Komatiites and the Early Evolution of the Earth

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Jesse Dann, Marten de Wit (UCT), Alan Wilson (WITS)

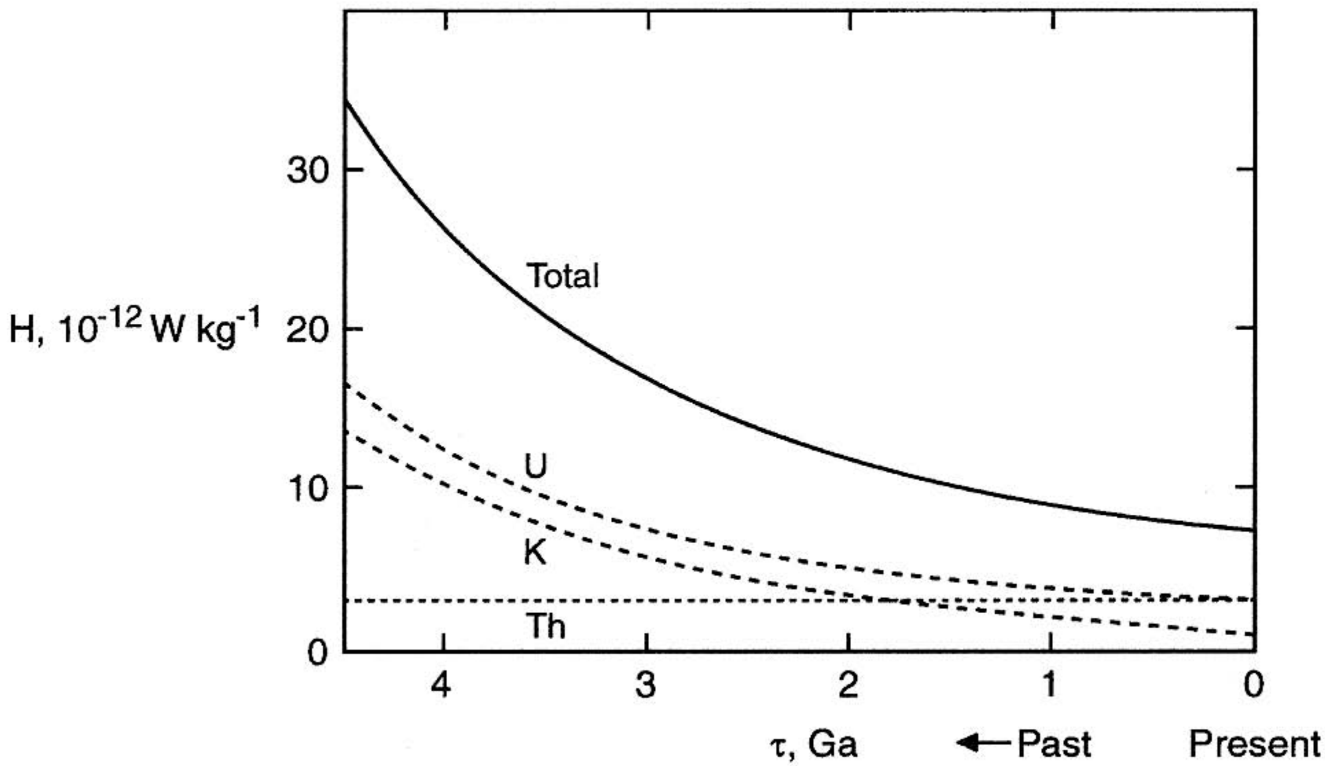
Outline

- Earth Evolution: theories and constraints
- Komatiites: evidence for a subduction origin
- Komatiite mantle melting process: a new-old model
- Implications for the Early Earth

Heat Sources in the Early Earth

- Radiogenic Heat
- Core Segregation
- Giant Impact/Accretionary Heat

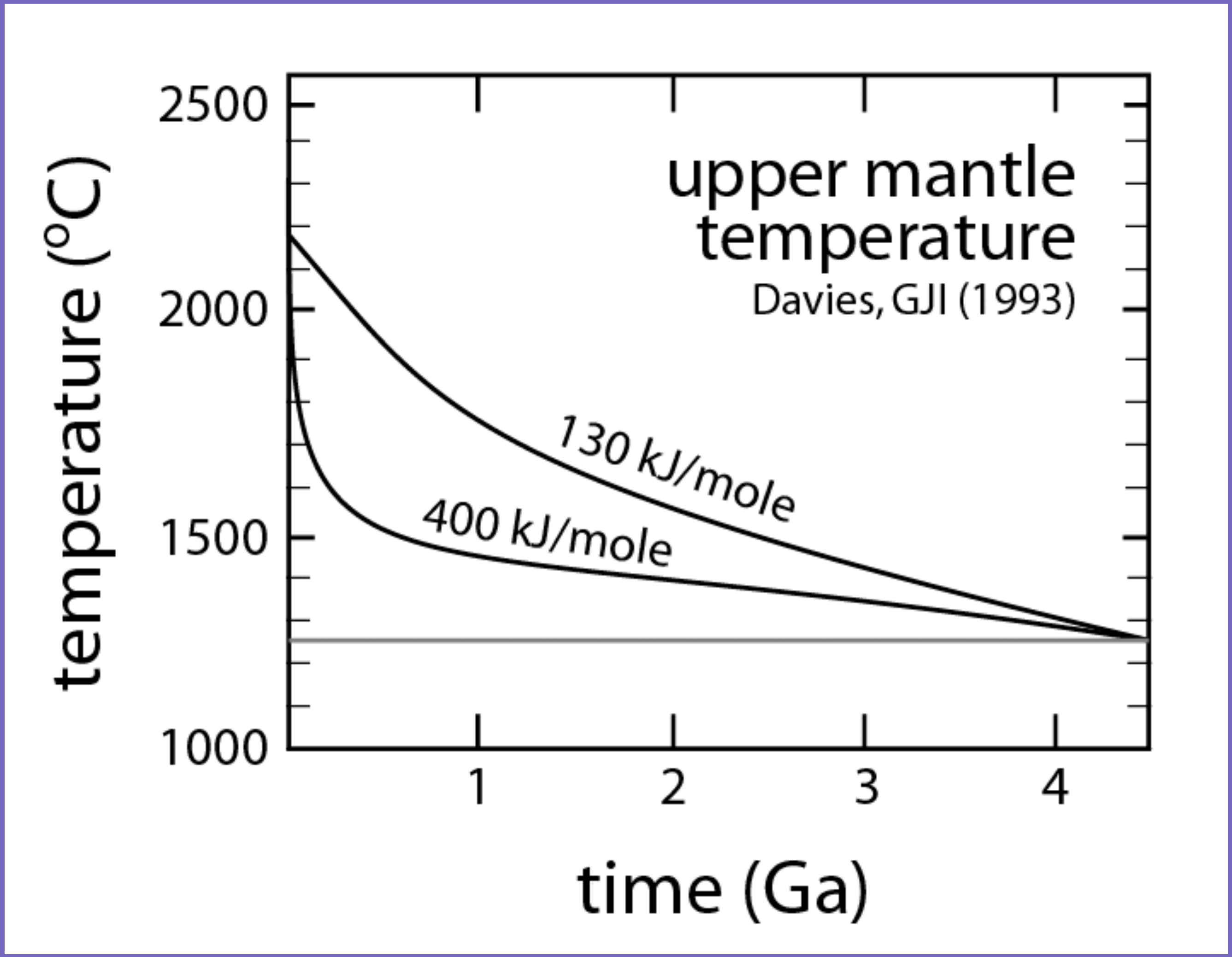
Heat Sources in the Early Earth



4–4 Mean mantle heat production rates due to the decay of the radioactive isotopes of U, Th, and K as functions of time measured back from the present.

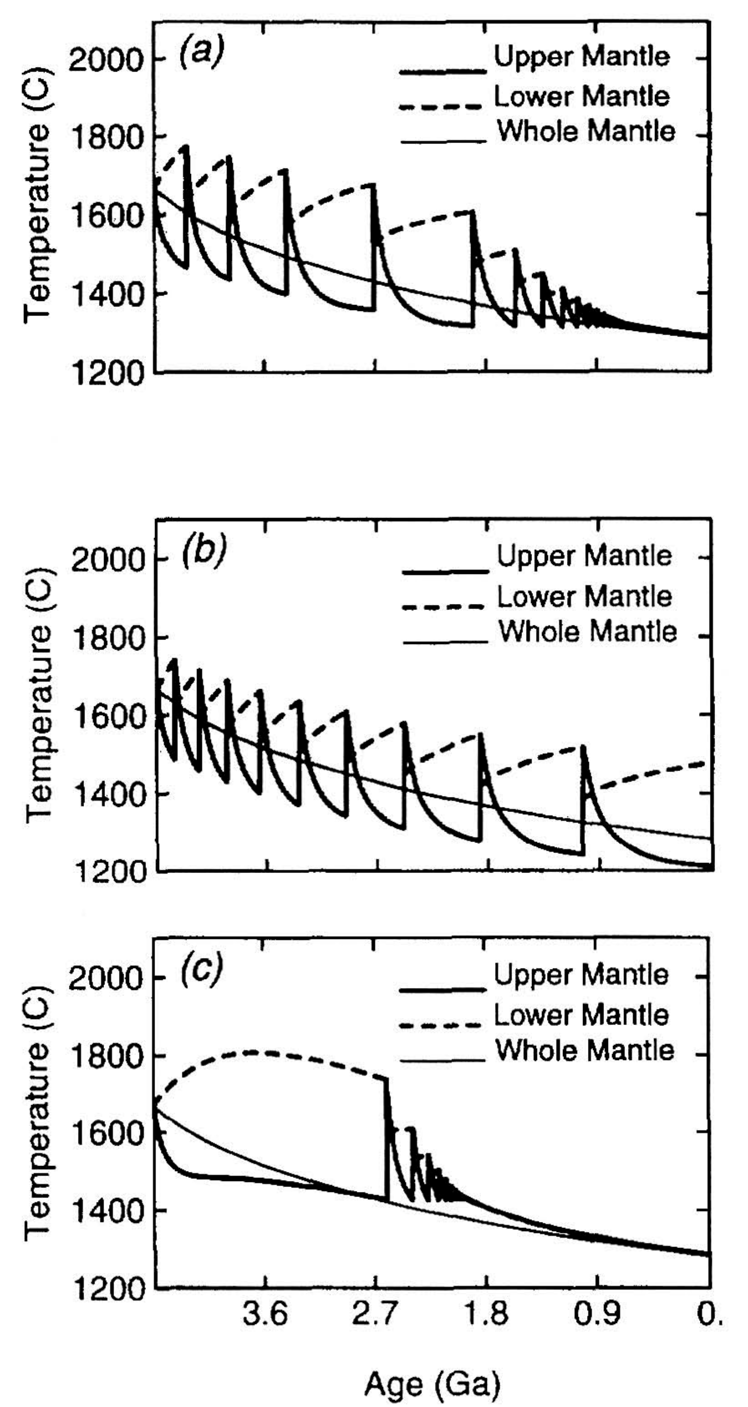
Turcotte and Schubert, Geodynamics (2002)

Geodynamic Models - basic



Geodynamic Models

episodic cooling due to phase transitions



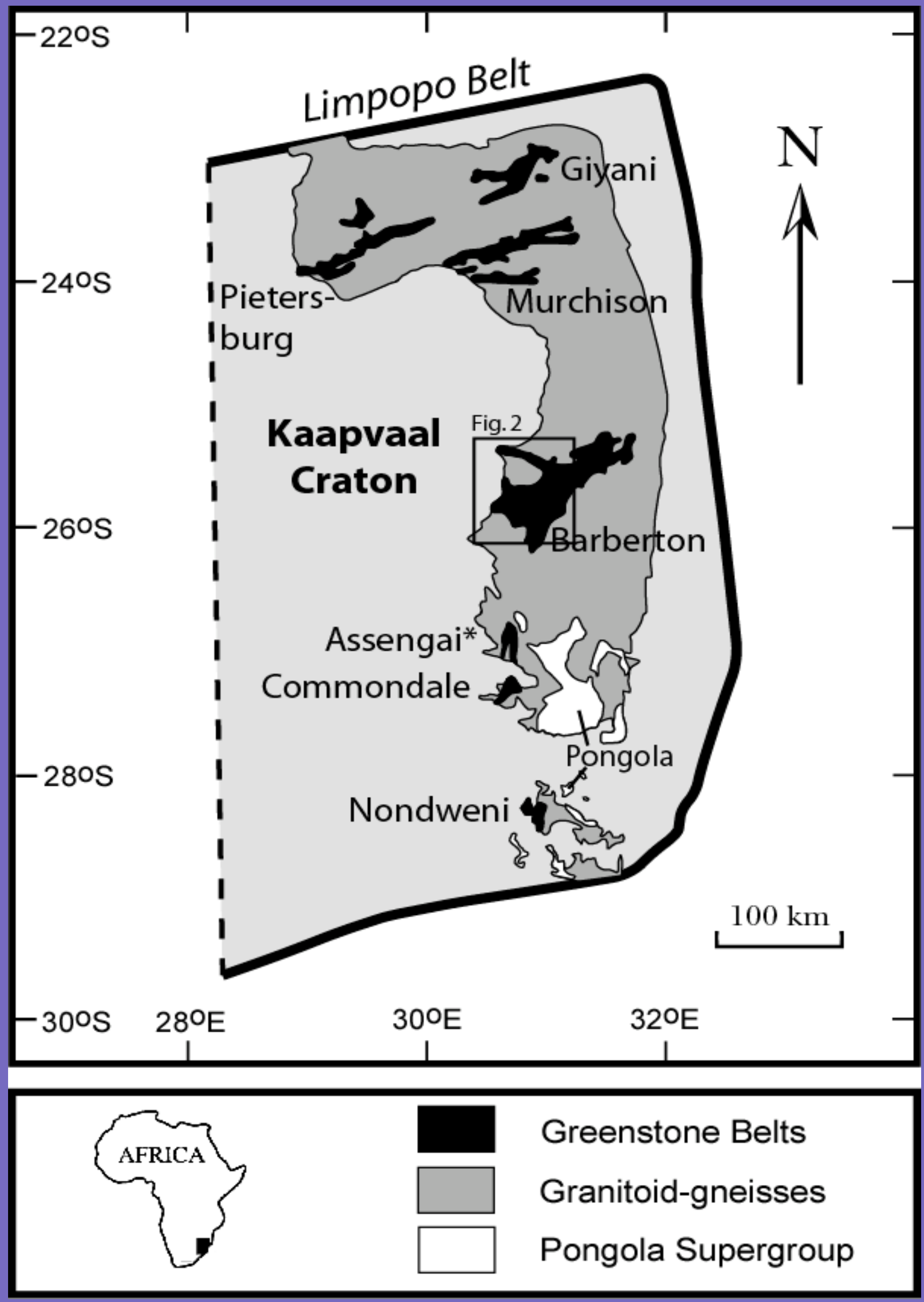
Davies, EPSL (1995)

Observational Constraints

- Metamorphic Gradients - **inconclusive**
- Tectonic Style (rigid vs gooey) - **inconclusive**

- Archean magmatic products - **promising**
  - Direct evidence of temperatures in the interior of the early Earth
  - Fundamental constraint on all **thermal and chemical** evolution models

Eastern Kaapvaal Craton



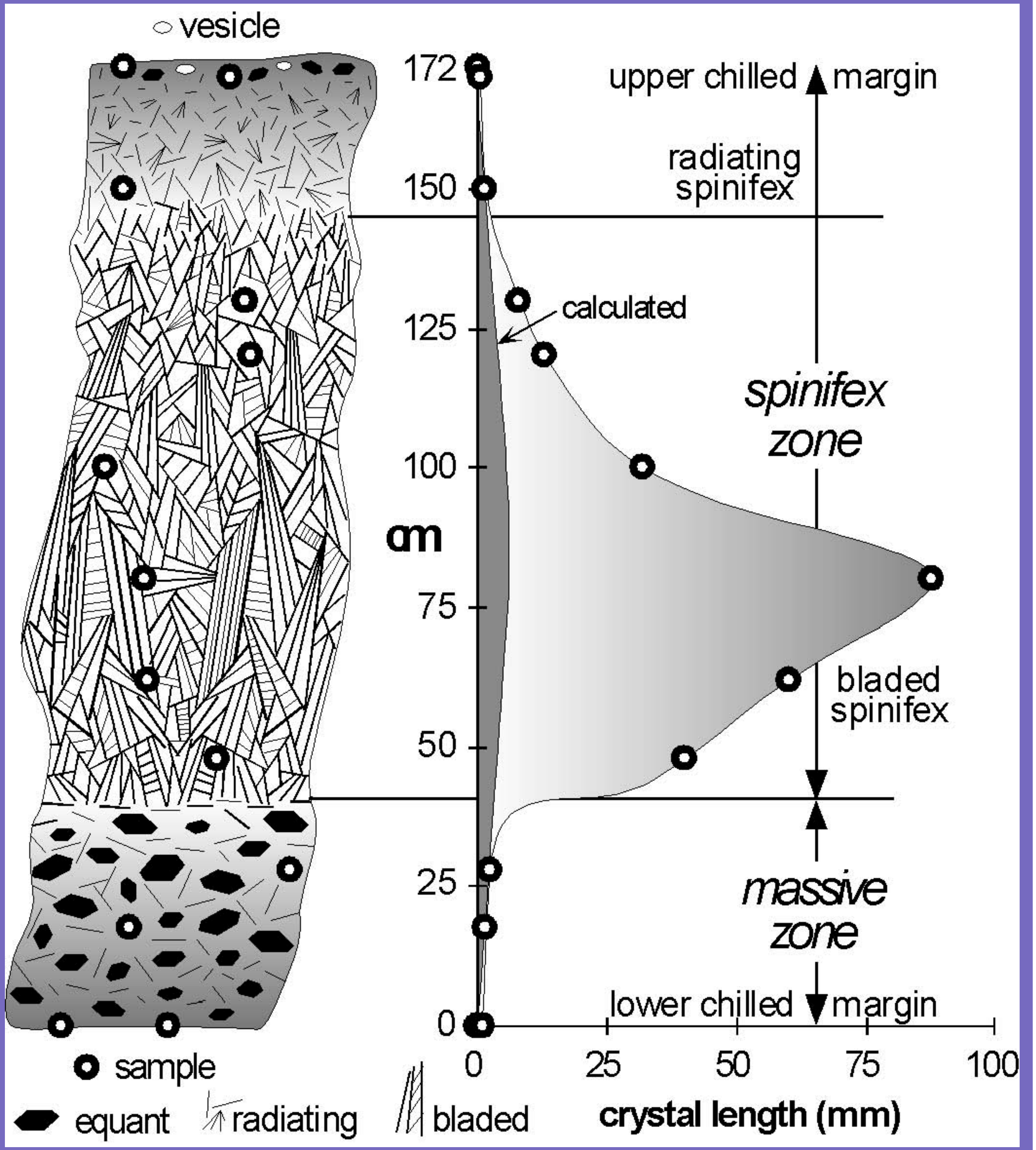
Not too different in the Archean

- Magmatic products in greenstone belts (to 3.5 Ga) and gneisses (to 4.0 Ga) are primarily **basalts and granites**. <u>No suggestion of higher temperatures.</u>

- 4.4 Ga zircons (Wilde et al., Nature, 2001) contain granitic inclusions and provide isotopic evidence for liquid surface water.

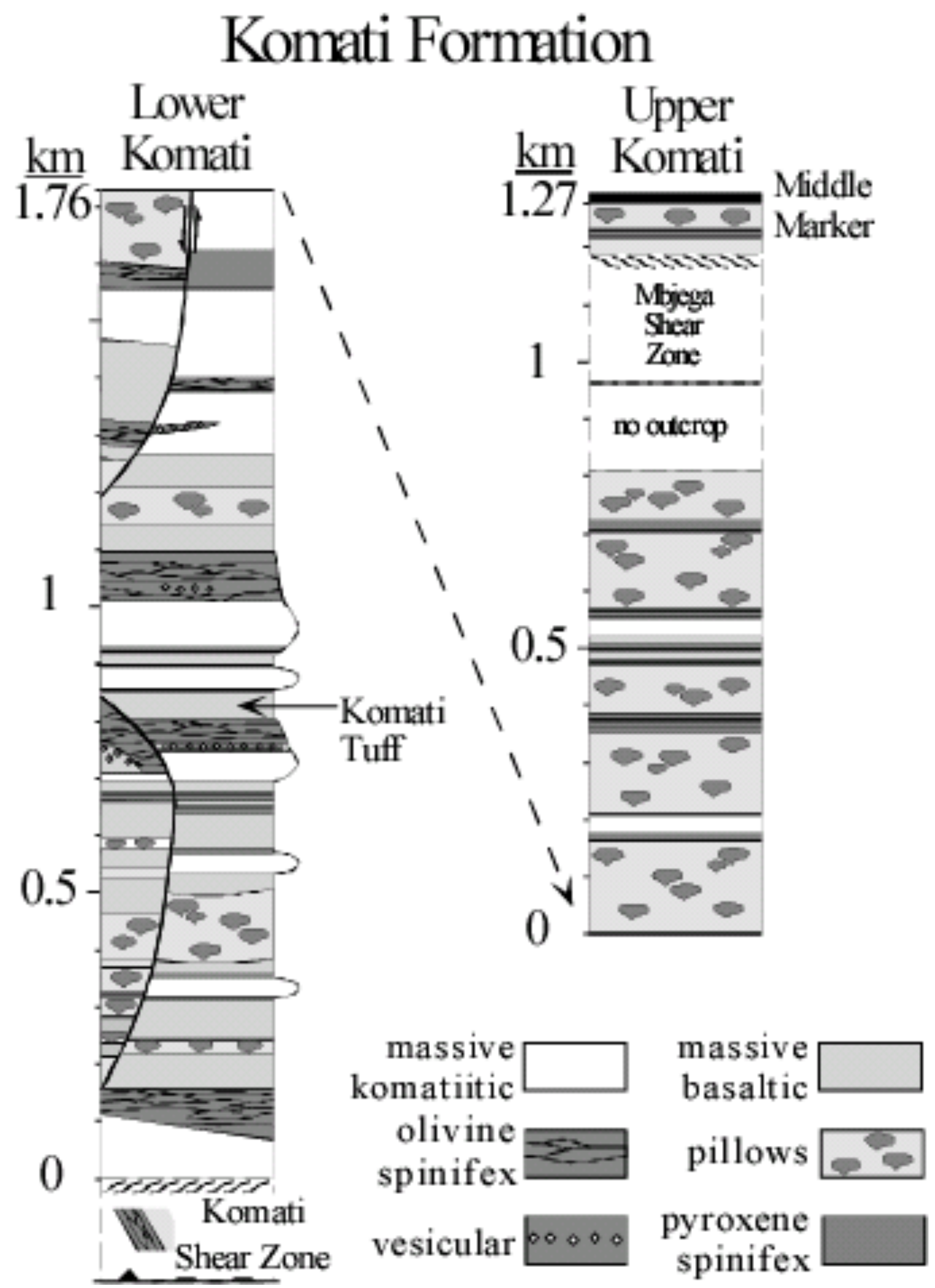
- Primary difference - presence of **komatiites** in many igneous sequences

1.7 m thick unit in Komati Fm.

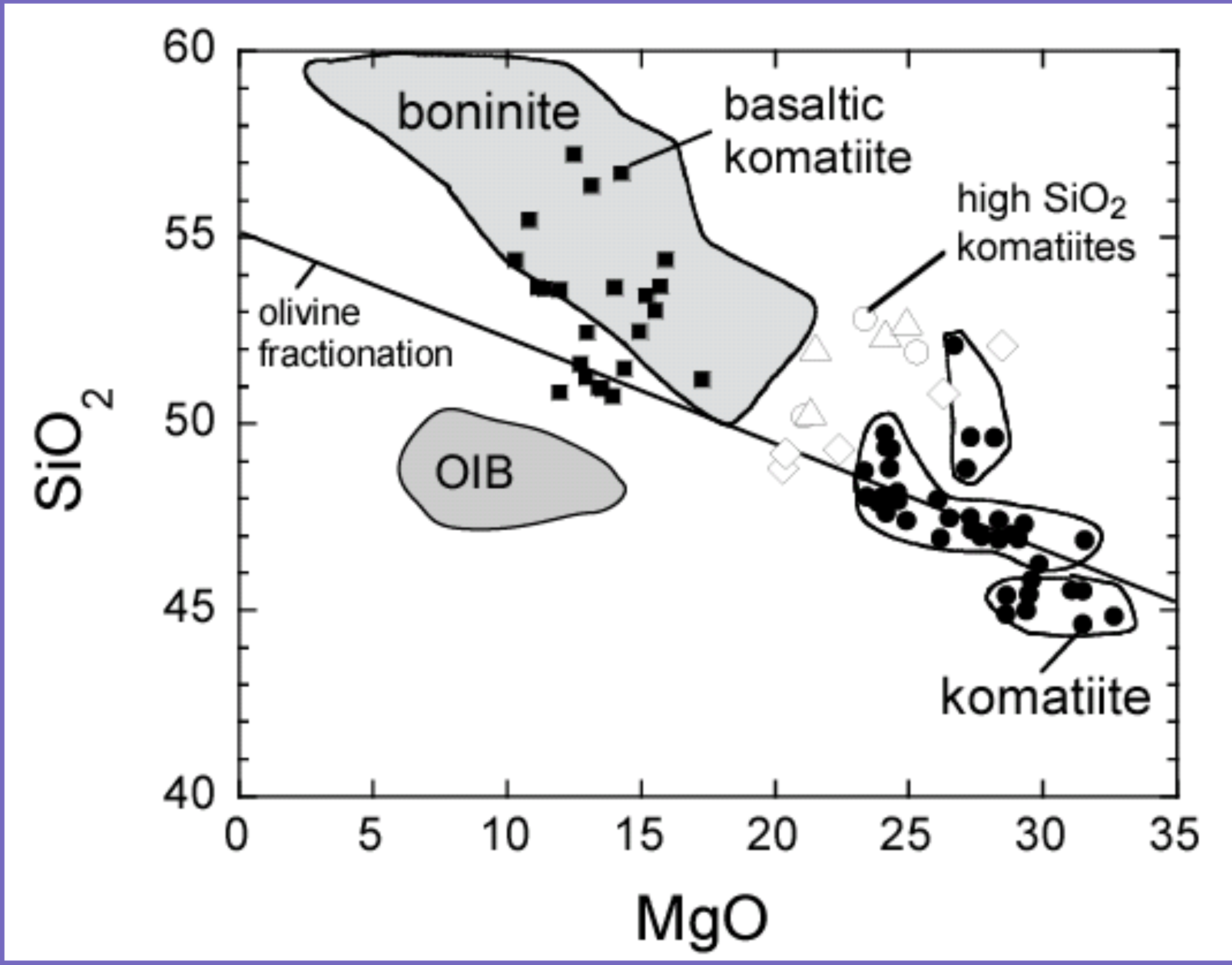


~10% of stratigraphic thickness is komatiite

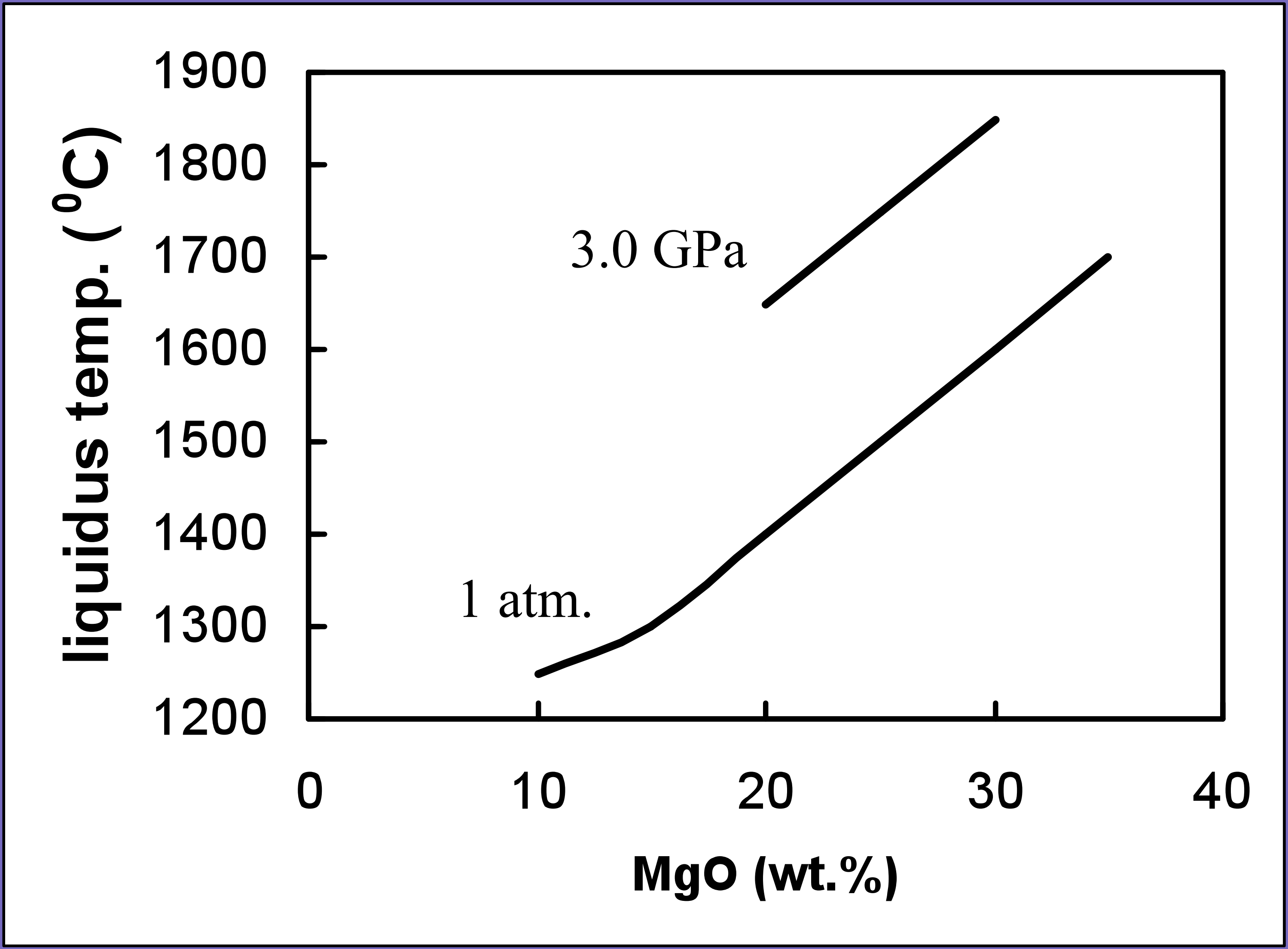
after J. Dann



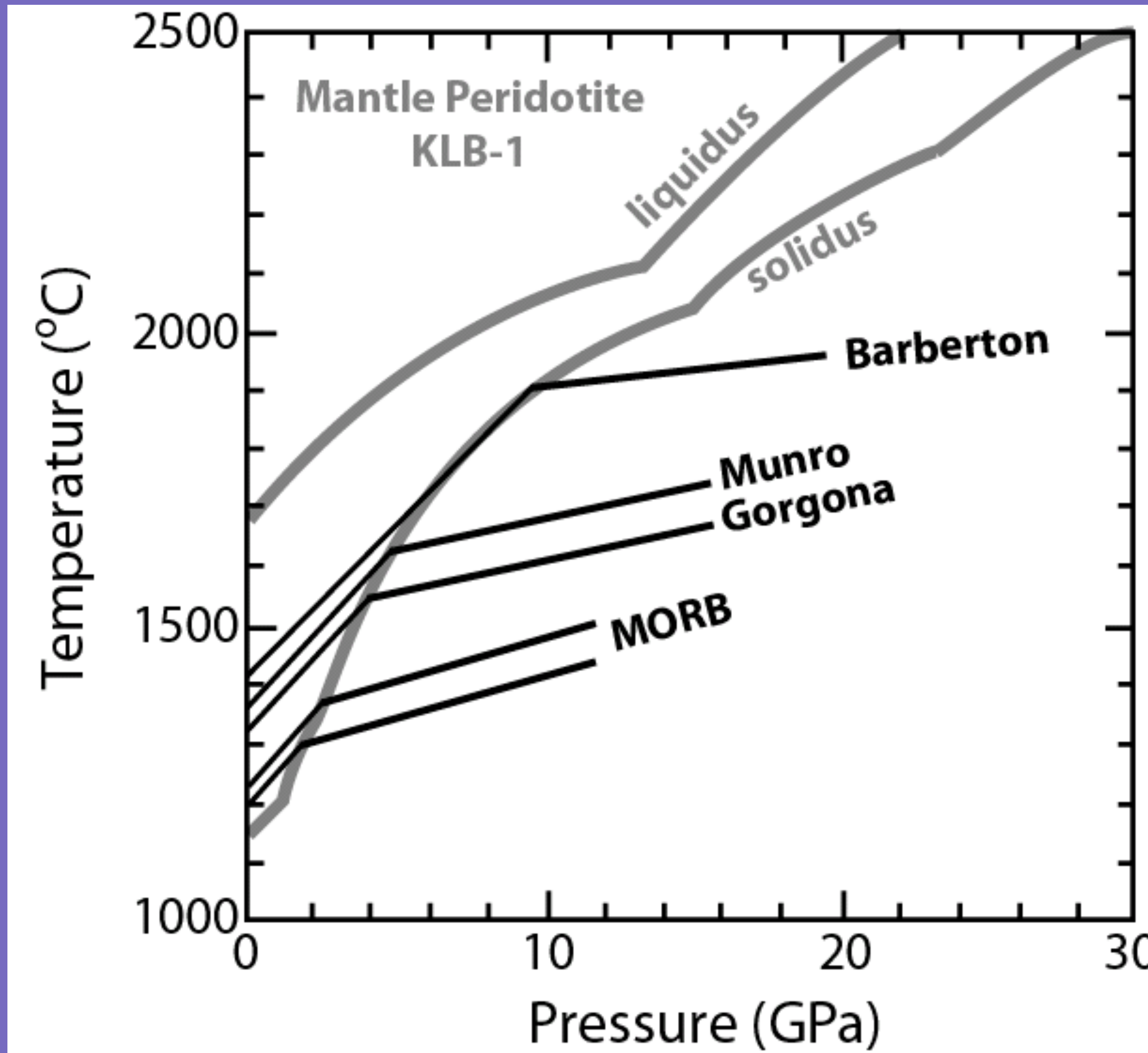
Really, really, really high MgO



High MgO means high T



Plume model

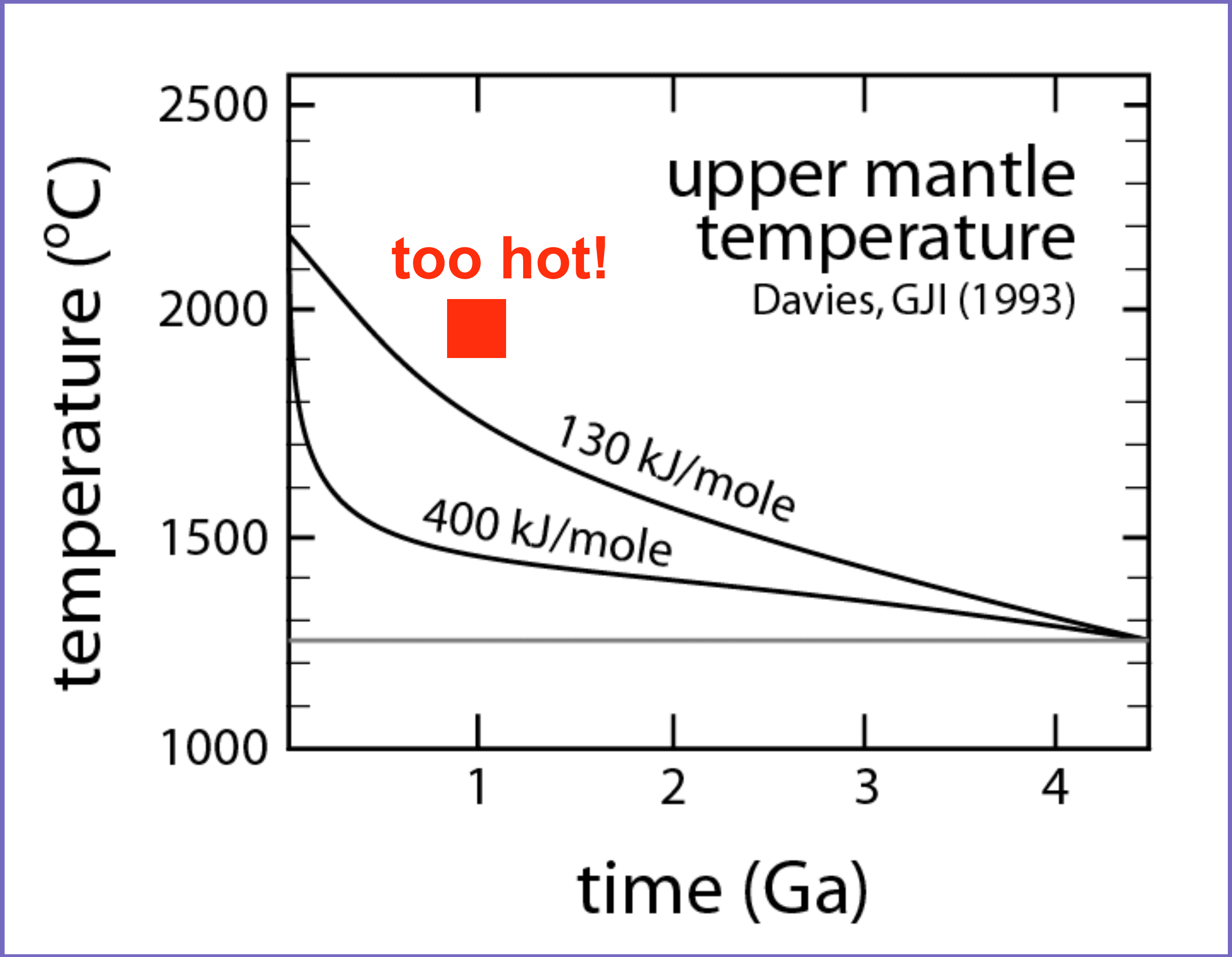


Herzberg, JGR (1992)

Inklings of a Problem

- Much of upper mantle would be molten
- Many komatiites interlayered with subduction related magmas
- Mounting evidence for high H_2O contents

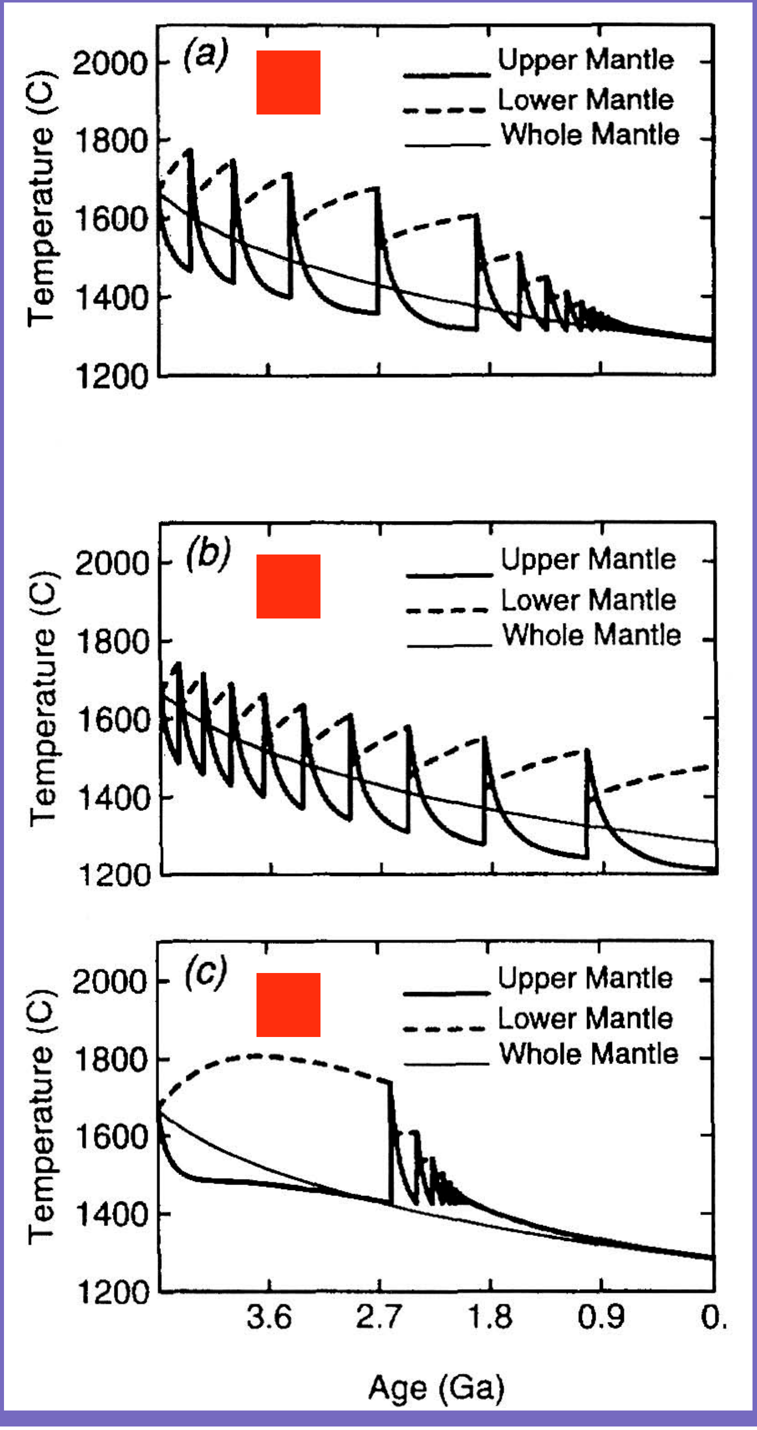
Not compatible with geophysical constraints



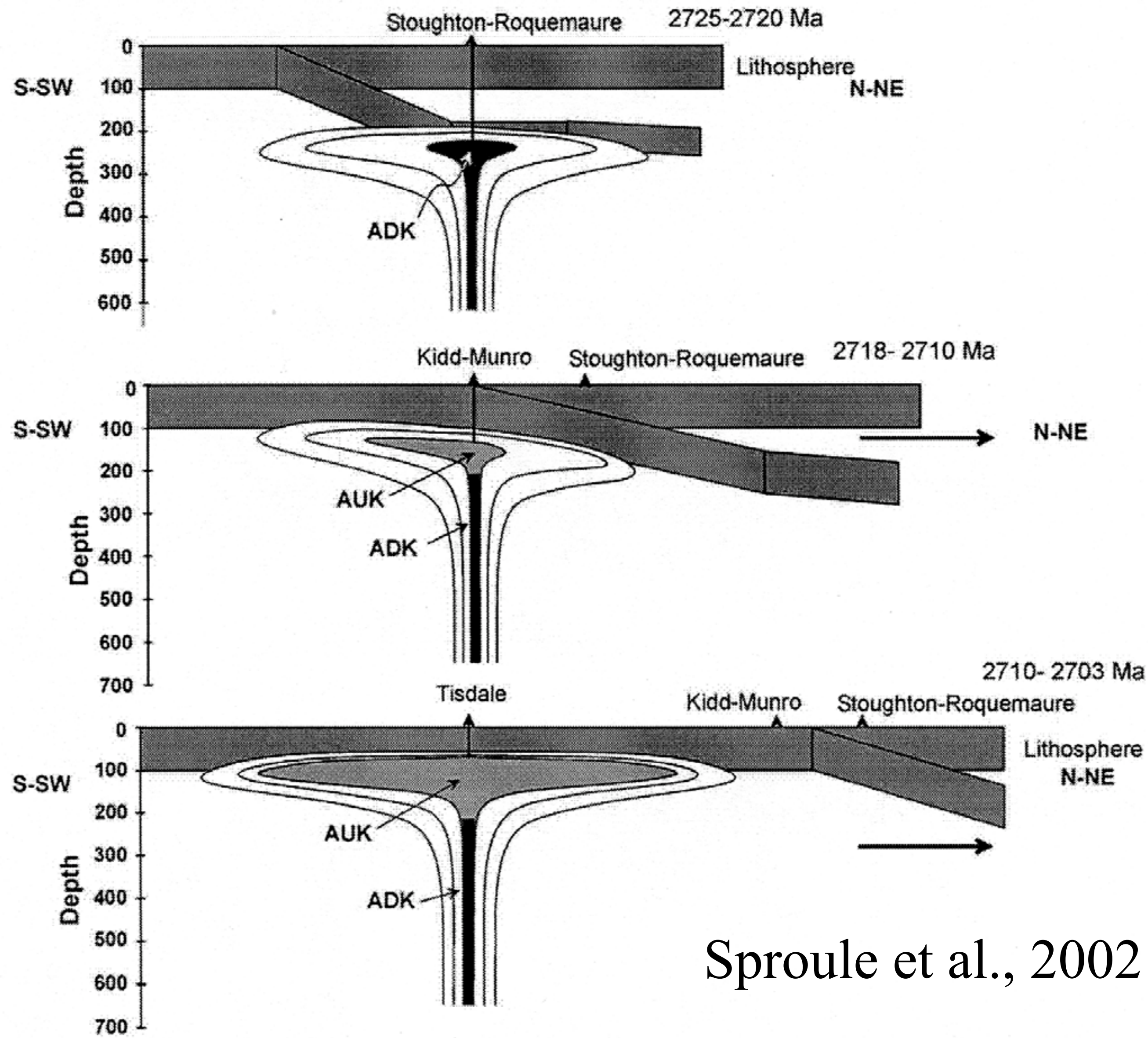
Comes close to lower mantle temperatures for episodic models

But melts in the lower mantle would sink!

Davies, EPSL (1995)



Plume-Arc Interaction



Sproule et al., 2002

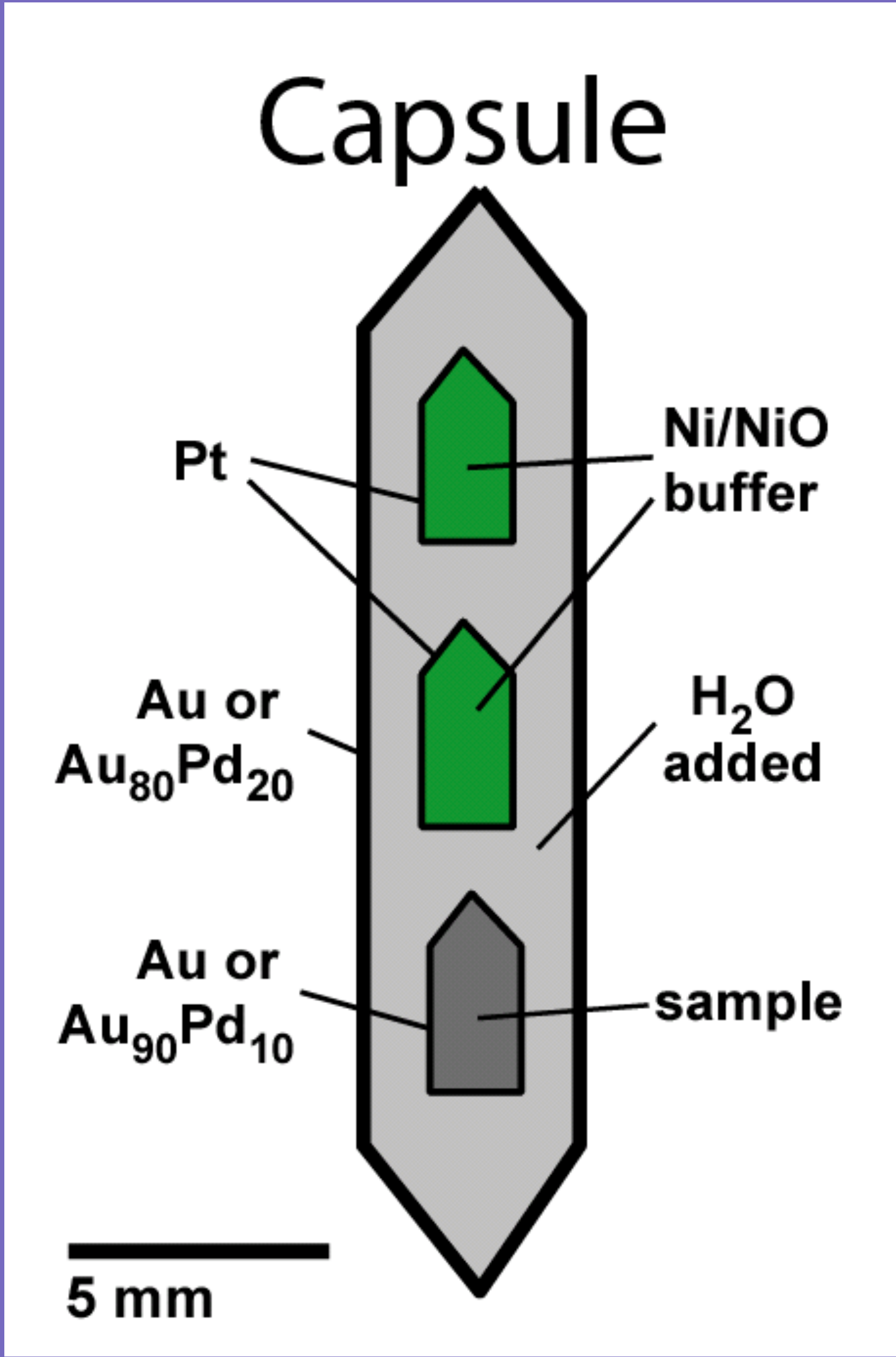
Evidence for H_2O in komatiite magmas

- Pyroxene compositions in Barberton and in Commondale komatiite

- Amphibole in komatiite and melt inclusions

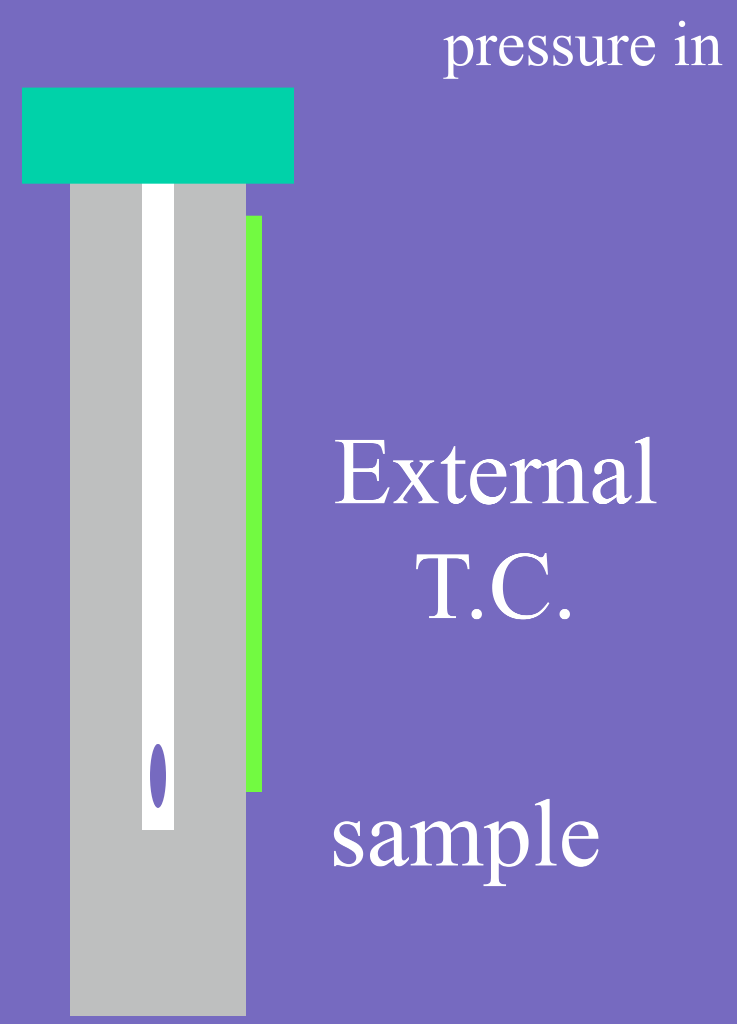
- High Pressure Phase Equilibria

Experiments on komatiites - TZM-bomb experimental set-up

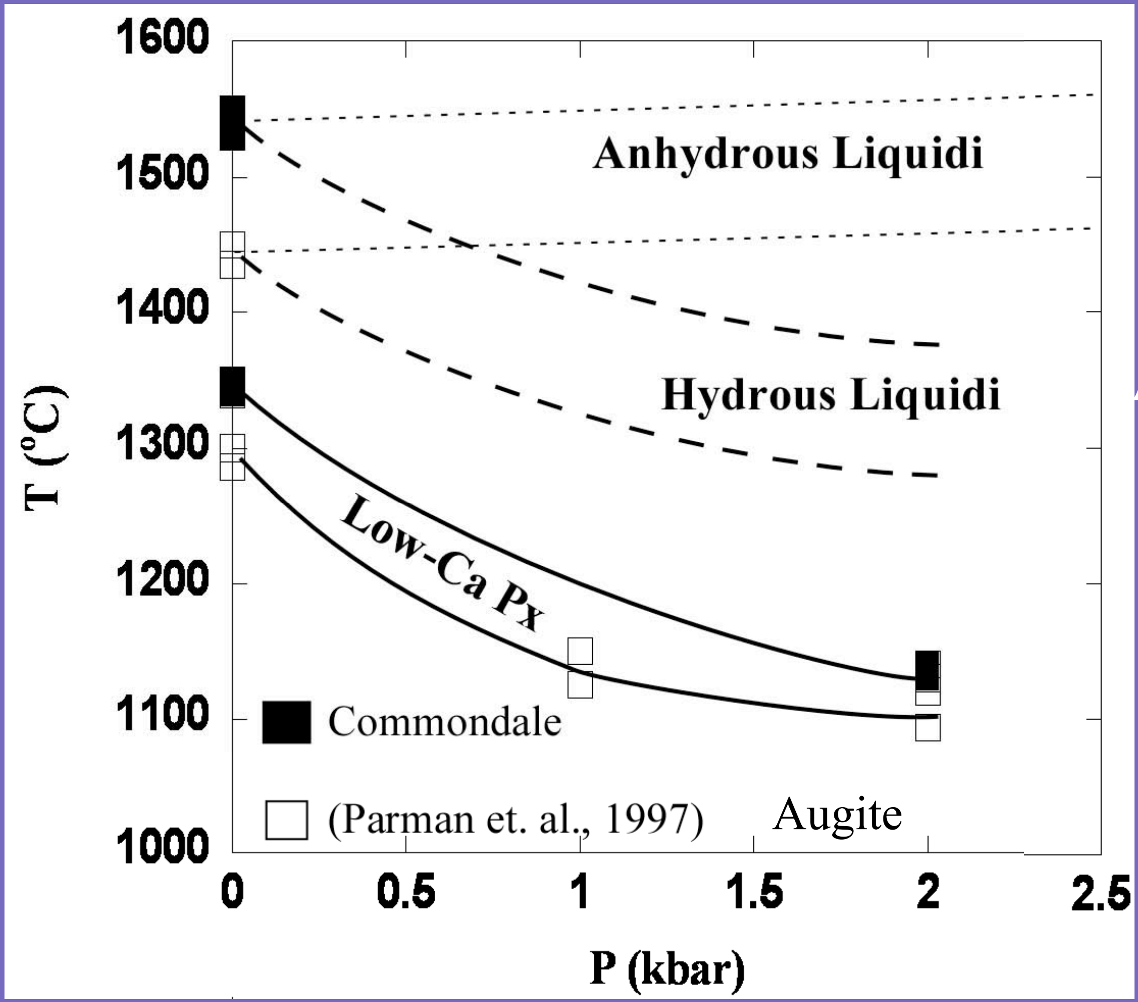


ZHM/MHC-bomb

- up to 3 kbar & 1350^{o}C
- gas pressure media
- fO_2 buffered by Ni-NiO



ZHM/MHC-bomb and furnace



Commondale komatiite

1-atm Liquidus: **1550°C**

1-atm Low-Ca Px: **1345°C**

2-kbar Low-Ca Px: **1135°C**

At 2-kbar Px suppression: **210 °C**

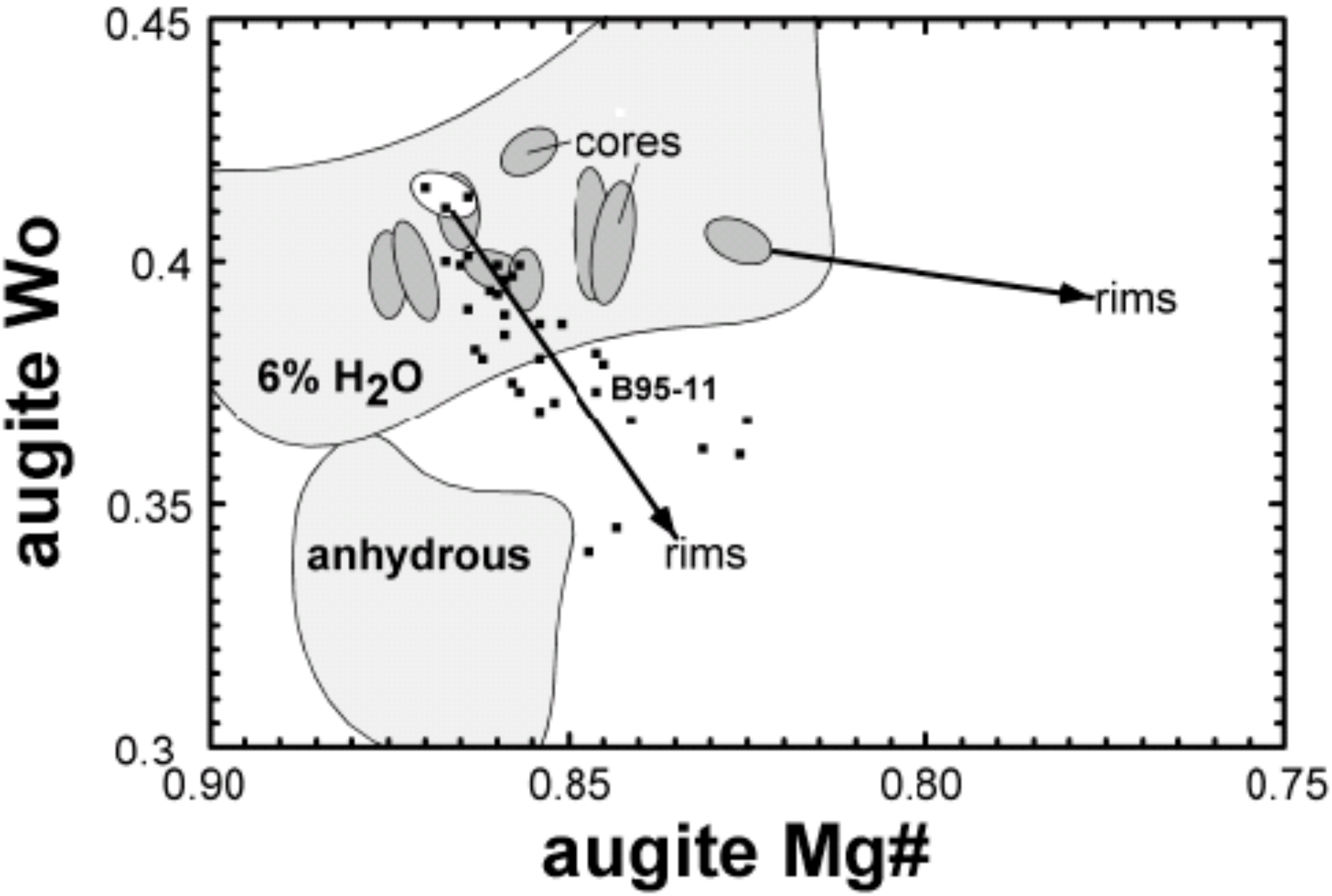
5 wt% H_2O

Barberton komatiite

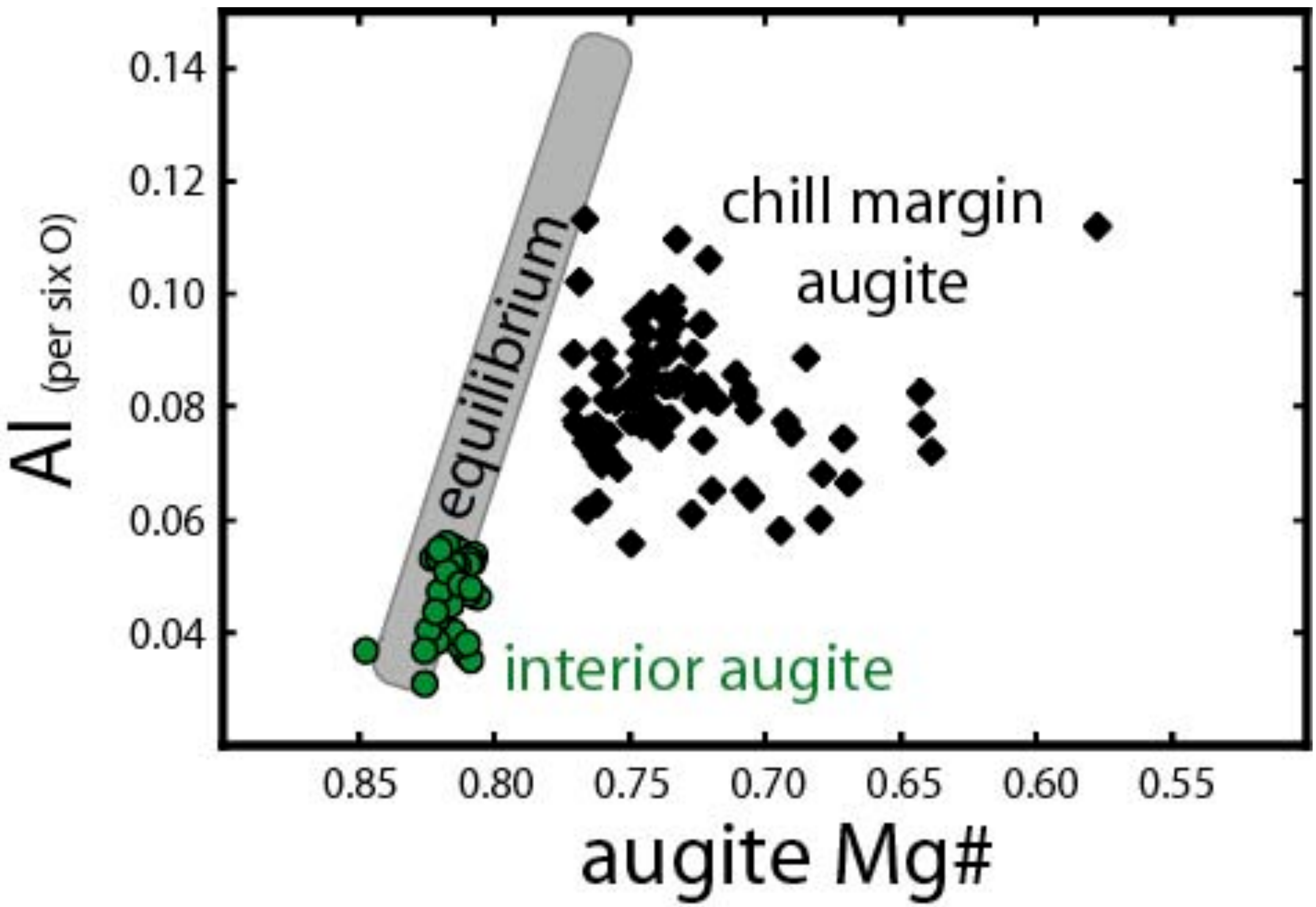
Parman et. al., 1997

At 2-kbar Px suppression **~200 °C**

Augite Wo contents in Barberton

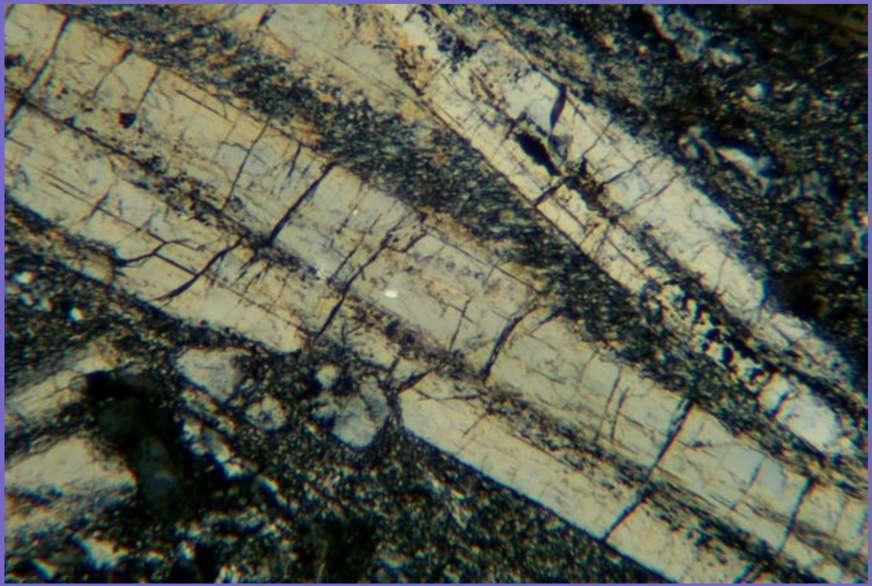


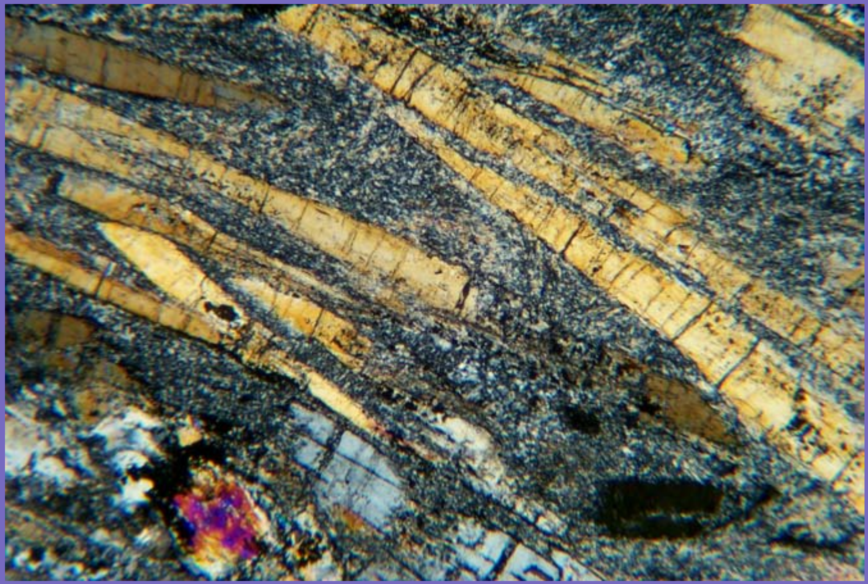
Augite Al contents



Preserved Igneous Pyroxenes

Orthoenstatite in Commondale



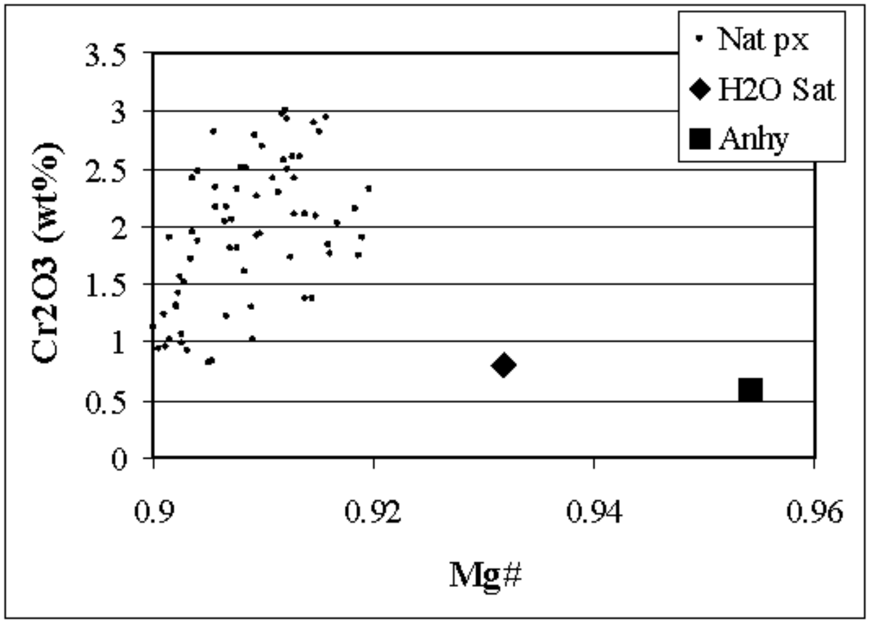


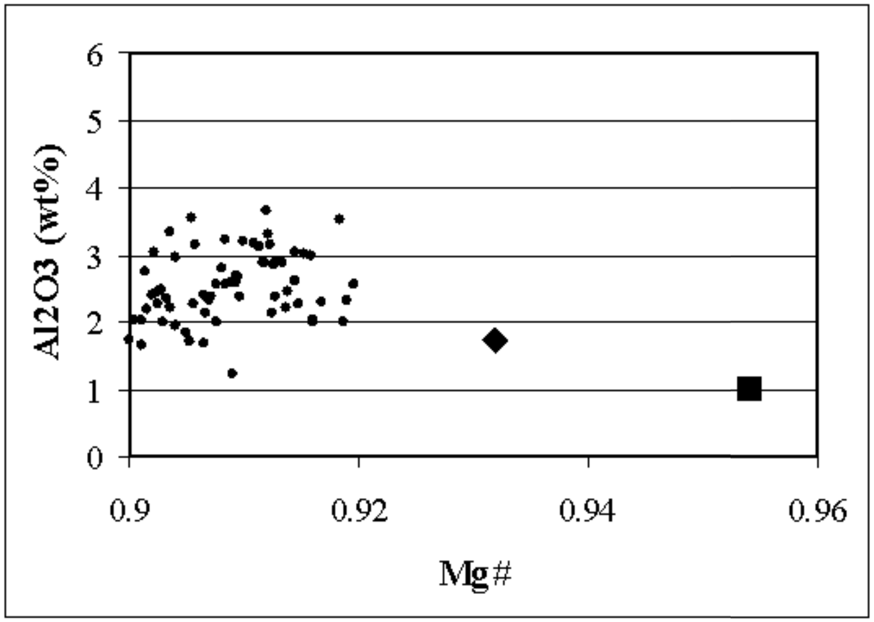
1 cm

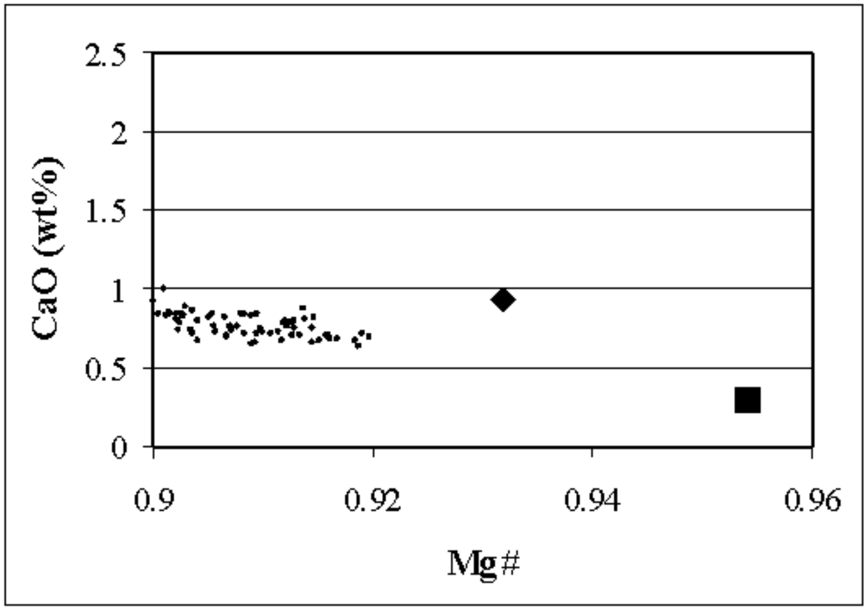
Pyroxene Mg#: <92

From the center of a several meter-thick flow

Equilibrium Pyroxene Growth



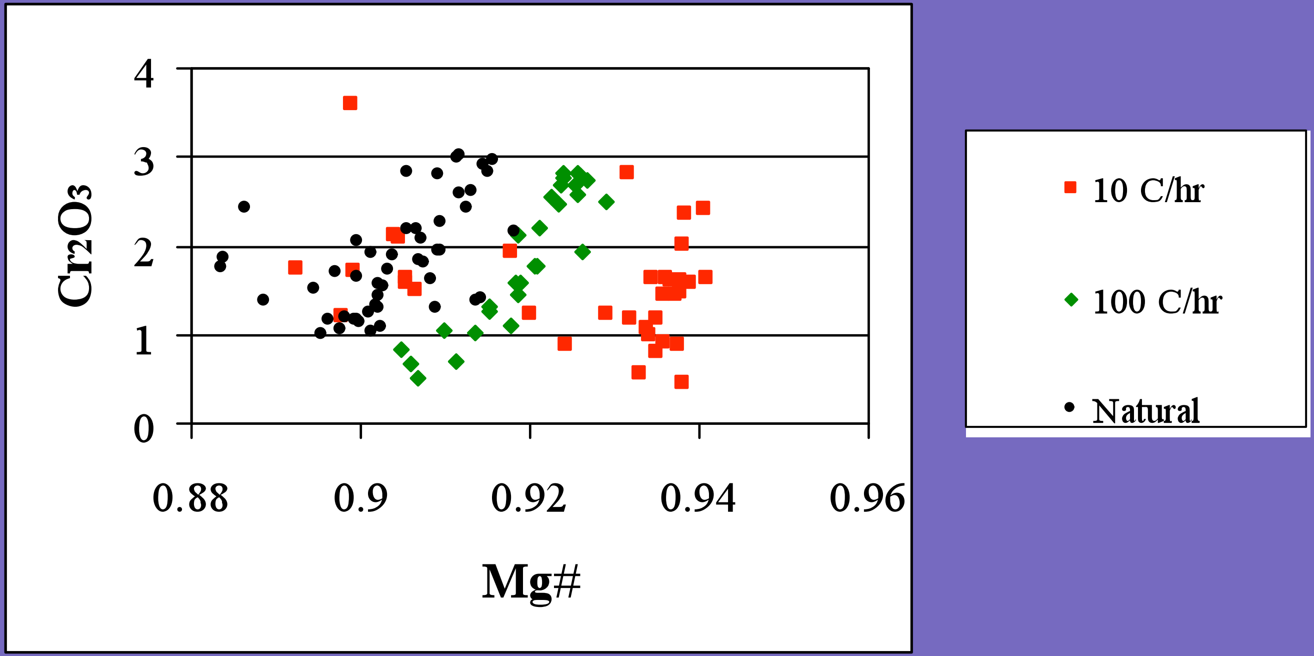


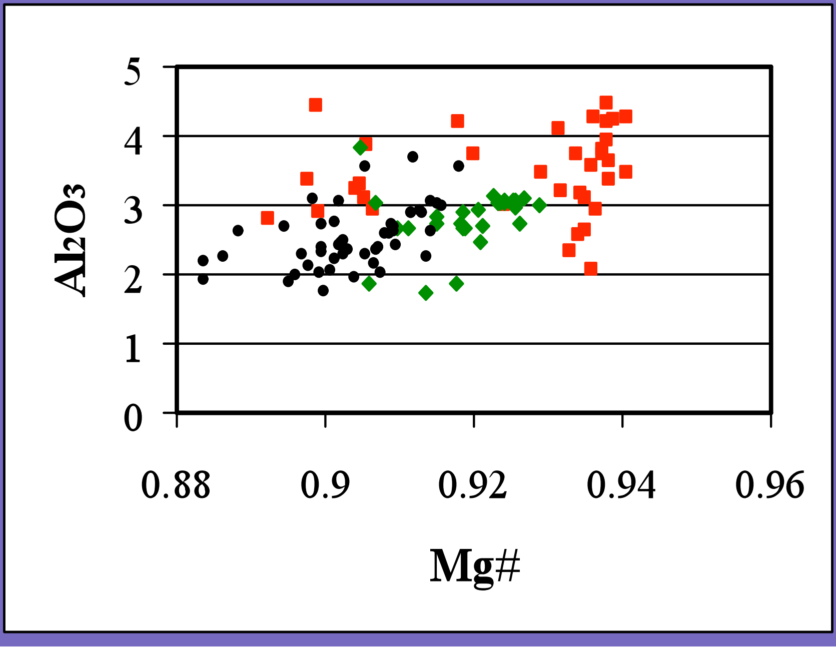


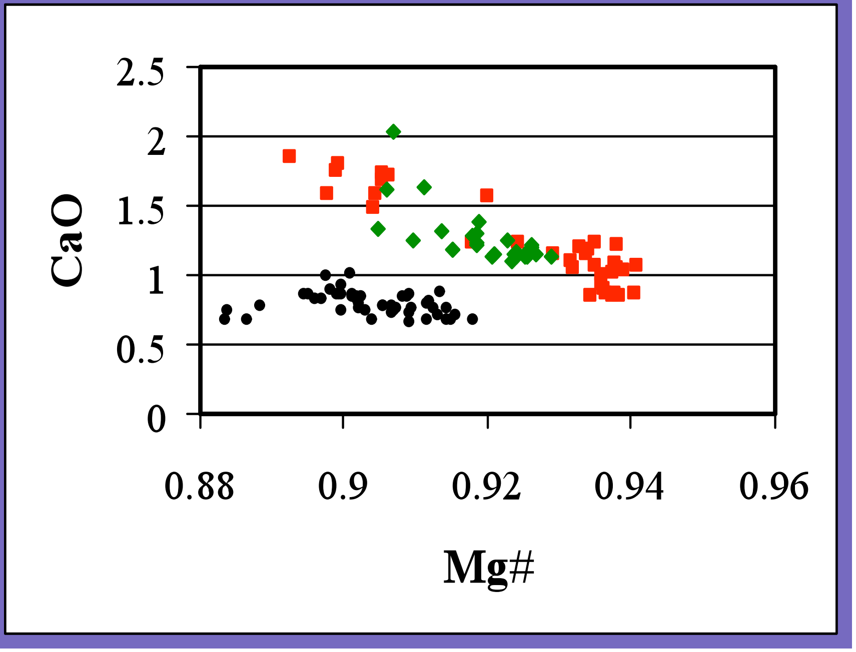
H_2O Saturated (when first opx appeared) = ~4.5 wt% H_2O

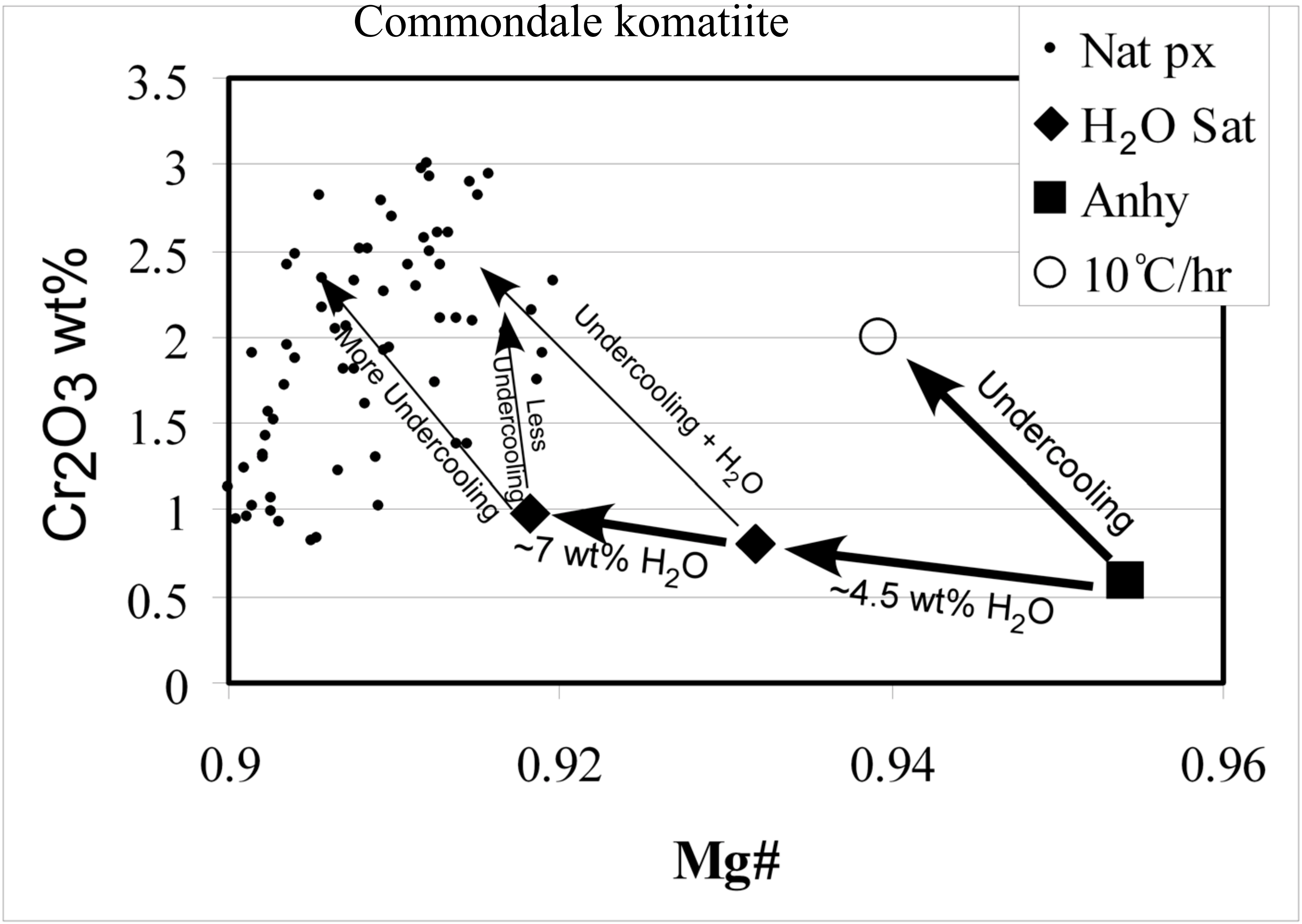
Commondale Komatiites

Chemical Trends Caused By Undercooling

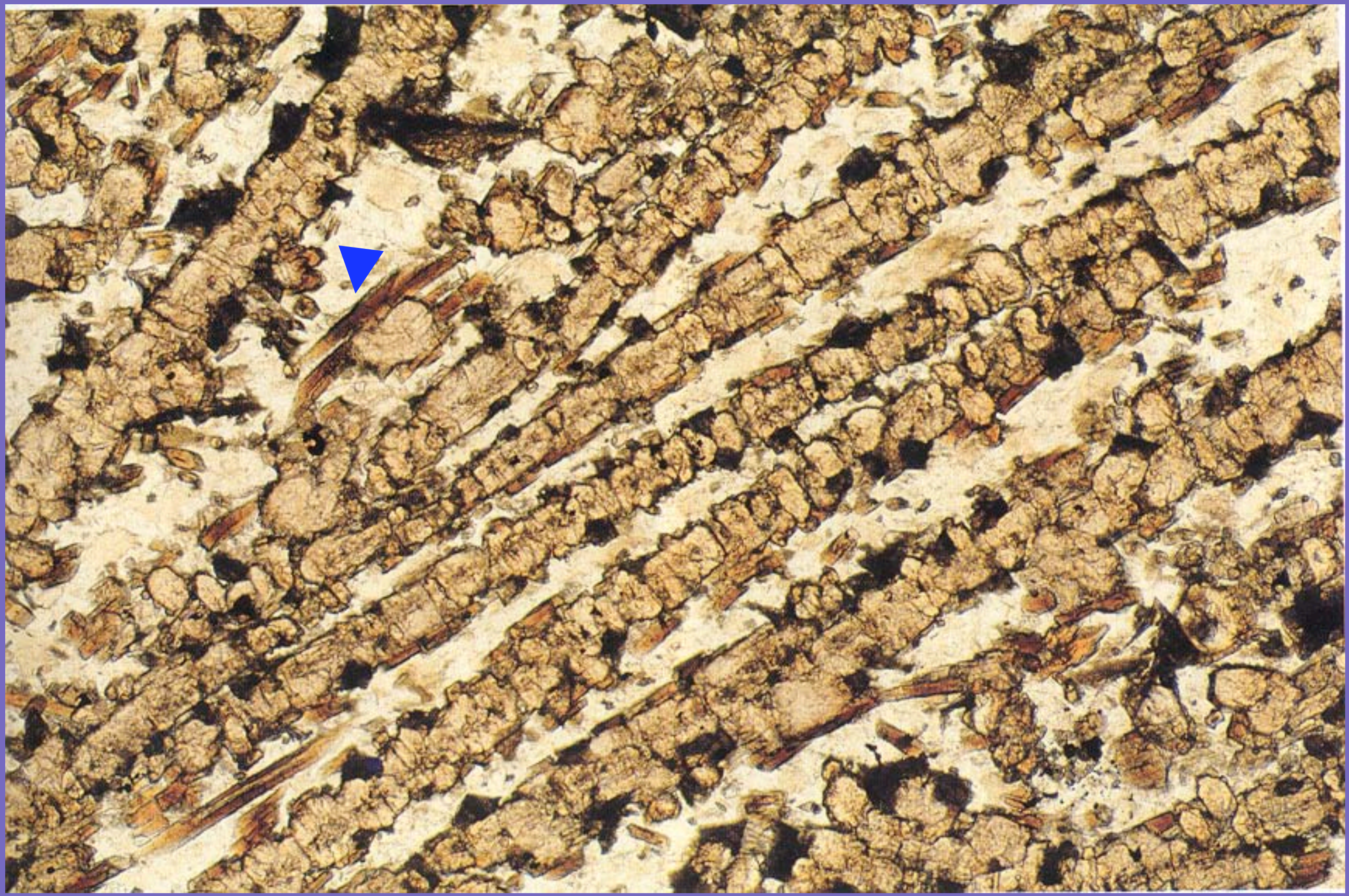






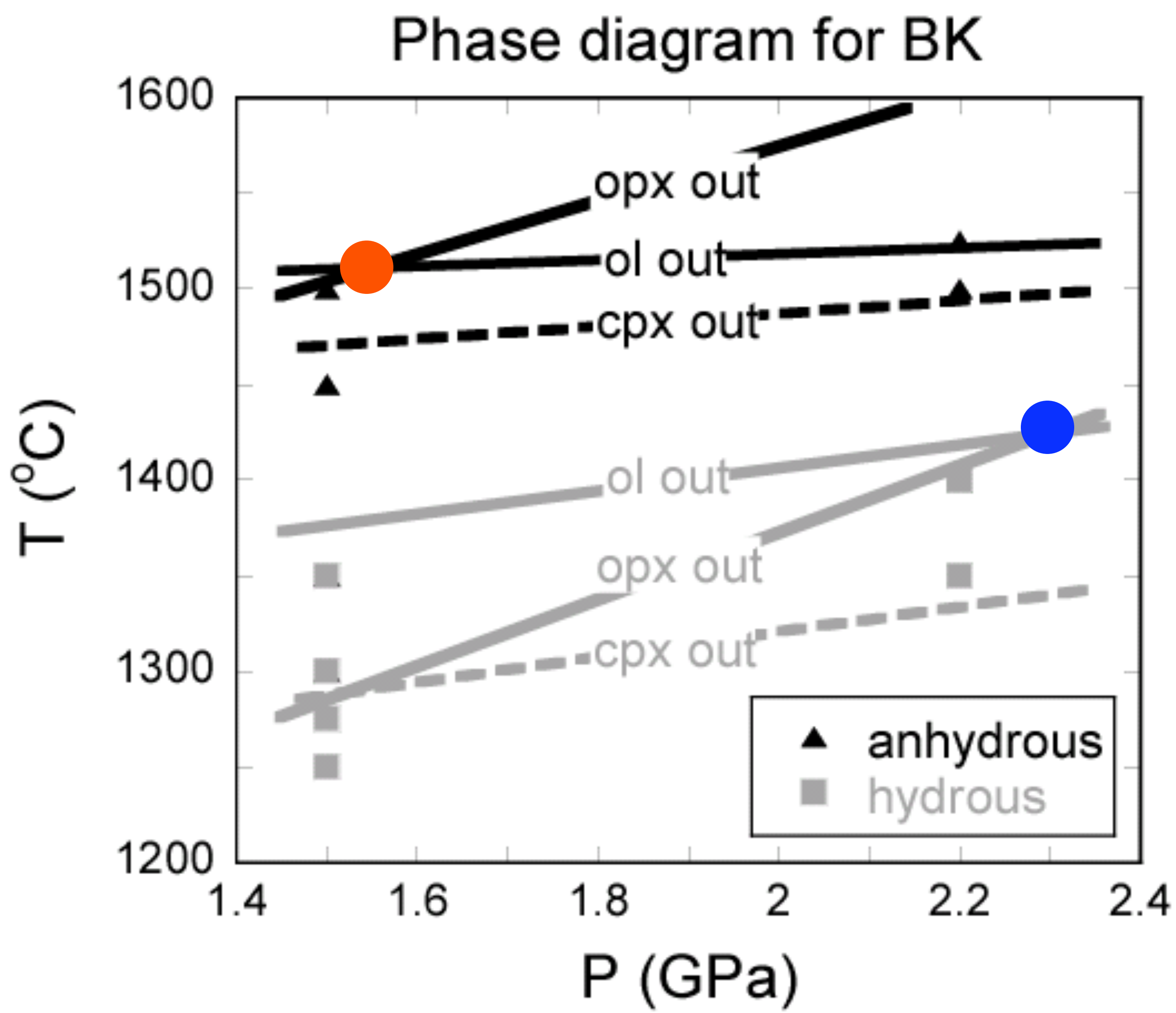

Commondale komatiite
Nat px
H2O Sat
Anhy
10℃/hr
3.5
3
2.5
2
1.5
1
0.5
0
Cr2O3 wt%
0.9
0.92
0.94
0.96
Mg#
More Undercooling
Less Undercooling
Undercooling + H2O
Undercooling
~7 wt% H2O
~4.5 wt% H2O

Amphibole in Proterozoic komatiites



Hanski, 1992

High-P melting experi-ments deeper = wet

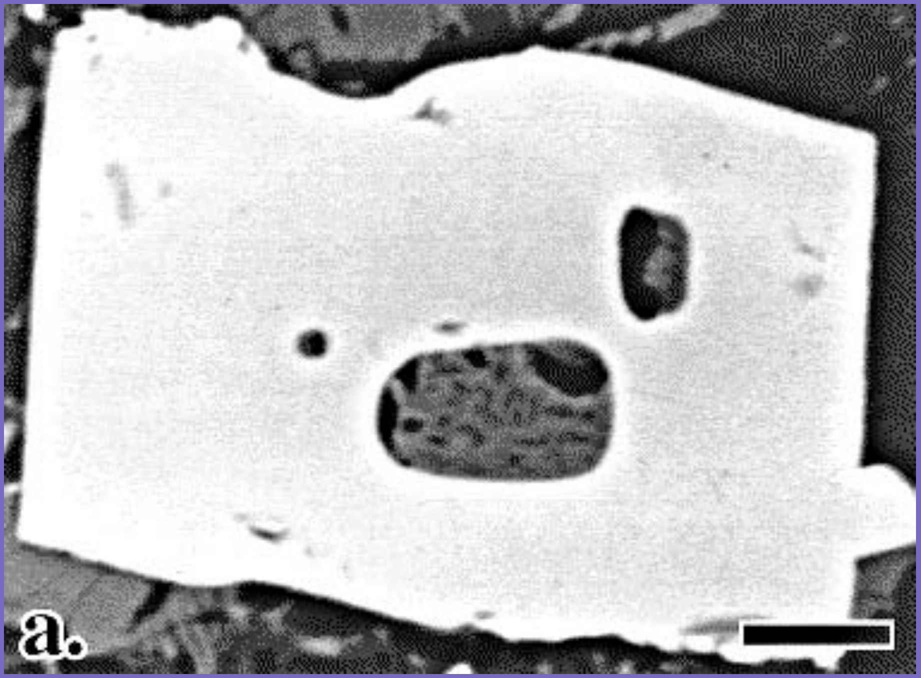


Other Potential Evidence for High H_2O

- Melt Inclusions
- Spinifex textures

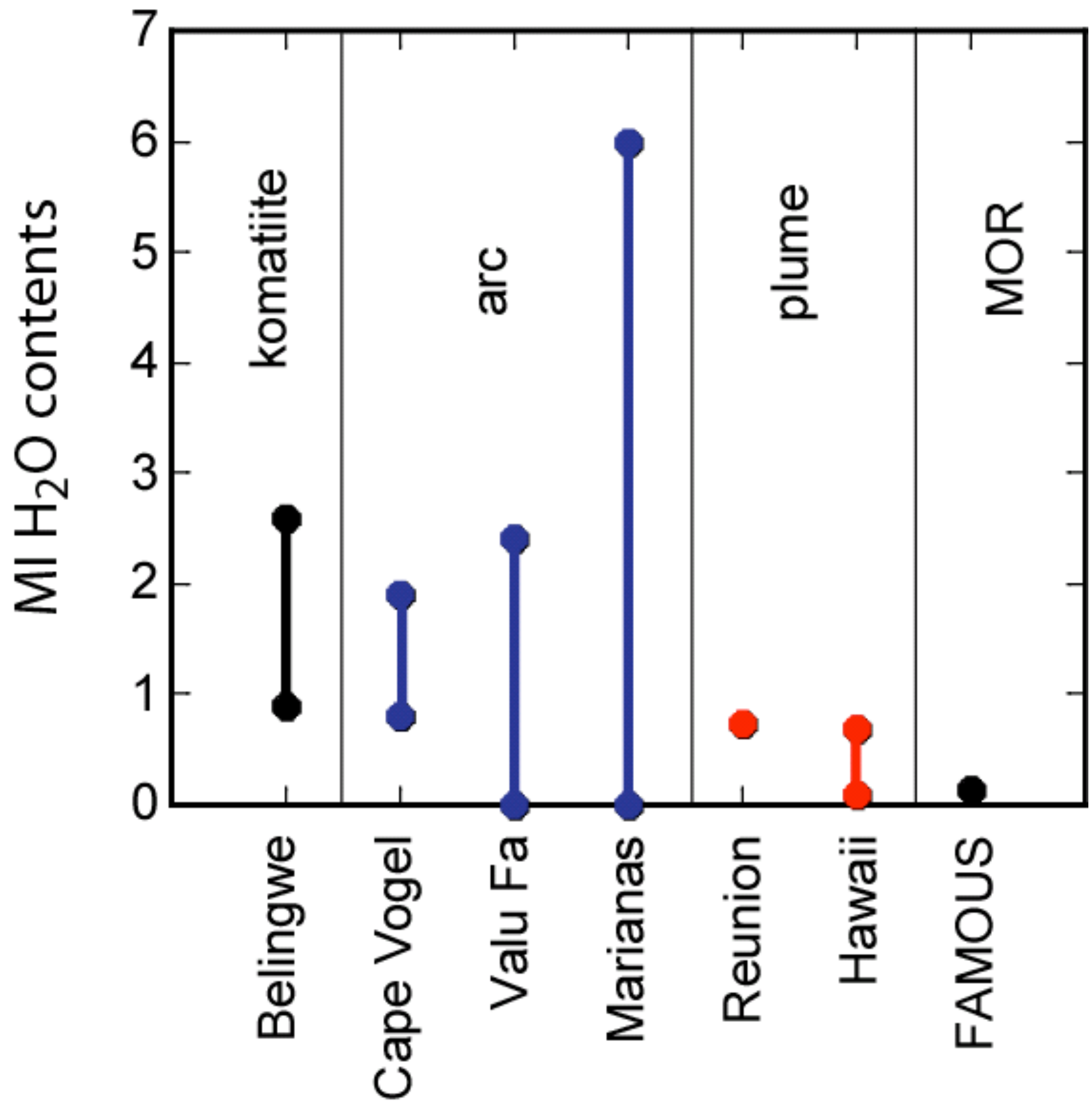
Melt Inclusions

- 1.1-2.6 wt.% H_2O
- devolatilization?
- re-equilibration?

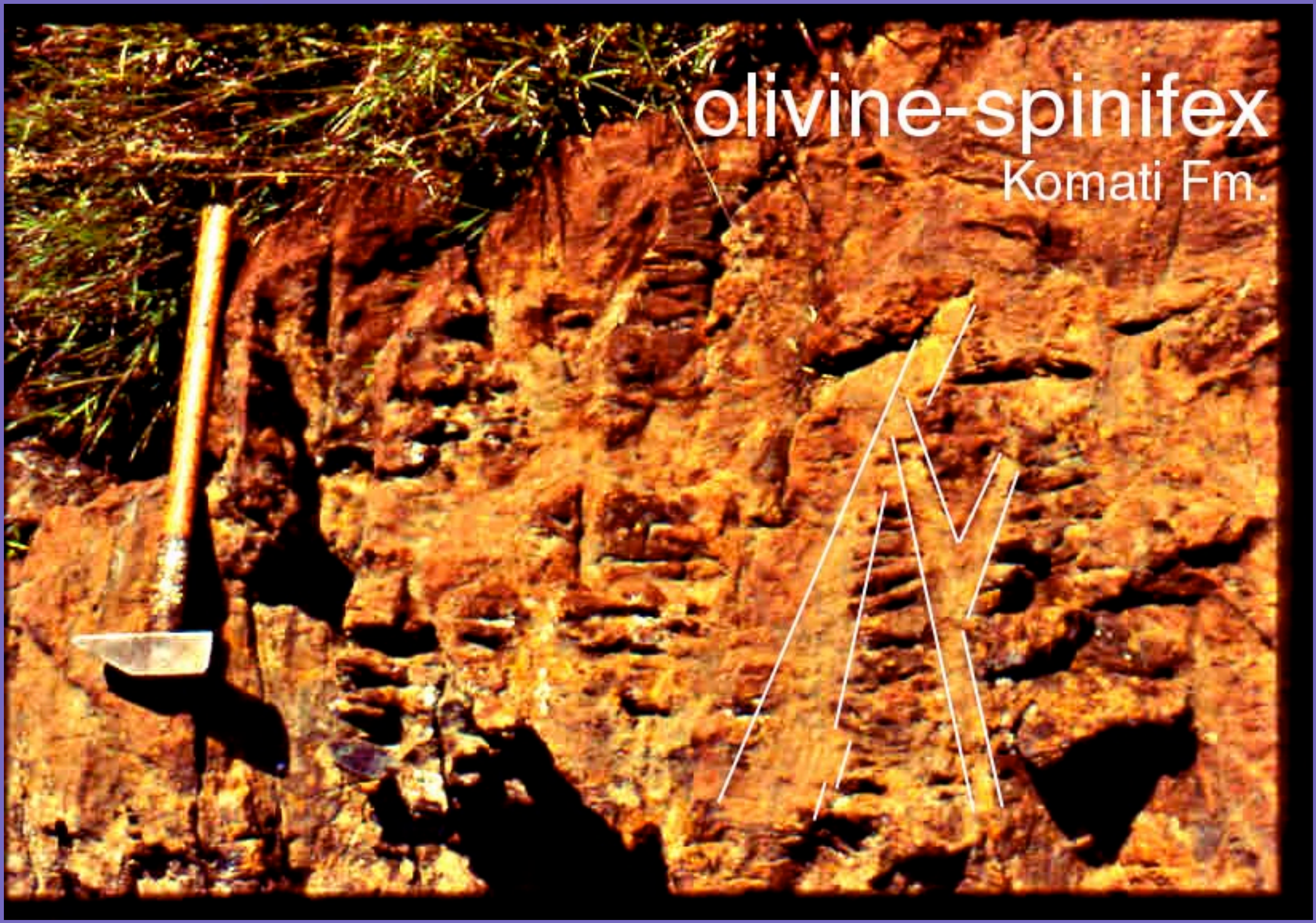


Shimizu et al., 2001

MI H_2O contents in modern magmas



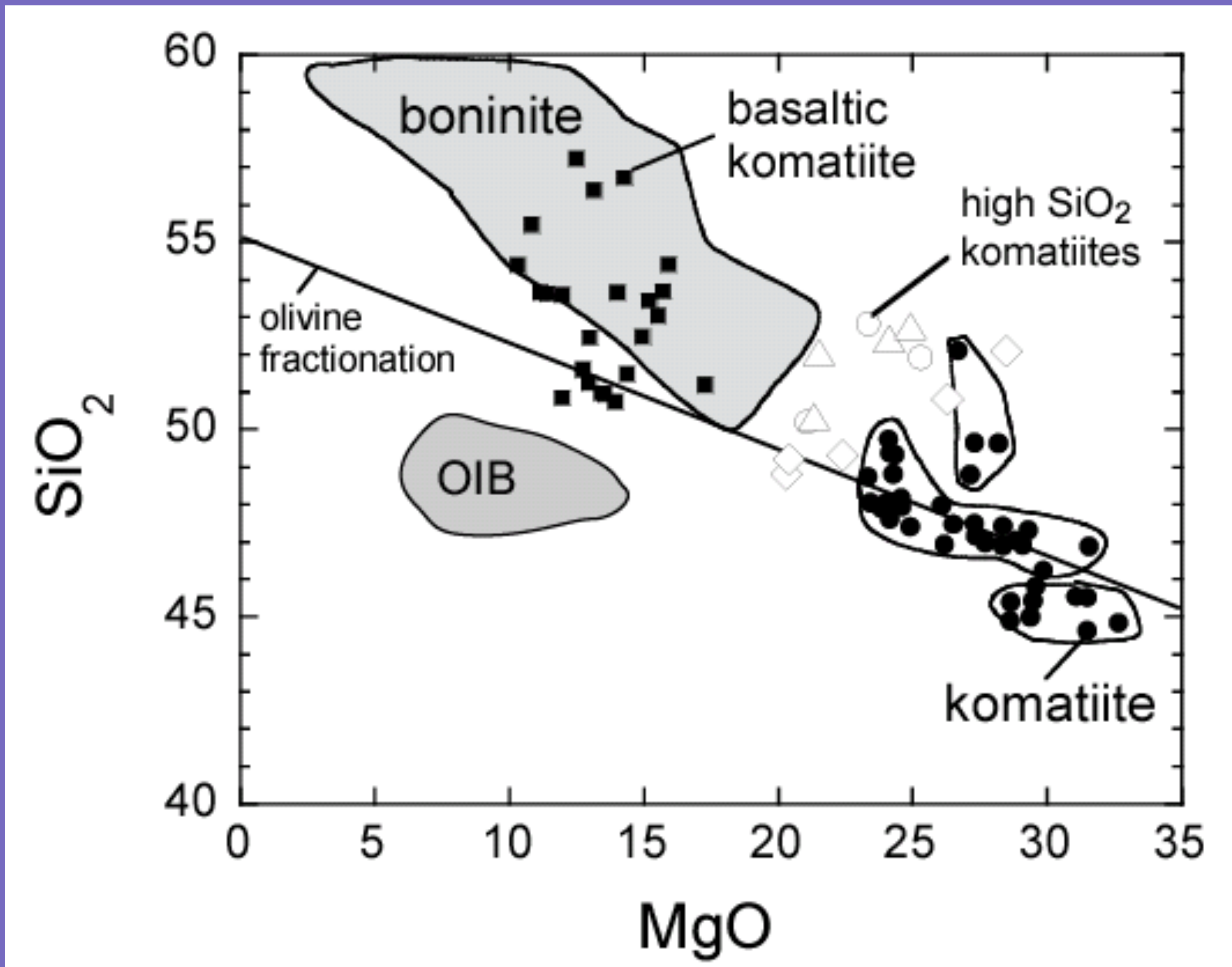
Spinifex texture



Subduction-like Geochemical Features

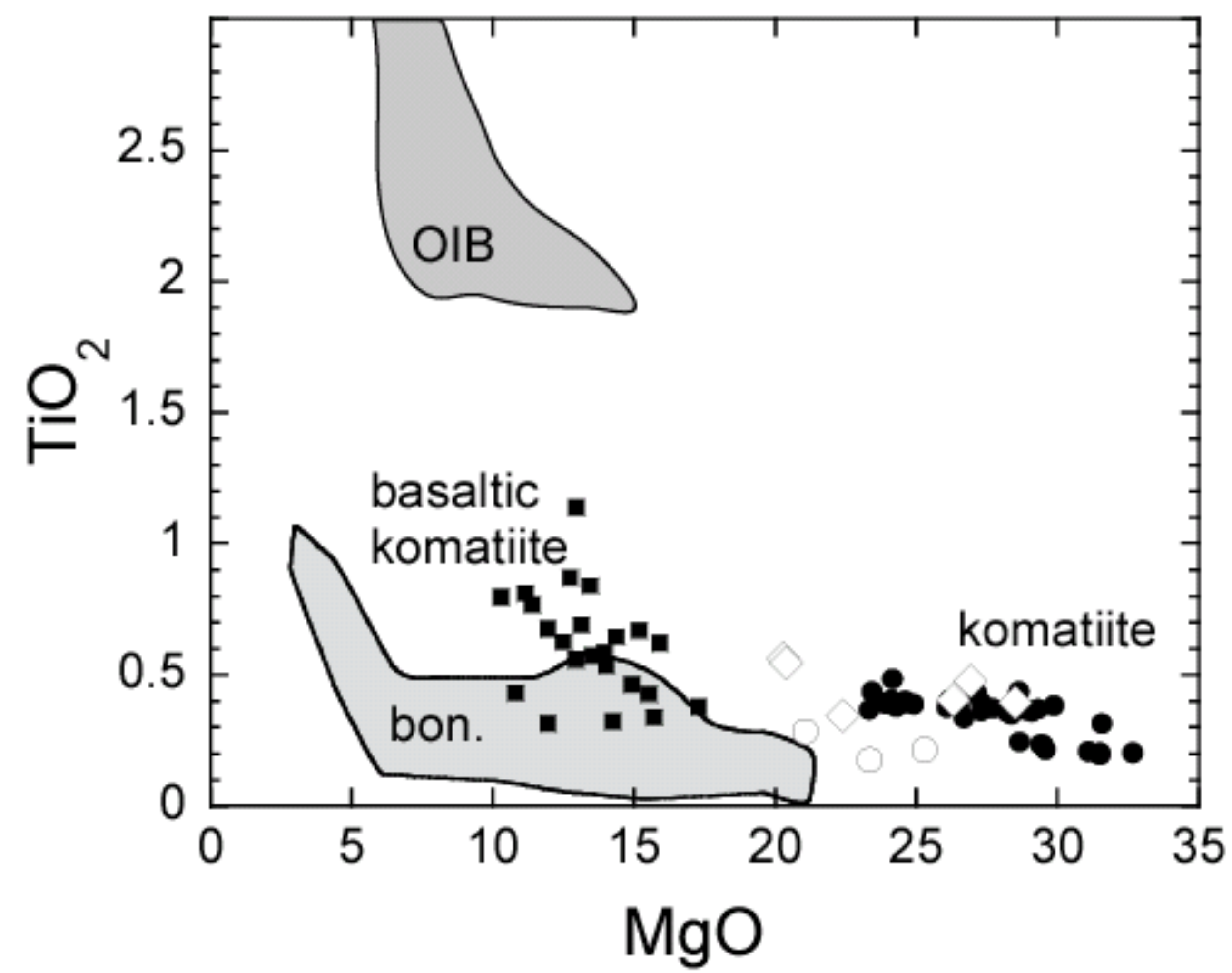
- Subduction-like characteristics
  - high SiO_2, MgO, CaO/Al_2O_3, low TiO_2
  - HFSE depletions
  - variable LREE
- Boninite-like characteristics
  - high MgO,
  - Ti/Zr and Nb/Th systematics
  - Positive Zr and Hf anomalies

High SiO_2



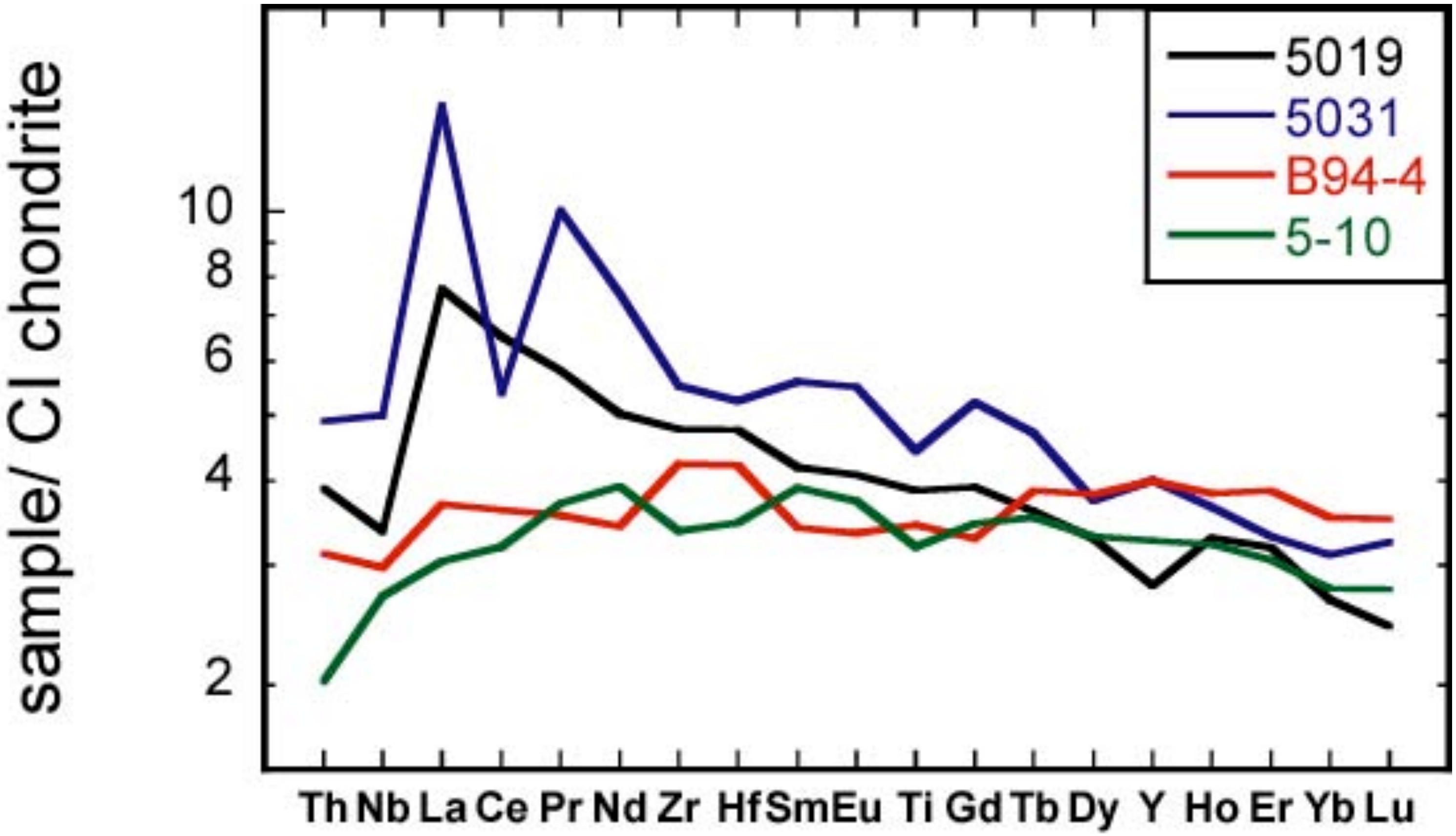
boninite
basaltic
komatiite
high SiO2
komatiites
olivine
fractionation
OIB
komatiite
SiO2
MgO
60
55
50
45
40
0
5
10
15
20
25
30
35

Low TiO_2

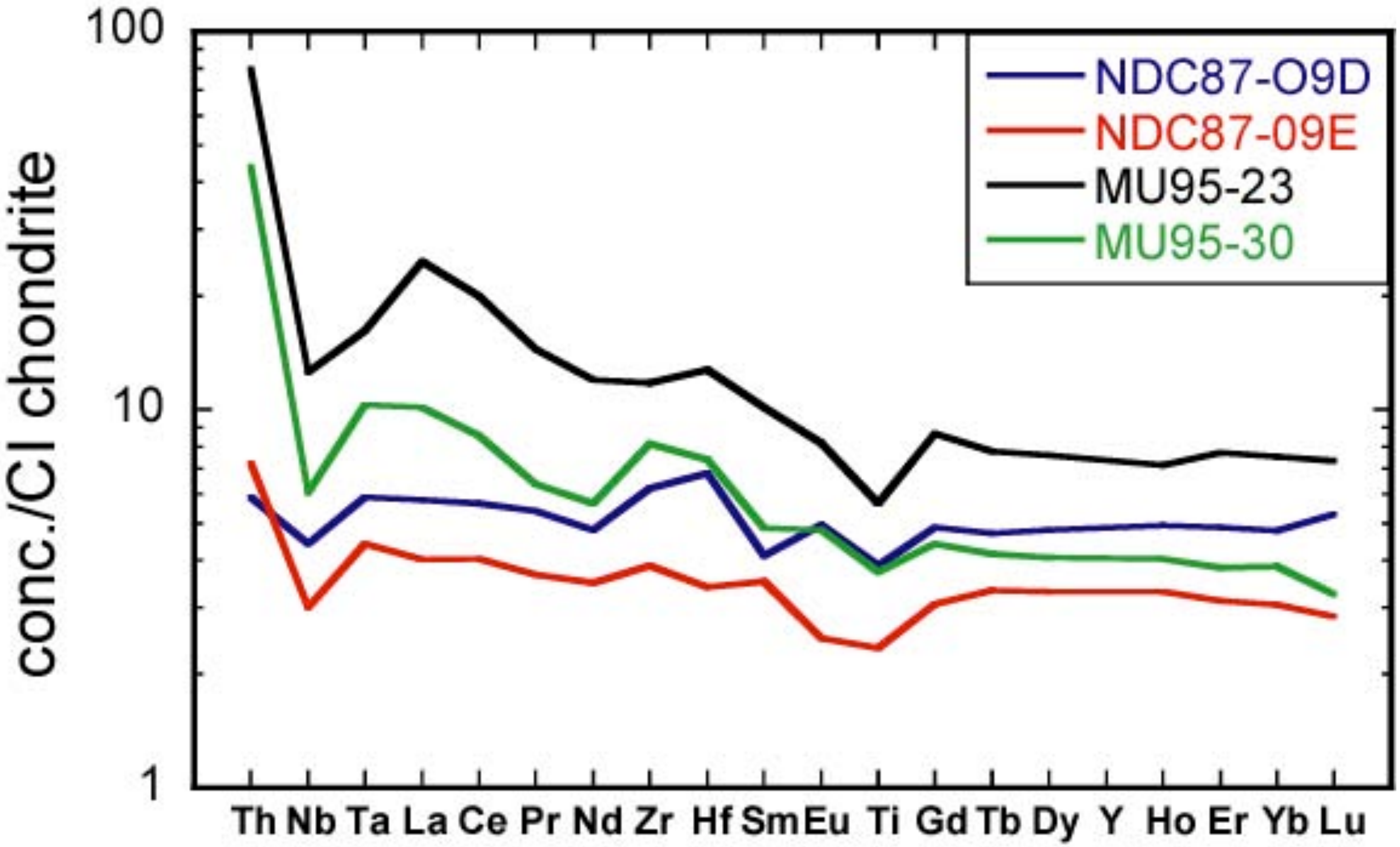


OIB
basaltic komatiite
bon.
komatiite
TiO_2
MgO
0
0.5
1
1.5
2
2.5
5
10
15
20
25
30
35

LILE variability, HFSE depletions

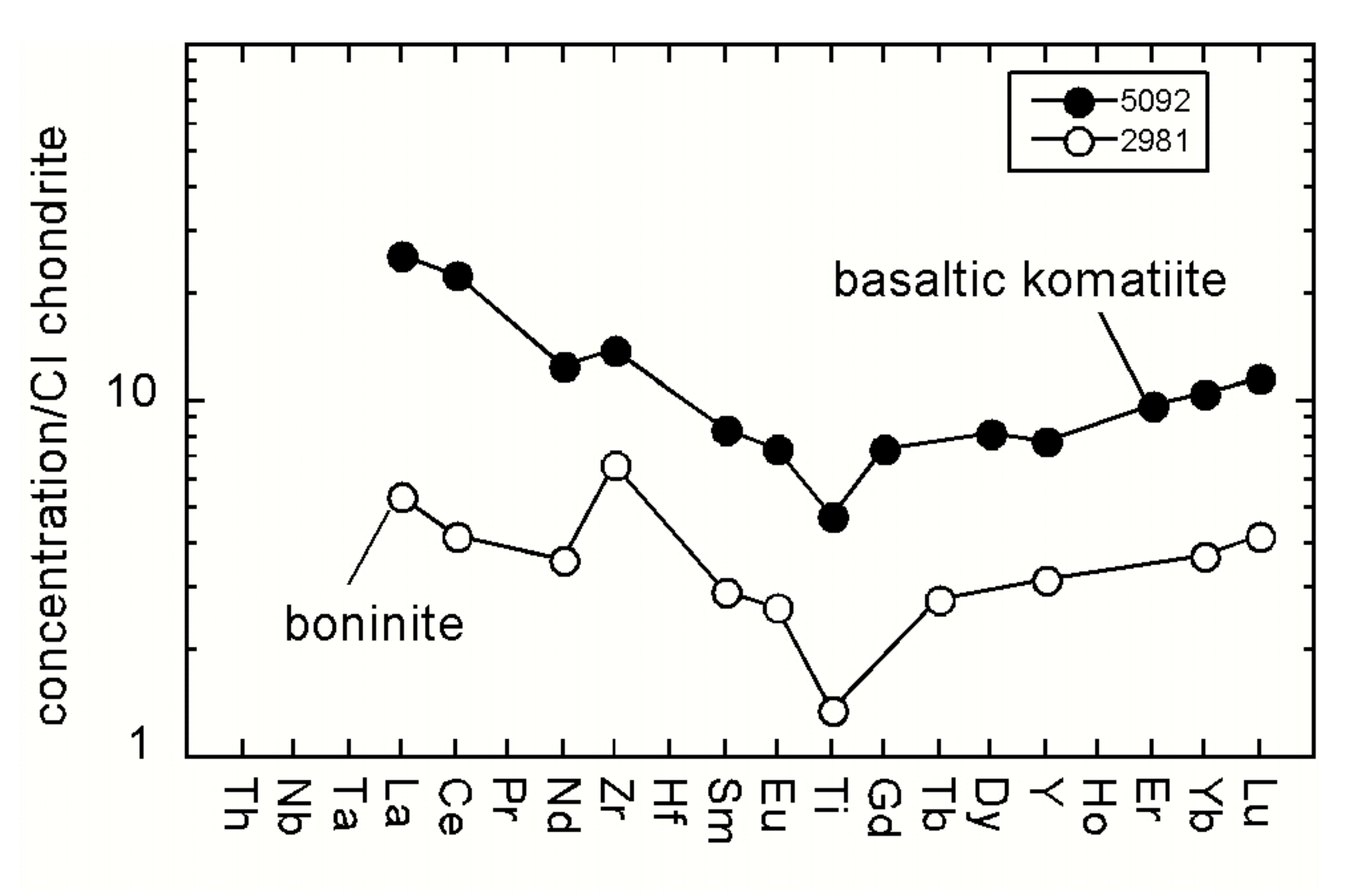


North Caribou, Superior Province

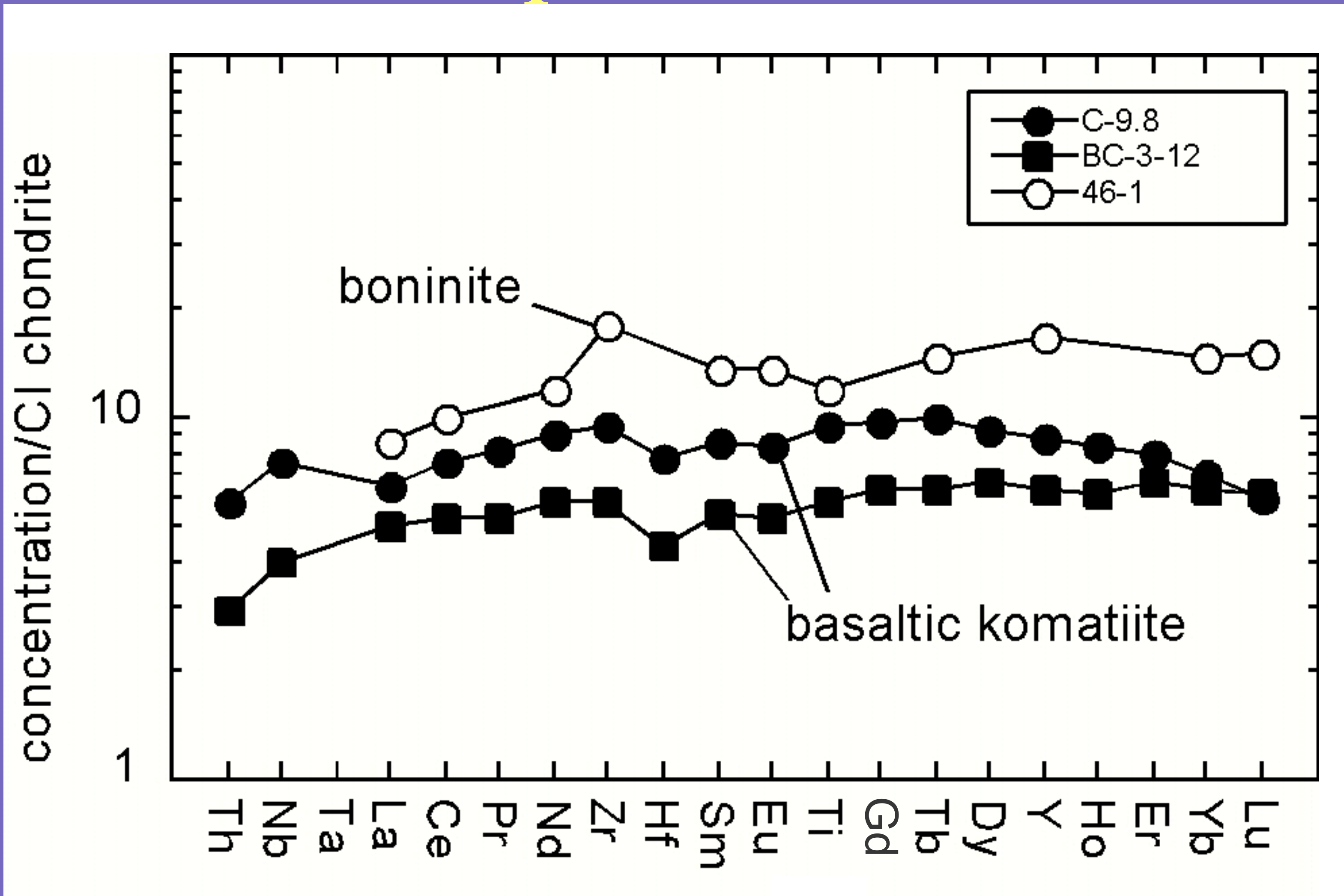


Hollings and Kerrich, 1999

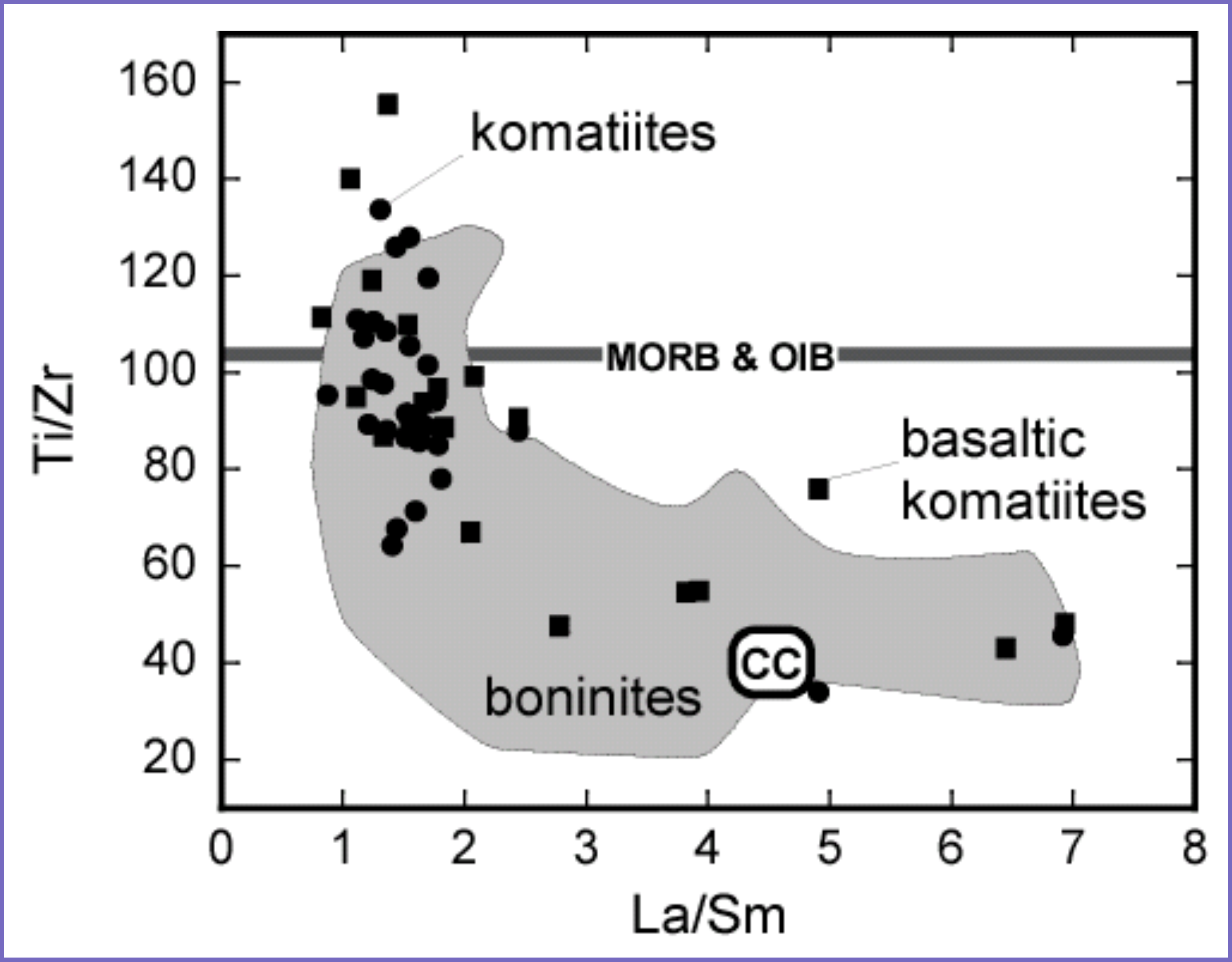
U-shaped pattern



LILE depleted boninites

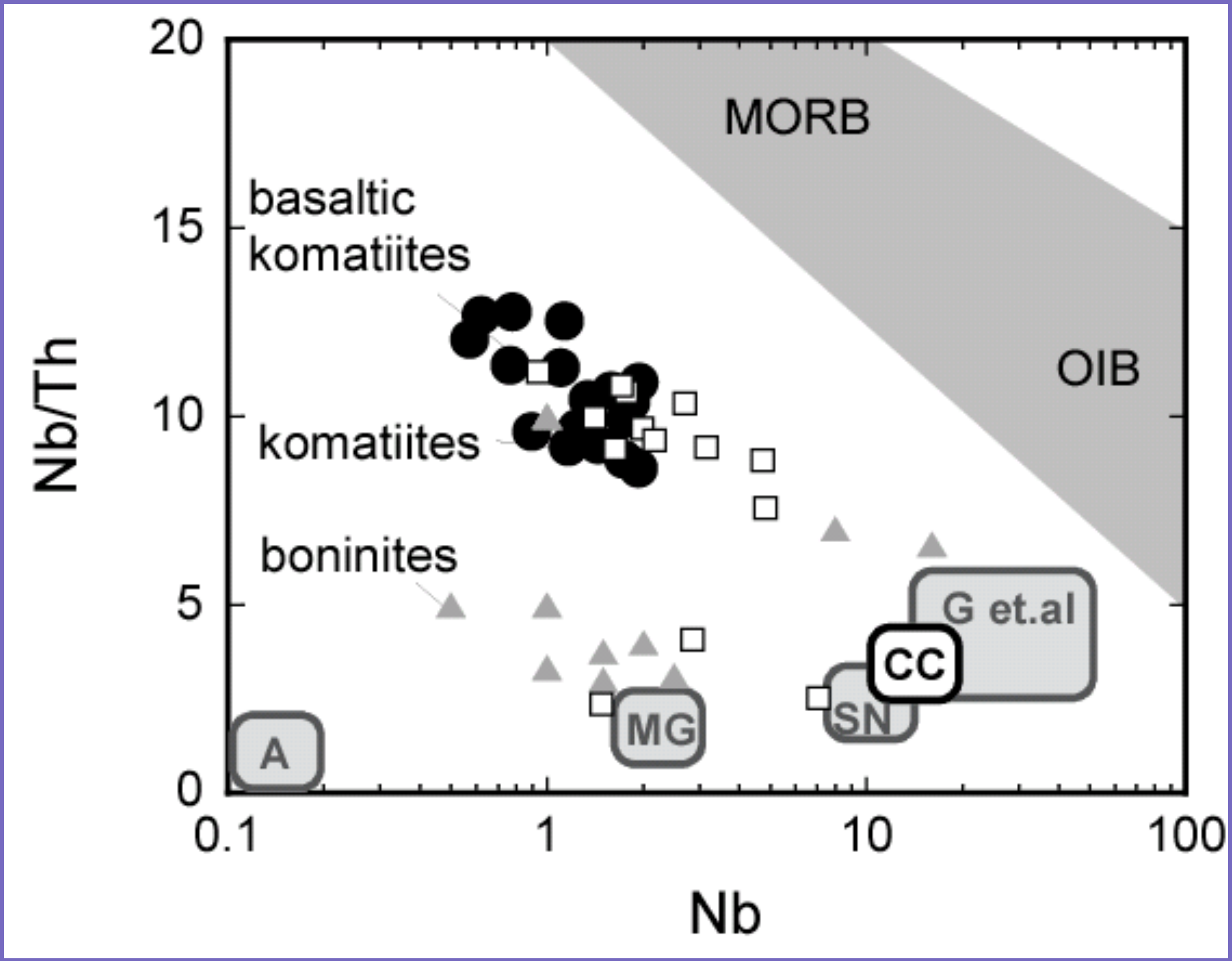


Mixing of fluid and dep. mantle



Nelson et al., 1984
Cameron et al., 1983
Sobolev&Danu., 1994

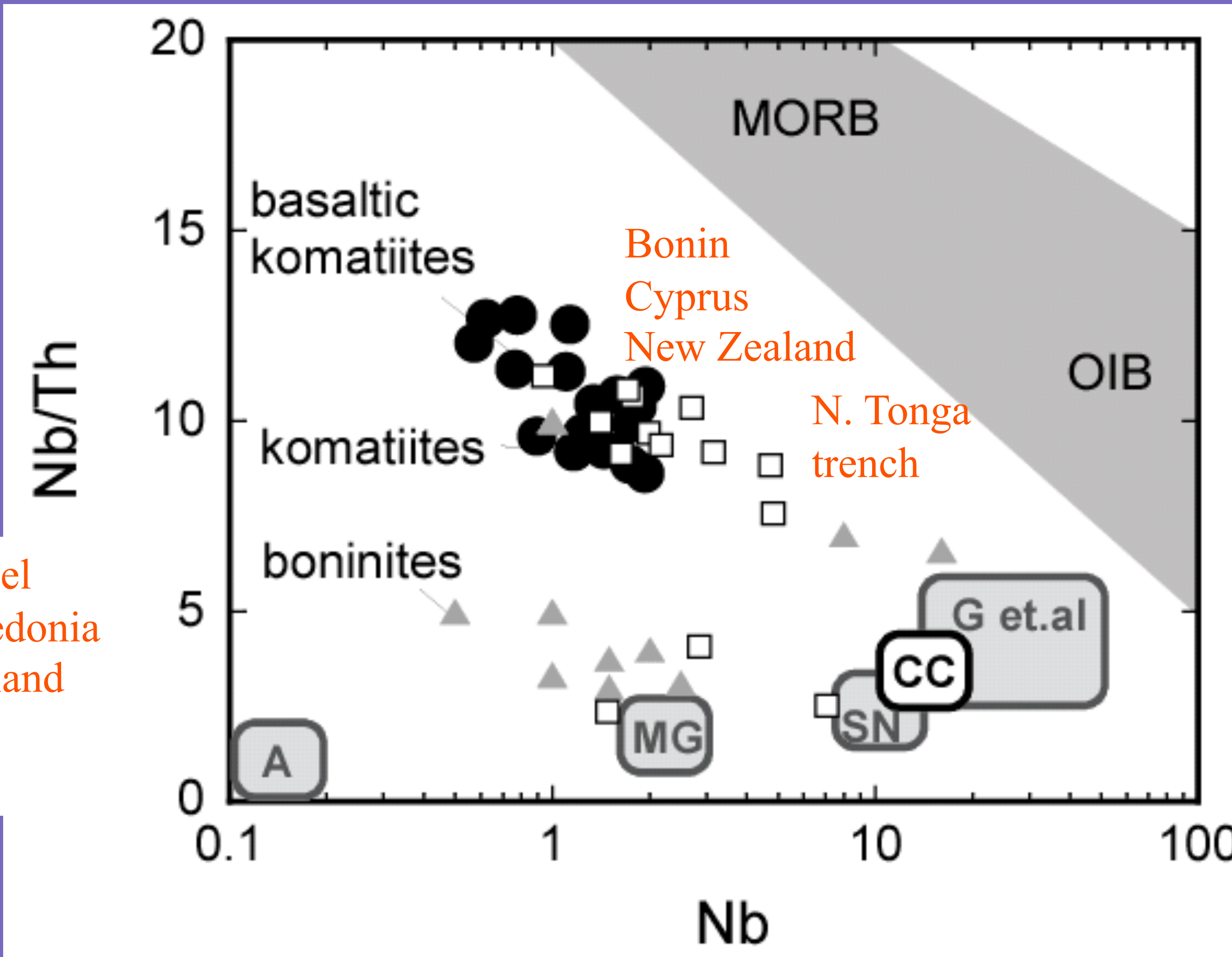
Bimodal trend



Nelson et al., 1984
Cameron et al., 1983
Sobolev&Danu., 1994

Bimodal trend

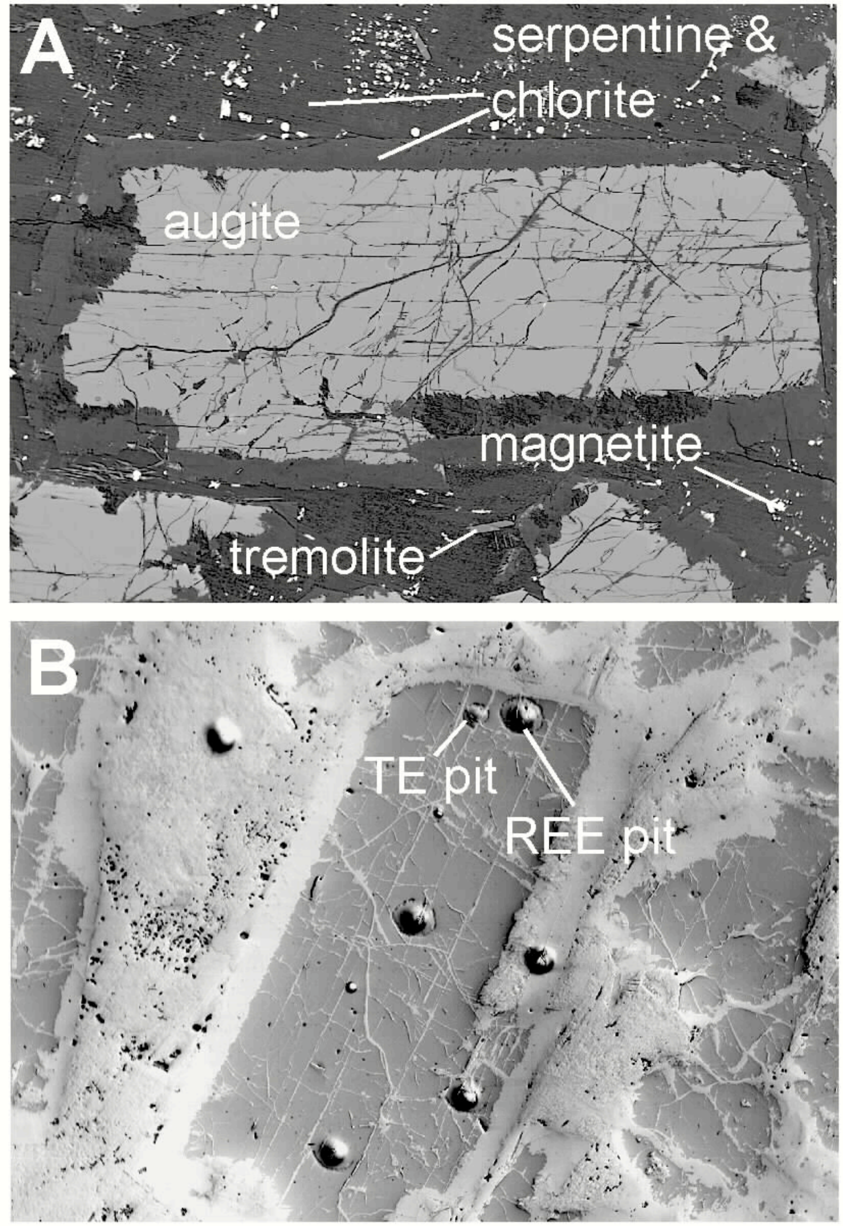
Cape Vogel
New Caledonia
New Zealand
Cyprus
Victoria



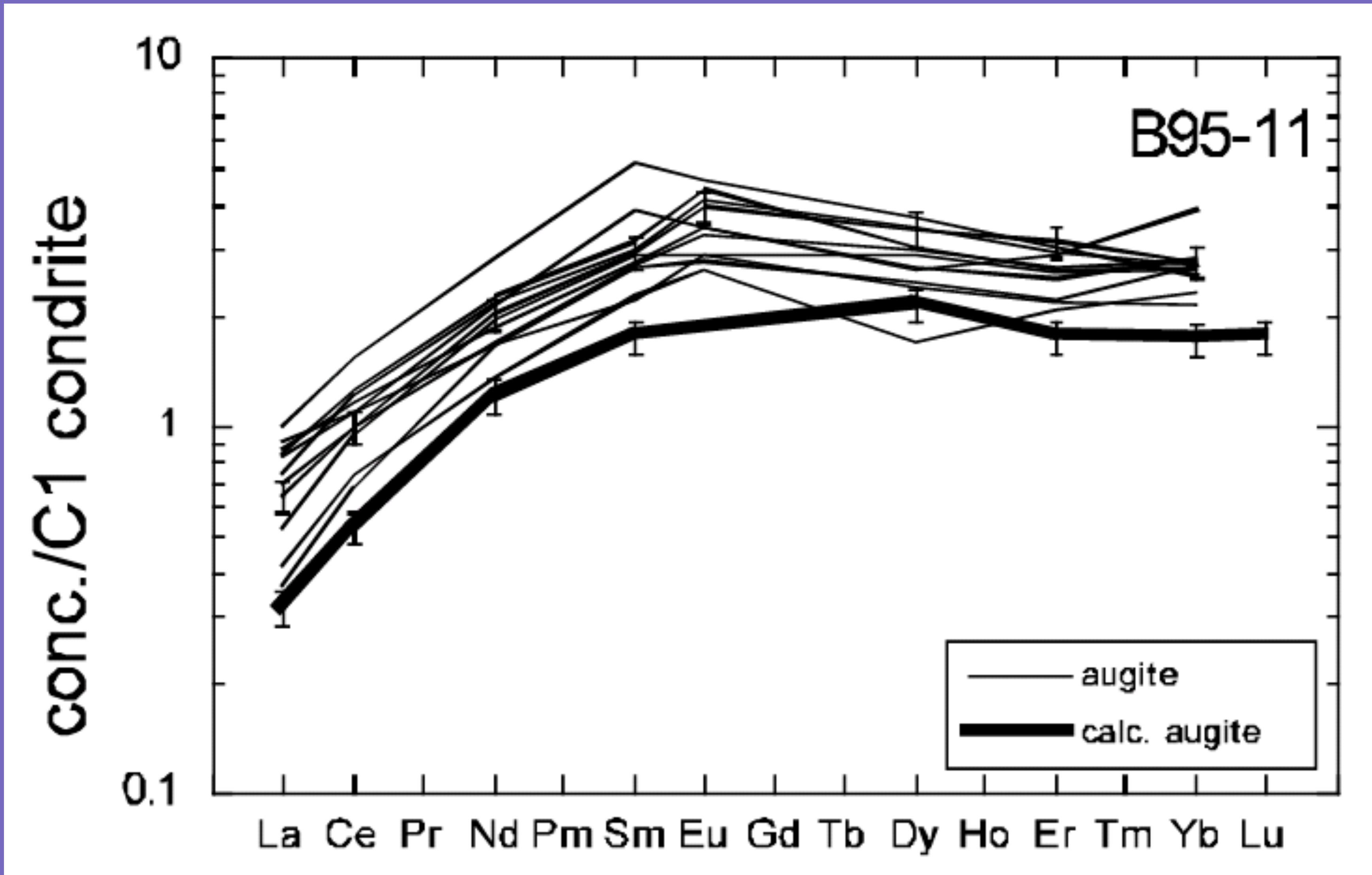
Weaknesses

- Differences in Ti, Fe, Nb/Th, Nd isotopes
- Distinguish chemical signature of slab fluid from crustal contamination
  - Zr anomalies, Nd isotopes?
- Correct for effects of alteration
  - high SiO_2

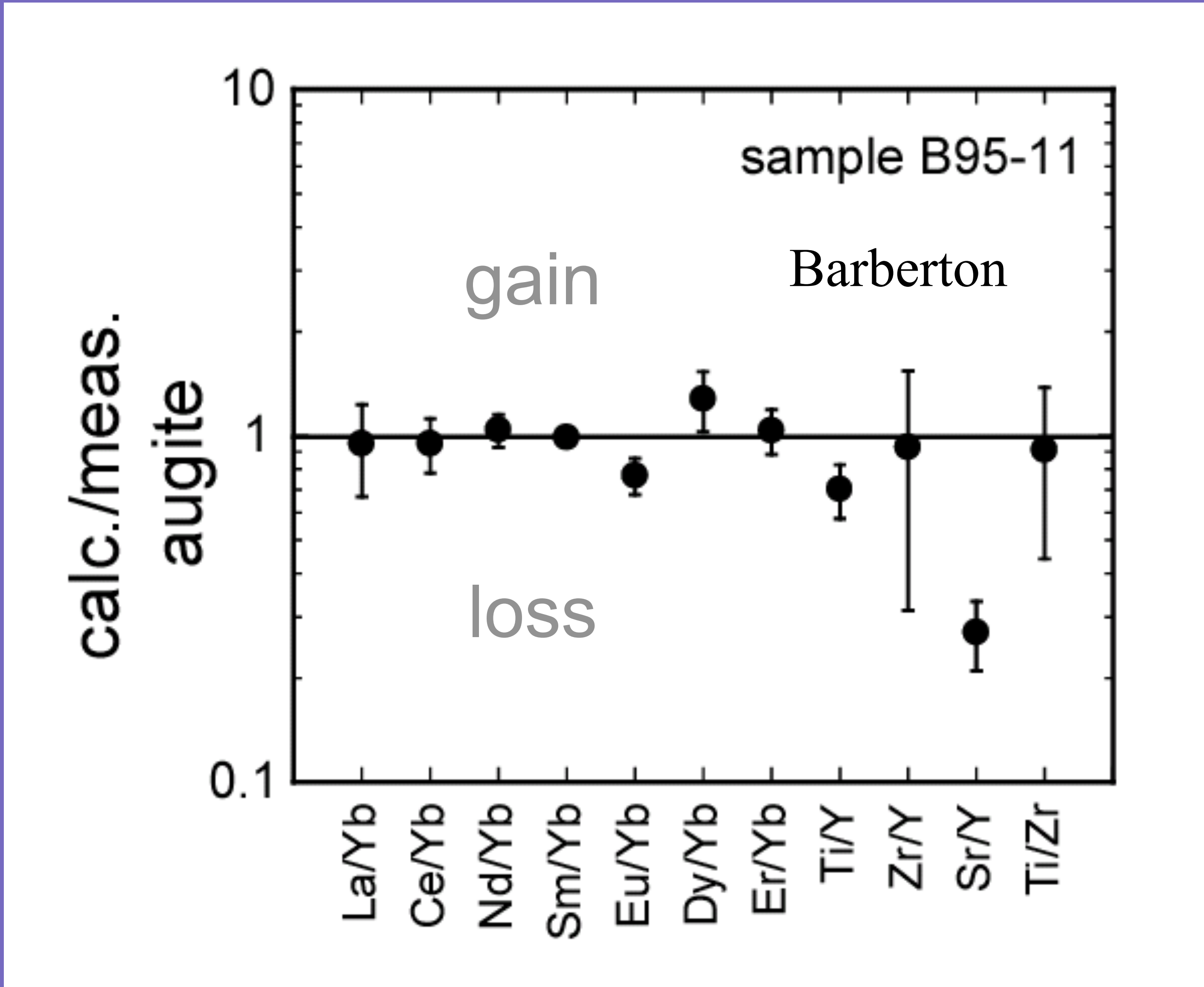
Ion Probe analyses of unaltered augite



Measured and Estimated Augite REE



Assessment of TE mobility

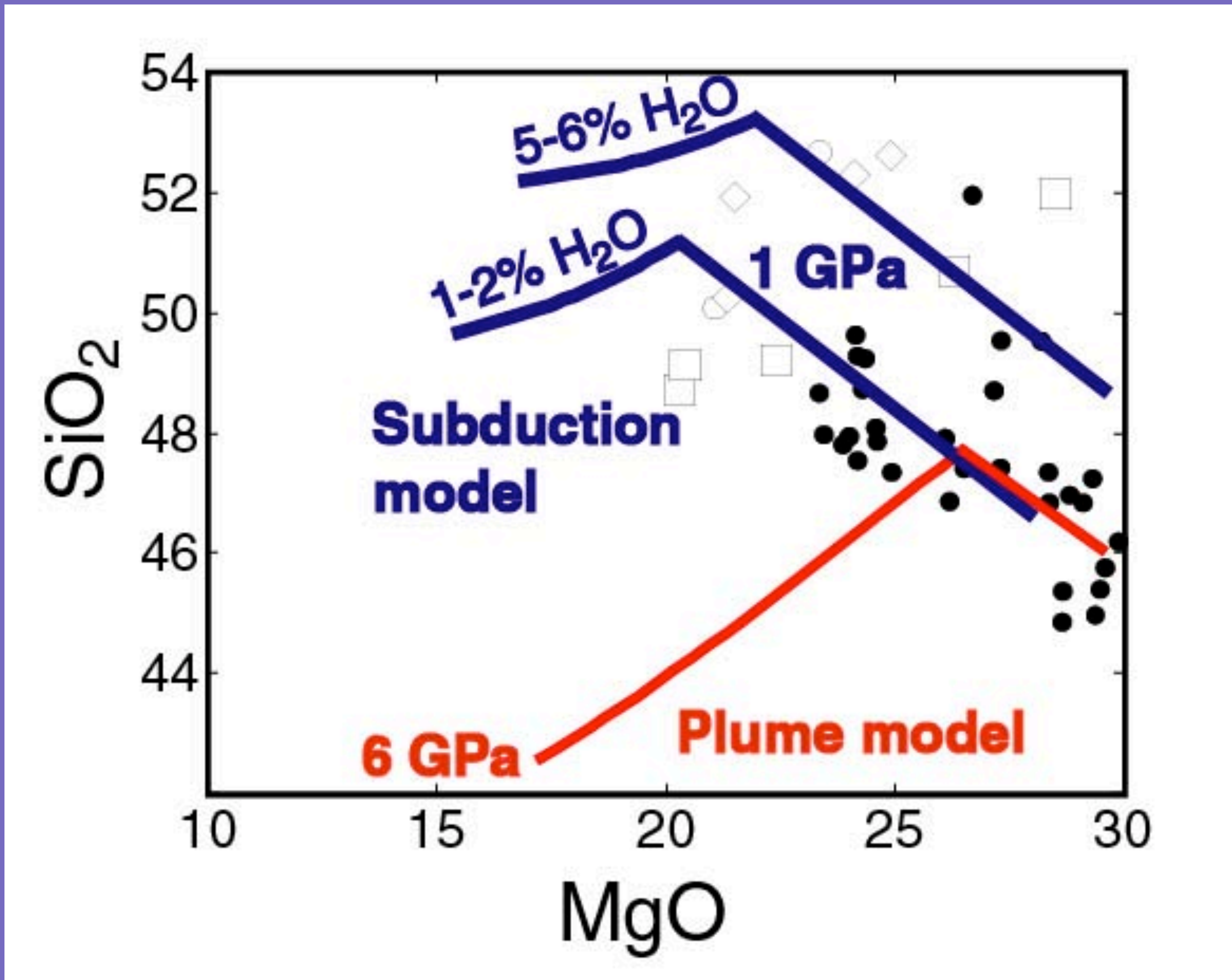


Subduction summary

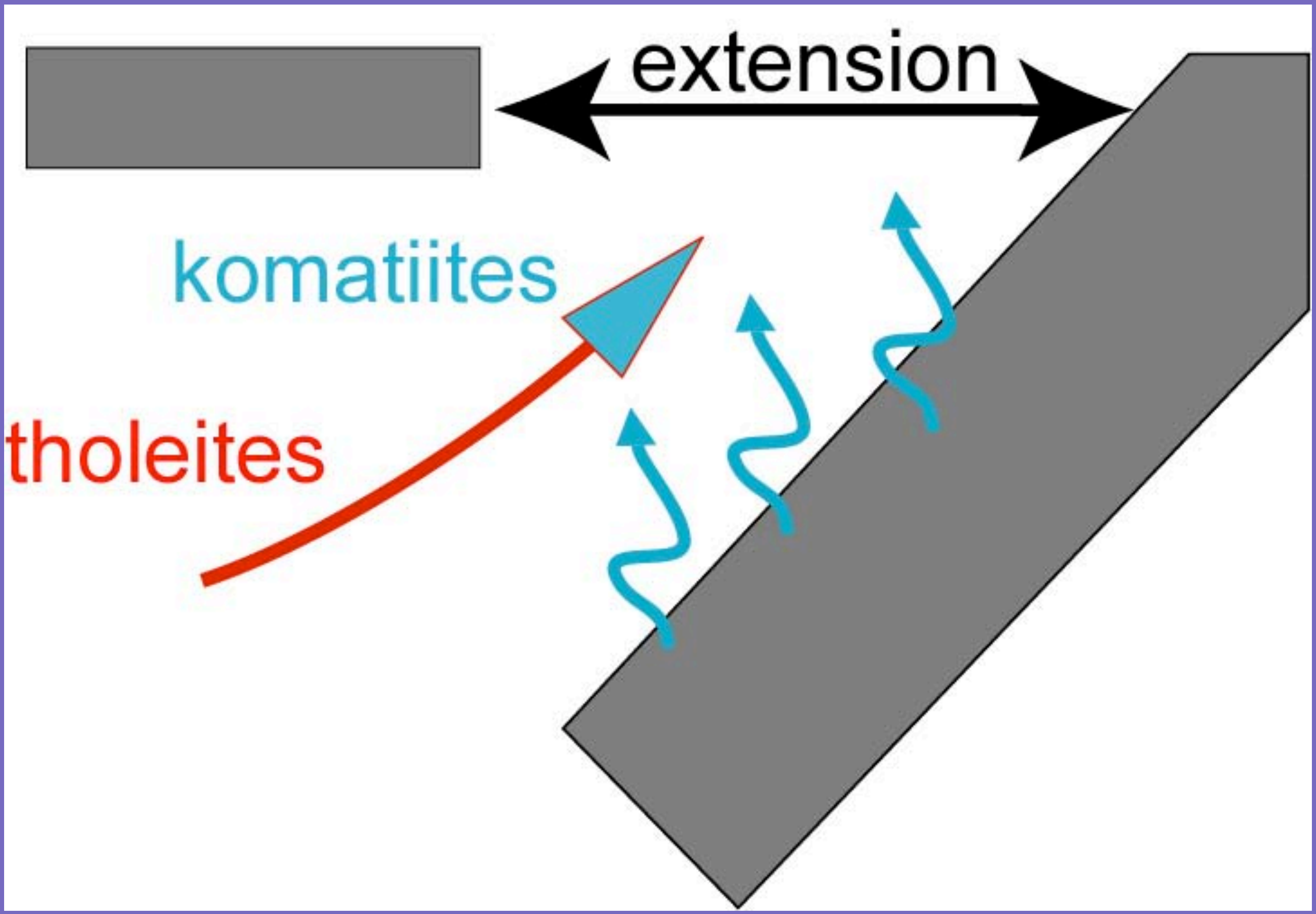
- Fits geochemistry
- Fits evidence for high H_2O
- Fits tectonic models of greenstone belt formation
- Requires a single, currently observed process = subduction

- **What are implications for Earth Evolution?**

Predicted melting conditions

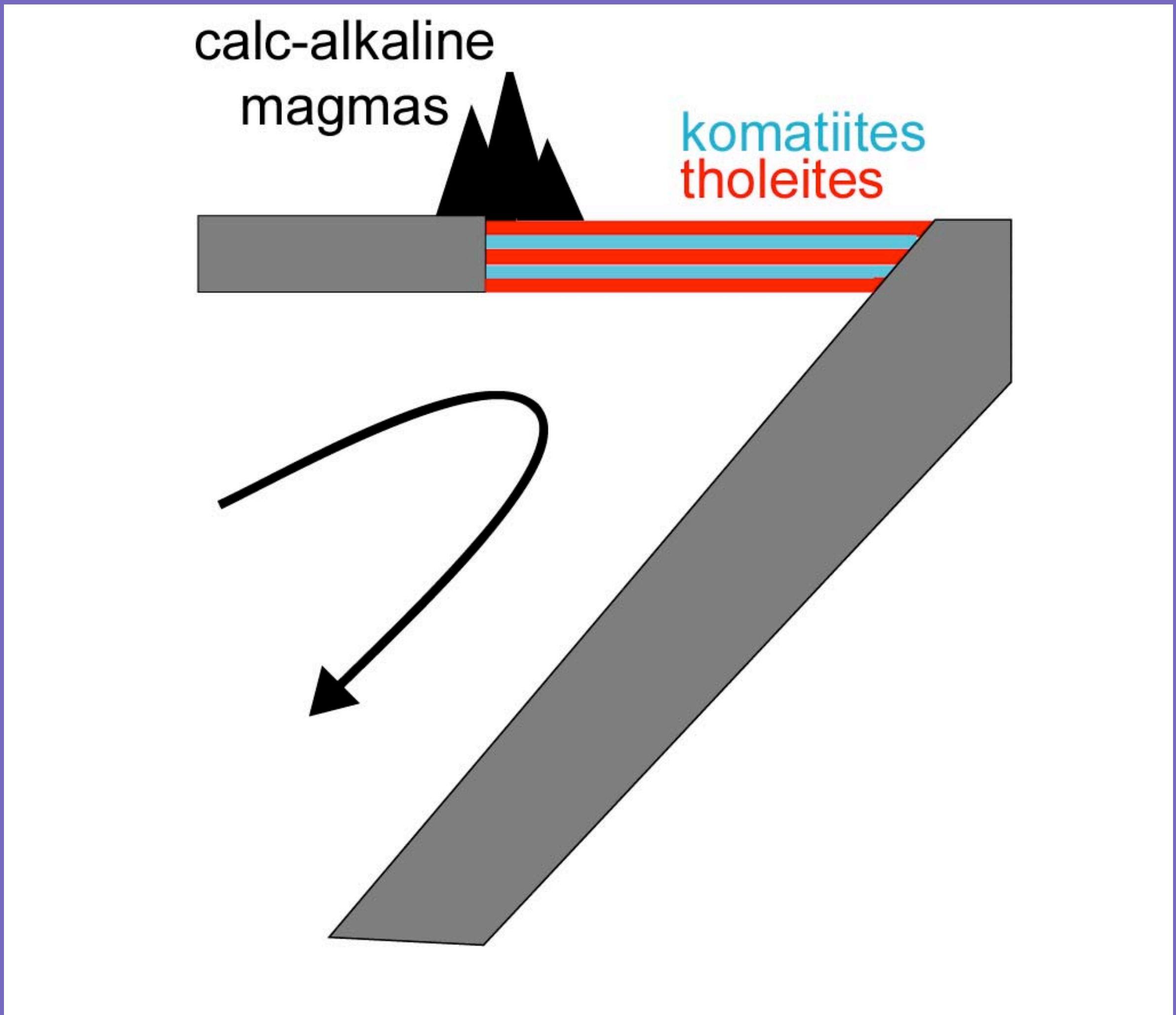


Subduction initiation

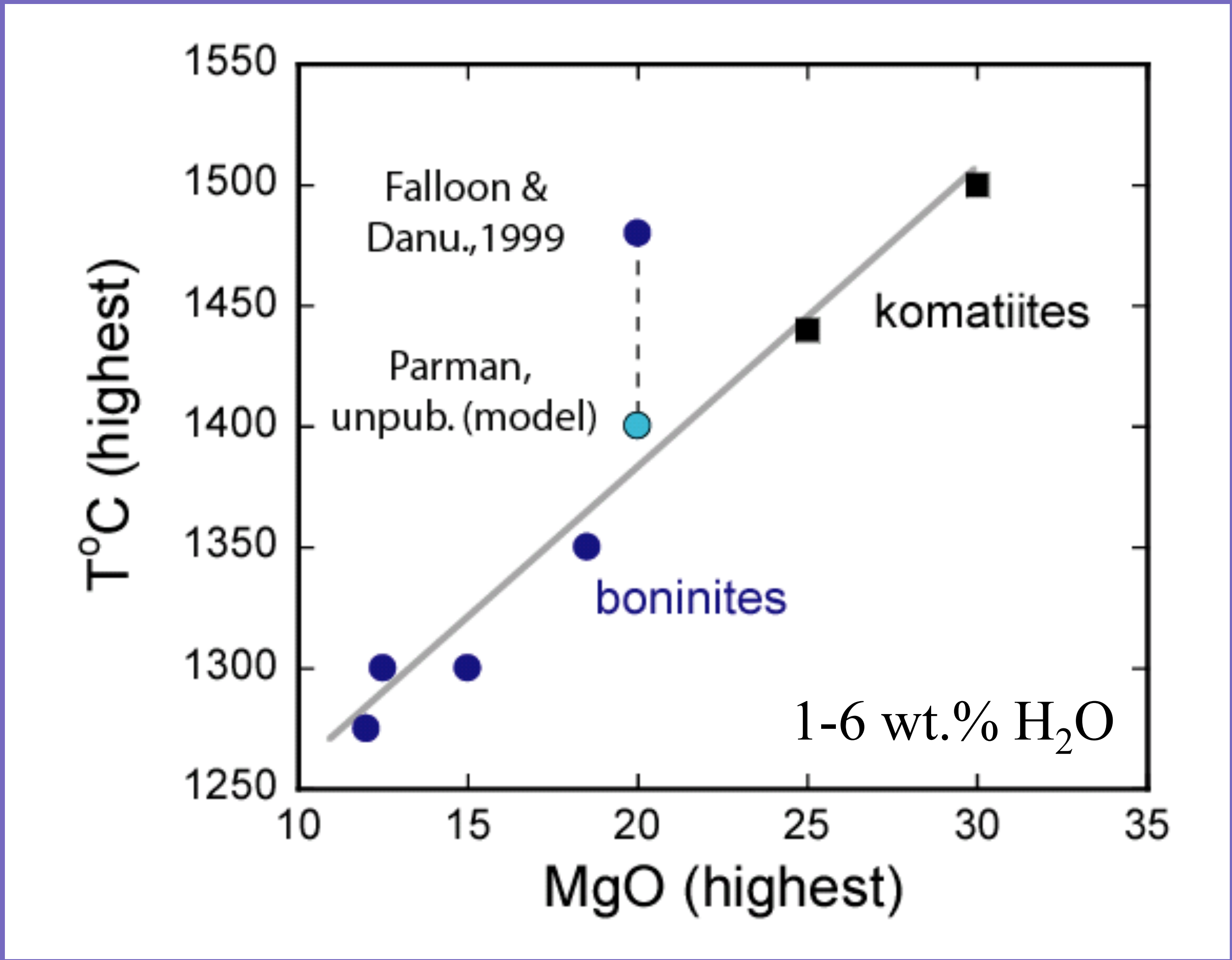


Based on boninite model of Stern and Bloomer, 1992

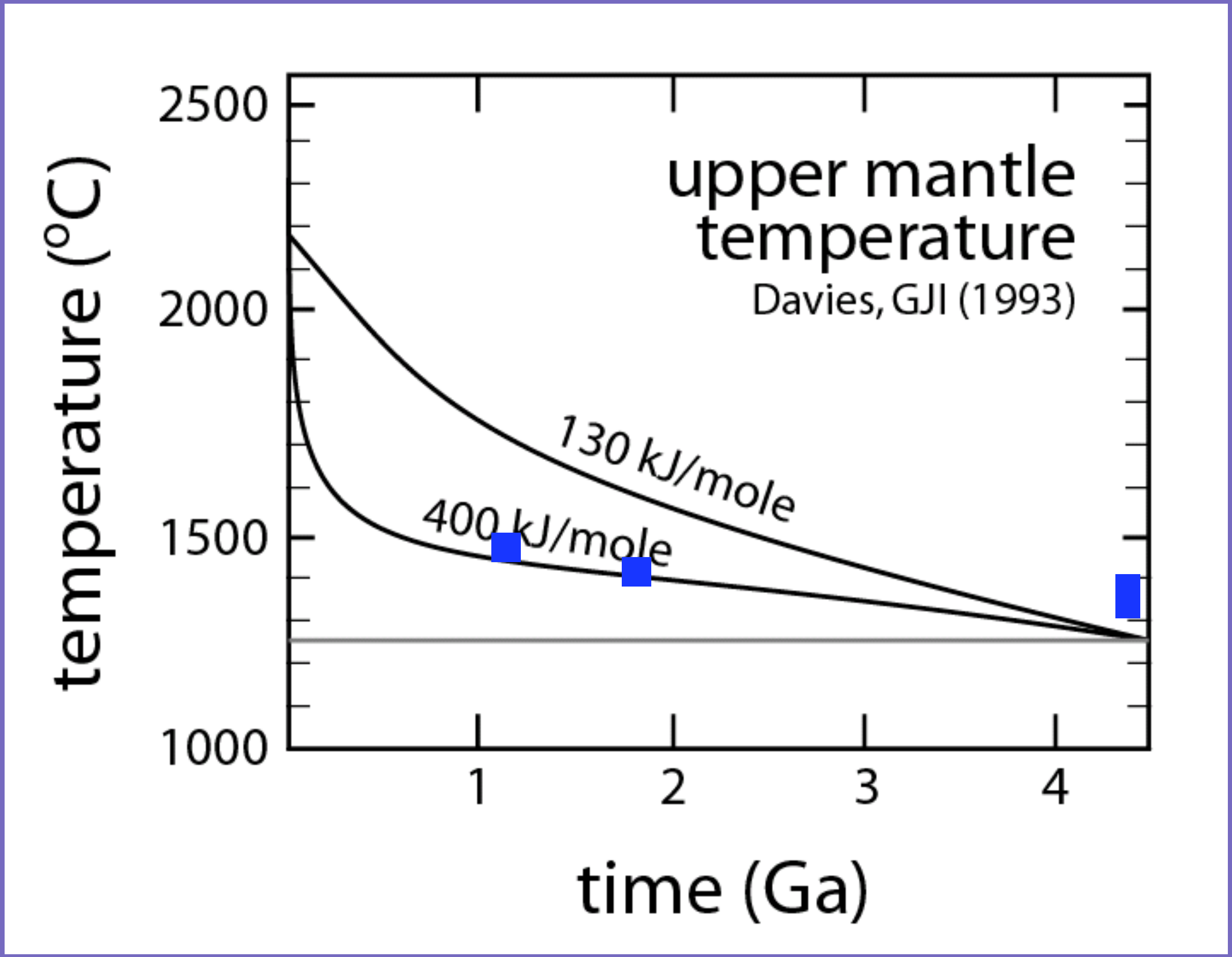
Mature subduction zone



Experimental Estimates of Hydrous Melting Conditions



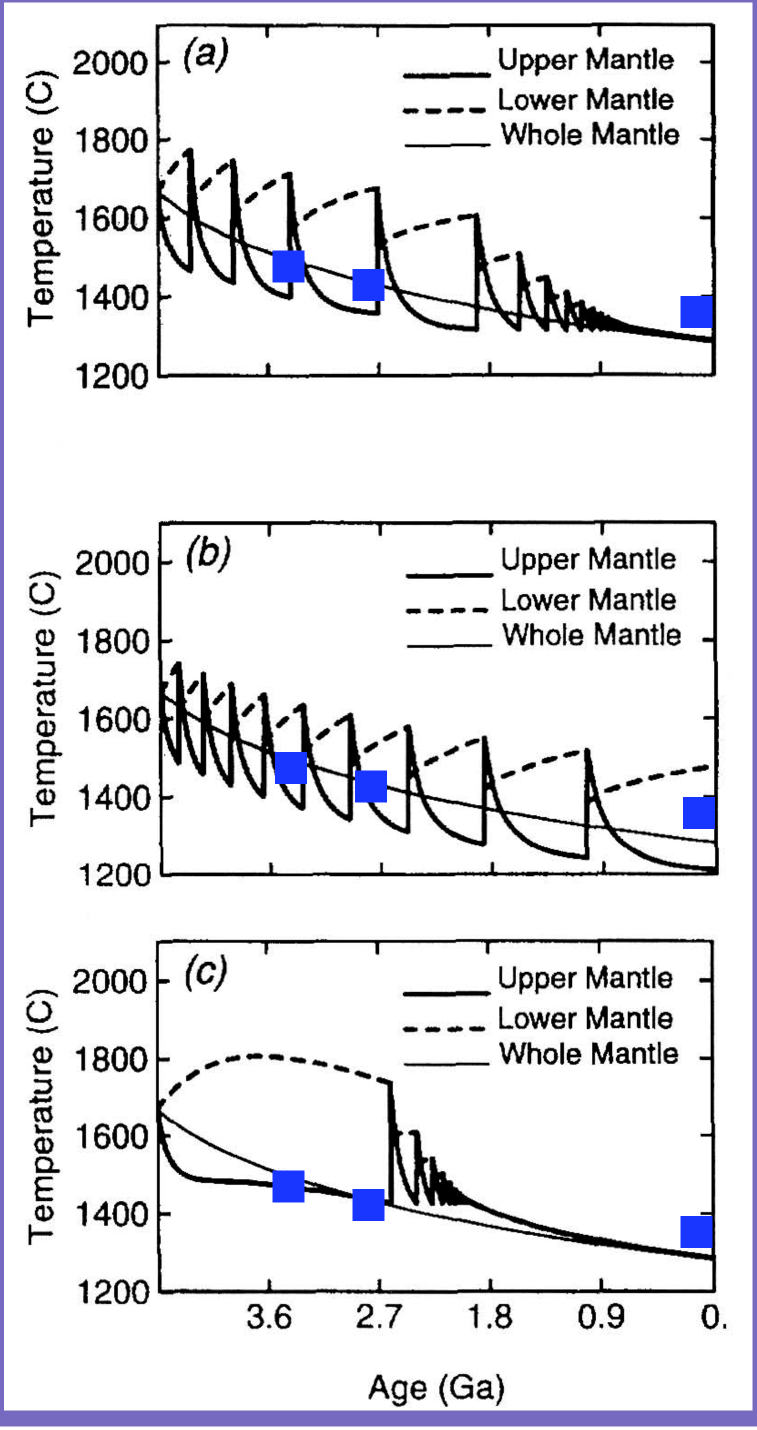
Geodynamic Models - basic

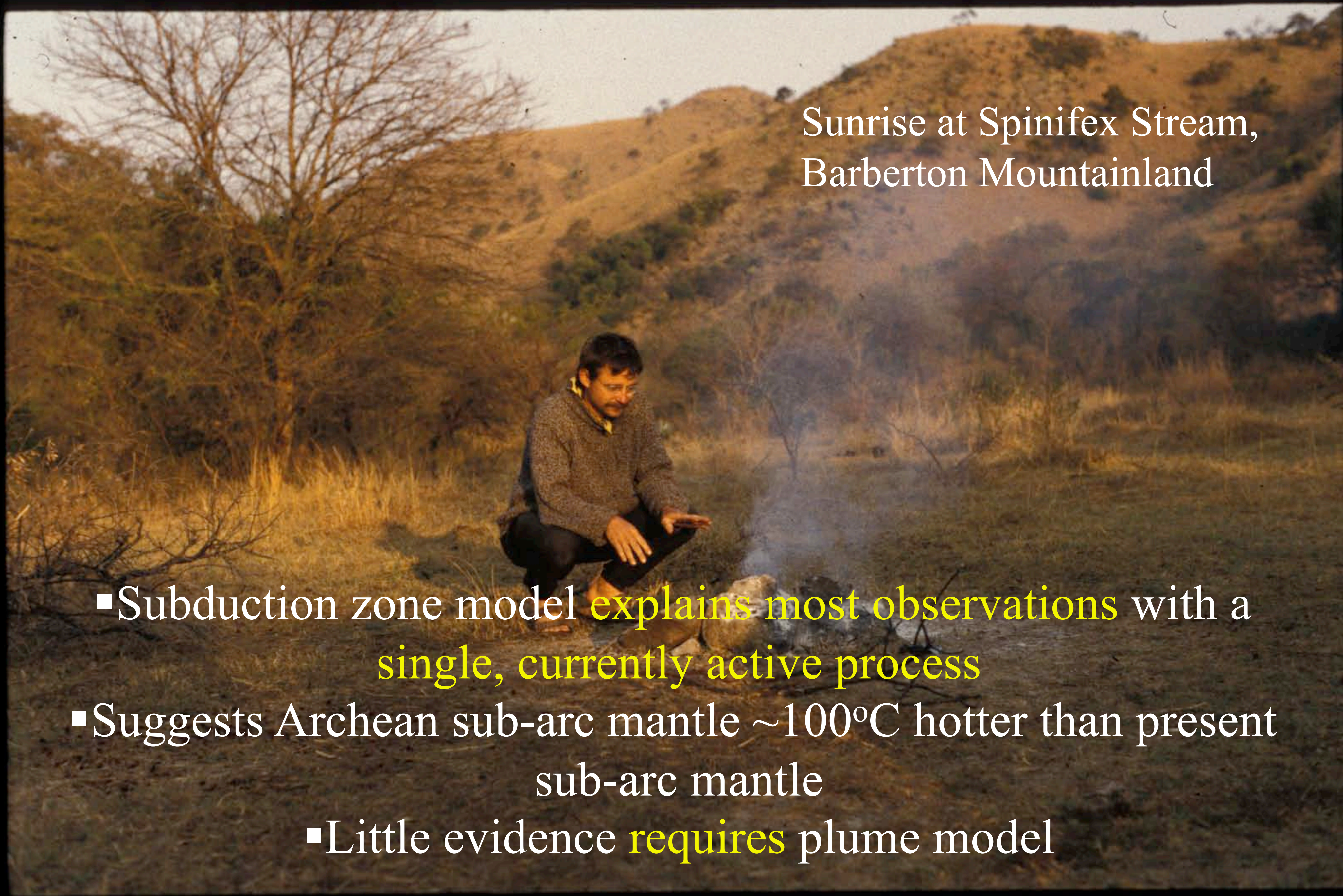


Geodynamic Models

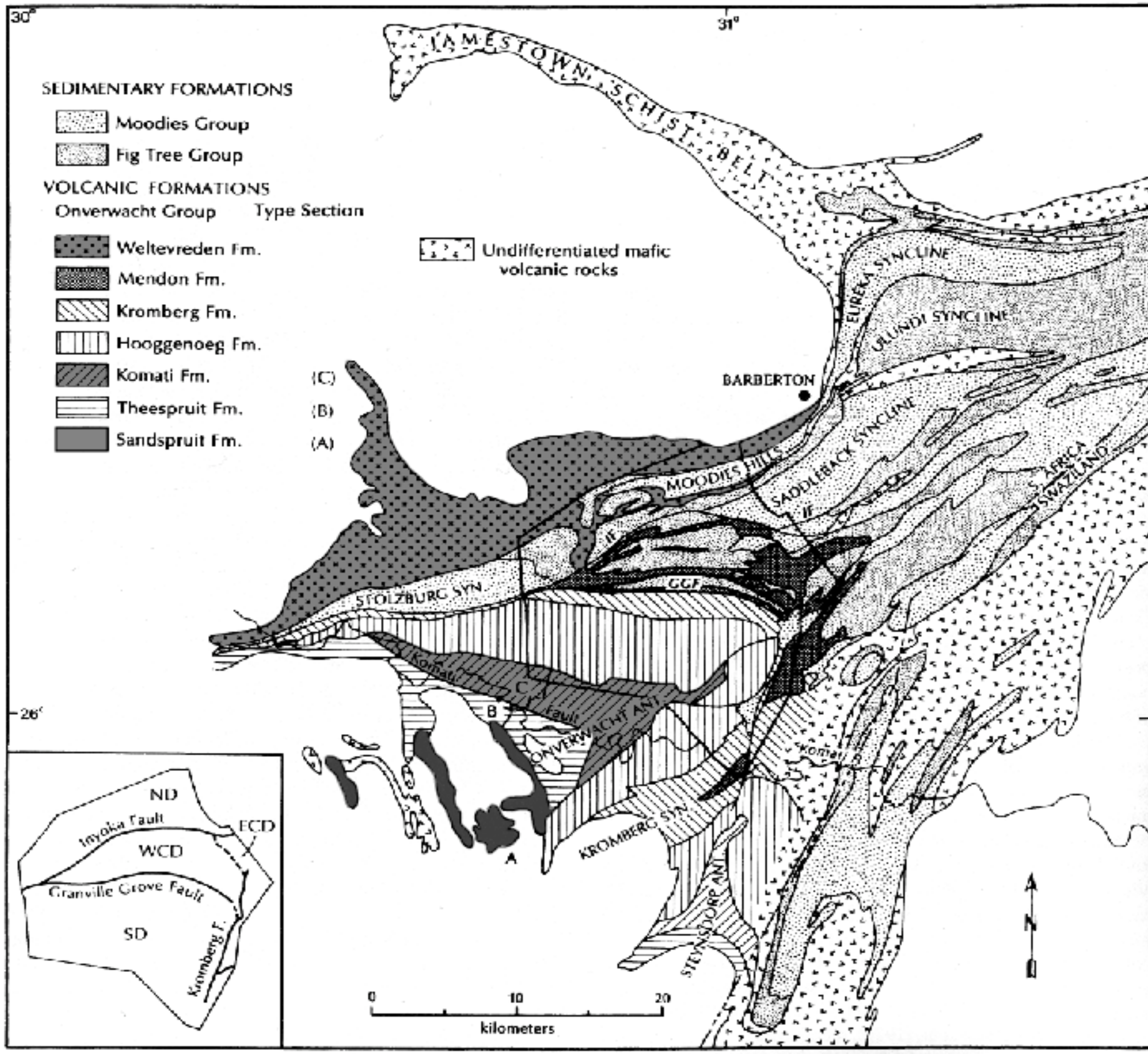
episodic cooling
due to phase
transitions

Davies, EPSL (1995)




Sunrise at Spinifex Stream,
Barberton Mountainland
▪Subduction zone model explains most observations with a single, currently active process
▪Suggests Archean sub-arc mantle ~100^{o}C hotter than present sub-arc mantle
▪Little evidence requires plume model

Western Barberton Greenstone belt

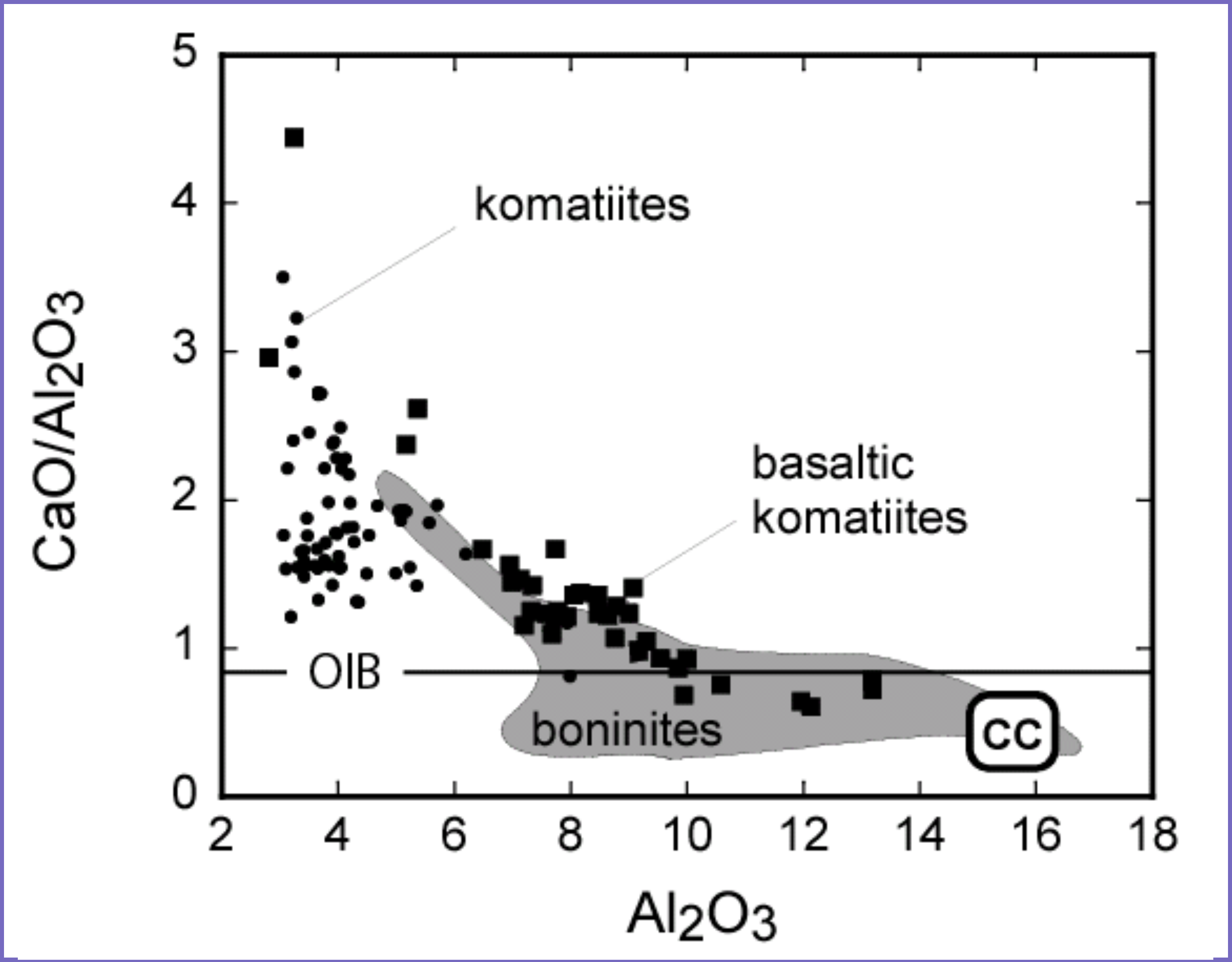


after Byerly

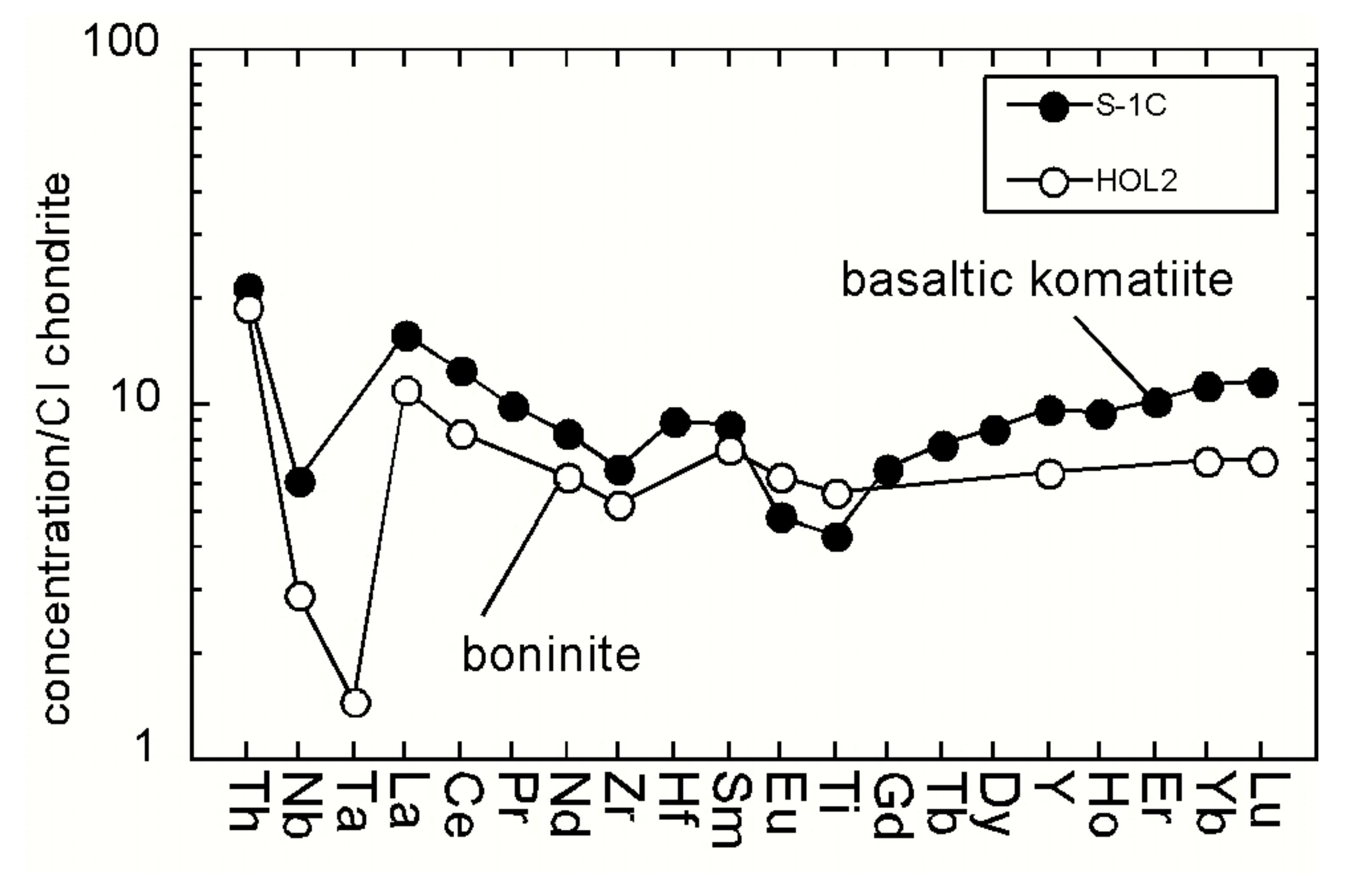
Evidence that does not constrain H_2O contents

- Presence of vesicles (tuffs)
- Depletion of source (epsilon $Nd_{(t)}$>0)
- Eruption on surface

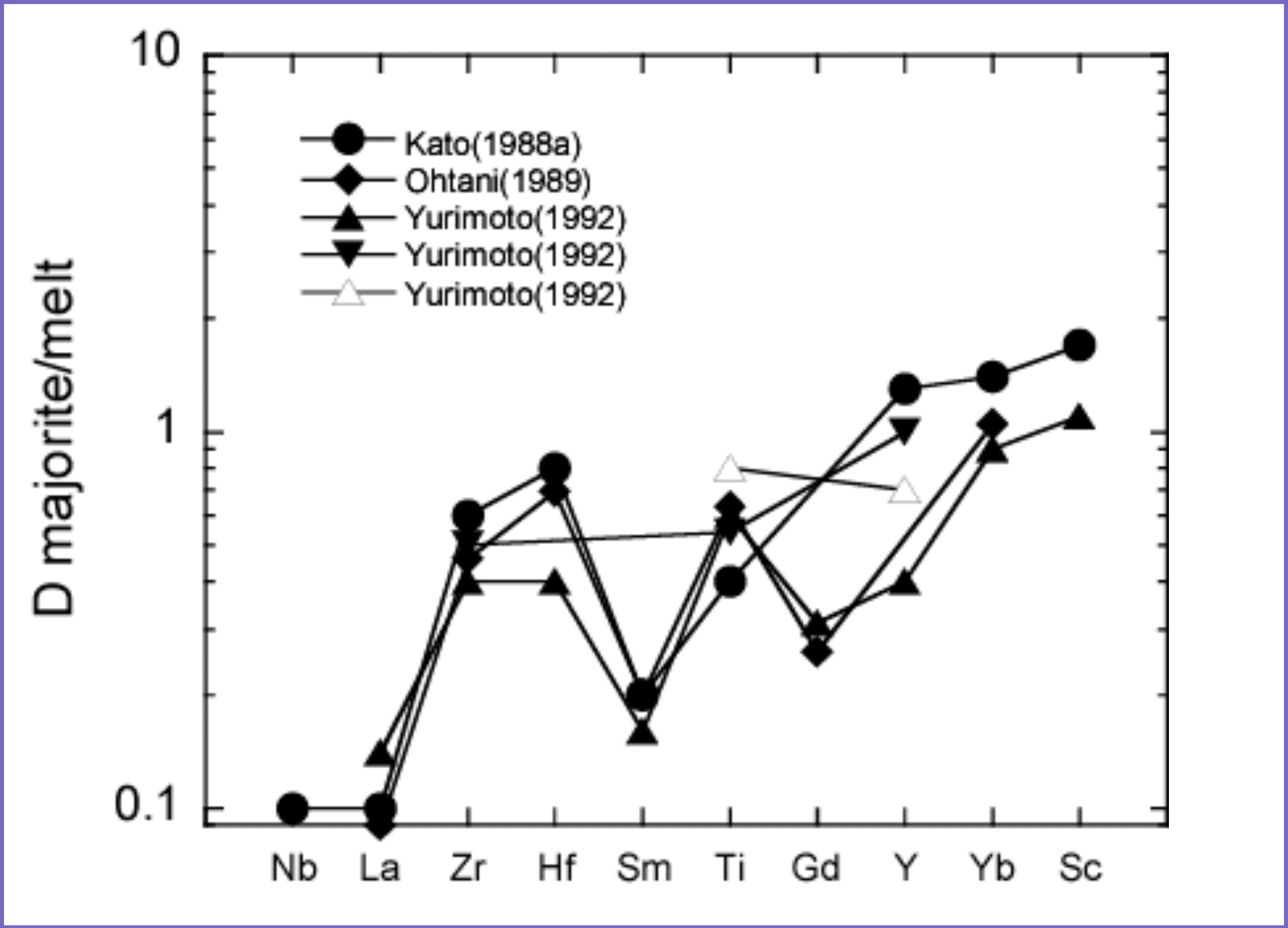
High CaO/Al_2O_3



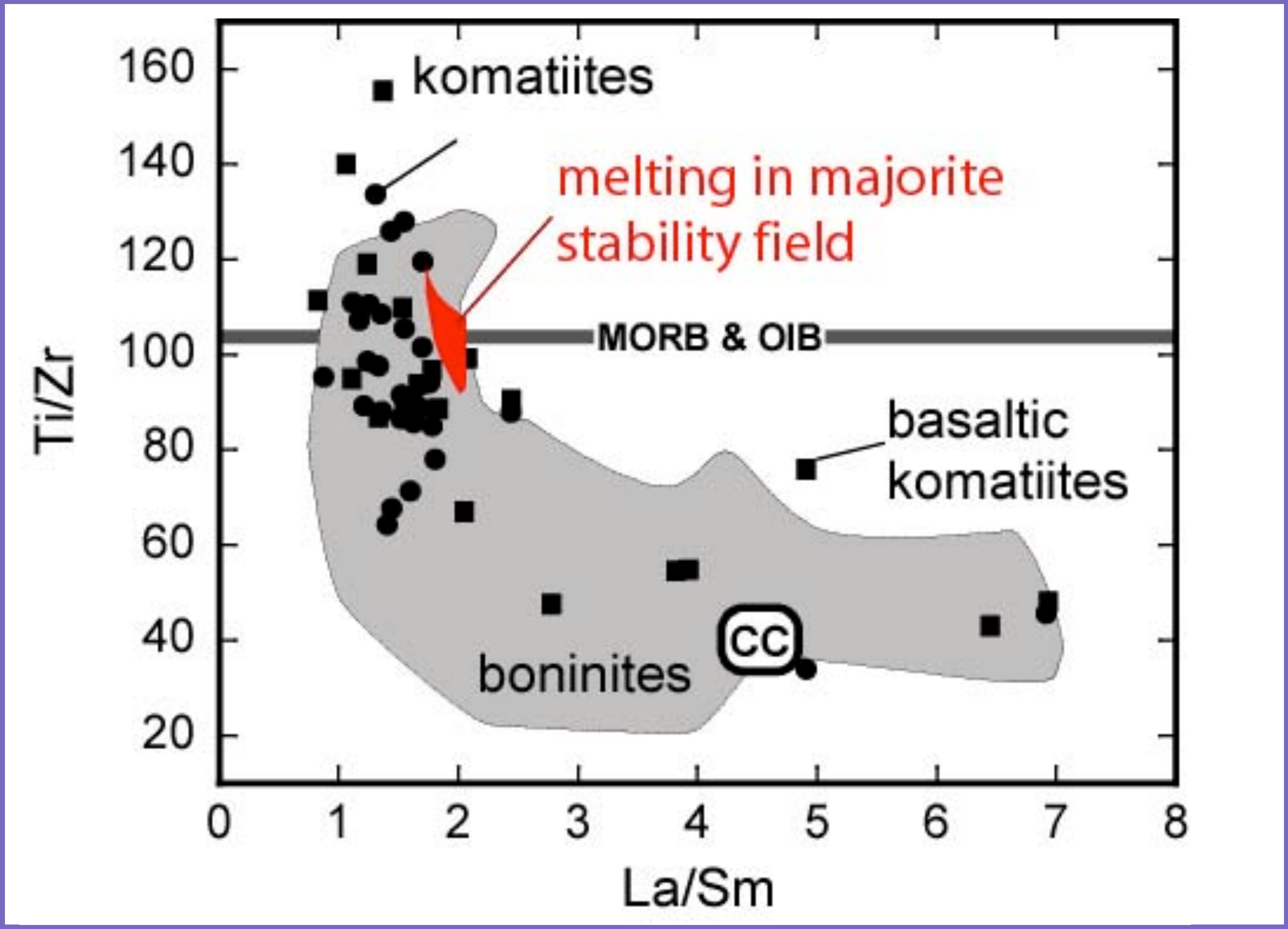
U-shaped pattern

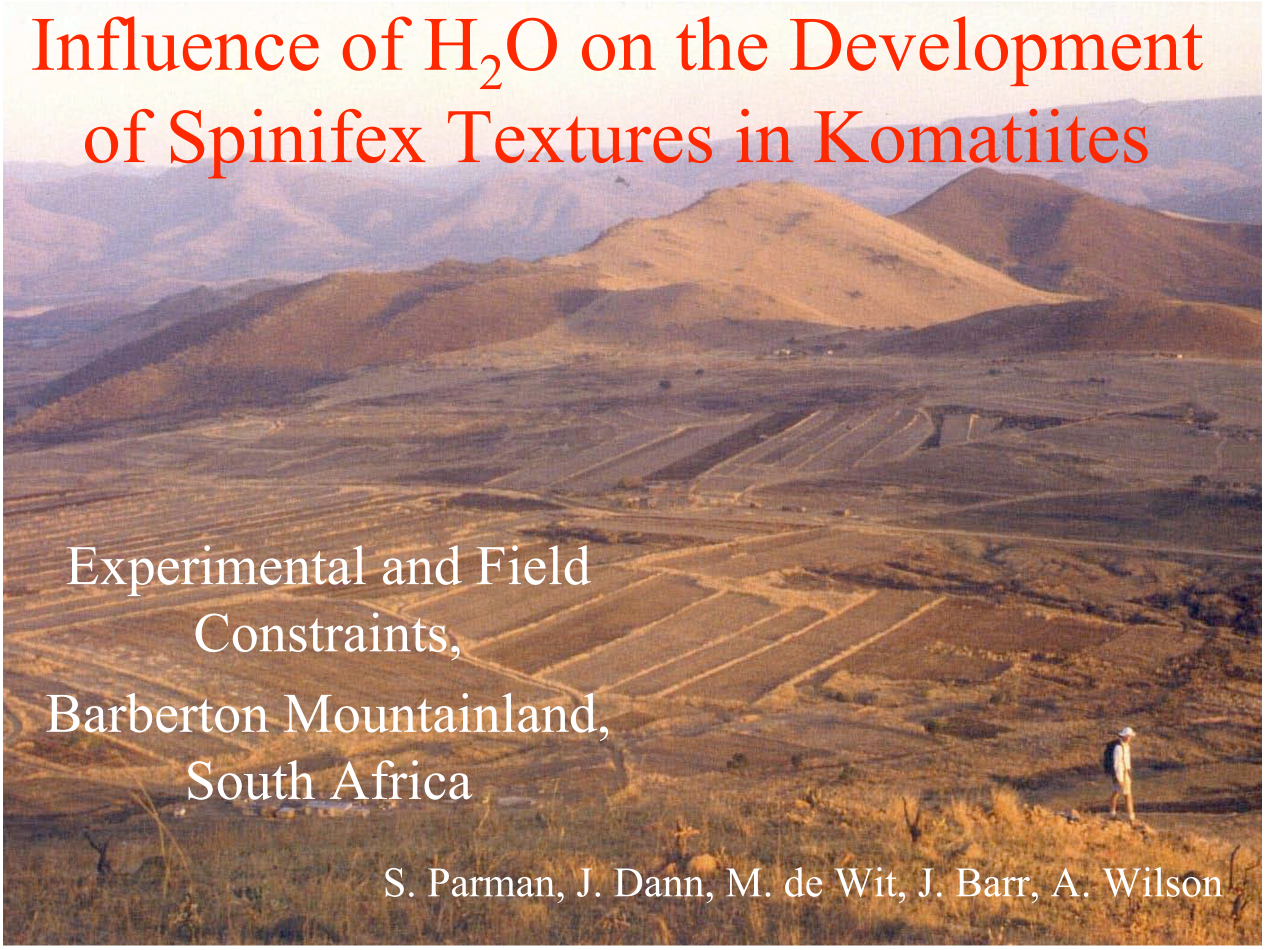


majorite TE partitioning



majorite fractionation

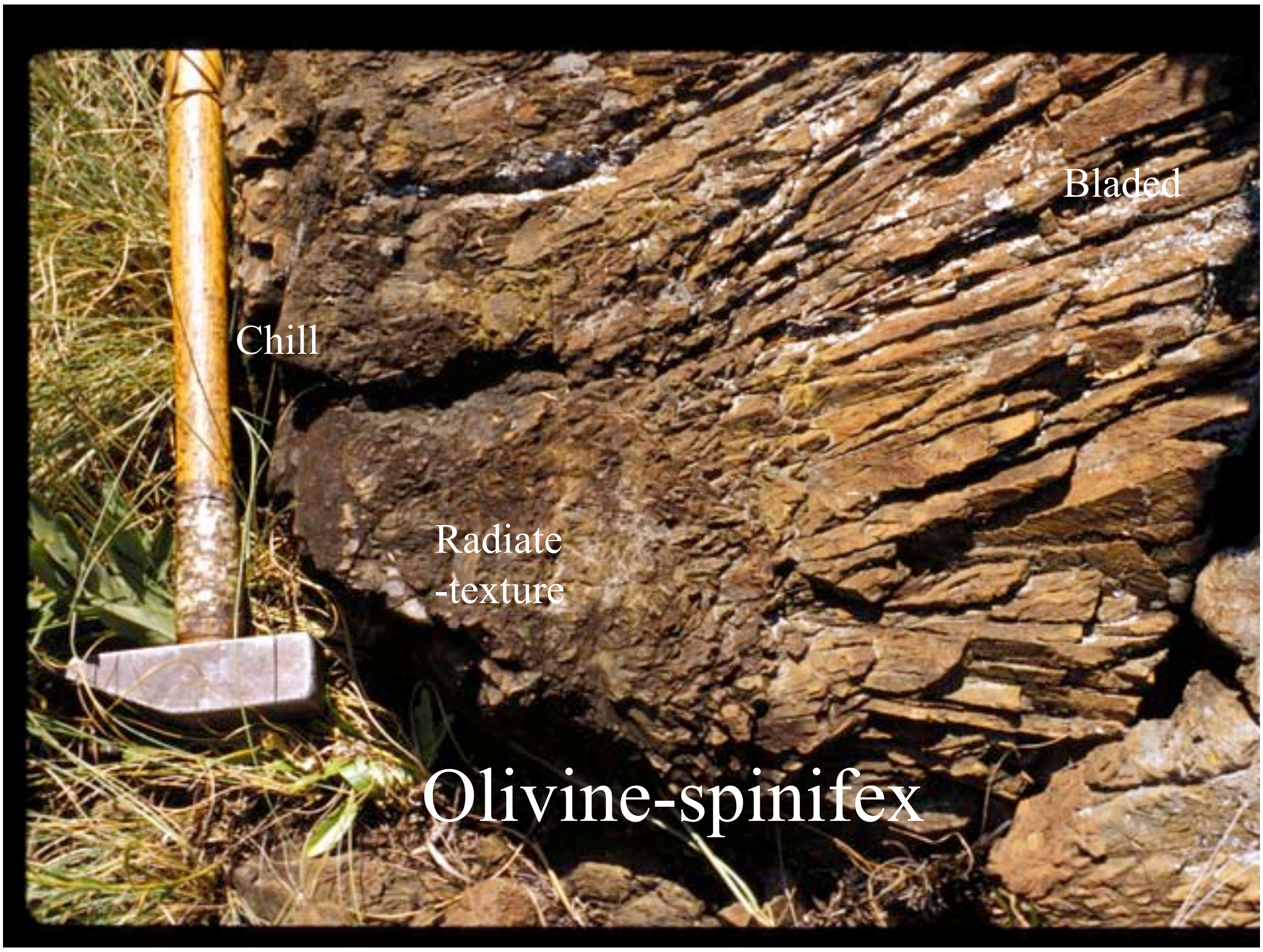




Conditions for formation of olivine spinifex in komatiites

- **Experimental Evidence** for spinifex formation
- Experimental Containers influence nucleation and growth
- H_2O changes nucleation and growth conditions

- **Field evidence** of initial conditions
- Melt arrives undercooled (supersaturated)
- Cooling rate is slow, but variable chill geometry influences cooling rate
- H_2O in melt is important



Hopper – like surface texture of olivine blade in coarse, bladed spinifex zone. Individual crystals ~30–40 cm length, grow 1 to 4 meters from heat loss boundary

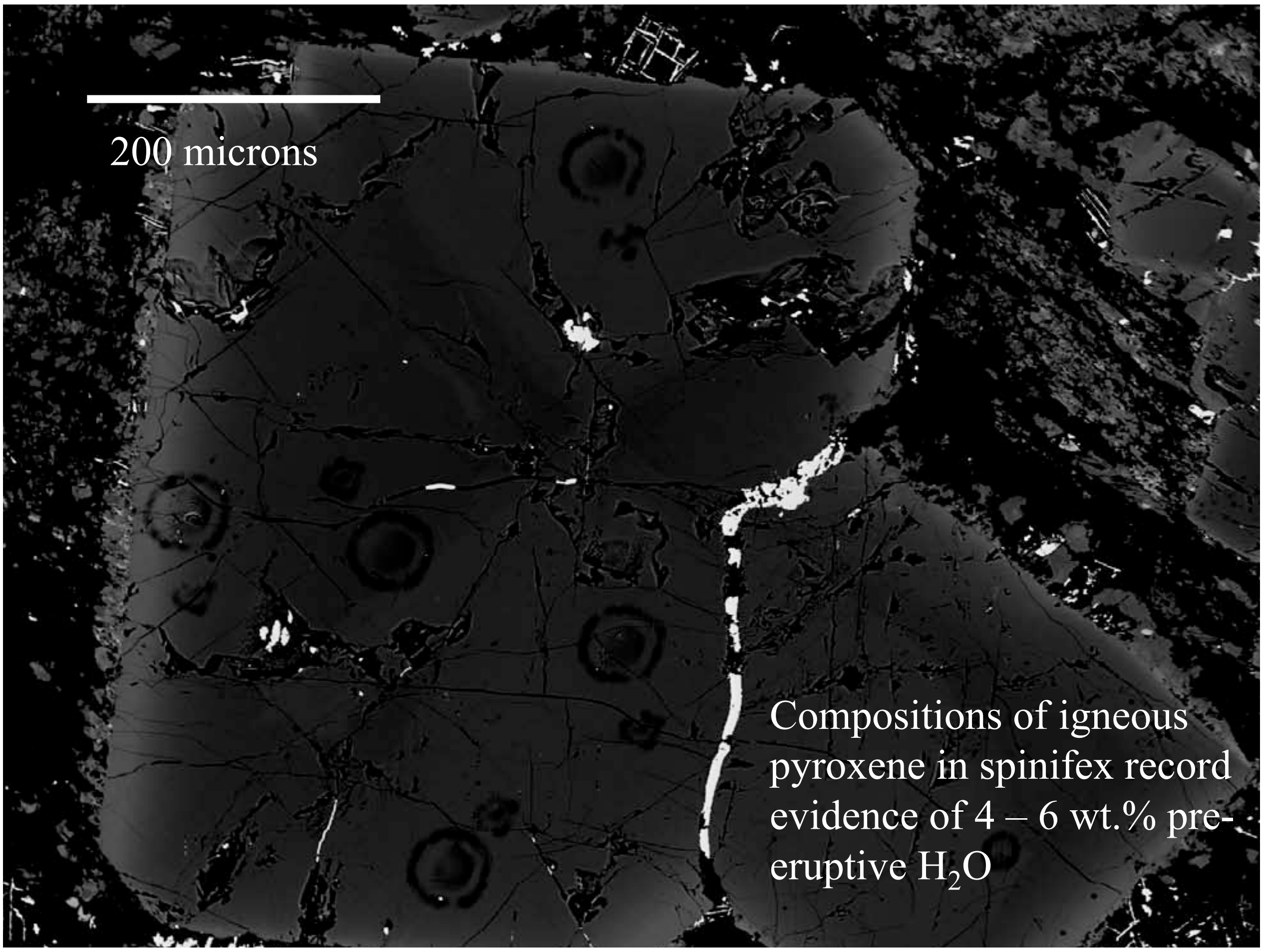
Petrologic Evidence suggest 4 – 6 wt. % H_2O pre-emplacement for Barberton komatiites (Parman et al., 1997)

H_2O can promote development of spinifex textures

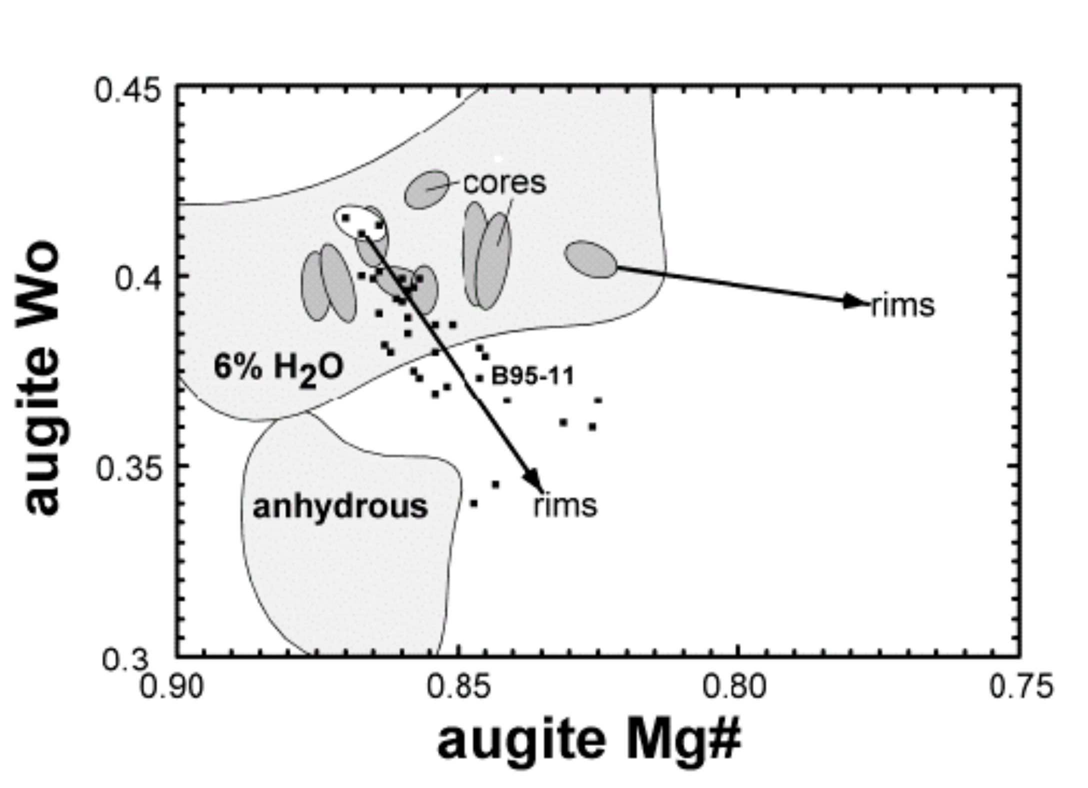
1) Changes in melt physical properties

- Lowers nucleation rate
- Increases growth rate

2 Undercooling by decompression of hydrous magma



Augite Wo contents



Experimental Evidence on Spinifex formation

Container size controls on spinifex development

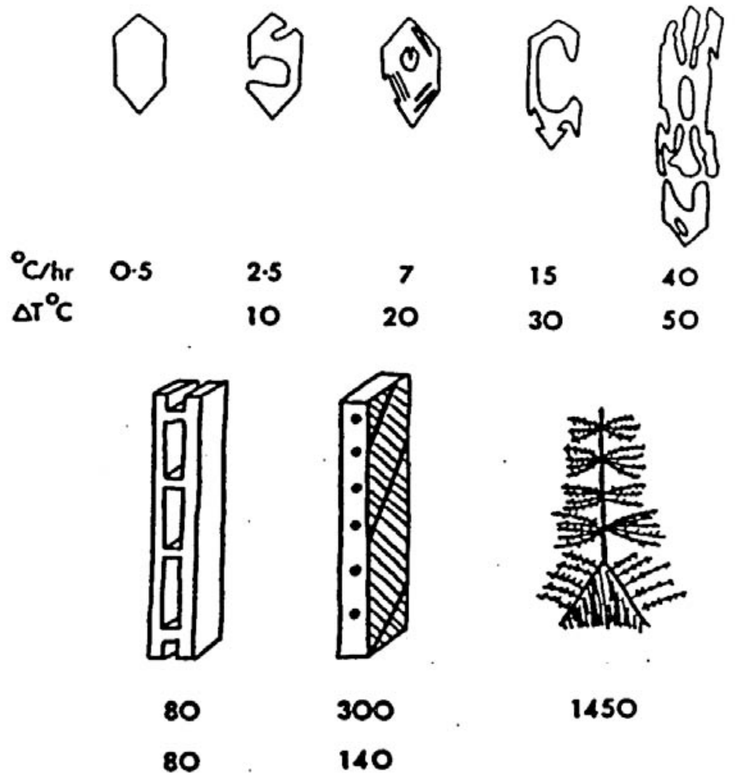
- 1 Larger container = lower nucleation rate
- 2 Leads to more dominant control of growth rate on crystal morphology

- H_2O lowers melt viscosity, lowers
- Lowers nucleation rate
- Speeds up growth rate
- Leads to growth of a few BIG crystals
- Ultramafic Pegmatites

Donaldson (1976) Olivine morphology vs cooling rate & undercooling

Micro-spinifex develops at rapid cooling rates

No spinifex textures were produced a at slow cooling rates



Experimental Approach

Munro township komatiite SSK 17 % MgO

$T_{initial}$ 1370 °C @ 0.1 MPa "DRY"

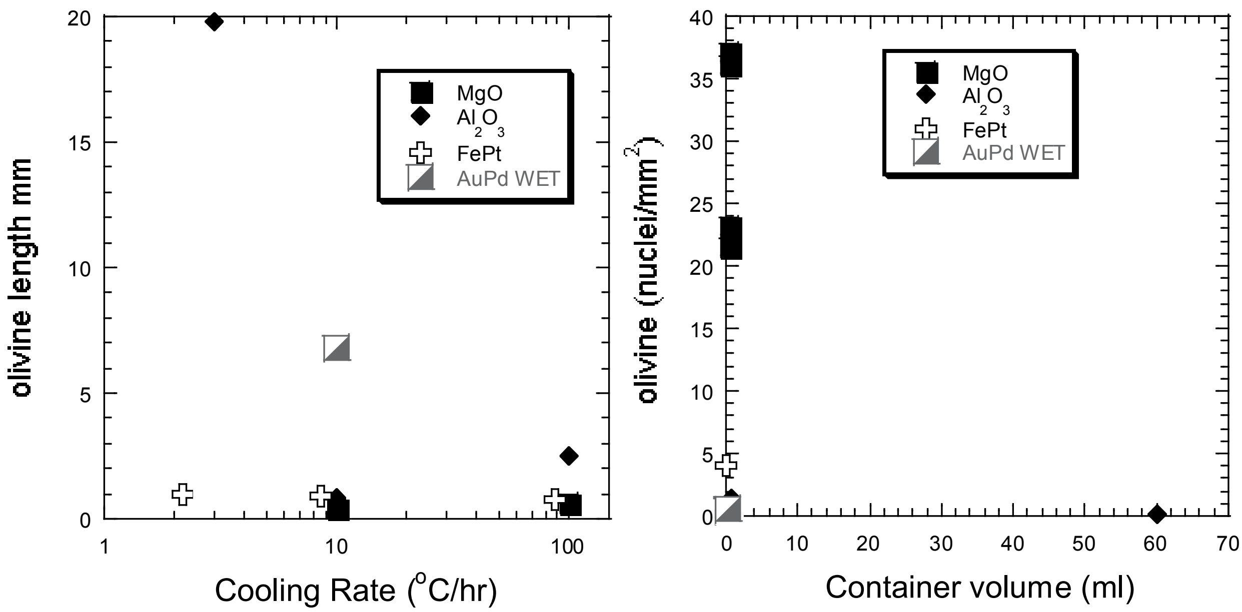
1300 °C @ 200 MPa H_2O-saturated "WET"

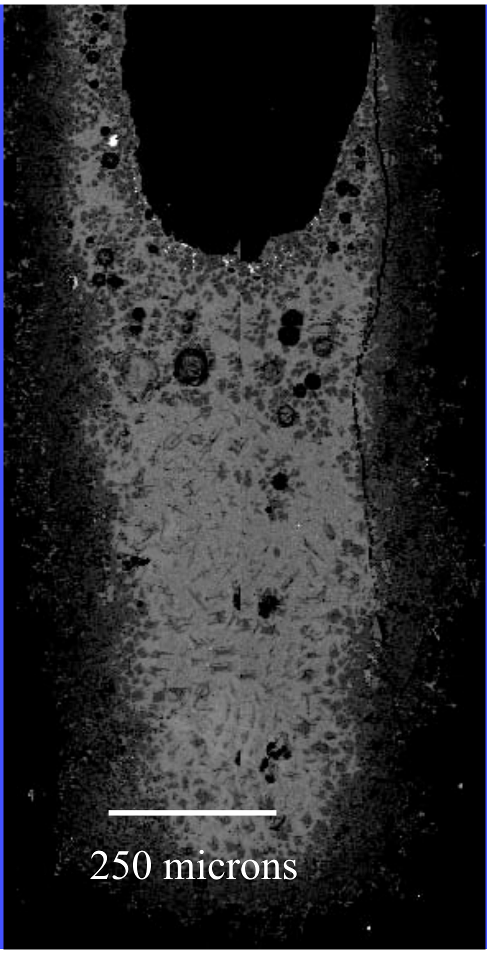
Variable cooling rate 3 to 100 °C/hr

Variable container

composition	volume (ml)	texture
MgO	0.4	granular-hopper
Al_2O_3	0.7 – 60	hopper-chain
SanCarlos	0.3	chain-euhedral
Pt-Fe loops	0.03	chain-euhedral
AuPd (200 MPa)	0.27	hopper-chain

Large container dry ~ 5 times larger
Small container "wet" ~ 7 times larger



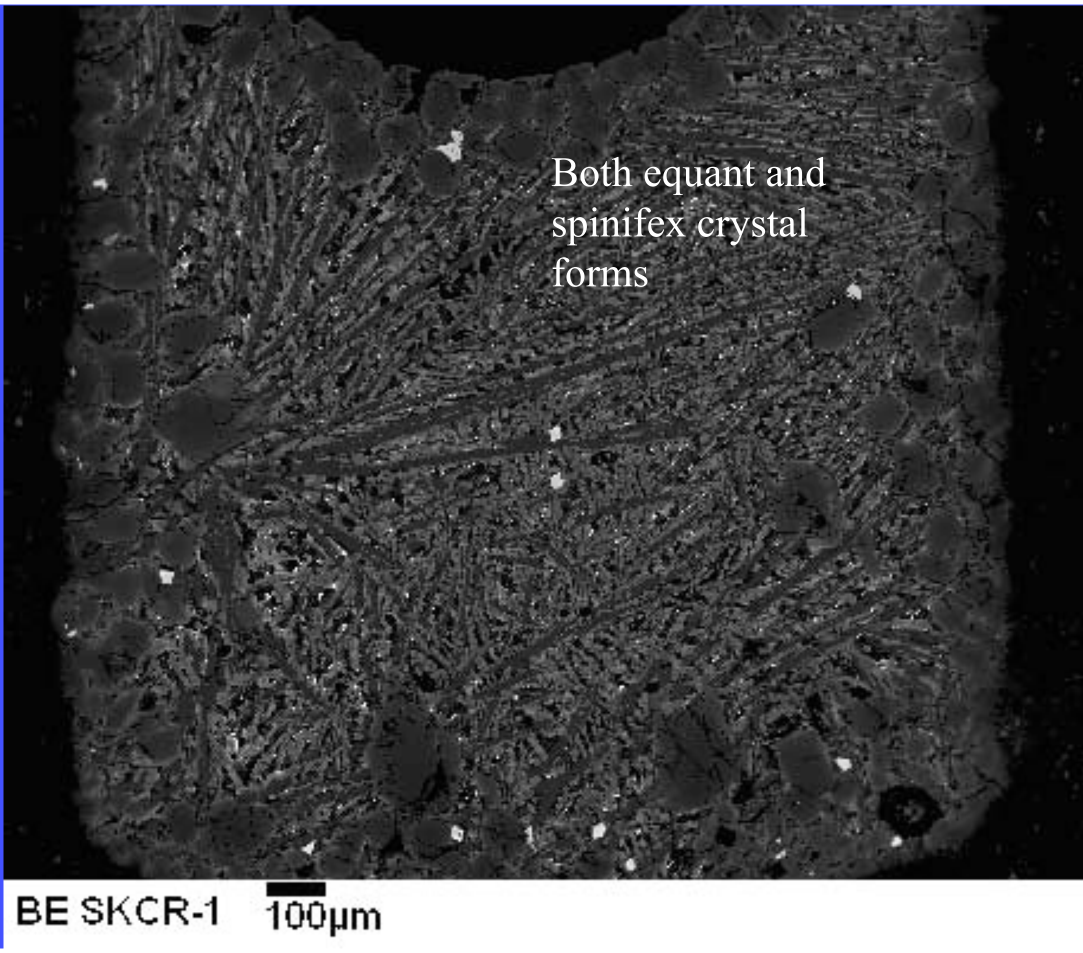


Possible to get a complete transition in crystal morphology at constant cooling rate

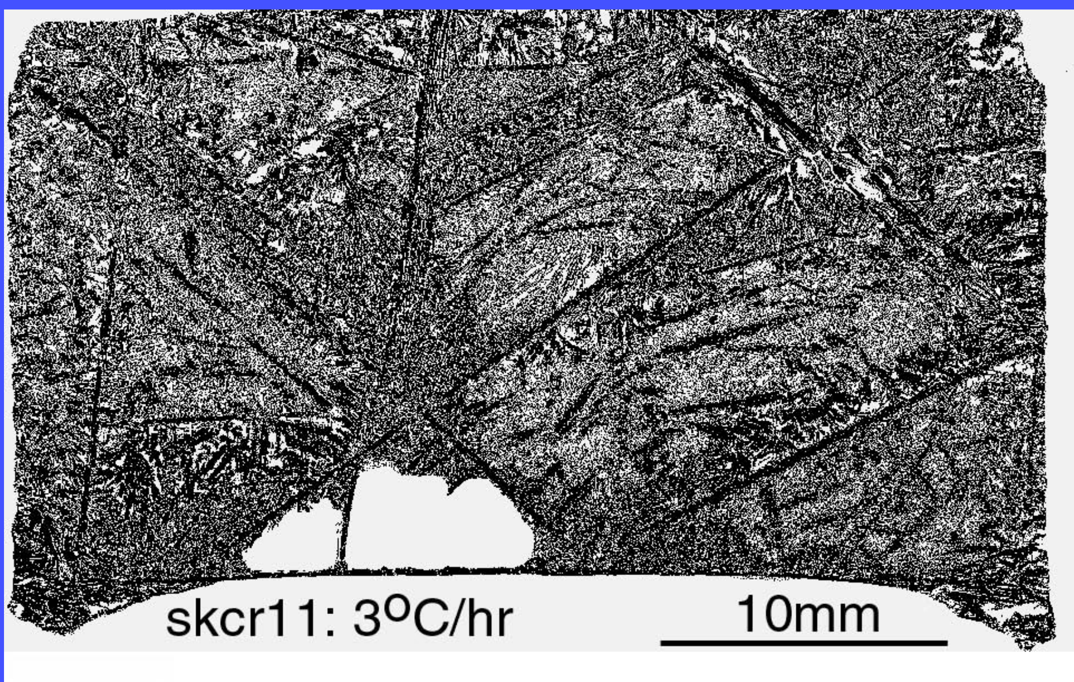
From many equant small crystals - shown here in a cooling rate experiment performed in an MgO capsule

To spinifex – just by lowering the the surface area to volume ratio

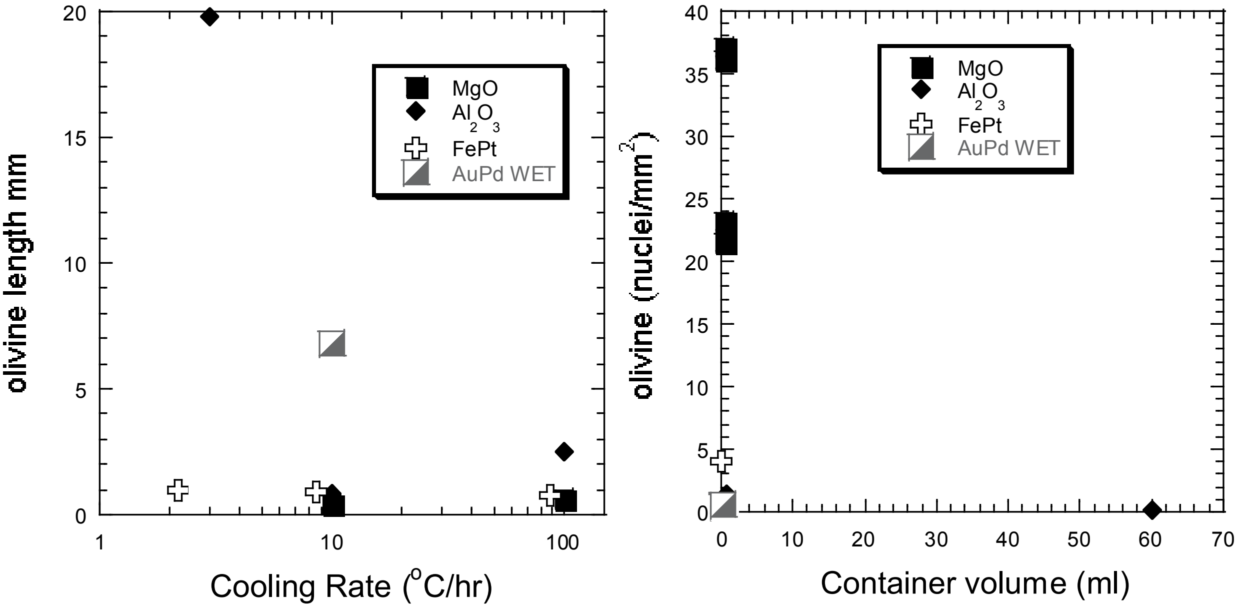
- reducing heterogeneous nucleation sites
- grow fewer longer crystals



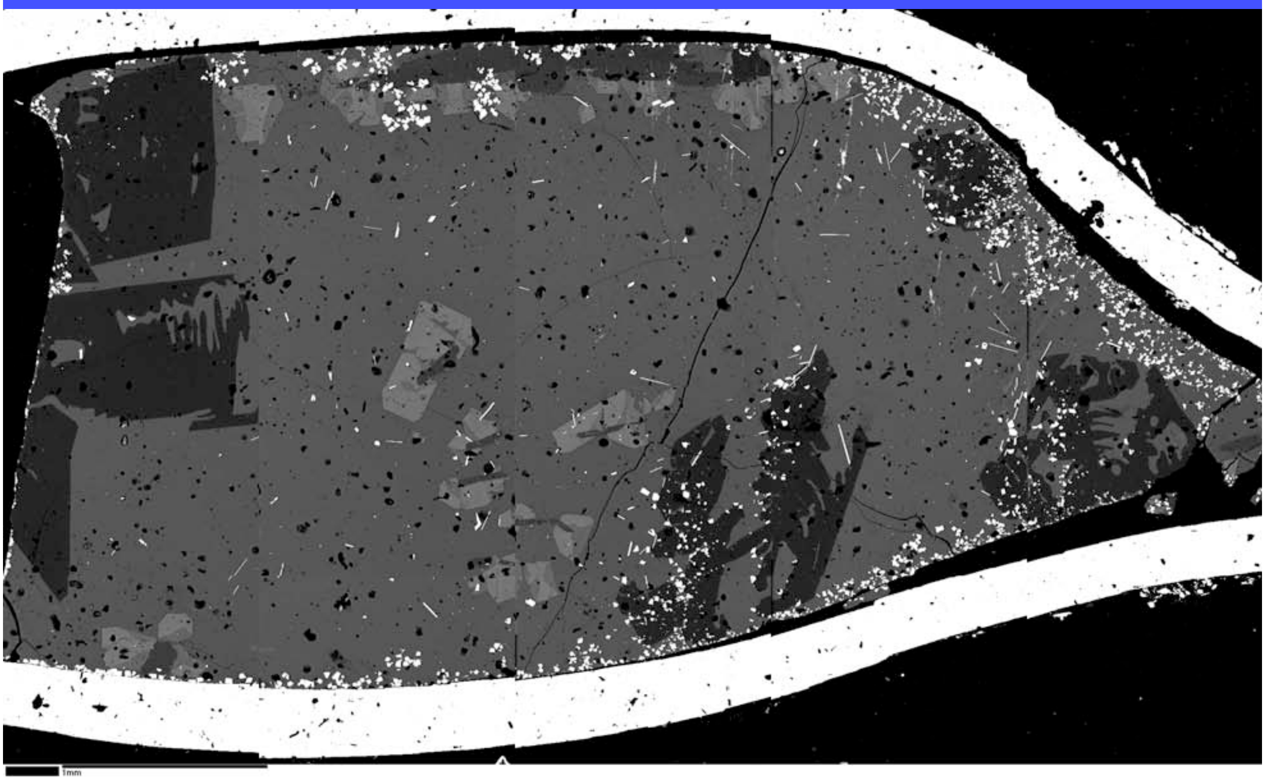
Large container – 60 ml crystals extend to edges



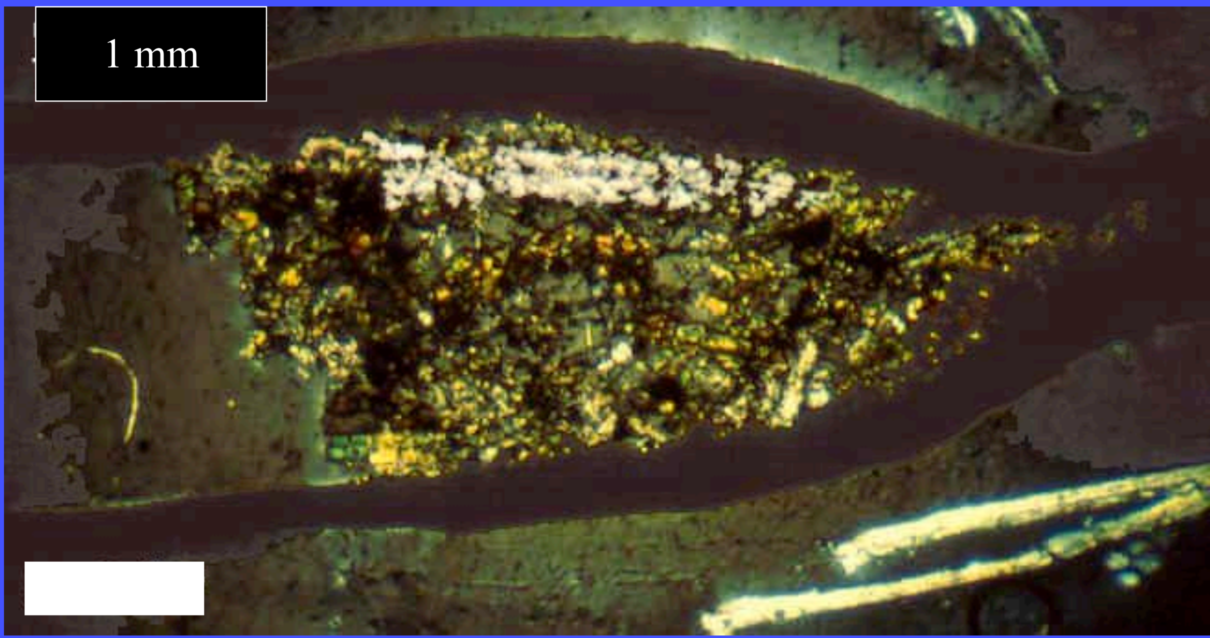
Large container dry ~ 5 times larger
Small container "wet" ~ 7 times larger



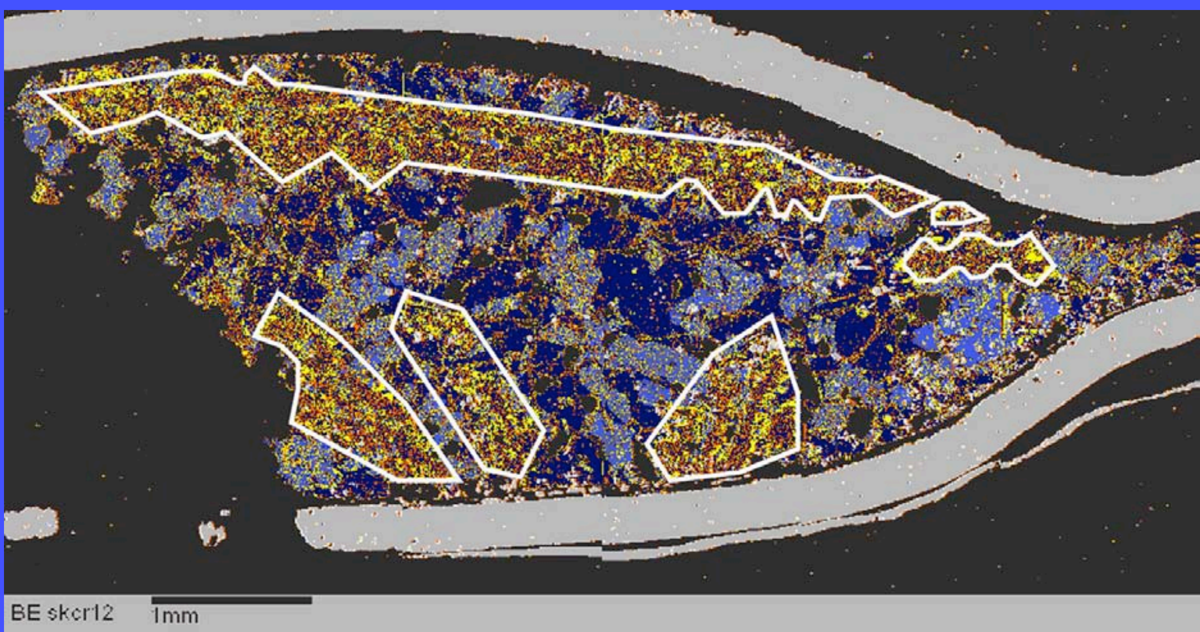
Adding H_2O increases crystal size and decreases nucleation density dramatically. 3 °C/hr expt. 200 MPa

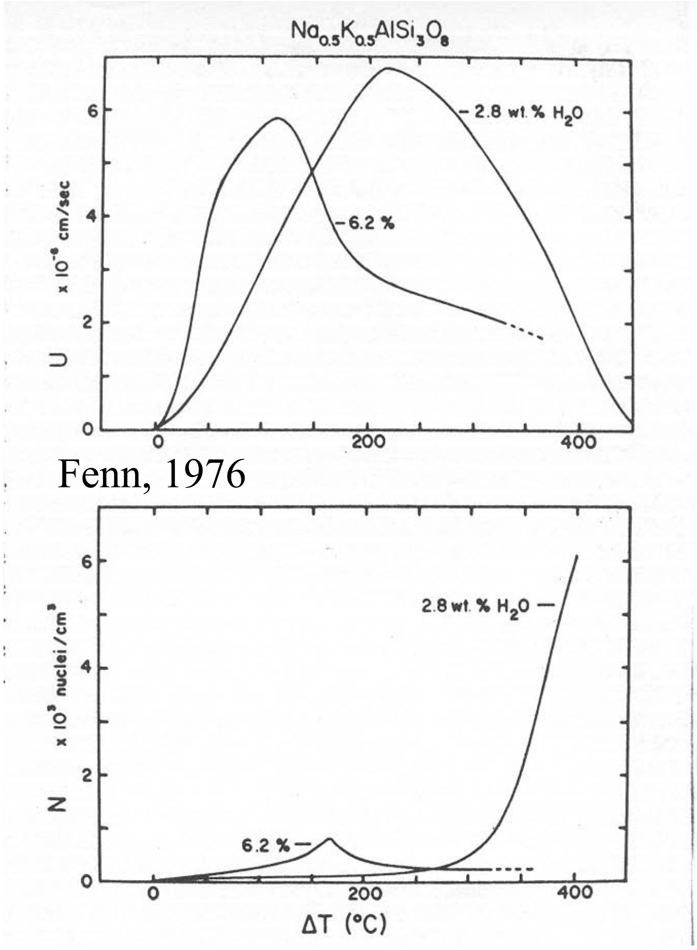


10°C/hr, 6 wt.% H_2O



10°C/hr, 6 wt.% H_2O





Fenn, 1976

ΔT = undercooling

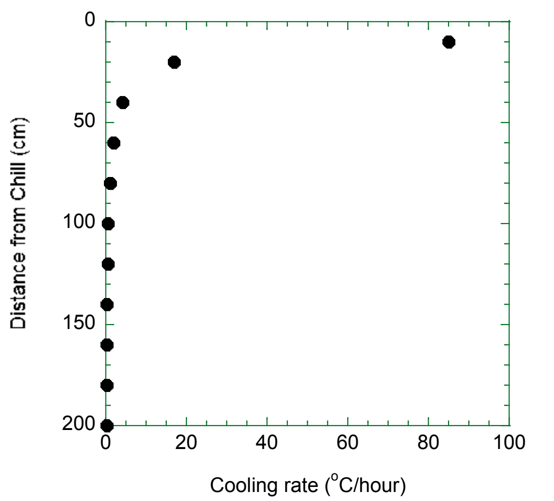
U = Growth rate

Influence of H_2O is to put peak in growth rate at LOWER undercooling

N = Nucleation density

At the same time H_2O addition reduces nucleation rate.

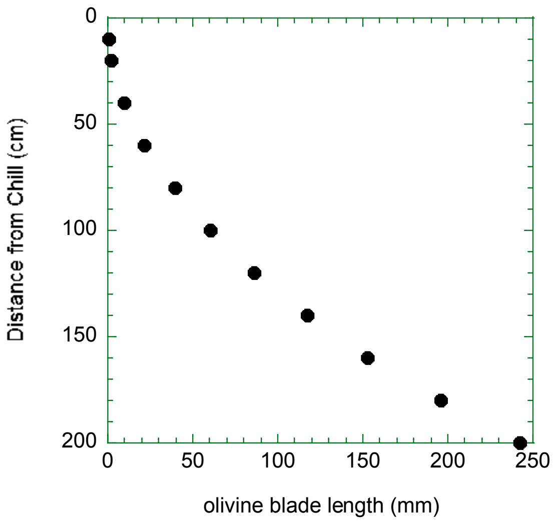
Result is fewer, bigger, faster growing crystals..



Here are predicted cooling rate vs distance and growth rate vs cooling rate for conductive cooling.

Cooling rate and crystal size are related, slow cooling bigger crystals.

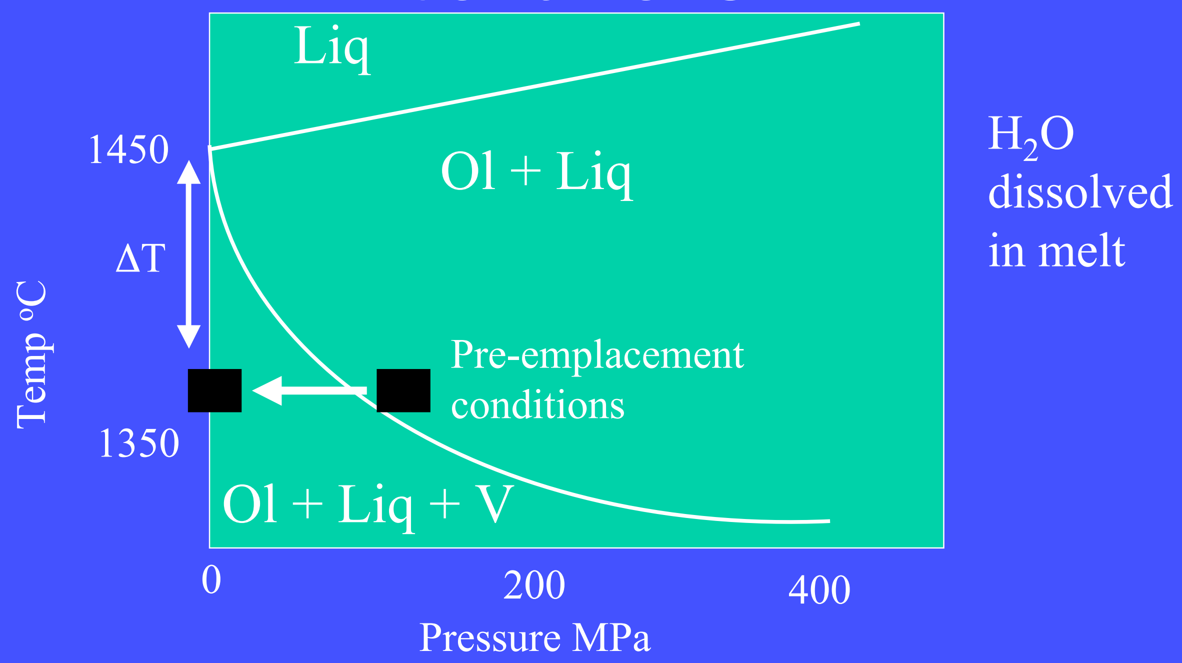
Predicted from wet cooling expts.

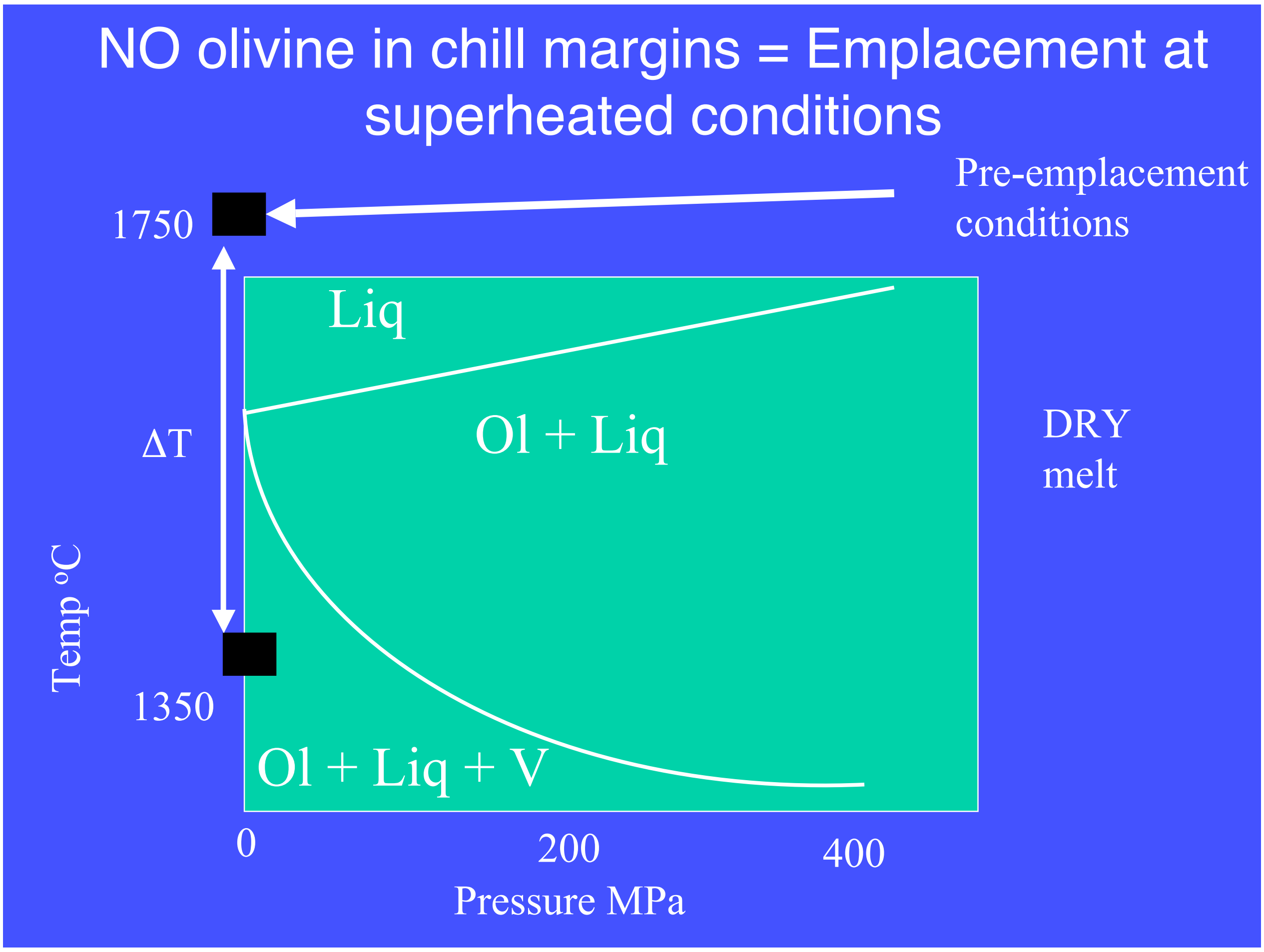


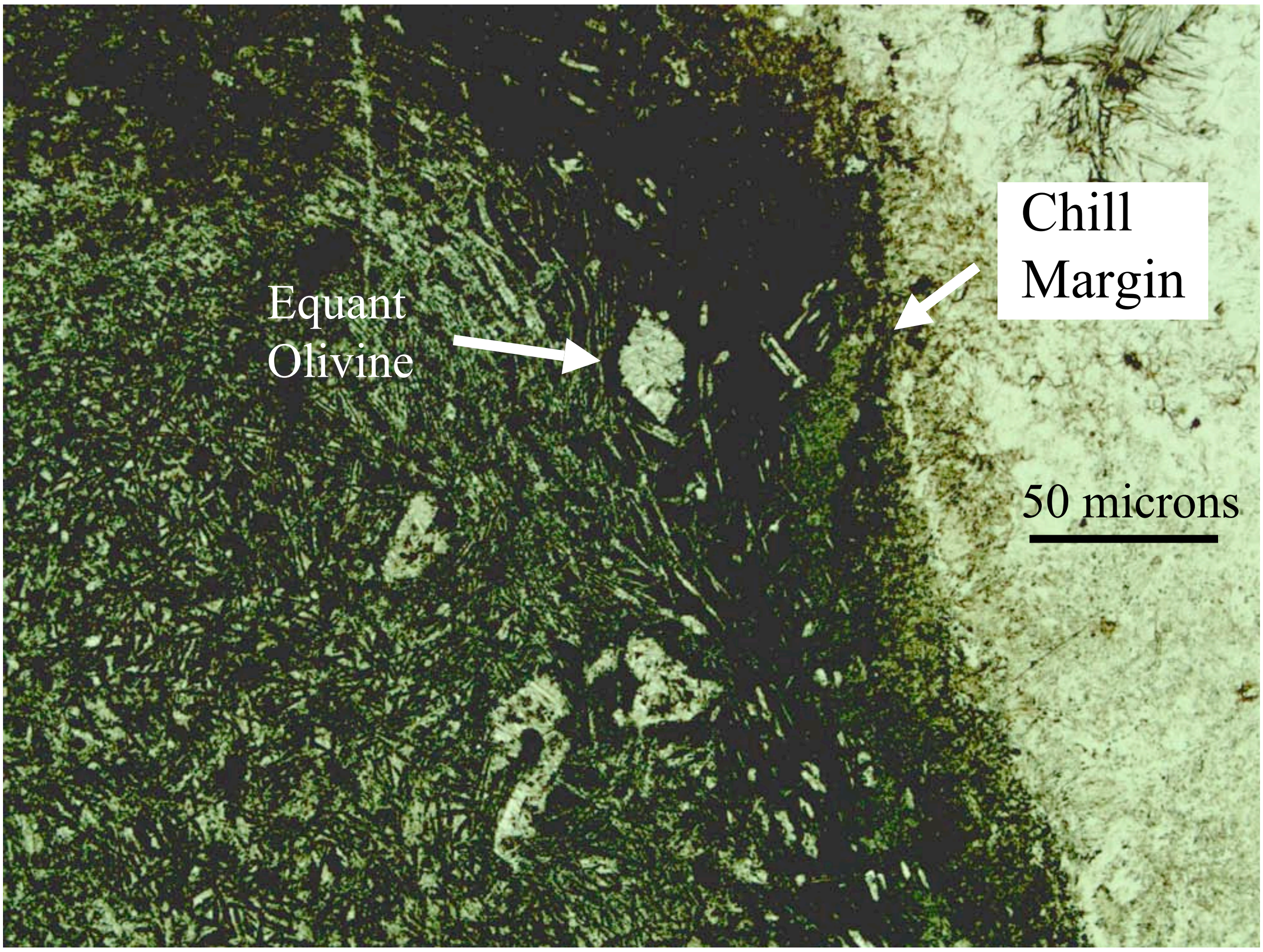
Field evidence in Barberton komatiites

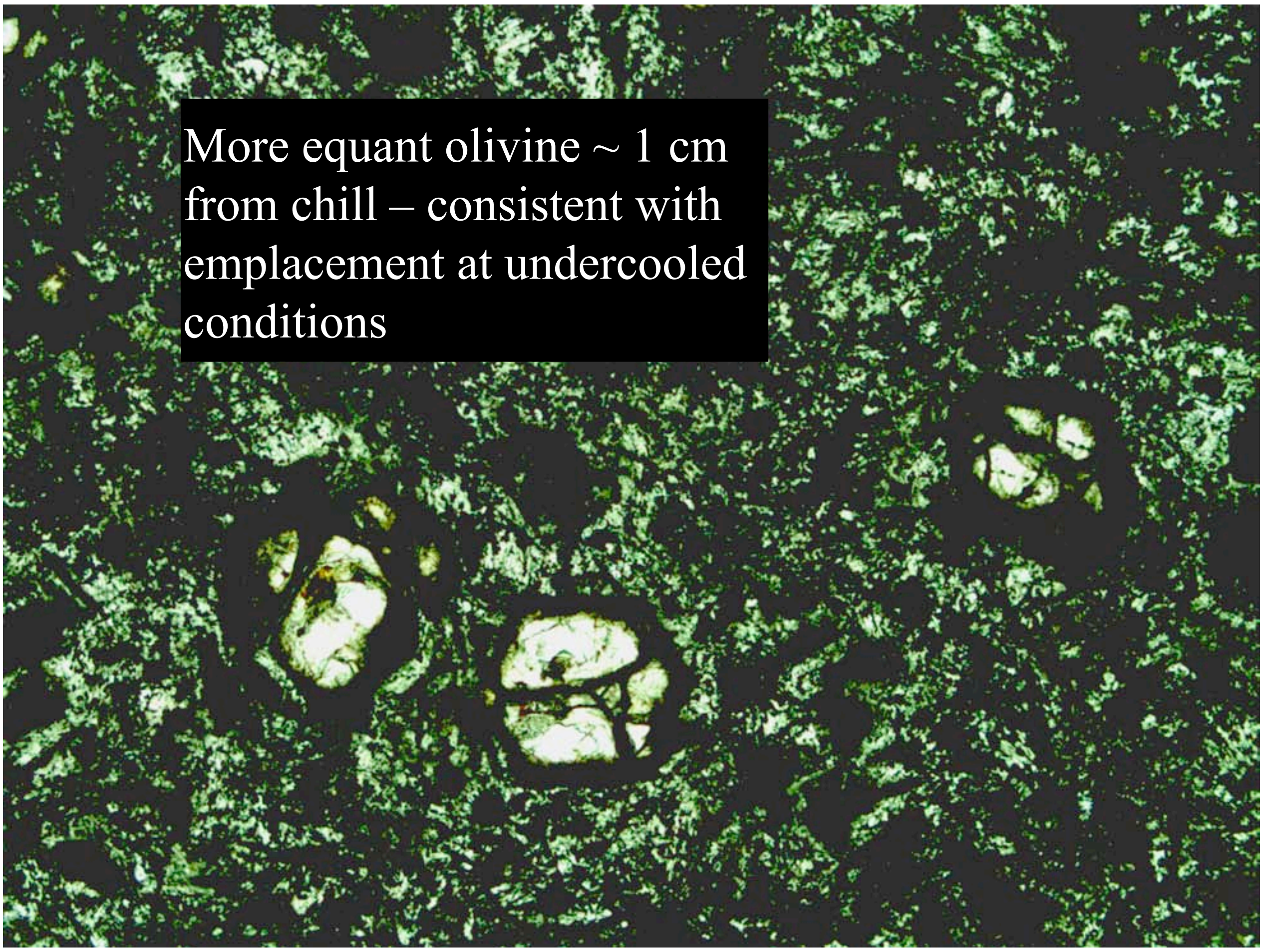
- Equant olivine present in chill margins
- Close spatial association of spinifex with granular-textured olivine
- Largest bladed spinifex forms at slowest cooling rates

Equant olivine in chill margins = Emplacement at undercooled conditions

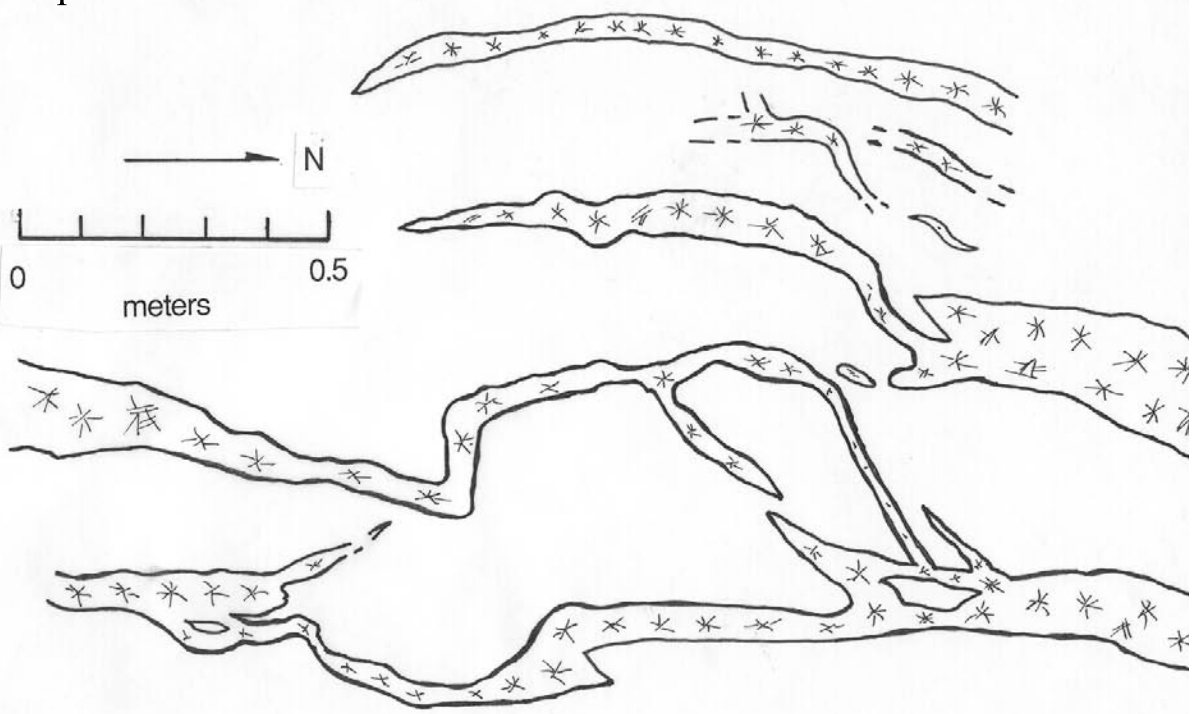


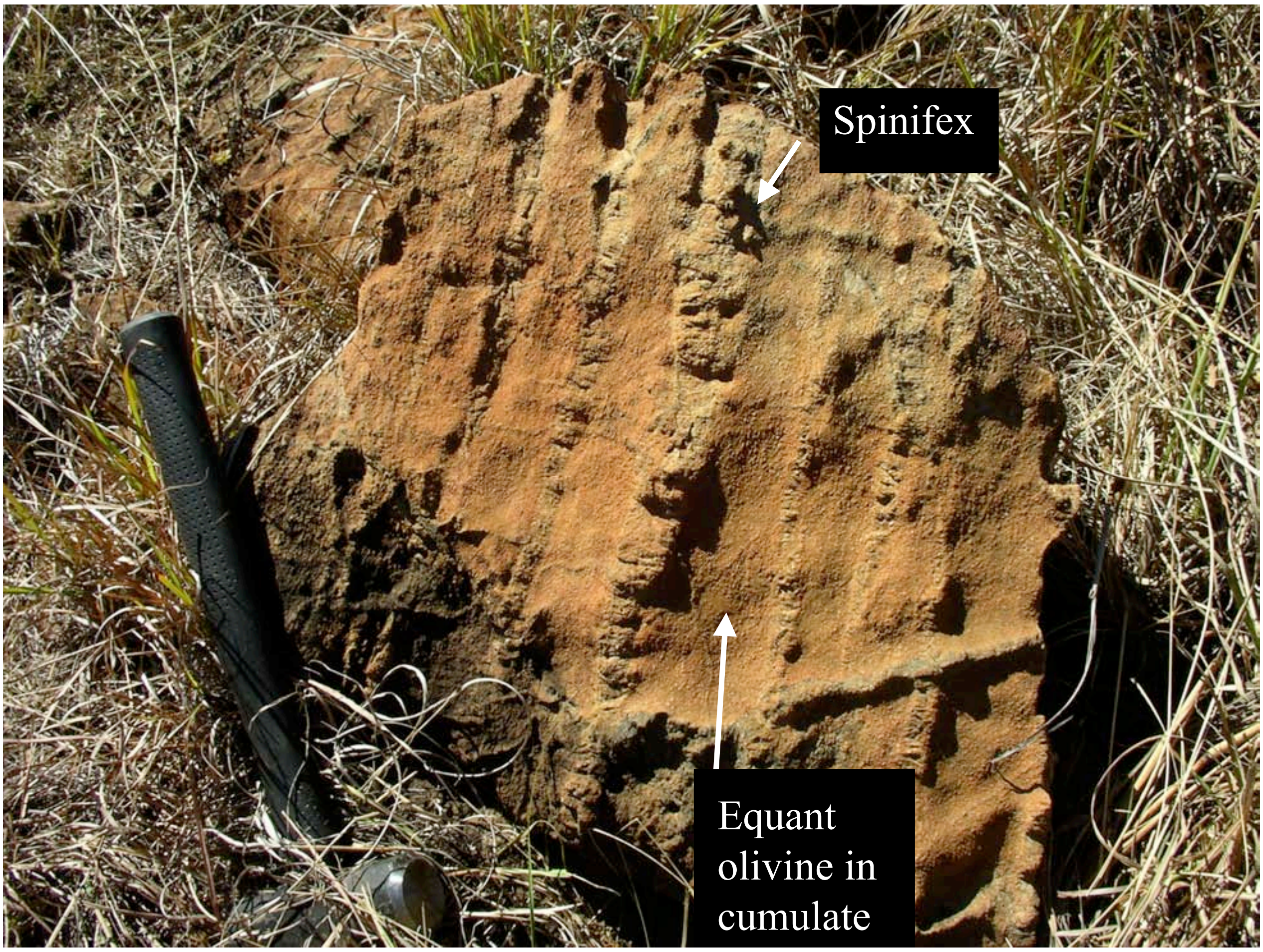

NO olivine in chill margins = Emplacement at superheated conditions
Pre-emplacement conditions
1750
Liq
ΔT
Ol + Liq
DRY melt
Temp °C
1350
Ol + Liq + V
0
200
400
Pressure MPa

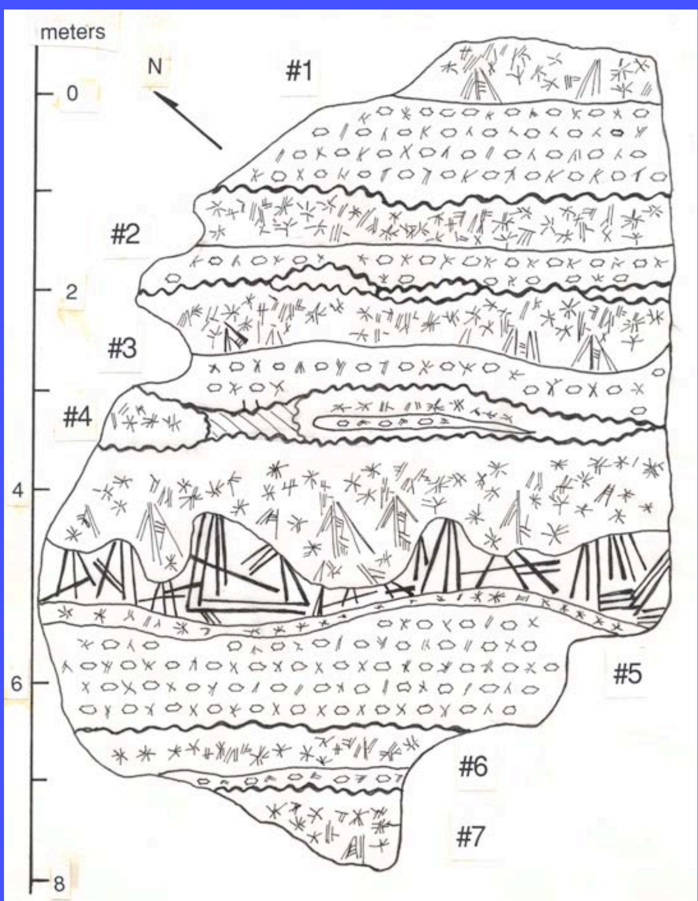

Chill Margin
Equant Olivine
50 microns



Inflation features - Spinifex veins intruding granular, equant olivine cumulate



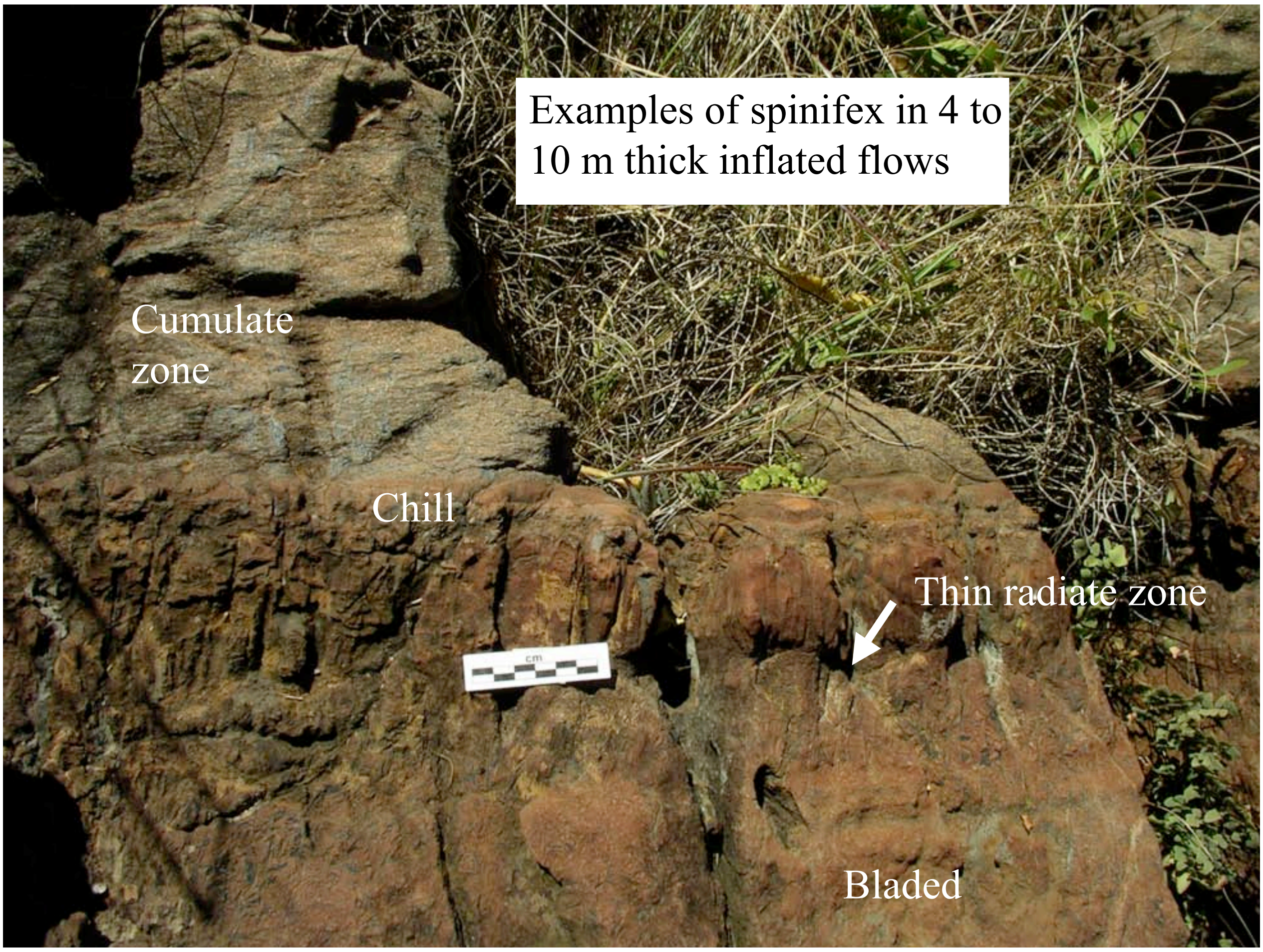




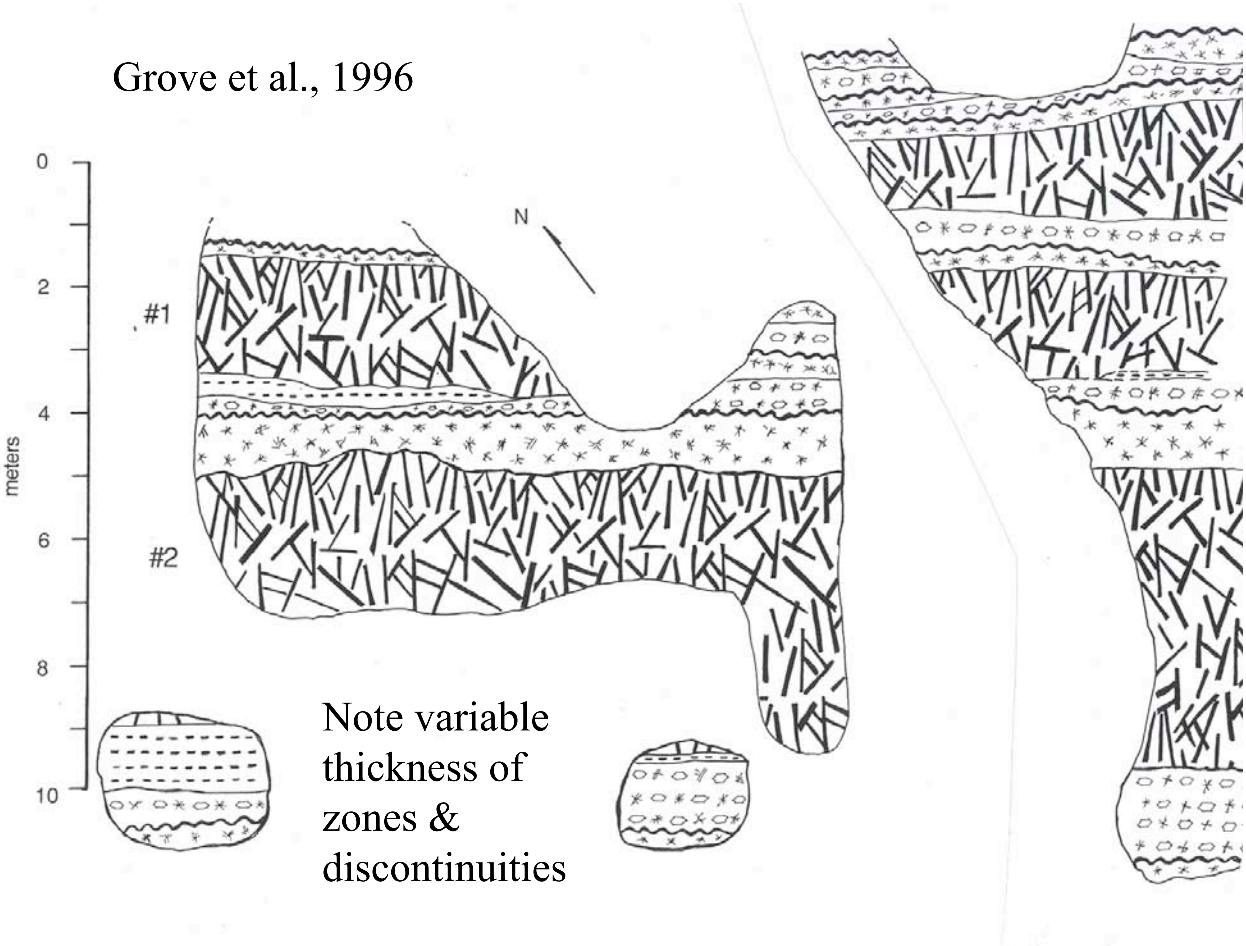
Thin pillows – no spinifex

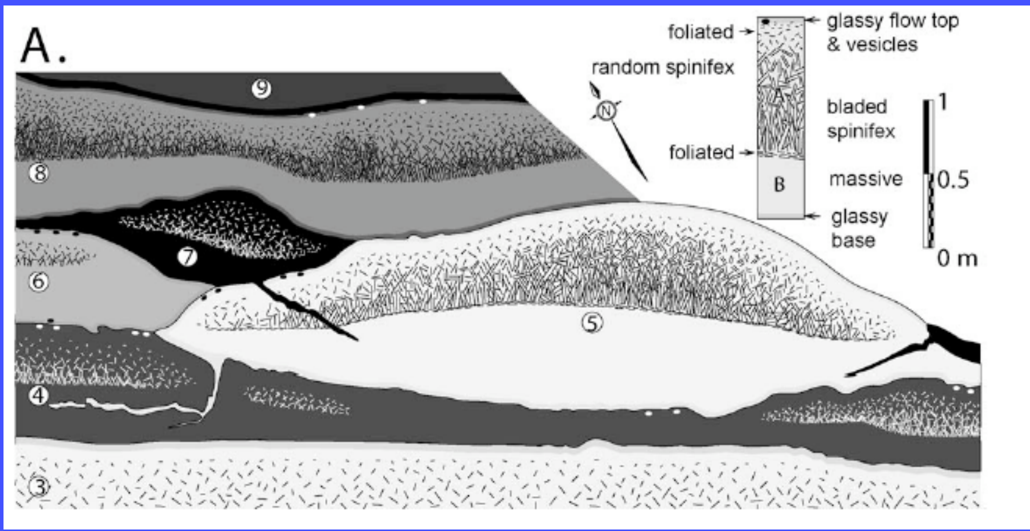
Thicker – only radiate - texture

Grove et al., 1996



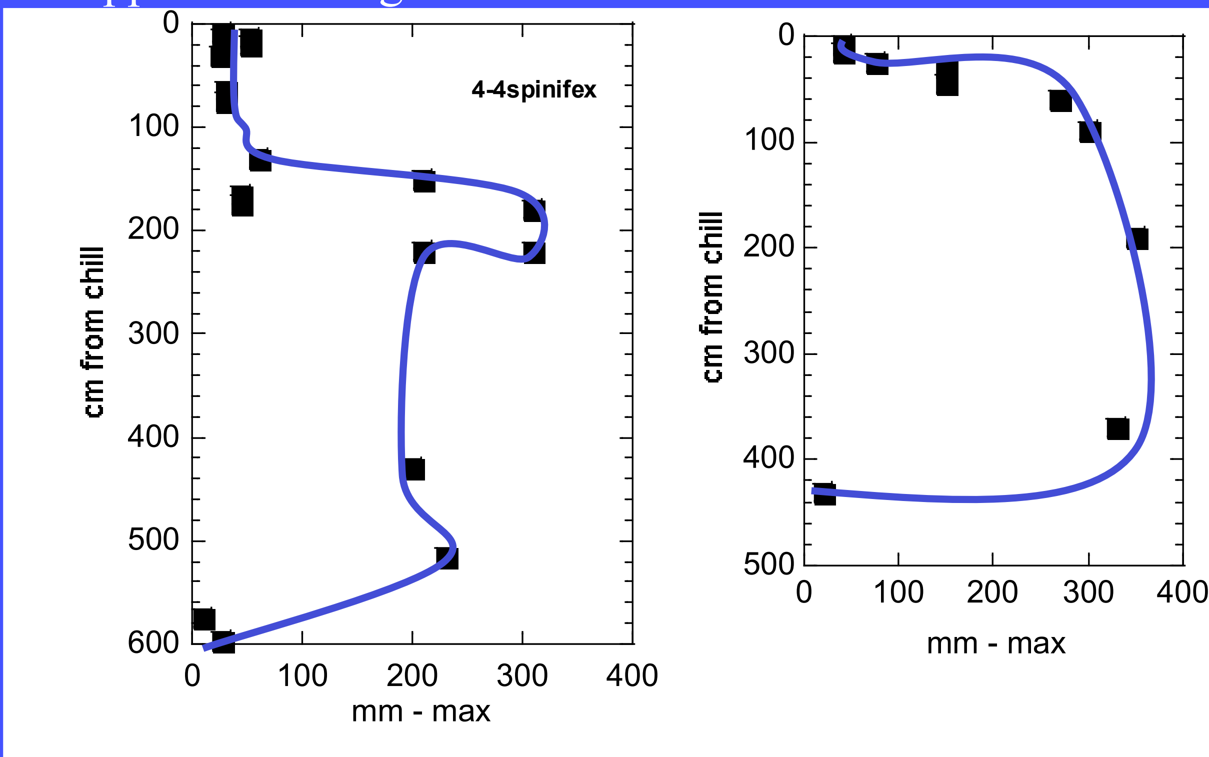
Grove et al., 1996

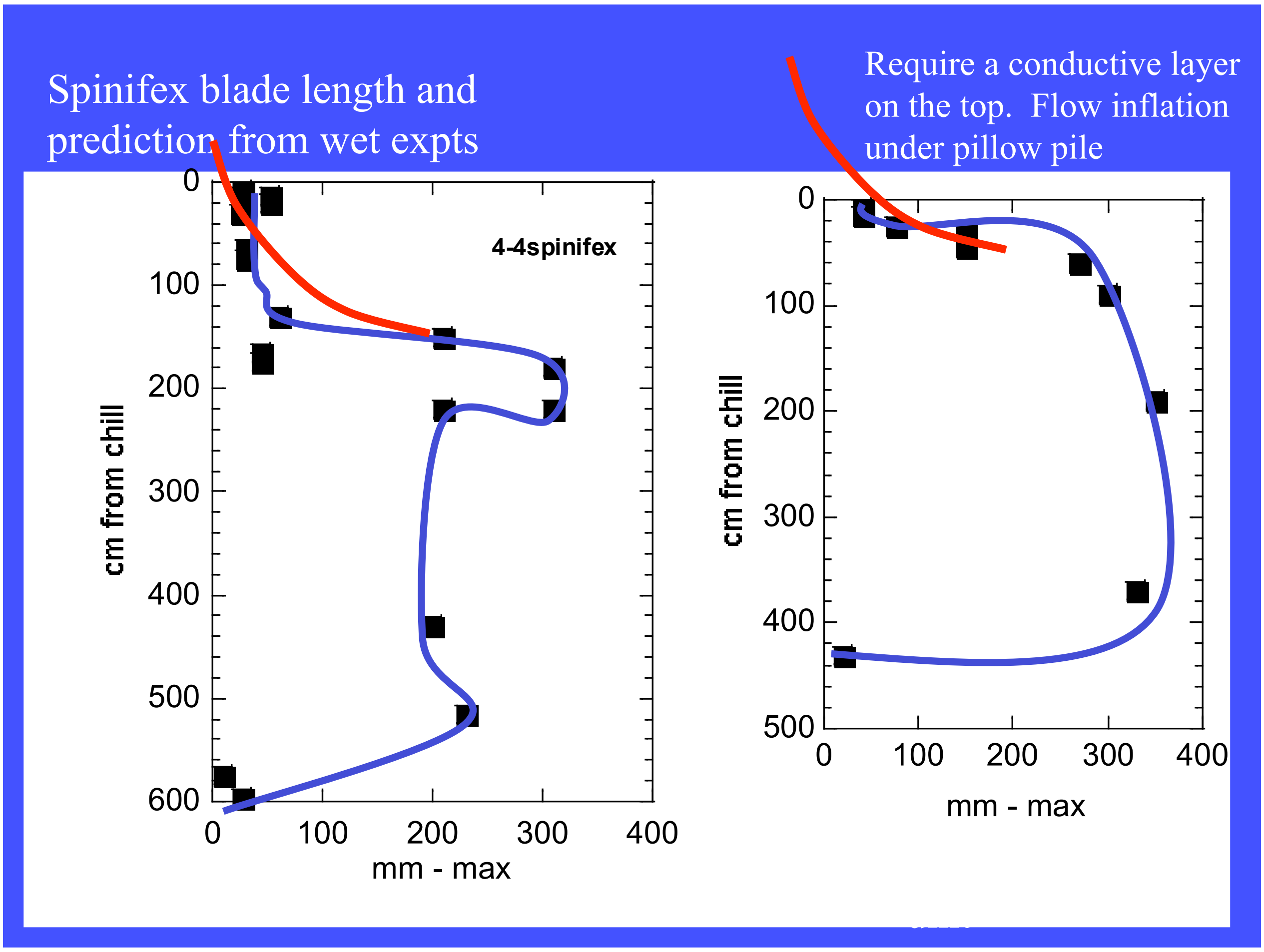




Inflation features imply conductive cooling conditions and overpressures that allow for slow cooling and development of spinifex textures

Spinifex blade maximum length vs distance from upper chill margin in Barberton komatiites





Conclusions

H_2O controls on development of spinifex textures

1) Undercooling by decompression/devolatilization of hydrous magma

2) H_2O changes melt physical properties

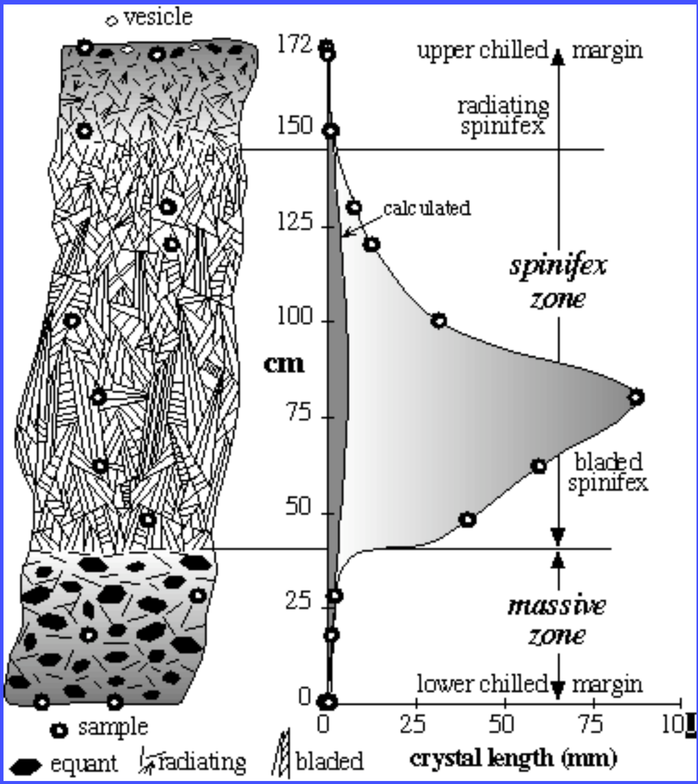
•Lowers nucleation rate – destroys nucleii

•Decreases melt viscosity – increases growth

rate at undercooled conditions

3) Injection of melt into cumulates and Flow inflation processes modify thermal conditionsleading to spinifex growth at slow cooling rates

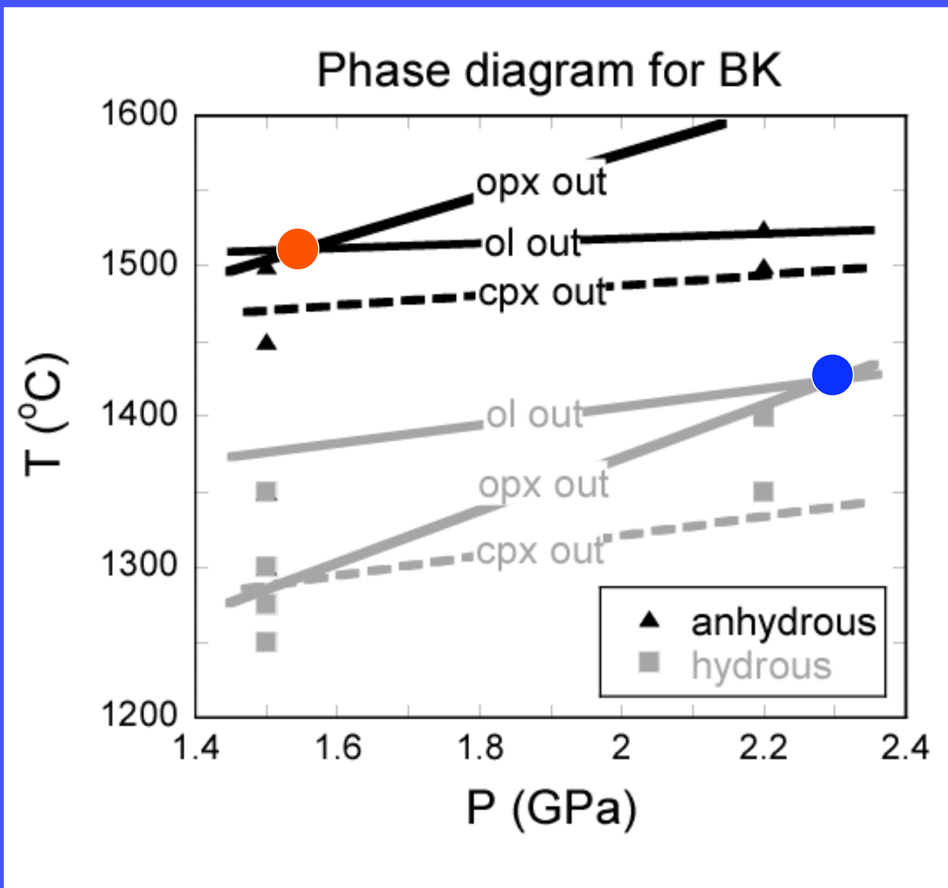
Spinifex flows = Ultramafic pegmatites



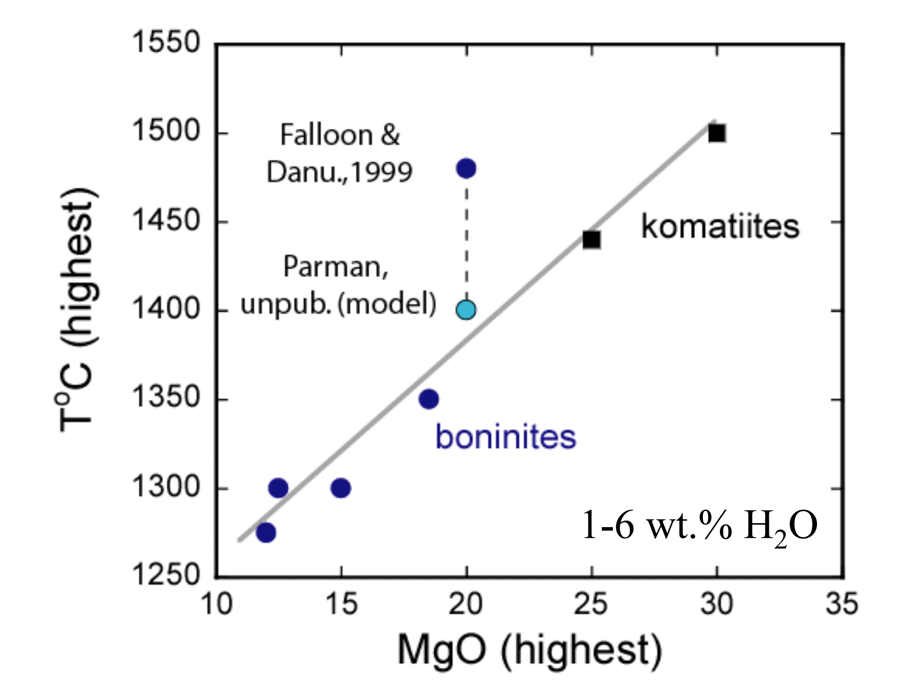
Crystal size vs. cooling rate calculated with dry small volume data

Grove et al., 1996

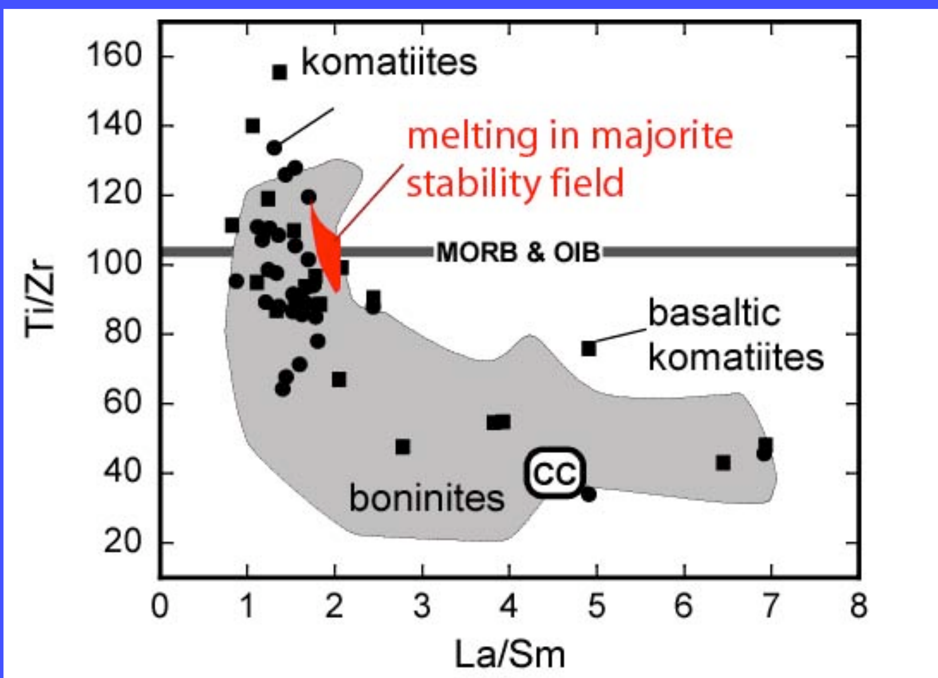
High-P melting experi-ments



Experimental Estimates of Hydrous Melting Conditions



majorite fractionation



Mixing of fluid and dep. mantle