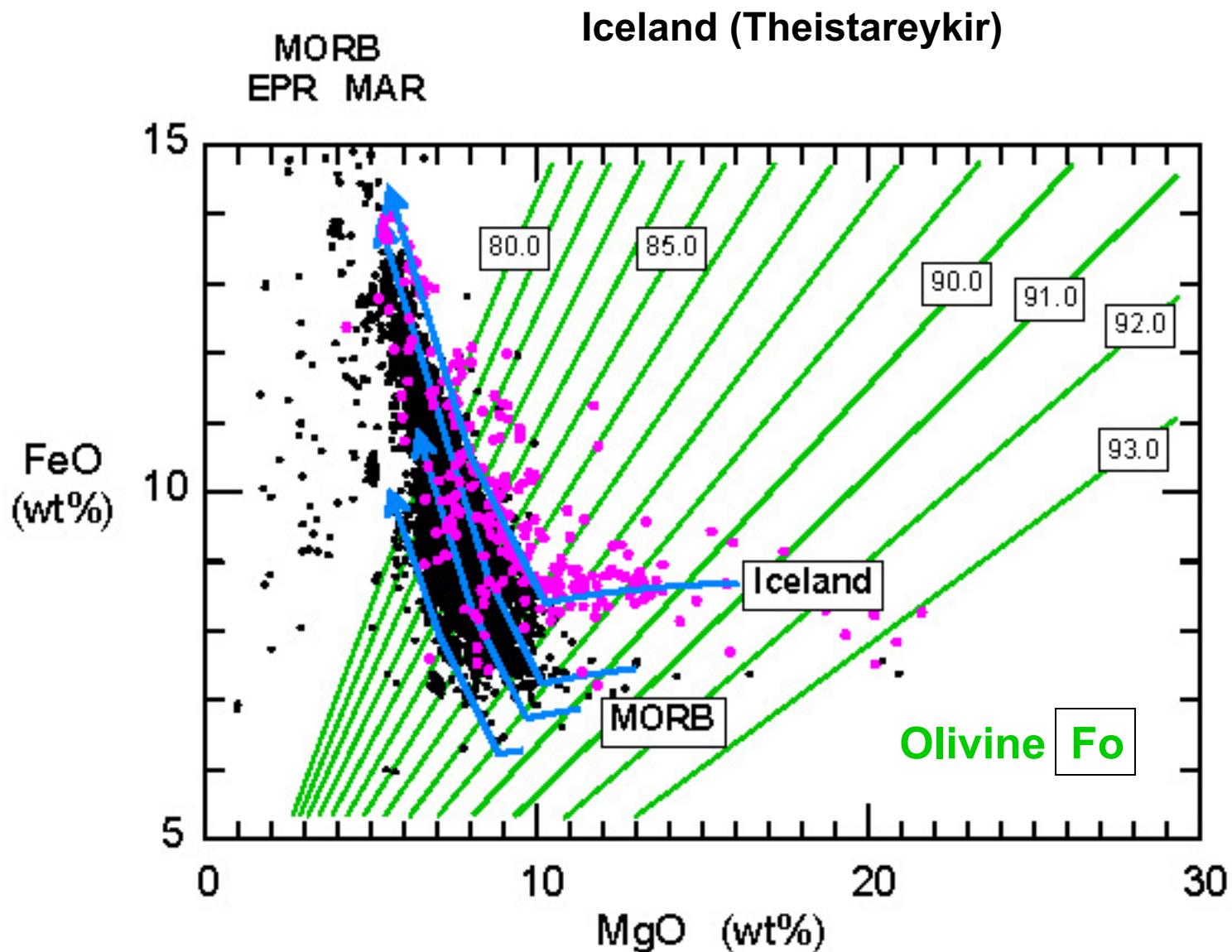
Peridotite
Solidus

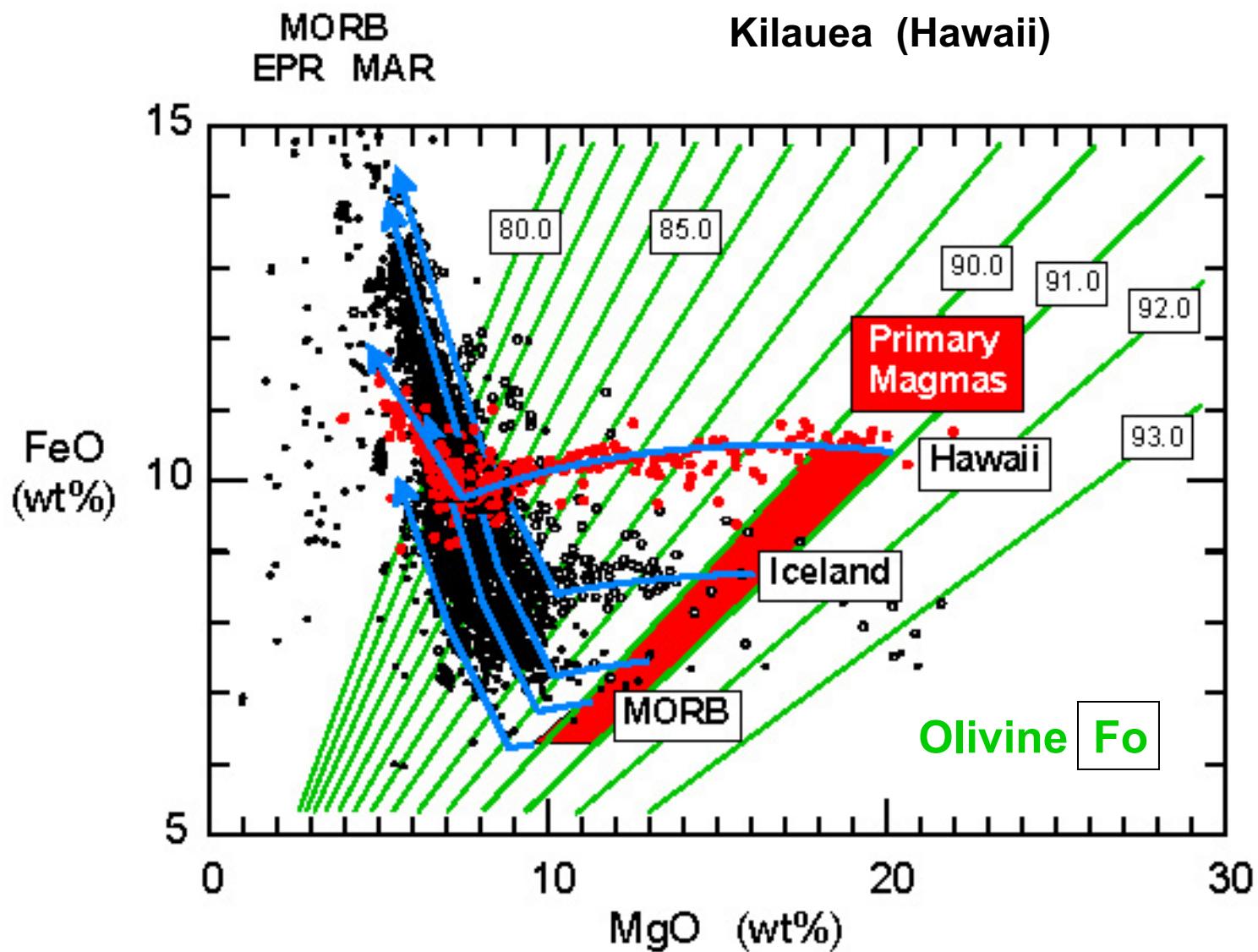


**East Pacific Rise
Mid-Atlantic Ridge**

MORB
EPR MAR

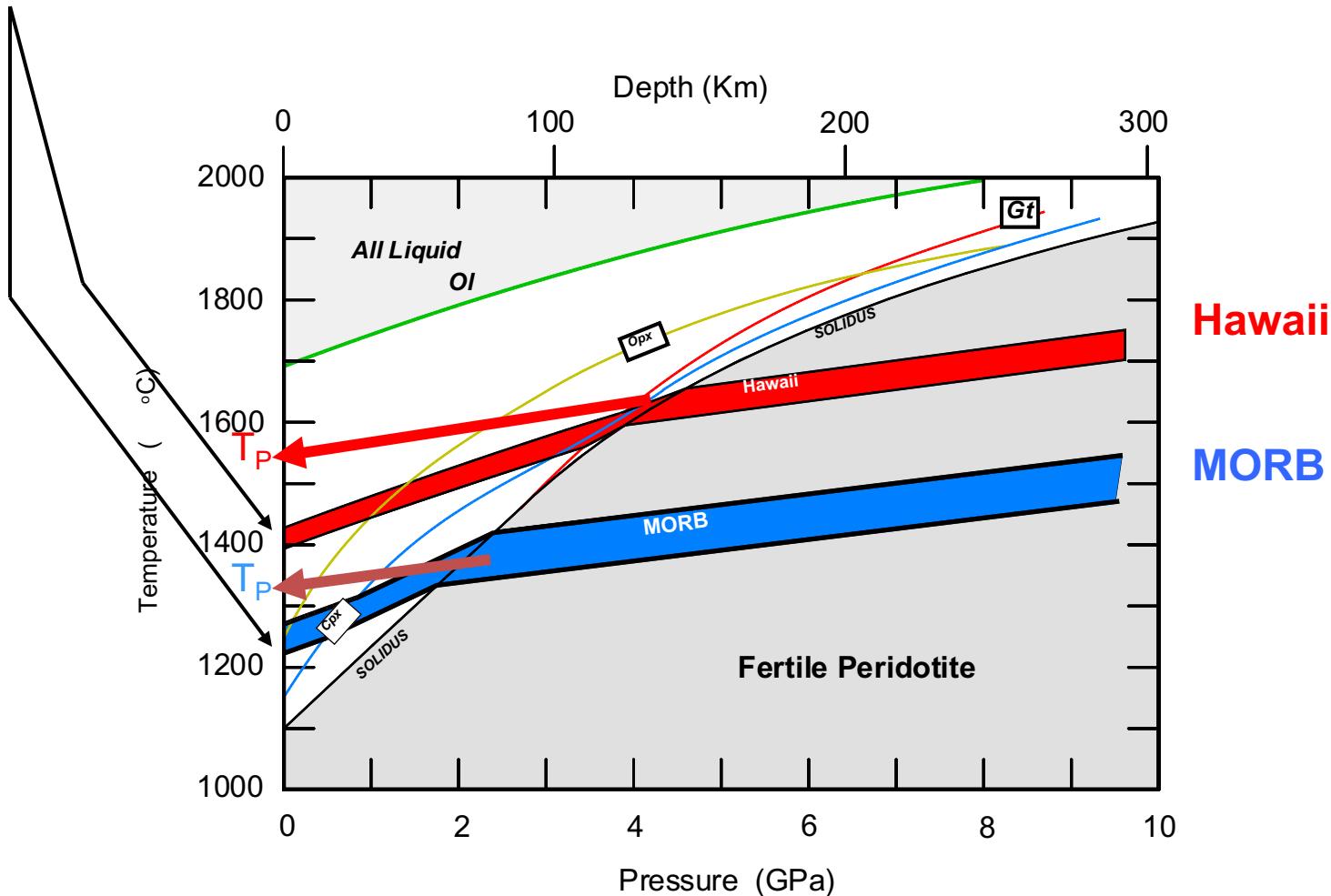




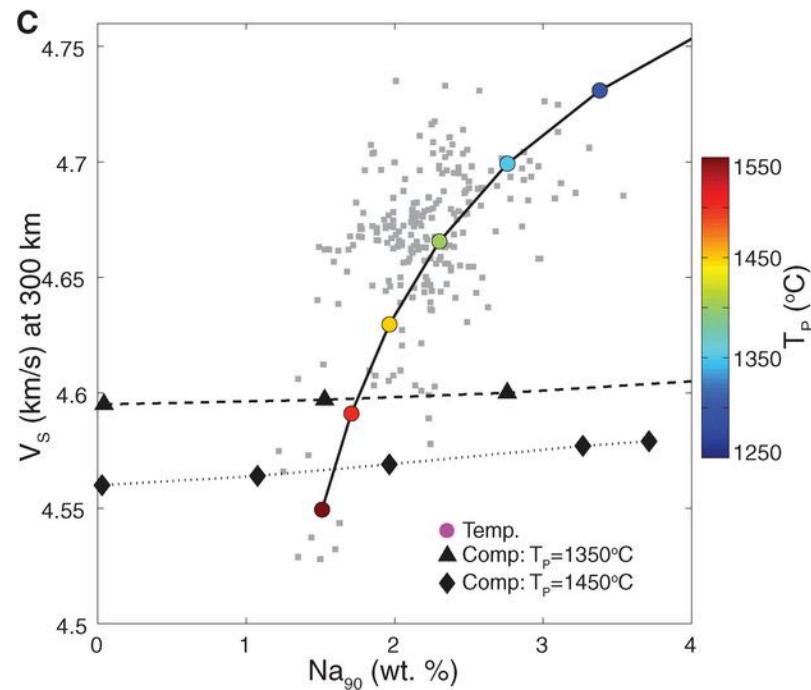
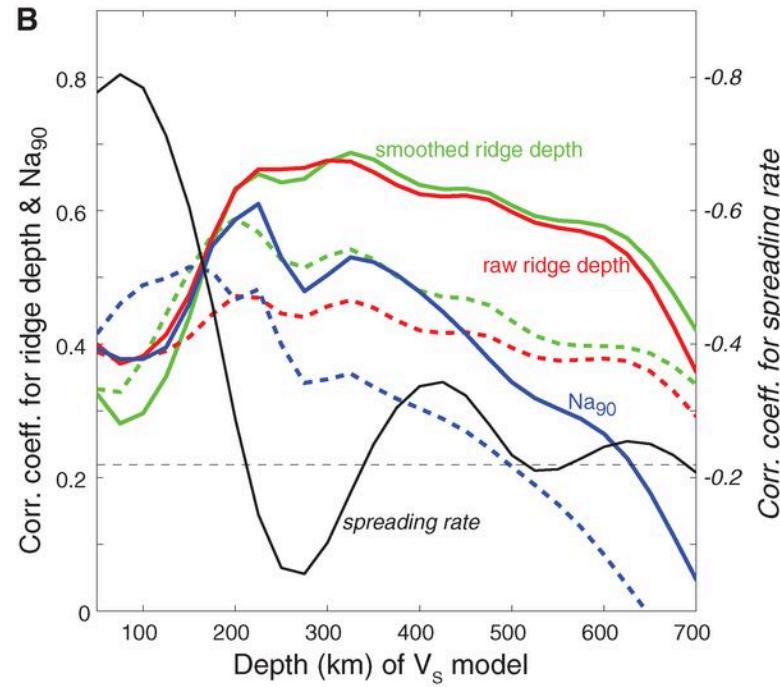
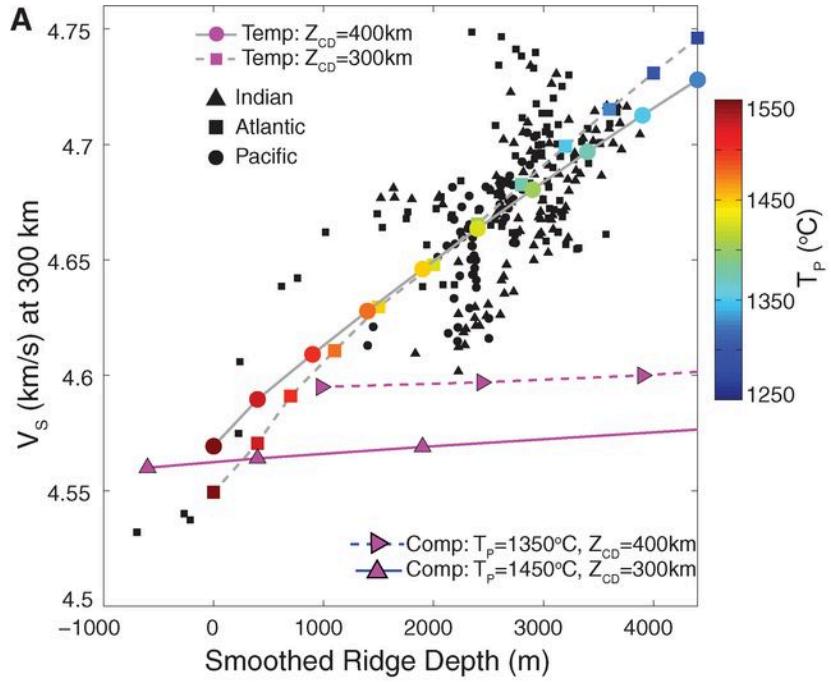


Herzberg et al. (2007)

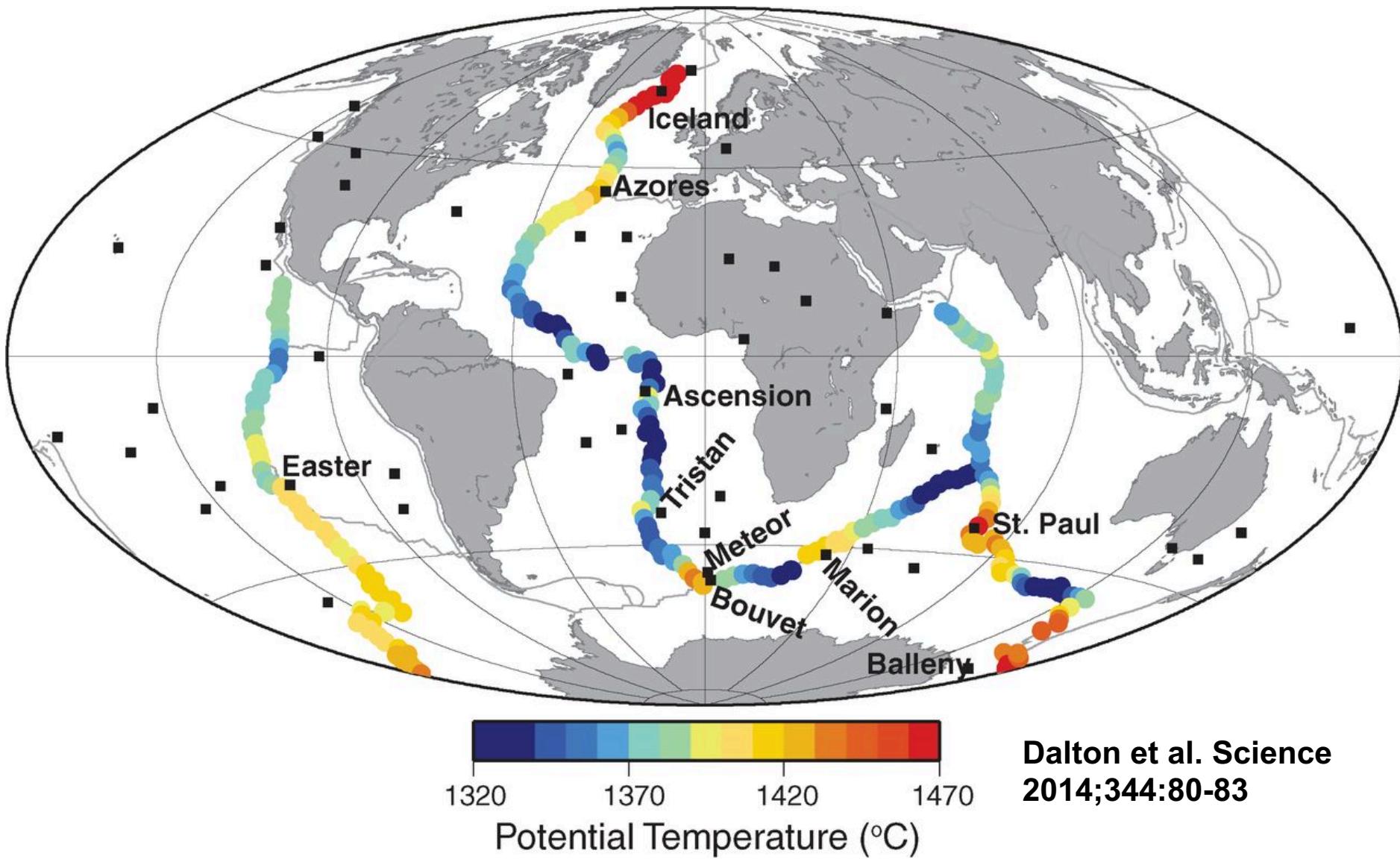
Eruption T =
Olivine Liquidus T



T_P = Mantle Potential Temperature
- T of a convective geotherm
if it could flow to the surface

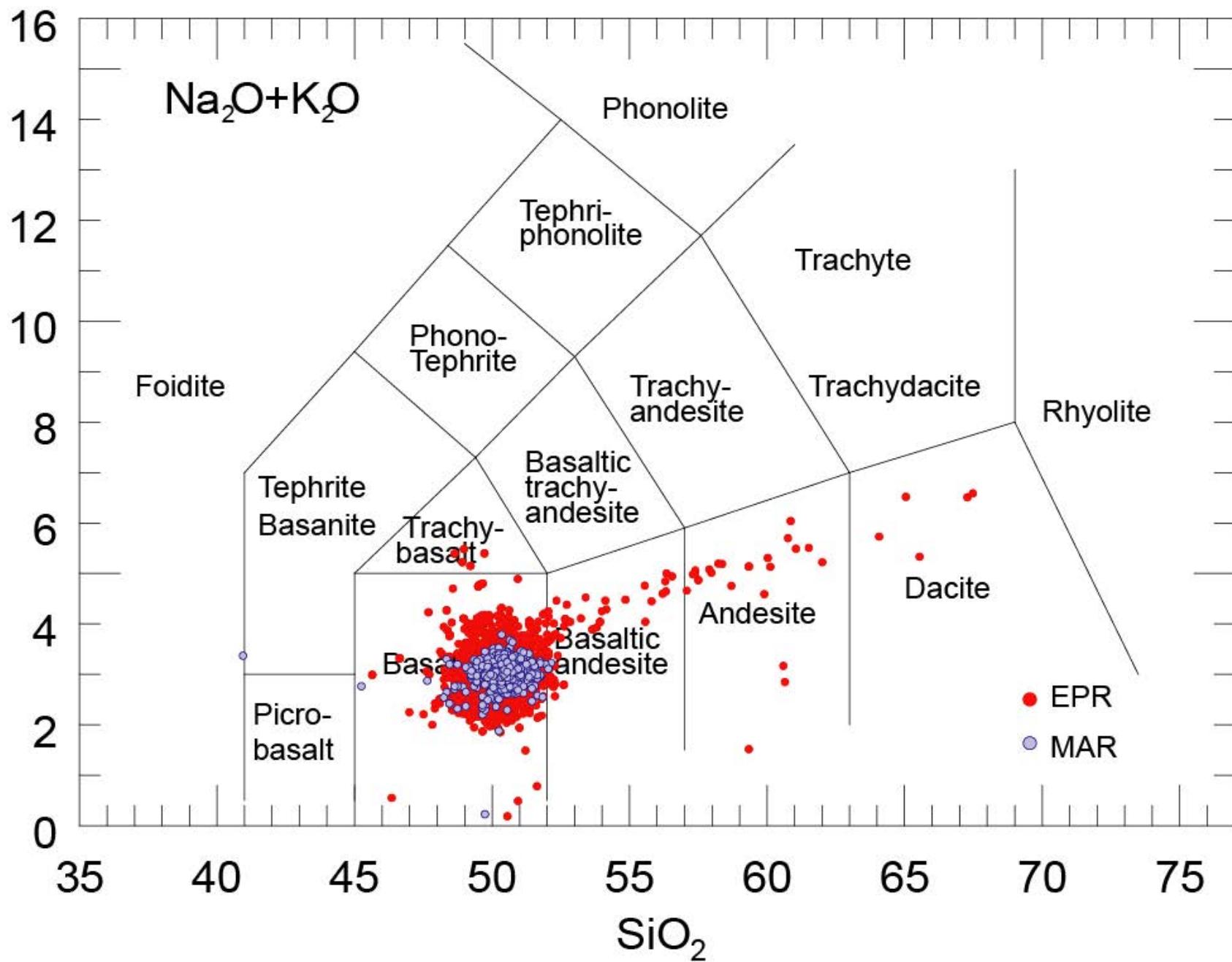


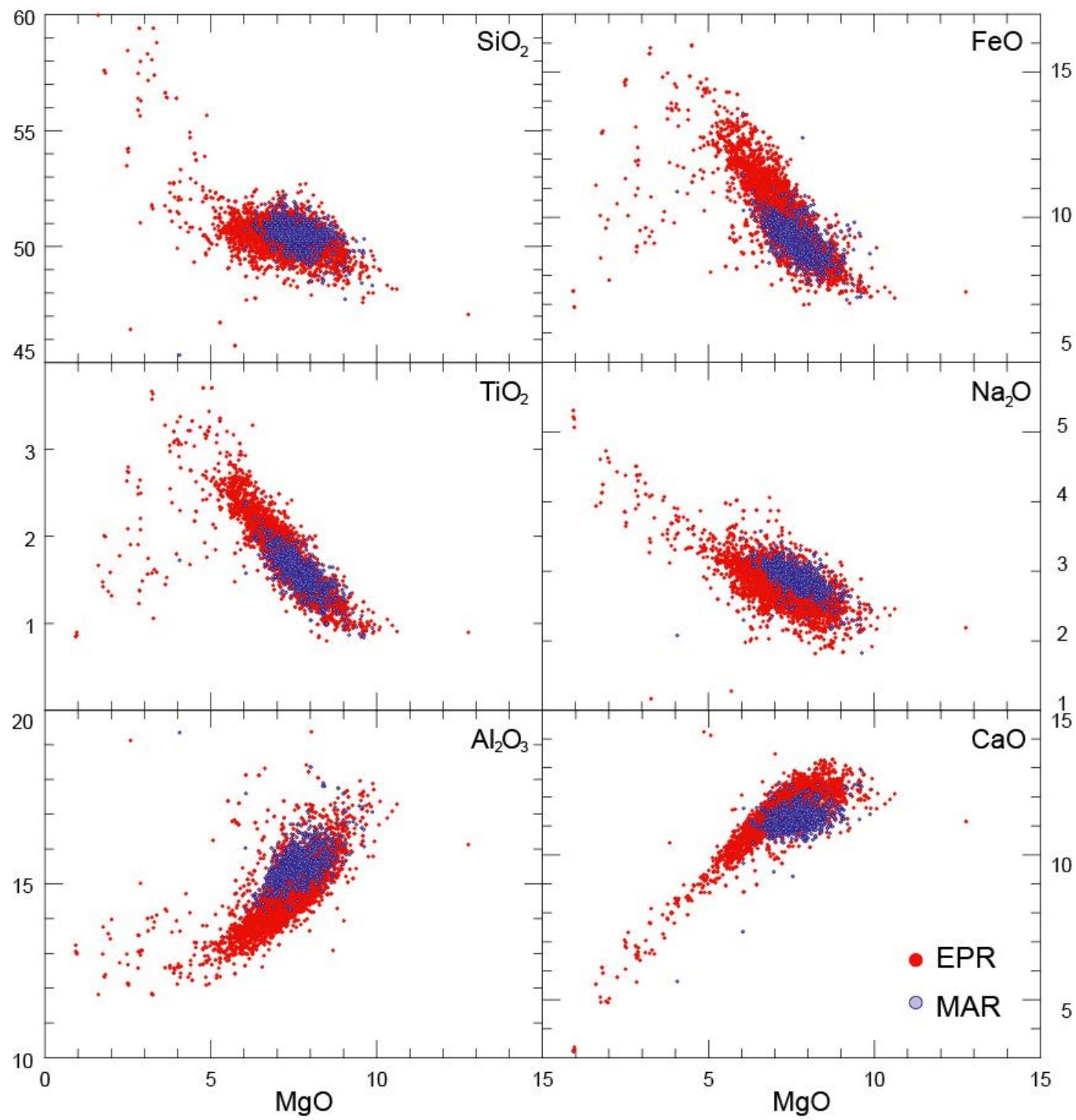
Along-ridge variation in T_p Averages of T_p estimated VS at 300 km



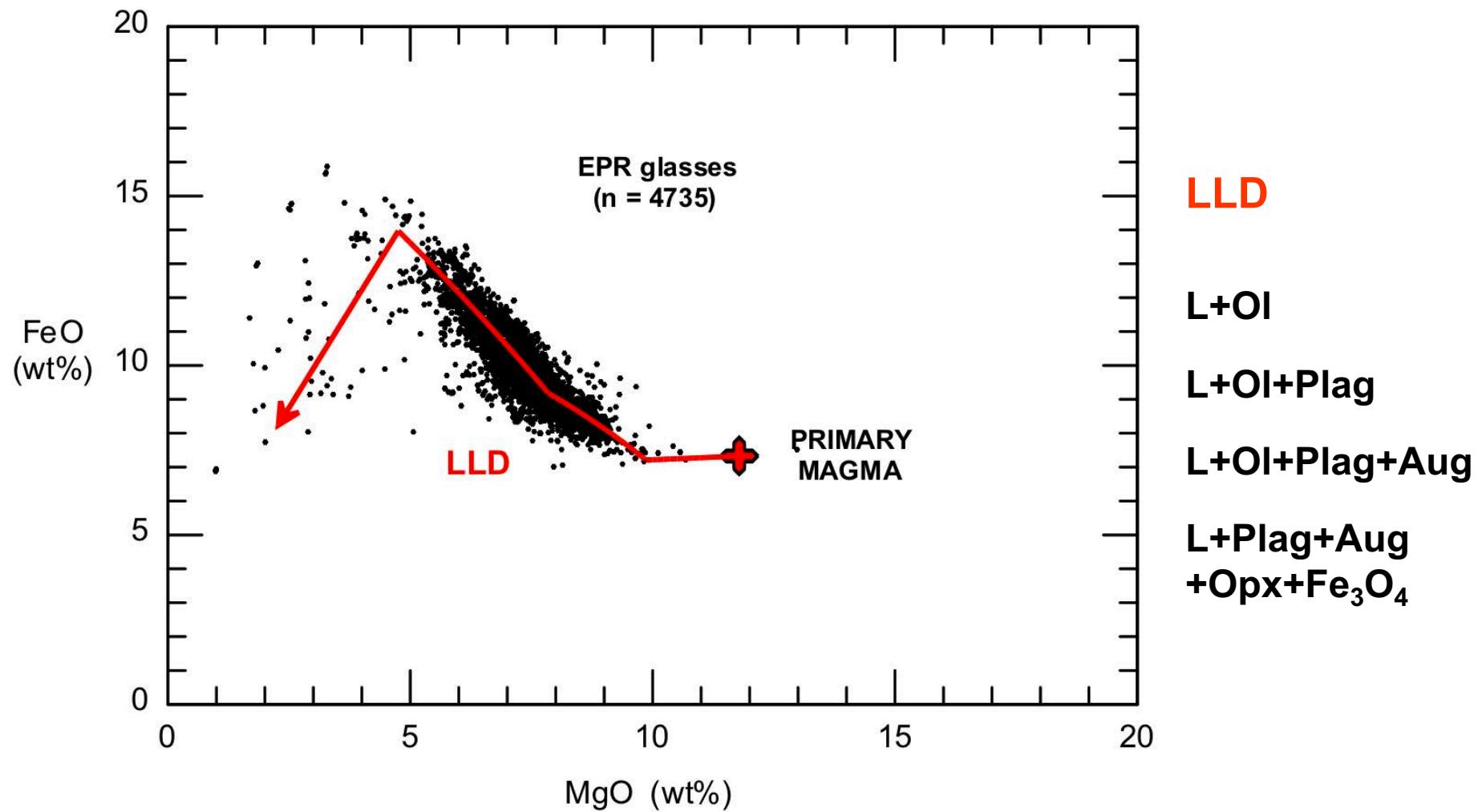
MORB

- A typical MORB is an olivine tholeiitic basalt, with low K_2O (<0.2) and TiO_2 (< 0.2).
- Originally considered as a simple processes, MORB are diverse and complex (we know this since O'Hara, 1968!)



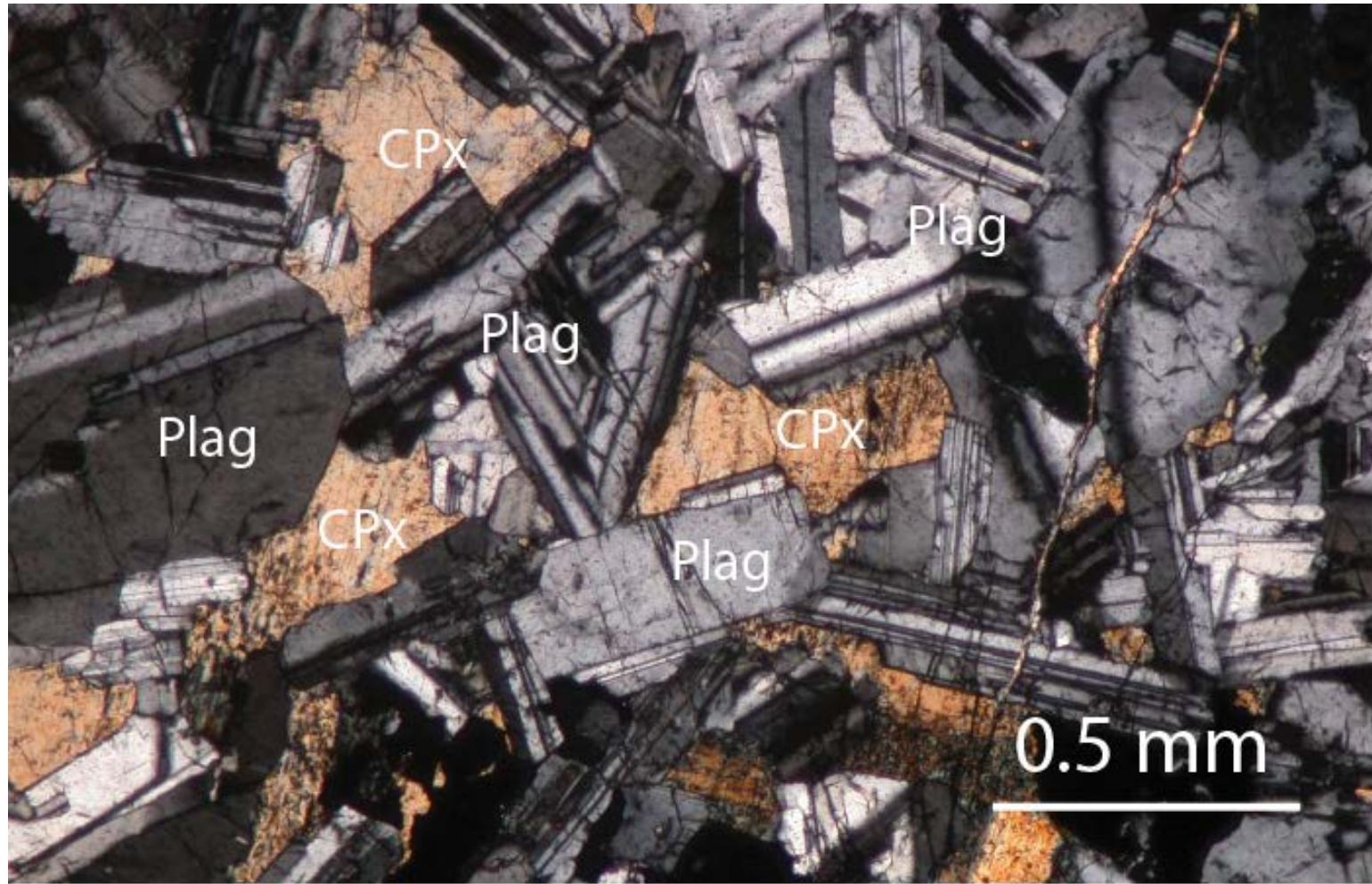


● EPR
○ MAR



Fractional crystallization lowers the MgO content of derivative liquids
Lavas with the highest MgO contents are most similar to PRIMARY magmas

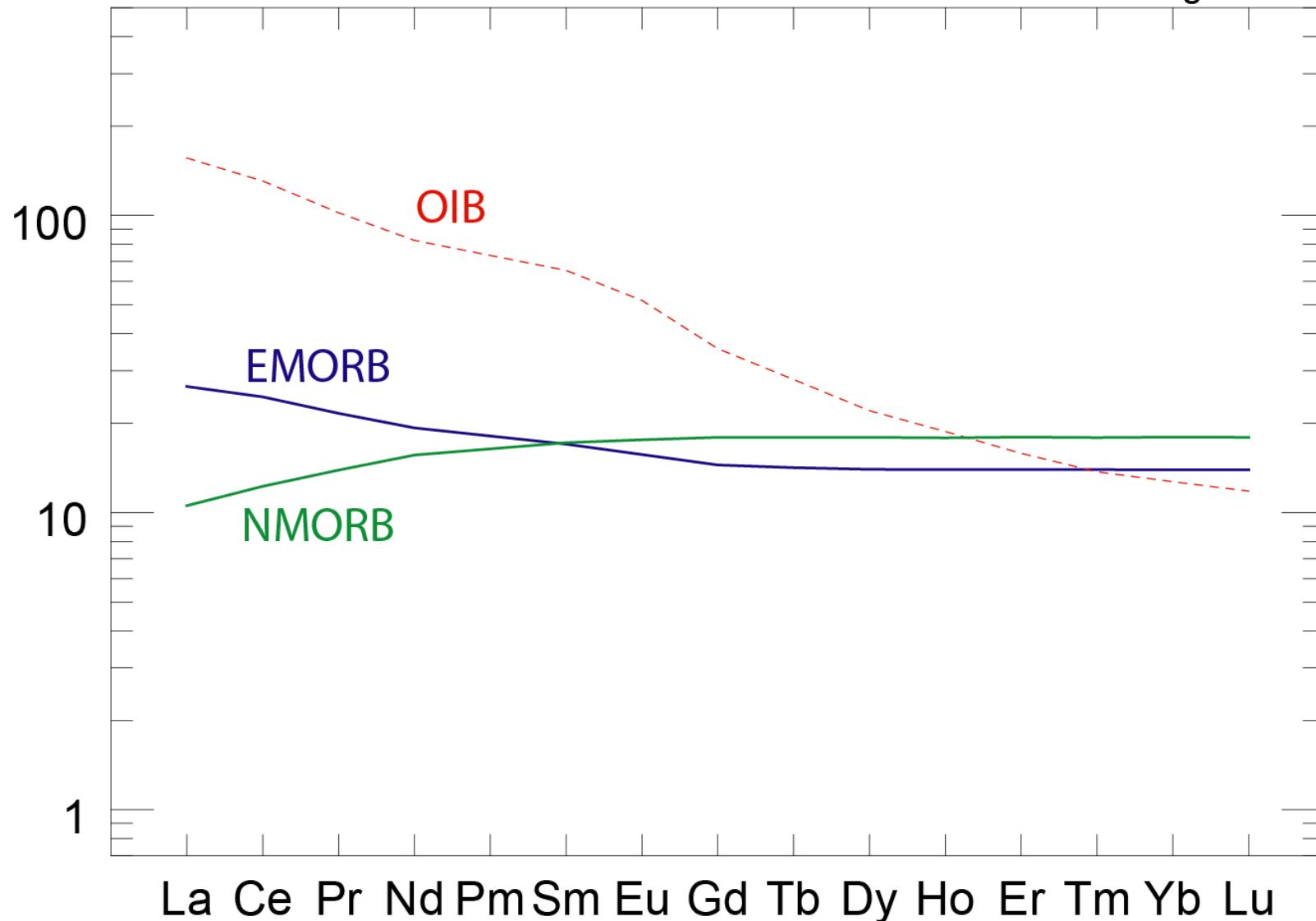




MORB types

Rock/Chondrites

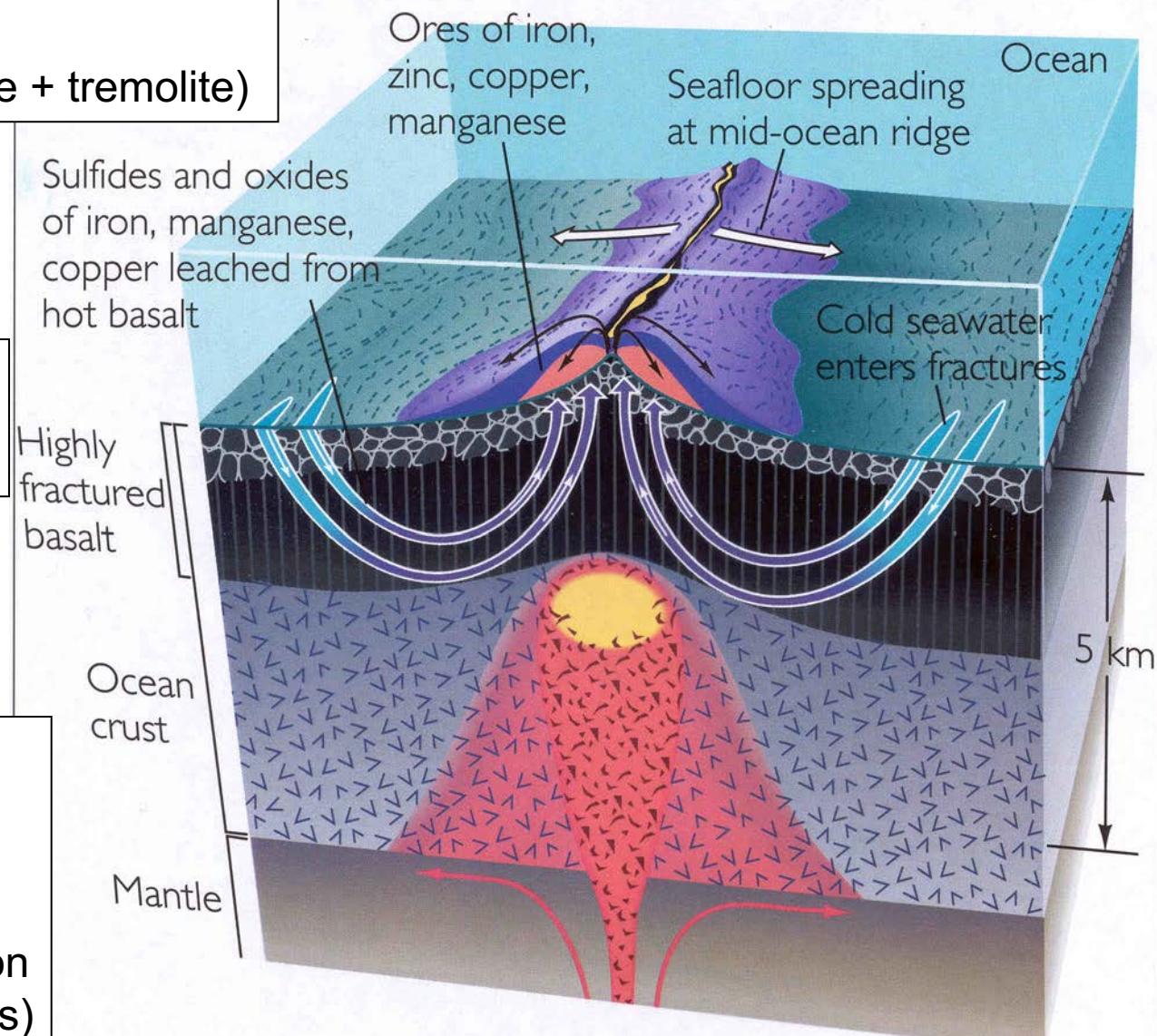
Sun&McDonough. 1989



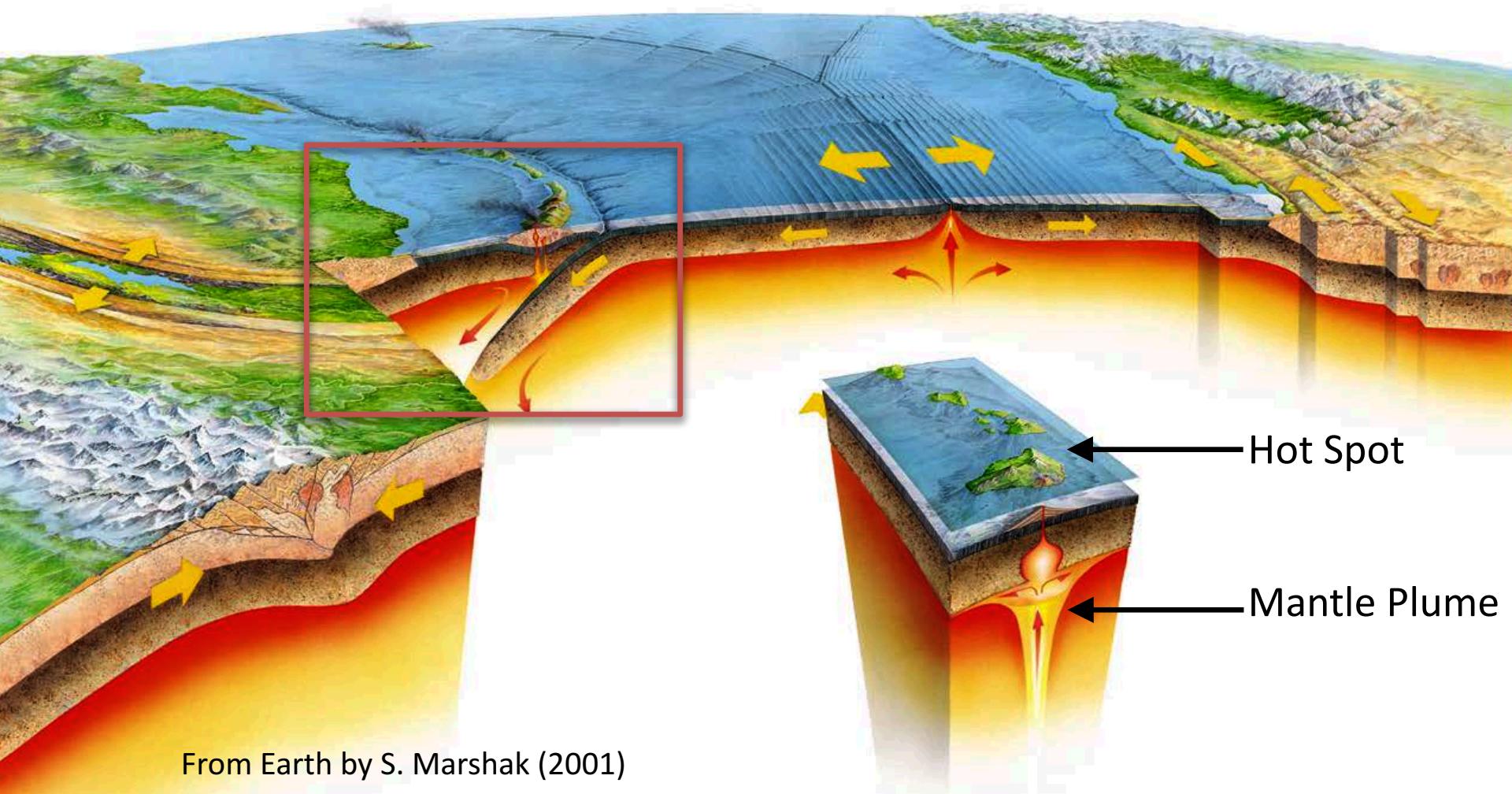
$\text{Sea H}_2\text{O} + \text{basalt} + \text{heat}1 =$
greenstones
(albite + epidote + chlorite + tremolite)

$\text{Sea H}_2\text{O} + \text{basalt} + \text{heat}2 =$
amphibolites
(plagioclase + hornblende)

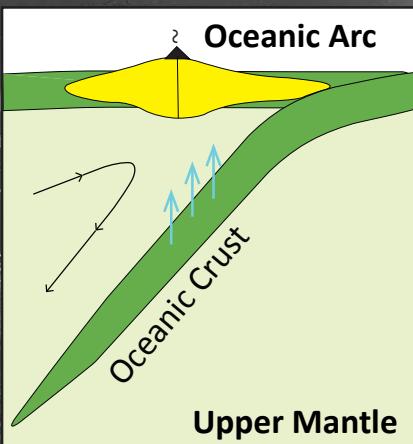
Sea H_2O becomes hot
- expelled on sea floor
as a hydrothermal vent
- rich in metals
- precipitate as sulfides on
sea floor (black smokers)



1. Mid Ocean Ridges
2. Subduction Zones
3. Mantle Plumes and Intraplate Magmatism



Aleutians



Izu-Bonin
& Marianas

Vanuatu

Tonga

180° E

100° W

CALB
Costa Rica
& Panama

Continental Arc

Upper Mantle

Oceanic Crust

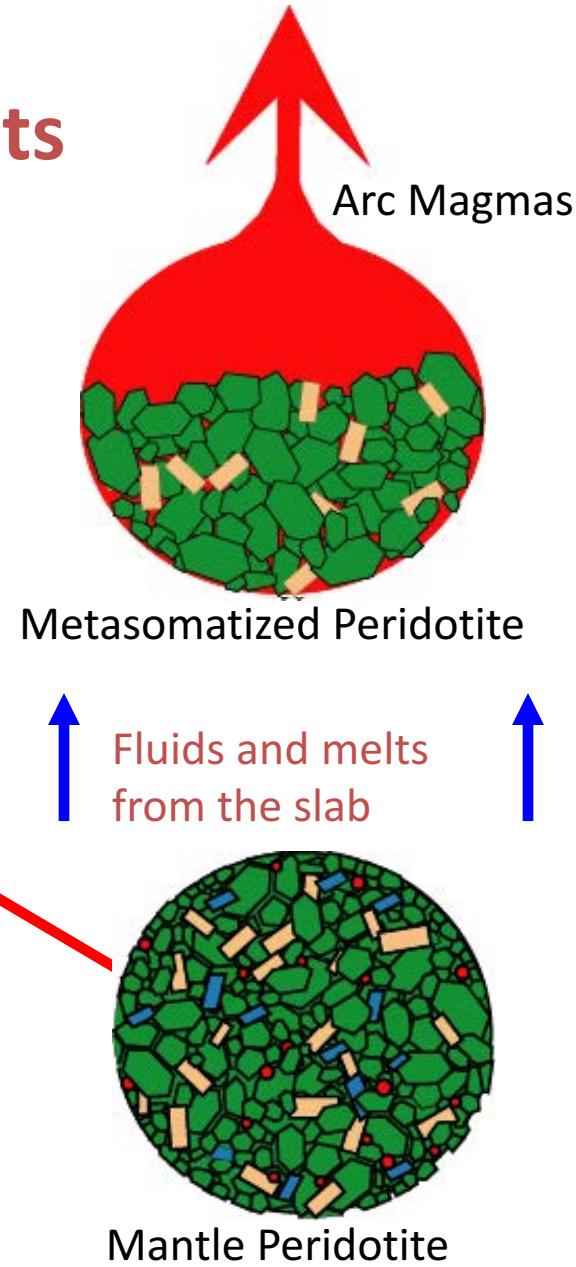
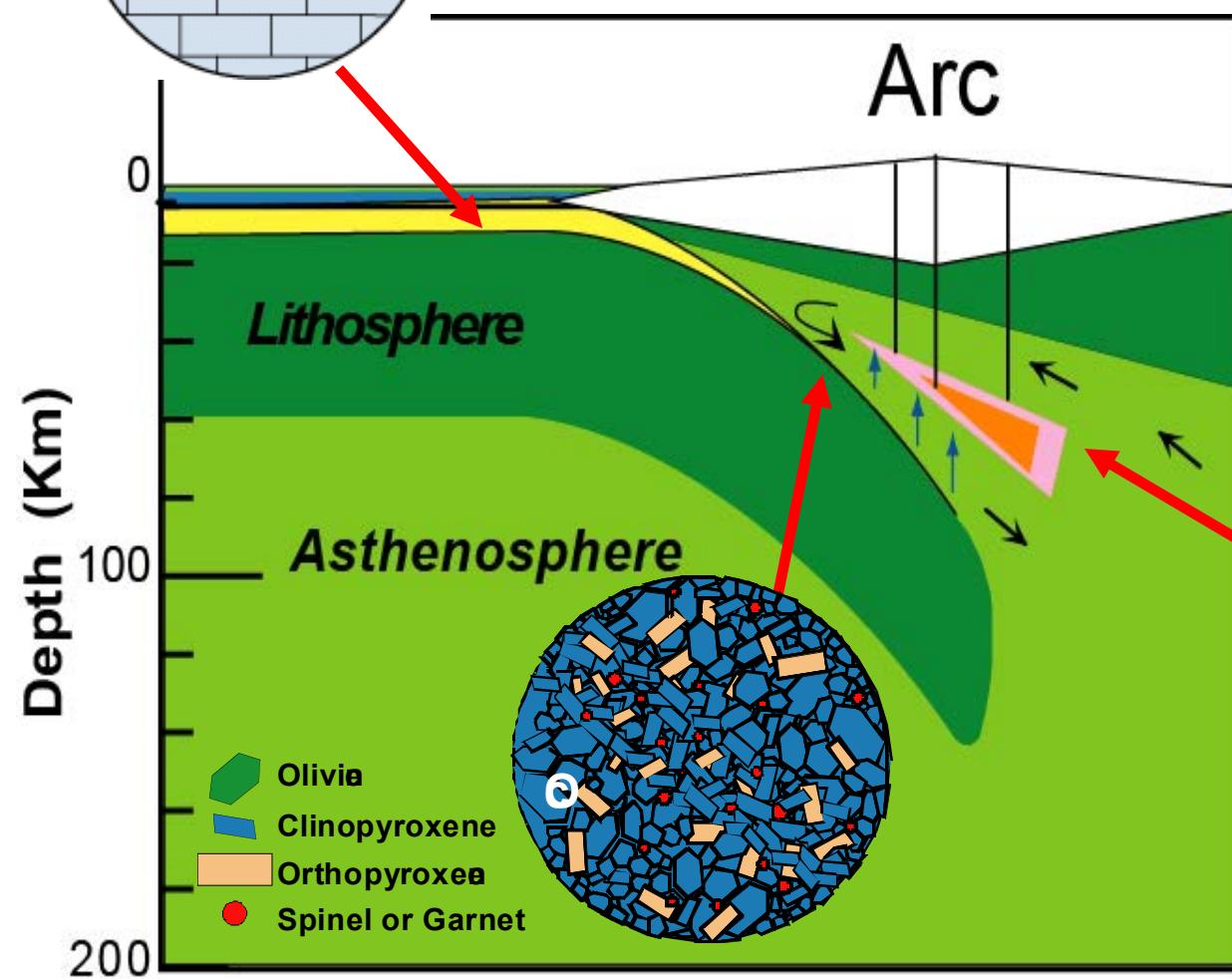
L. Antilles

S. Scotia

0°

40° S

Subduction Components



Phaseplot H₂O Demo

Open the Mac App Store to buy and download apps.



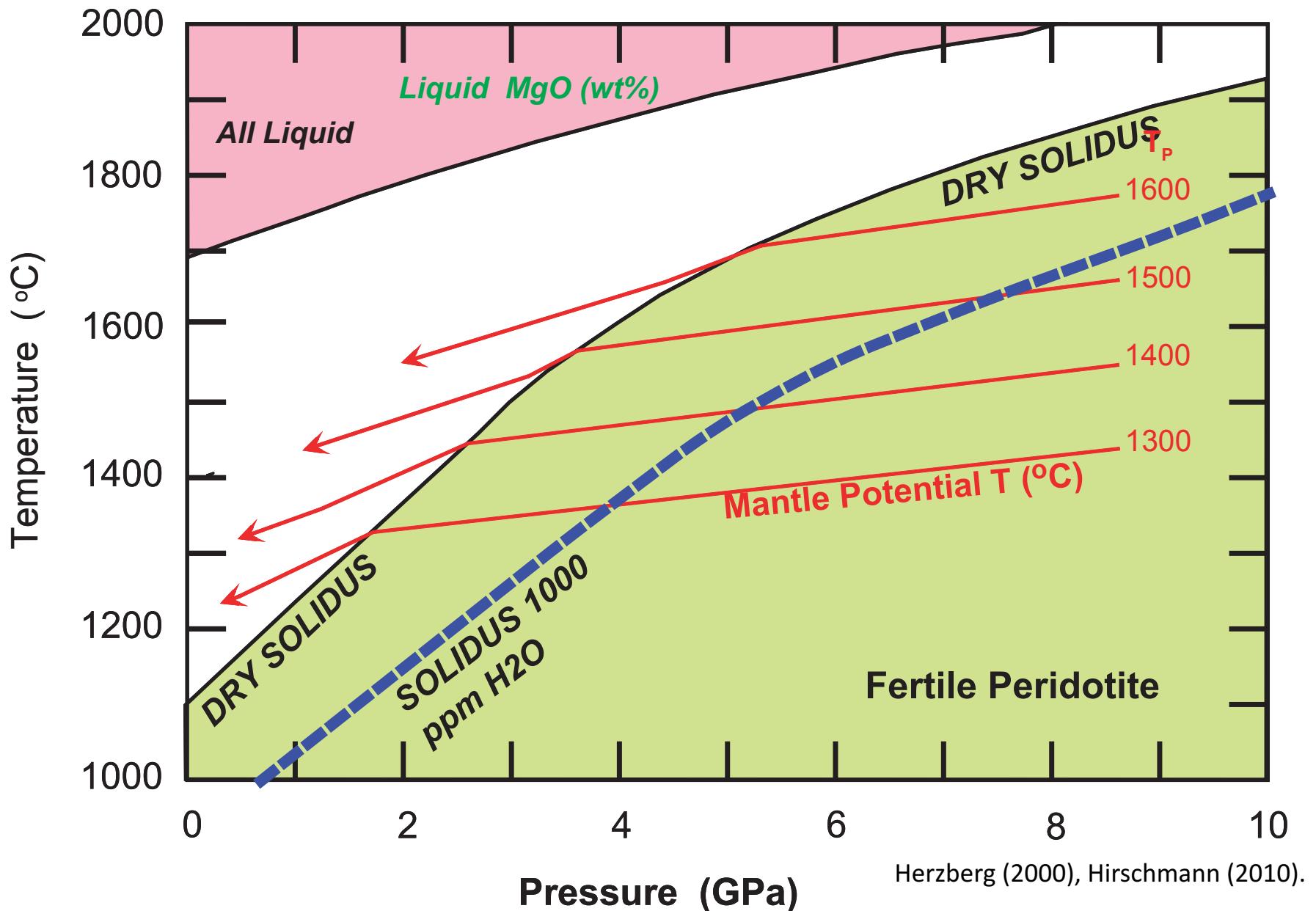
PhasePlot 4+

Mark Ghiorso CT Software

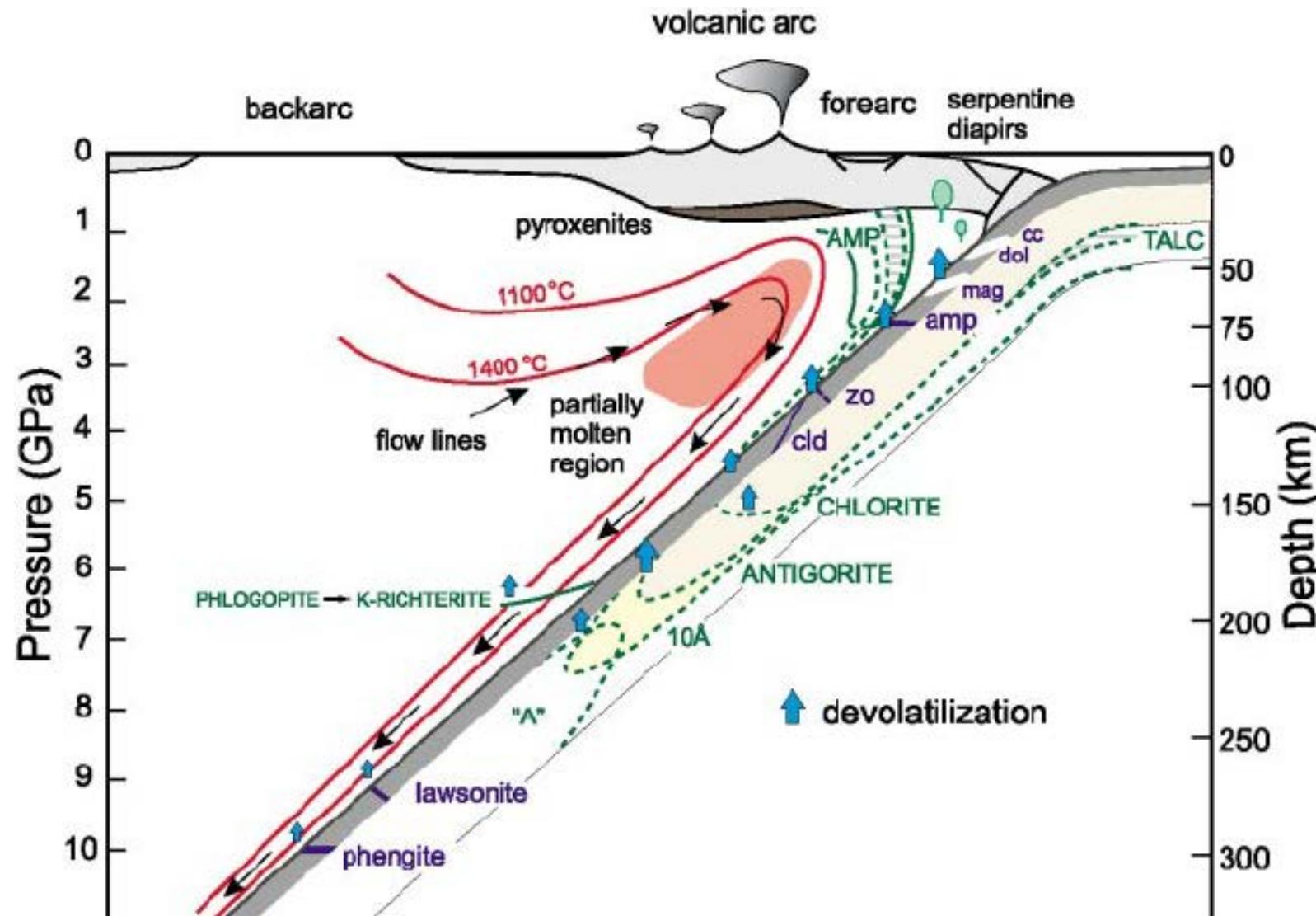
Free

[View in Mac App Store ↗](#)

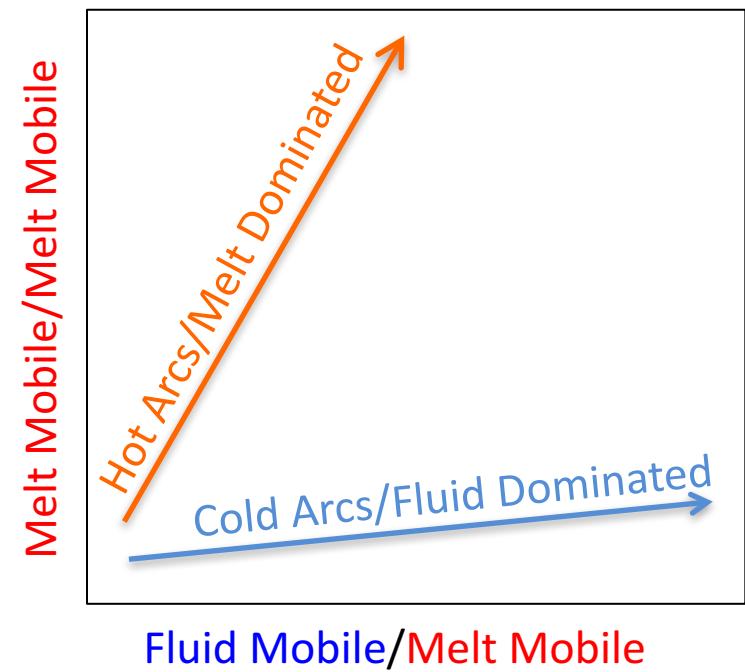
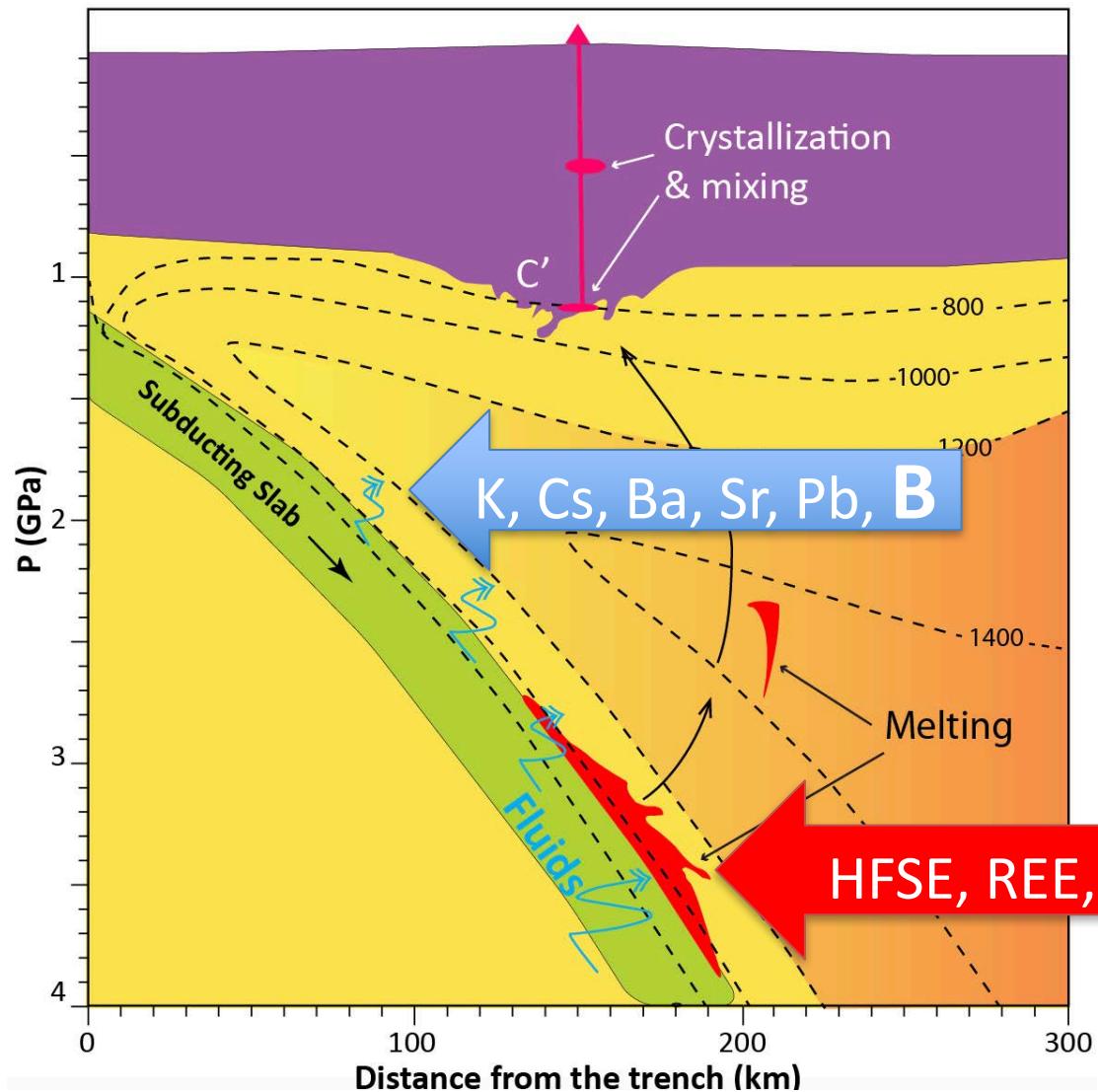
Effect of H₂O



Breakdown of minerals in a subducting slab



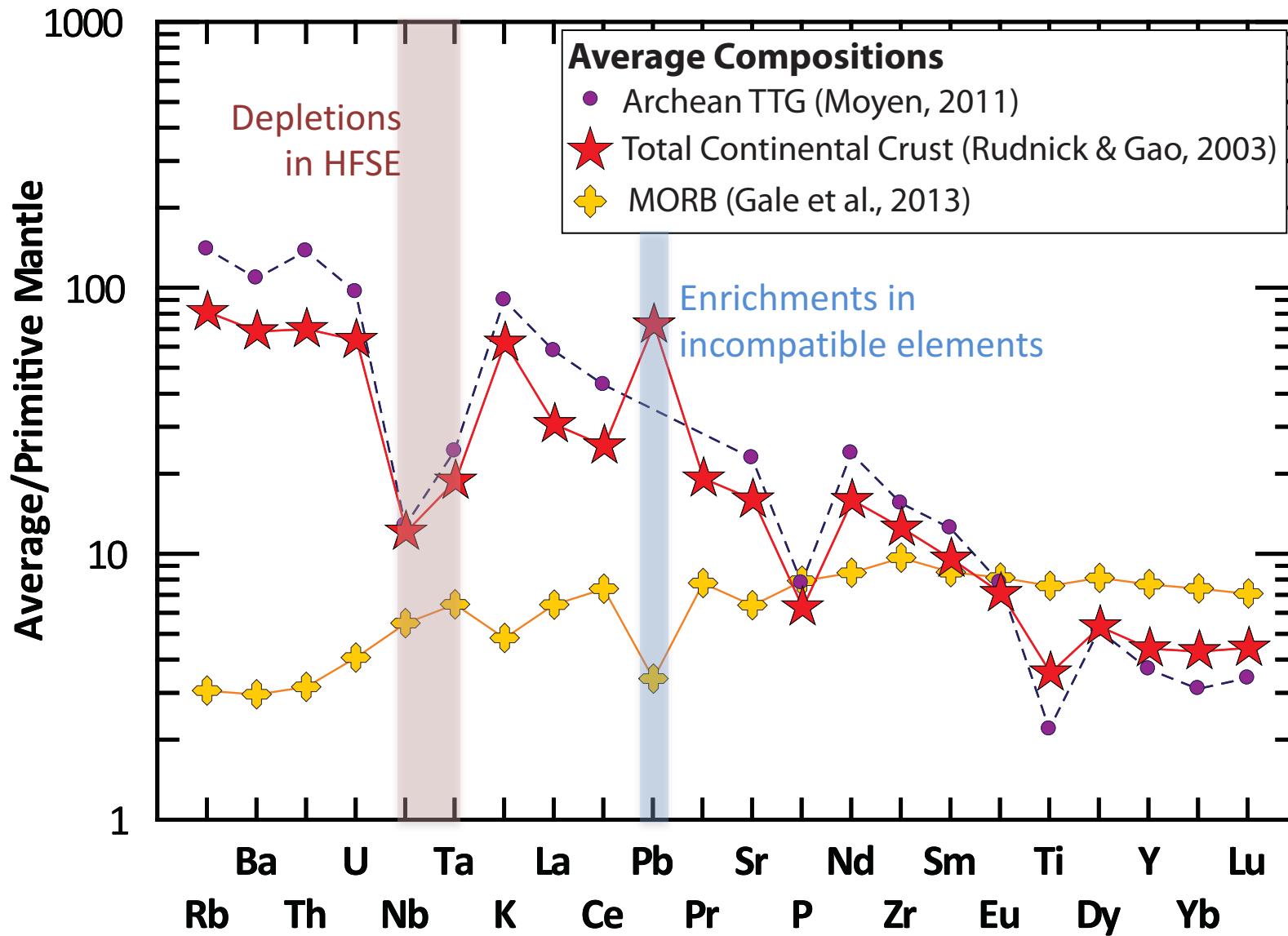
Element behaviour in a Subduction Zone



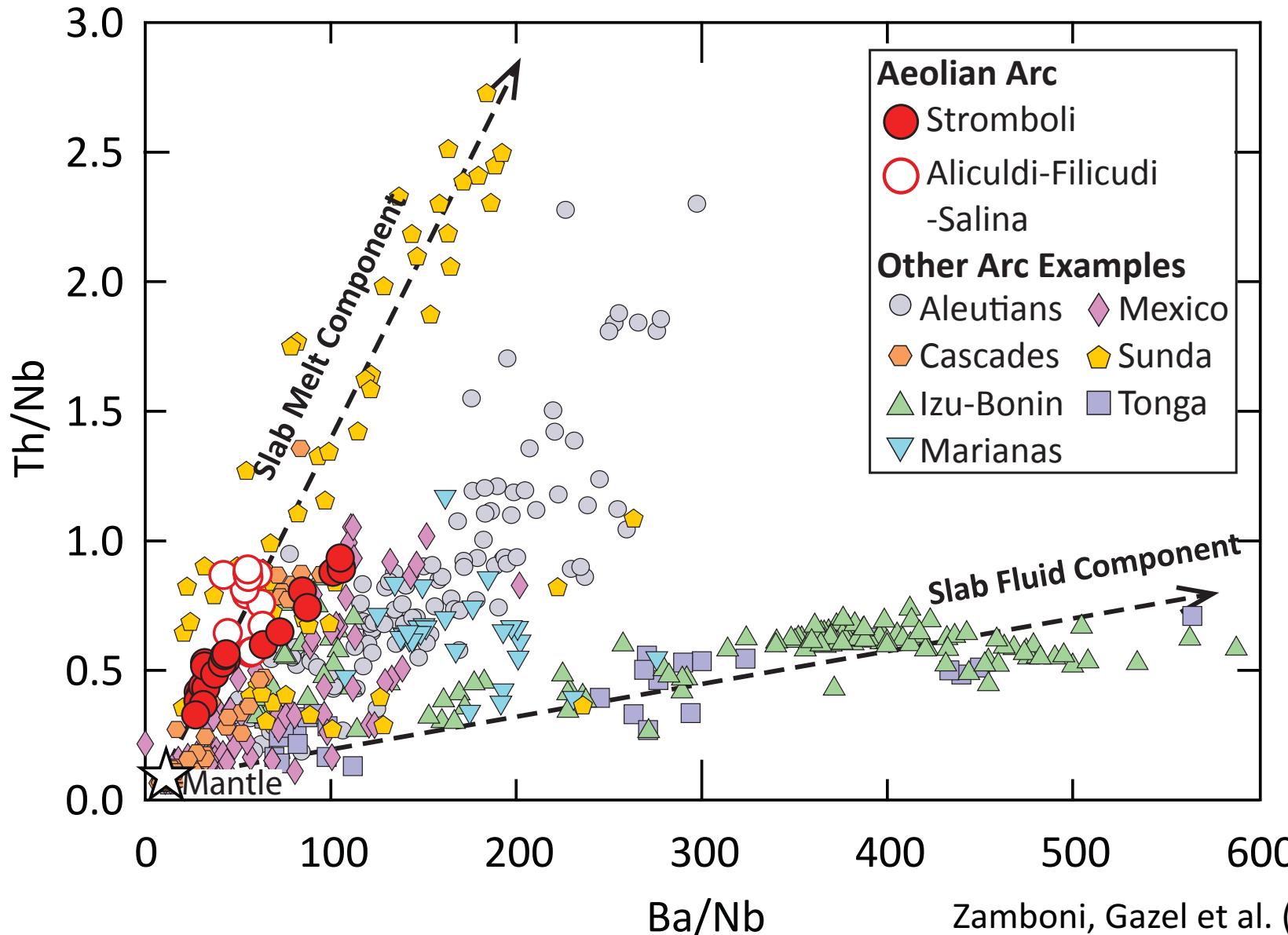
See Plank and Langmuir (1993), Ryan and Chauvel (2014), Turner and Langmuir (2015)

Incompatible Element Composition of Continental Crust

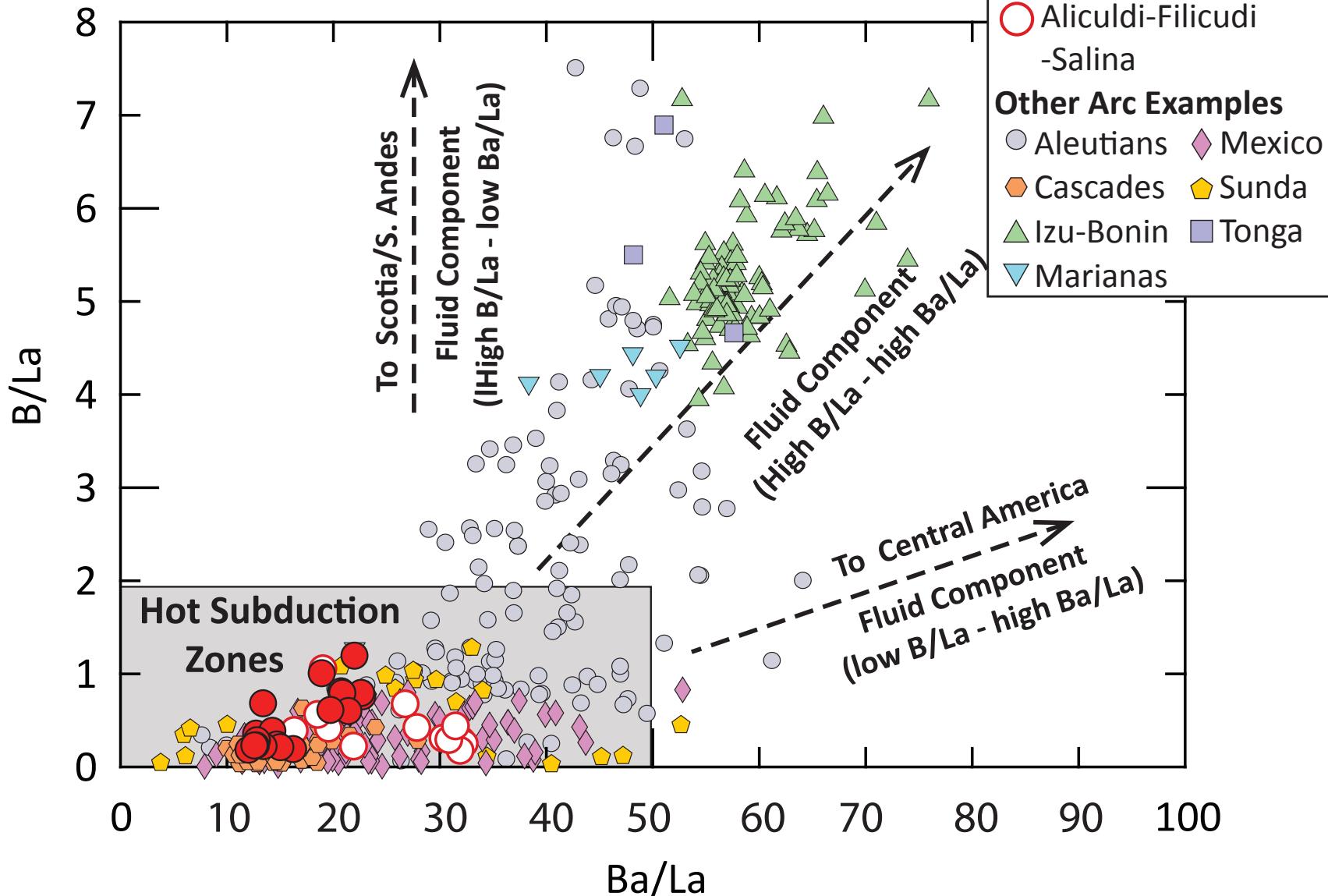
Requires of Subduction Processes



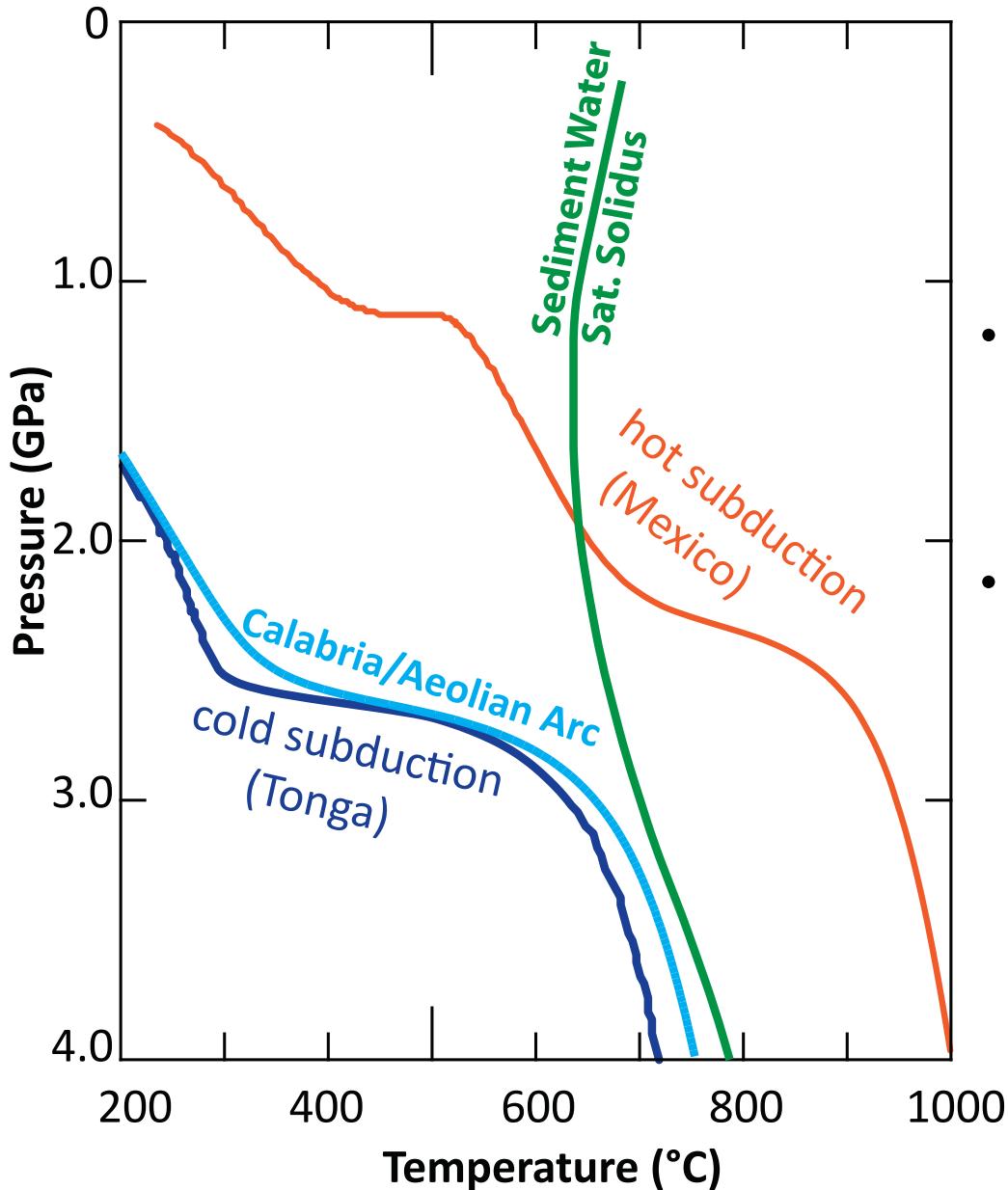
Trace element ratios of the Aeolian, Sunda, Cascades, Mexico primitive lavas suggest a slab melt-derived component and thus **hot subduction** zone conditions.



Fluid flavors can inform about cold vs hot subduction zones

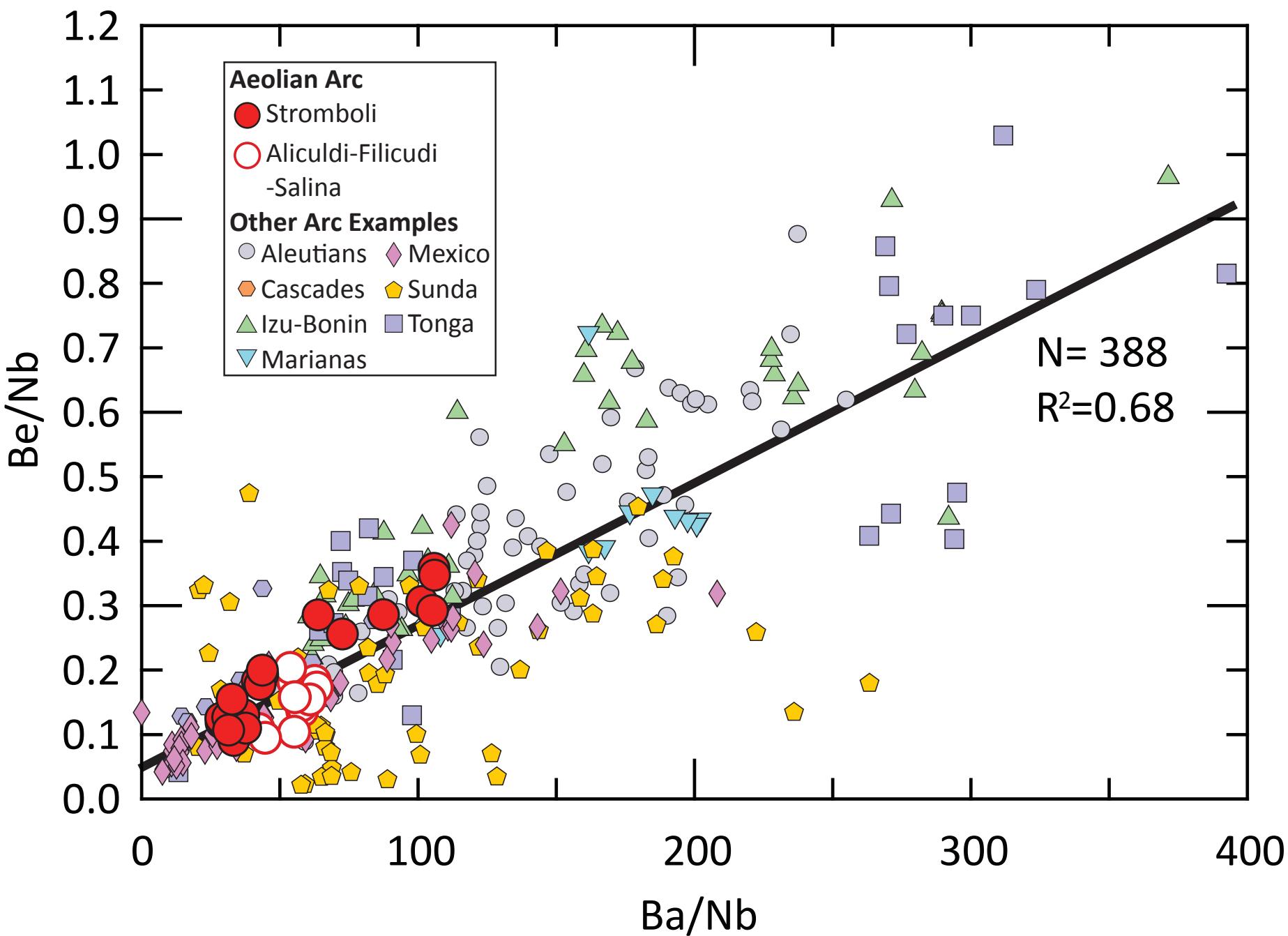


Sediment melting vs fluid signatures

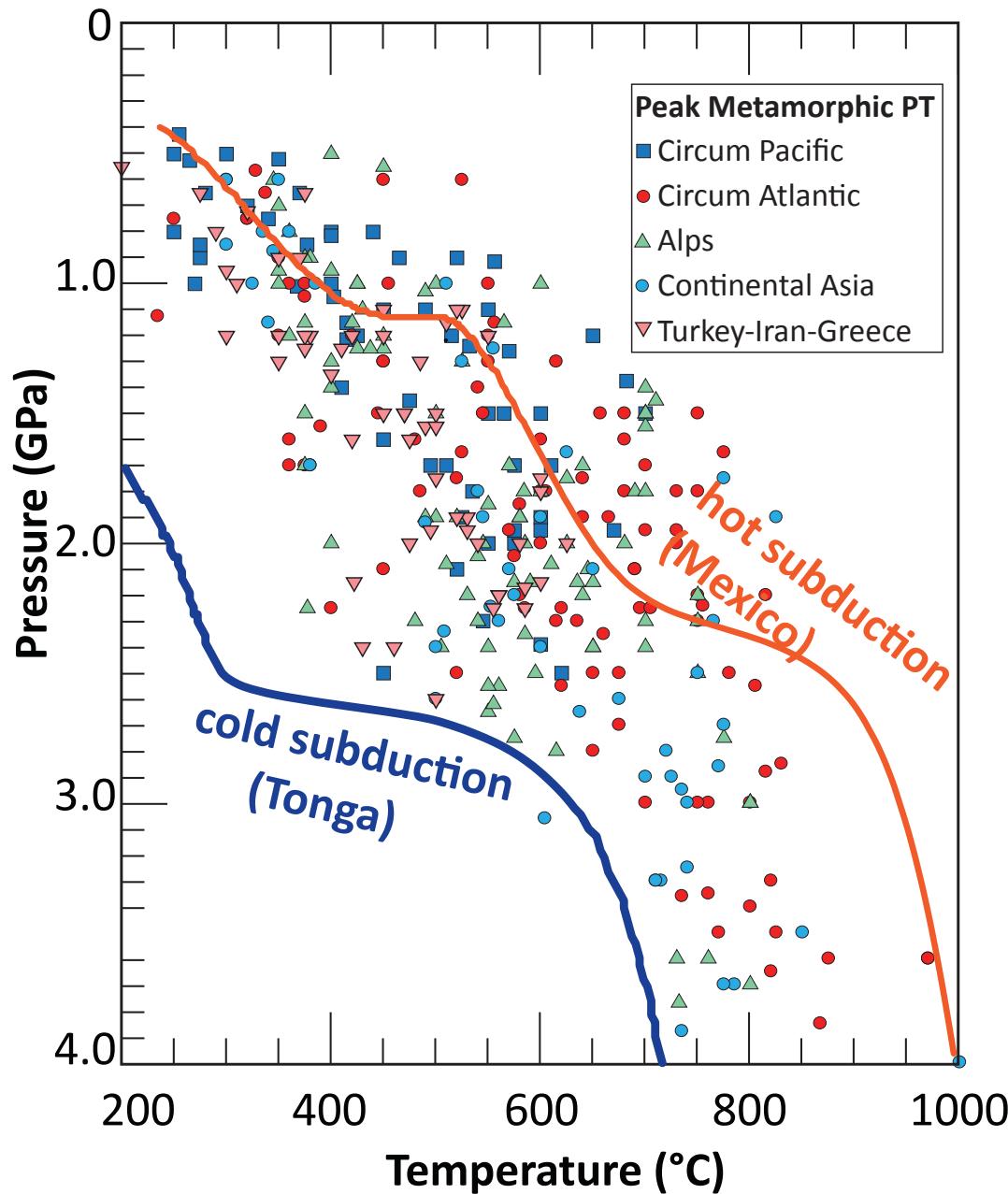


- Subduction paths from Syracuse et al. (2010).
- Sediment water saturated solidus from Mann and Schmidt (2015)

Sediments melts world-wide?

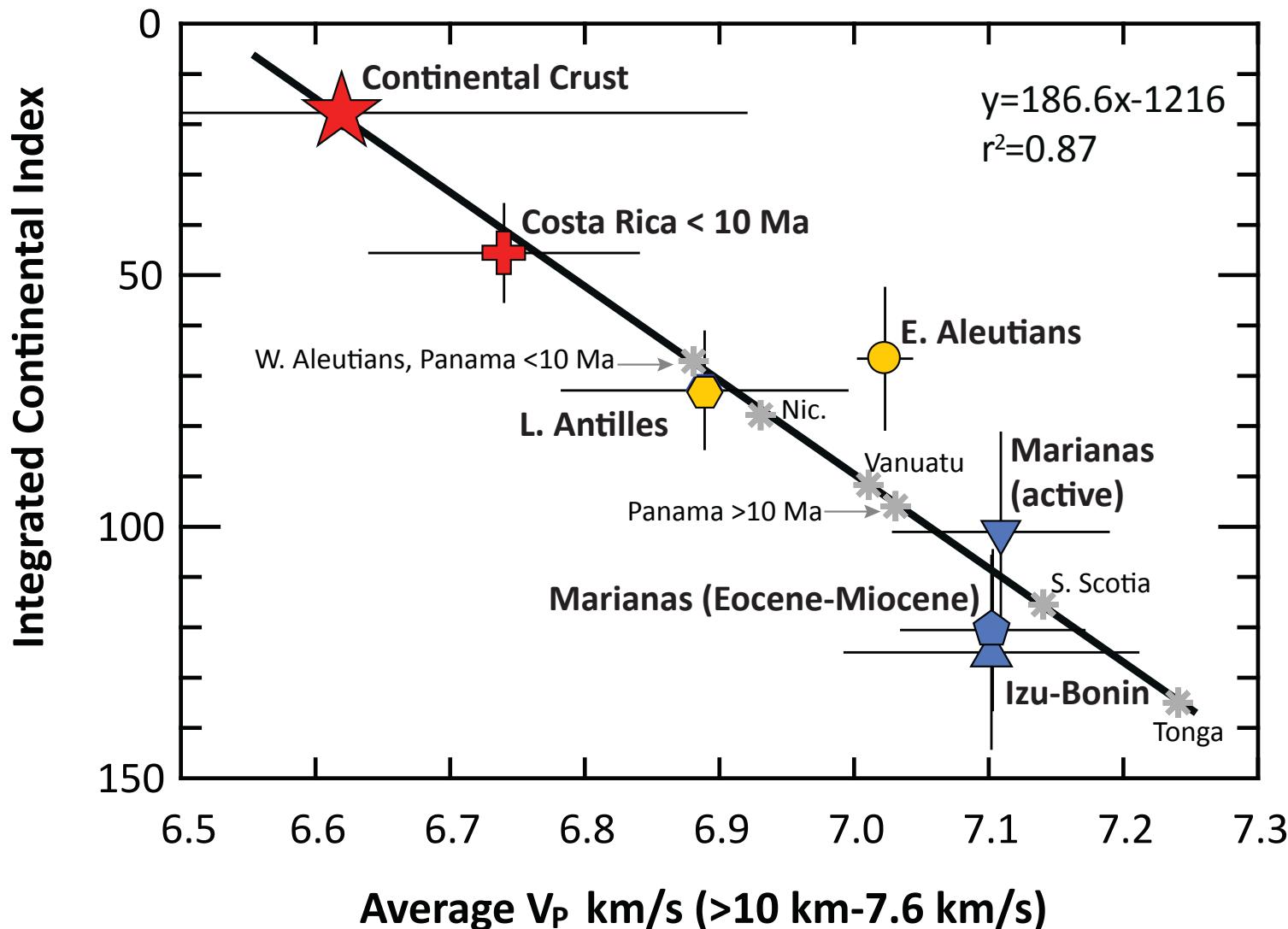


Peak PT Metamorphic Record: towards the hot side

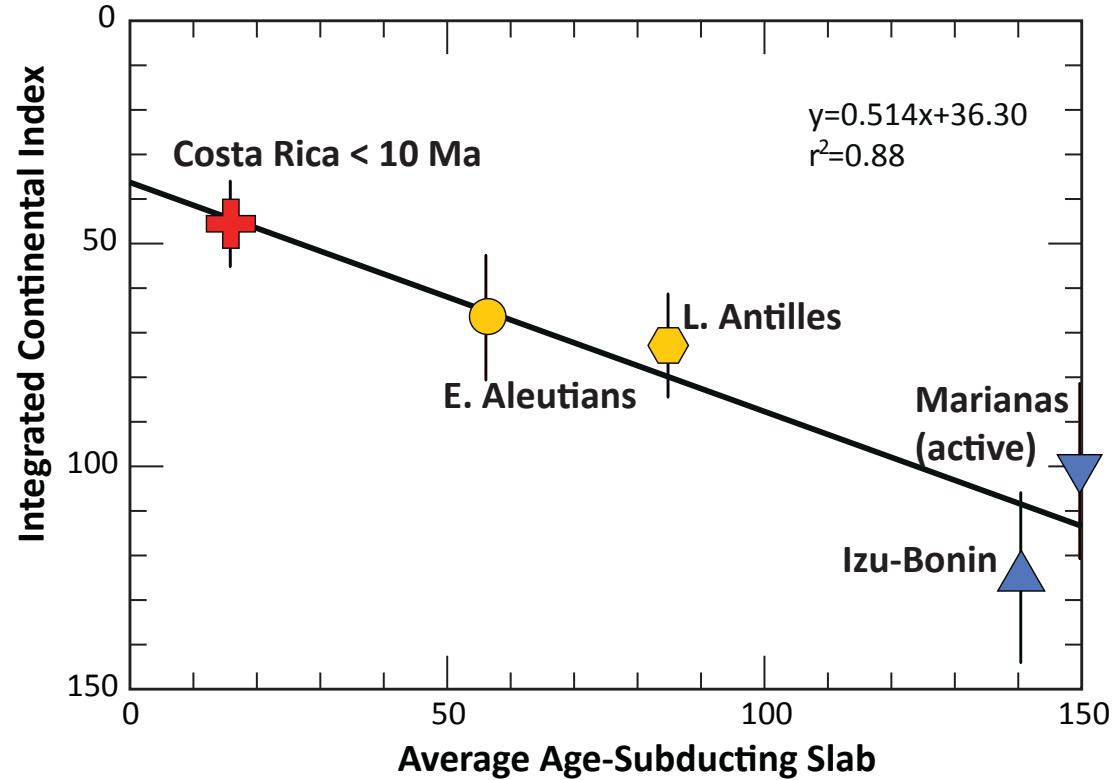


- Subduction paths from Syracuse et al. (2010)
- PT data compiled by Penniston-Dorland et al. (2015)

Arc dominated by slab melts produce juvenile continental crust



The Galapagos tracks melt (not only sediment but also subducting enriched oceanic crust)



According to Martin (1999):

Age of subducted lithosphere: need to have young (<30 Ma), hot lithosphere with high thermal gradient to hit solidus before dehydration.

-CALB=12-15 Ma

Rate of subduction: Fast subduction rates (~10 cm/y) impart high shear stress that facilitates melting.

- CALB of ~10 cm/y

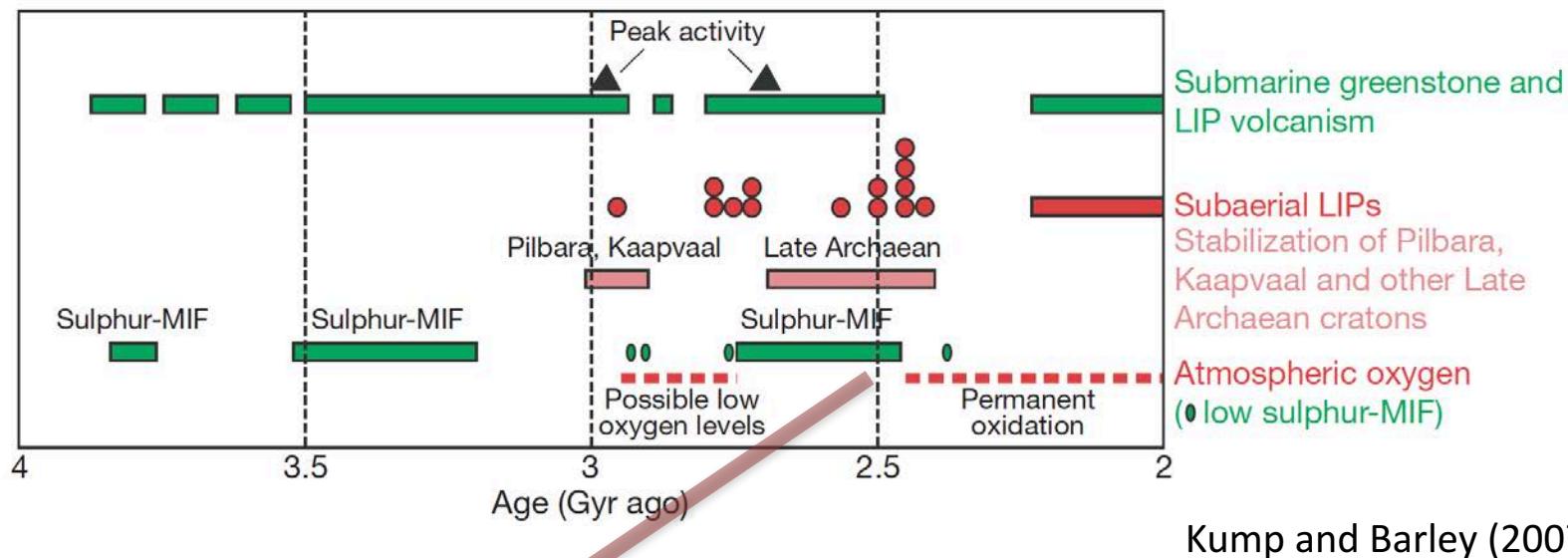
Slab age from Syracuse & Abers (2006)

A good crust is important

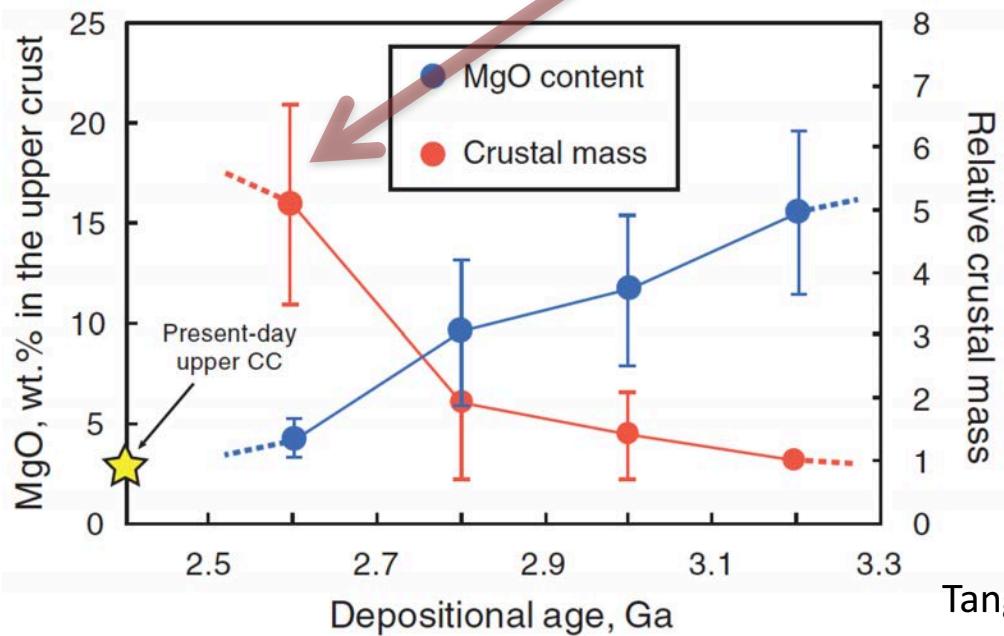


Production of Continental Crust:

Shifted all geochemical cycles and directly impacted life on Earth

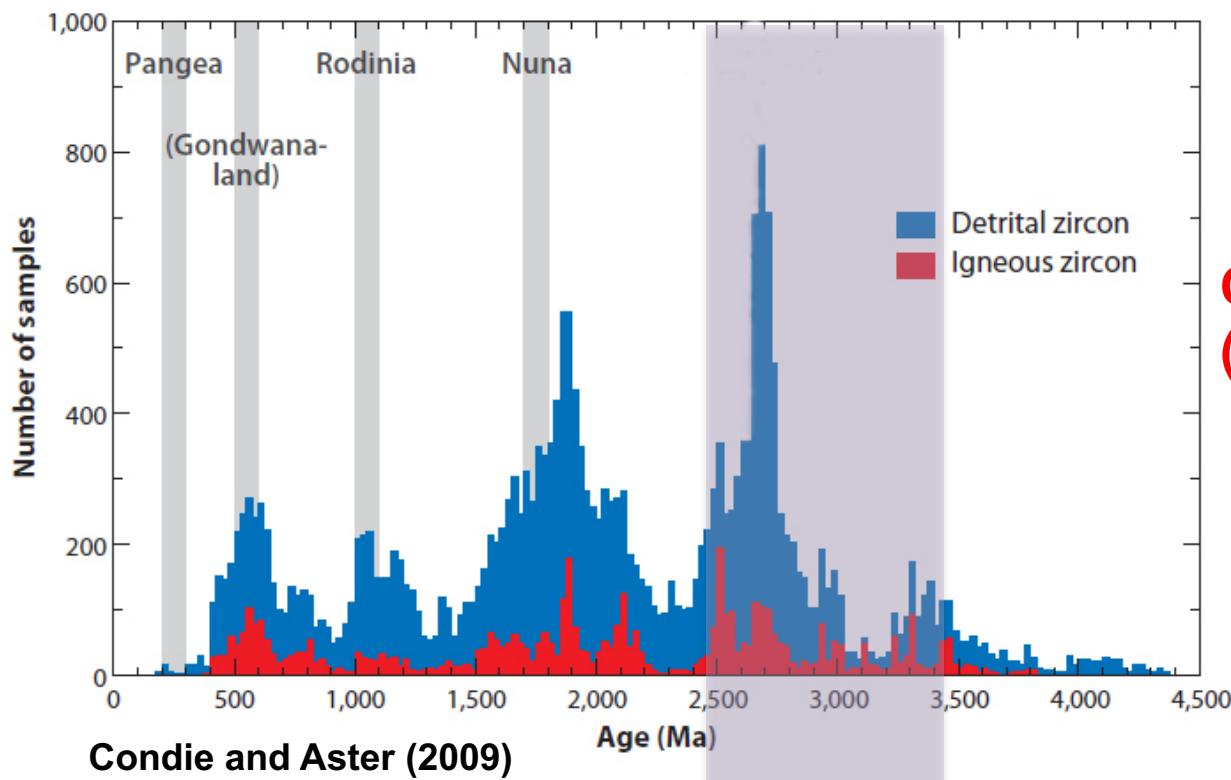


Kump and Barley (2007)



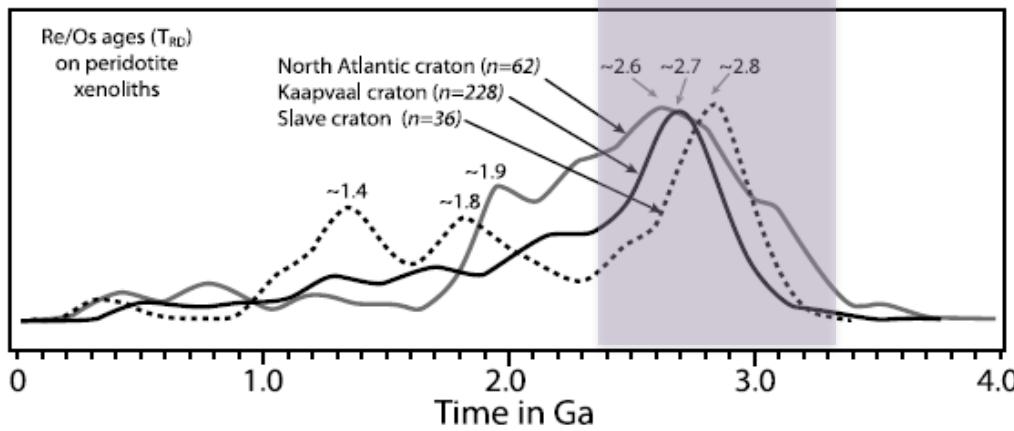
Continental crust: areas of buoyant, thick silicic crust that are a unique characteristic of Planet Earth





Condie and Aster (2009)

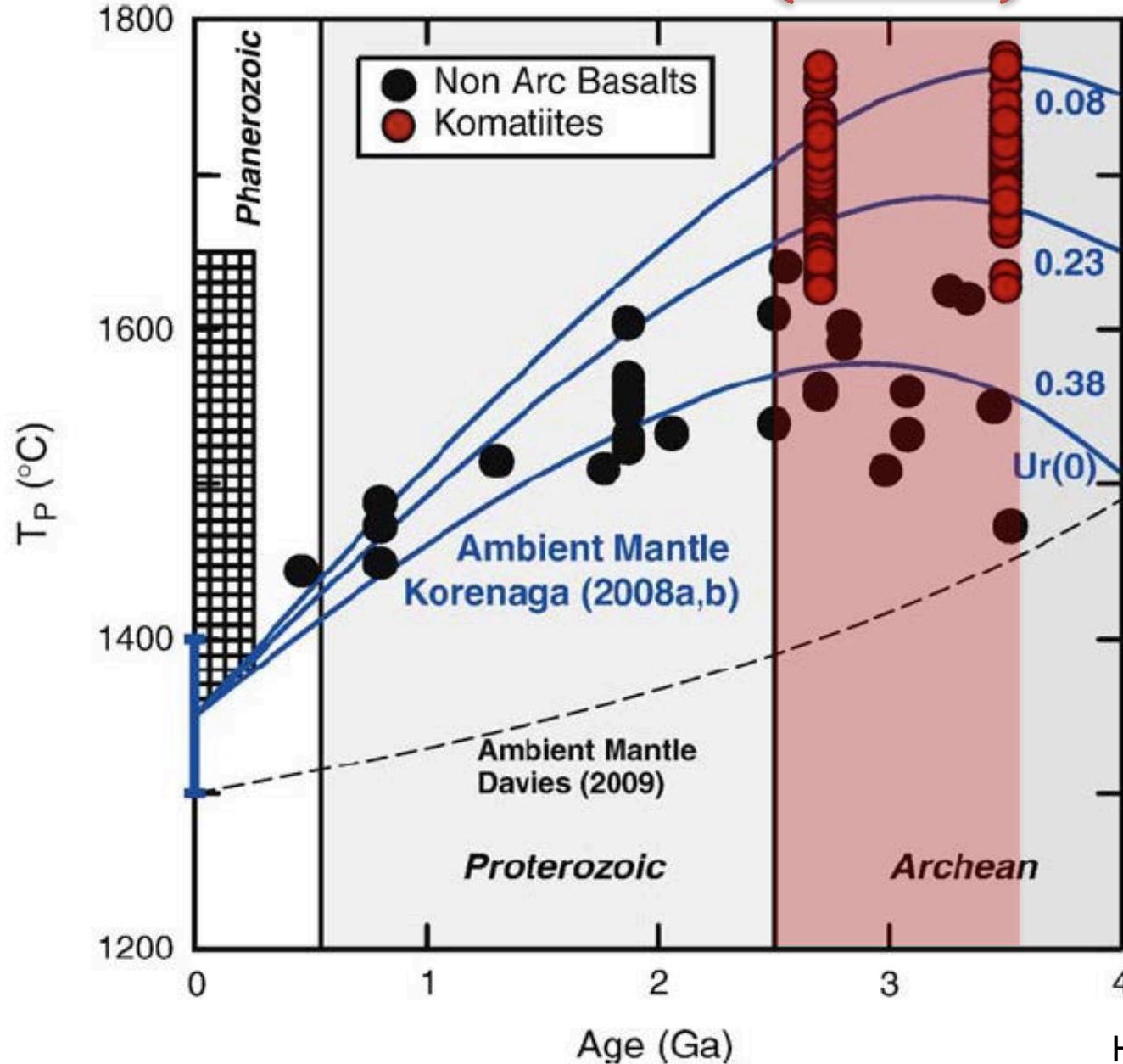
Continental Crust Ages (U/Pb)



Ionov et al. (2015)

Lithosphere Mantle Peridotite Ages (Re/Os)

Peak of Cratonization: 2.5-3.5 Ga



Mantle T
 >1600 $^{\circ}$ C

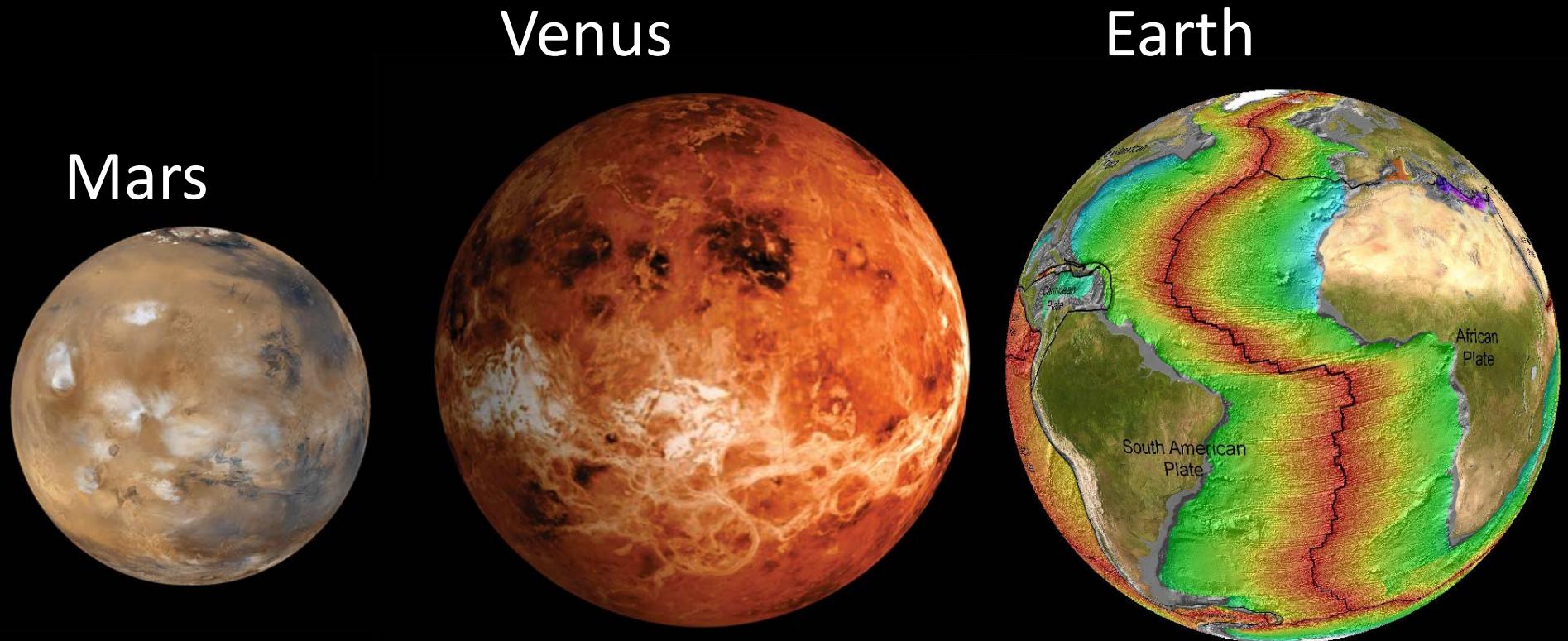
Archean
Hot Mantle
=Cont. Crust?

How to make the starting materials of continents ?

- Two competing models
 - **Stagnant lid model**
 - Lower crust delamination
 - **Subduction model**
 - Provides the water necessary to make “granitic” rocks
 - Onset of plate tectonics in the Archean

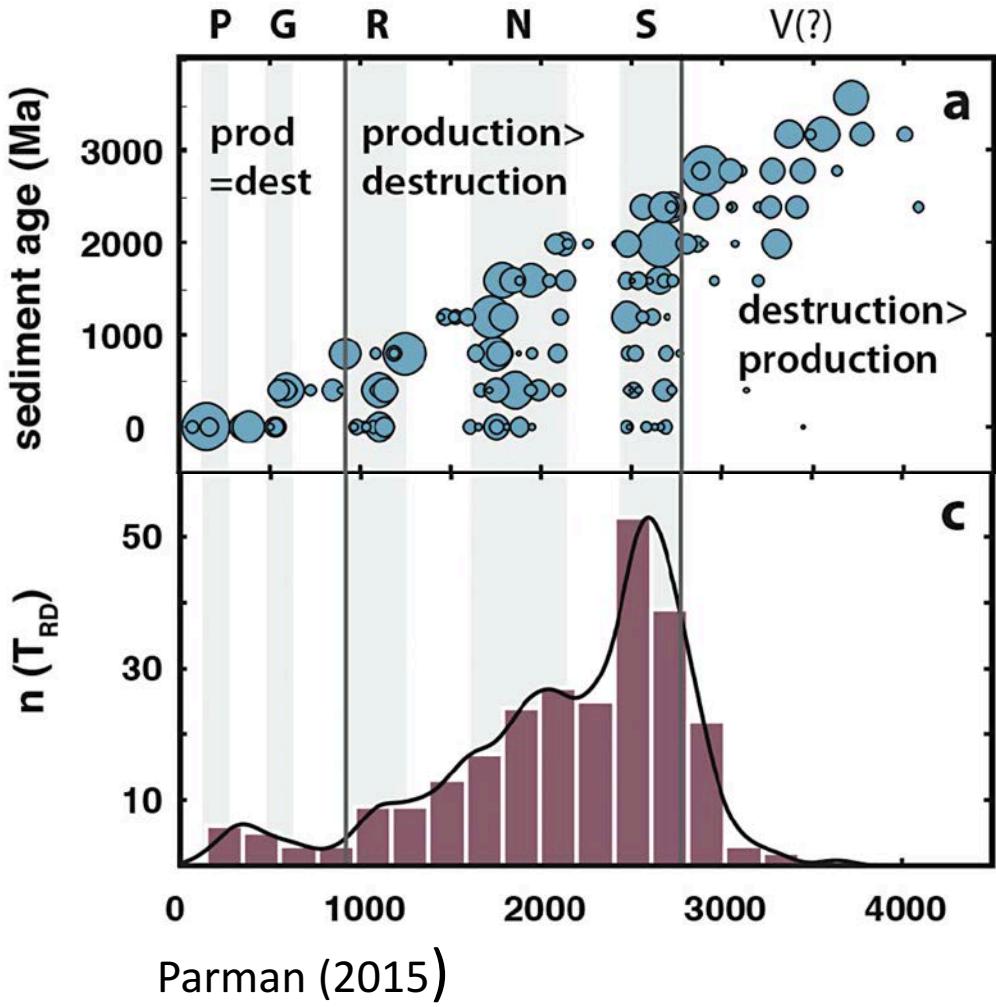


Continental Crust: Unique to Earth as Plate Tectonics



Stagnant Lid= Basaltic Crusts =
No Continental Crust

Plate Tectonics = Produce
Oceanic and **Continental Crusts**

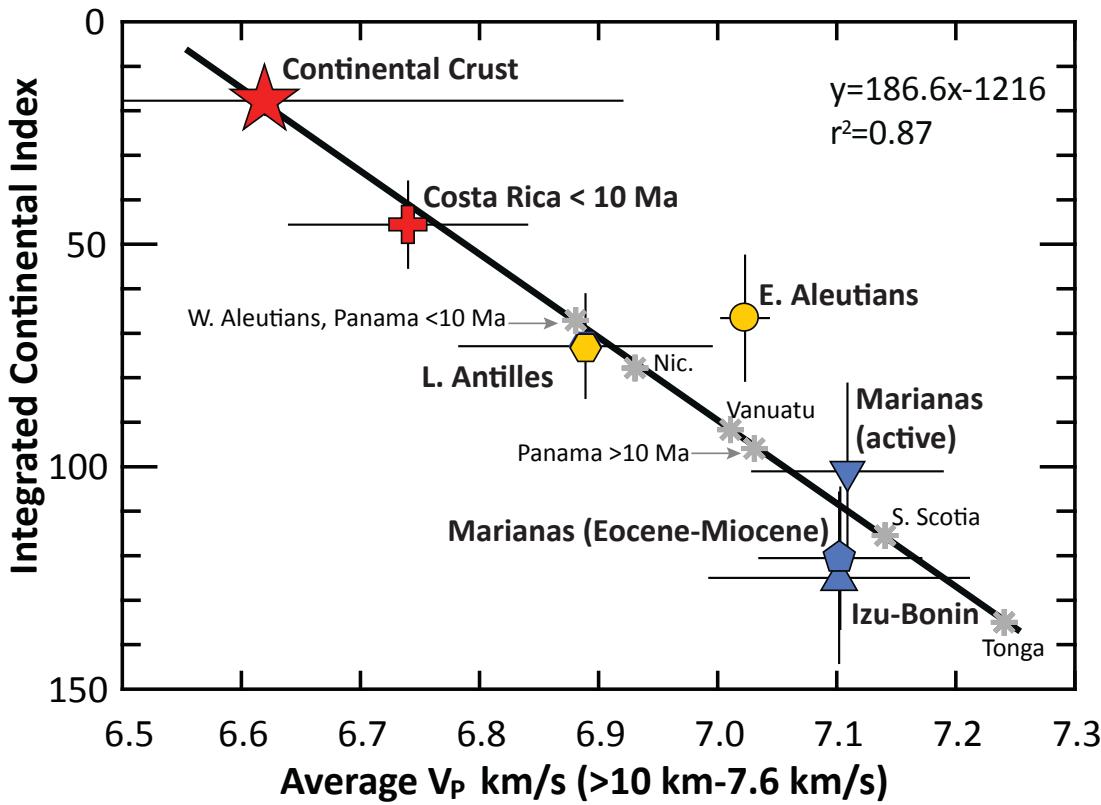
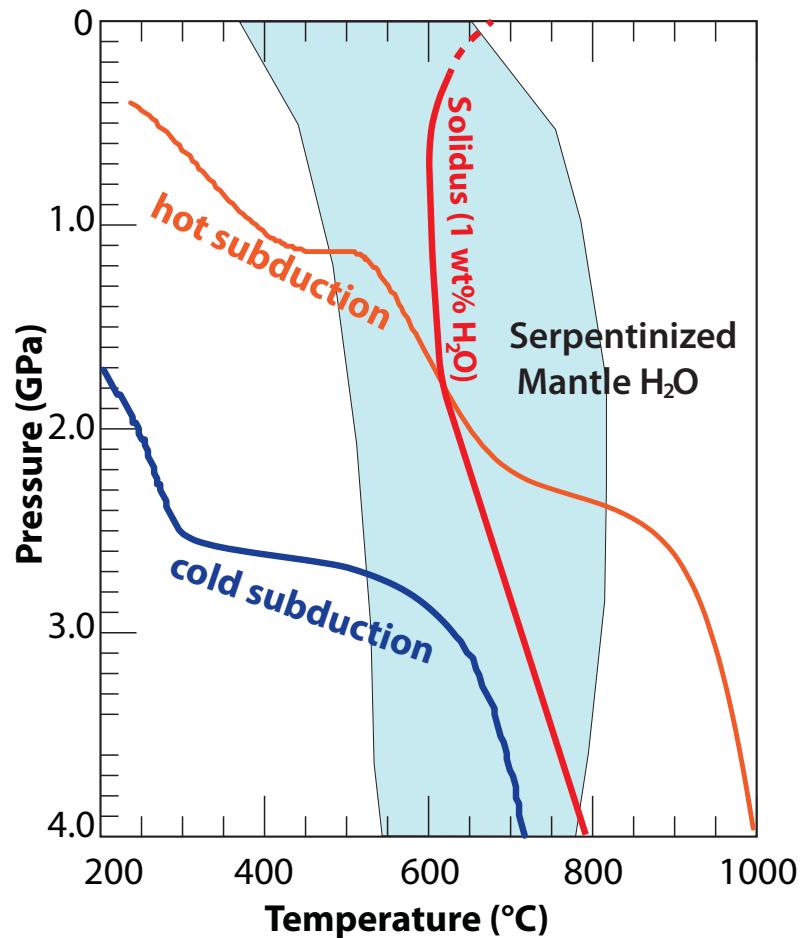


Based on the zircon record there is possibility of subduction and thus plate tectonics since early Earth evolution.

But, it is until **~2.7 Ga** where the **continental masses** became stable and survived destruction.

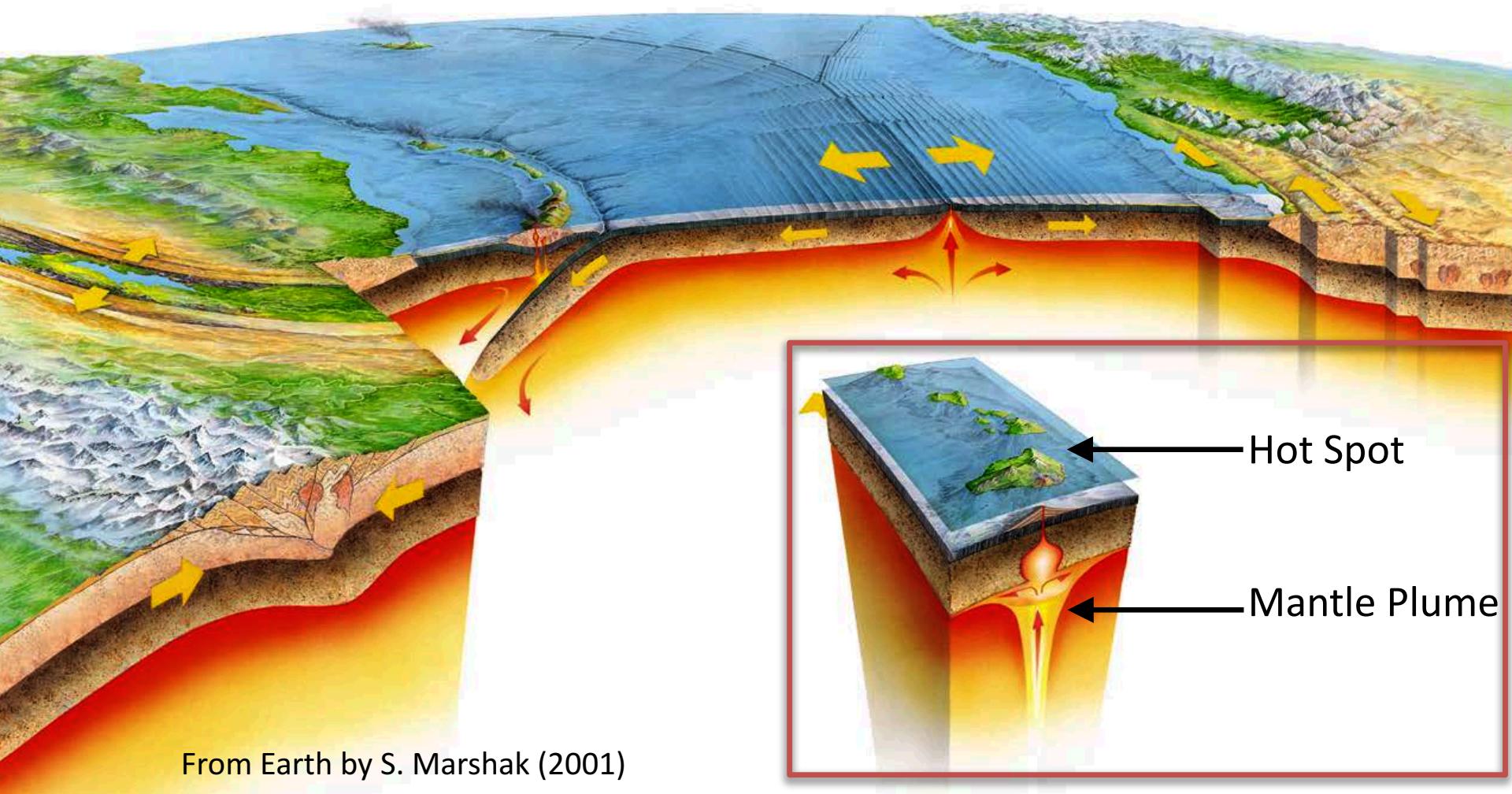
- The new data from Central America presented today suggest that **melting an enriched subducting slab is key to produce continents** as recorded by Archean TTG

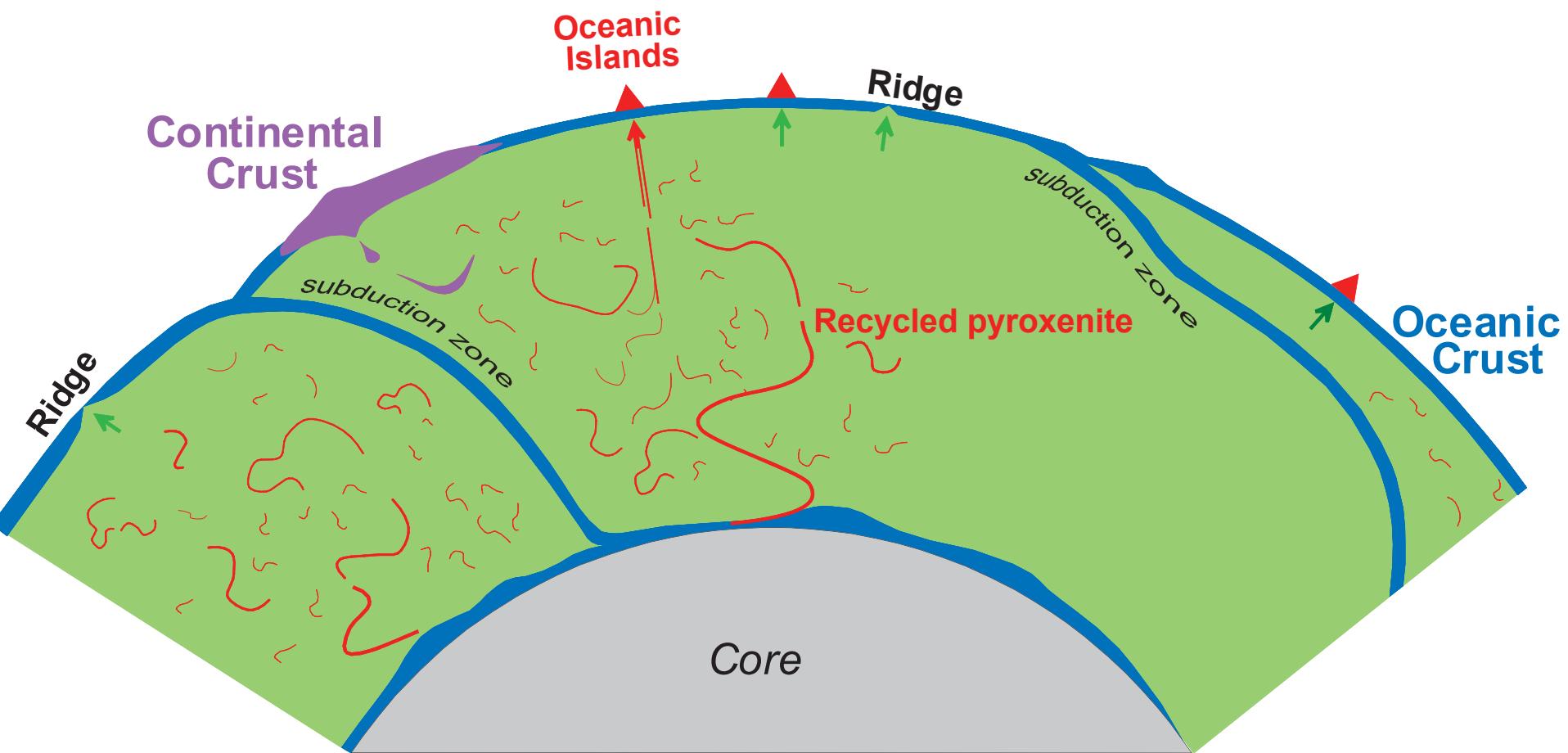
Slab melts vs. slab fluids



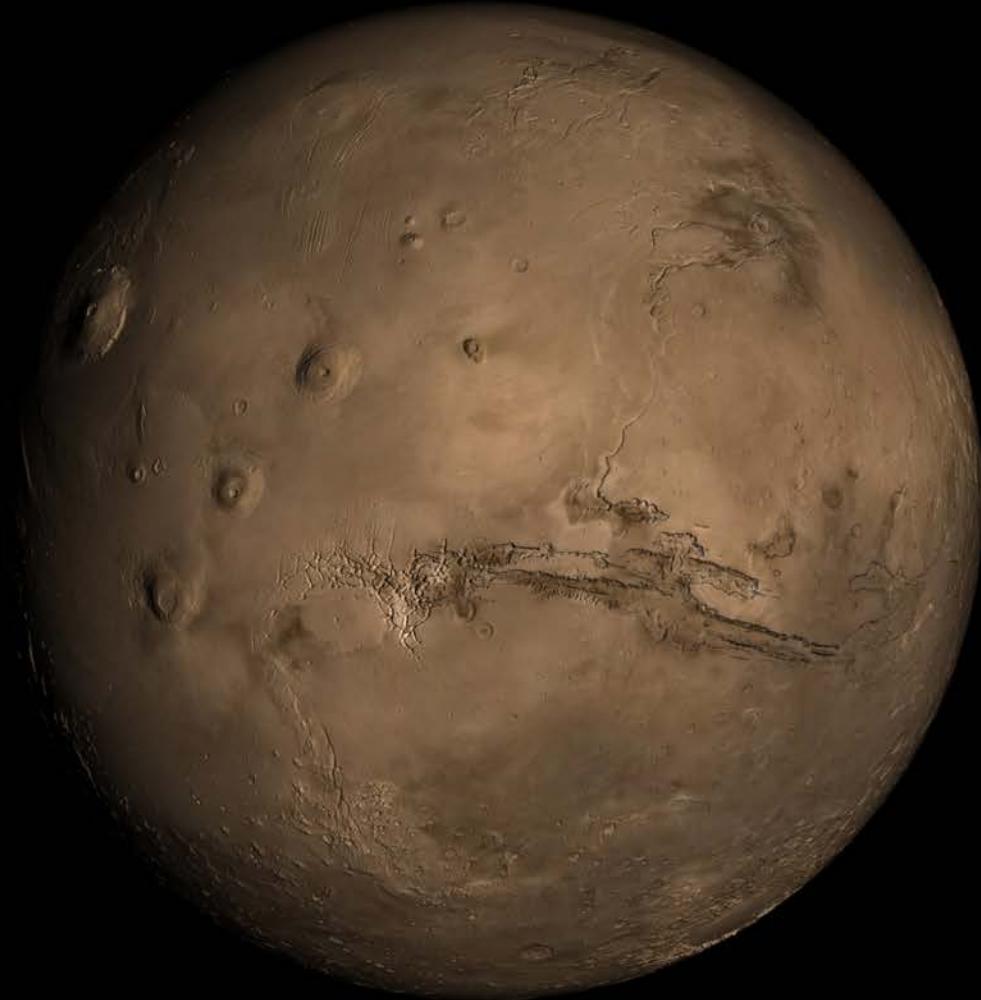
For detailed numerical model see van Keken et al. 2011 (JGR) and Bouilhol et al. (2015 EPSL)

1. Mid Ocean Ridges
2. Subduction Zones
3. Mantle Plumes and Intraplate Magmatism



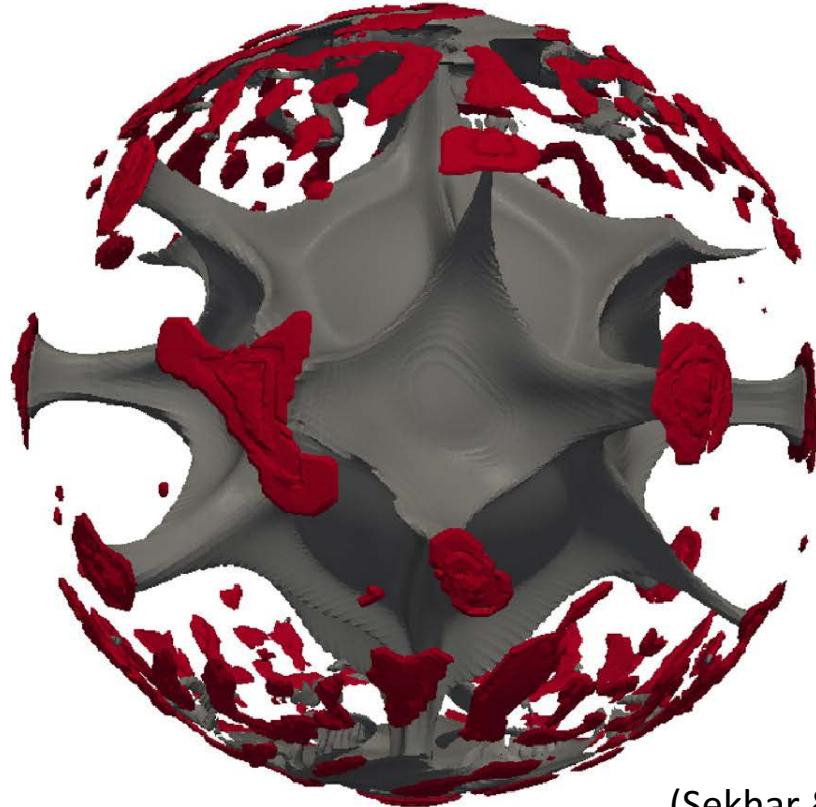


Mantle plumes and volcanism in Mars



Mantle plumes and volcanism in Mars

a



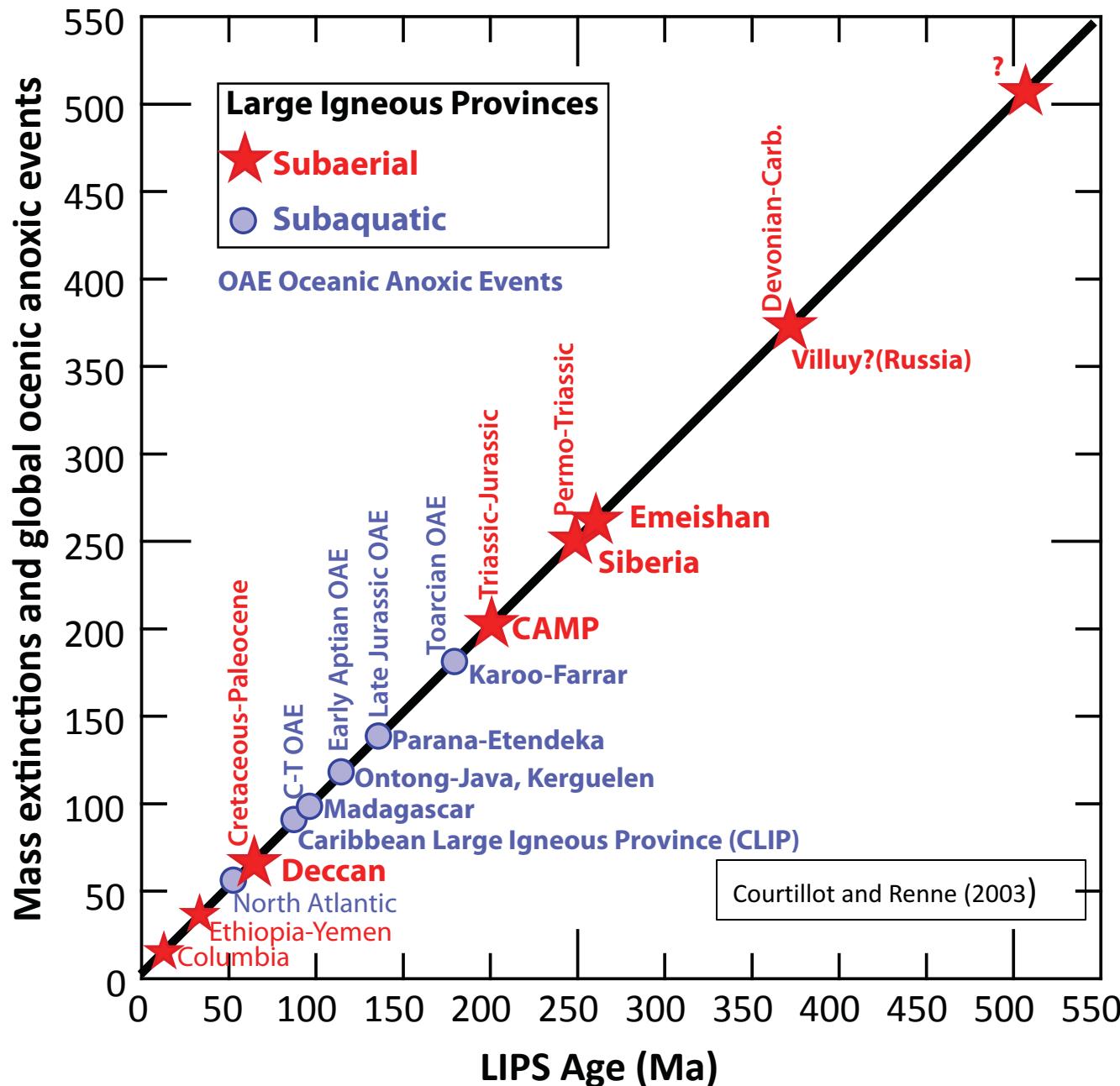
b



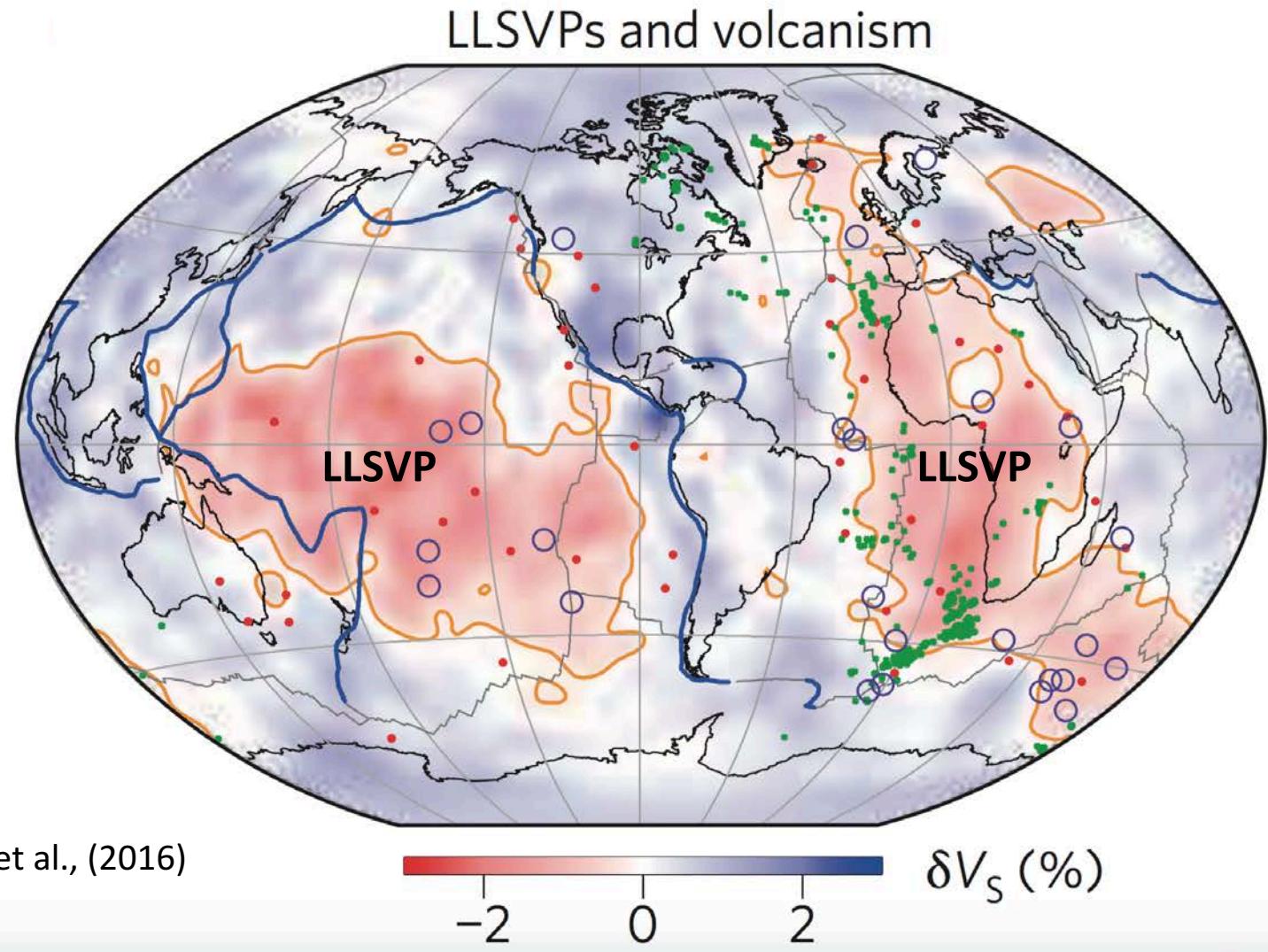
(Sekhar & King,
EPSL 2014)

- Convection calculations and melt location (red), with the 4 Ga (left), and 0.3 Ga (right)
- Constant heat source calculations produce sufficient melt to create Tharsis early in martian history and continue to produce significant melt to explain the activity of Arsia Mons up to $\sim 2\text{ Ma}$
- The isothermal structure corresponds to 1788 K and 1420 K respectively

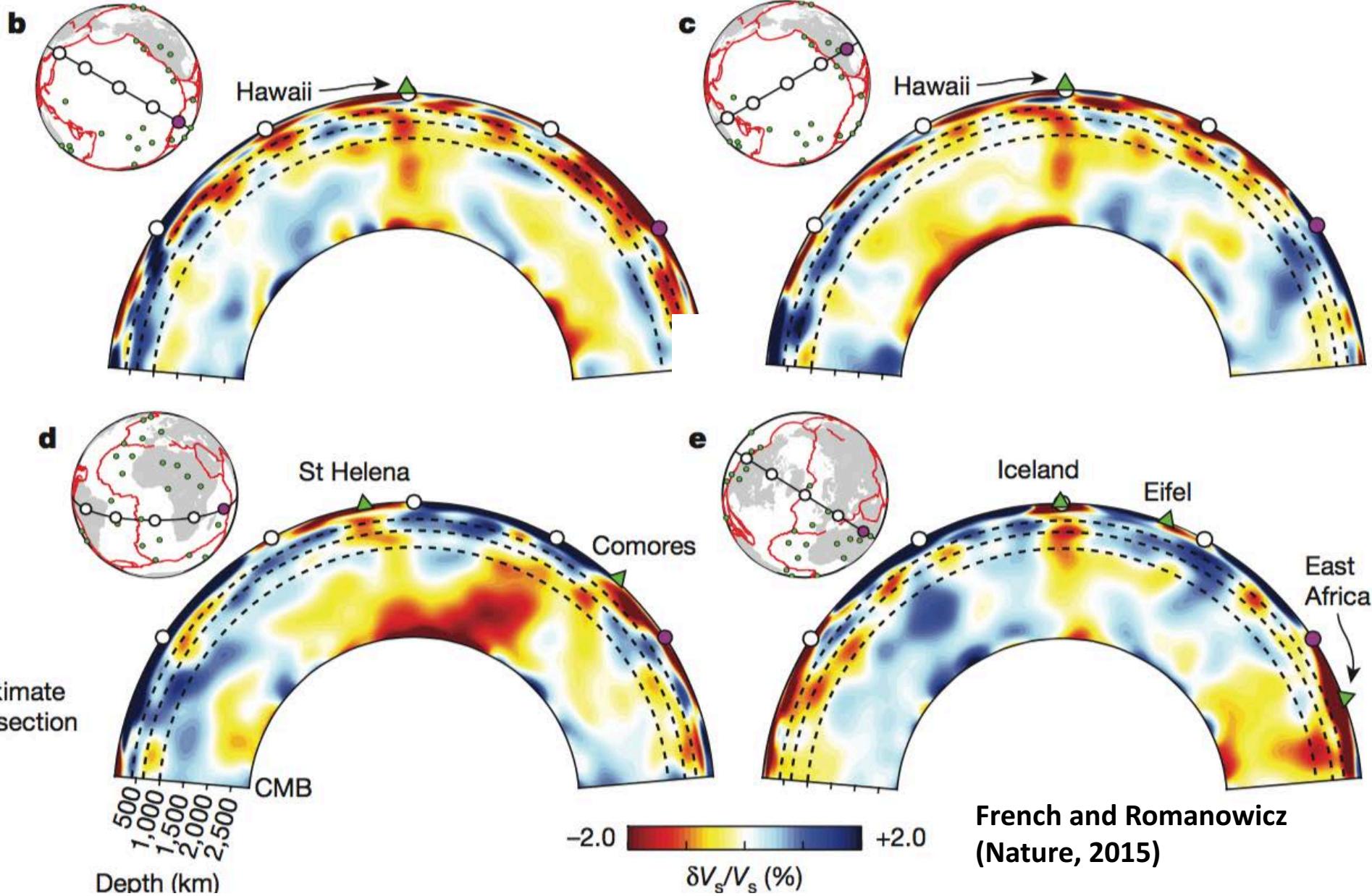
Why we should care: strong correlation between LIPS and mass extinctions

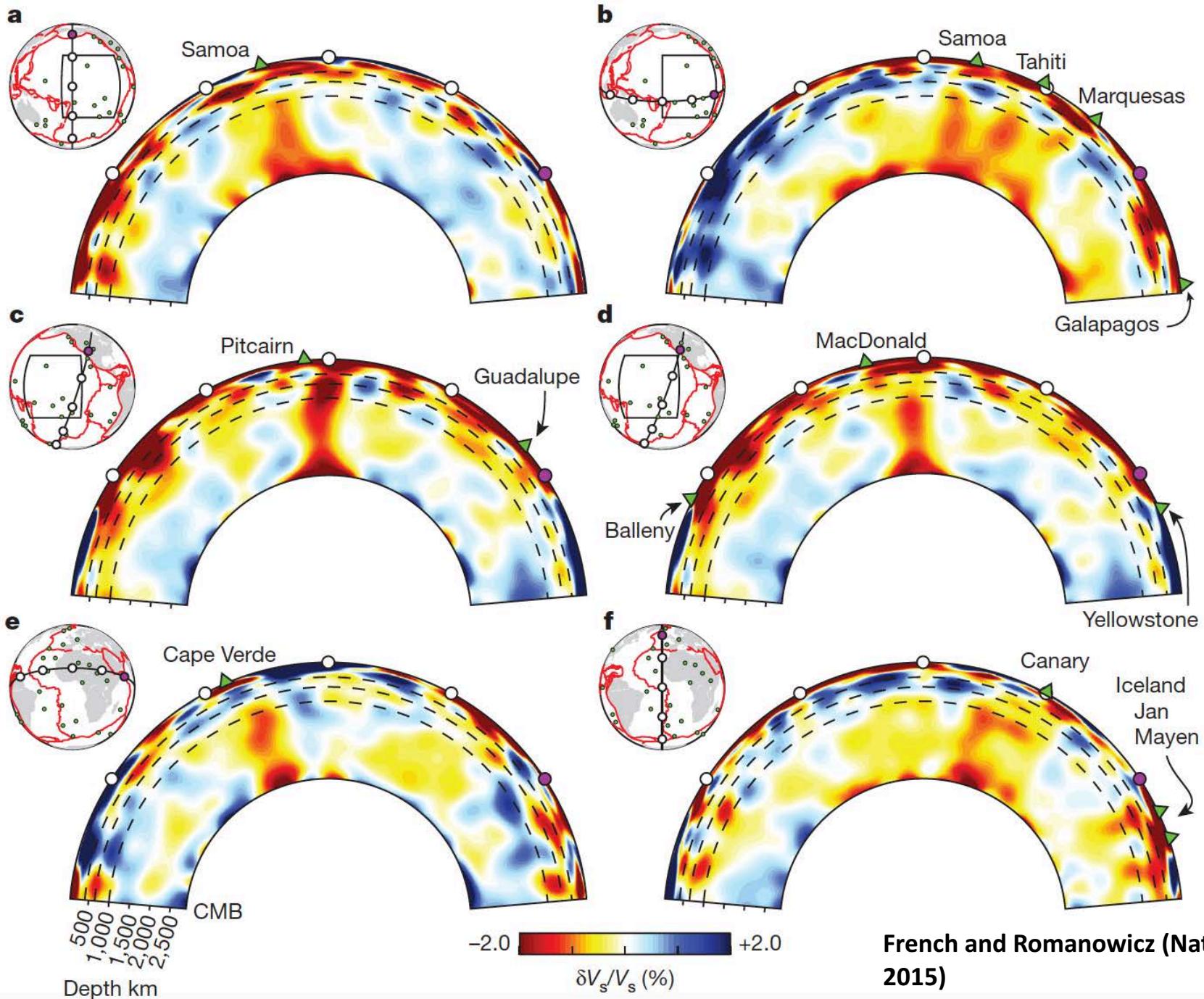


Plume-related hotspots are spatially associated with slow seismic anomalies called **Large Low-Shear Velocity Provinces** located at the core-mantle boundary



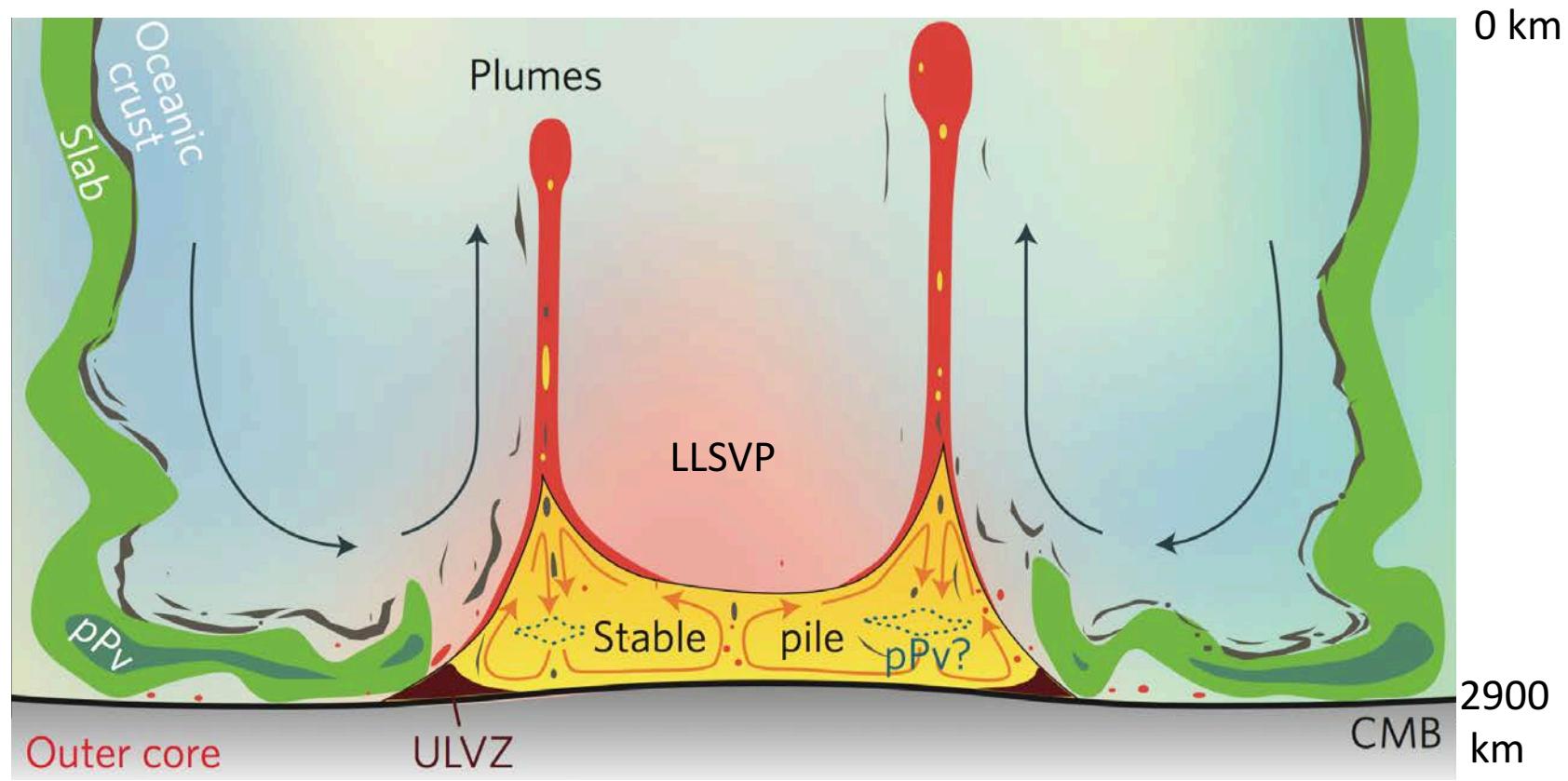
SEMUCB-WM1 broad plumes with a 1.5%–2% reduction of shear-wave velocity in the lower mantle beneath hotspots connected to the LLSVPS.





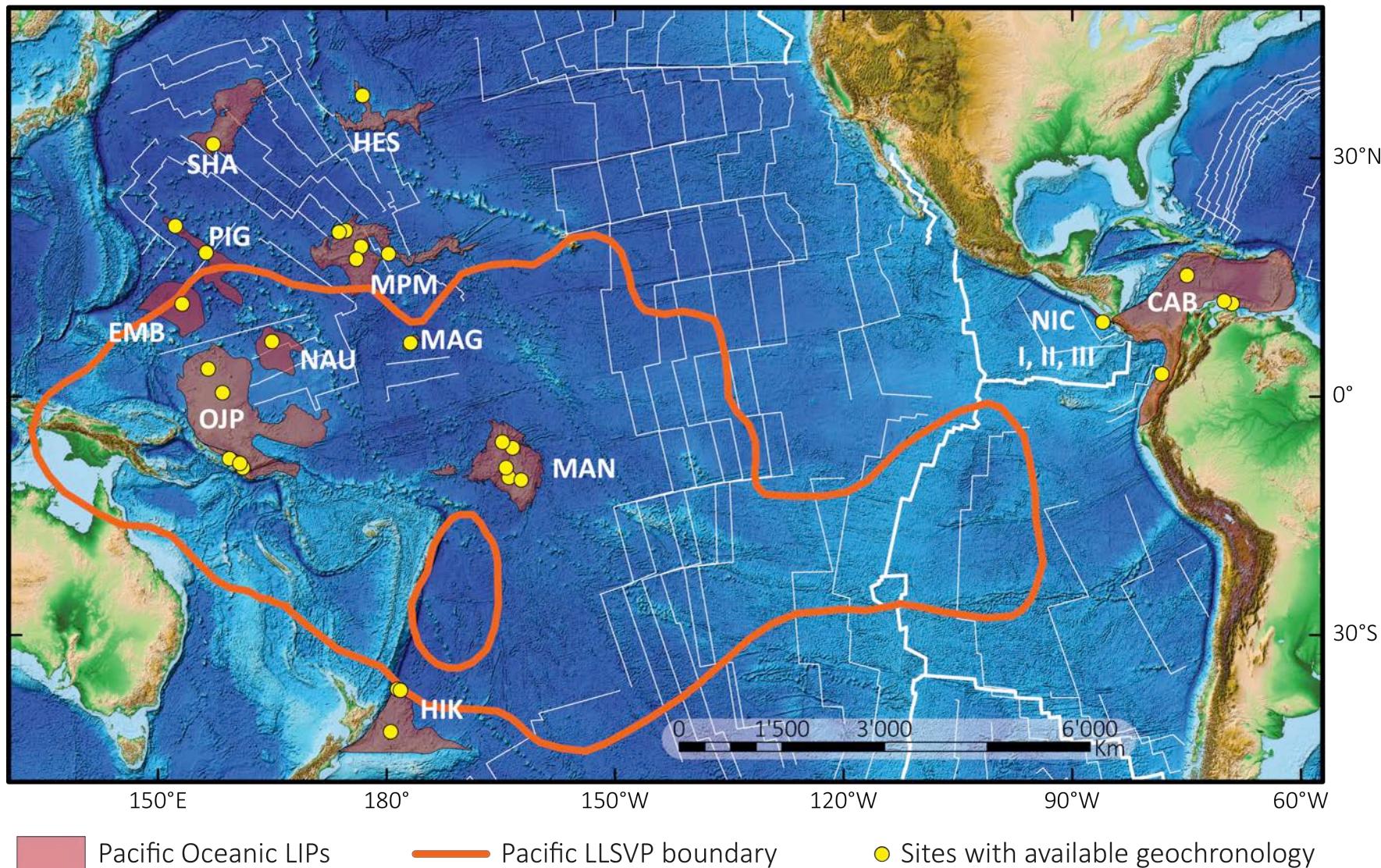
French and Romanowicz (Nature, 2015)

- Modern day mantle plumes originate LLSVPs at the core-mantle boundary.
- These thermochemical piles provide the only windows into the deep Earth
- Are LIPs also related to the LLSVP?



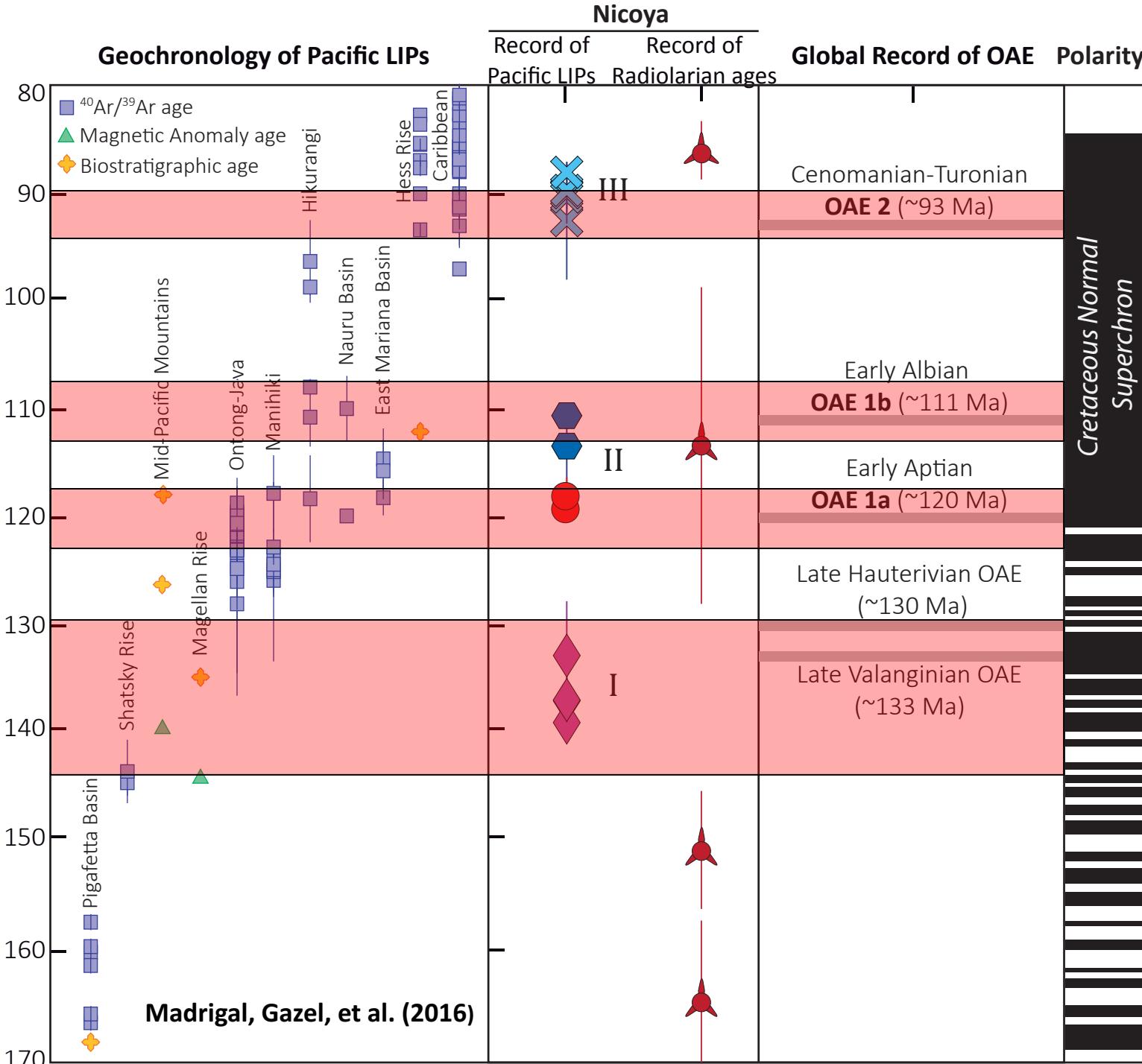
Garnero et al., (2016)

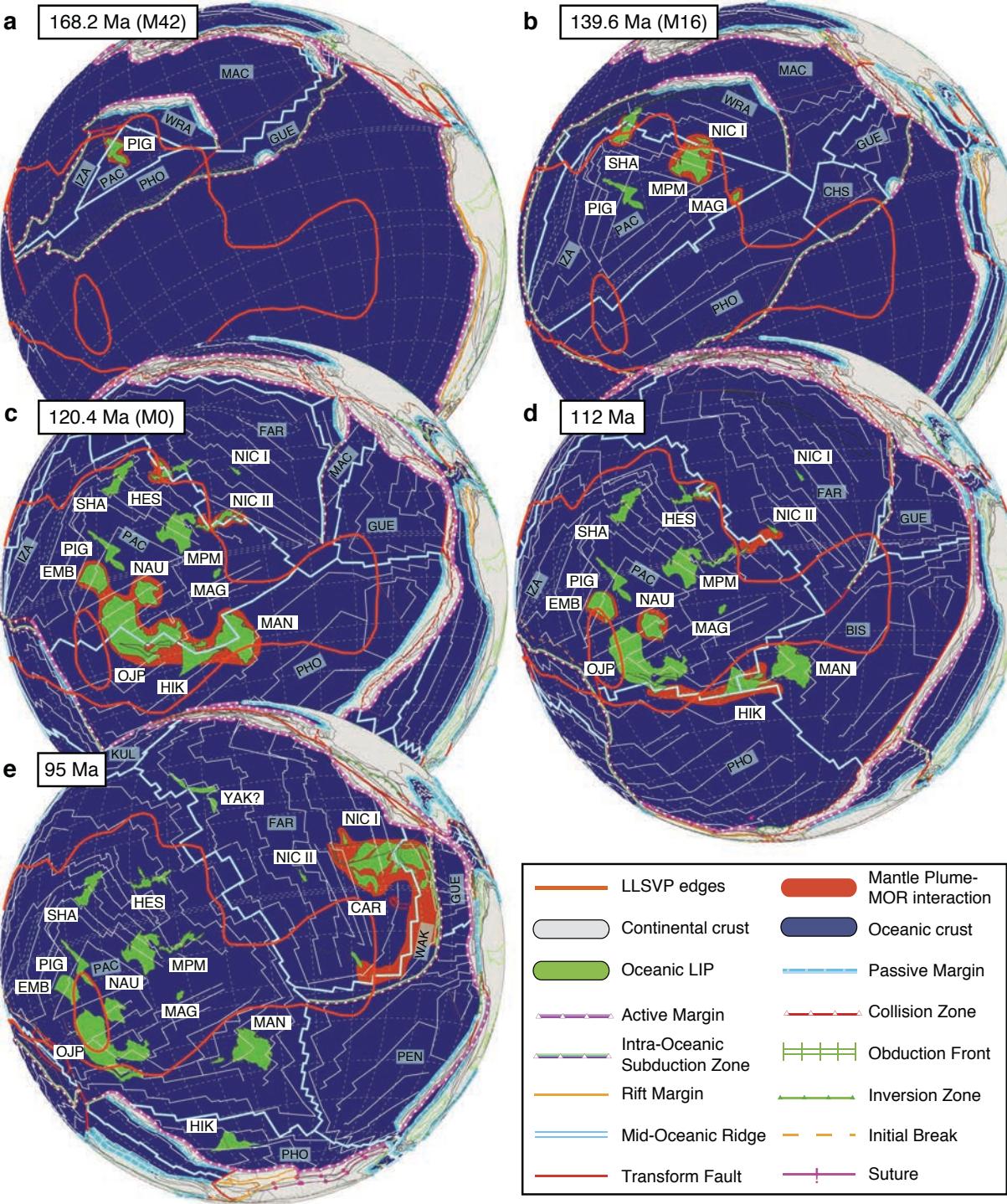
A global survey of oceanic LIPS



Madrigal et al. (2016)

nature
COMMUNICATIONS





(a) At ~168.2 Ma (M42) the Pacific Plate was at its onset. Pigafetta Basin (PIG) was forming.

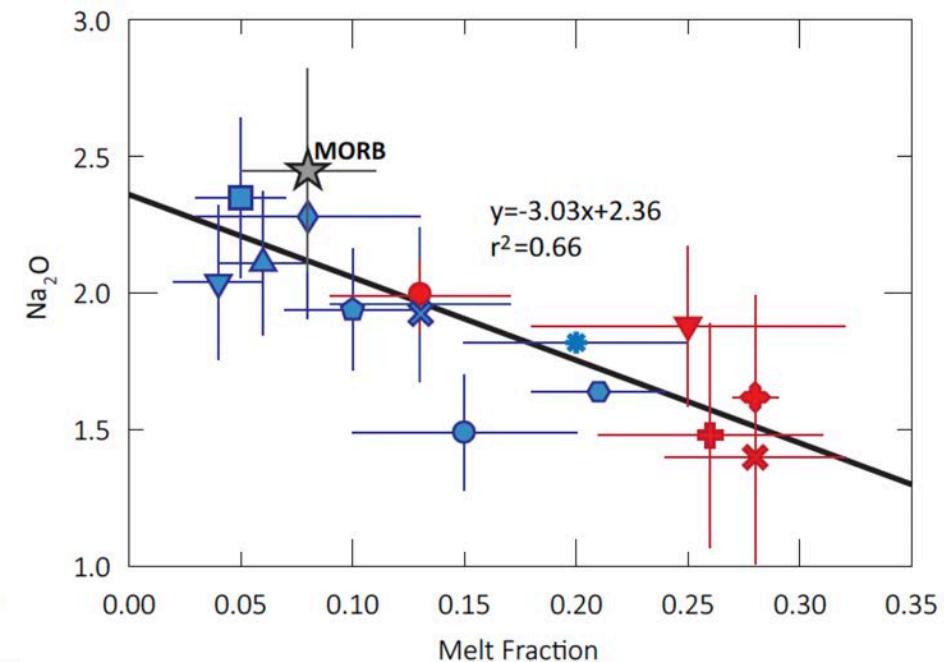
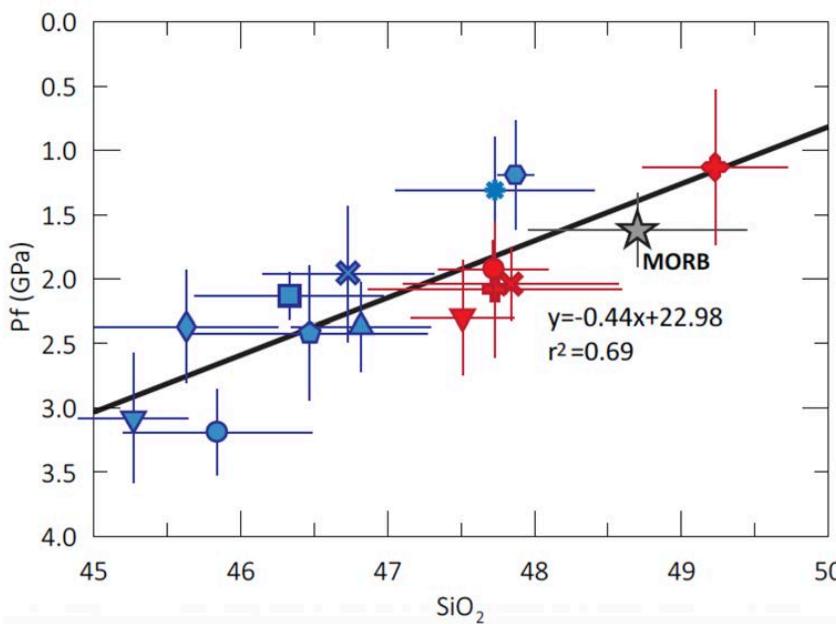
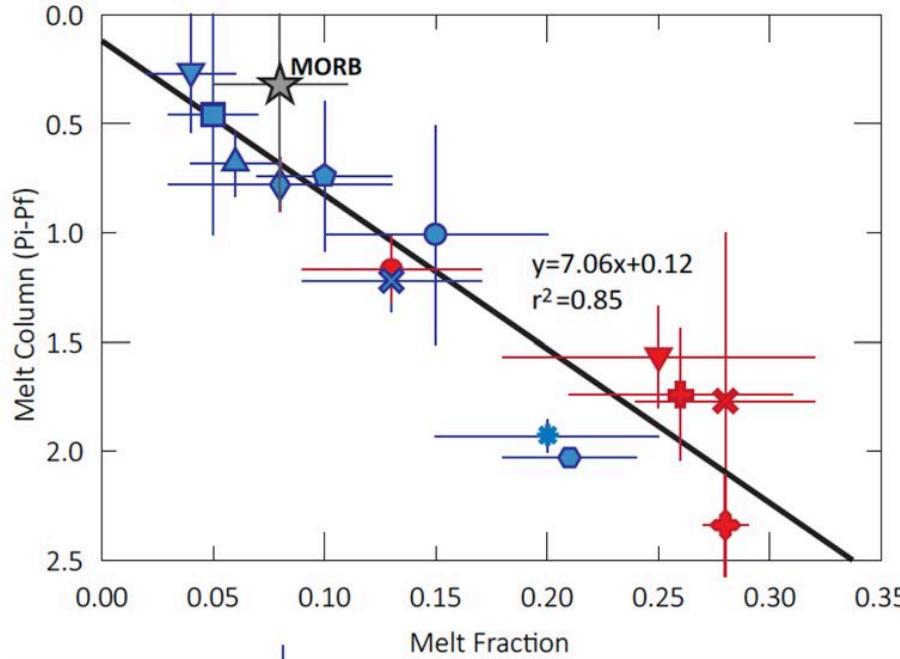
(b) At ~139.6 Ma (M16) formation of Shatsky Rise (SHA), Nicoya I (NIC I) plateau, the Mid-Pacific Mountains (MPM) and Magellan Rise (MAG).

(c) At ~120.4 Ma (M0) Ontong-Java (OJP), Manihiki (MAN) and Hikurangi (HIK) Plateau event. The Nicoya II (NIC II) erupting close to the northern margins of the LLSVP. Also East Mariana Basin (EMB), near the W margins of the Pacific LLSVP..

(d) At ~112 Ma the southern margin of the LLSVP remains active and in interaction with a MOR, forming sections of the Hikurangi Plateau, Nauru Basin (NAU) and East Mariana Basin.

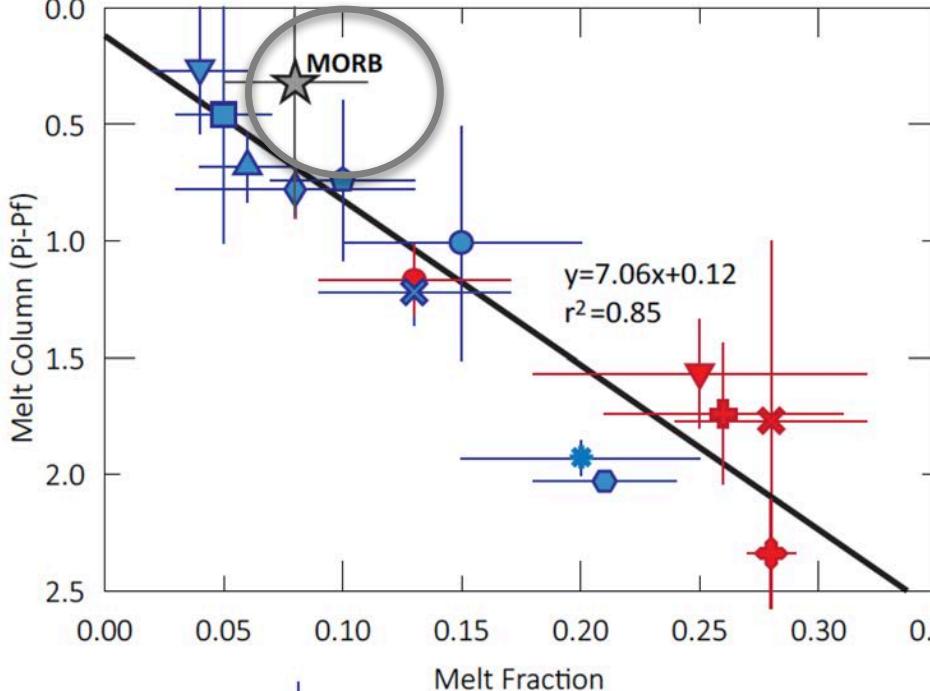
(e) At ~95 Ma the easternmost margins of the Pacific LLSVP became active forming the Caribbean Plateau (CAR) at the intersection with a MOR.

Tectonic plate abbreviations BIS (Biscoe), CHS (Chonos), FAR (Farallon), GUE (Guerrero), IZA (Izanagi), KUL (Kula), MAC (Mackinley), PAC (Pacific), PEN (Penas), PHO (Phoenix), WAK (Washikemba), WRA (Wrangellia) and YAK (Yakutat).



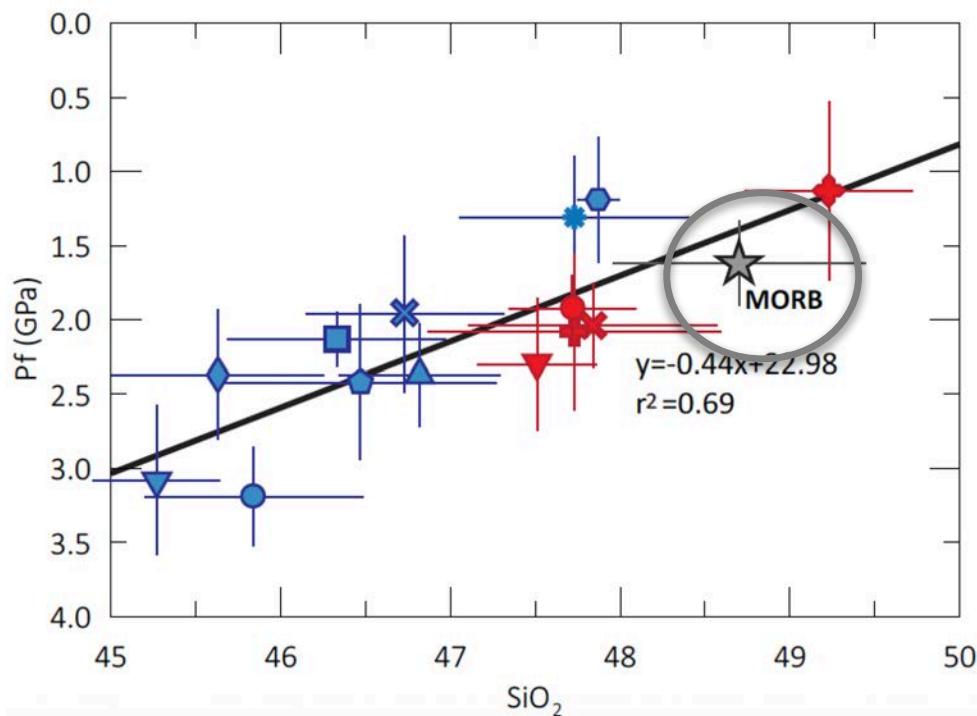
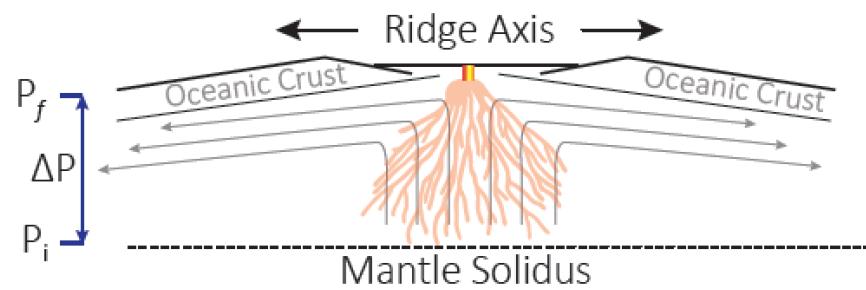
- | Ocean Islands | | | | | |
|---------------|----------------------|-------------|--|--|--|
| ■ Azores | ▲ Galapagos | ✖ Marquesas | | | |
| ◆ Canaries | ● Hawaii (Mauna Kea) | ✳ Pitcairn | | | |
| ▼ Cook | ◆ Iceland | ♦ Samoa | | | |
-
- | Pacific LIPS | | | | | |
|---------------------|----------------------------------|----------------------------------|--|--|--|
| ✚ Caribbean Plateau | ✖ Nicoya (120 Ma) | ✖ Onton-Java Plateau | | | |
| ▼ Magellan Rise | ● Pigafetta (Ocean Flood Basalt) | ● Pigafetta (Ocean Flood Basalt) | | | |

Madrigal et al. (Nature Communications, 2016)

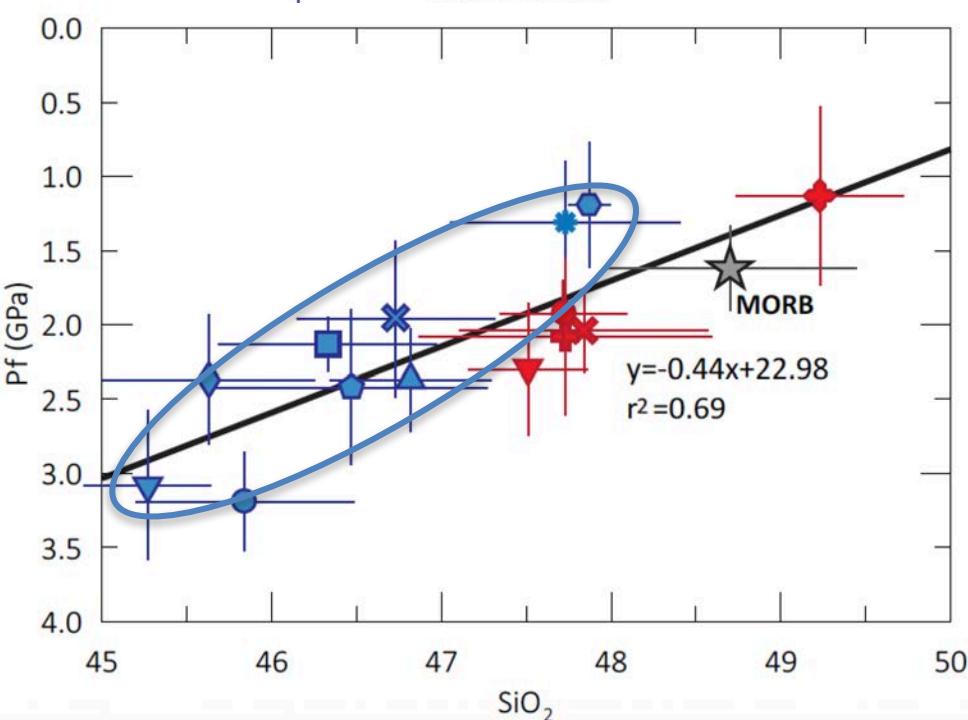
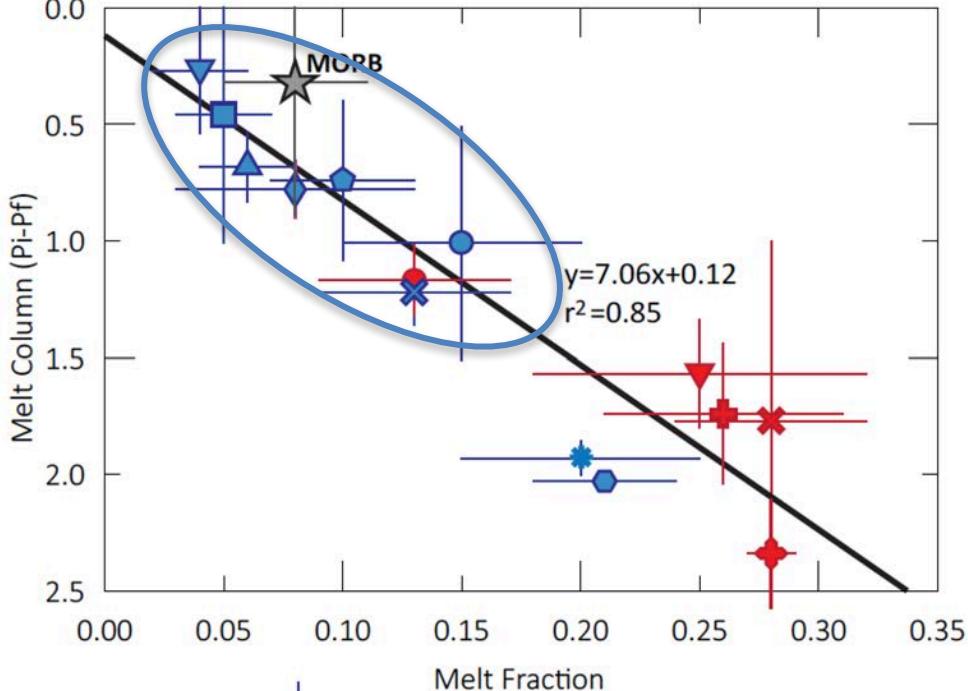


Mid-Ocean Ridge (MORB)

Short and Shallow Melting Column (ΔP)
Low Melt Production

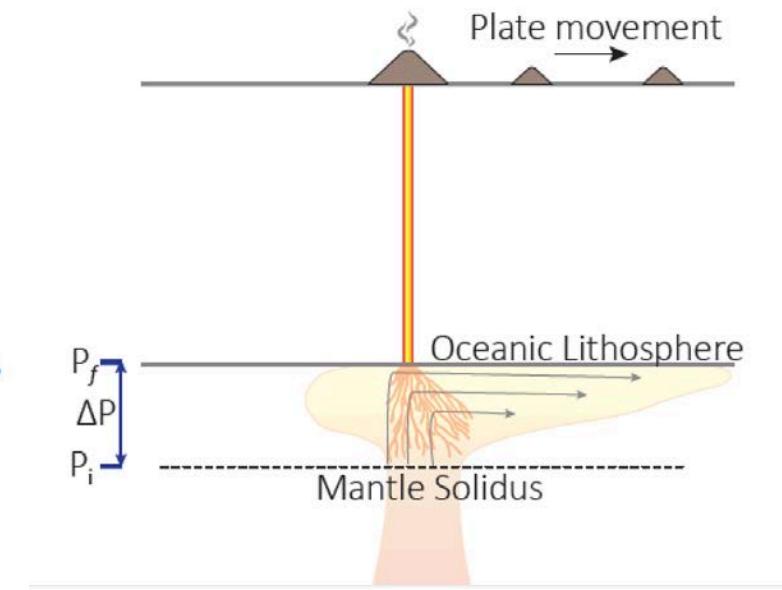


- Ocean Islands**
- Azores
 - ▲ Galapagos
 - ◆ Canaries
 - ▼ Cook
 - Hawaii (Mauna Kea)
 - ★ Pitcairn
 - Iceland
 - ◇ Samoa
- Pacific LIPS**
- ✚ Caribbean Plateau
 - ▼ Magellan Rise
 - ✖ Nicoya (120 Ma)
 - ✖ Onton-Java Plateau
 - Pigafetta (Ocean Flood Basalt)



Ocean Island (OIB)

Short and Deep Melting Column (ΔP)
 Limited Melt Productivity

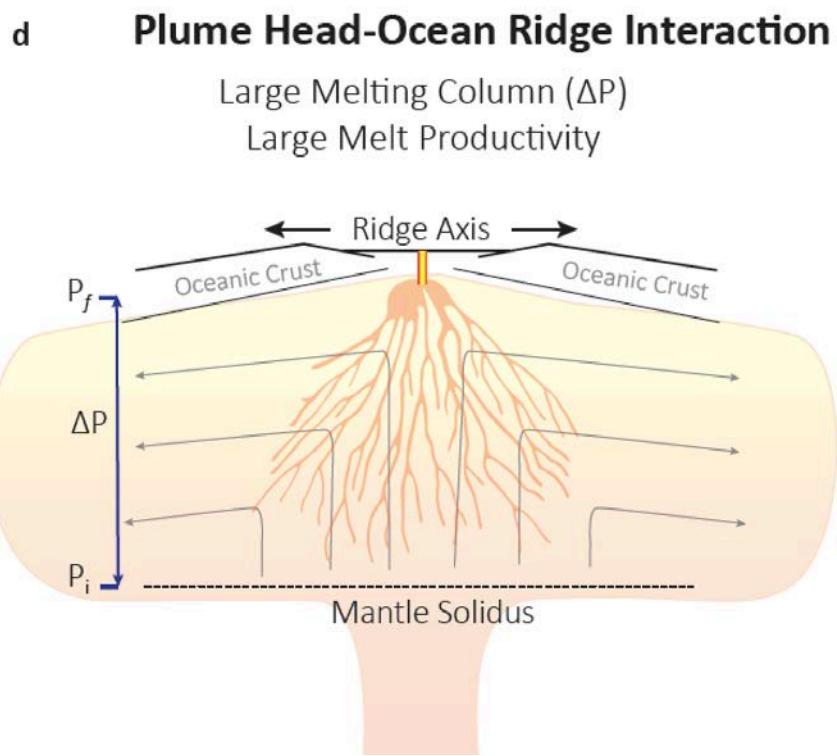
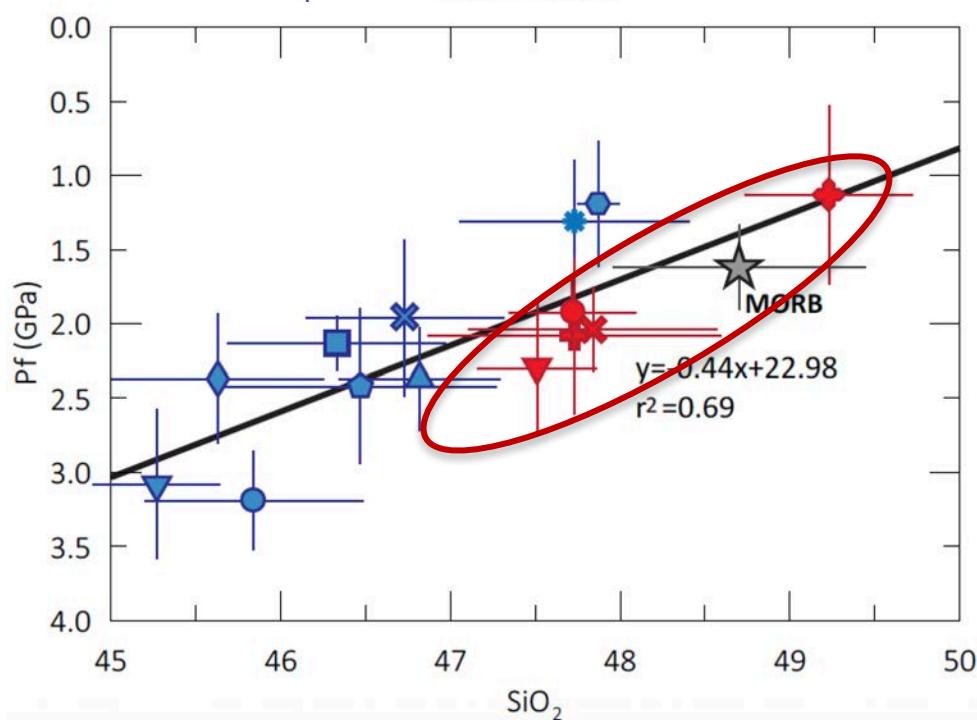
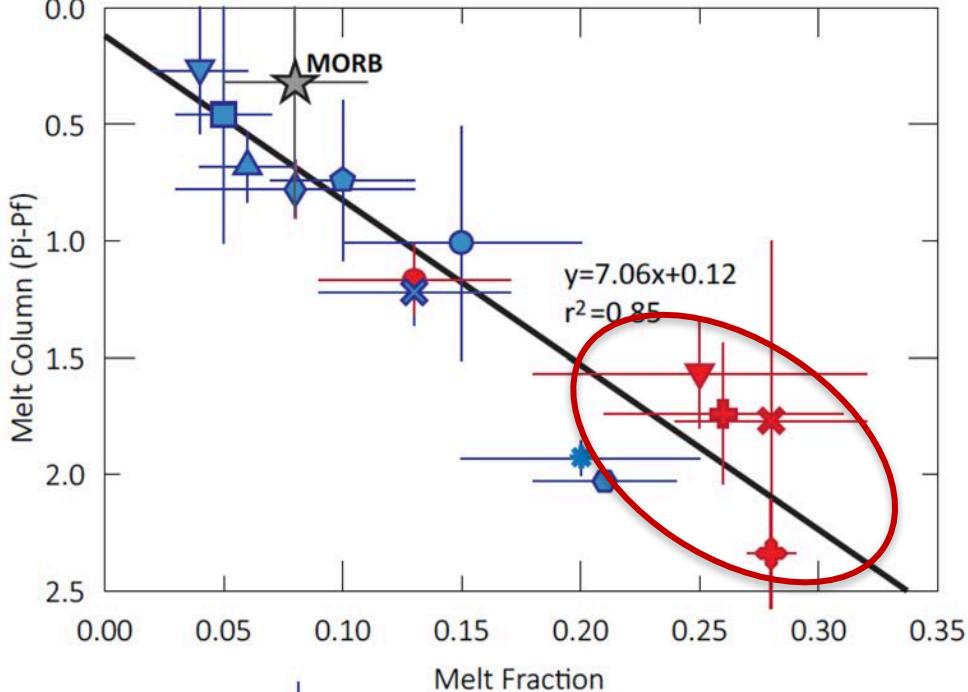


Ocean Islands

- | | | |
|------------|----------------------|-------------|
| ■ Azores | ▲ Galapagos | ✖ Marquesas |
| ◆ Canaries | ● Hawaii (Mauna Kea) | ✳ Pitcairn |
| ▼ Cook | ◆ Iceland | ♦ Samoa |

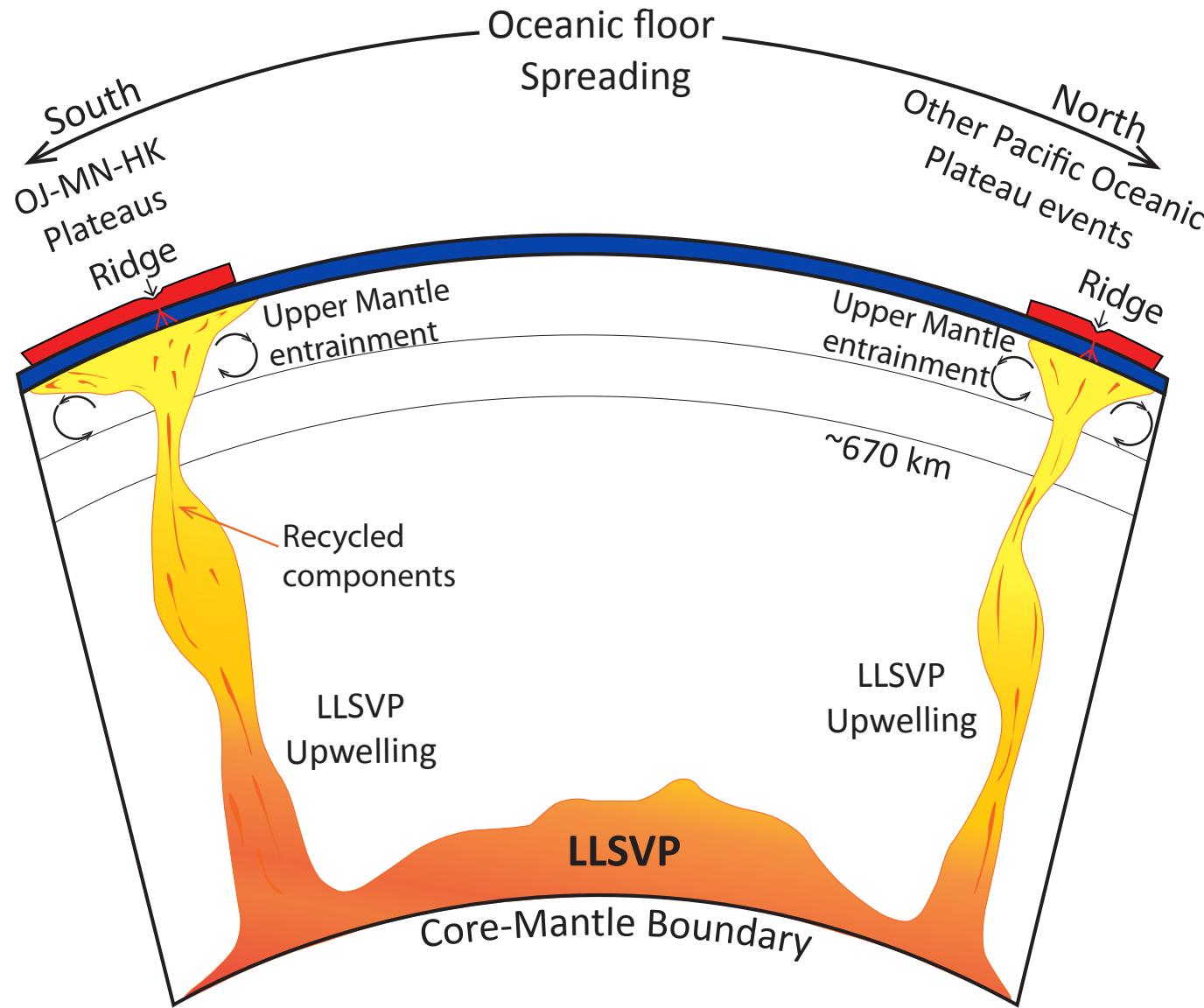
Pacific LIPS

- | | |
|---------------------|----------------------------------|
| ✚ Caribbean Plateau | ✖ Onton-Java Plateau |
| ▼ Magellan Rise | ● Pigafetta (Ocean Flood Basalt) |
| ♦ Nicoya (120 Ma) | |

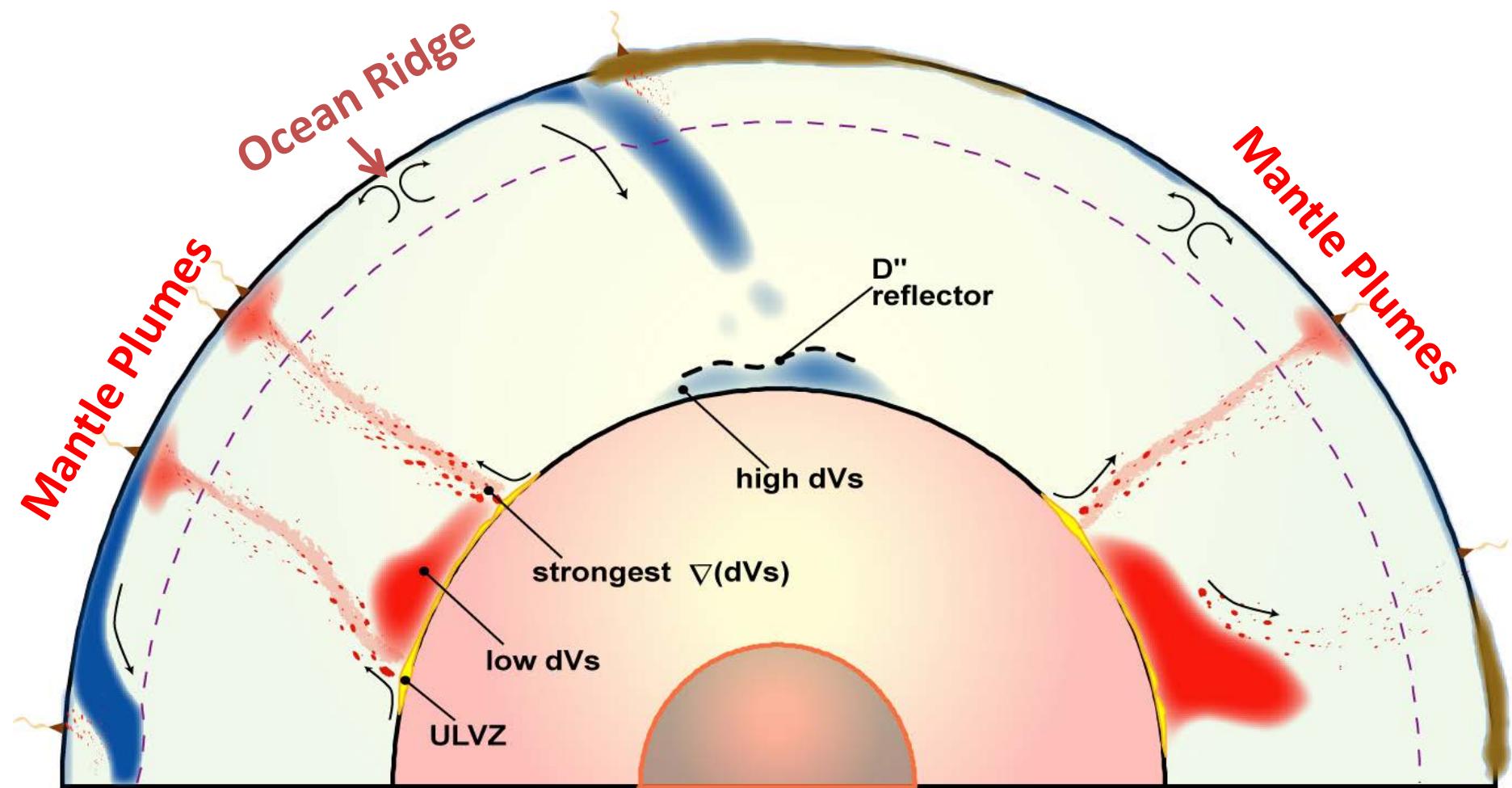


- Ocean Islands**
- Azores
 - ▲ Galapagos
 - ◆ Canaries
 - ▼ Cook
 - Hawaii (Mauna Kea)
 - Pitcairn
 - Iceland
 - Samoa
- Pacific LIPS**
- Caribbean Plateau
 - ▼ Magellan Rise
 - ◆ Nicoya (120 Ma)
 - Onton-Java Plateau
 - Pigafetta (Ocean Flood Basalt)

LIPs were probably also connected to the LLSVPs and triggered rifting of the lithosphere



Then if mantle plumes bring material from the deep Earth
Mantle plumes must be hot!

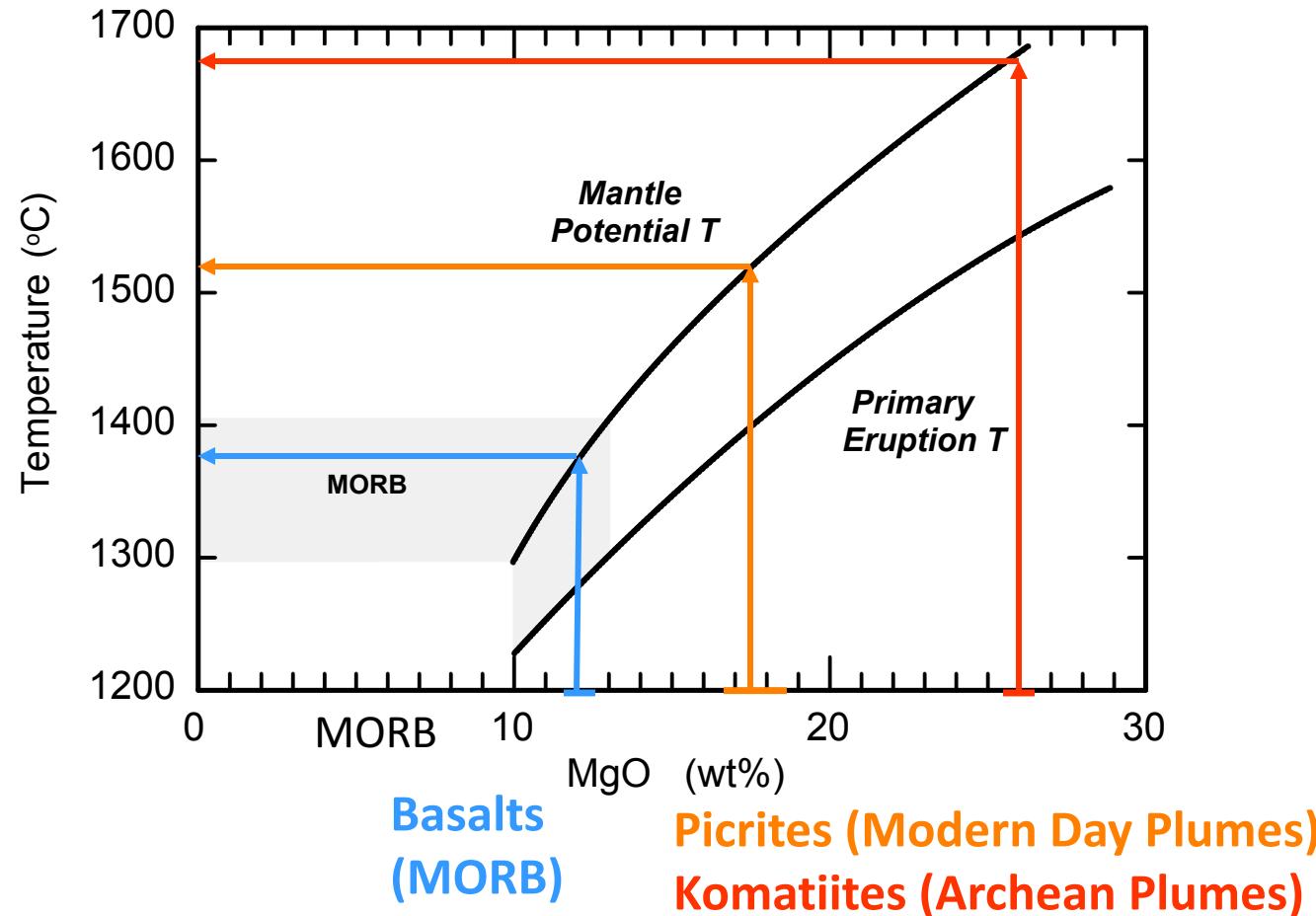


Thorne et al. (2004)

How we calculate the temperature of the mantle?

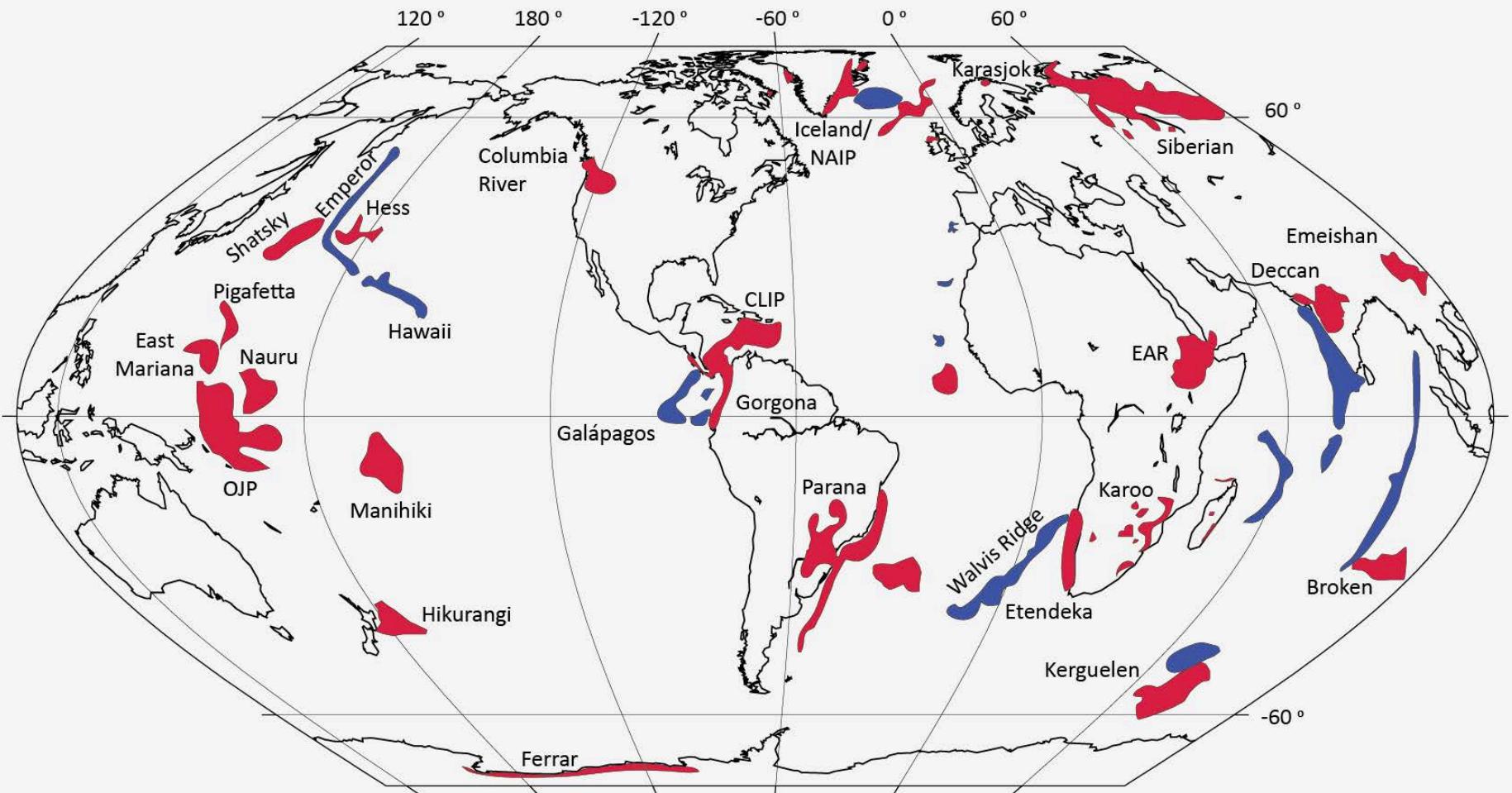
MgO contents of primary magmas = Thermometer

Tutorial this afternoon!

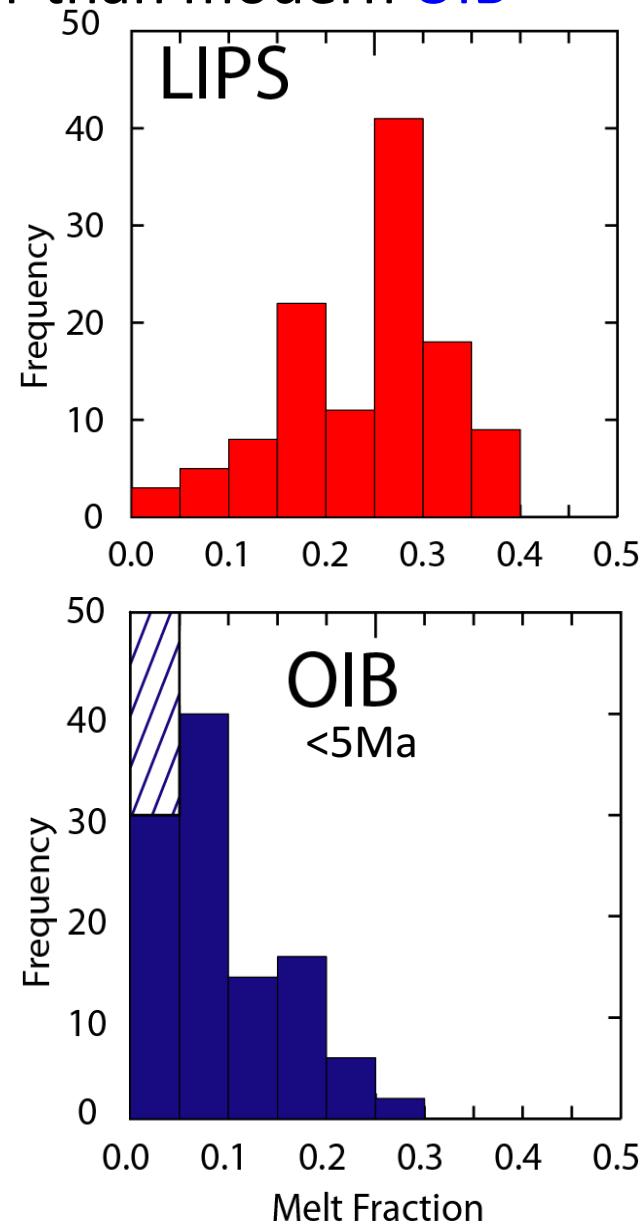
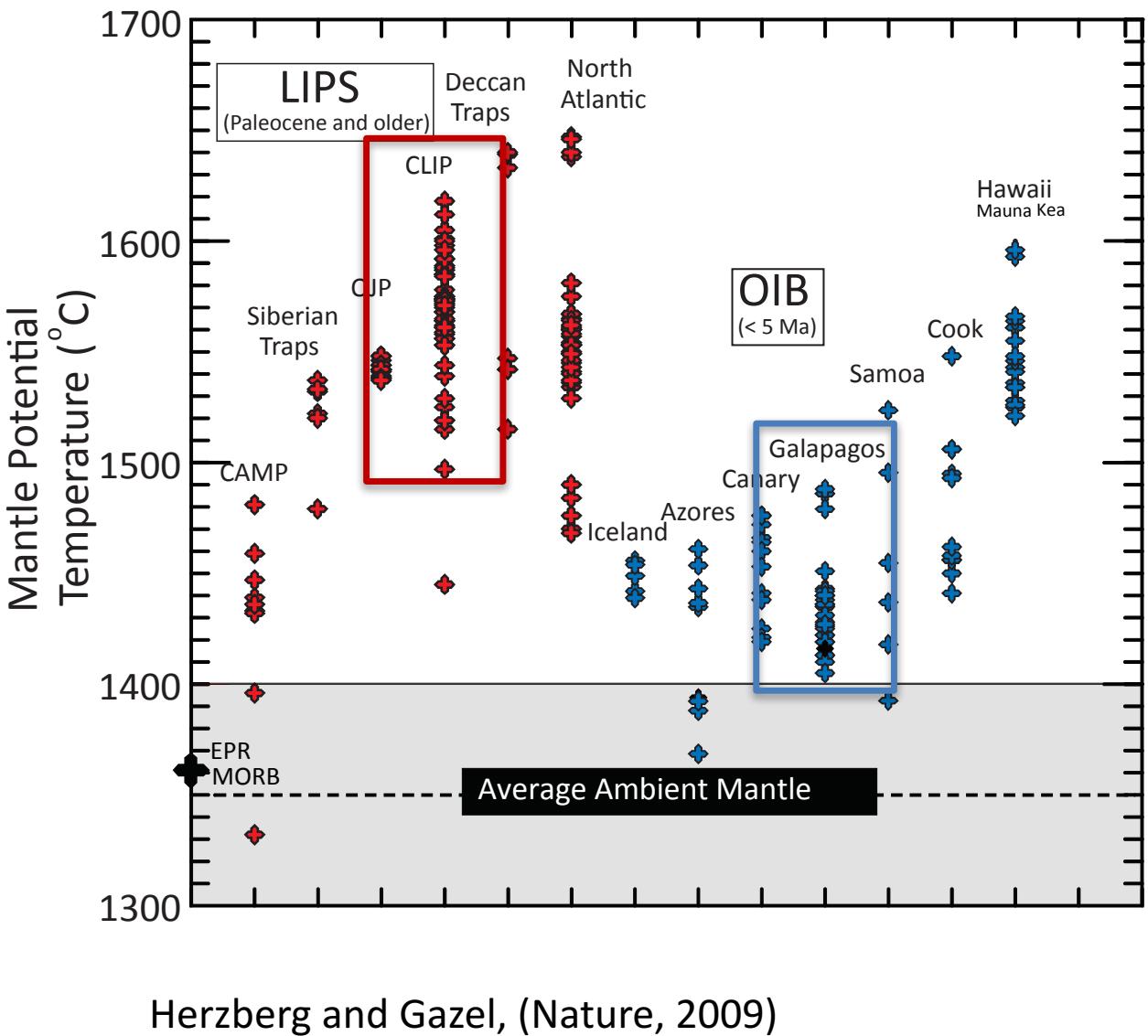


$$T_p = 1025 + 28.6\text{MgO} - 0.084\text{MgO}^2 \quad (\text{Based on experimental calibrations, Herzberg and Asimov, 2015})$$

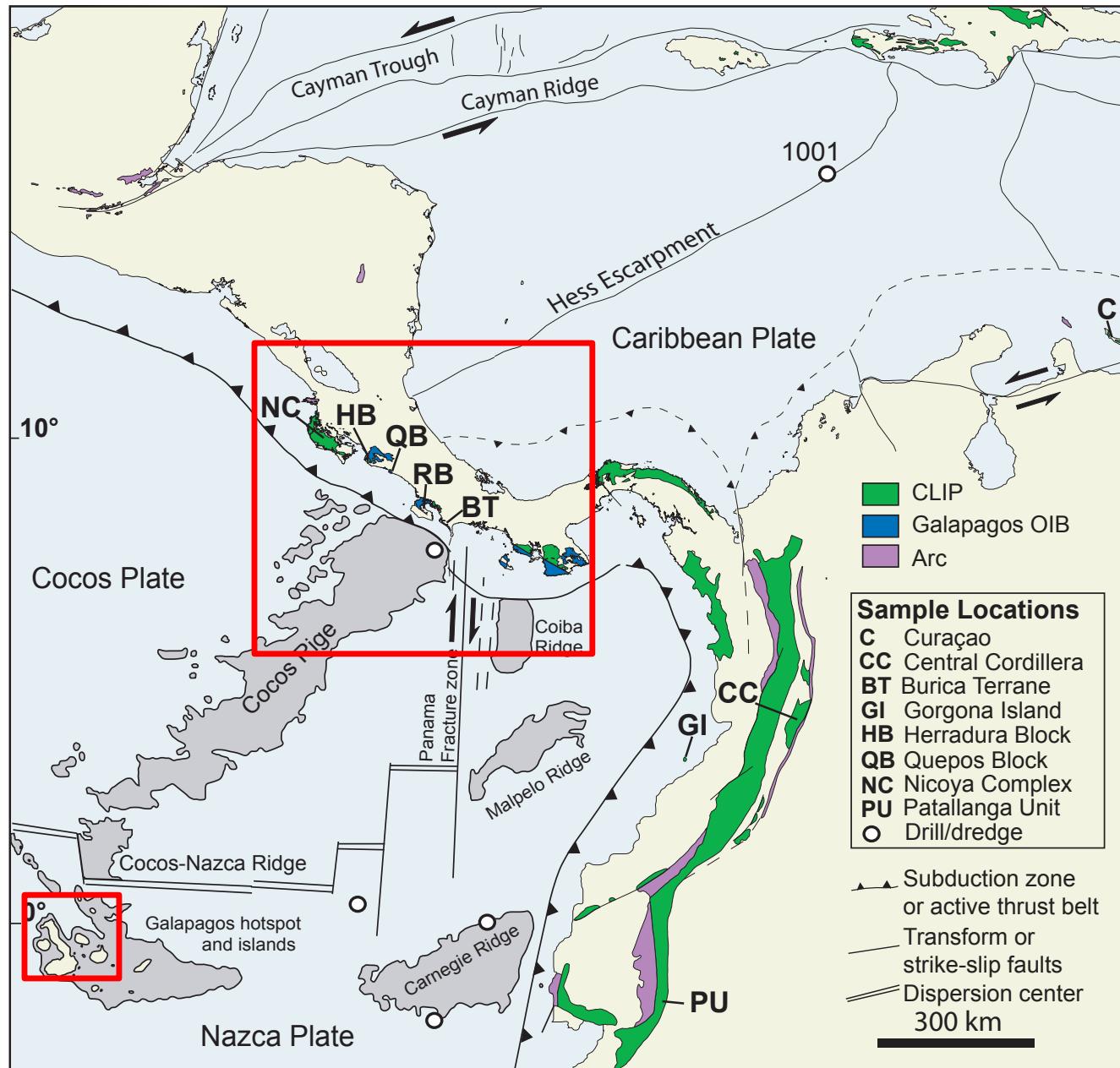
Mantle potential temperature (T_p) calculations from: Large Igneous Provinces (LIPs) and Ocean Island Basalt (OIB)



Both LIPs and OIB melted at higher temperatures than ambient MORB mantle, but LIPs were hotter than modern OIB



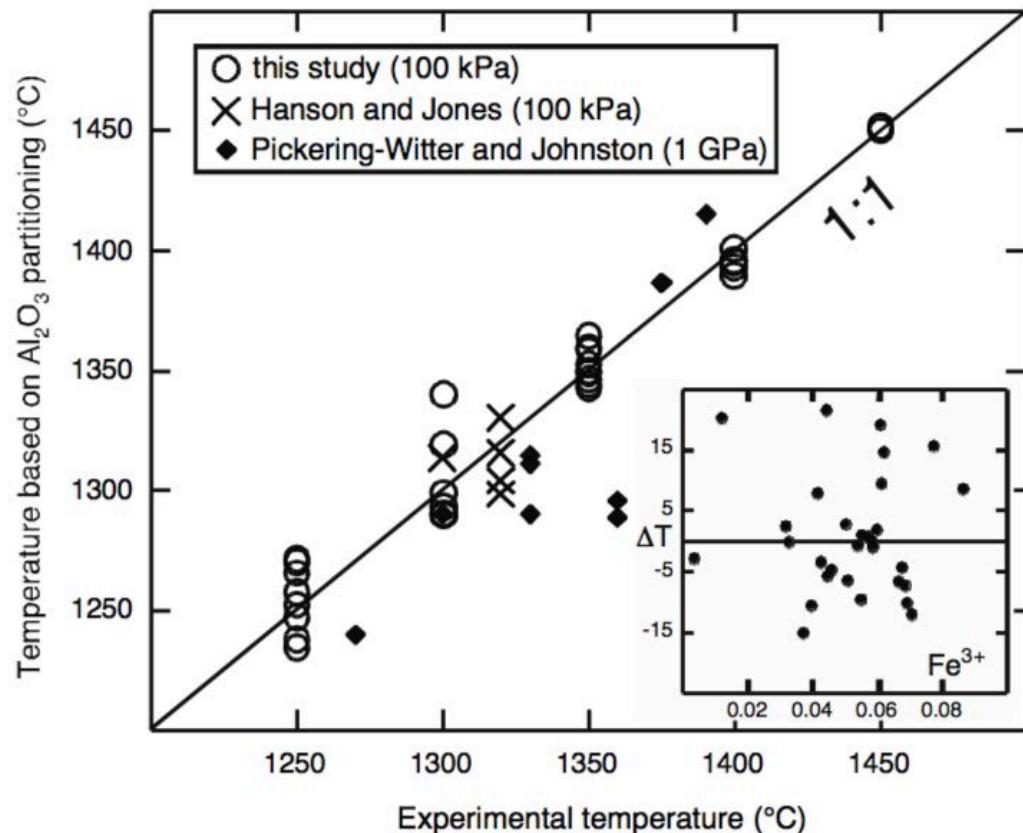
Primitive Galapagos-related lavas are spread all over



Melting temperatures from lavas are model dependent

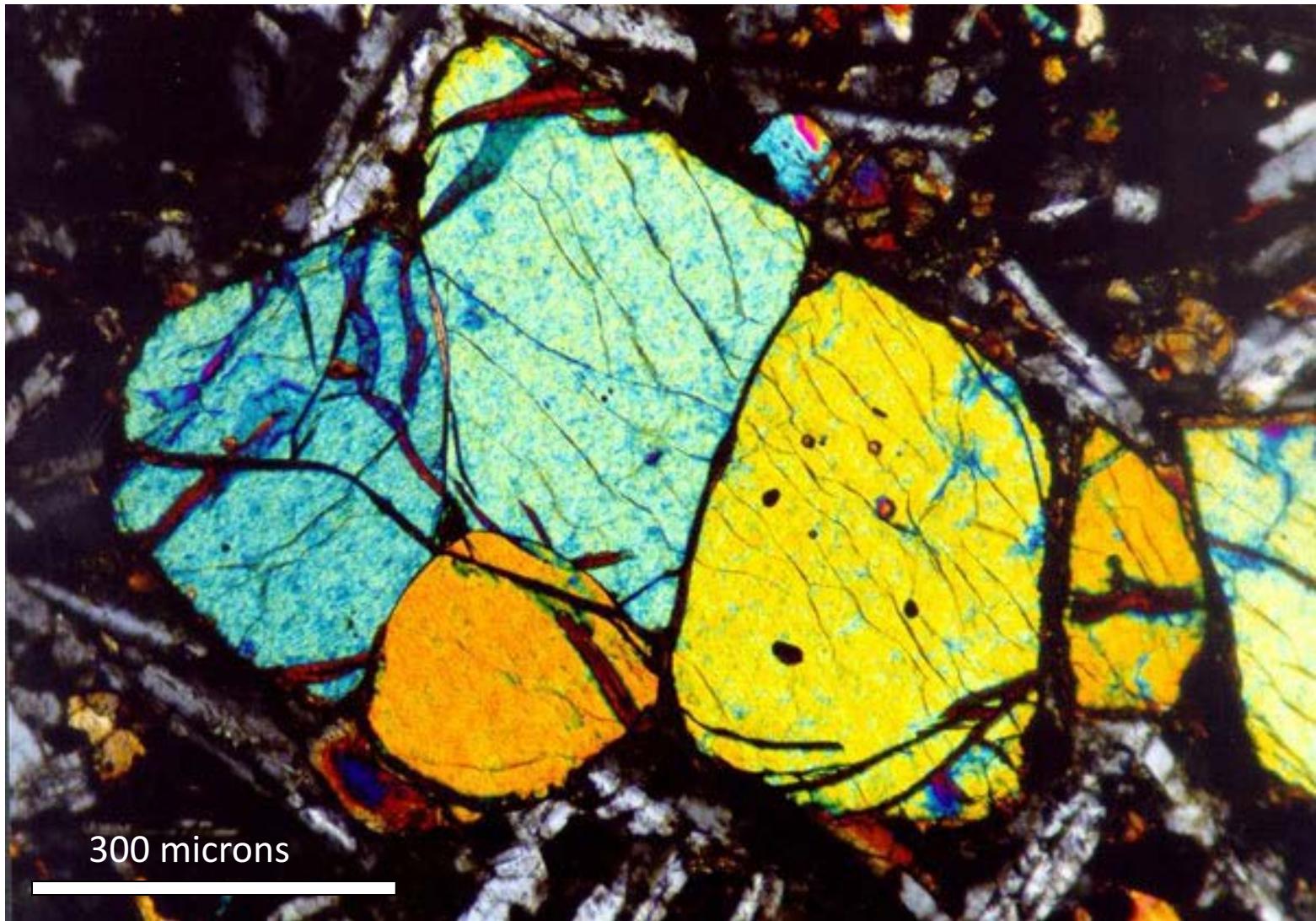
A more precise thermometer is the Al-in-olivine crystallization

- Thermometer dependents on
 - Al-in olivine and
 - Cr-in spinel
- More Al-in olivine and more Cr in spinel = Higher T
- $K_d = \text{Al}_2\text{O}_3^{\text{ol}}/\text{Al}_2\text{O}_3^{\text{spinel}}$
- No water or $f\text{O}_2$ dependent
- Independent from source compositions
- No Fe-Mg diffusion or exchange assumptions

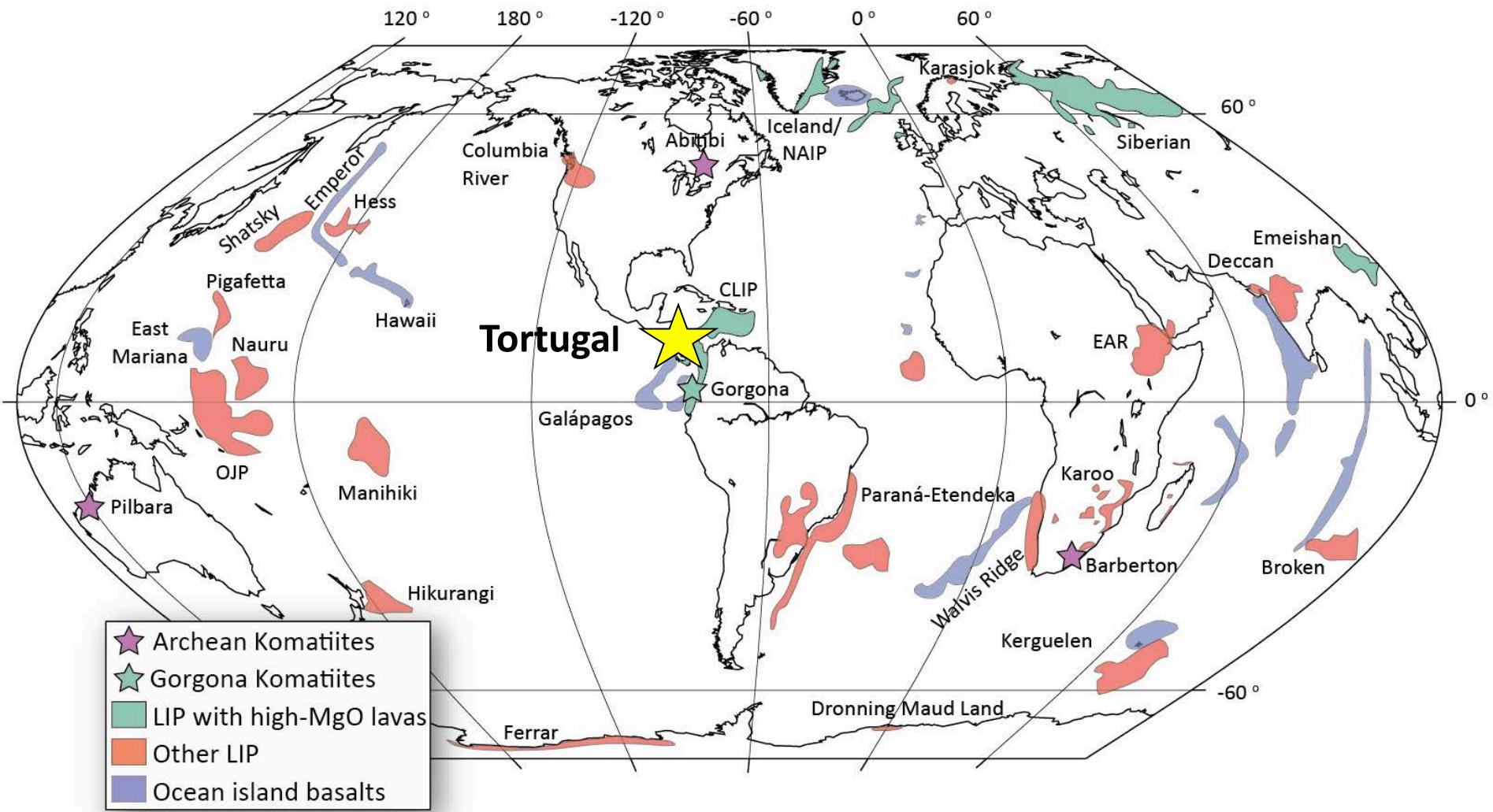


$$T (\text{°C}) = \frac{10\,000}{0.512 + 0.873Y_{\text{Cr}} - 0.91\ln(K_D)} - 273$$

Wan et al., (2008)
Coogan et al. (2014)



So lets revisit Phanerozoic High MgO Lavas from LIPs and Komatiites Temperatures Using the Al-in-olivine thermometer



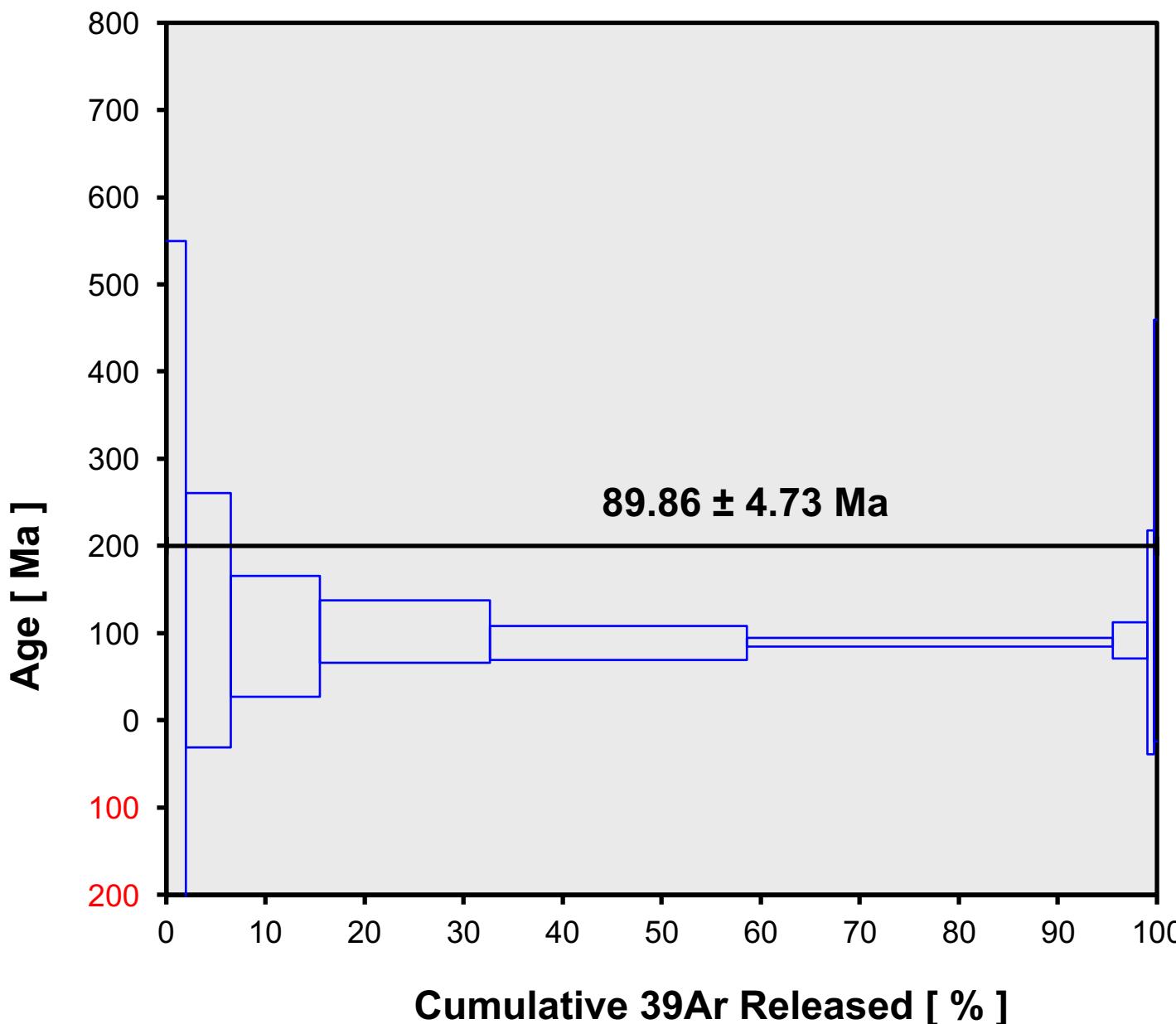
Including **Tortugal** as new komatiite-like Phanerozoic location

What are komattites?

- Mid-ocean ridge basalt = T_p 1350 °C
- Hawaiian pircites = T_p 1600 °C
- Archean Komatiite lava T_p > 1600 °C
- Komatiites: remnants of a hotter Earth?



We confirmed a ~90 Ma for Tortugal: the age of the onset of the Galapagos Plume



Ar-Ages in Ma

WEIGHTED PLATEAU
89.86 ± 4.73

TOTAL FUSION
95.29 ± 14.67

NORMAL ISOCHRON
88.82 ± 5.44

INVERSE ISOCHRON
88.84 ± 5.43

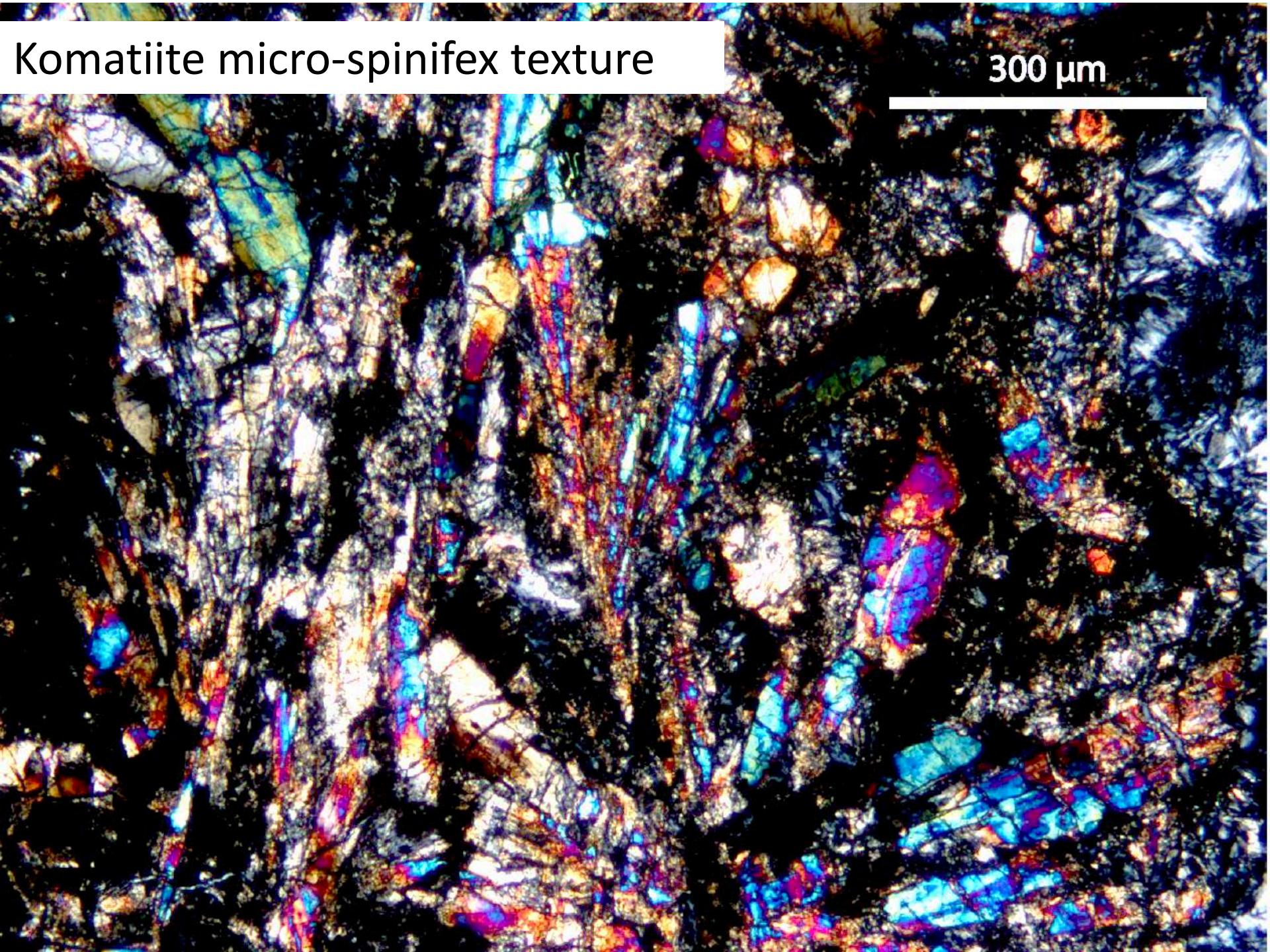
MSWD (PROBABILITY)
0.23 (98%)

Sample Info

IRR = UW122
J = 0.00524780 ±
0.00000289

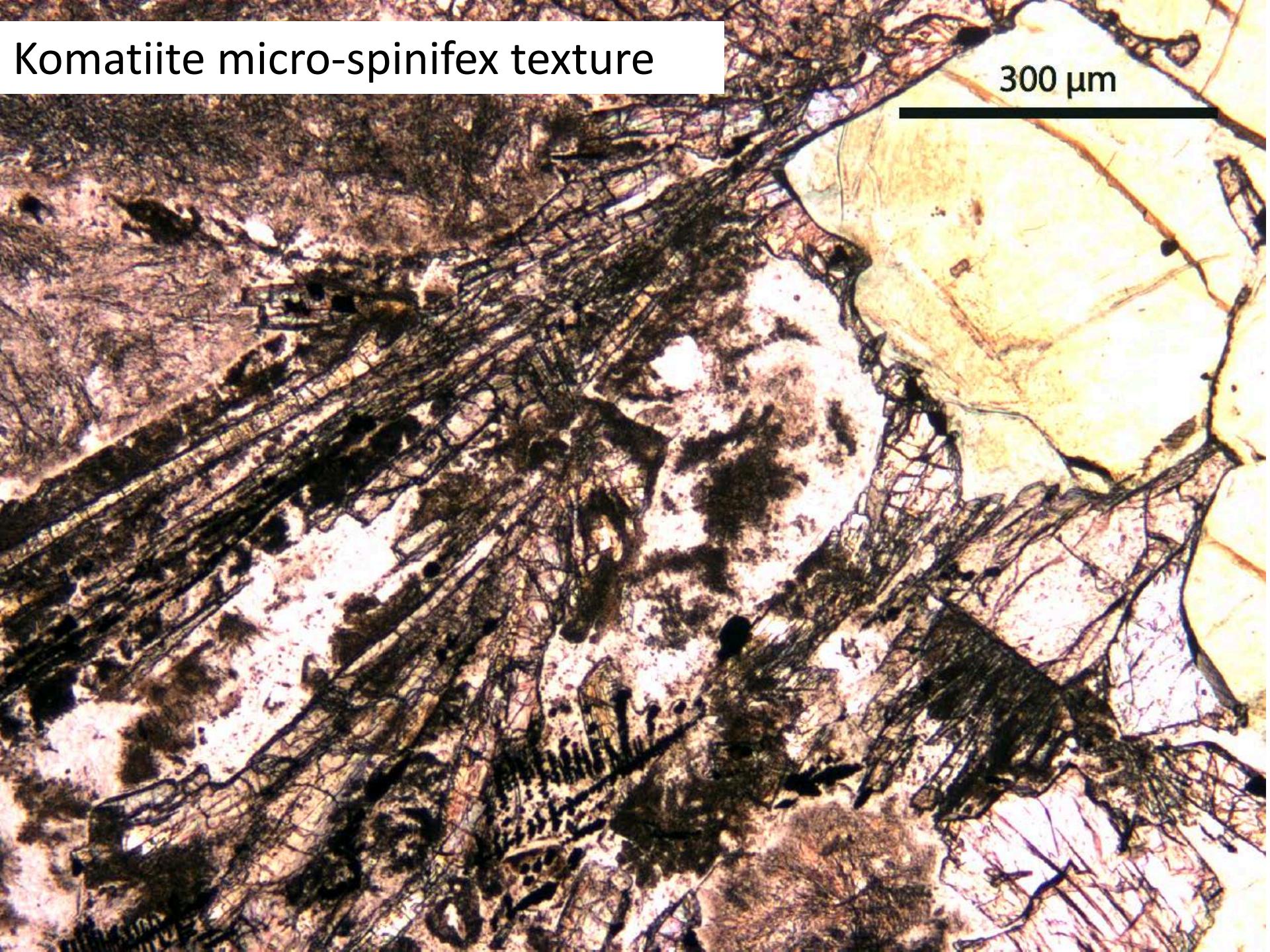
Komatiite micro-spinifex texture

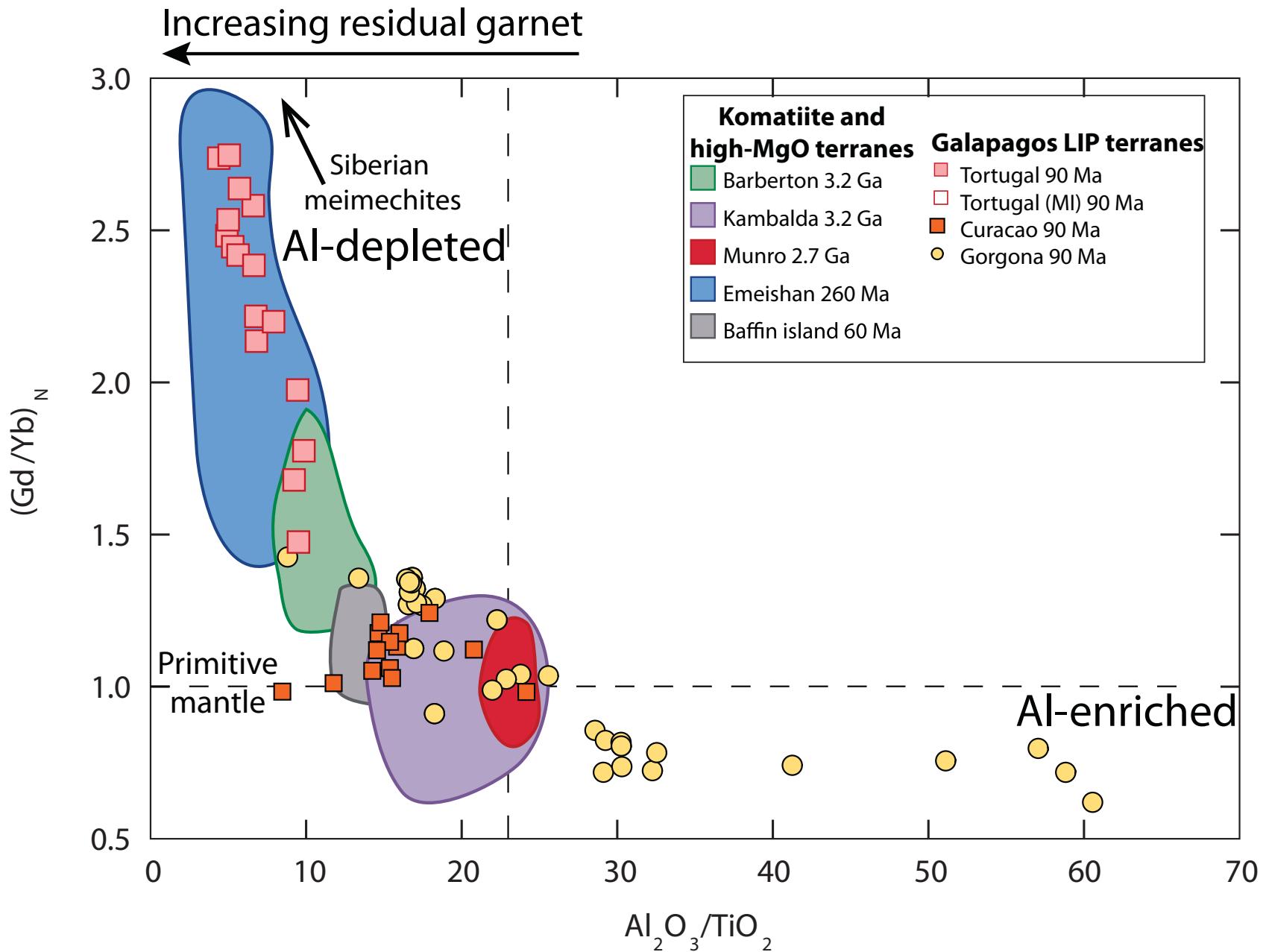
300 μm



Komatiite micro-spinifex texture

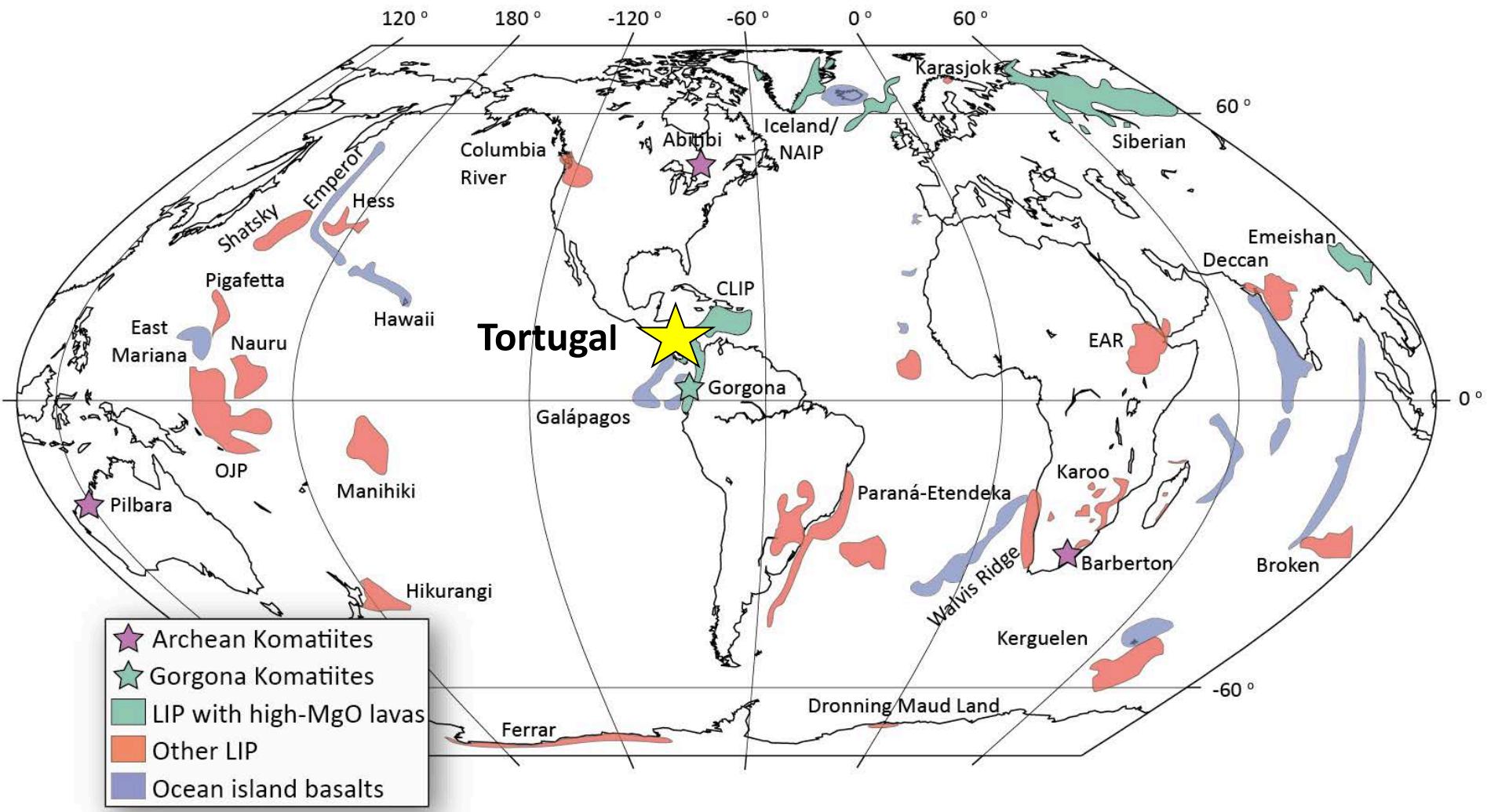
300 μm



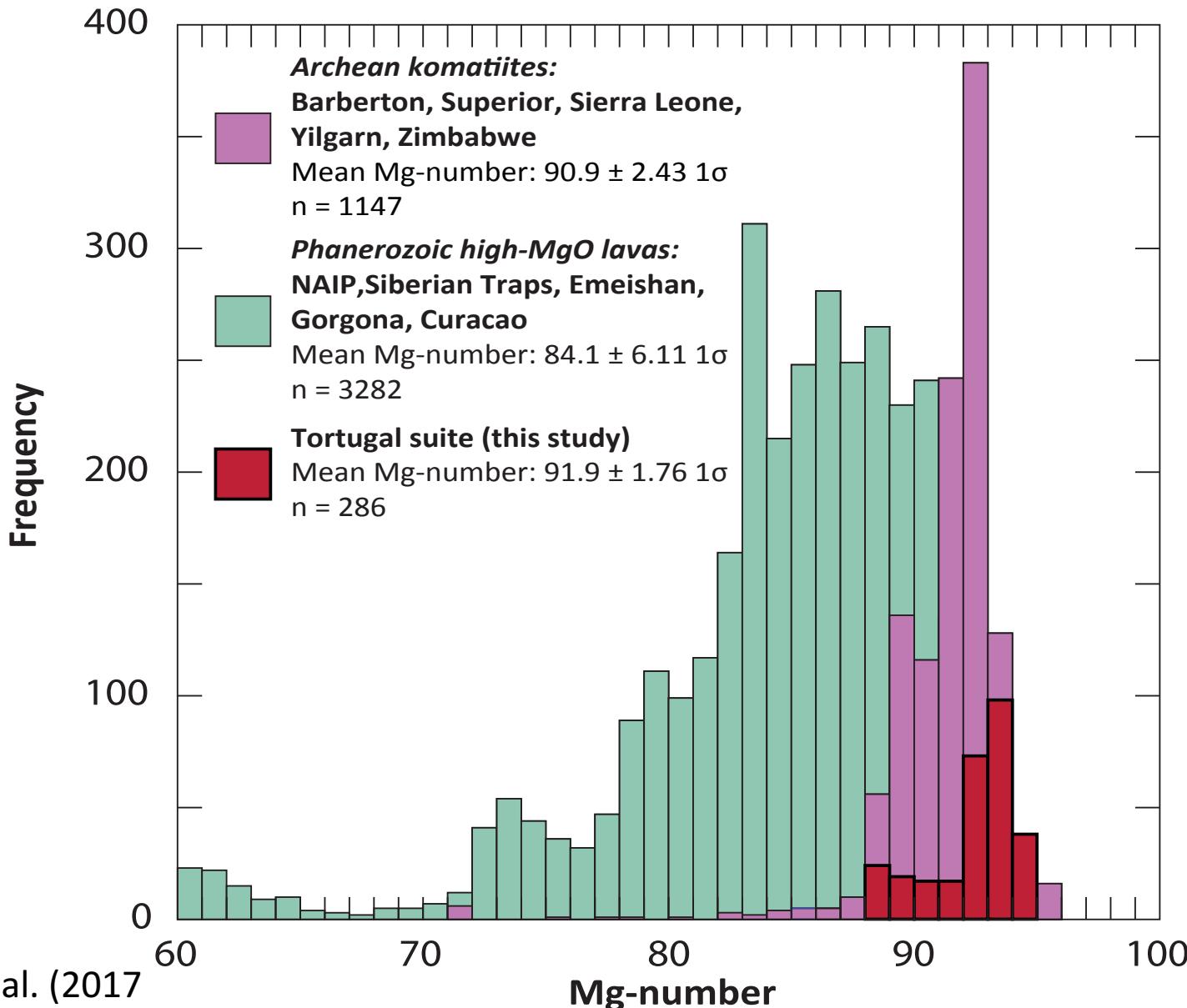


Hanski et al. (2001), Trela et al. (2017)

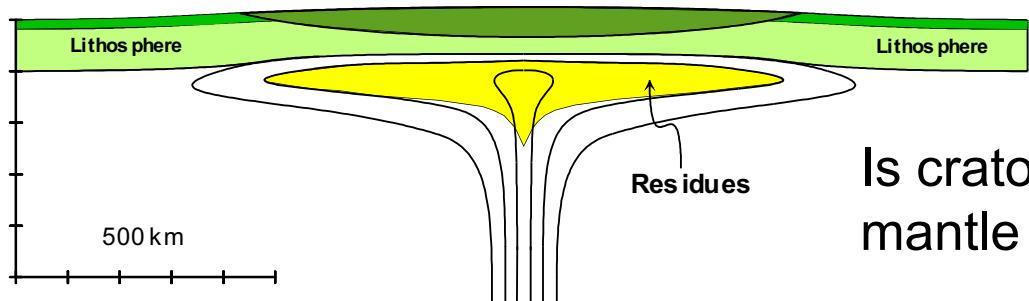
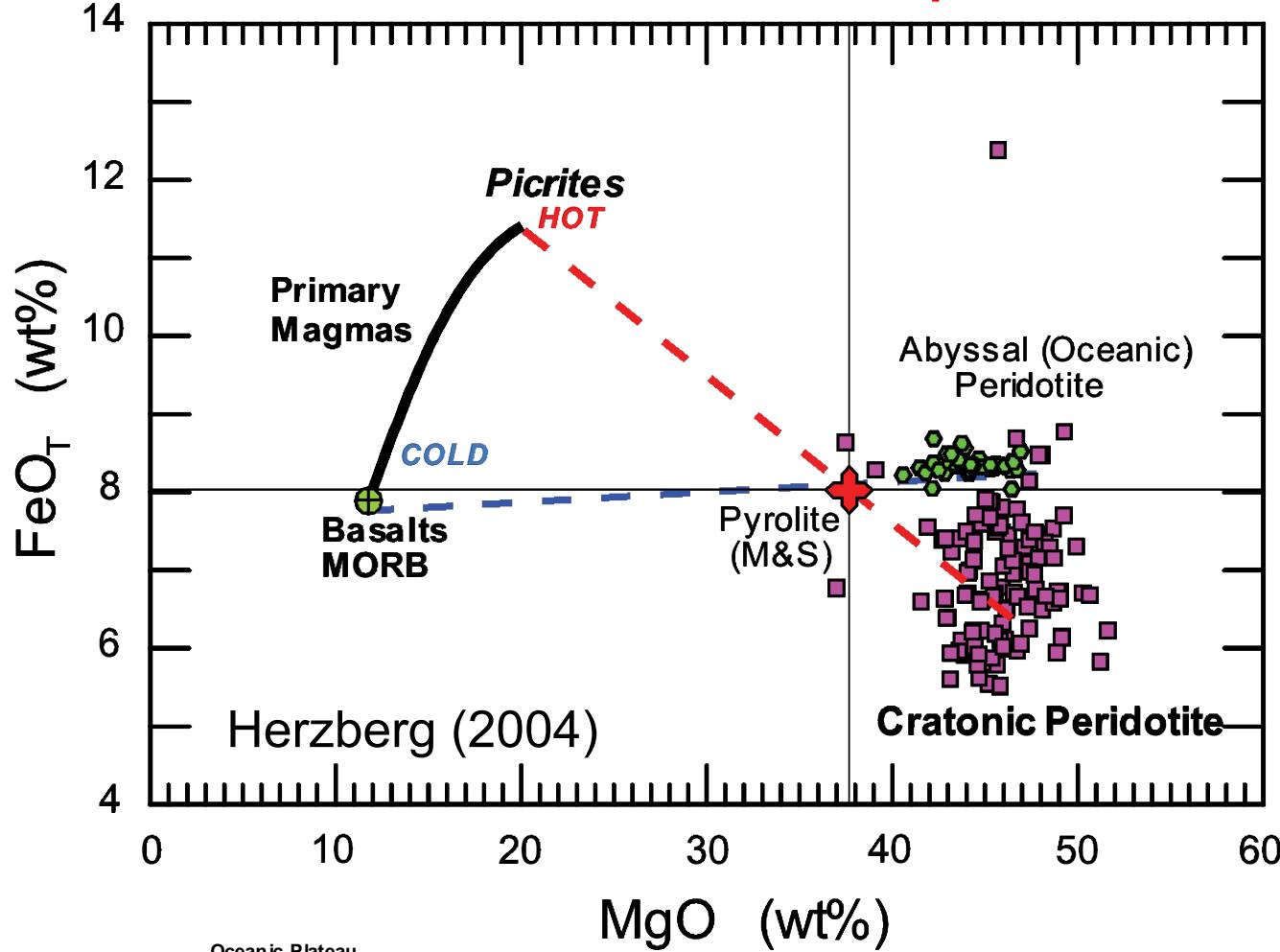
How does this terrane (Tortugal Suite) compares with Archean Komatiites and other high-MgO Phanerozoic locations?



Tortugal olivine Mg#s high and consistent with Archean komatiites with max values of 94.3%

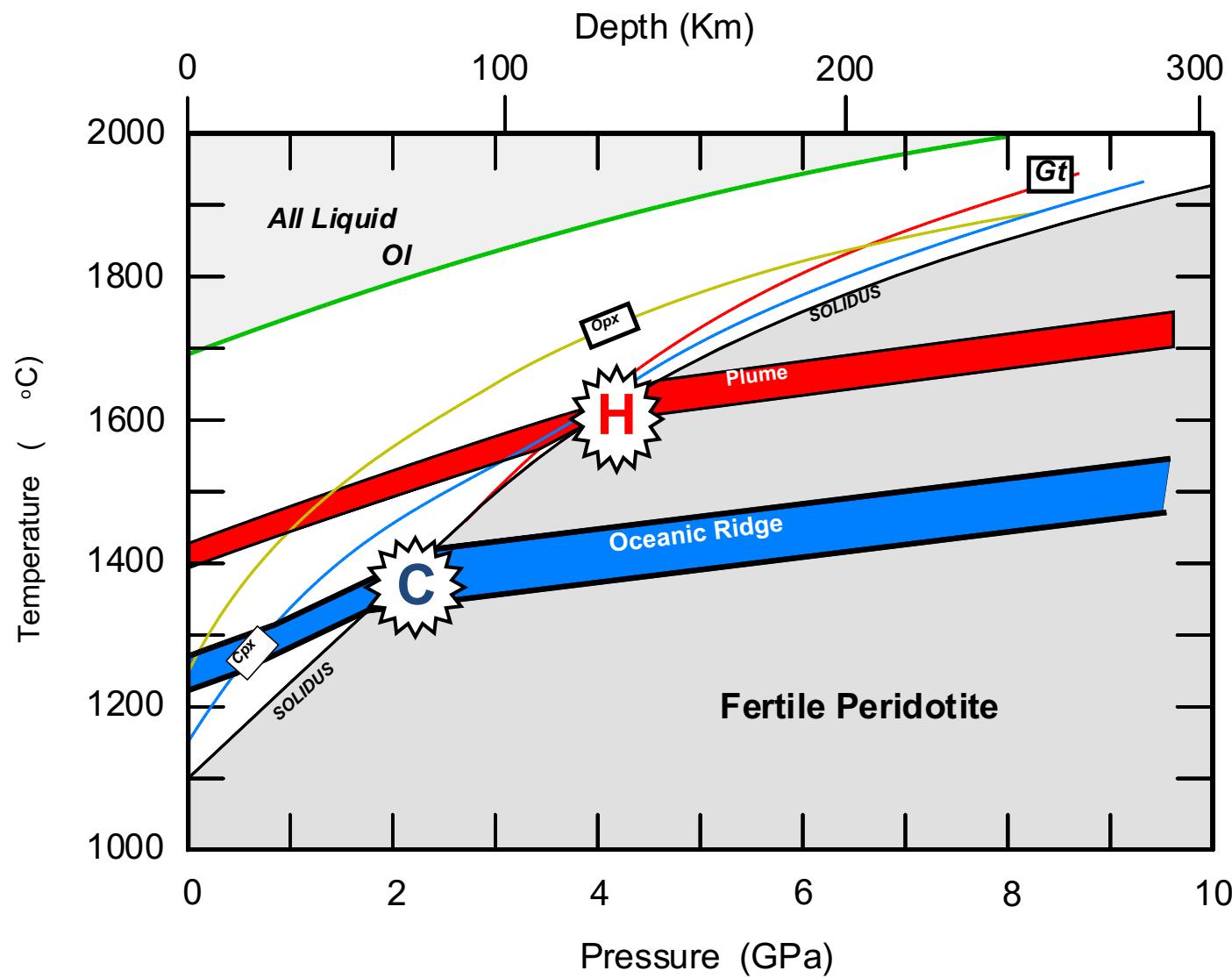


Mantle Plumes: Cratonic Lithospheric Mantle



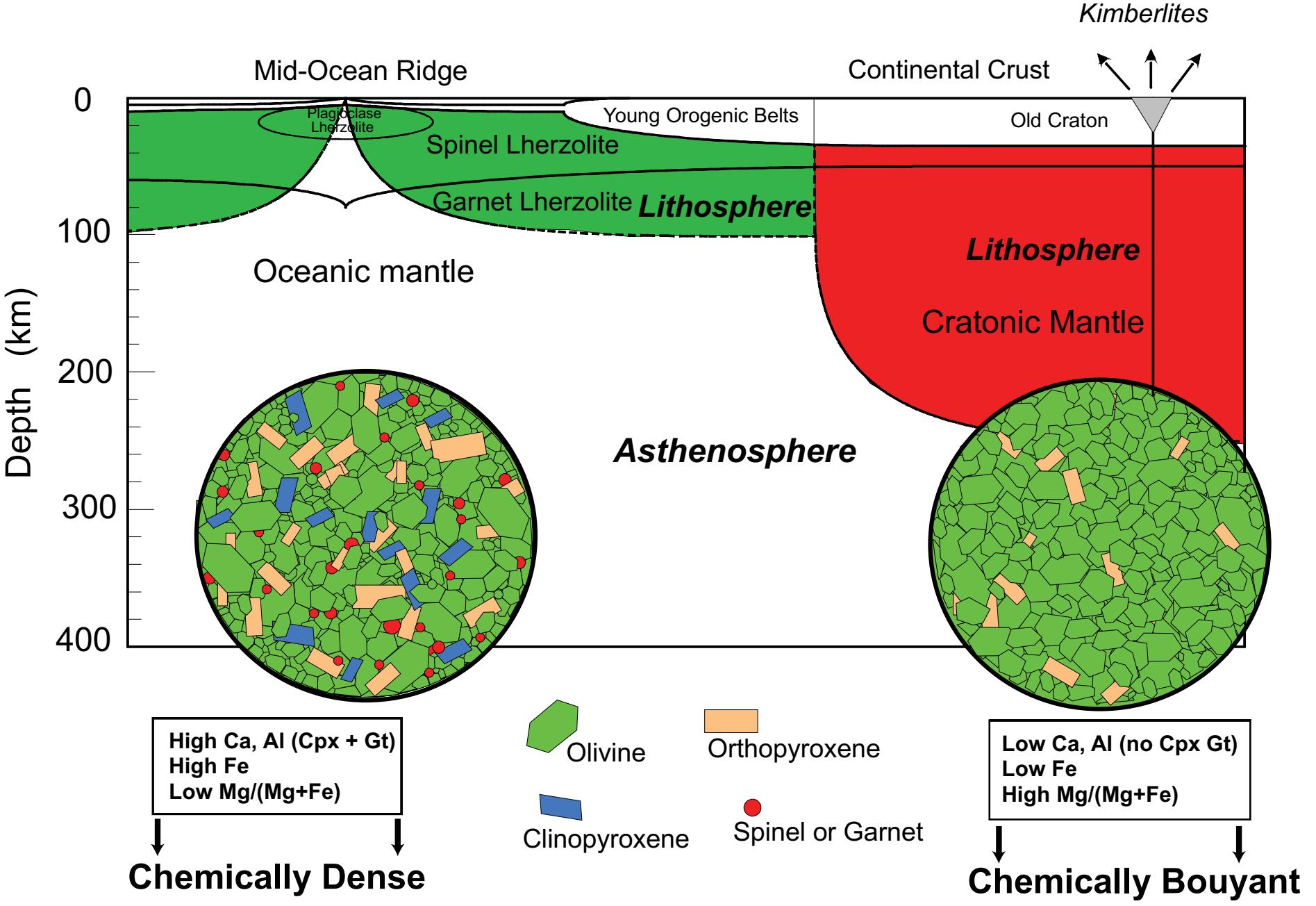
Herzberg (2004)

Is cratonic lithosphere the residue of mantle plumes?

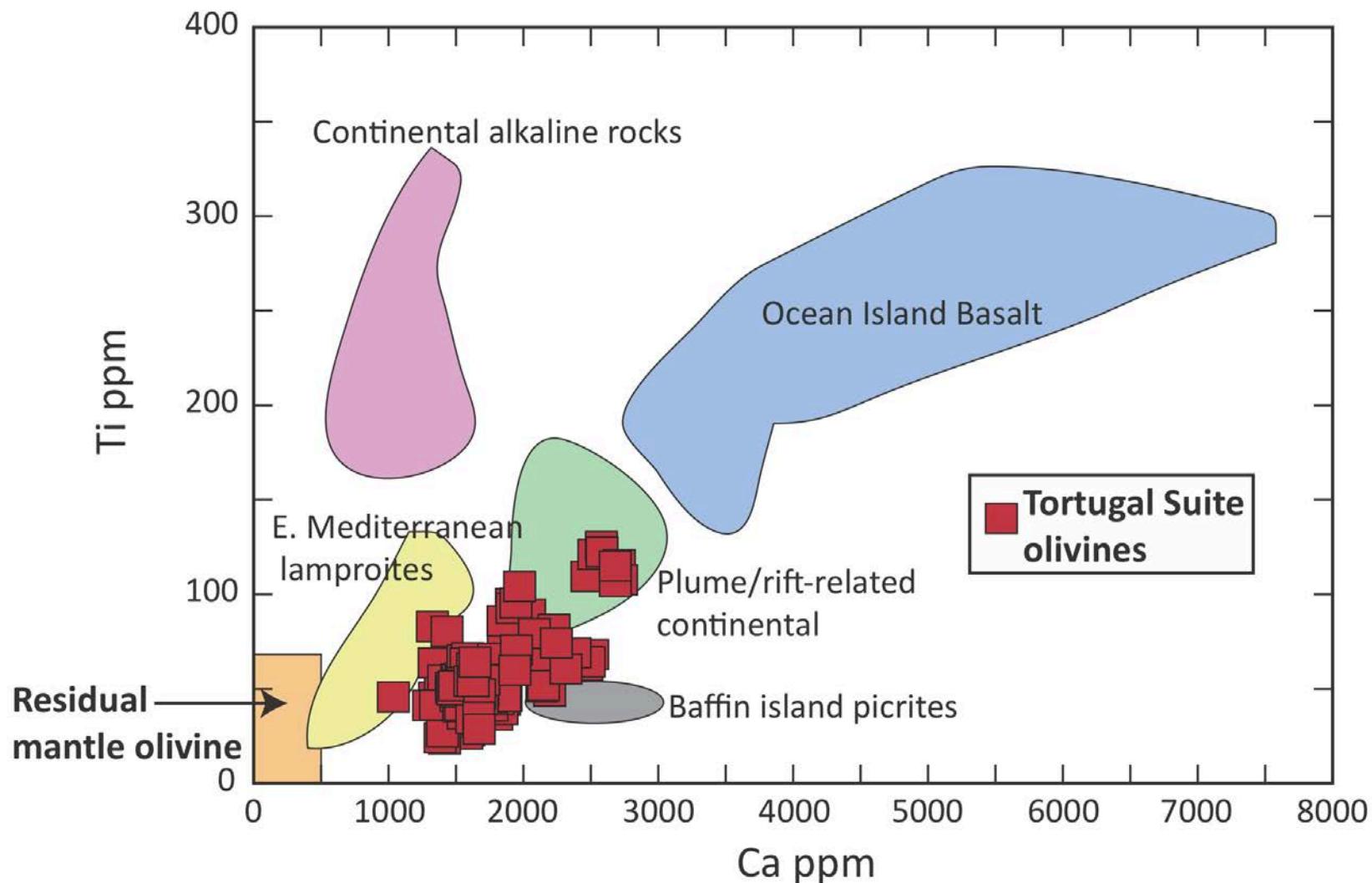


H = Hot residues (low Fe, Ca, Al , chemically buoyant)

C = Cold residues (chemically dense)

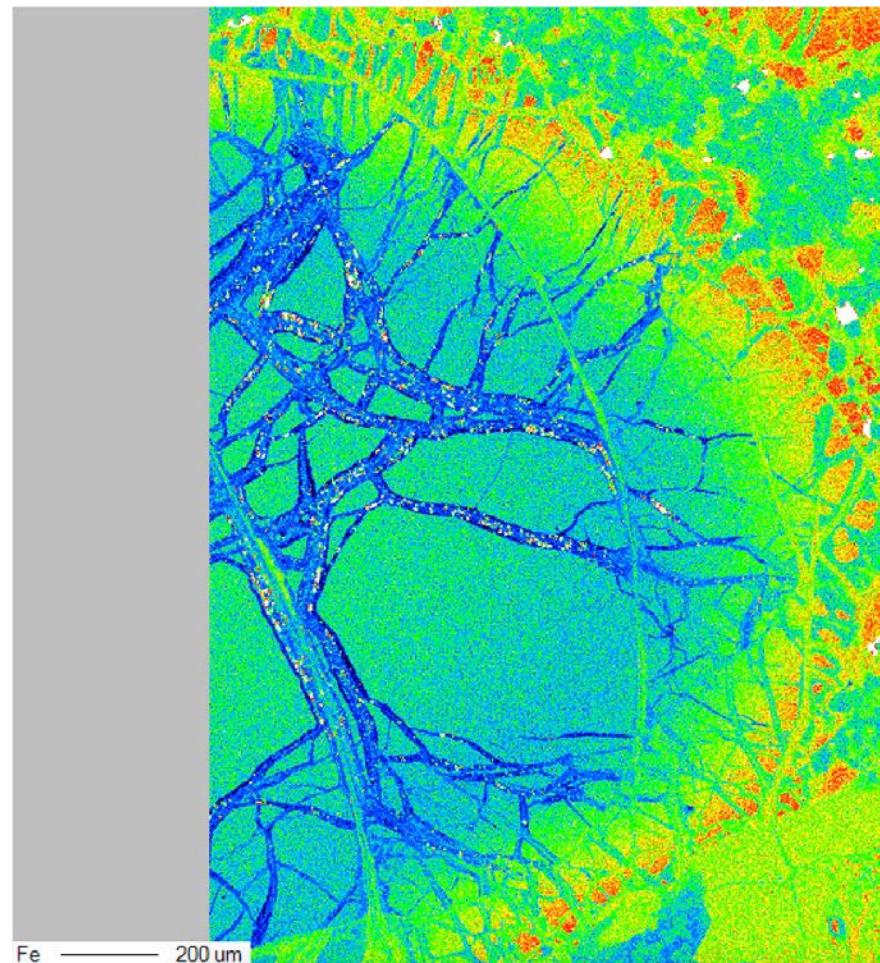
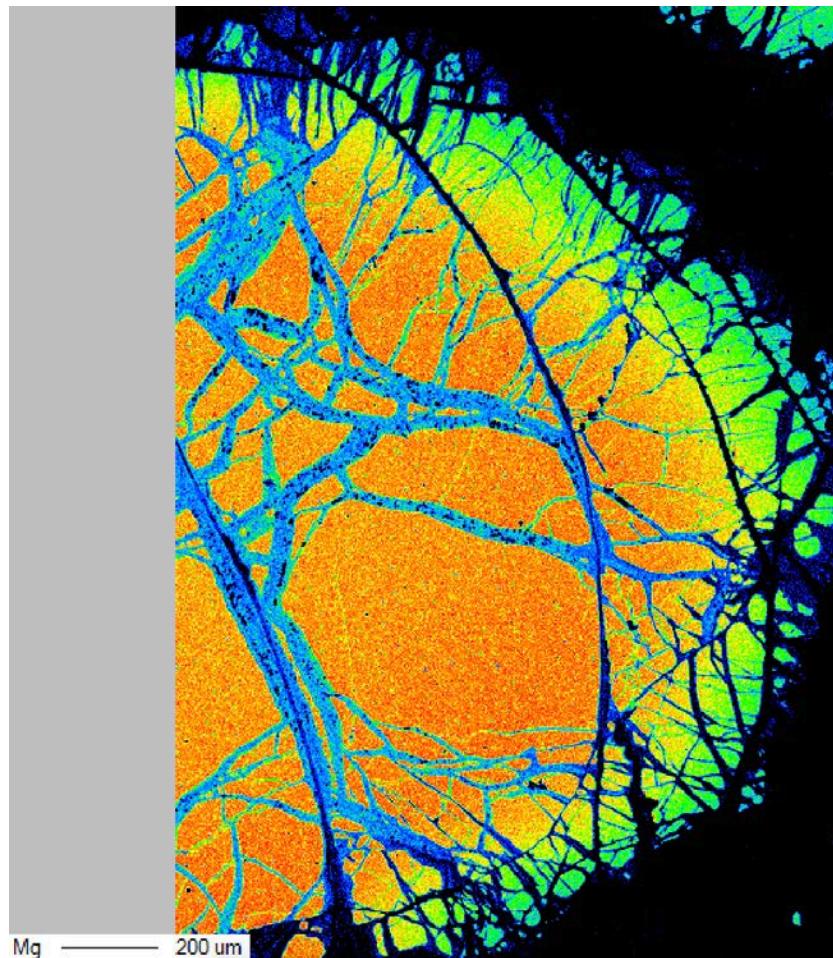


Tortugal olivines are higher in Ti and Ca than residual mantle olivine confirming that they crystallized from a melt

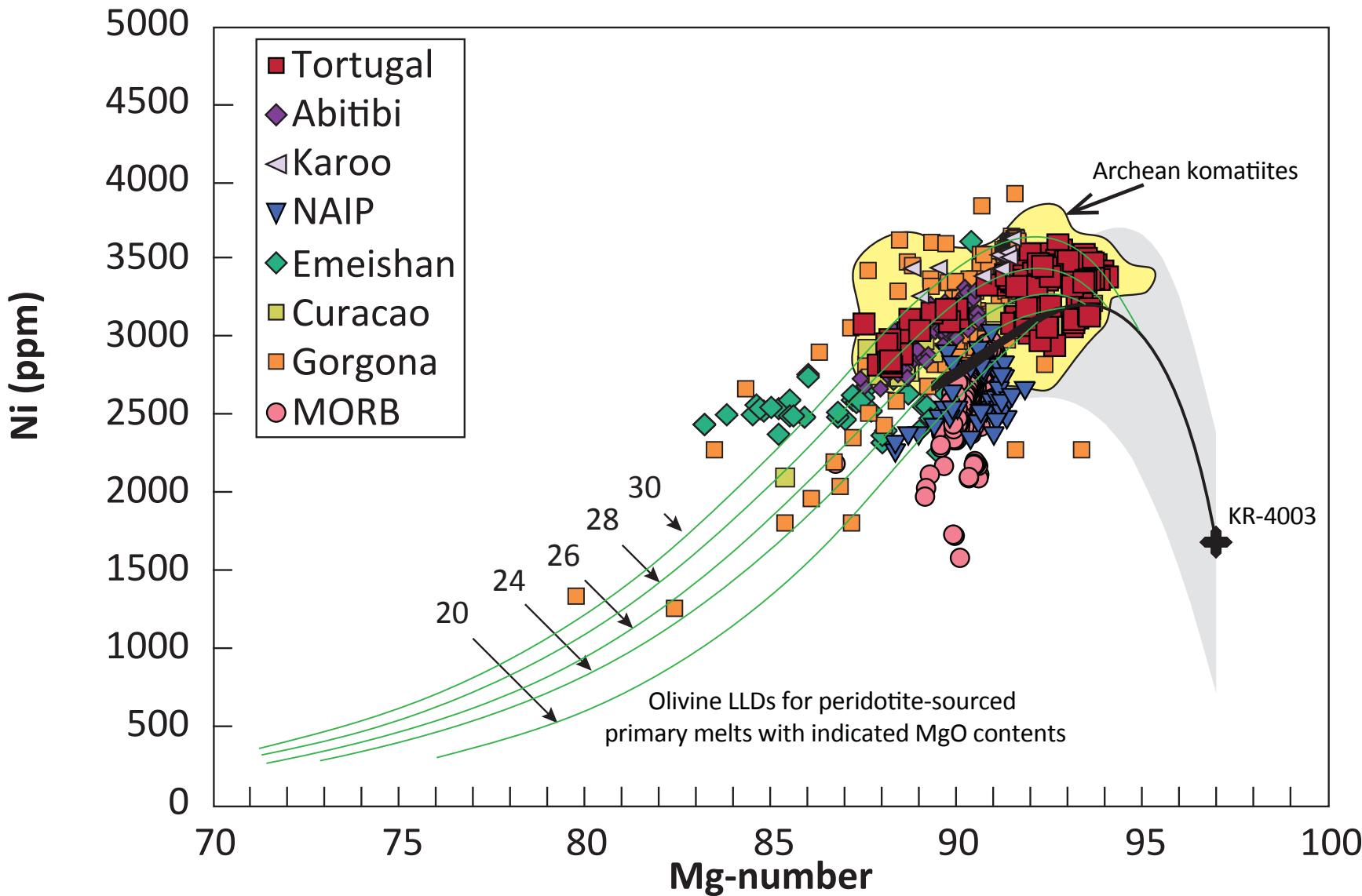


Modified from Foley et al., (2013).

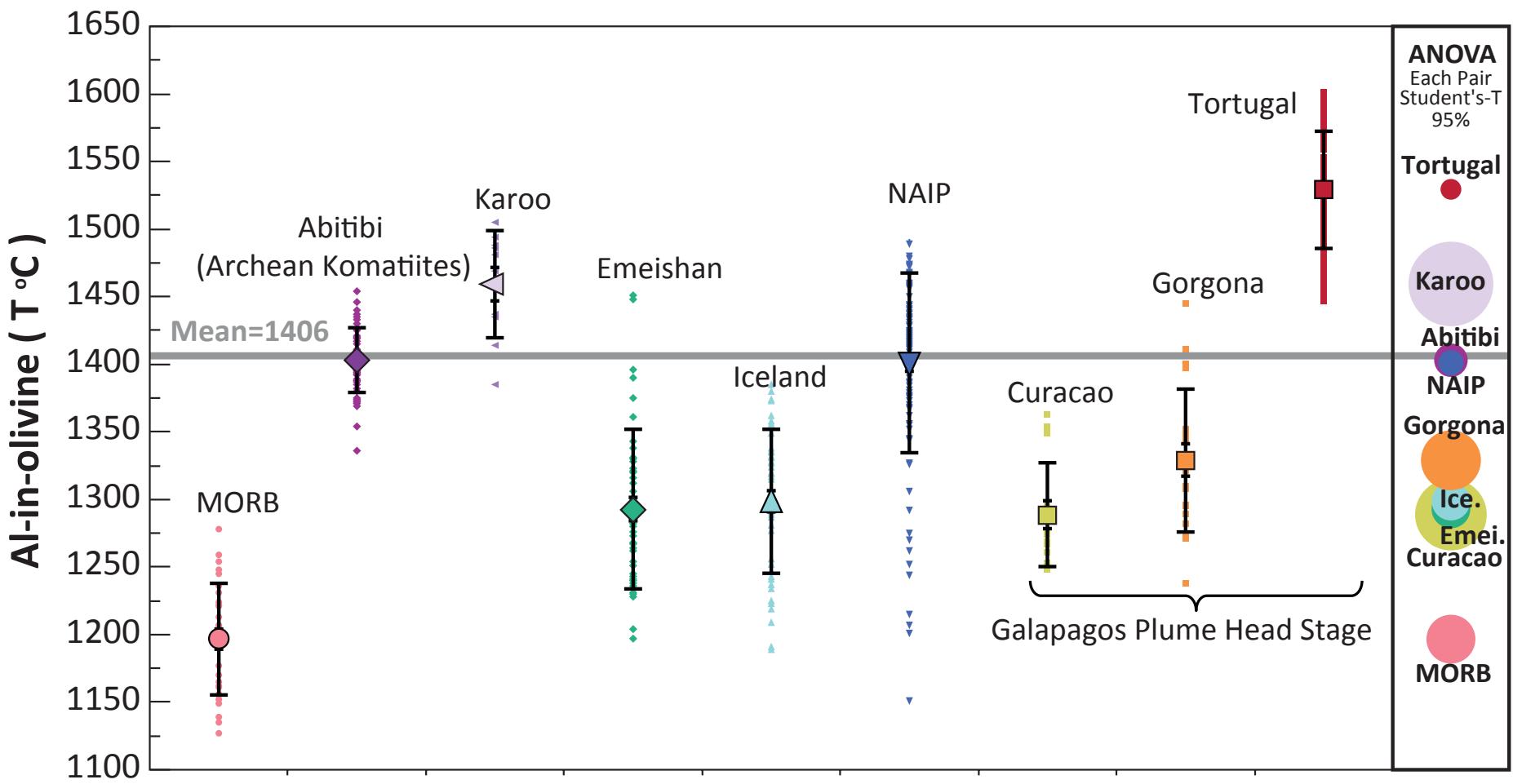
X-ray map of the concentration and distribution of MgO in an olivine phenocryst from the Tortugal Suite showing a range of forsterite content of 93.3 % in the core to 86% to the rim due to normal magmatic zonation.



Tortugal olivine plot within the Barberton komatiite olivine field and are consistent with olivine that crystallized from a peridotite-derived primary liquid with 26-30 wt% MgO.



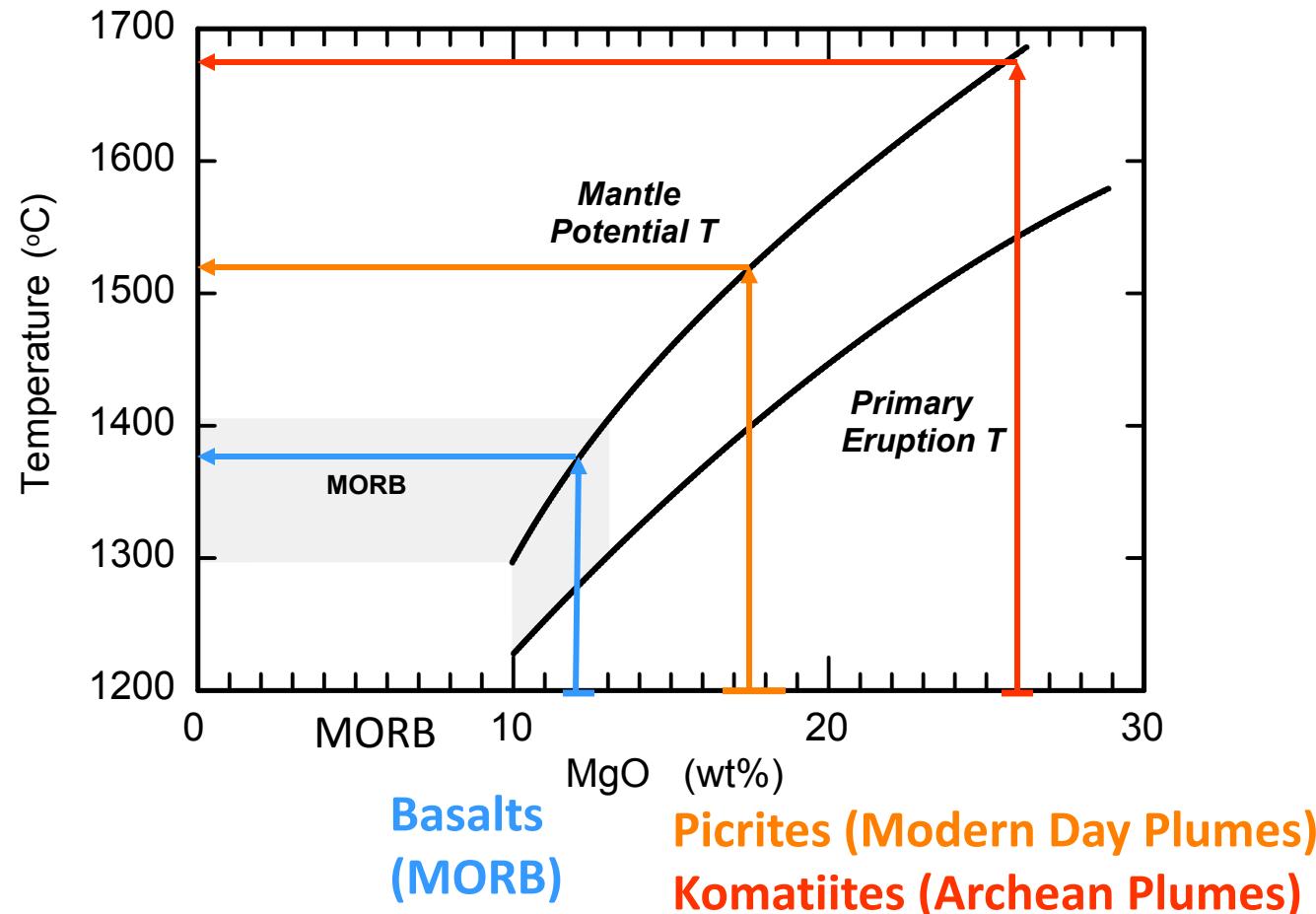
Tortugal olivines crystallized at higher temperatures than any previously studied location. Other Phanerozoic plumes probably experienced ambient mantle entrainment. That decreased the overall temperature of the plume recorded by Al-in-olivine thermometry but still much higher T than ambient MORB mantle



Additional data from Coogan et al. (2014) and Sobolev et al (2016)

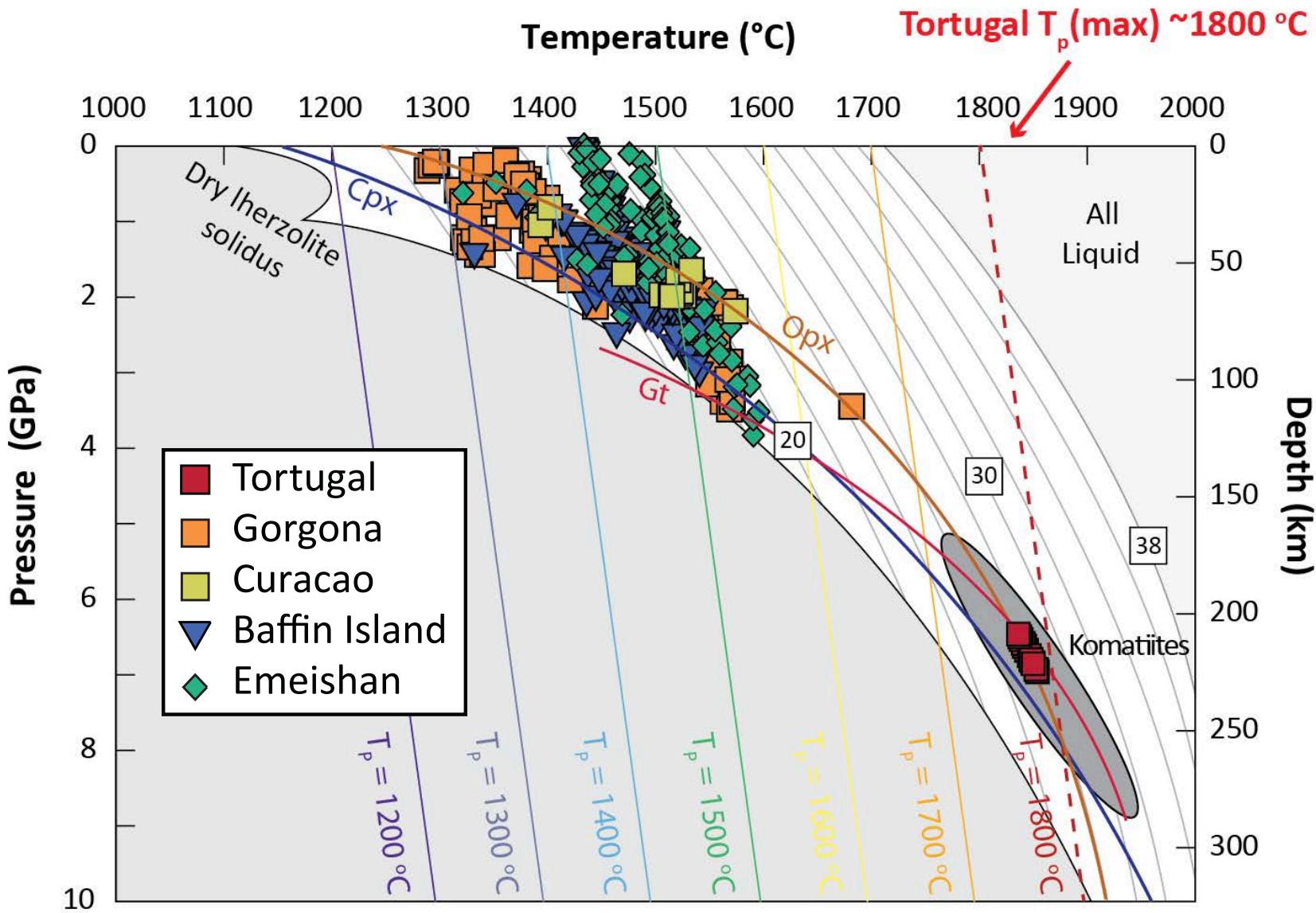
How we calculate Mantle Potential Temperature T_p ?

MgO contents of primary magmas = Thermometer

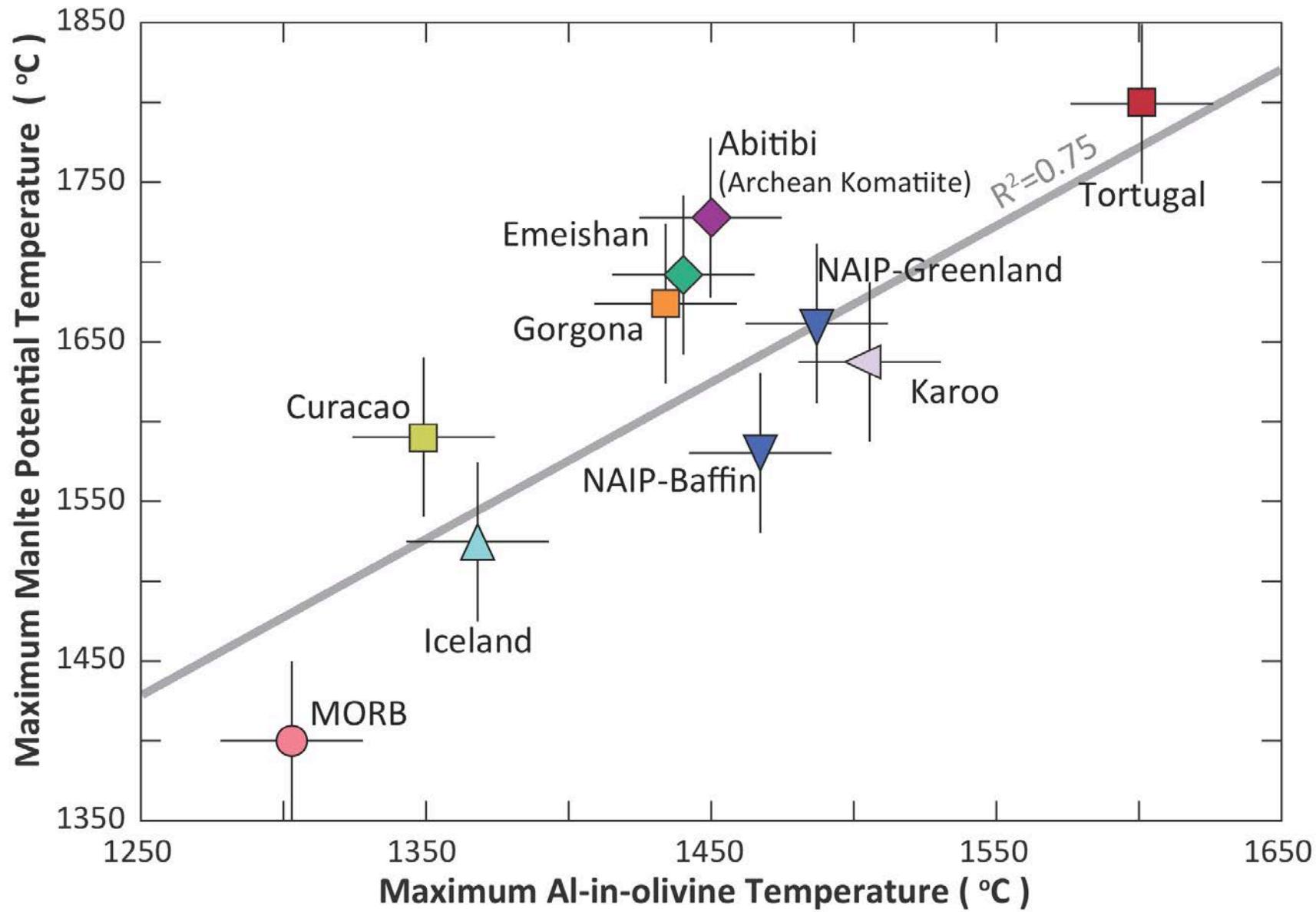


$$T_p = 1025 + 28.6\text{MgO} - 0.084(\text{MgO})^2 \quad (\text{Based on experimental calibrations, Herzberg and Asimov, 2015})$$

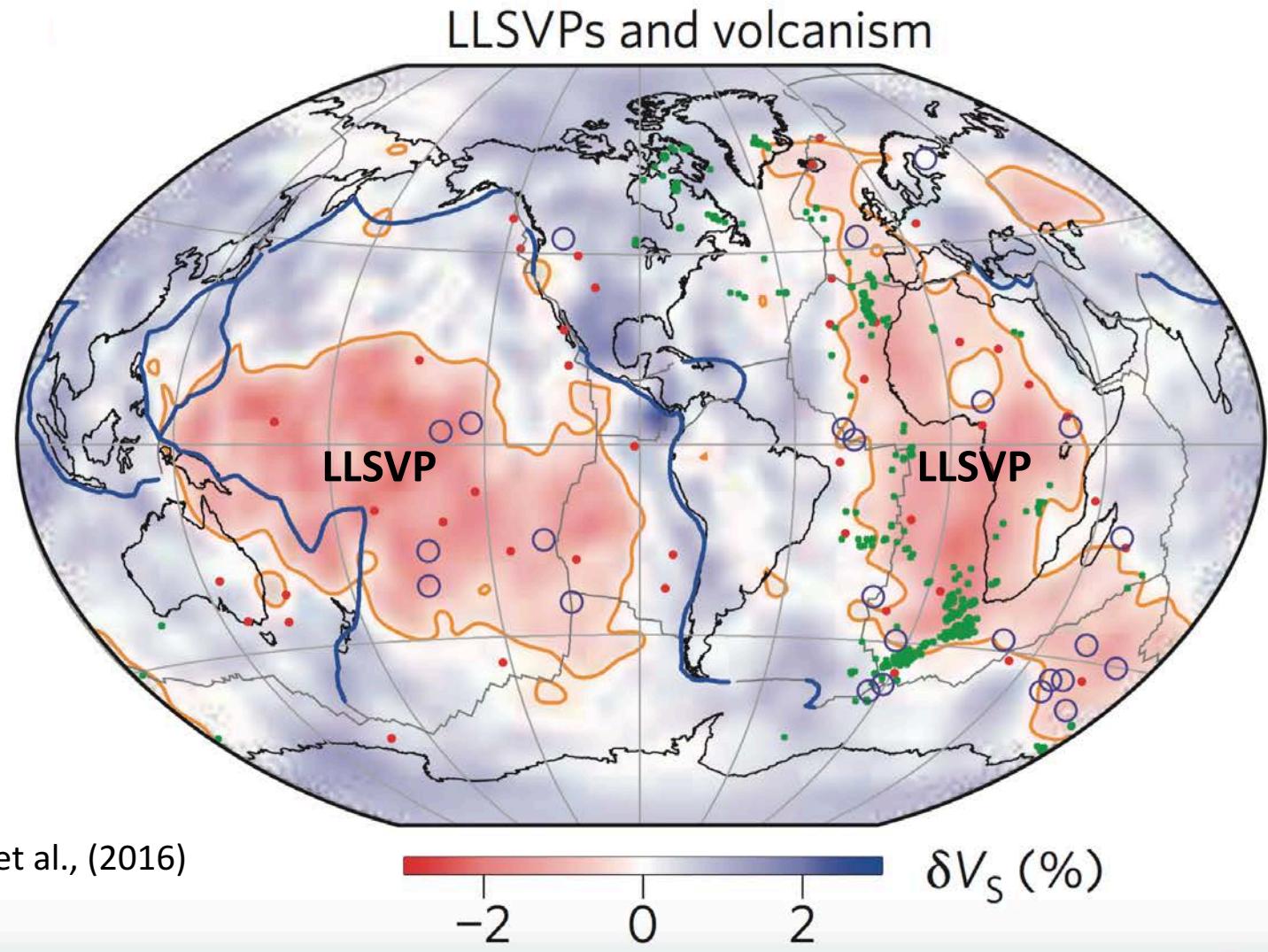
Tortugal petrologically-derived mantle potential temperature is also consistent with Archean komatiites



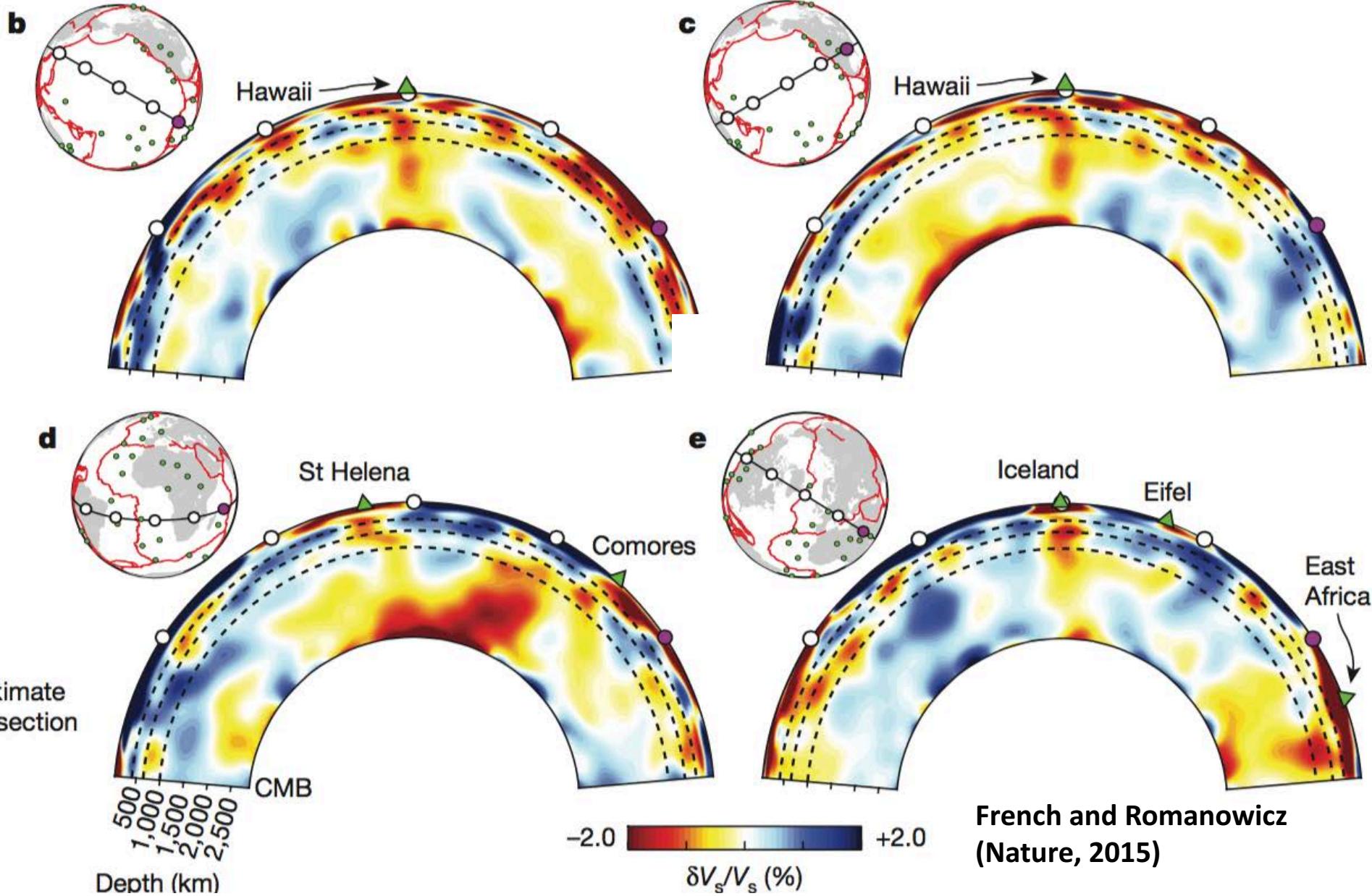
When compared globally, we found strong correlation between Al-in-olivine crystallization temperatures and petrologically-derived mantle potential temperatures

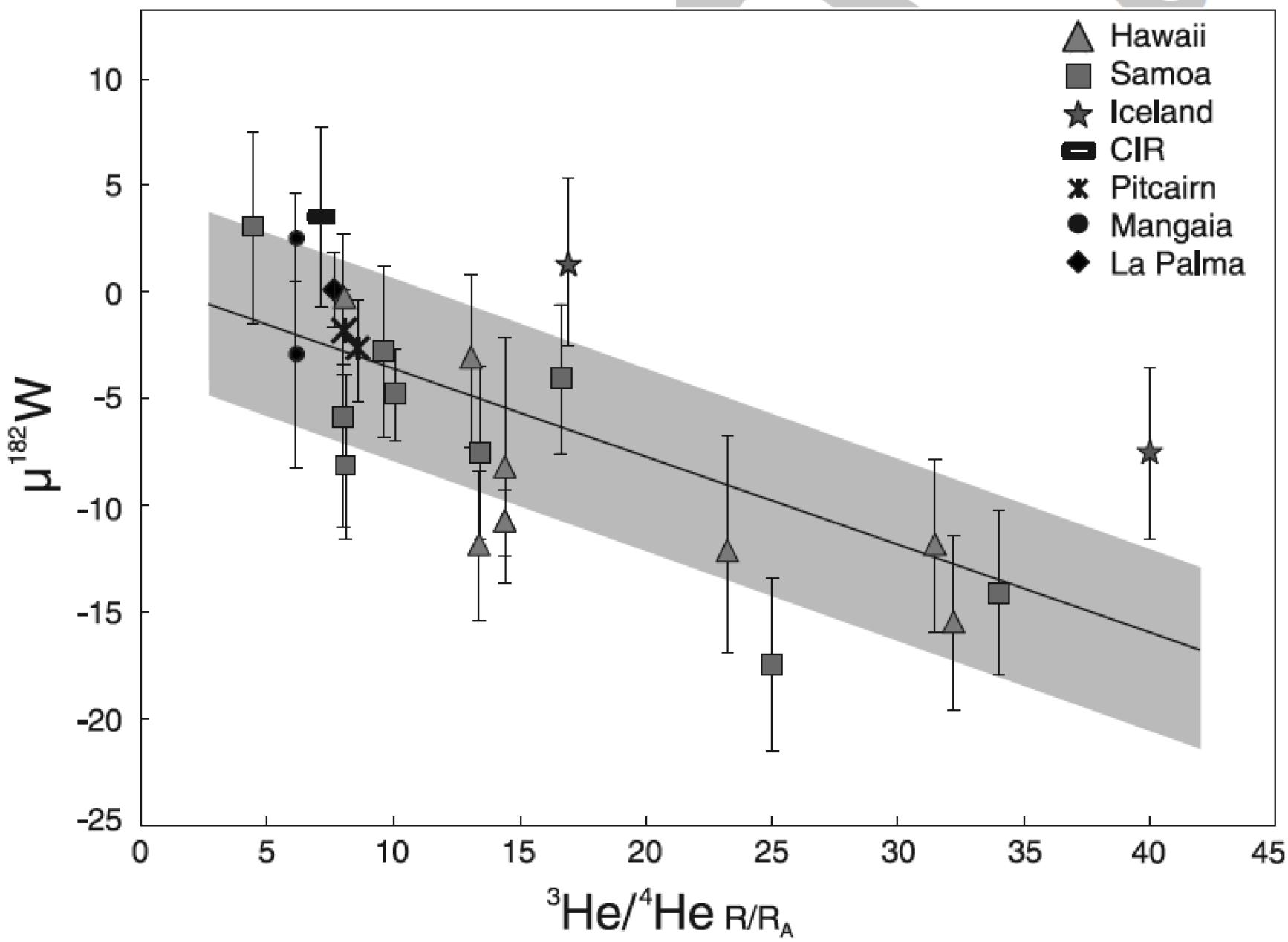


Plume-related hotspots are spatially associated with slow seismic anomalies called **Large Low-Shear Velocity Provinces** located at the core-mantle boundary



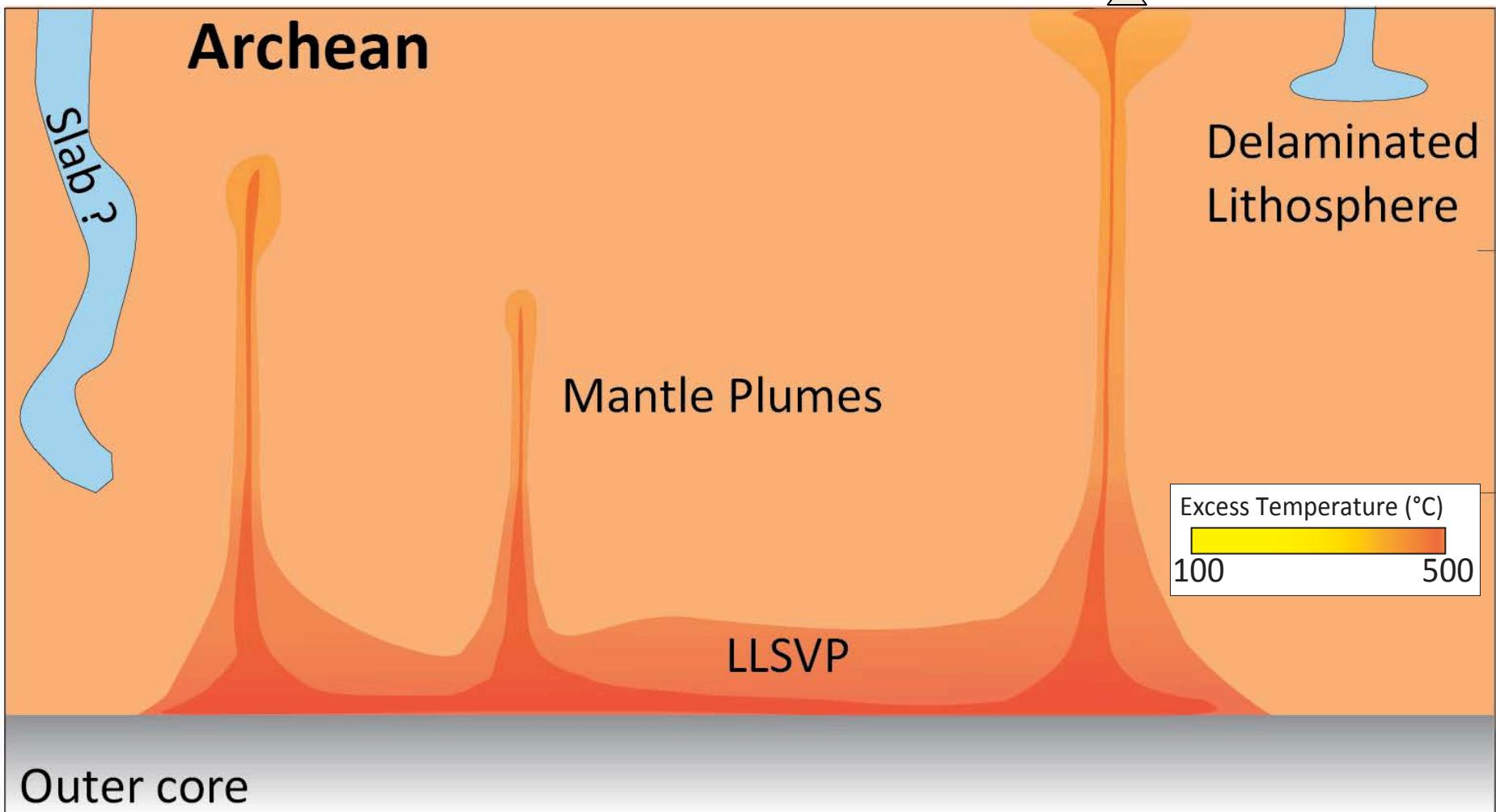
SEMUCB-WM1 broad plumes with a 1.5%–2% reduction of shear-wave velocity in the lower mantle beneath hotspots connected to the LLSVPS.





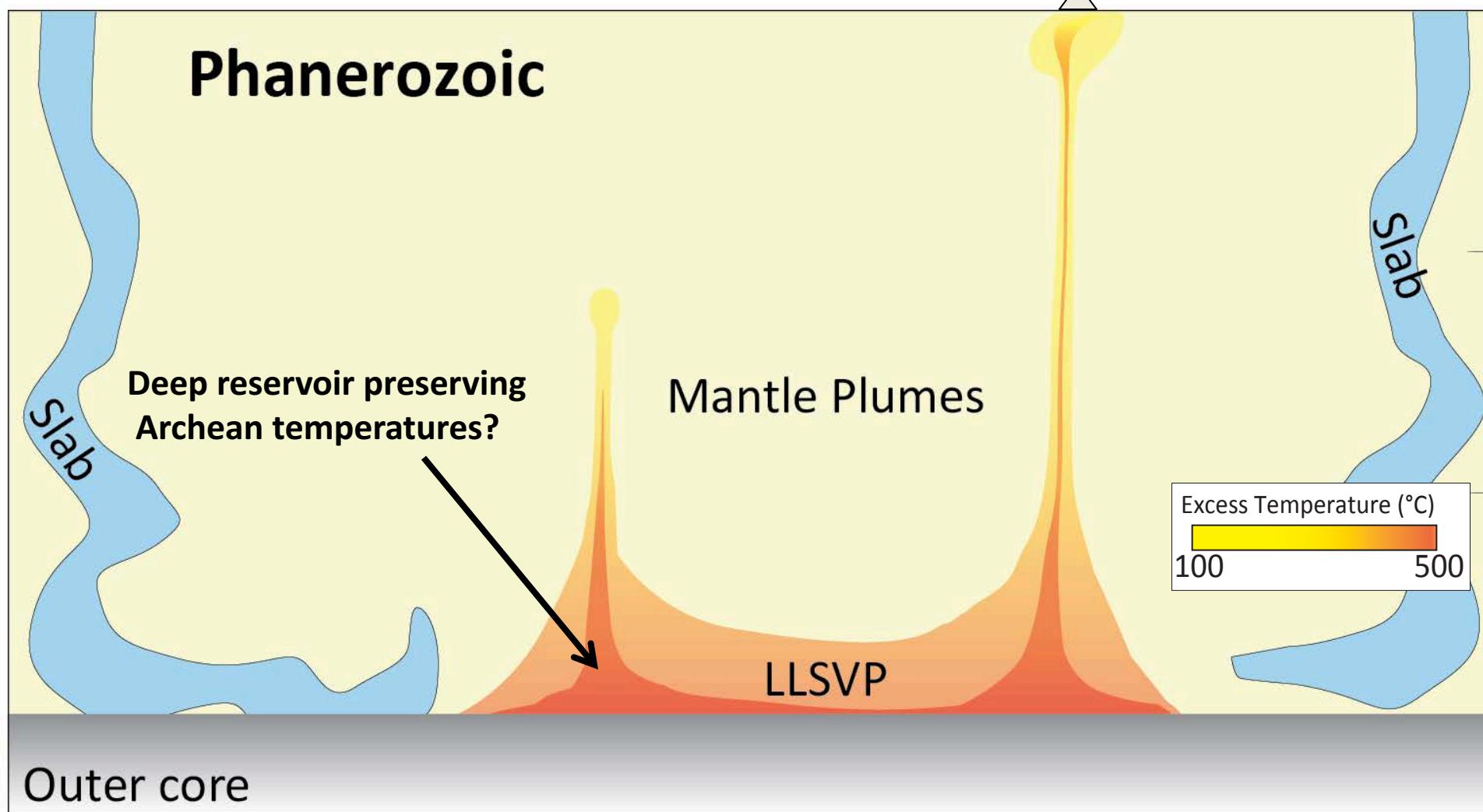
Archean komatiites are the record of a hotter Earth

Komatiites ($T_x > 1450 \text{ }^{\circ}\text{C} / T_p > 1600 \text{ }^{\circ}\text{C}$)

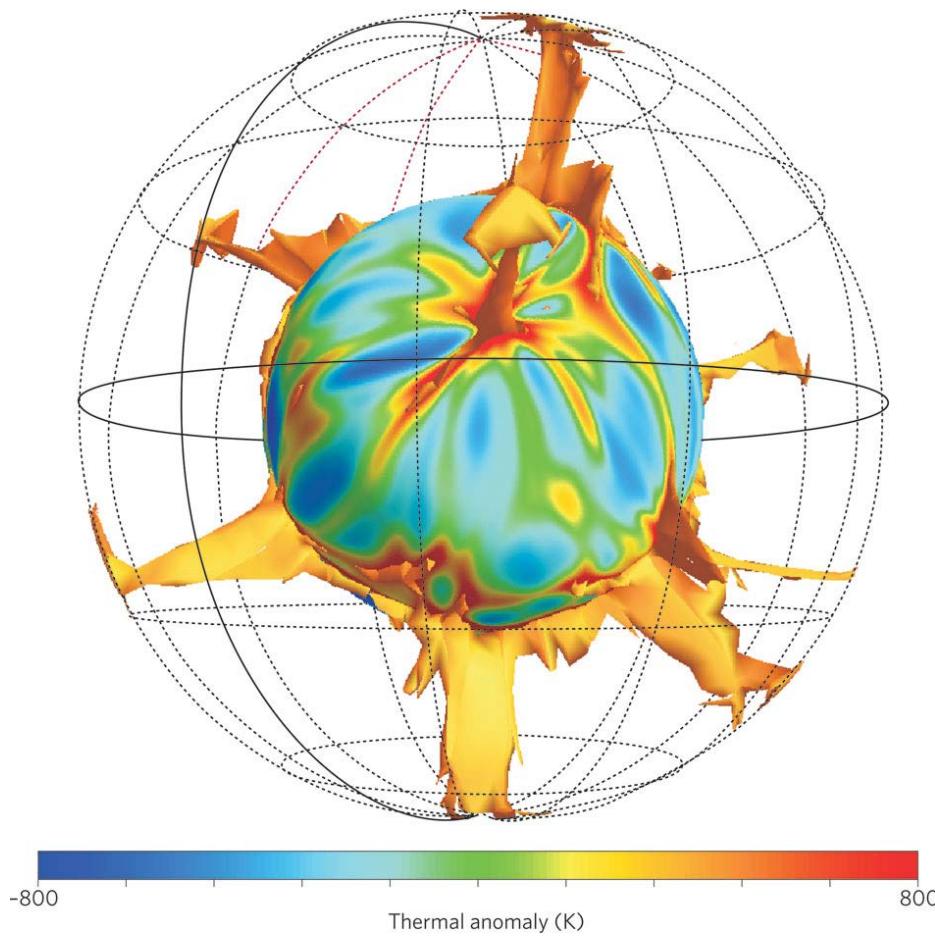


Tortugal originated from melting of a reservoir that preserves Archean temperatures (crystallization $T_x = 1600 \text{ }^{\circ}\text{C}$ and $T_p = 1800 \text{ }^{\circ}\text{C}$)

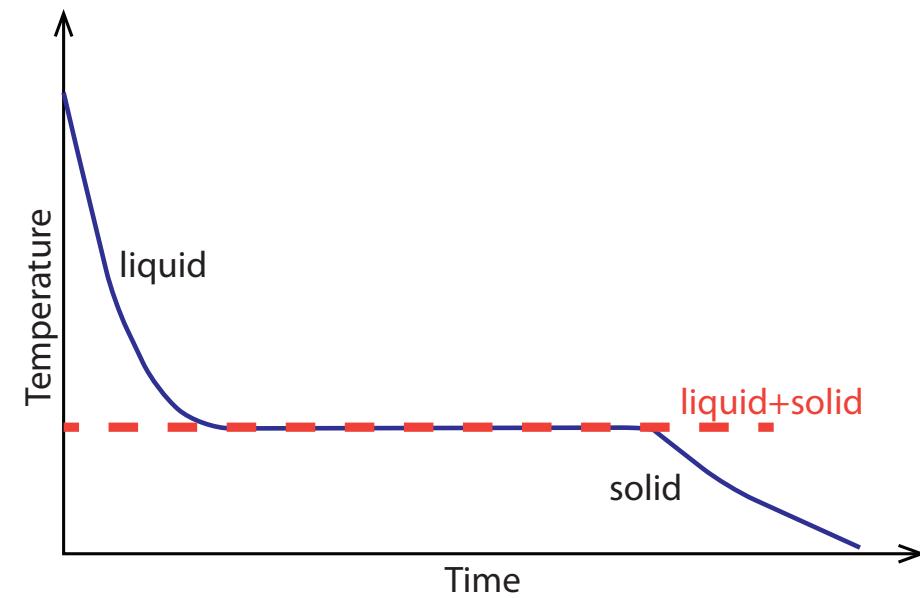
Tortugal ($T_x = 1600 \text{ }^{\circ}\text{C}/T_p = 1800 \text{ }^{\circ}\text{C}$)



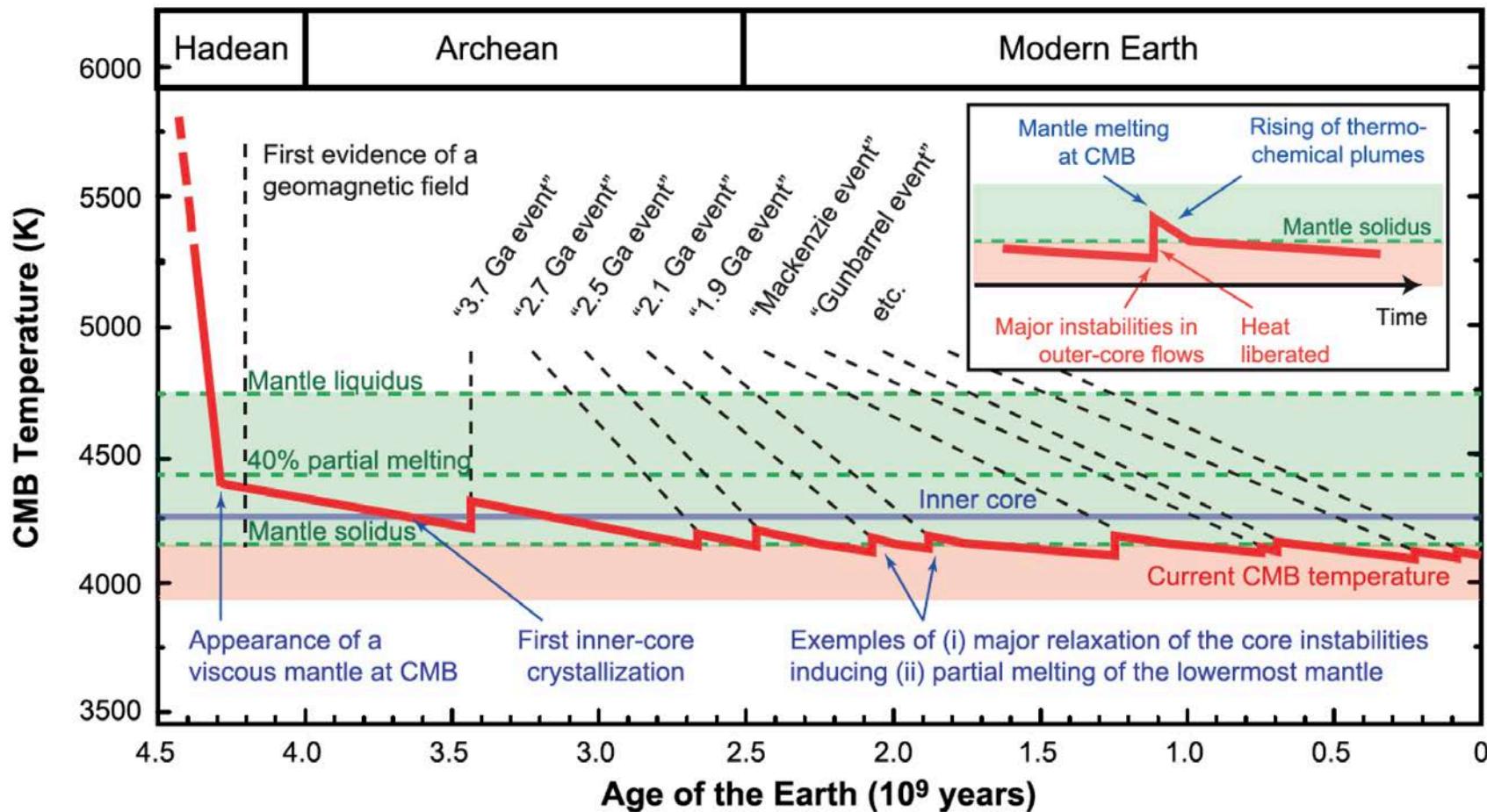
The core crystallization is a ~two-phase solid liquid system and thus temperature is ~isobaric constant to the extent that solidification fills the core from the bottom up



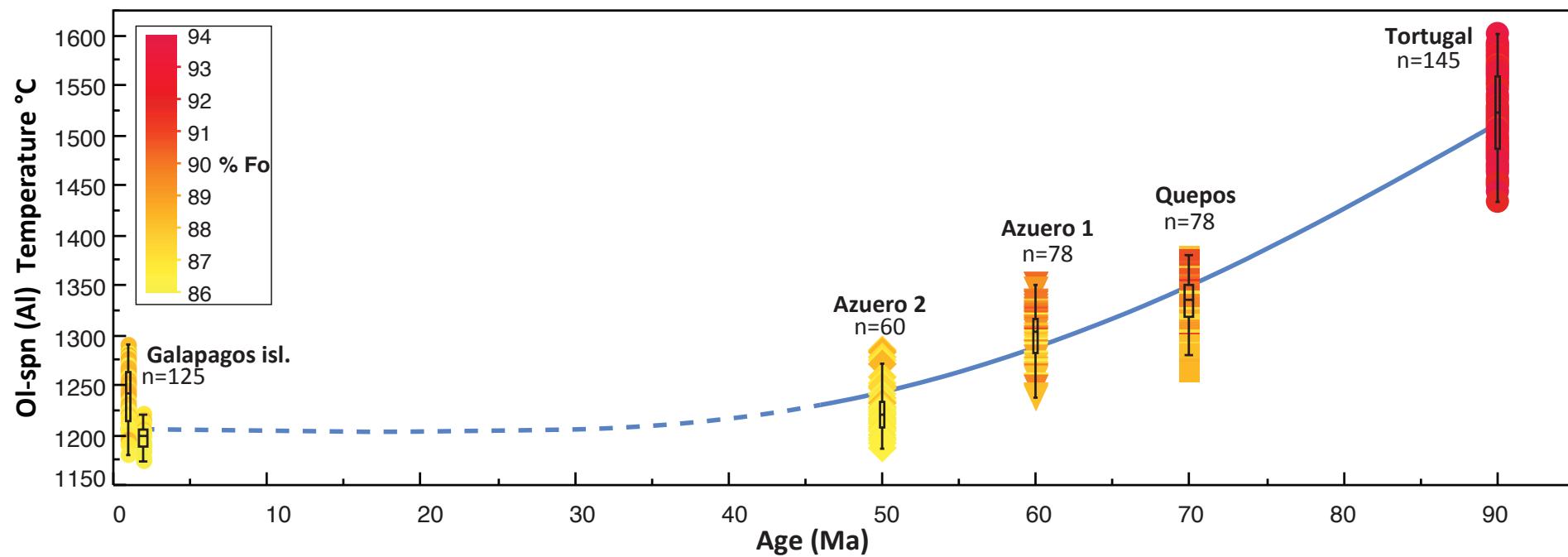
(Davies & Davies, EPSL 2009)



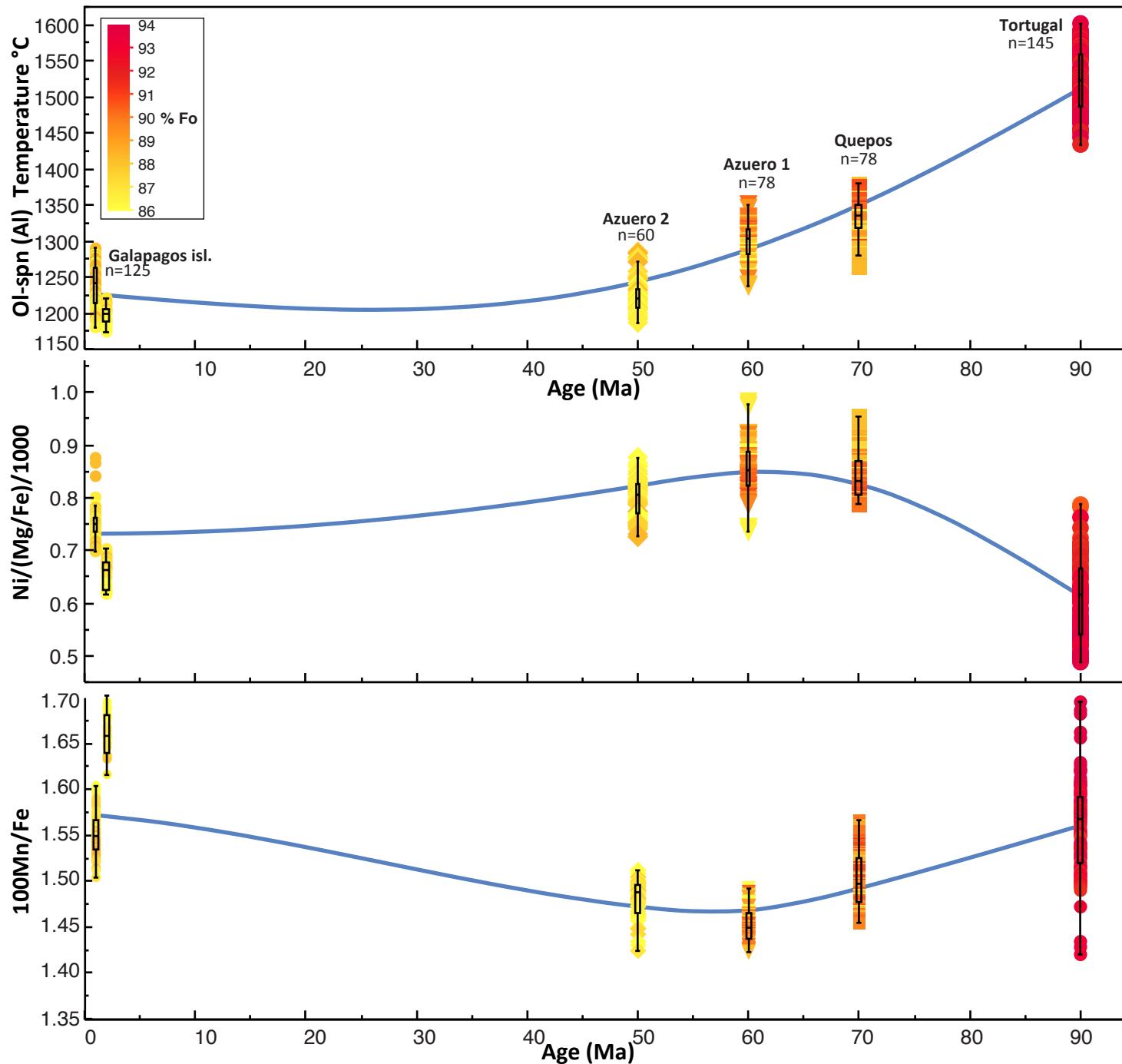
Alternatively the presence of magma ocean at the CMB can also explain long term buffering of T (Andraut et al., 2016)



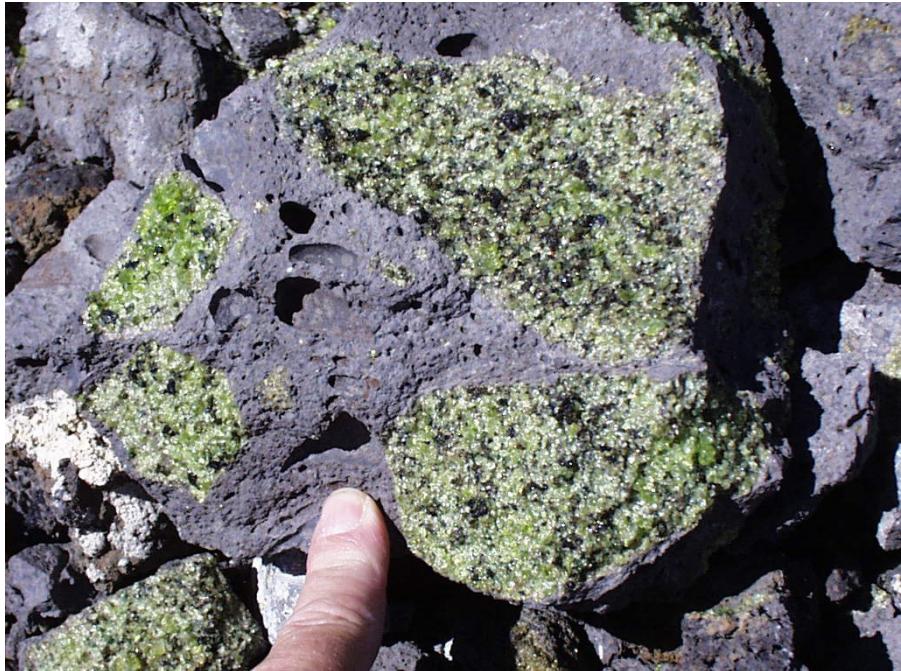
Secular cooling in the Galapagos Plume after the LIP event as recorded by Al-in-olivine temperatures



The extreme temperatures from Tortugal are not longer recorded after the LIP event, so plumes do cool down with time as they entrain ambient mantle



Mantle rocks



Peridotite: main component
 $\text{ol} + \text{cpx} + \text{opx} + \text{Al}$ phase (pl, spn, ga)



Pyroxenite:
 $\text{ga} + \text{cpx} + \pm \text{qtz} + \text{rut} \dots = \text{recycled oceanic crust}$
 $\text{ga} + \text{cpx} \pm \text{opx} \pm \text{ol} = \text{high-P crystallization}$

Phaseplot_Pyroxenite Demo

Open the Mac App Store to buy and download apps.



PhasePlot 4+

Mark Ghiorso CT Software

Free

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