Komatiites and the Continental Lithospheric Mantle

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Characteristics of Komatiites

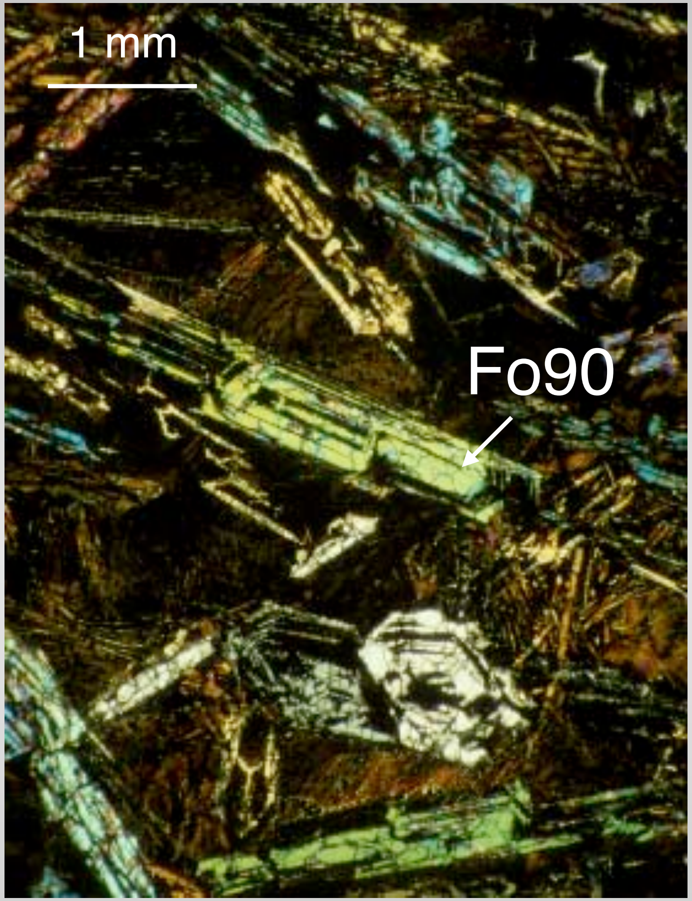
- Ultramafic volcanic rocks (lavas, high-level intrusions). Minor component (0-20%) of Archean greenstone belts; rare to absent in younger belts.
- Mineralogy: olivine (chromite) + late-crystallizing clinopyroxene (rare opx); olivine Fo_{95-80}
- Chemical composition: several types (1) Al-depleted komatiites have garnet subtraction signature; (2) Al-undepleted komatiites no garnet signature, depletion of incompatible elements
- Origin: high-degree melting deep in the mantle

Spinifex textured komatiite

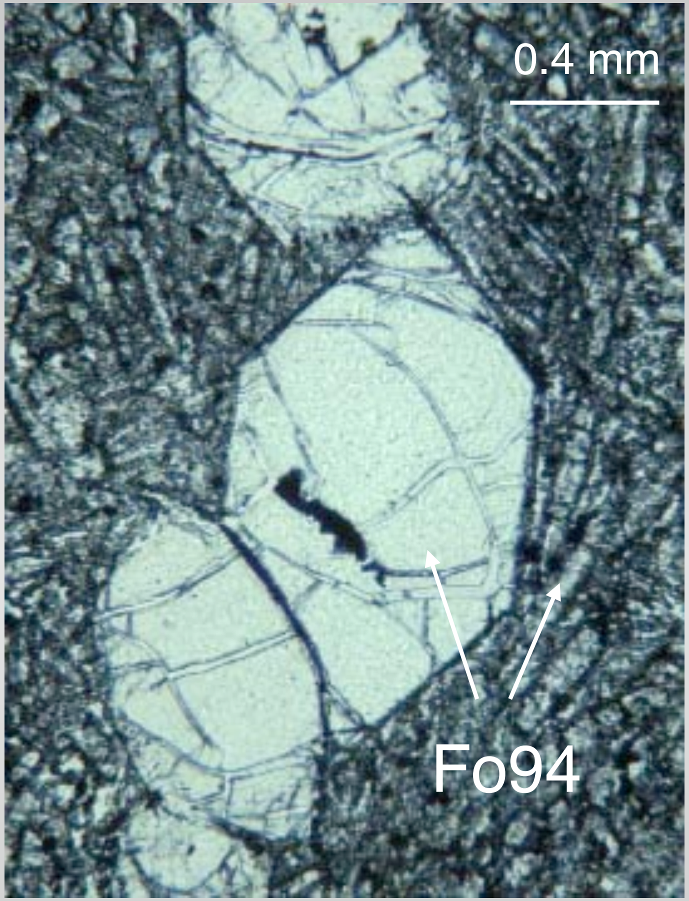
Big olivine plates

Munro, Canada, 2.7 Ma

Komatiites: evidence of a hot Archean mantle



Spinifex-textured komatiite from Zimbabwe - ~22% MgO



Quenched flow top from Alexo, Canada - ~28% MgO

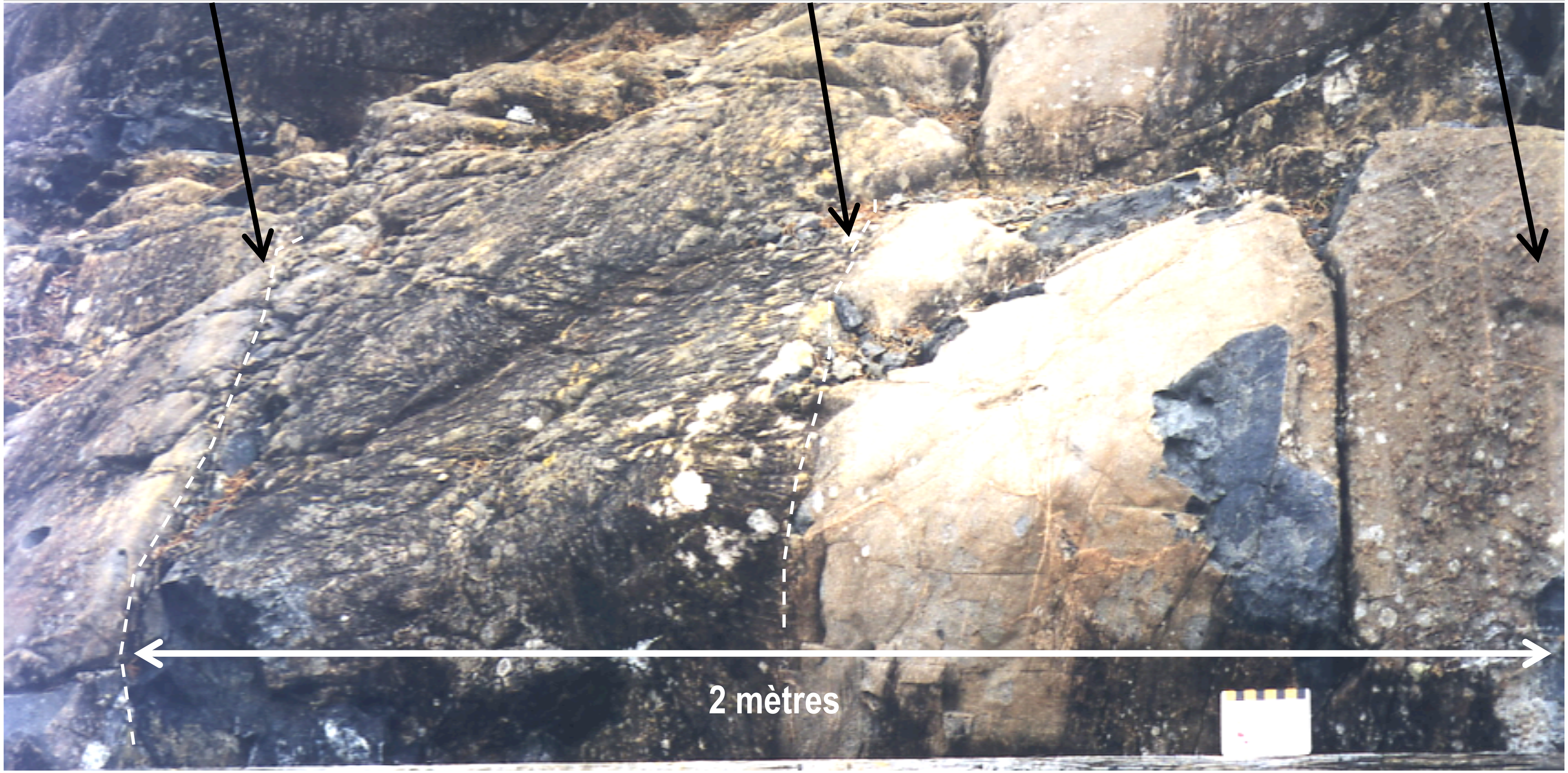
28% MgO --> 1560°C eruption temperature (cf 1200°C for basalt)

A komatiite lava flow

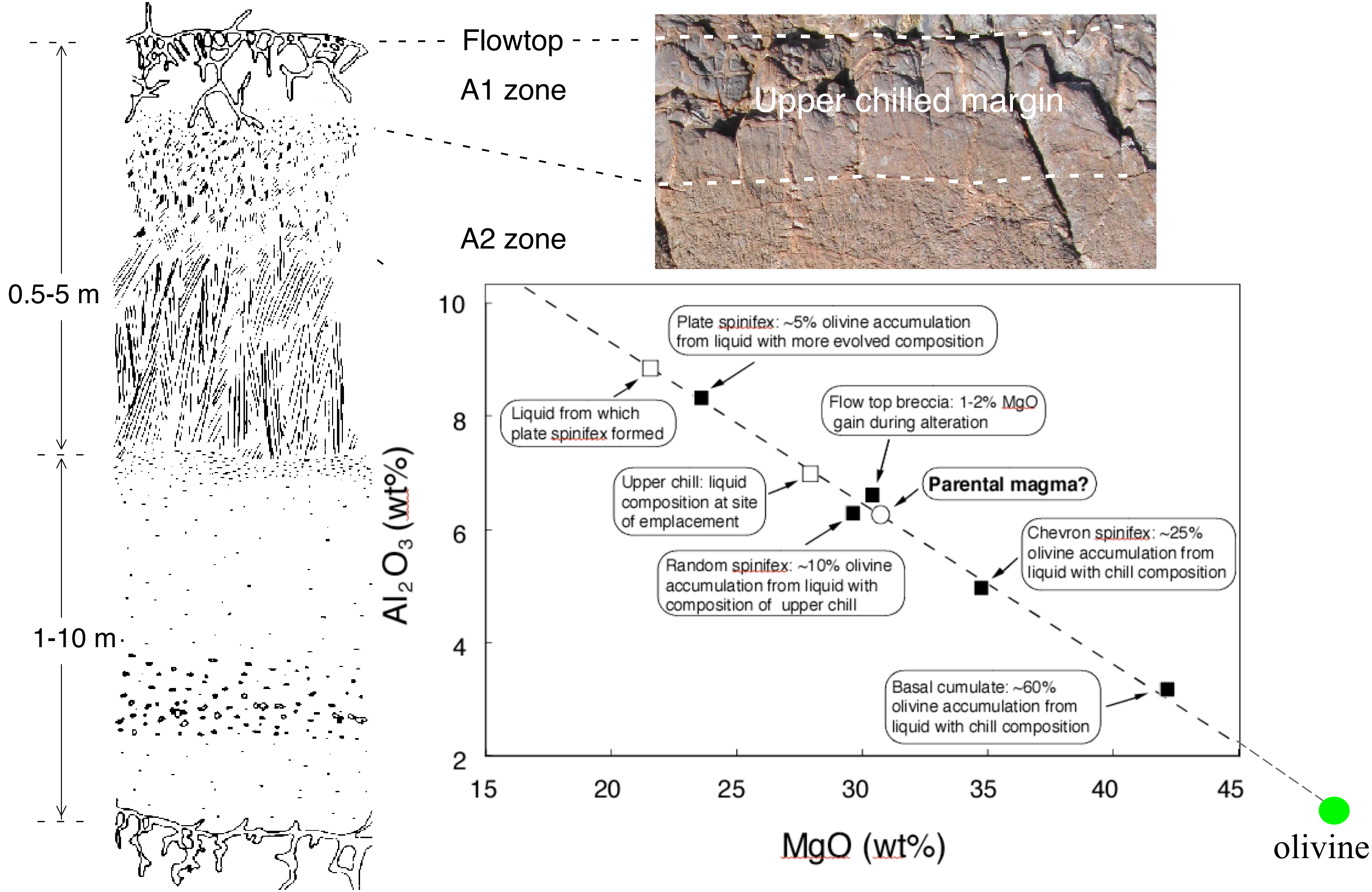
Flow top

base of spinifex zone

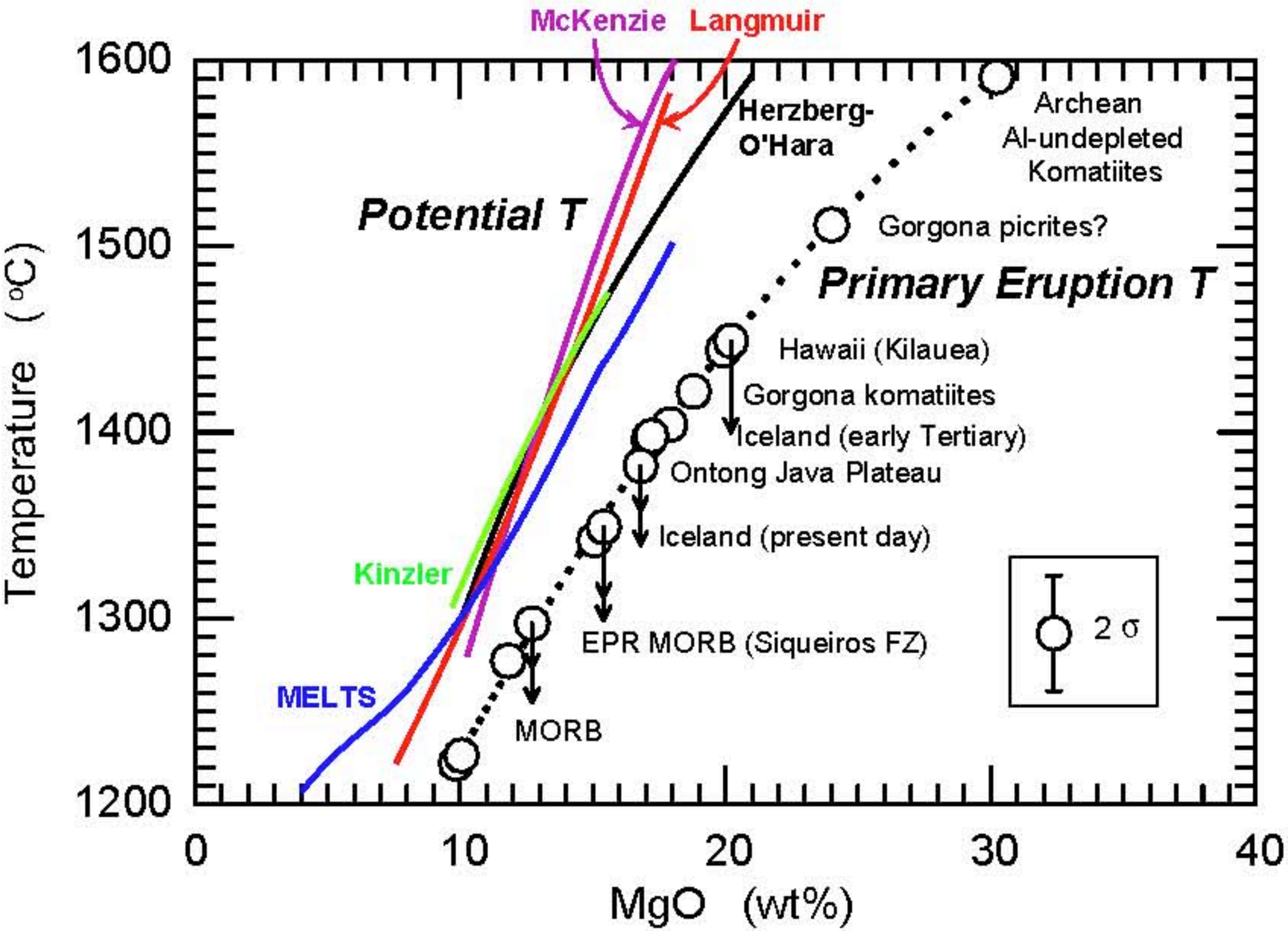
base of flow



Differentiation of a komatiite flow



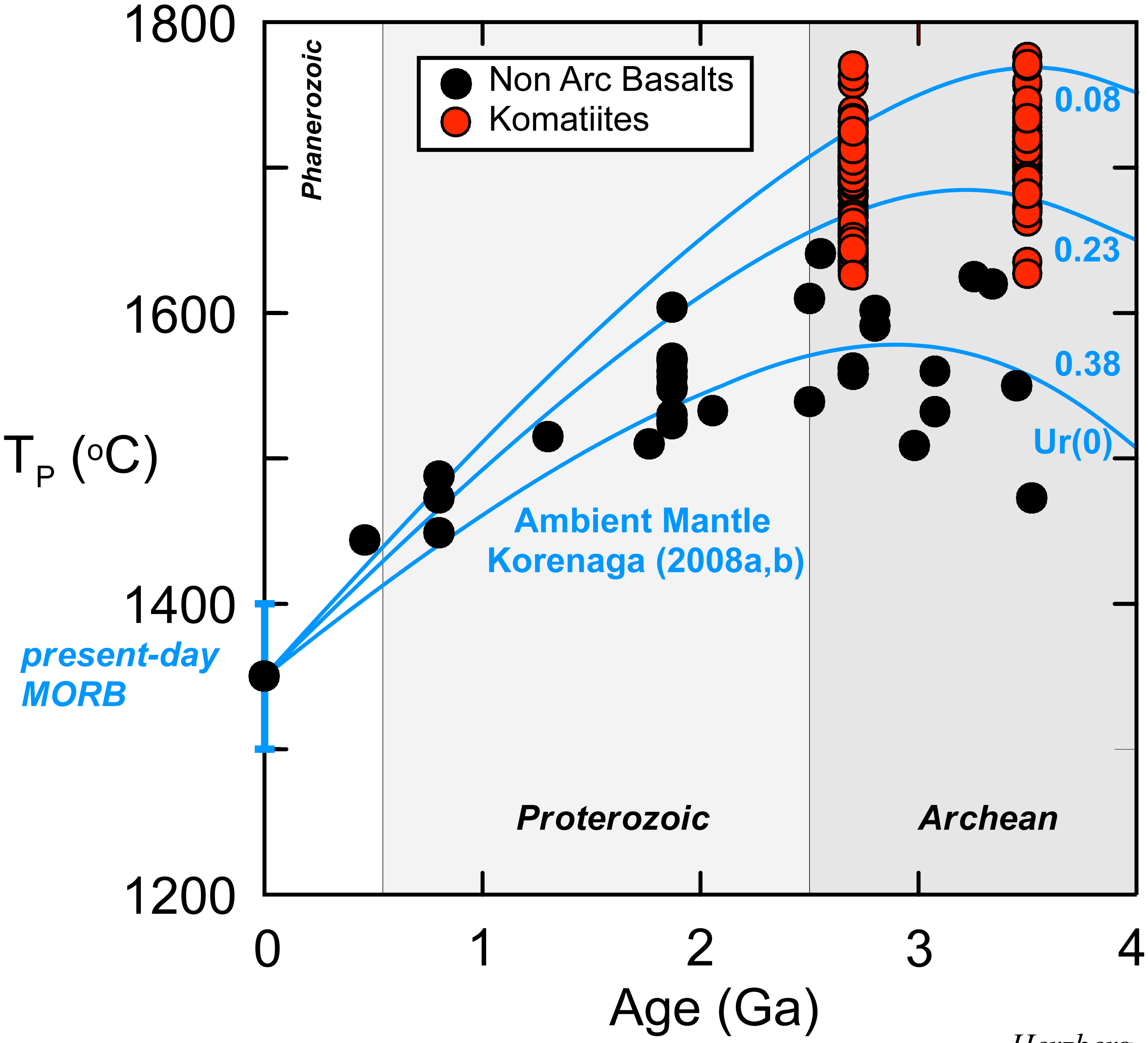
Calculated MgO contents and eruption temperatures



Eruption temperatures calculated using using $T(°C) = MgO_{liq} * 20 + 1000$

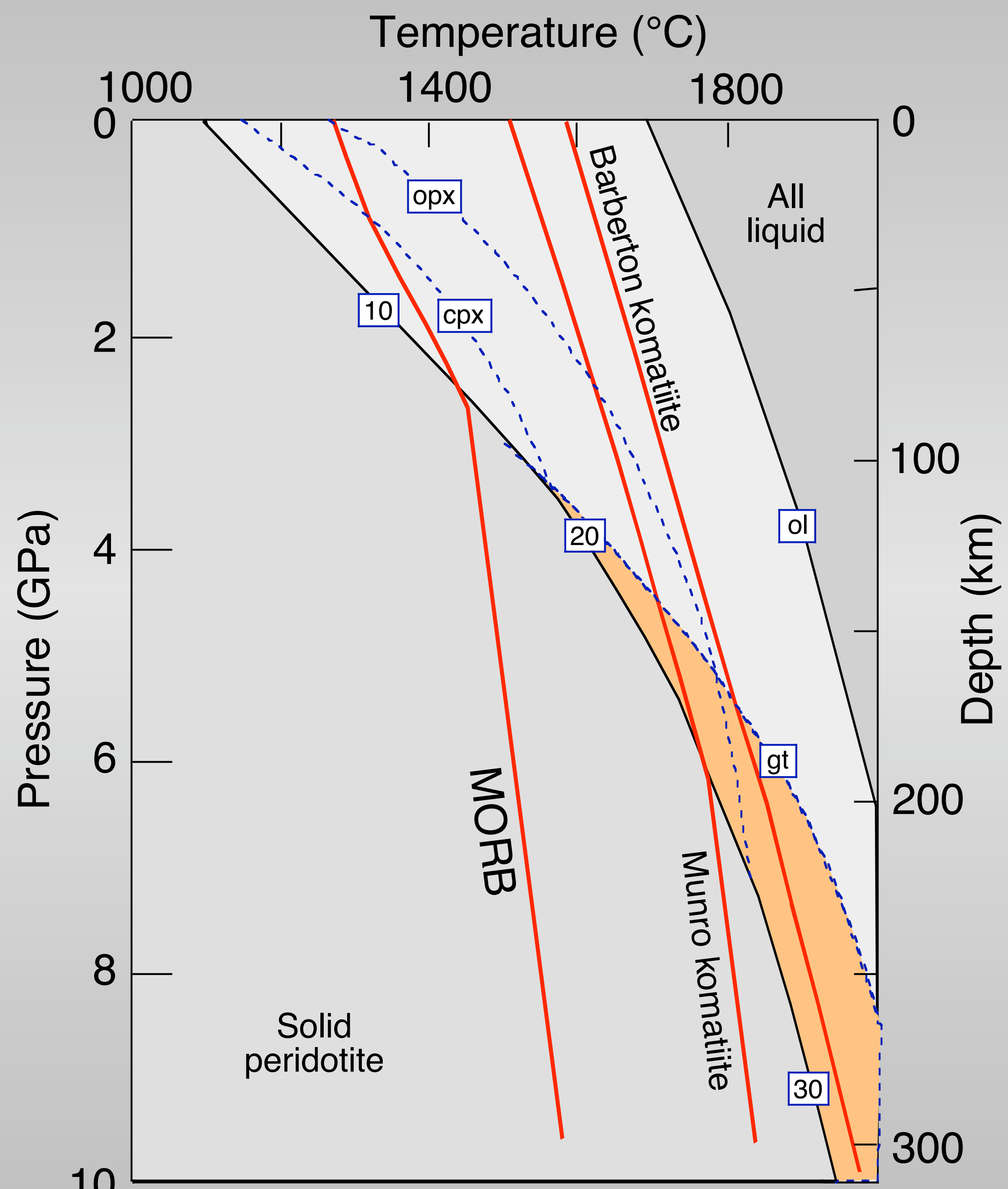
Herzberg, (2008)

Source temperatures

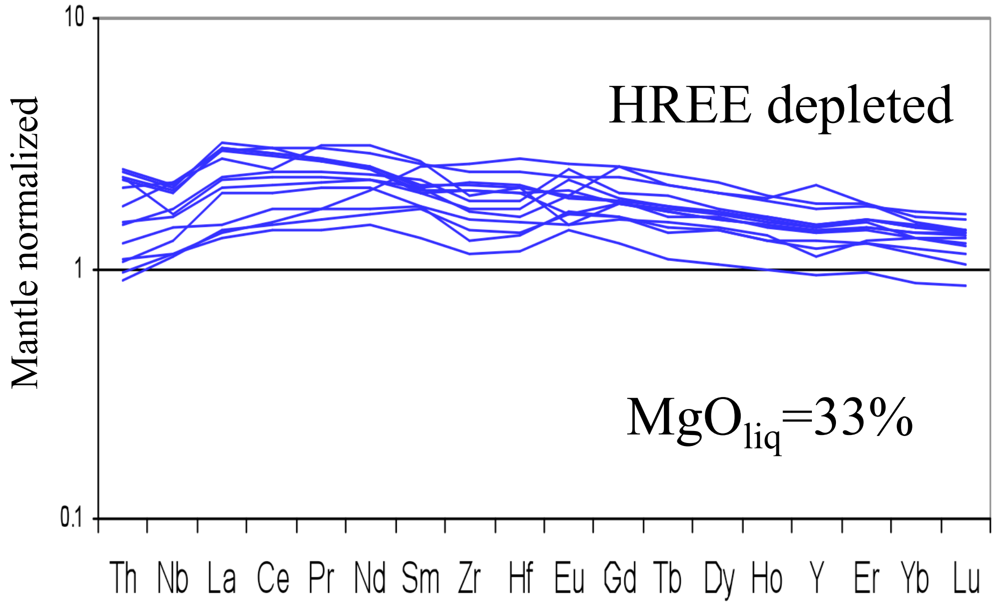


Herzberg, Condie, Korenaga (2010)

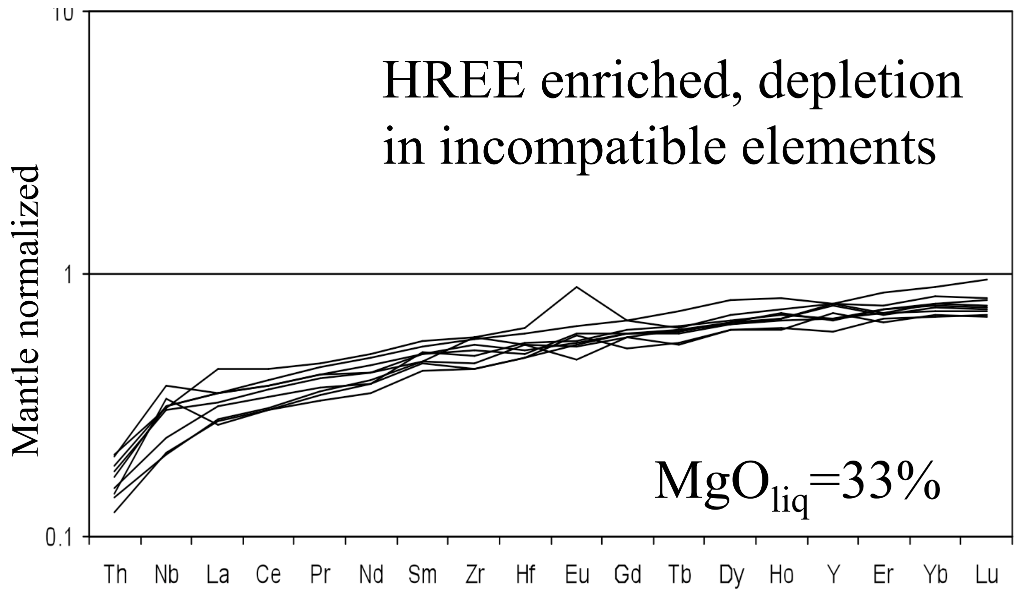
Origin of komatiites



Origin of komatiite magma - trace-element data provide some clues

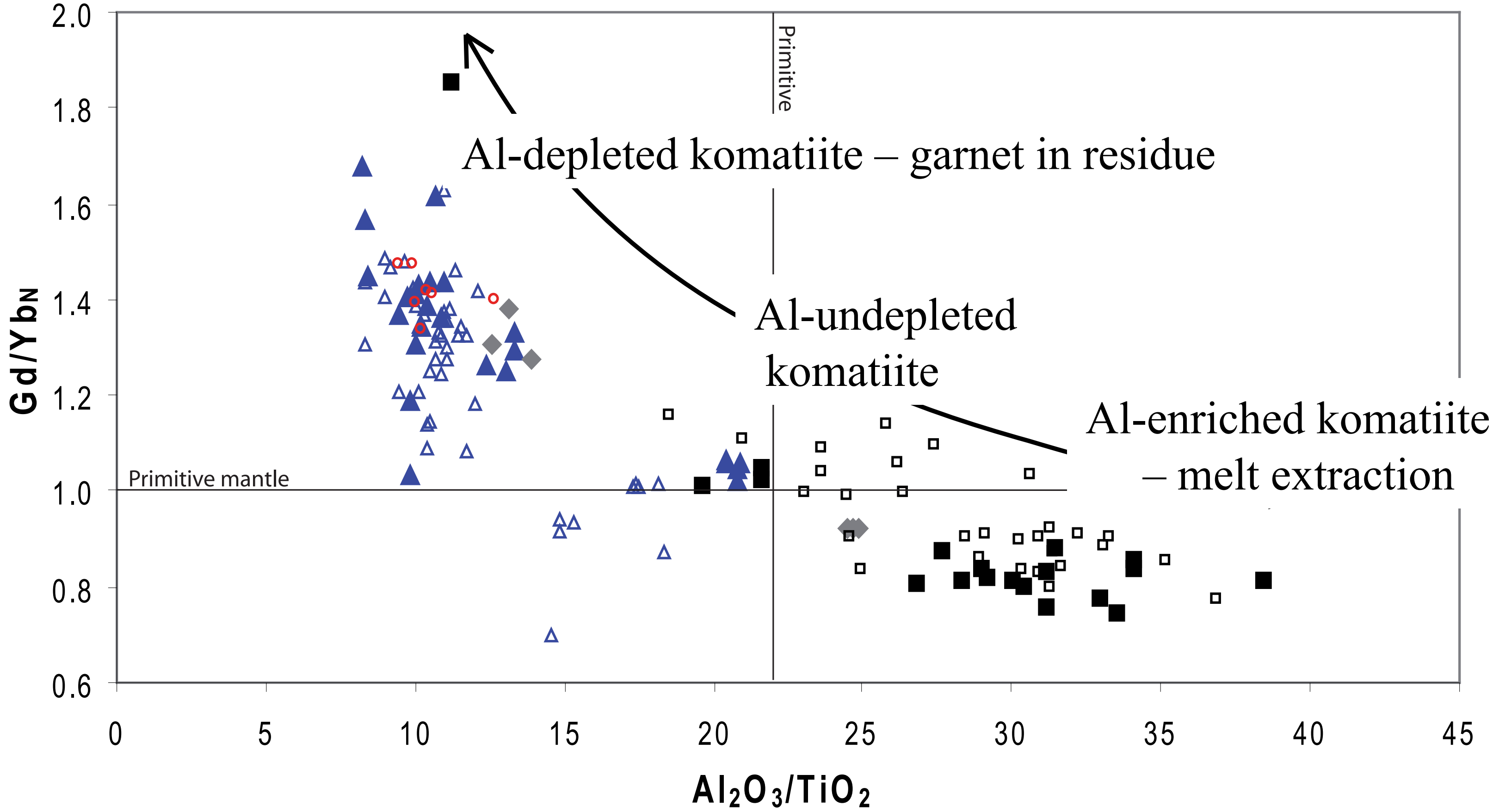


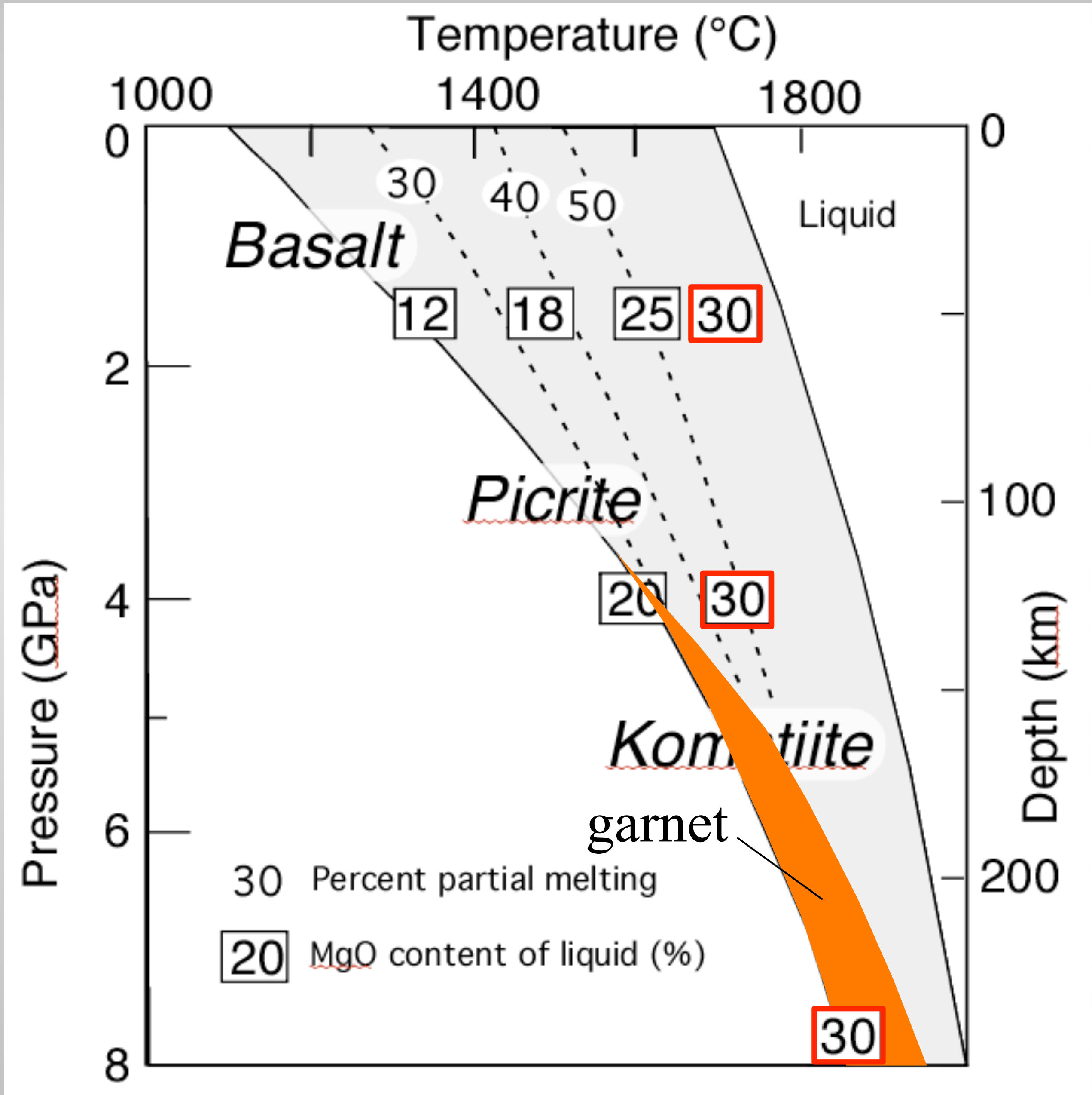
Al-depleted komatiite: depletion of heavy rare-earth elements (HREE) indicates that garnet was left in the residue



Al-enriched komatiite: HREE enrichment indicates no garnet in the residue; depletion of incompatible elements means previous melt extraction

The main types of komatiite form under contrasting conditions

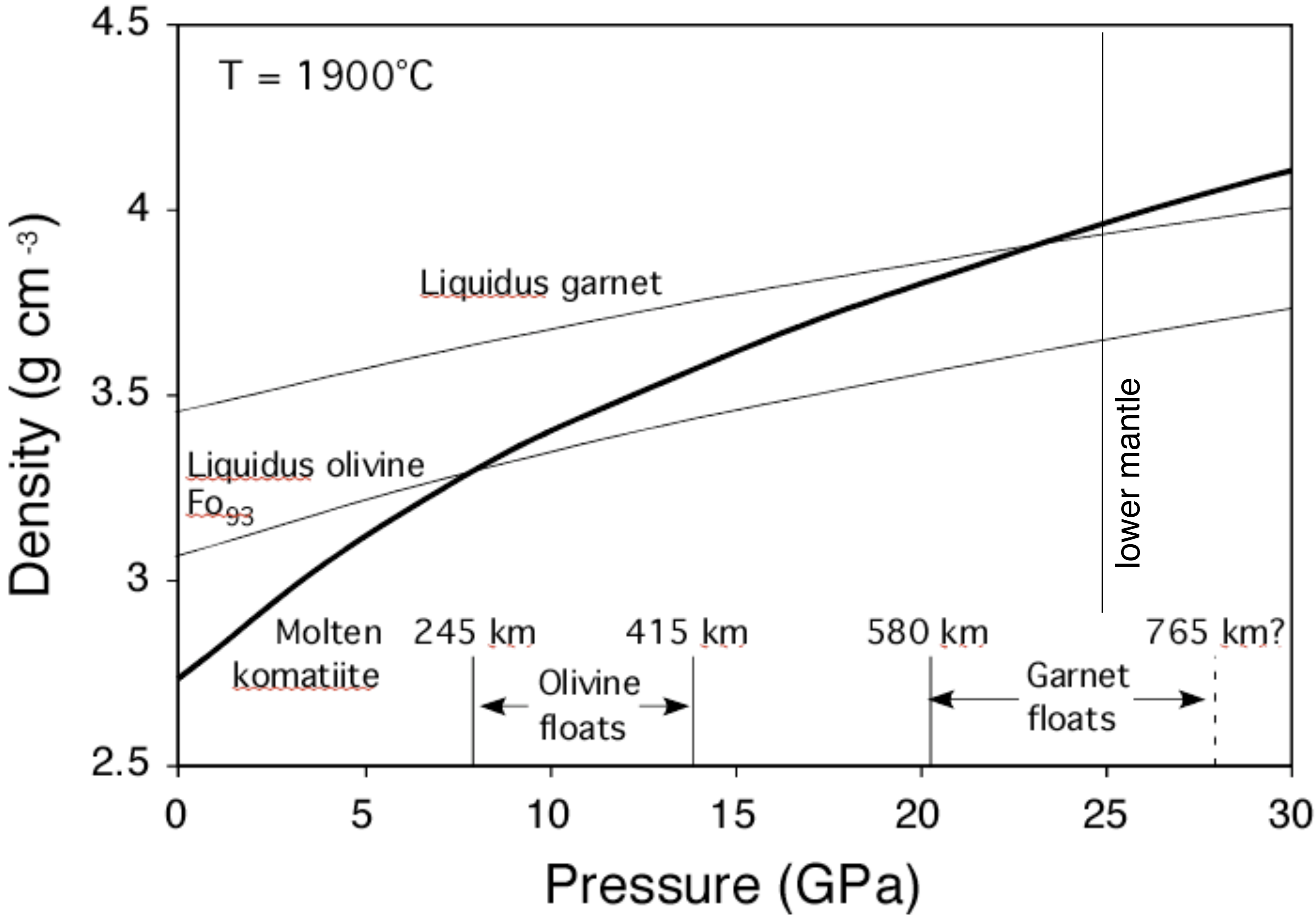


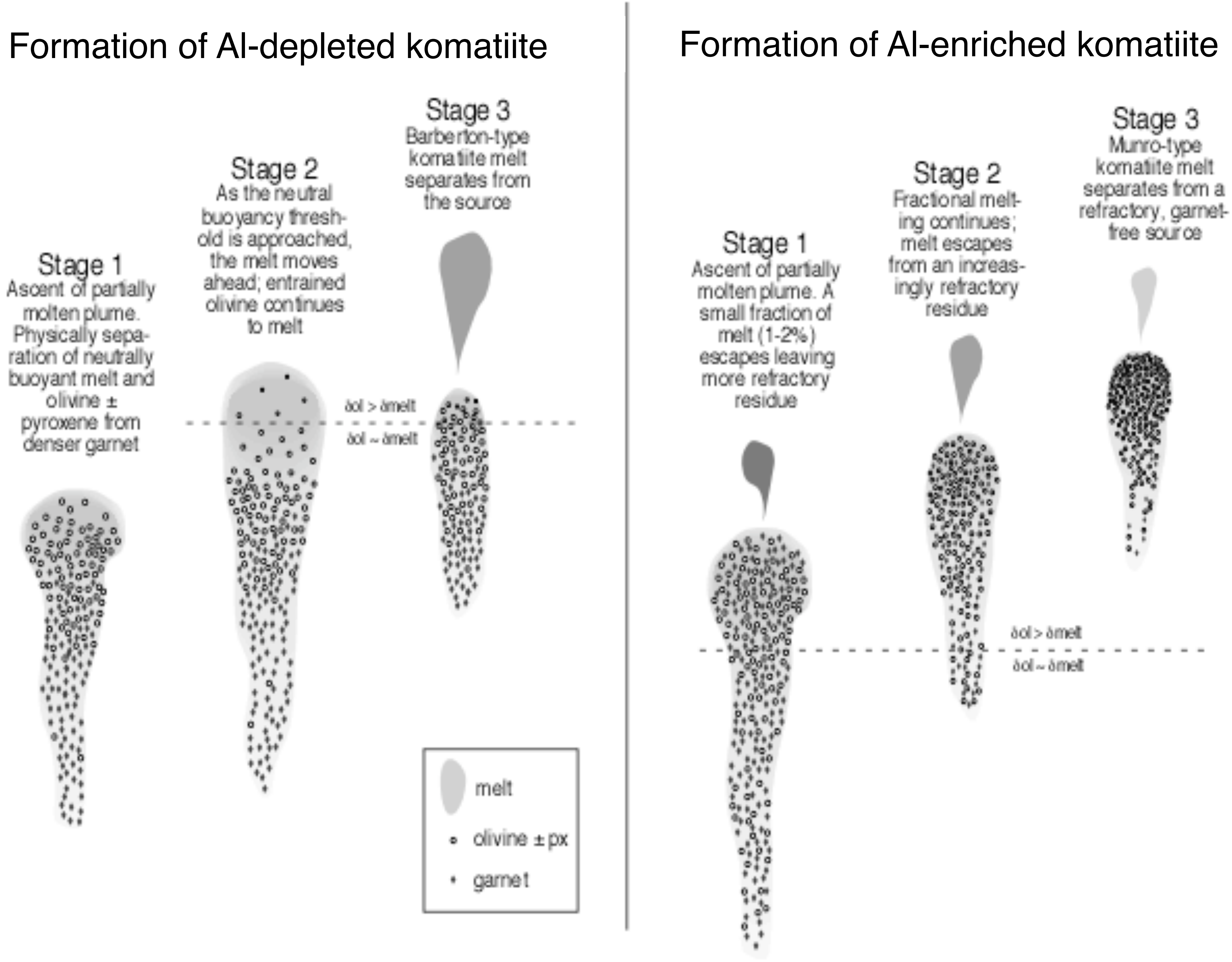


Komatiite with >30% MgO forms either:

- by high-degree melting at shallow depth
- by low-degree melting at great depth

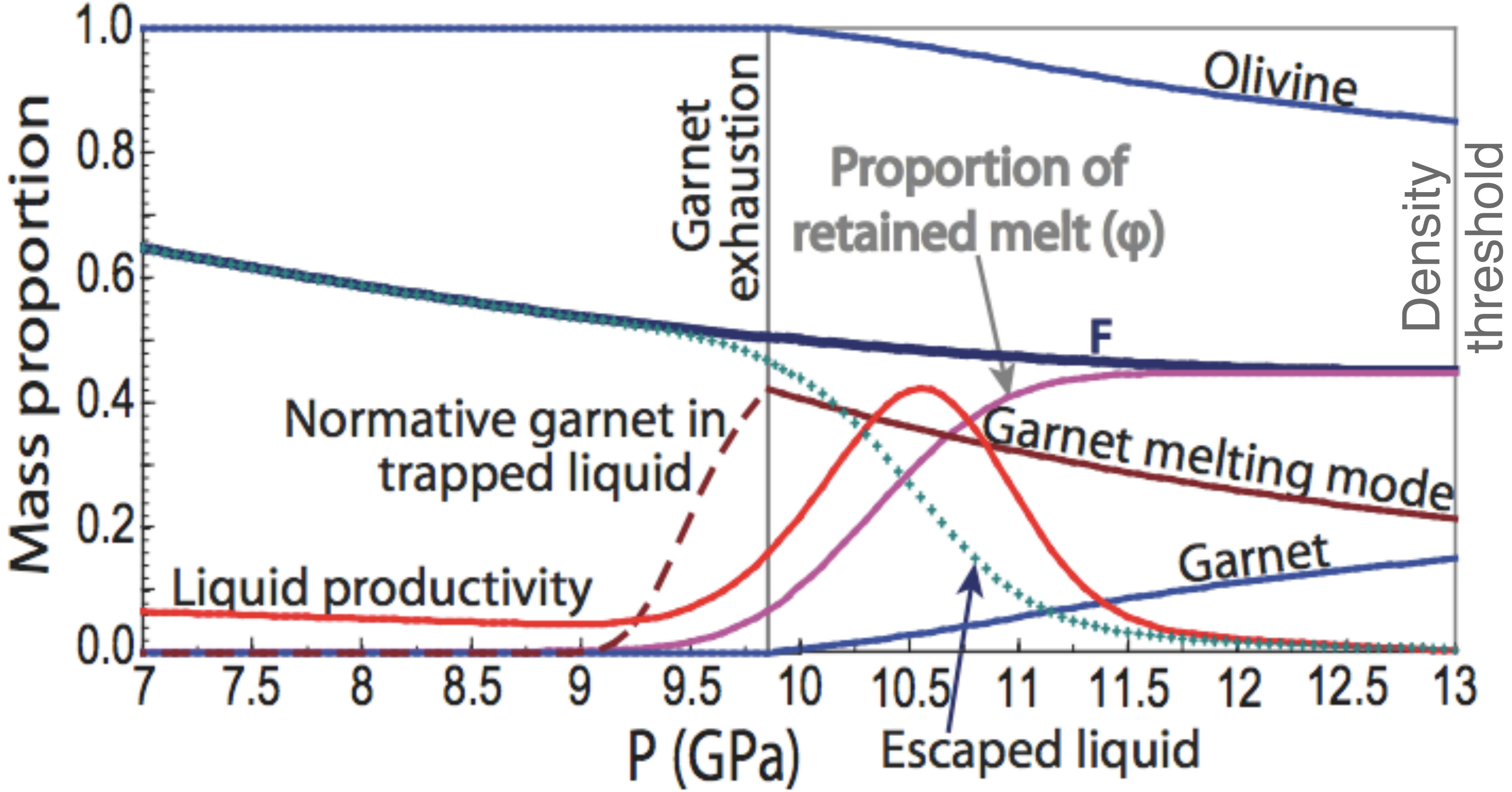
Presence of residual garnet indicates melting at great depth


T = 1900°C
Density (g cm -3)
Pressure (GPa)
Liquidus garnet
Liquidus olivine
Fo93
lower mantle
Molten
komatiite
245 km
415 km
580 km
765 km?
Olivine
floats
Garnet
floats
4.5
4
3.5
3
2.5
0
5
10
15
20
25
30

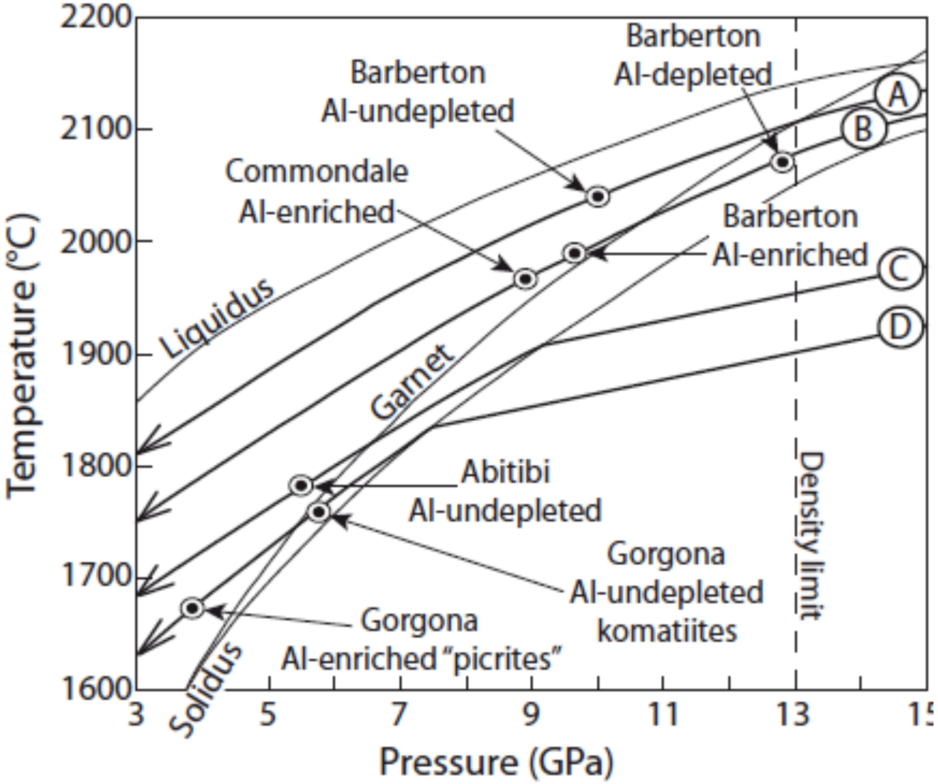


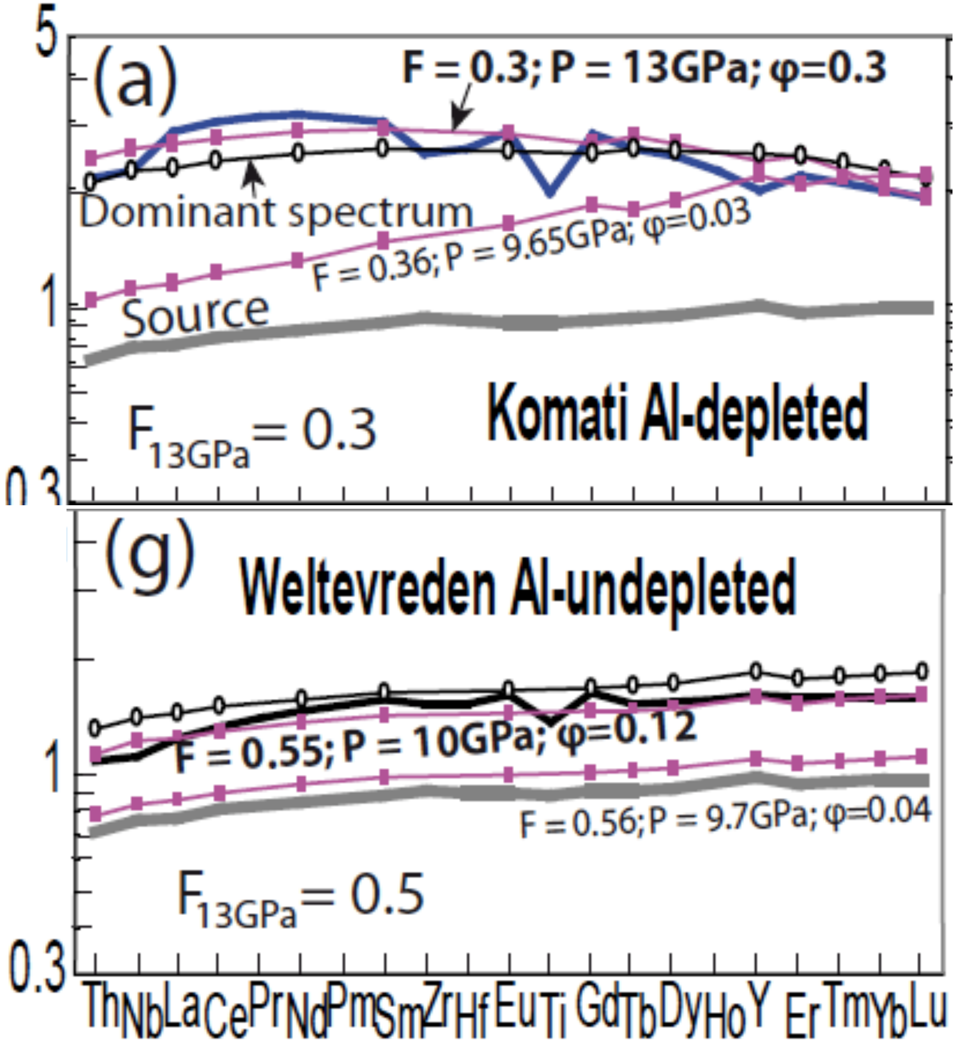
Formation of Al-depleted komatiite
Stage 1
Ascent of partially molten plume. Physically separation of neutrally buoyant melt and olivine ± pyroxene from denser garnet
Stage 2
As the neutral buoyancy threshold is approached, the melt moves ahead; entrained olivine continues to melt
Stage 3
Barberton-type komatiite melt separates from the source
δol > δmelt
δol ~ δmelt
melt
olivine ± px
garnet
Formation of Al-enriched komatiite
Stage 1
Ascent of partially molten plume. A small fraction of melt (1-2%) escapes leaving more refractory residue
Stage 2
Fractional melting continues; melt escapes from an increasingly refractory residue
Stage 3
Munro-type komatiite melt separates from a refractory, garnet-free source
δol > δmelt
δol ~ δmelt

Christophe Robin (PhD 2011)
modelling of melting in a deep plume



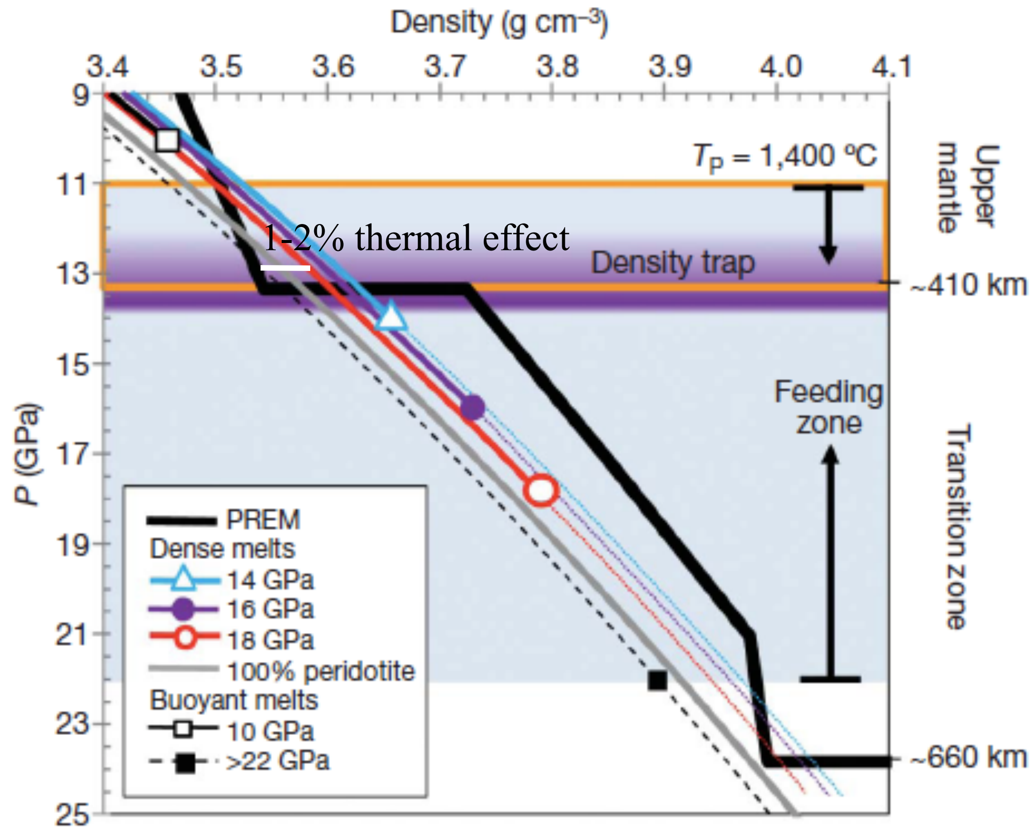
Christophe Robin (PhD 2011) modelling of melting in a deep plume

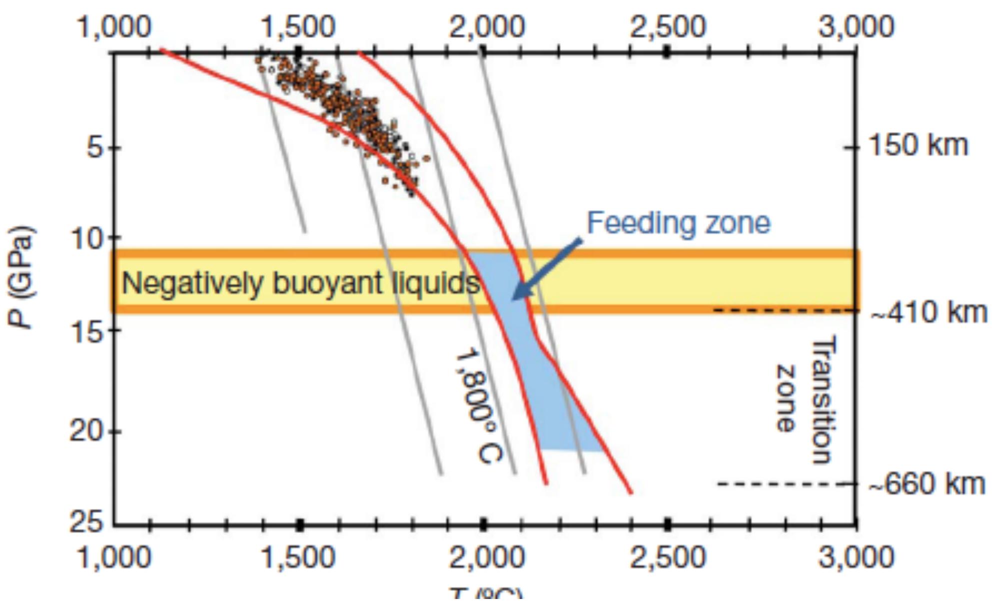


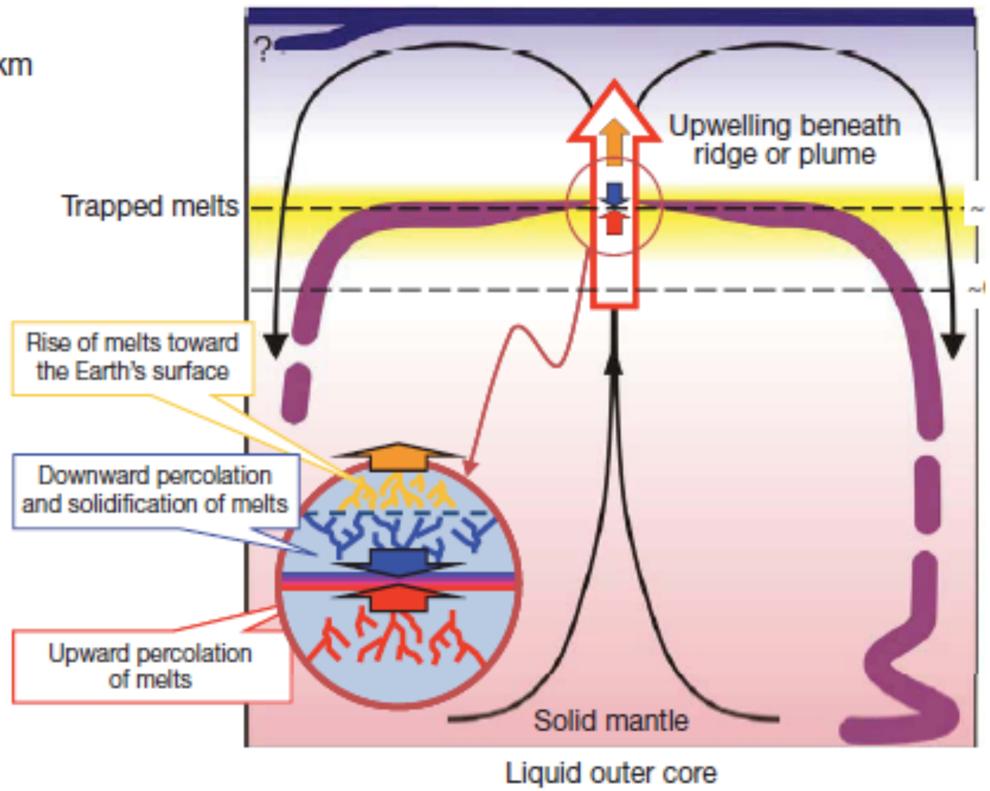


Upside-down differentiation and generation of a 'primordial' lower mantle

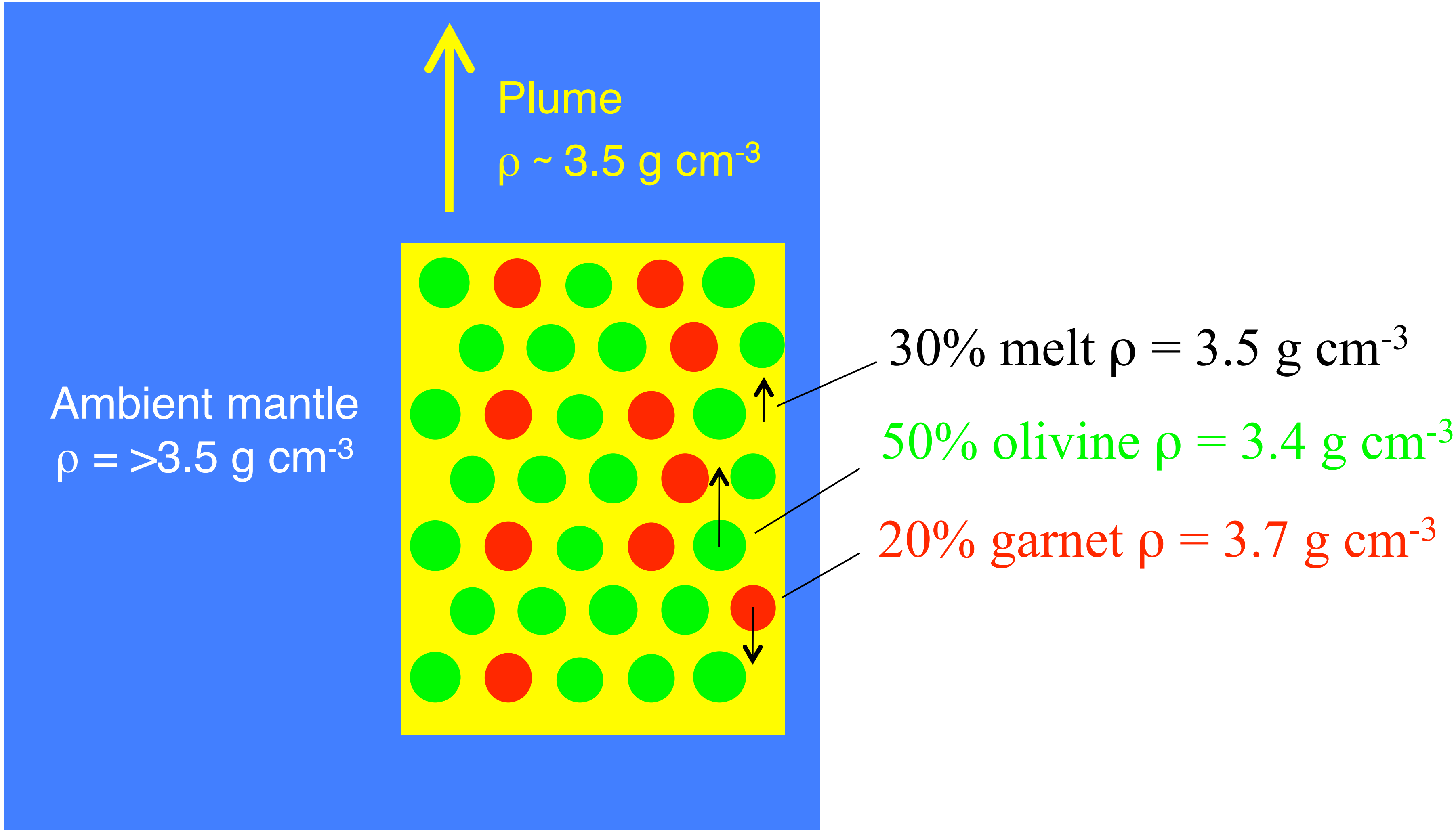
Cin-Ty Lee et al (2010)







Differentiation in a deep rising mantle plume



Conclusions – first part

- Komatiites form by melting deep in the mantle (> 300 km)
- They provide evidence of a hot mantle source in the Archean
- They separated from their source at depths well below the lithosphere
- Details of melt-extraction process remain to be resolved

Characteristics of the Continental Lithospheric Mantle

- Mainly peridotite (±pyroxenite ±eclogite)
- Archean lithospheric mantle
  - harzburgite with Fo-rich olivine (Fo_{90-94}) and abundant orthopyroxene
  - Low concentrations in incompatible trace elements and usually no "subduction signature"

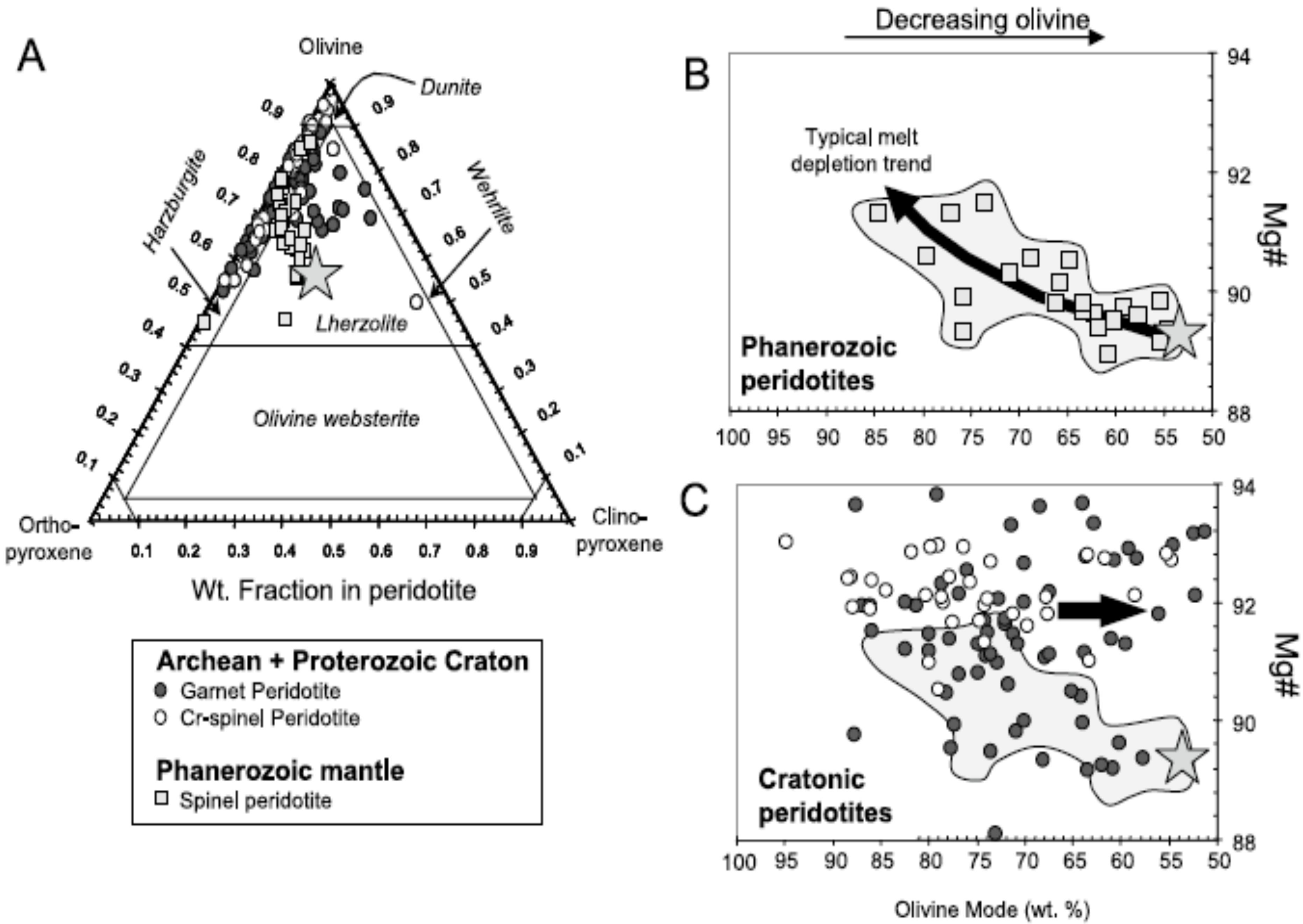
Proterozoic and Phanerozoic lithospheric mantle

  - lherzolite with olivine + orthopyroxene + clinopyroxene + garnet or spinel
  - More Fe-rich compositions (Fo_{88-90}), more "fertile" composition = more abundant clinopyroxene and garnet/spinel; more abundant incompatible trace elements

Characteristics of the Continental Lithospheric Mantle

Age of lithospheric mantle ~ age of overlying crust

- Lithosphere was stable over billions of years, despite being colder than surrounding mantle
- To survive for billions of years, it must have been inherently less dense and more viscous --> anhydrous highly magnesian olivine ± opx



A
Olivine
Dunite
Harzburgite
Wehrlite
Lherzolite
Olivine websterite
Ortho-
pyroxene
Clino-
pyroxene
Wt. Fraction in peridotite
Archean + Proterozoic Craton
Garnet Peridotite
Cr-spinel Peridotite
Phanerozoic mantle
Spinel peridotite
Decreasing olivine
B
Typical melt
depletion trend
Phanerozoic
peridotites
Mg#
C
Cratonic
peridotites
Olivine Mode (wt. %)

Origin and Evolution of Continental Lithospheric Mantle

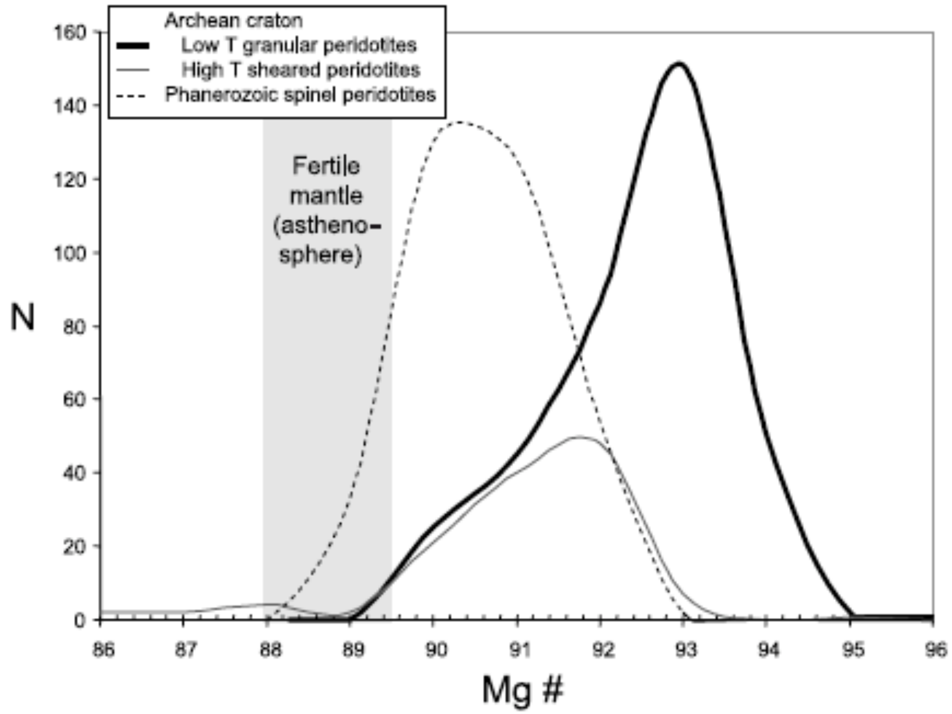
1. How did the lithospheric mantle form?

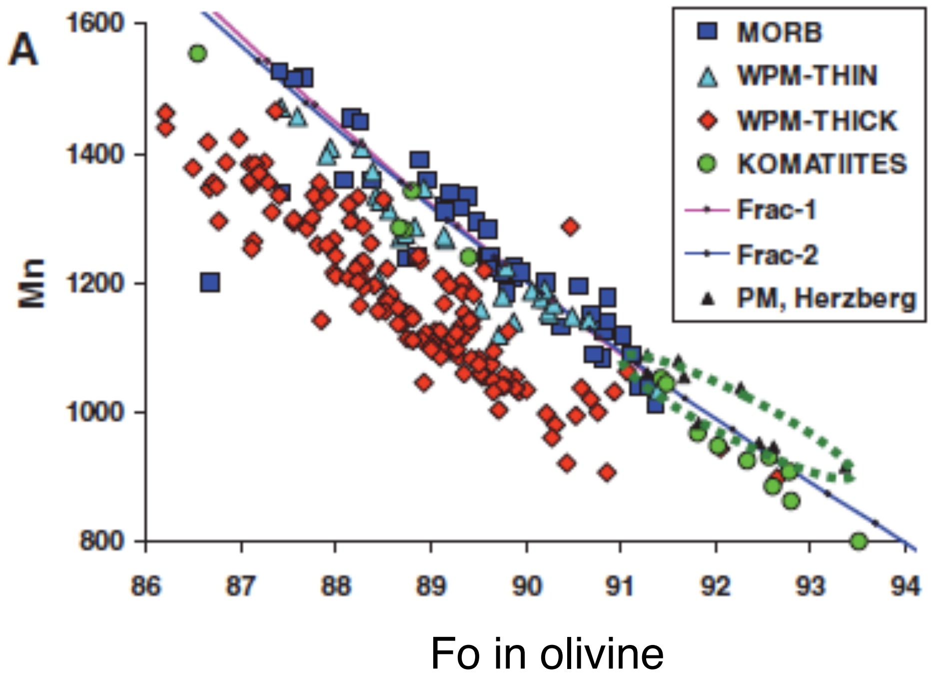
2. How did it survive?

3. What has happened to it since its formation?

How is a vast volume of rock composed essentially of magnesian olivine ($Fo_{>92}$) ± opx formed?

Minerals with these compositions are rare in the mantle





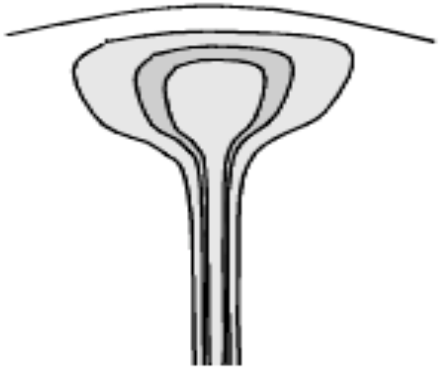
How is a vast volume of rock composed essentially of magnesian olivine ($Fo_{>92}$) ± opx formed?

Possibilities:

1. Residue of high-degree melting, as during the formation of komatiite in a mantle plume
2. Stacking of slabs of ocean lithosphere
3. Residue of water-fluxed melting in a subduction zone

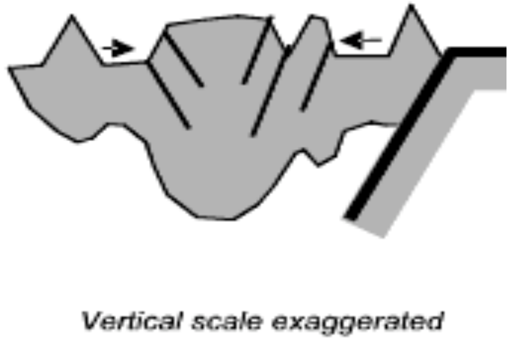
In either case, the magnesian minerals must be sorted from the products of lower-degree melting

a. Mantle plume



b. Stacking/accretion of oceanic lithosphere

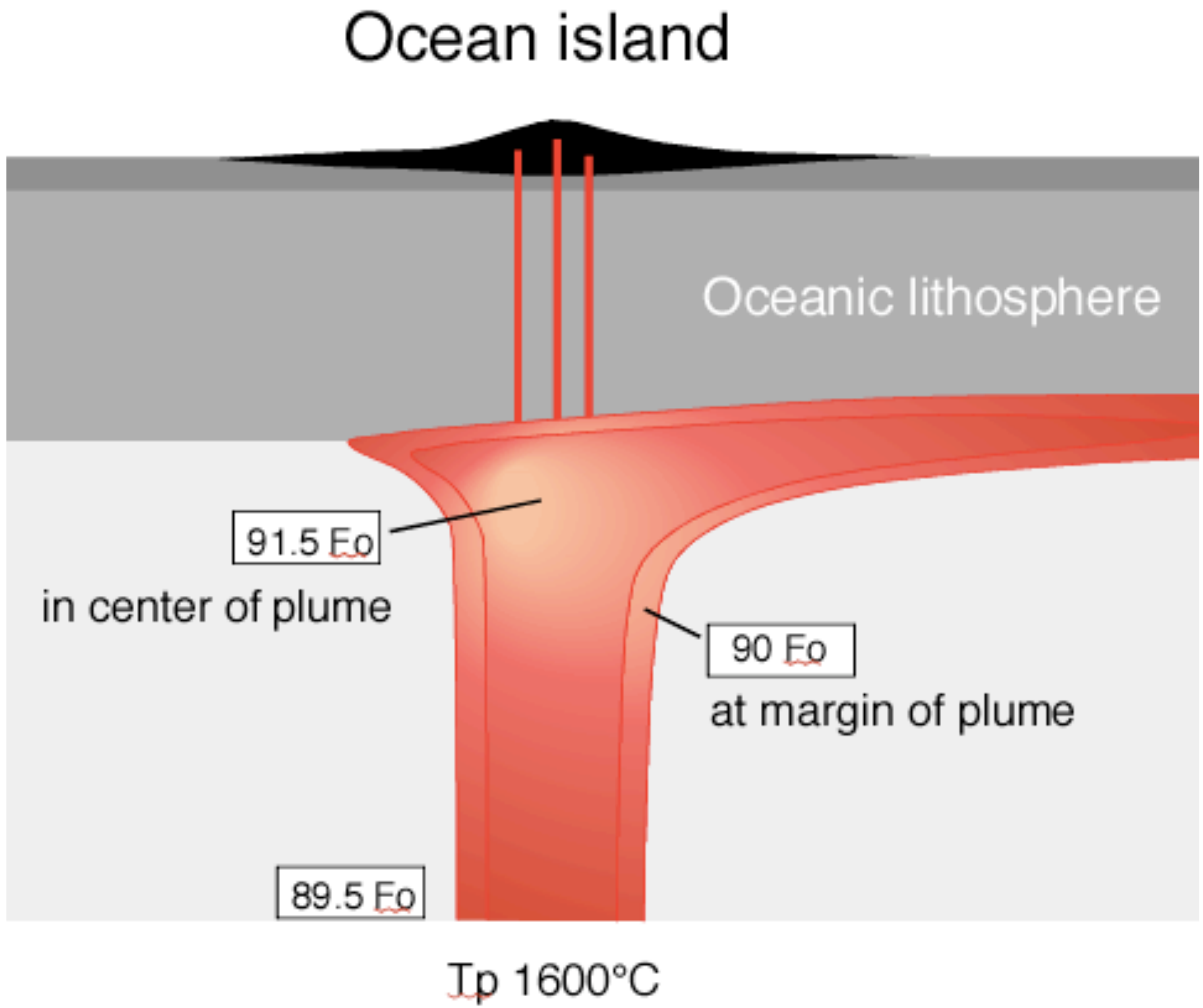
c. Reprocessing in subduction zones



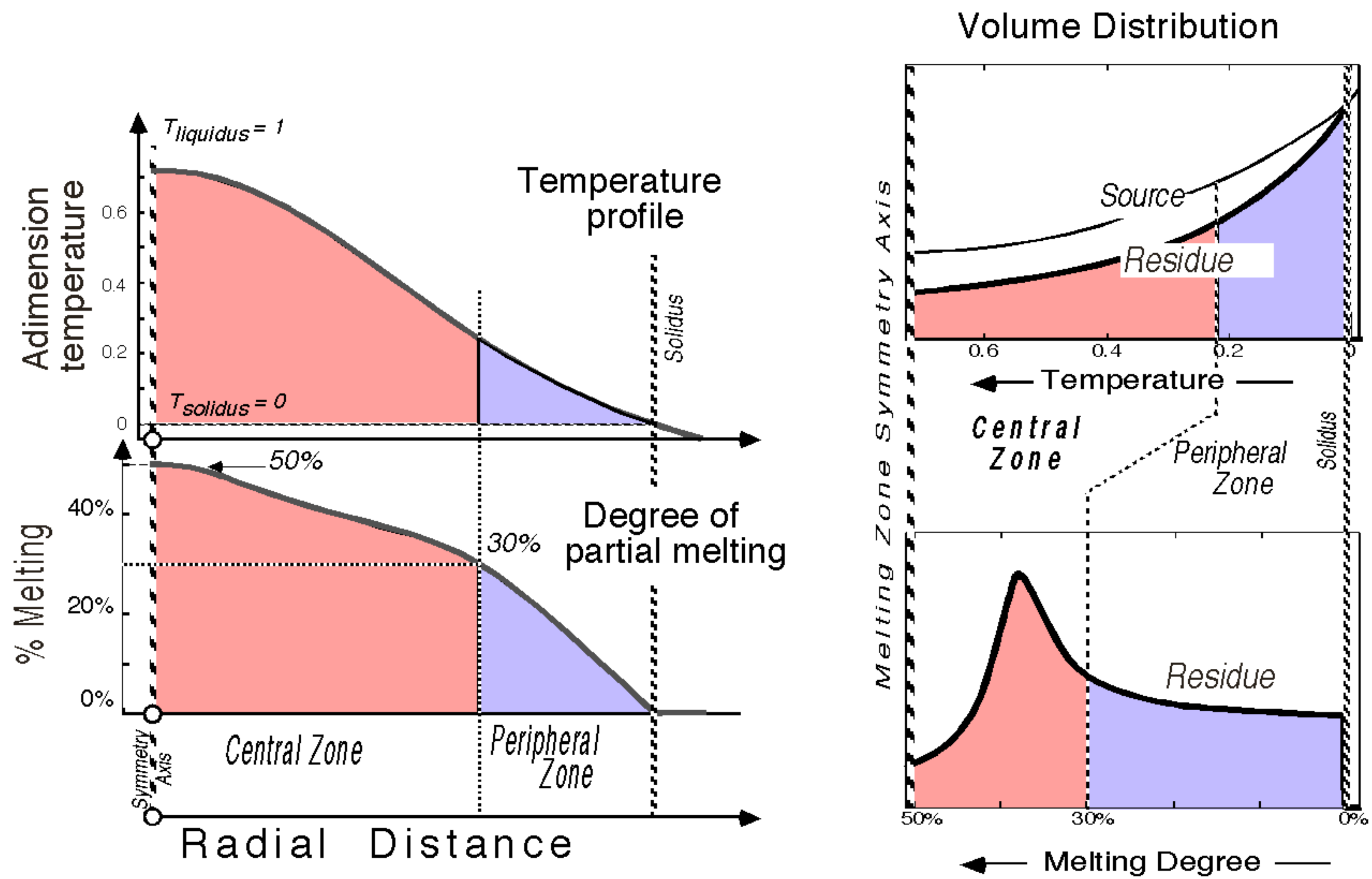
Predictions

a. Mantle plume	b. Stacking/accretion of oceanic lithosphere	c. Reprocessing in subduction zones
Polybaric melting	Low-pressure melting	Low-pressure melting
Formation of abundant anhydrous refractory harzburgite or dunite	Low proportion of refractory harzburgite or dunite	Formation of abundant refractory harzburgite or dunite
Increasing Mg# with shallowing depth	Large variety of rock types, abundant eclogite	Increasing Mg# with shallower depth - reorganization required to achieve gravitational stability
Isopicnicity (gravitational stability) possible from the outset	No systematic stratification of Mg# with depth	Possibility that peridotitic residue was hydrous and contained a subduction geochemical signature
	Unlikely to be neutrally buoyant from the outset - unless there was internal reorganization of density or large amounts of eclogite were lost	

Melting in a mantle plume

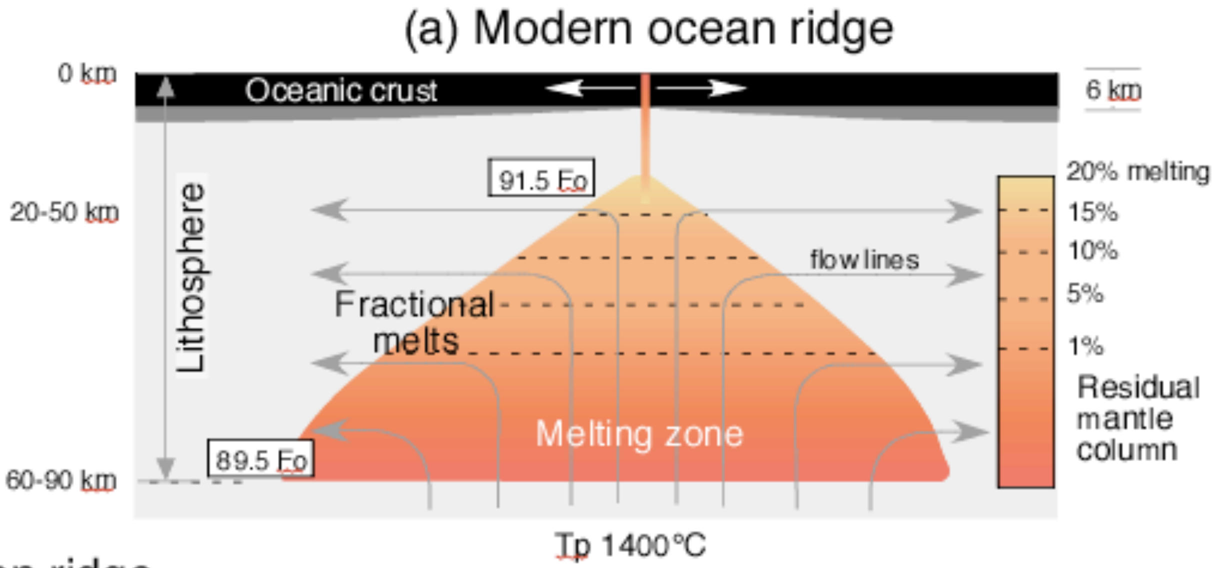


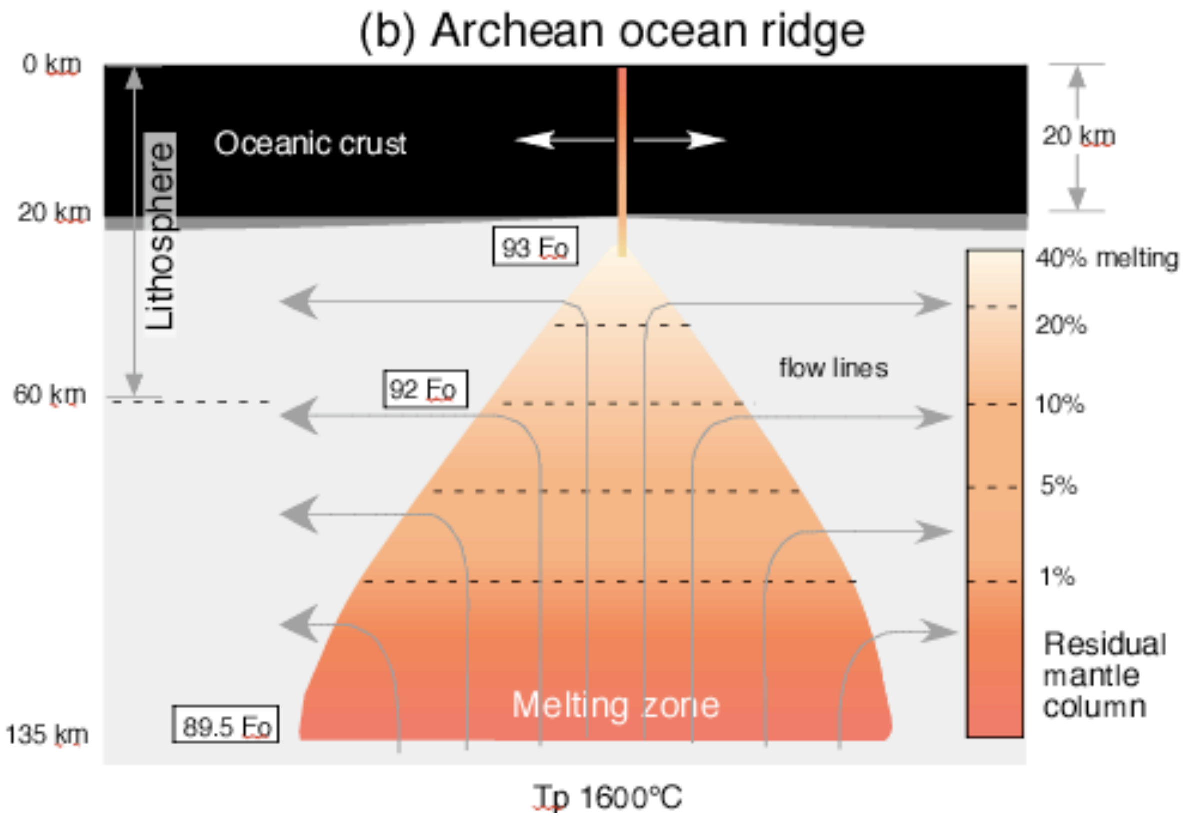
Melting in a mantle plume



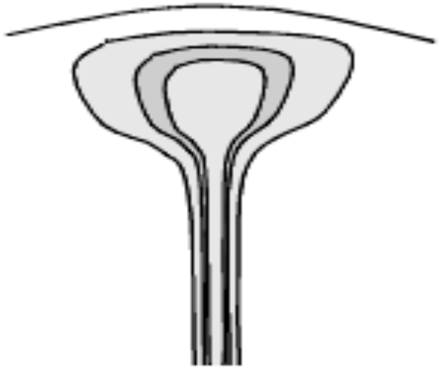
At least half the residue results from low-degree melting: it contains olivine with <90% Fo

Melting at a mid-ocean ridge





a. Mantle plume



b. Stacking/accretion of oceanic lithosphere

c. Reprocessing in subduction zones

Vertical scale exaggerated

Predictions

a. Mantle plume

Polybaric melting

Formation of abundant anhydrous refractory harzburgite or dunite

Increasing Mg# with shallowing depth

Isopicnicity (gravitational stability) possible from the outset

b. Stacking/accretion of oceanic lithosphere

Low-pressure melting

Low proportion of refractory harzburgite or dunite

Large variety of rock types, abundant eclogite

No systematic stratification of Mg# with depth

Unlikely to be neutrally buoyant from the outset - unless there was internal reorganization of density or large amounts of eclogite were lost

c. Reprocessing in subduction zones

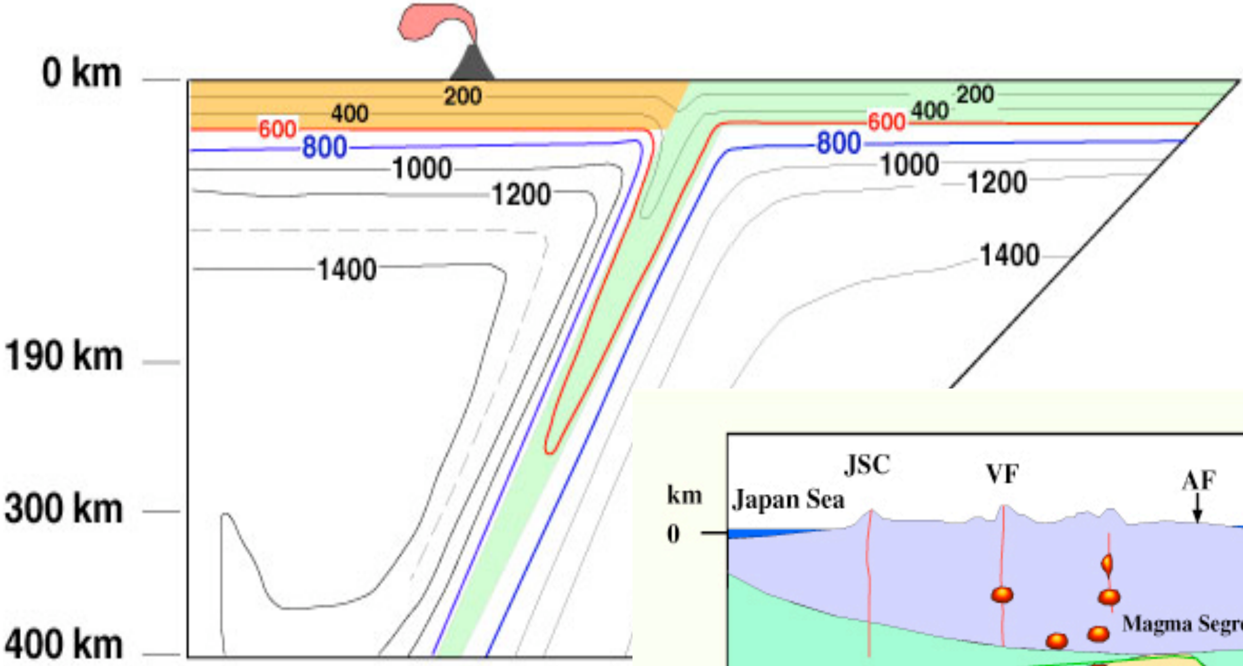
Low-pressure melting

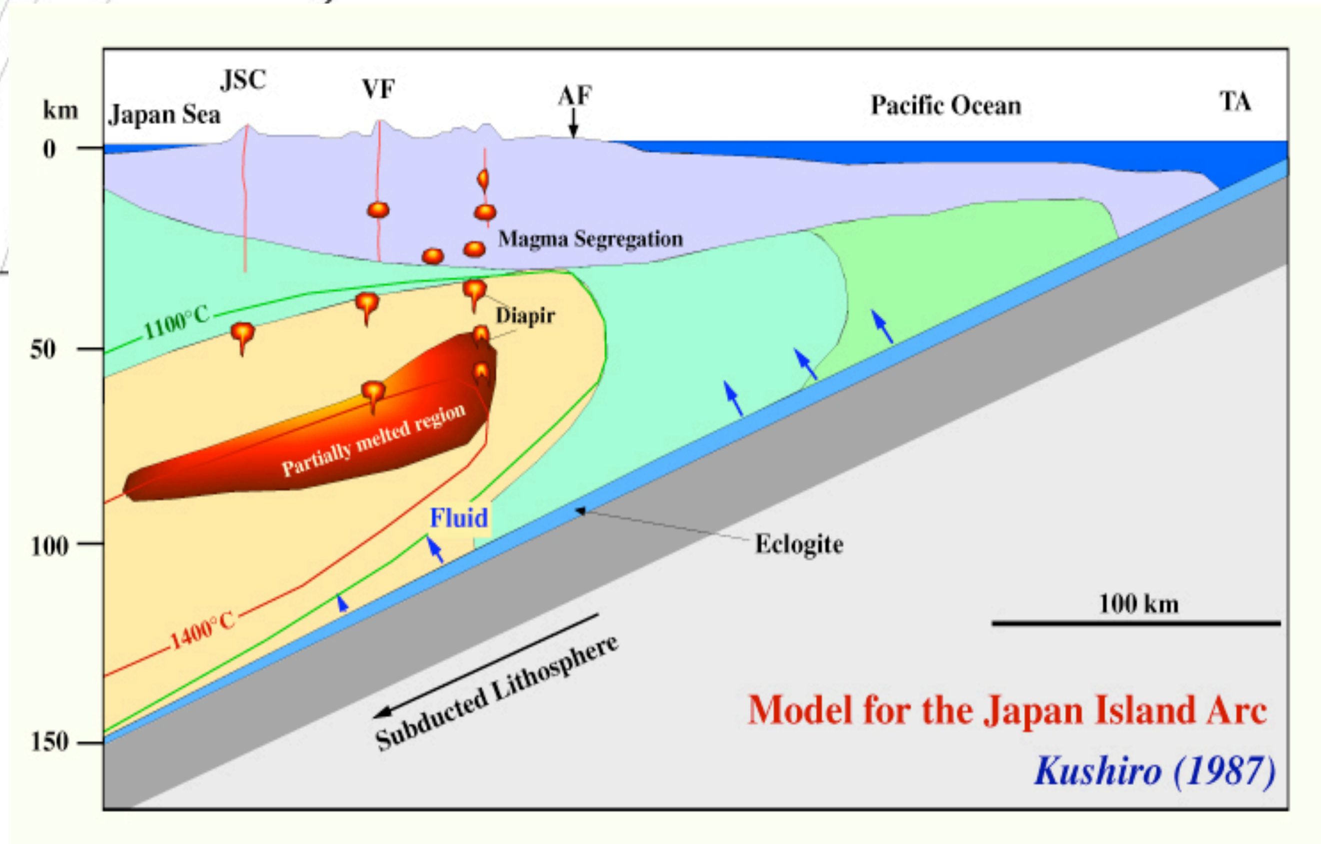
Formation of abundant refractory harzburgite or dunite

Increasing Mg# with shallower depth - reorganization required to achieve gravitational stability

Possibility that peridotitic residue was hydrous and contained a subduction geochemical signature

The alternative: lithosphere forms in hot Archean subduction zones





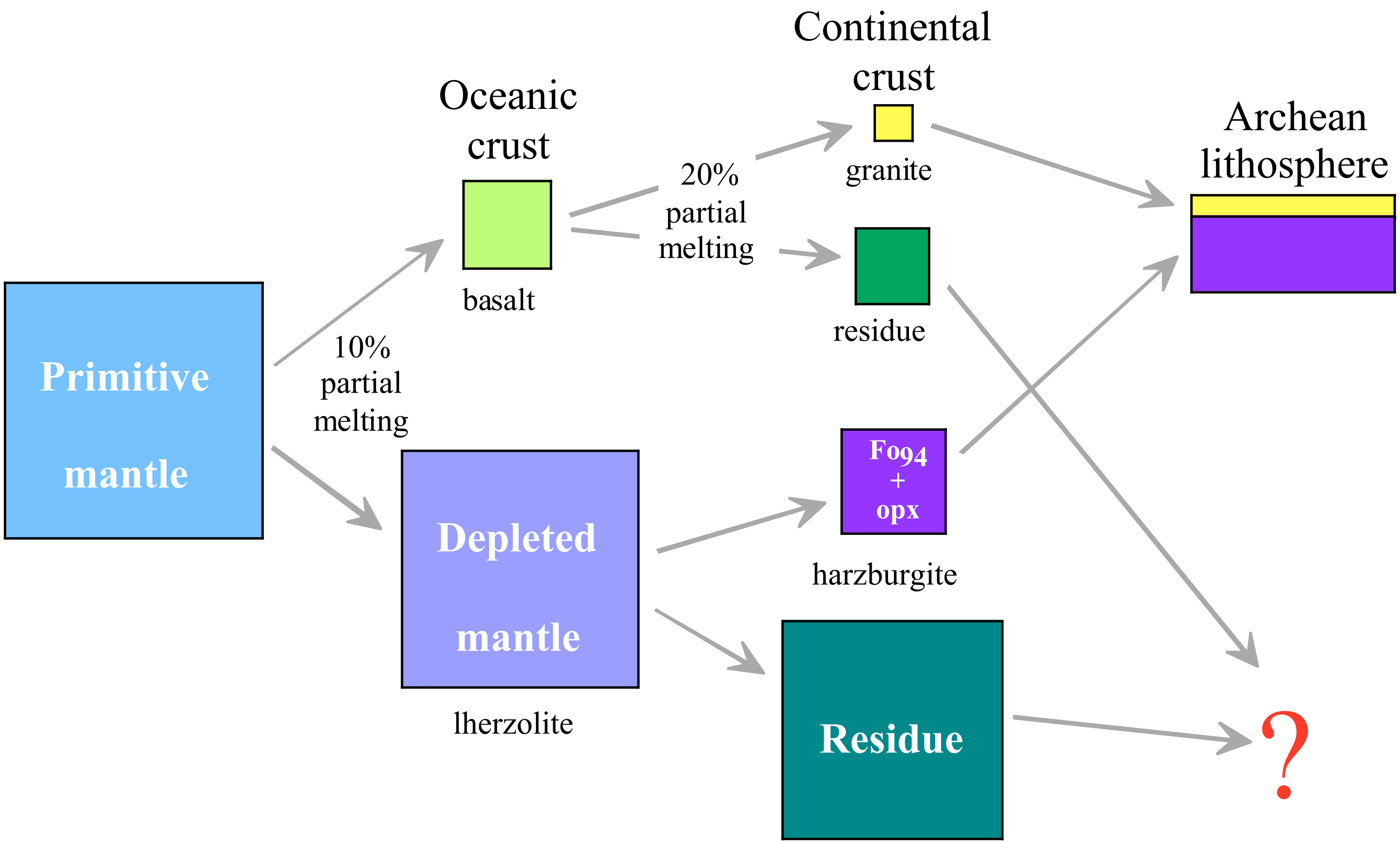
Temperatures in modern subduction zones

Arguments against a subduction origin of lithospheric mantle

1. Absence of the “subduction signature”

2. Requirement that lithosphere is anhydrous

Formation of continental lithosphere - the waste-disposal problem



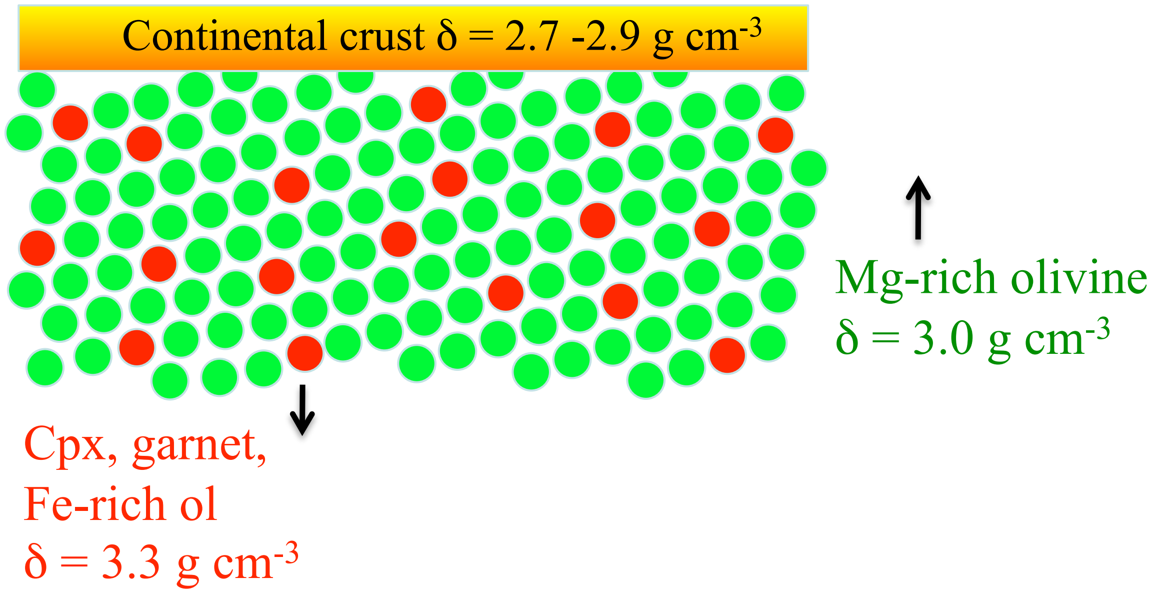
Archean lithosphere is a sandwich of rare materials: low-temperature distillates (granite), and high-temperature refractory residues (harzburgite)

Synneusis - the "floating together" of the least dense fractions left after mantle melting

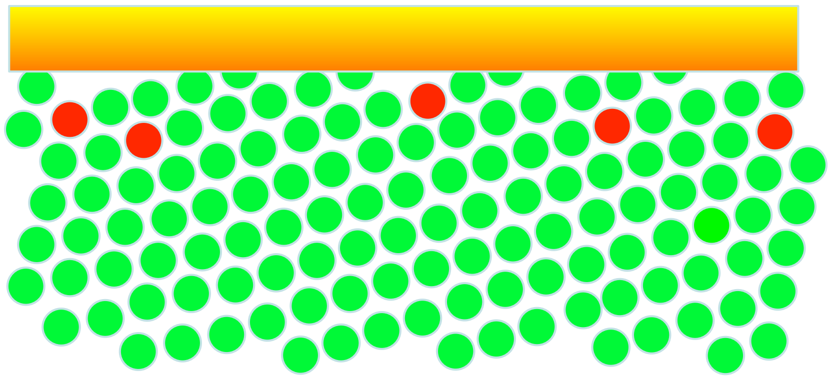
1. Continental crust - the distillate of mantle melting processes
2. Continental lithospheric mantle - the most refractory fraction of the residue of melting

The denser components – residue of low-degree melting, slabs of oceanic lithosphere, etc, founder during deformation because of their high density

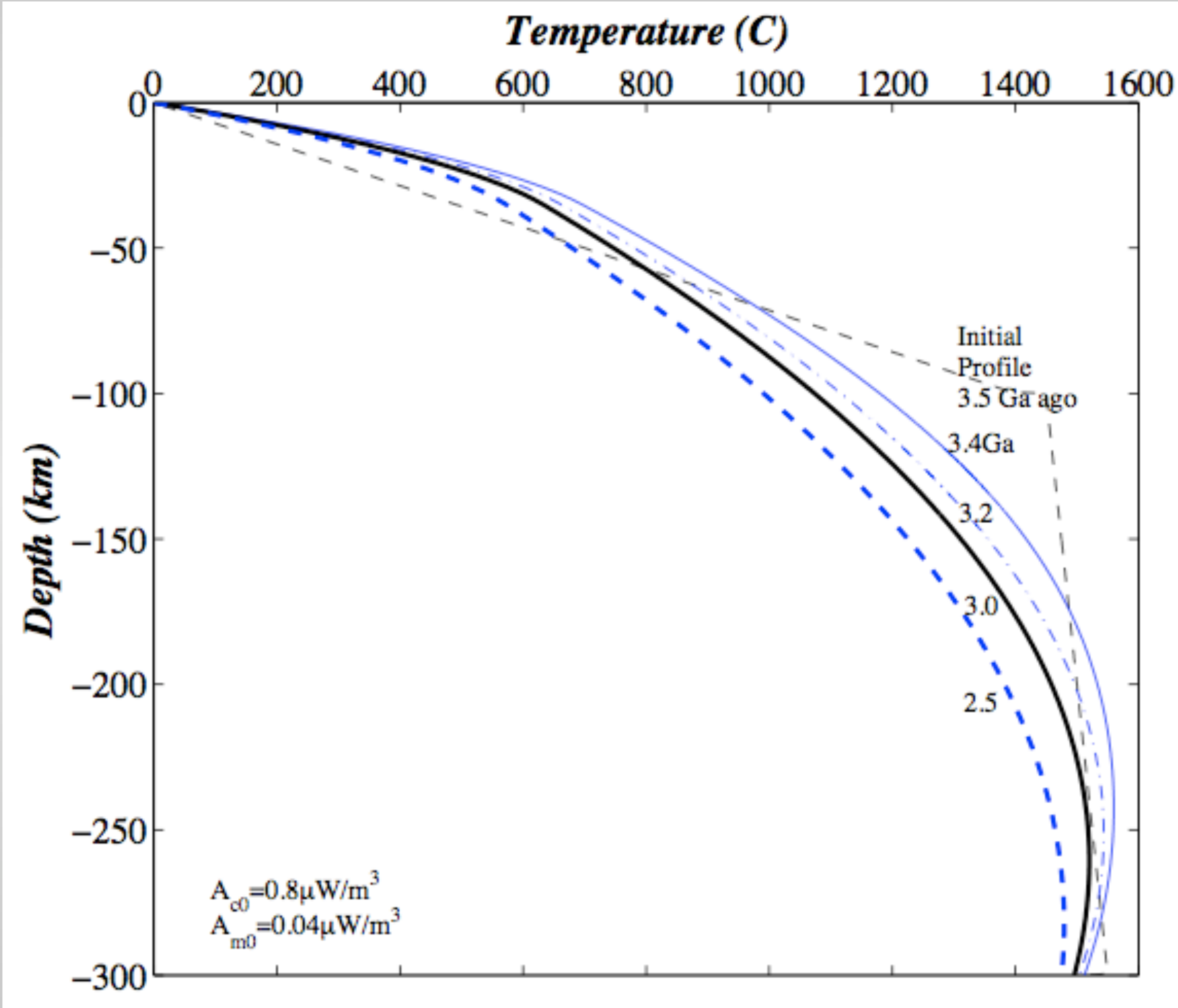
1. Formation of proto-lithosphere



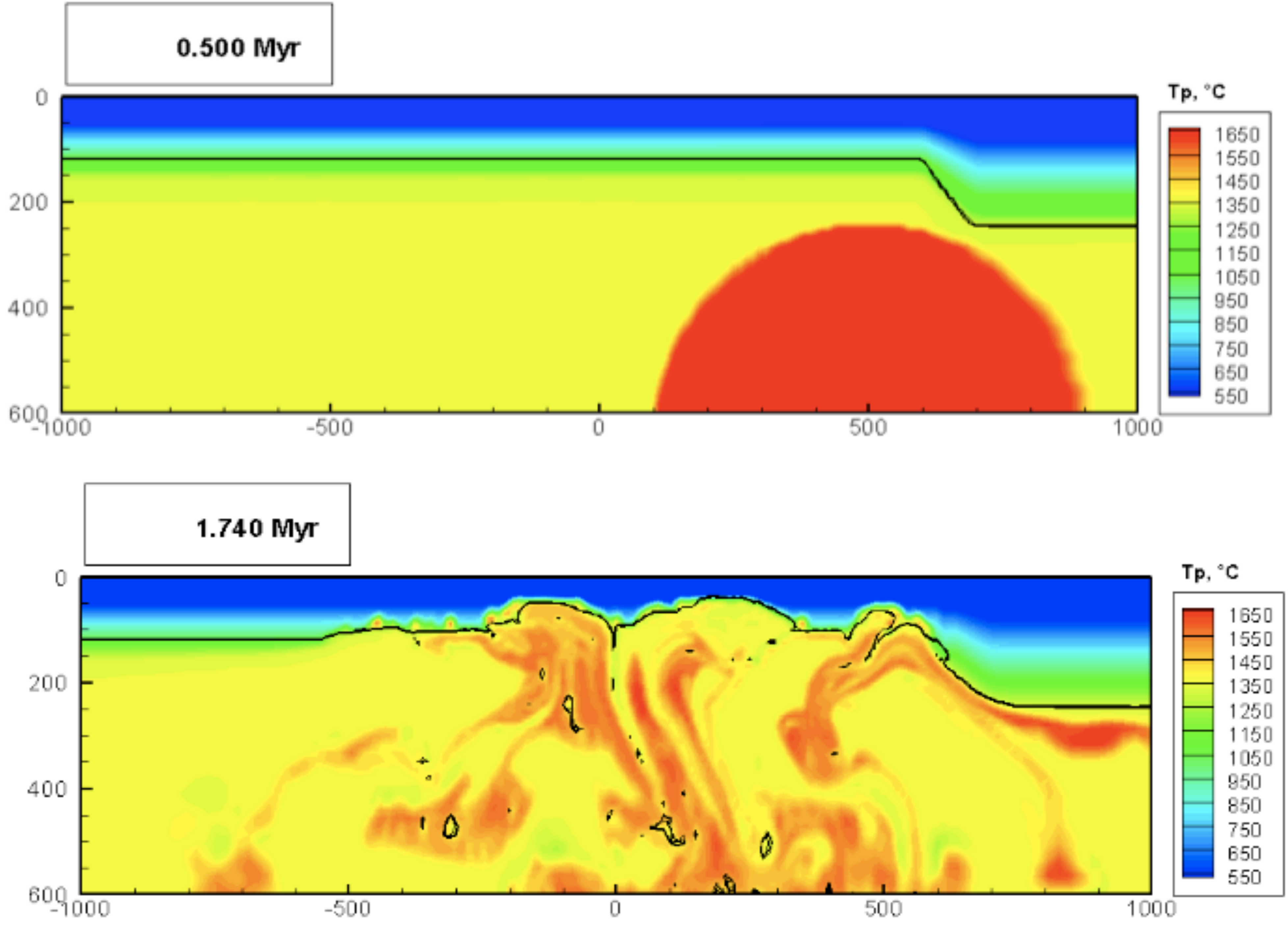
2. Foundering of dense phases



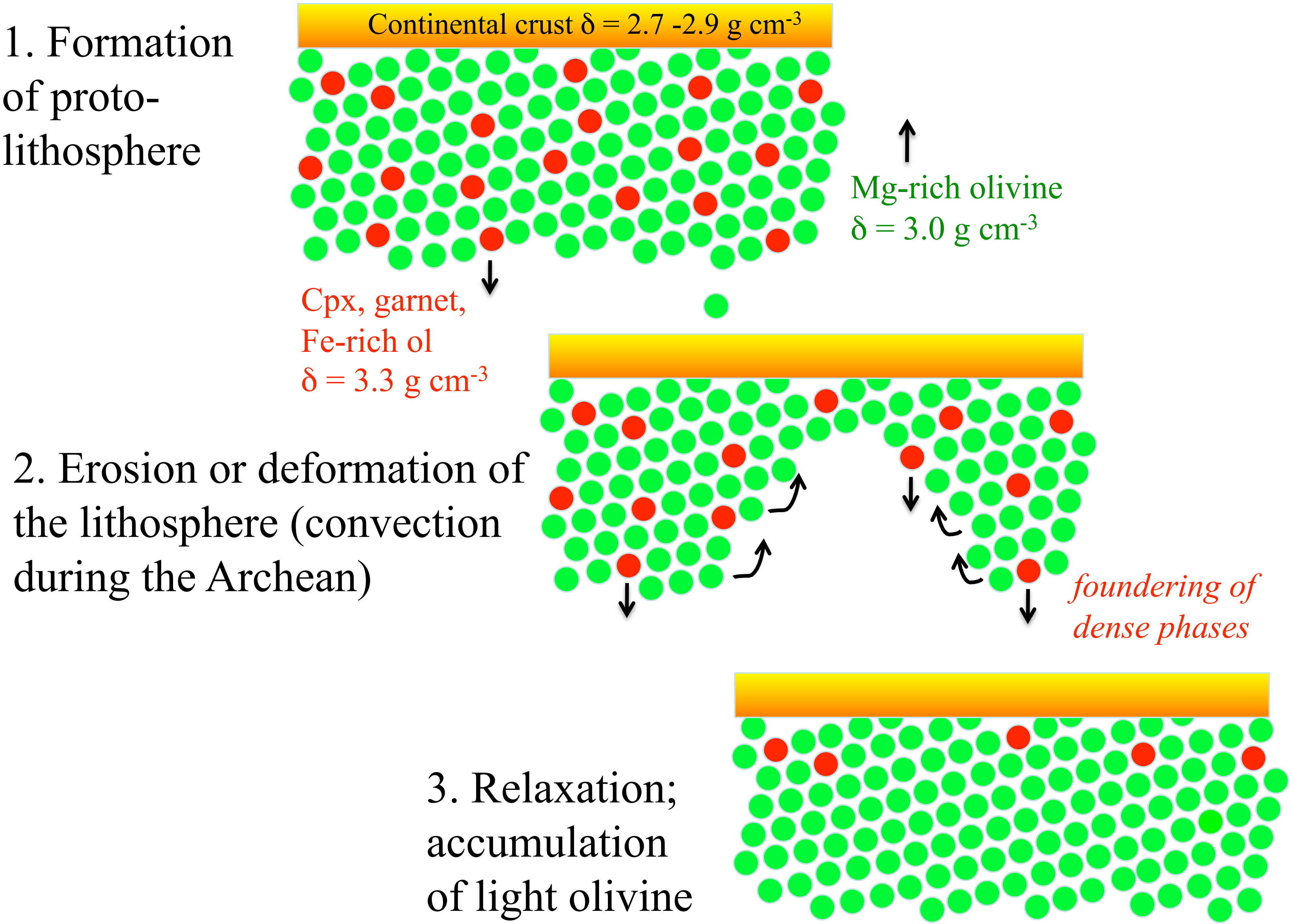
High temperatures in Archean cratonic mantle



Marescal et al (2009)



0.500 Myr
Tp, °C
1650
1550
1450
1350
1250
1150
1050
950
850
750
650
550
0
200
400
600
-1000
-500
0
500
1000
1.740 Myr
Tp, °C
1650
1550
1450
1350
1250
1150
1050
950
850
750
650
550
0
200
400
600
-1000
-500
0
500
1000


1. Formation of proto-lithosphere
Continental crust δ = 2.7 -2.9 g cm-3
Mg-rich olivine
δ = 3.0 g cm-3
Cpx, garnet,
Fe-rich ol
δ = 3.3 g cm-3
2. Erosion or deformation of the lithosphere (convection during the Archean)
foundering of dense phases
3. Relaxation; accumulation of light olivine

Conclusions – second part

- Cratonic lithosphere is an accumulation of rare mantle phases – Fo ± opx
- No model can generate their composition by purely petrochemical processes – density sorting is required
- Continental lithosphere is a sandwich of low-density phases that are stable near the surface
- Reworking of the lithosphere – crust and mantle - continues through geological time

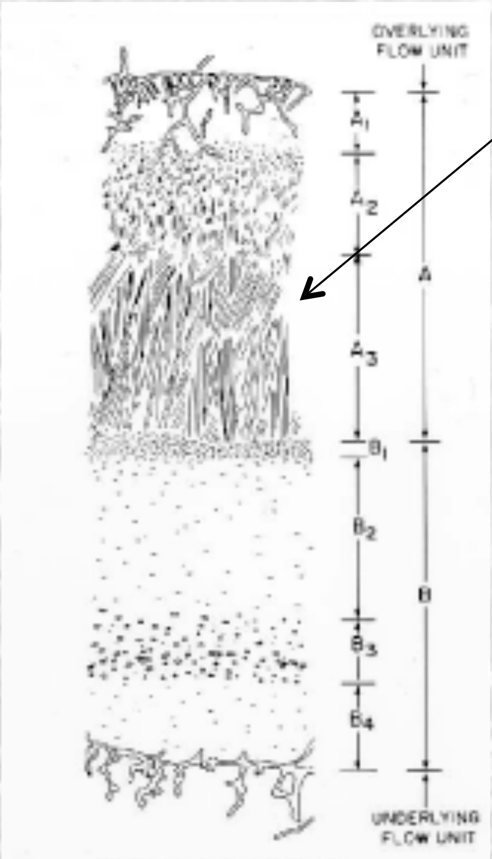
The wet komatiite hypothesis, as originally formulated by de Wit *et al.* (1987), Parman *et al.* (1997) & Grove *et al.* (1997)

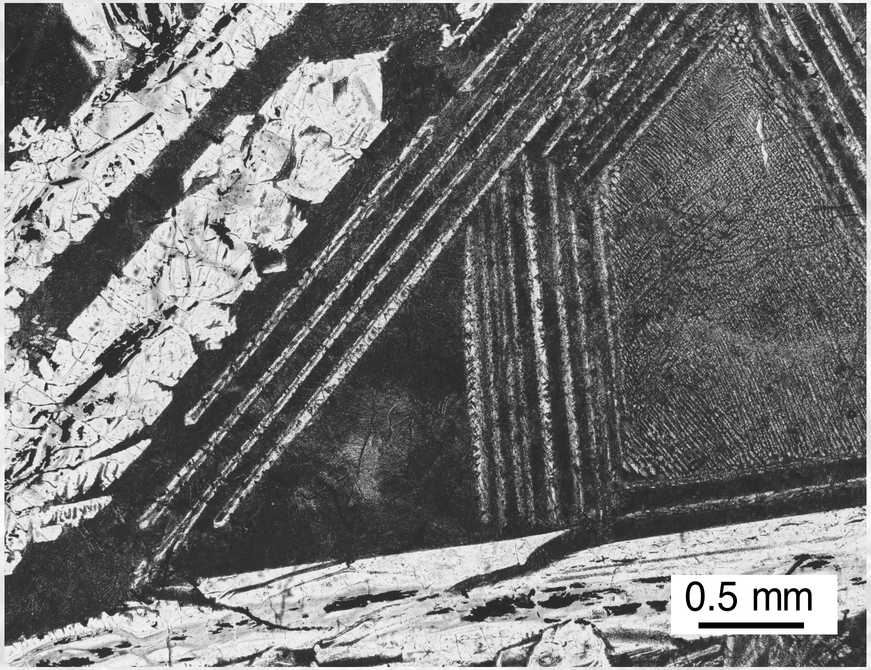
Komatiites from the Barberton greenstone belt in South Africa intruded as hydrous magma at ~6 km depth in a basaltic lava pile

Principal arguments for the hypothesis

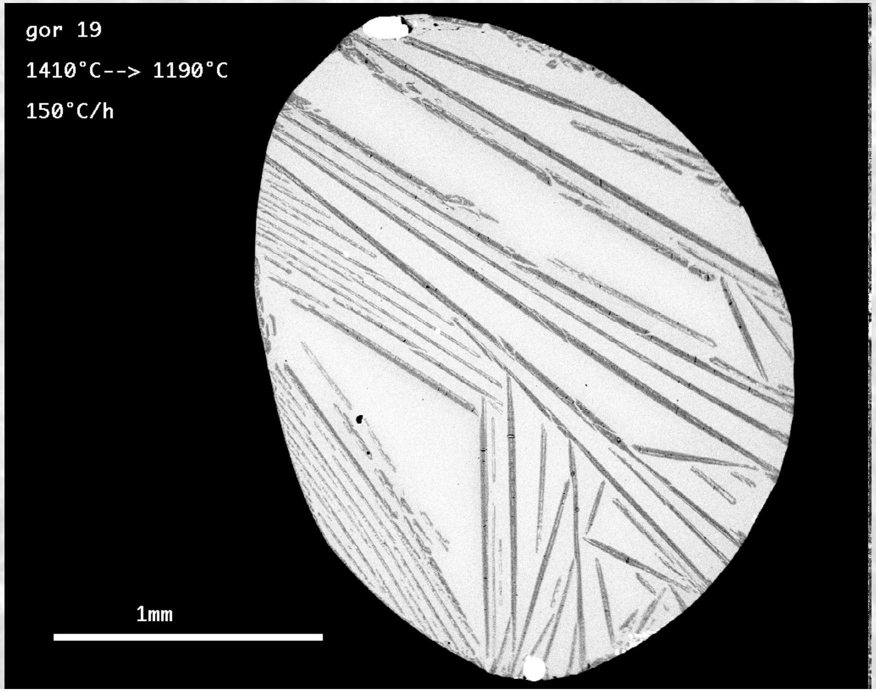
- Spinifex texture is not reproduced in dynamic cooling experiments on anhydrous komatiite
- Intrusive contacts at the margins of komatiite units
- Some komatiites are vesicular
- Pyroxene have high Wo contents consistent with crystallization in hydrous magma at 1-2 kbar pressure.

Spinifex texture does not form in experiments on anhydrous komatiite; olivine morphologies deep in the interior of komatiite units correspond to impossibly high cooling rates





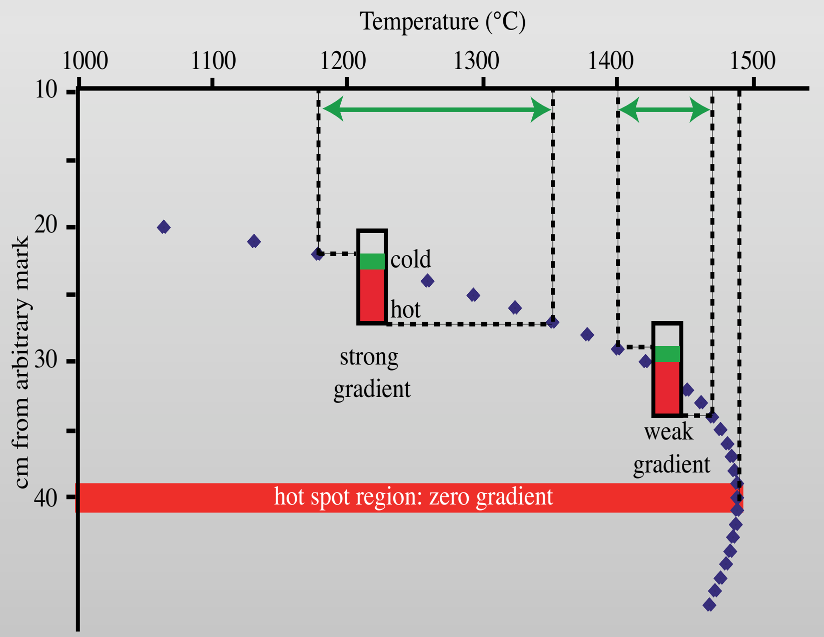
Natural spinifex from 1m below flow top; cooling rate >5°C/h

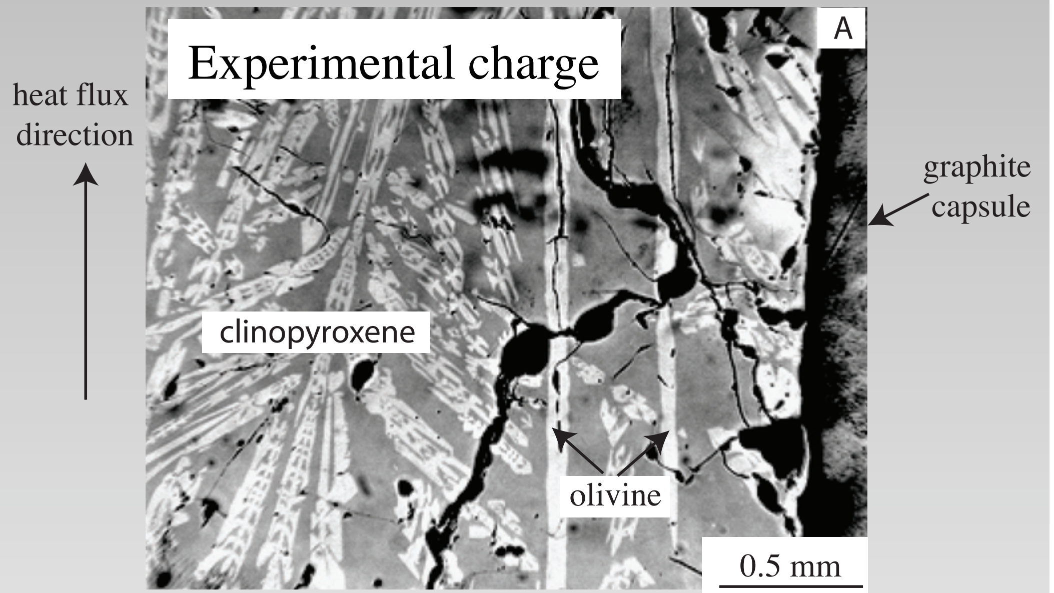


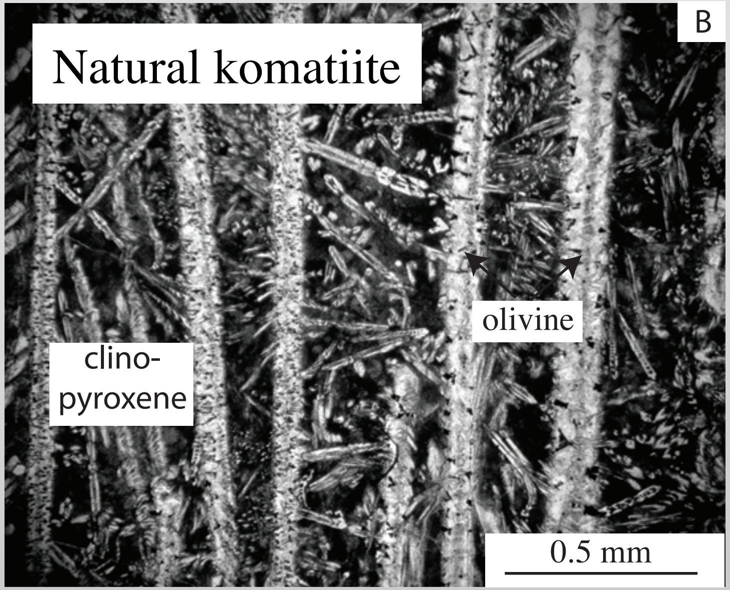
Spinifex in experiments (Ginibre, 1987) 150°C/h

Faure *et al.*'s experiments
(J Petrol. 2005)

Experiments conducted in the thermal gradient of a furnace to reproduce conditions in the crust of a lava flow

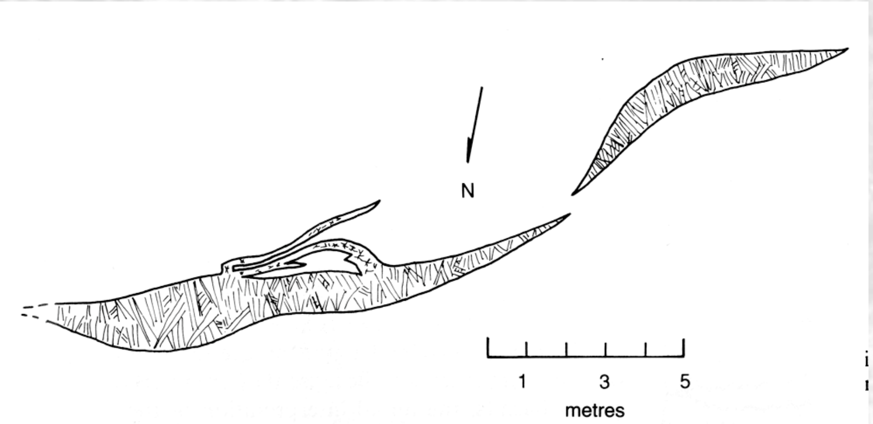


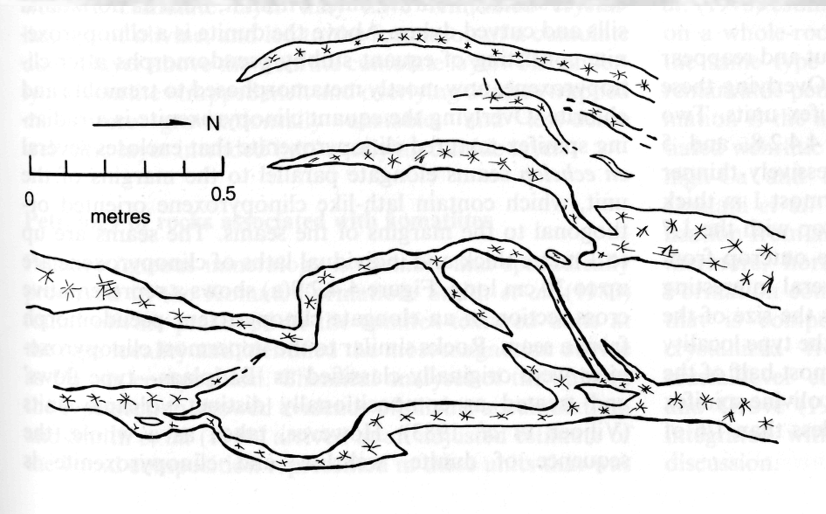




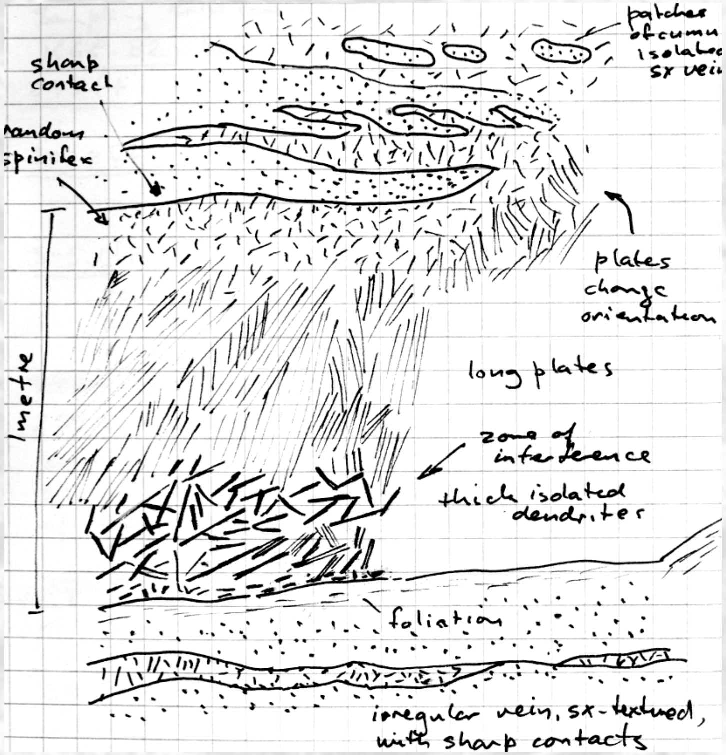
In the presence of a thermal gradient, spinifex is reproduced experimentally

Intrusive contacts





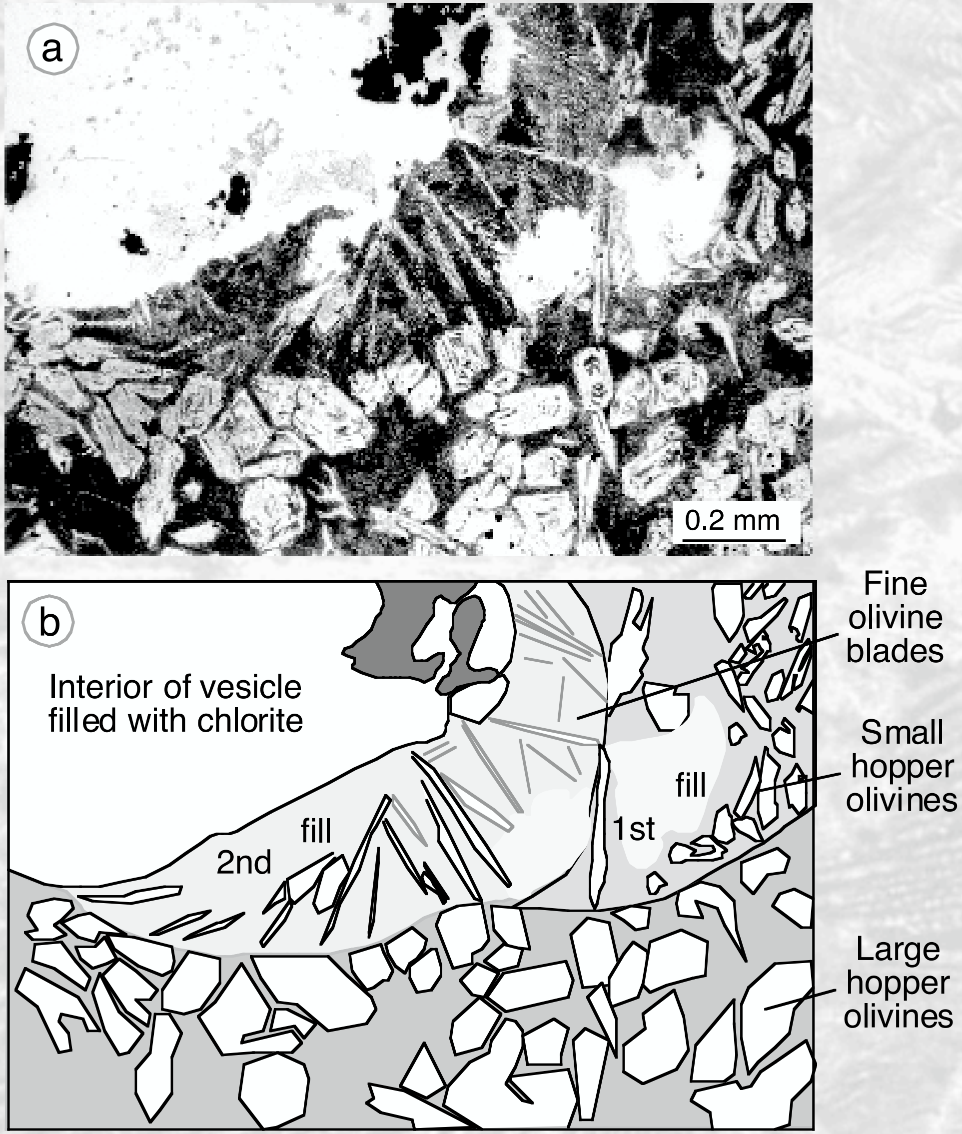
Sketches of veins in Barberton komatiites (Grove *et al*. 1997)



Veins in komatiite flows from the Abitibi belt

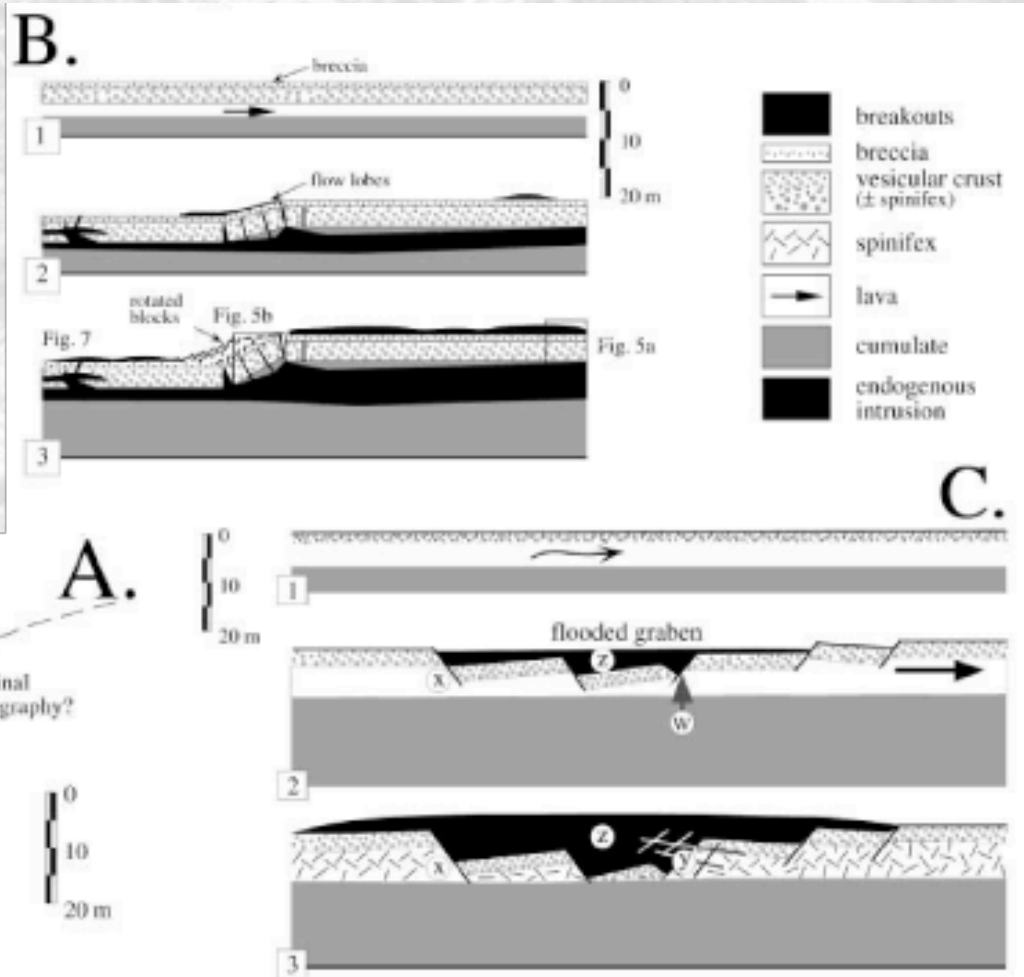
These are internal structures <u>within</u> lava flows

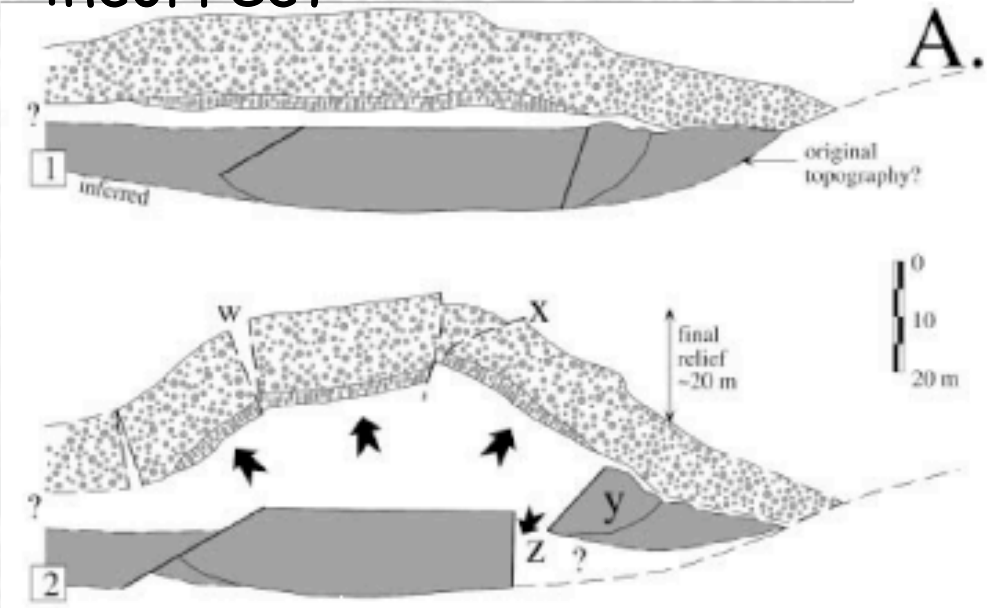
Vesicular komatiites exist but they are relatively rare and vesicles are never very abundant



Jesse Dann's (2000) mapping of Barberton komatiites

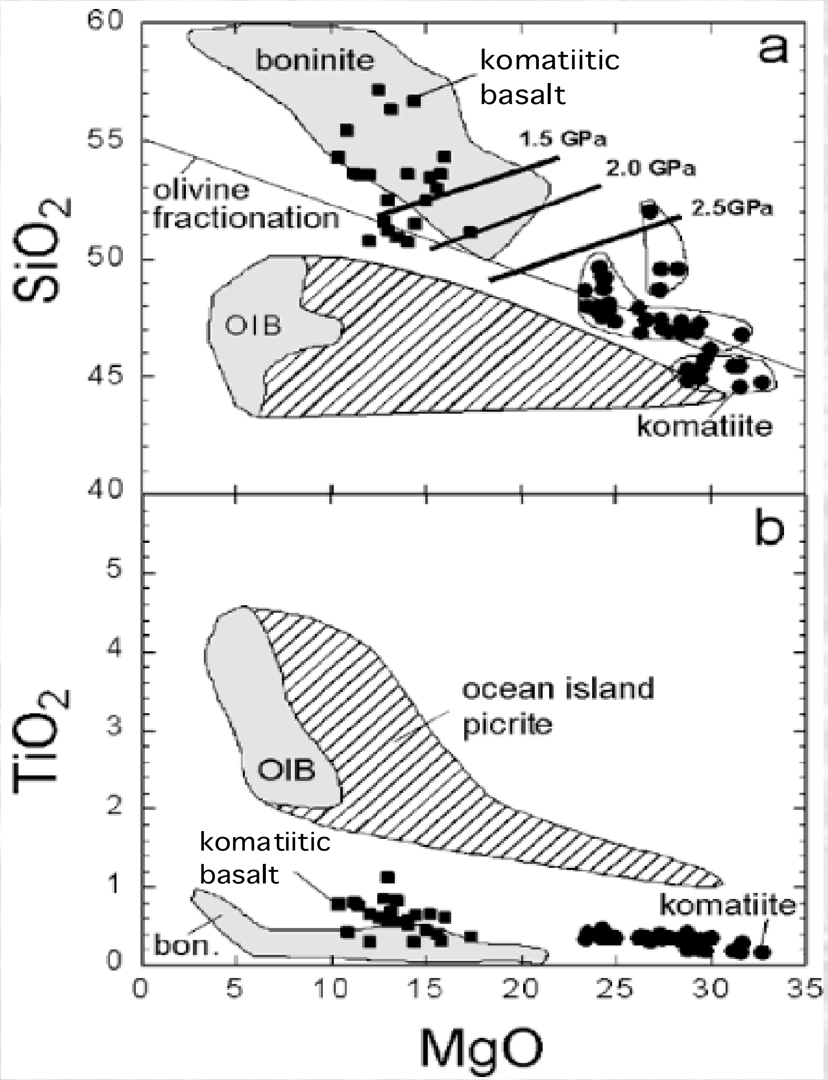
Barberton komatiites are lava flows, not intrusions. The arguments for crystallization at moderate pressure are incorrect



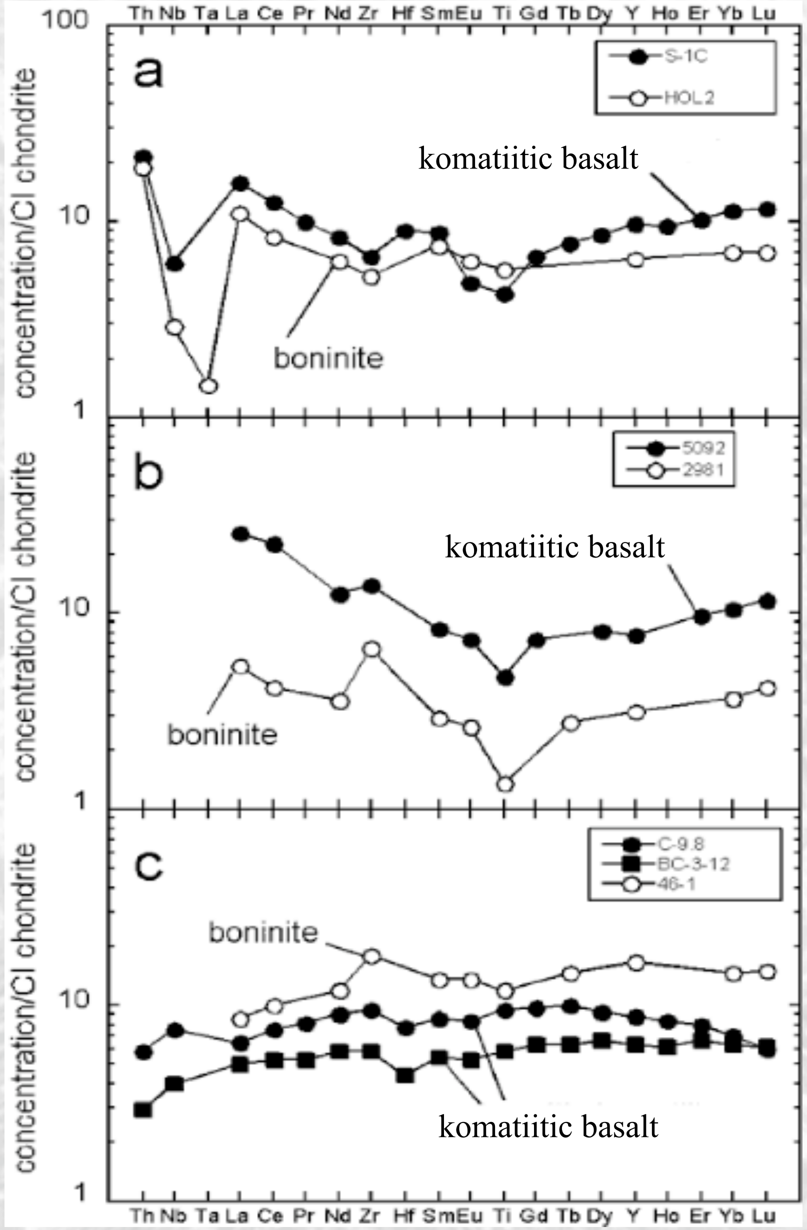


Parman *et al*. (2004)

komatiites form in subduction zones

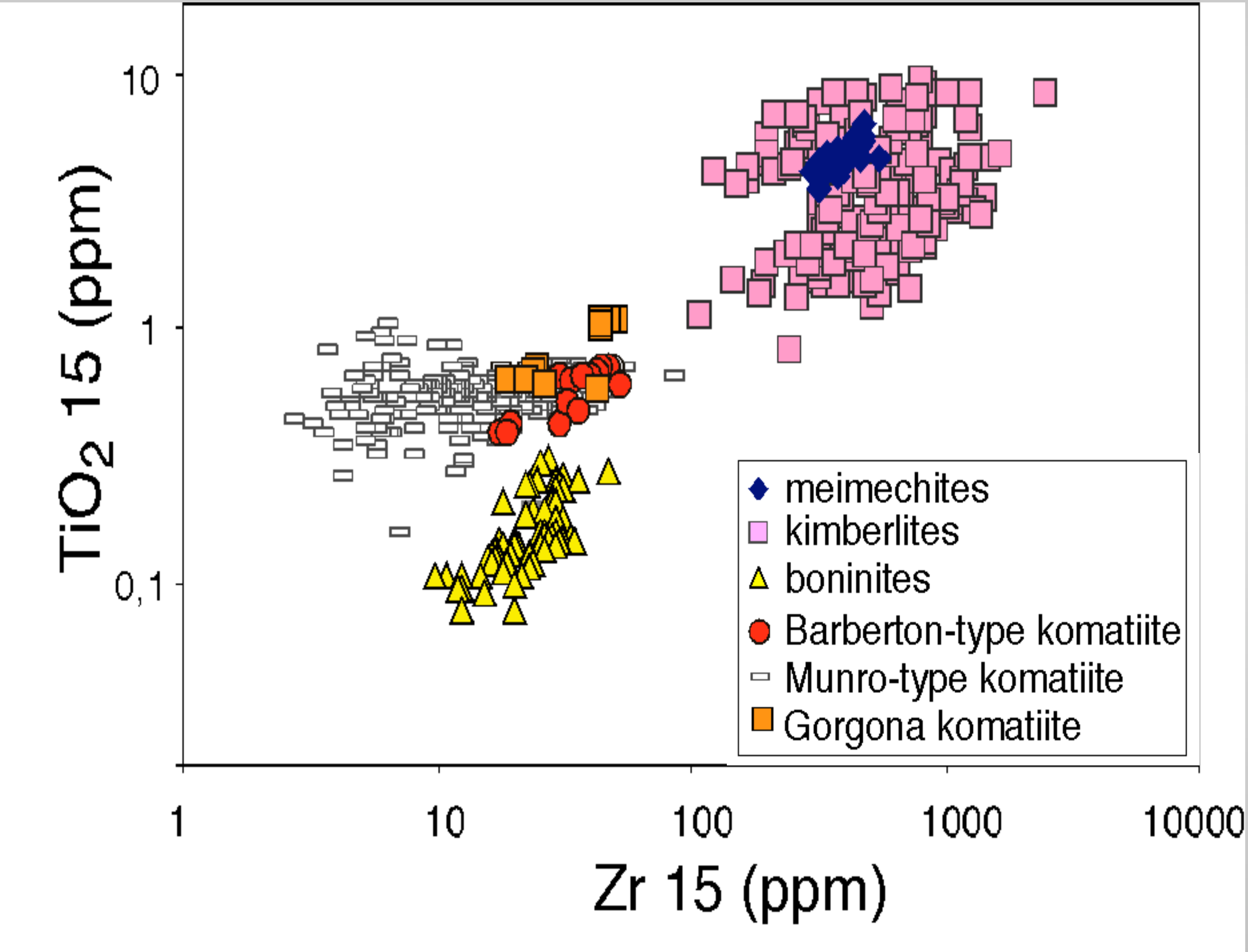


Barberton komatiites have high Si and low Ti, approaching those of boninites



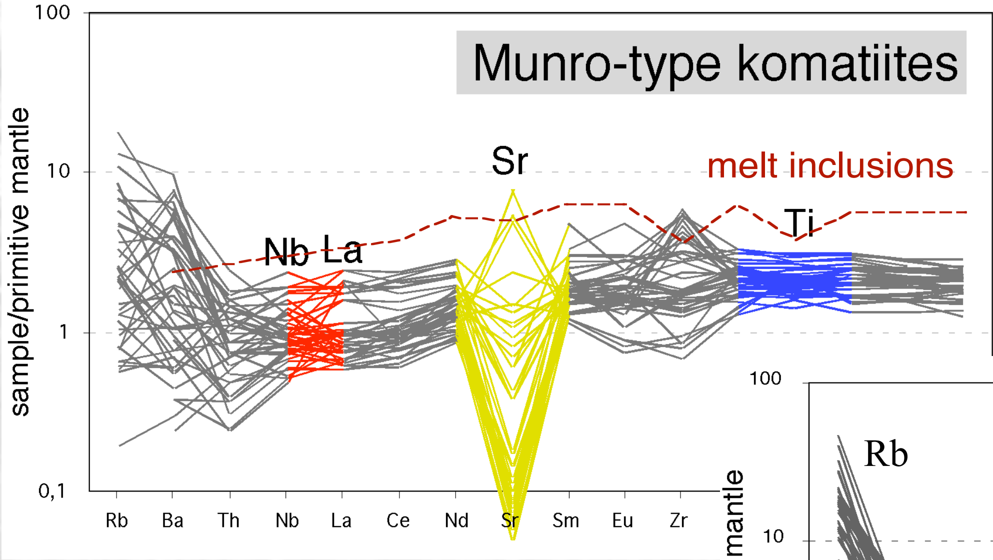
Some komatiitic basalts have trace element patterns like some boninites

xx

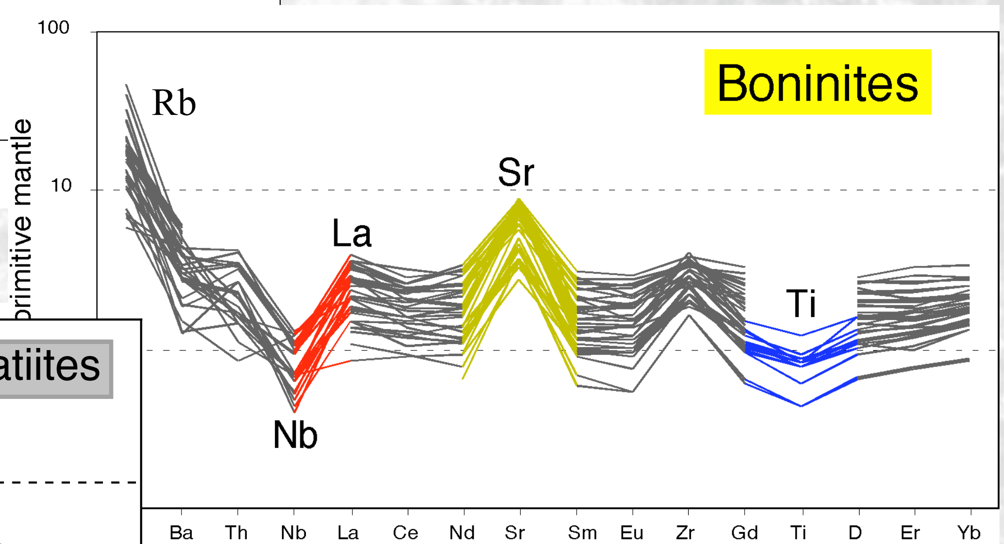


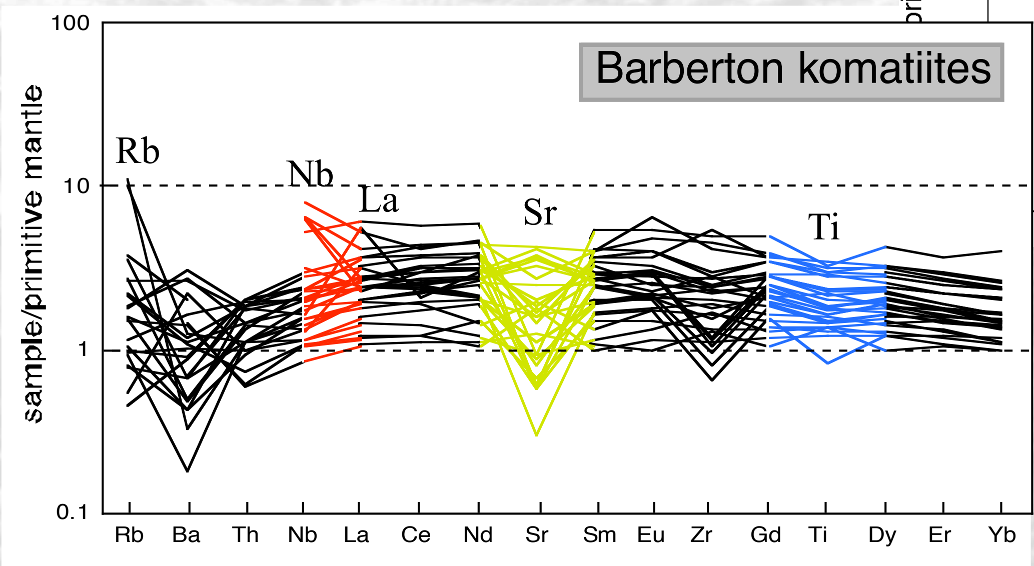
10
1
0,1
1
10
100
1000
10000
TiO2 15 (ppm)
Zr 15 (ppm)
meimechites
kimberlites
boninites
Barberton-type komatiite
Munro-type komatiite
Gorgona komatiite

Mantle-normalised trace elements



A U-shaped pattern, low Nb and Ti, and high Rb and Sr is the "subduction signature"





Subduction signature in boninite not in komatiite

Pyroxene compositions
(Parman *et al.* 1997)

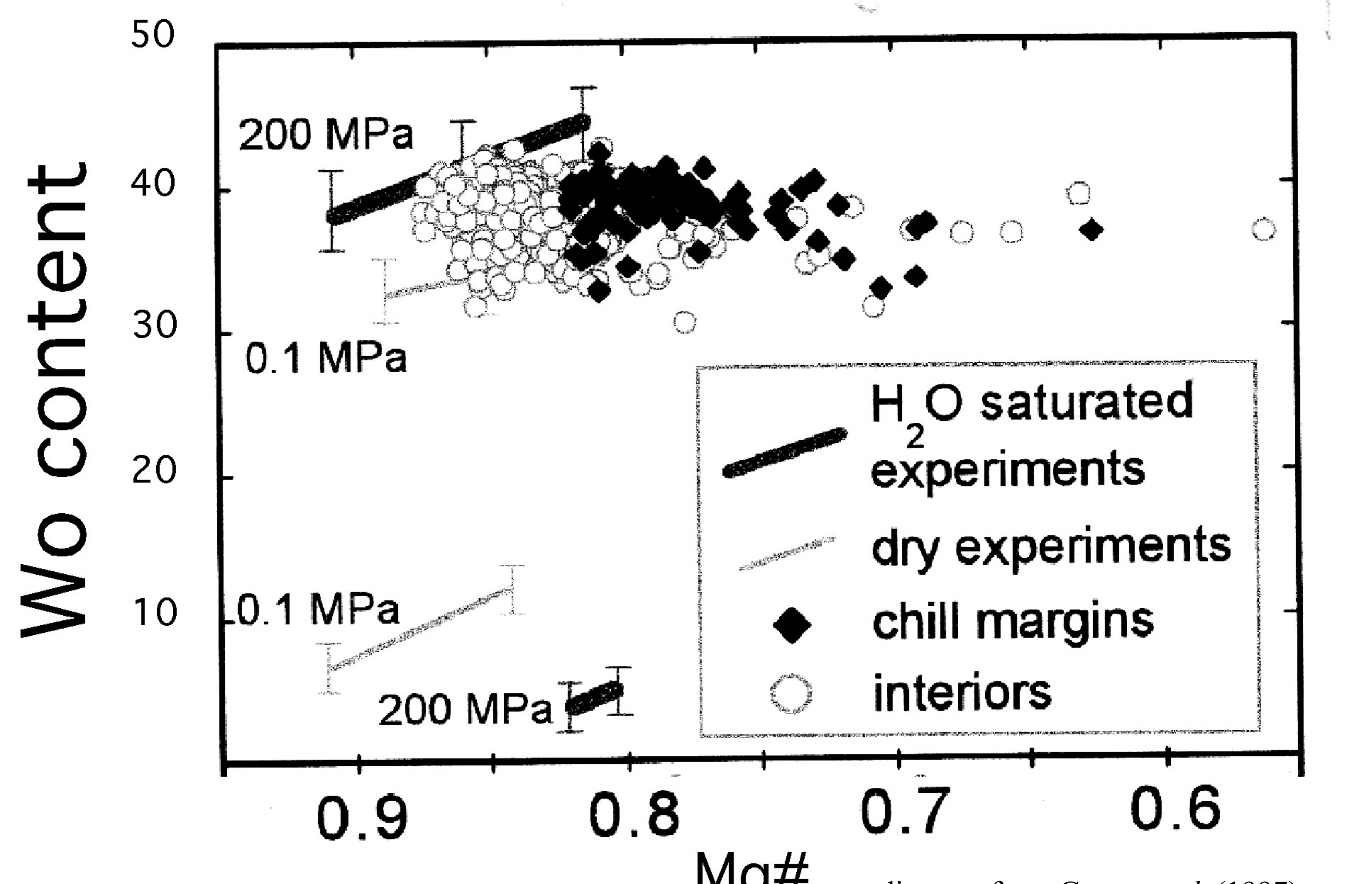


diagram from Grove *et al.* (1997)

Compositions of some augites in Barberton komatiites correspond to those of pyroxene that crystallizes in experiments on hydrous komatiite at 100-200 MPa