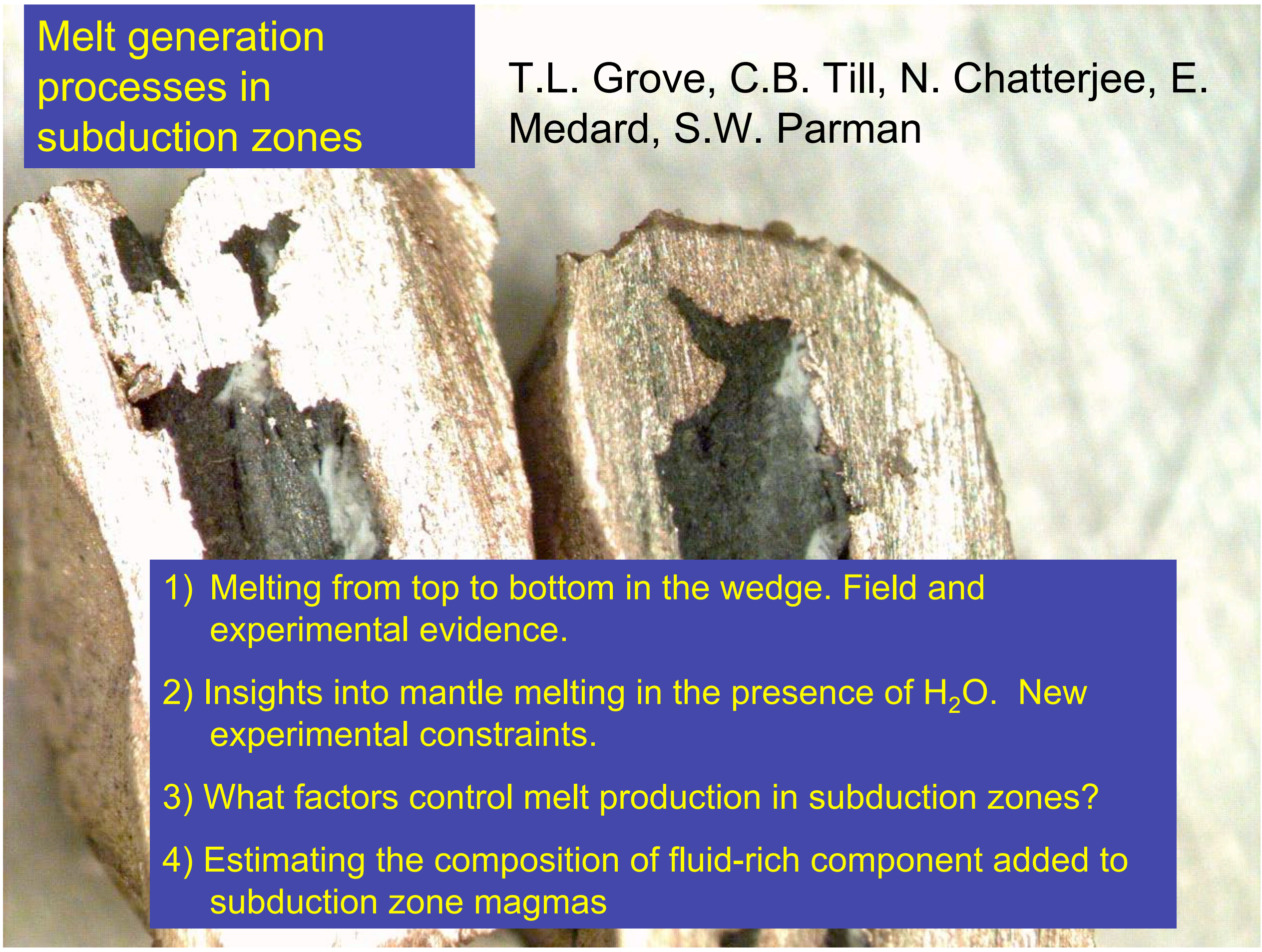
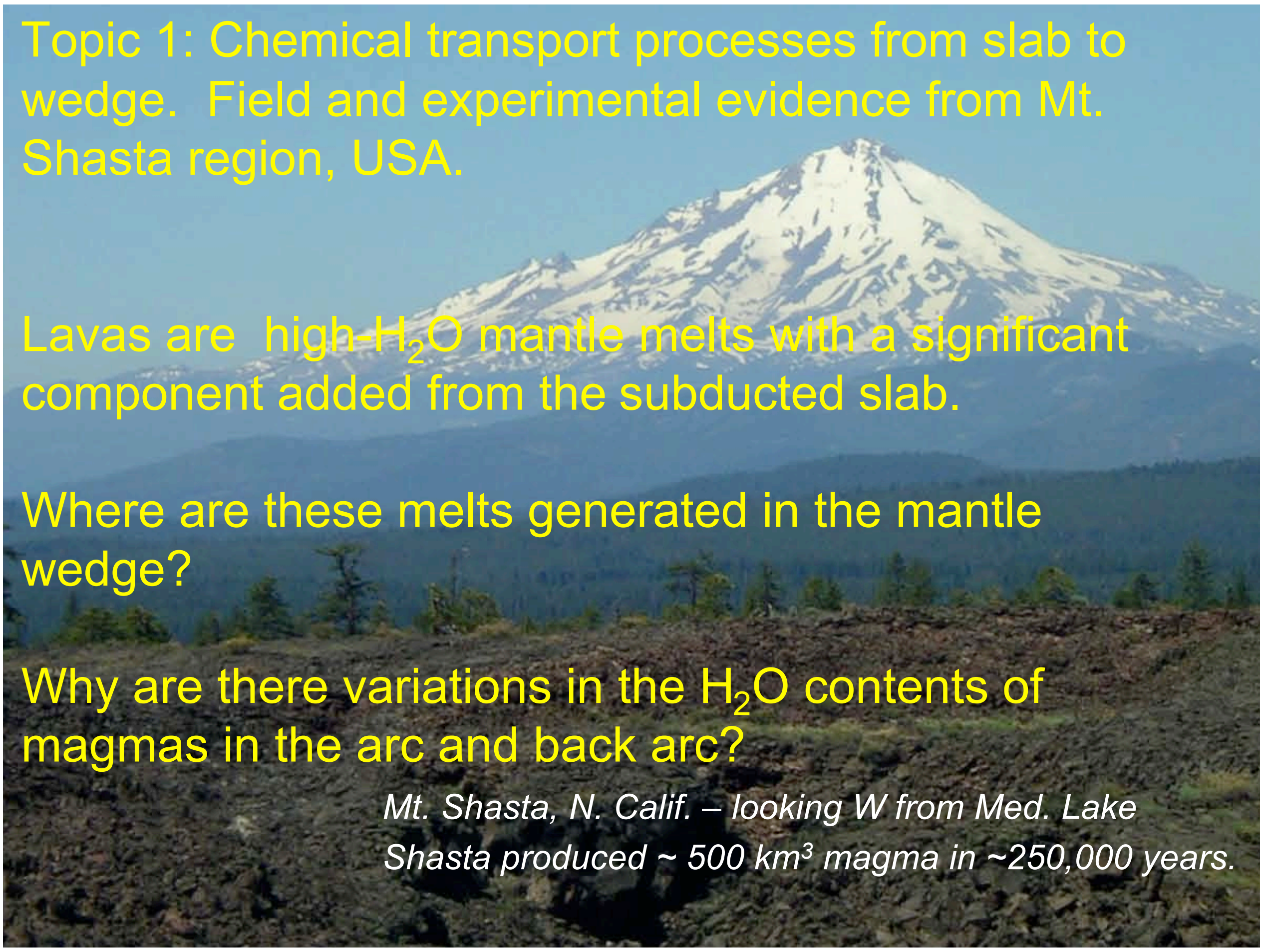


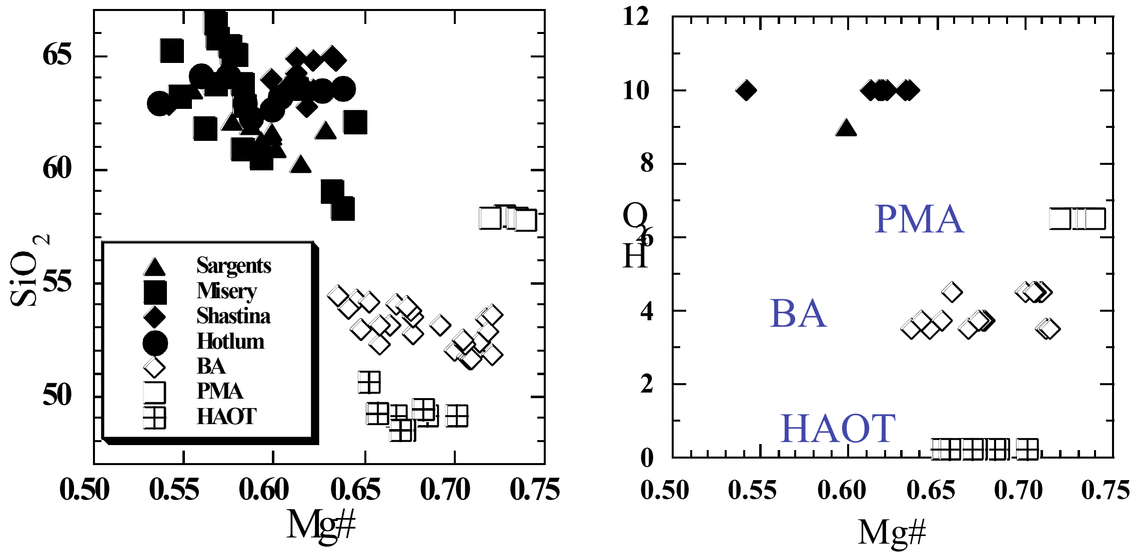
Melt generation processes in subduction zones
T.L. Grove, C.B. Till, N. Chatterjee, E. Medard, S.W. Parman
1) Melting from top to bottom in the wedge. Field and experimental evidence.
2) Insights into mantle melting in the presence of H_2O. New experimental constraints.
3) What factors control melt production in subduction zones?
4) Estimating the composition of fluid-rich component added to subduction zone magmas

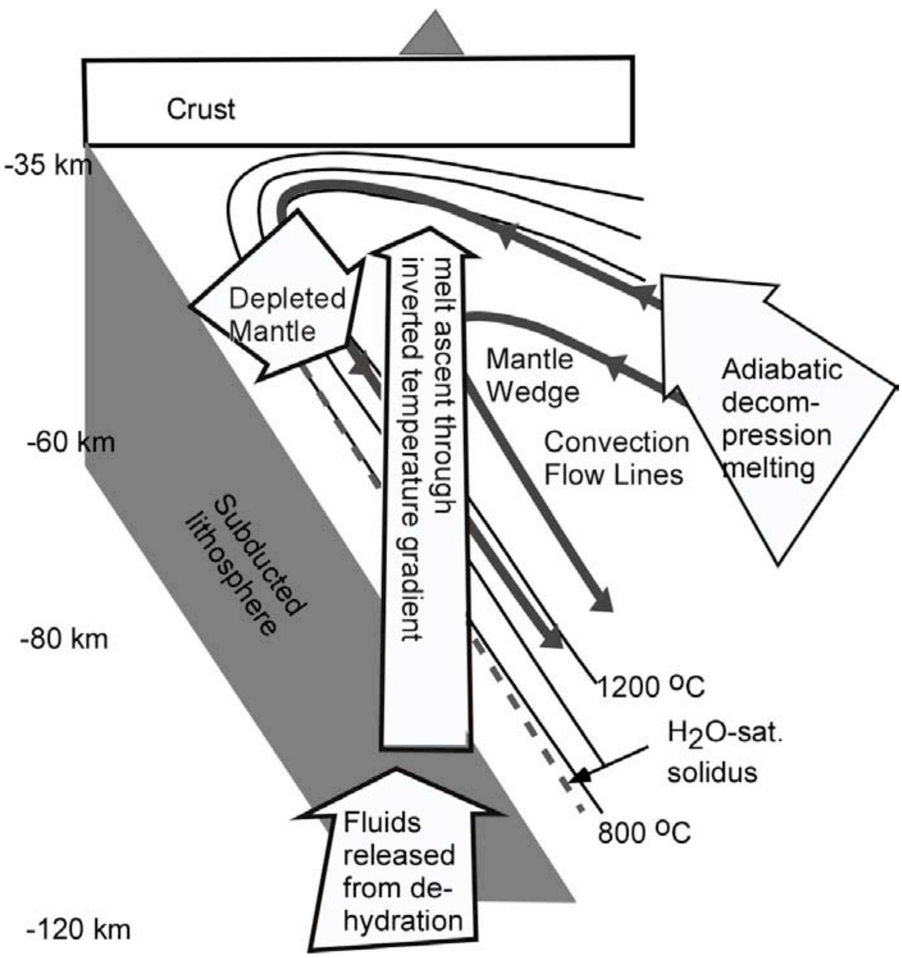


Topic 1: Chemical transport processes from slab to wedge. Field and experimental evidence from Mt. Shasta region, USA.
Lavas are high-H_2O mantle melts with a significant component added from the subducted slab.
Where are these melts generated in the mantle wedge?
Why are there variations in the H_2O contents of magmas in the arc and back arc?
Mt. Shasta, N. Calif. – looking W from Med. Lake
Shasta produced ~ 500 km^3 magma in ~250,000 years.

Major elements and H_2O

Wet, primitive andesites are in equilibrium with mantle residues = melts of depleted mantle





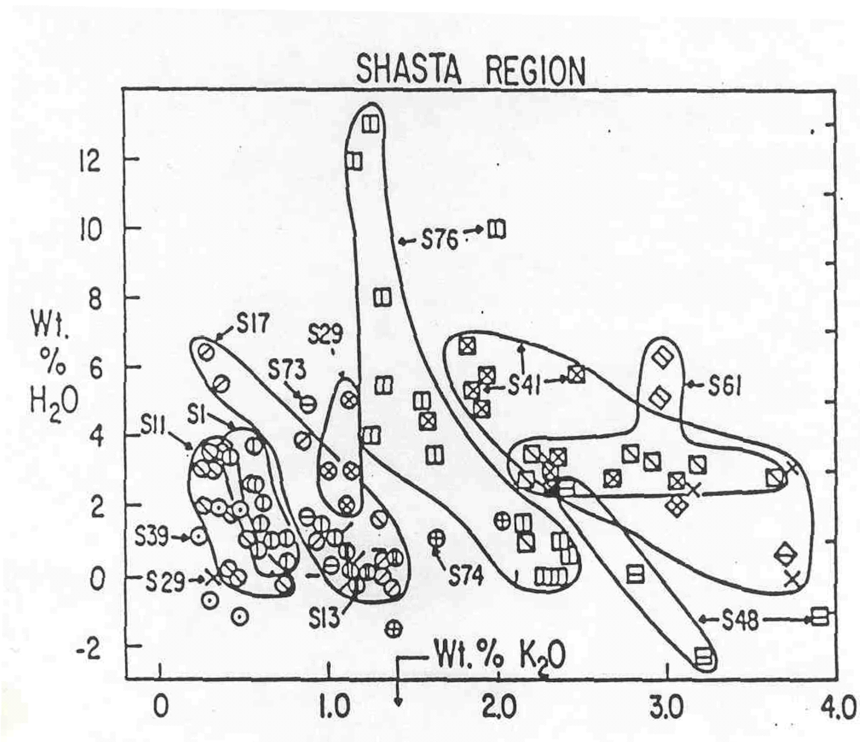
Mantle melts in Two ways in subduction zones:

Dry, adiabatic decompression

Hydrous, porous flow flux melting

Estimates of Pre-eruptive H_2O

- H_2O solubility in silicate melts is P-dependent and goes to ~ 0 at P = 1 bar.
- So, H_2O is often lost as a gas phase
- Pre-eruptive H_2O contents are obtained using:
  - Thermodynamic models of mineral/melt equilibria.
  - Effect of H_2O on "freezing path" or melt composition produced during fractional crystallization.
  - Direct measurement of H_2O in melt inclusions.

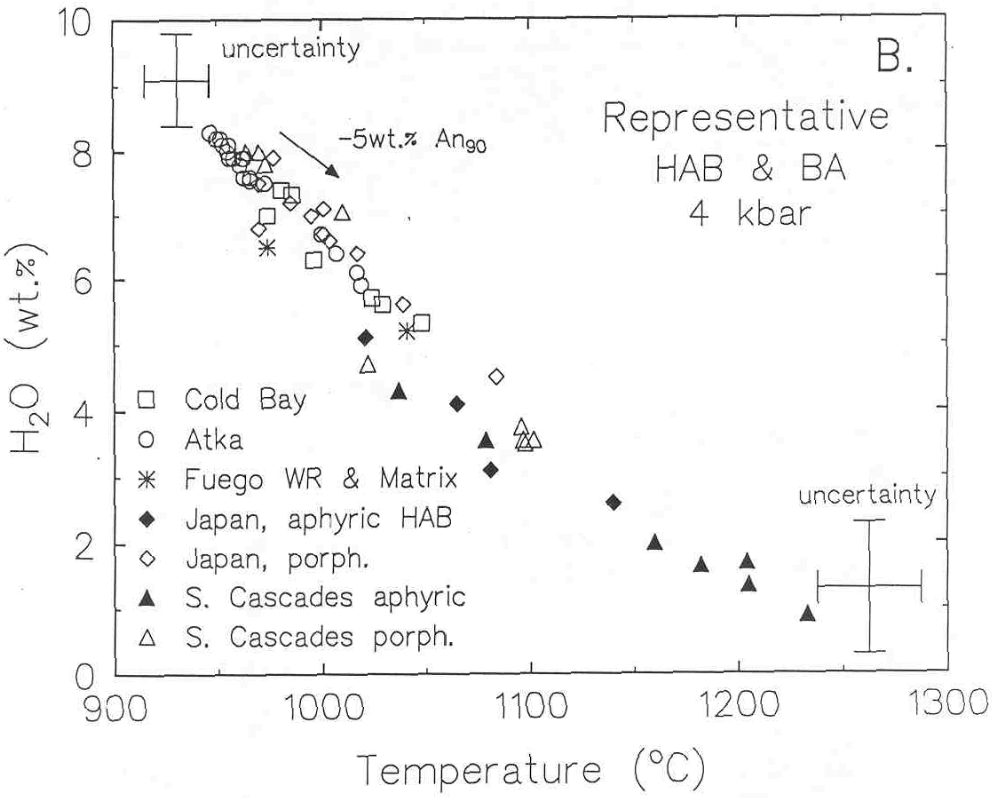


Direct measurement of H_2O in Shasta melt inclusions (Anderson, 1979).

H_2O-contents of arc magmas seem to be too high to result from any batch melting process of any potential H_2O-bearing mantle source.

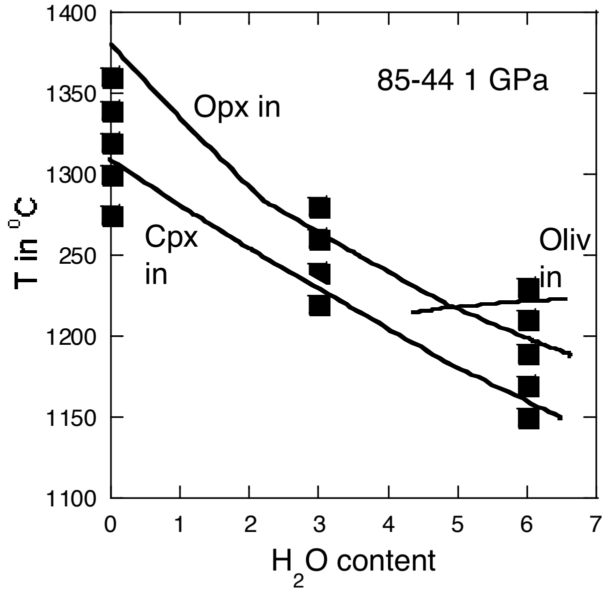
New experimental evidence changes this.

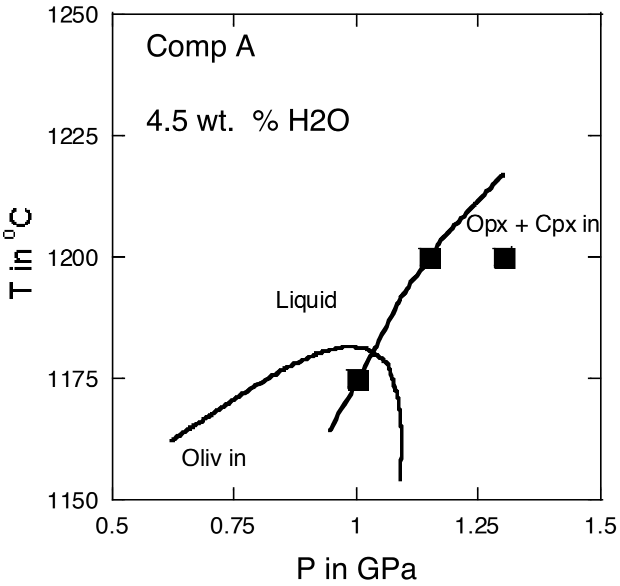
Sisson & Grove (1993)

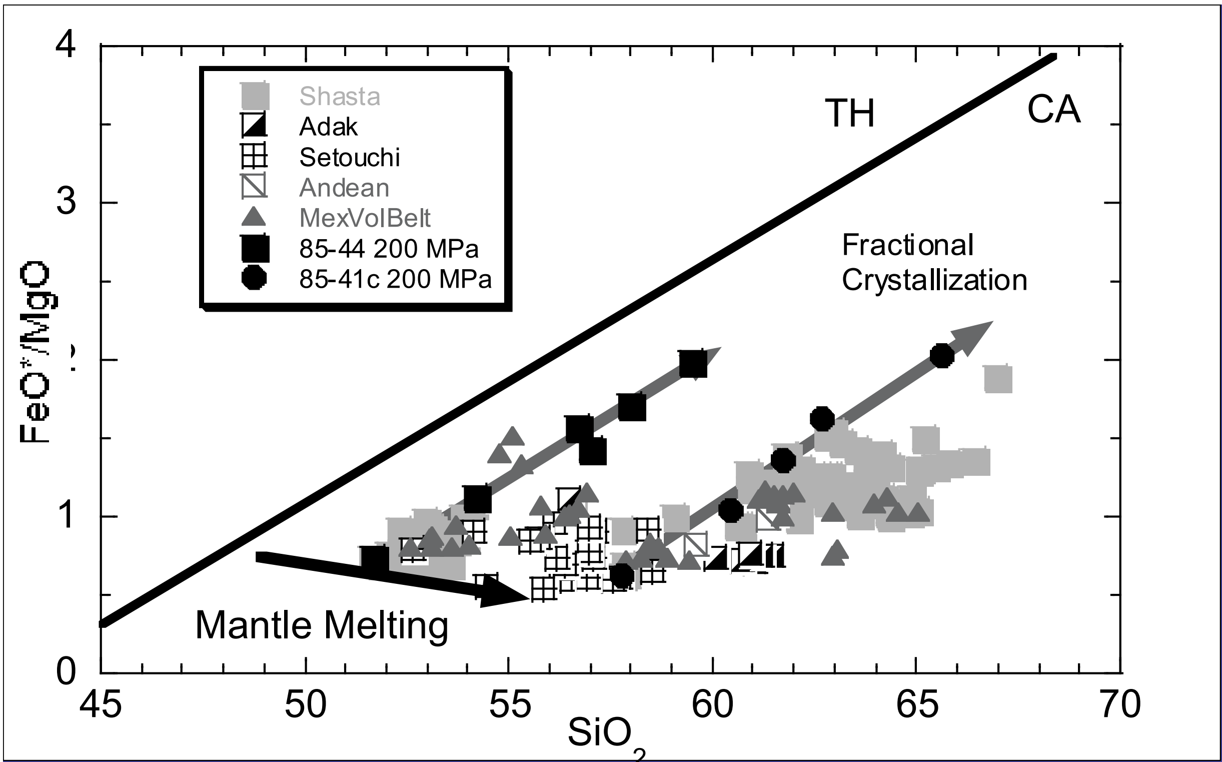


Estimation of pre-eruptive H_2O content

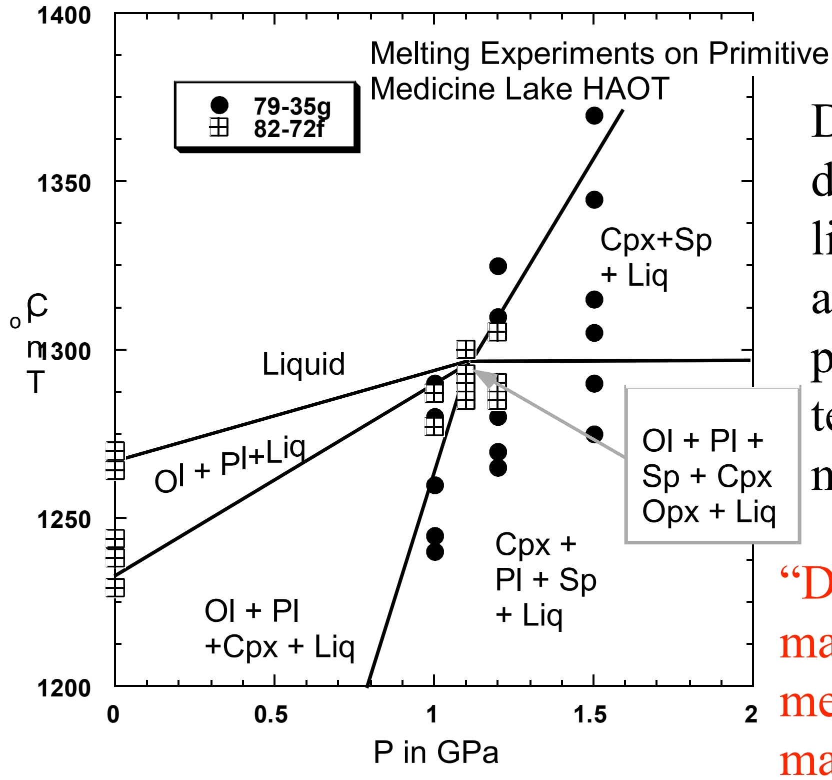
Primitive BA (S-1) and PMA (S-17) – Hydrous melts saturated with a harzburgite residue at top of mantle wedge > 25 % melting.





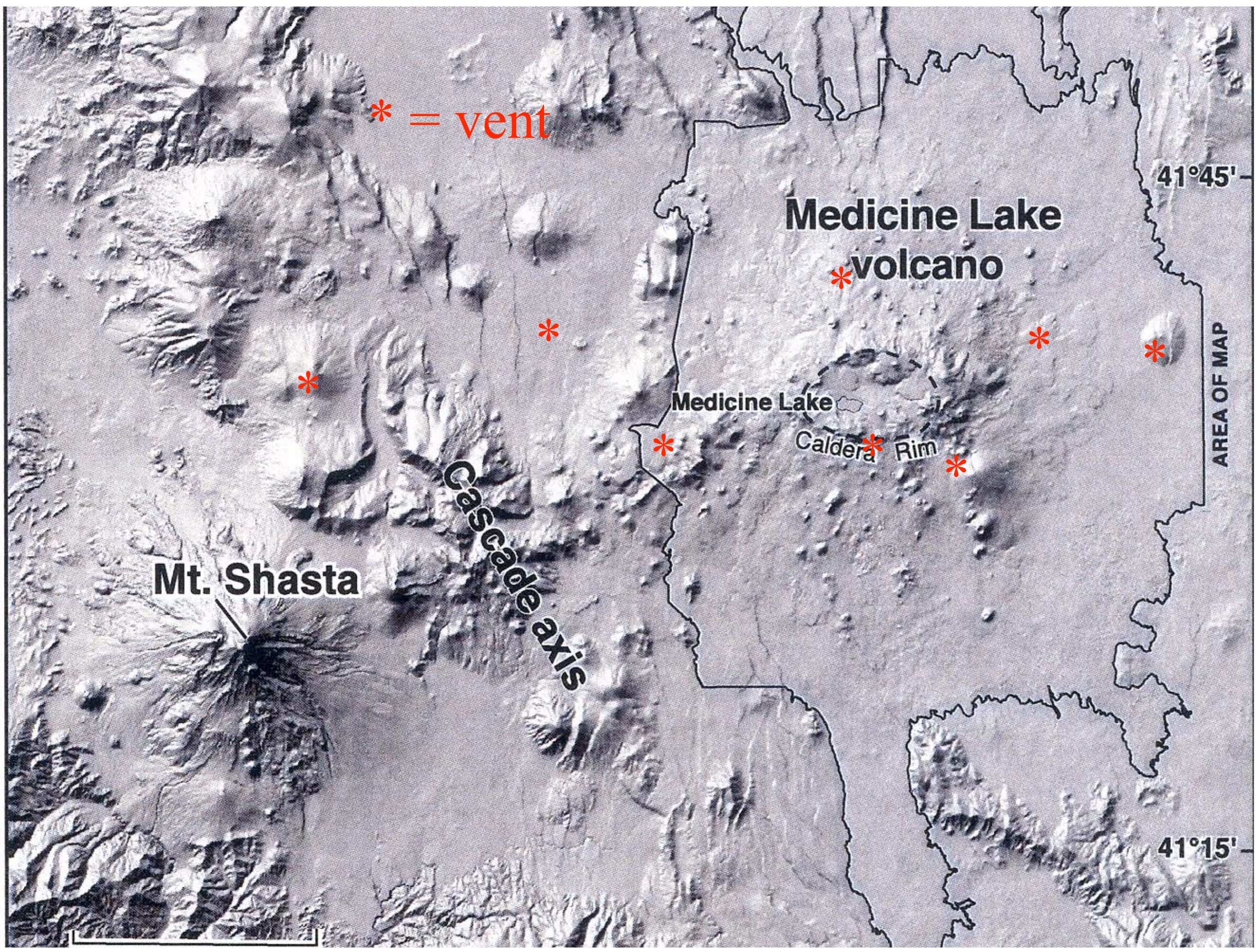


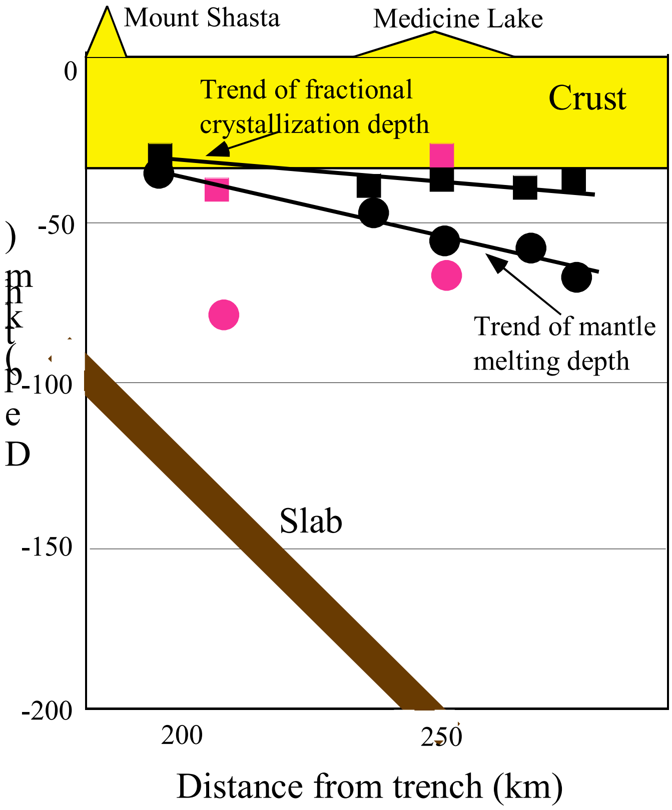
Shasta H_2O-rich lavas have high SiO_2 and low FeO*, similar to adakites and Japanese sanukitoids: characteristics inherited from low-P mantle melting.



Direct determination of liquidus mineral assemblage at high pressure and temperature = mantle conditions

"Dry" HAOT magmas record melting as convecting mantle is drawn into the wedge



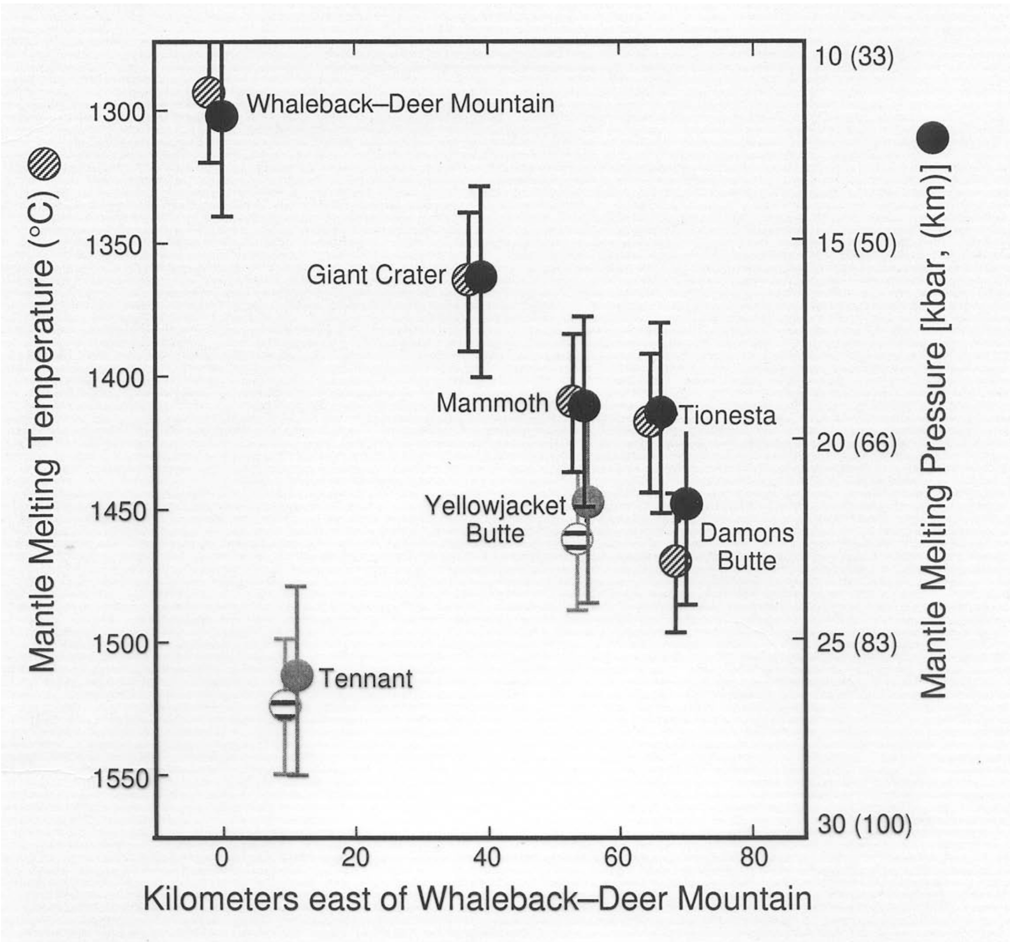


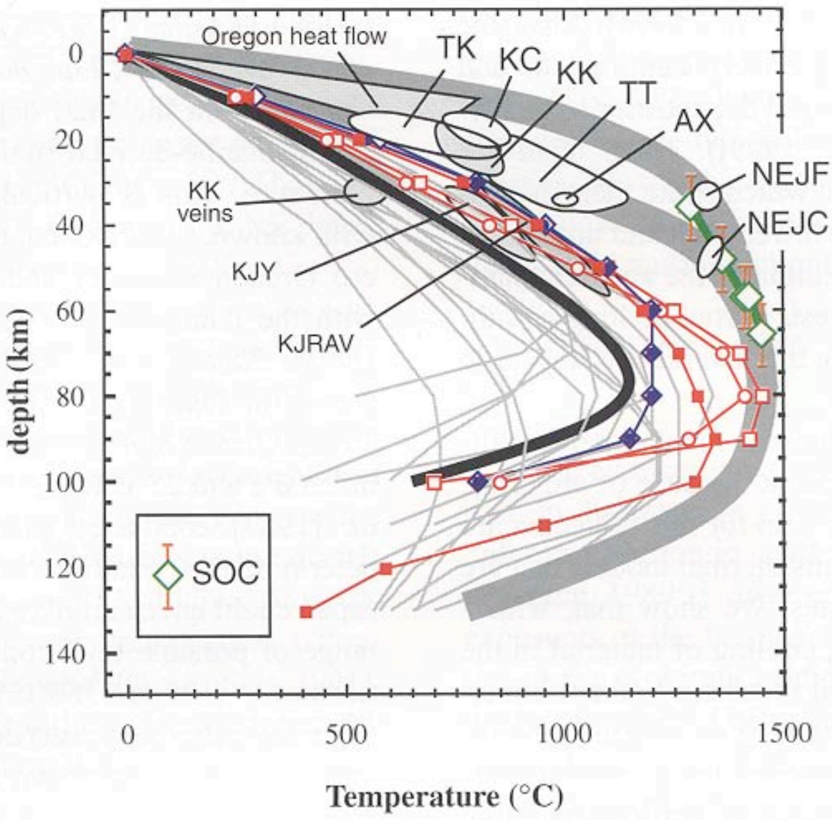
Shallow, hot mantle melting beneath the Cascades

Inferred from Pressure of multiple saturation.

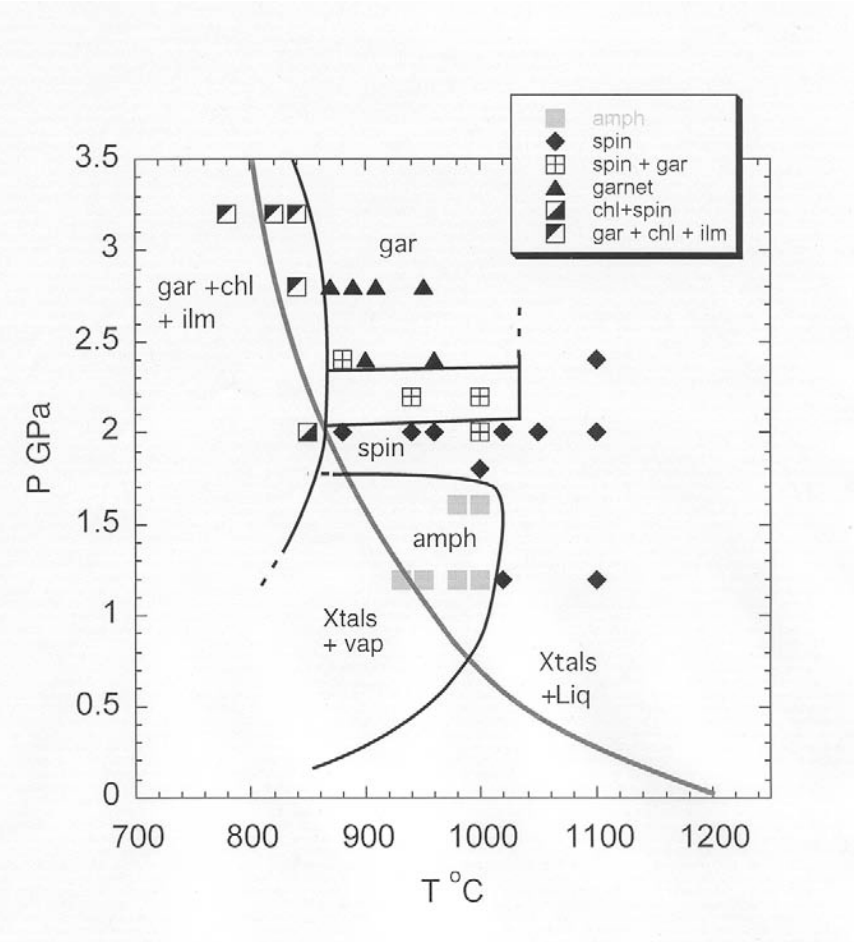
T = 1300 – 1450 ^{o}C.

Elkins-Tanton et al. (2001)





T estimates of the shallow mantle wedge from Kelemen et al. (2003) includes thermal models and petrologic estimates

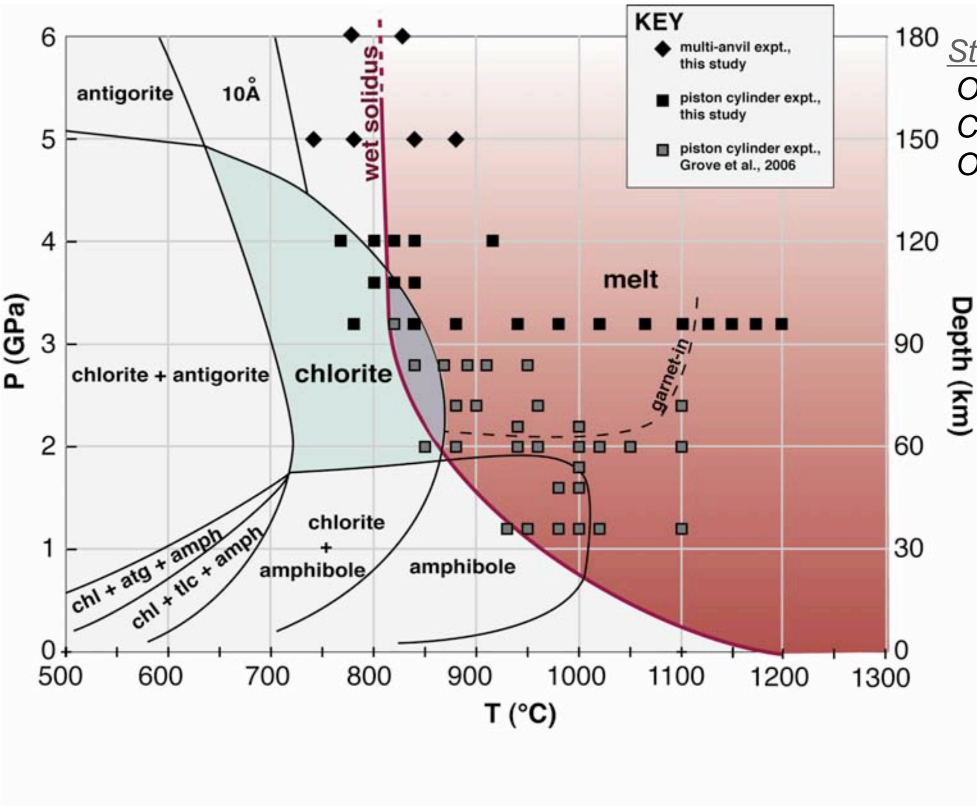


Experimental data from Grove et al. (2006) EPSL 249: 74-89

Shows that hydrous phases are stable on the vapor-saturated mantle solidus.

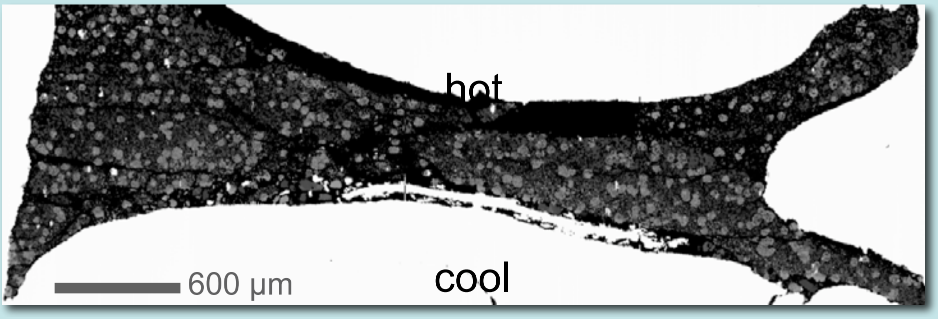
We will use this data to develop a model for melting in the mantle wedge.

Work in Progress by Till et al. (2008) is extending H_2O-Saturated melting



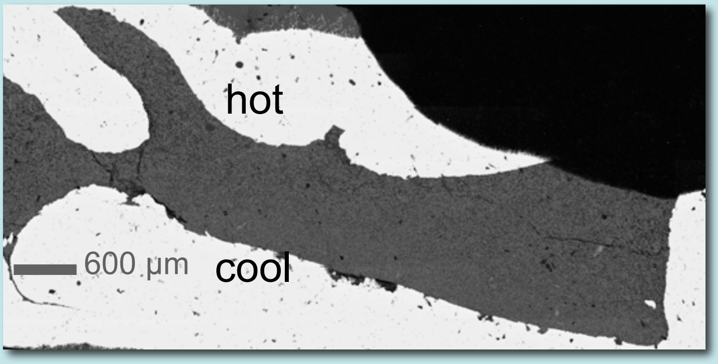
<u>*Stable Everywhere*</u>*:*
Olivine
Clinopyroxene
Orthopyroxene

Piston Cylinder Experiments



super-solidus (melted)

texturally zoned
4 GPa

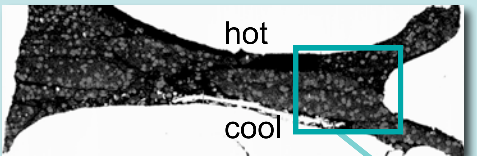


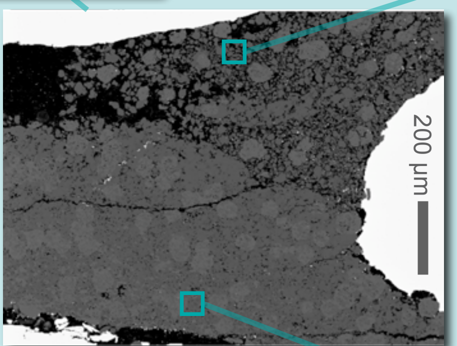
sub-solidus (unmelted)

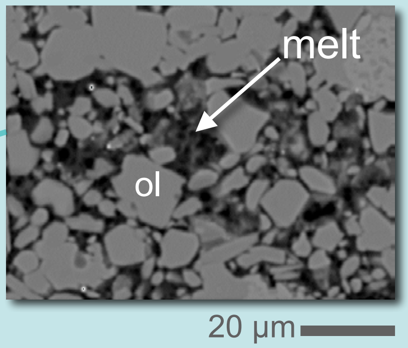
homogeneous
2 GPa

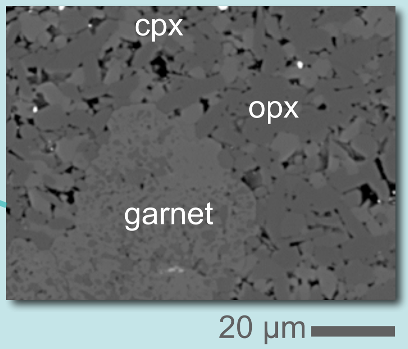
Piston Cylinder Experiment

820°C, 4 GPa, 168 hrs

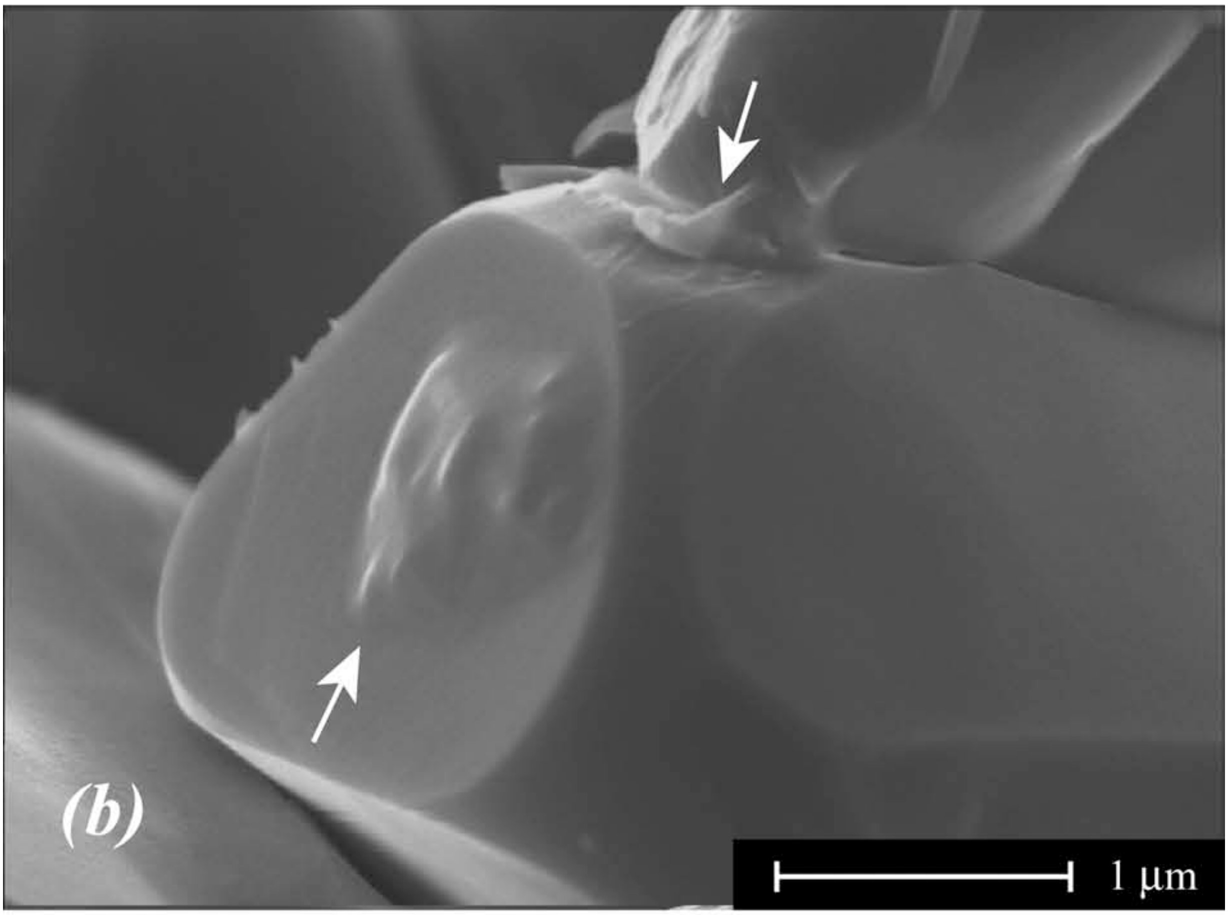






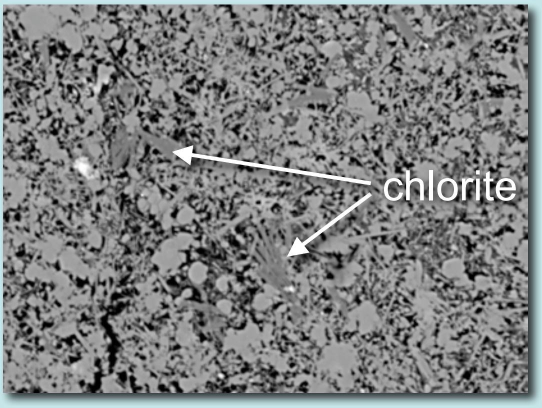


Zoning due to melting reaction:
Cpx + Opx + Al-phase ➔ Ol + Melt



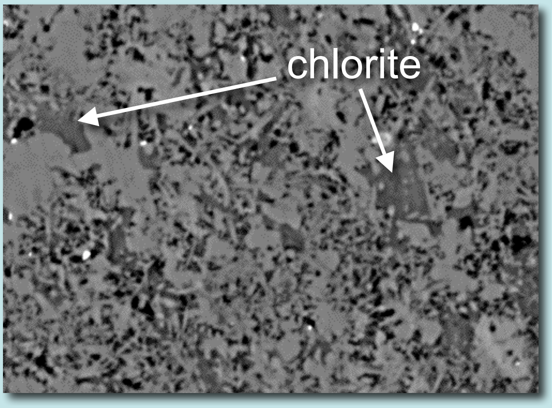
Chlorite stable on wet solidus
2.0 - 3.6 GPa

Piston Cylinder Experiment
850°C, 2.0 GPa



20 µm

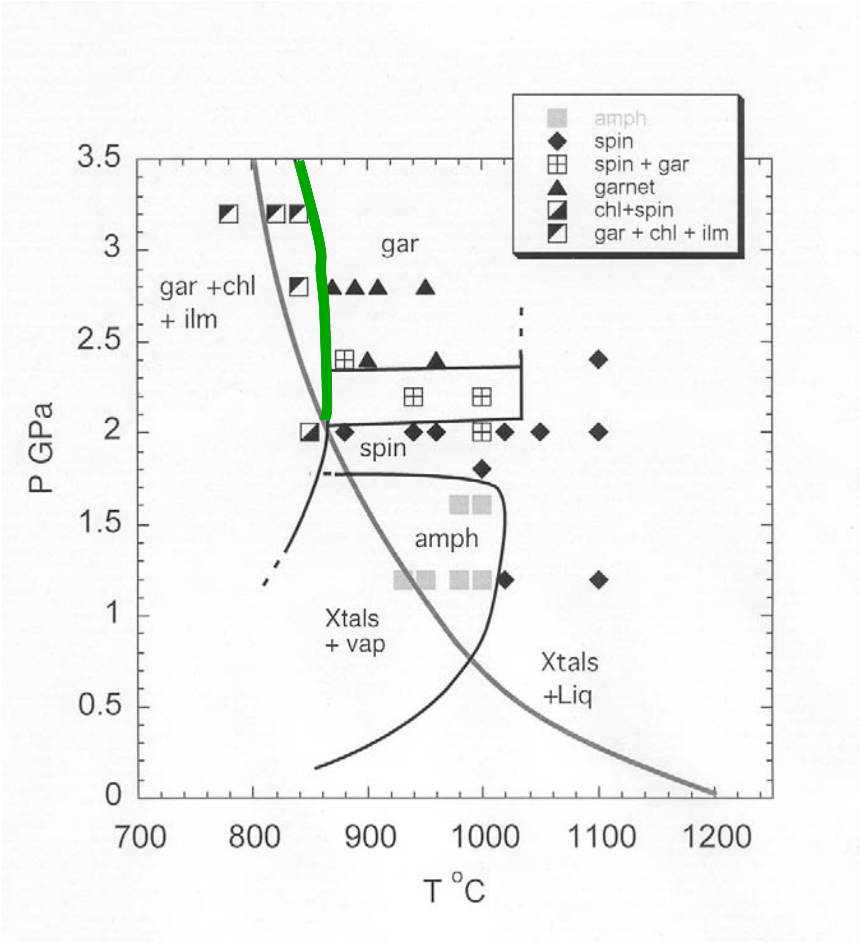
Piston Cylinder Experiment
840°C, 3.2 GPa



20 µm

Chlorite contains 12 wt % H_2O

Clinochlore: $(Mg_5Al)(AlSi_3)O_{10}(OH)_8$



Chlorite on the vapor - saturated solidus

– a way to transport H_2O deep into the wedge

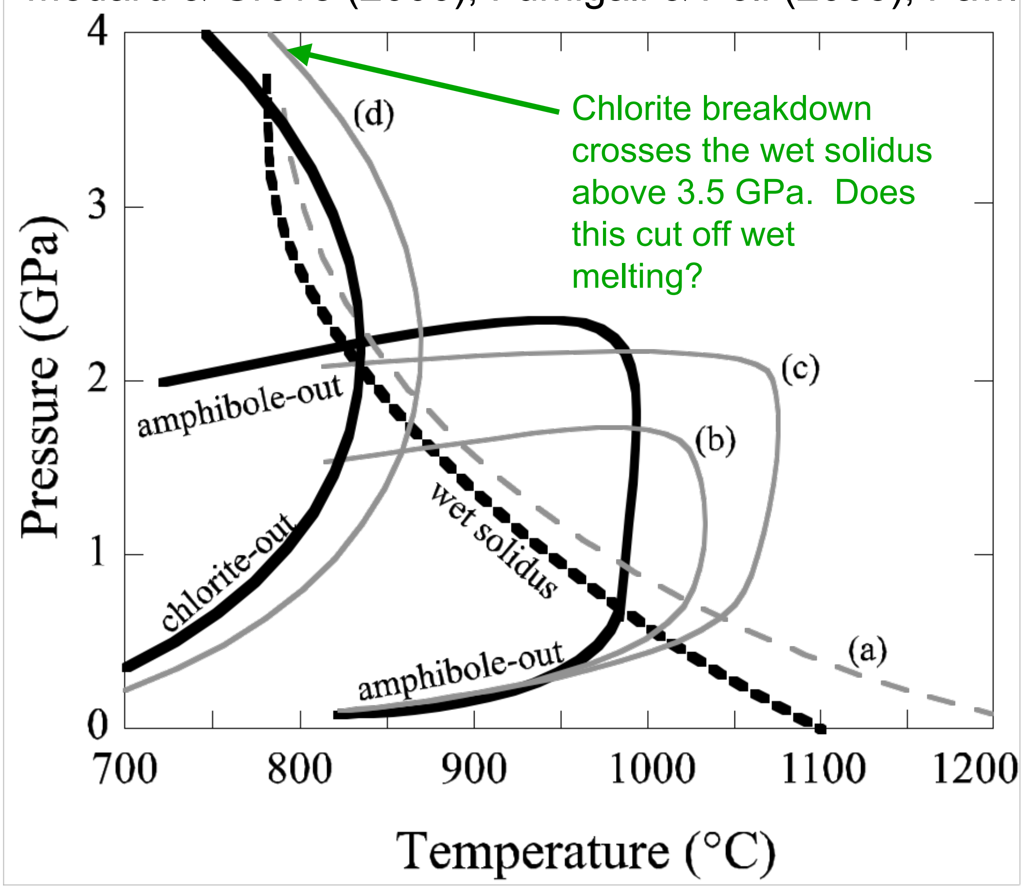
Also, Ilmenite,

Rutile &

Ti-clinohumite

are stable.

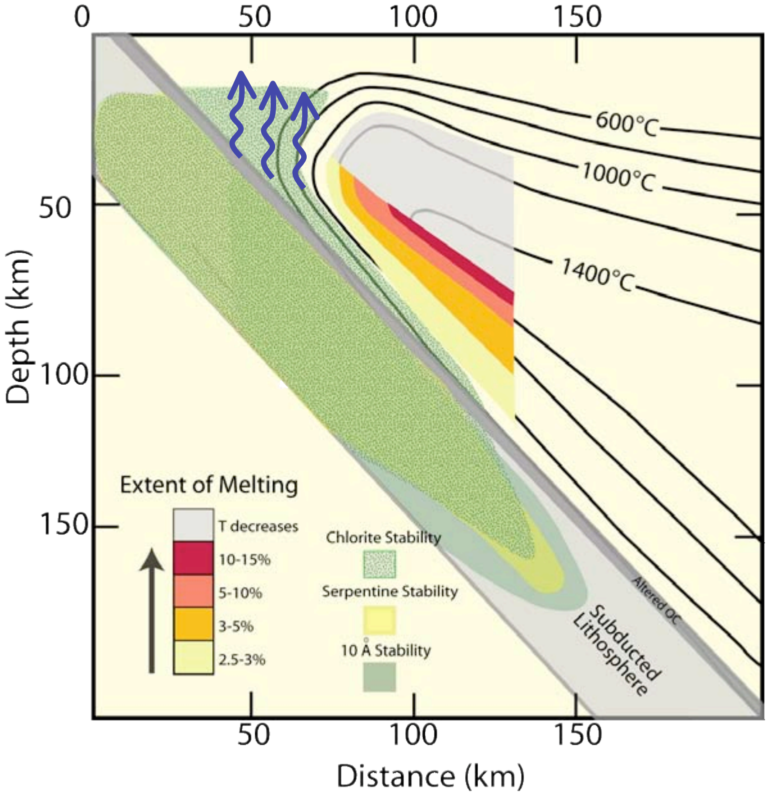
Medard & Grove (2006), Fumigali & Poli (2005), Pawley (2003)



Black is Martian mantle

Grey is Earth's mantle

Where is water stored in the wedge?



Hydrous phases in the mantle wedge & subducted slab.

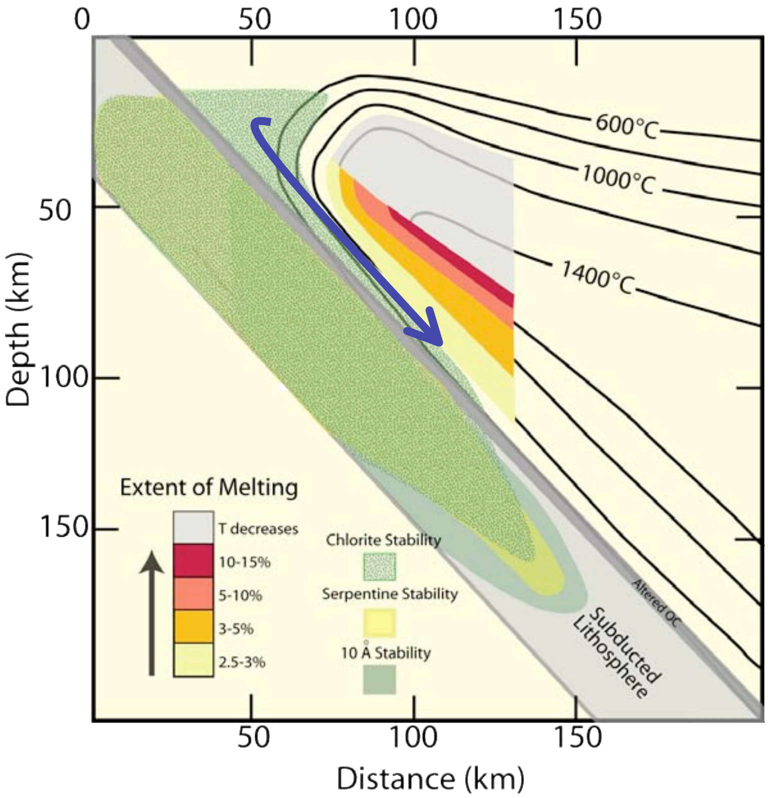
Chlorite provides a source of H_2O for wet arc melting that is above the slab.

Produced by fluid released from the slab at shallow depths.

H_2O is stored even when the slab is too hot.

Chlorite also stable below the slab-wedge interface in the cool core of the slab.

Where is water stored in the wedge?



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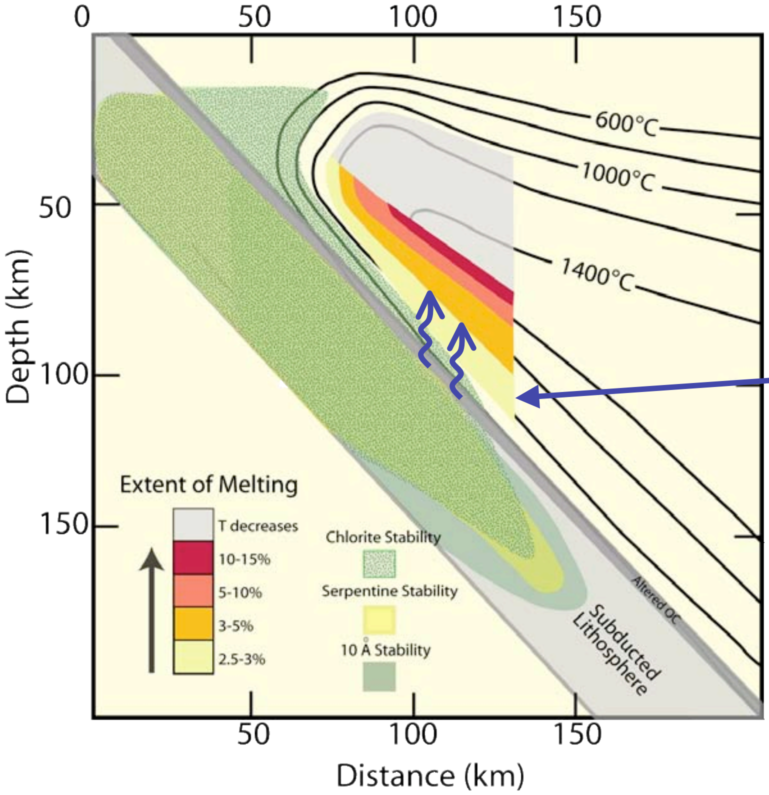
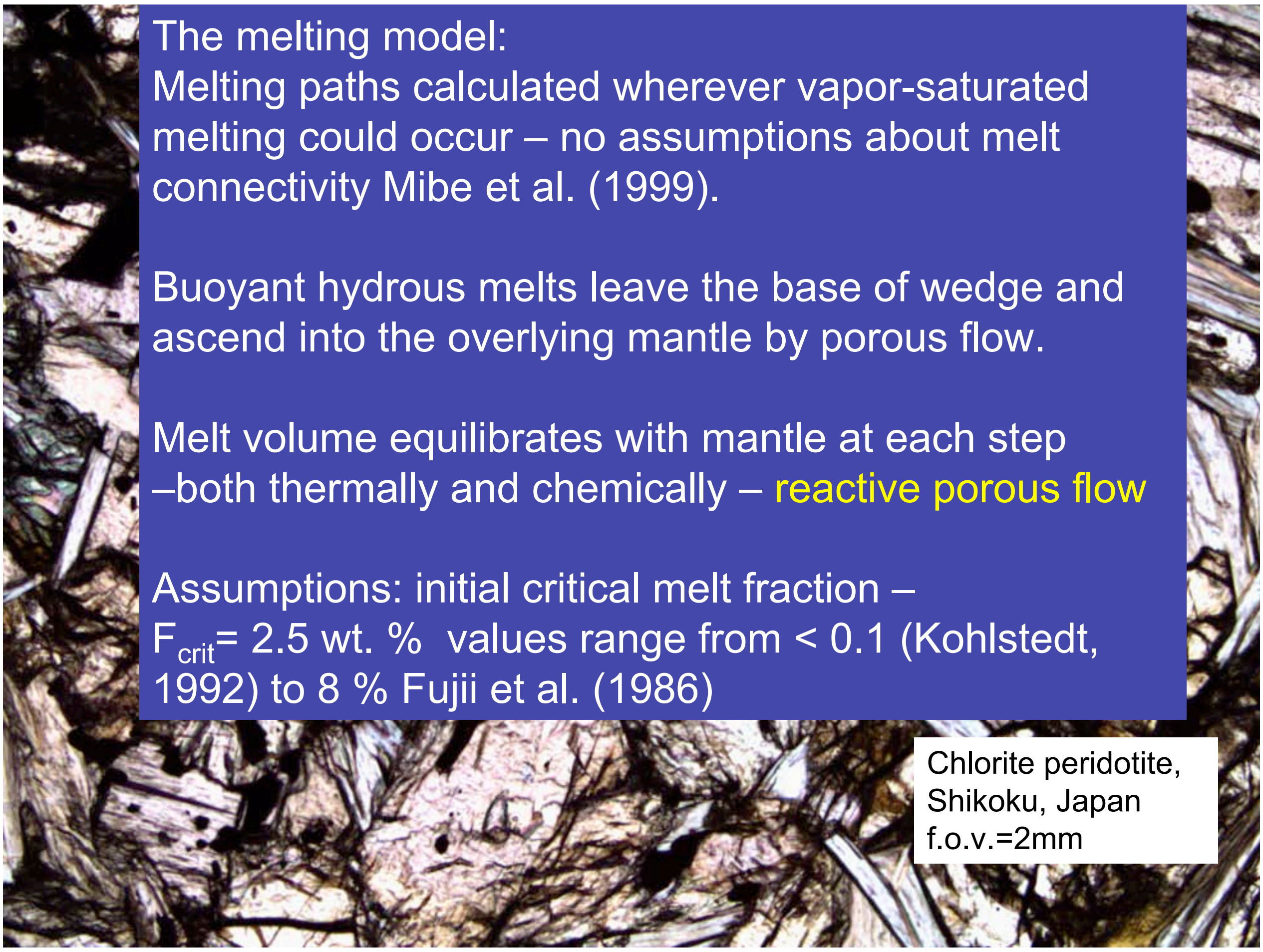


Chlorite breaks down as pressure increases.

Thus, the H_2O supply through chlorite breakdown will stop at slab depths of 120 – 150 km.

Chlorite is stable below the slab-wedge interface in the cool core of the slab and this could supply H_2O.



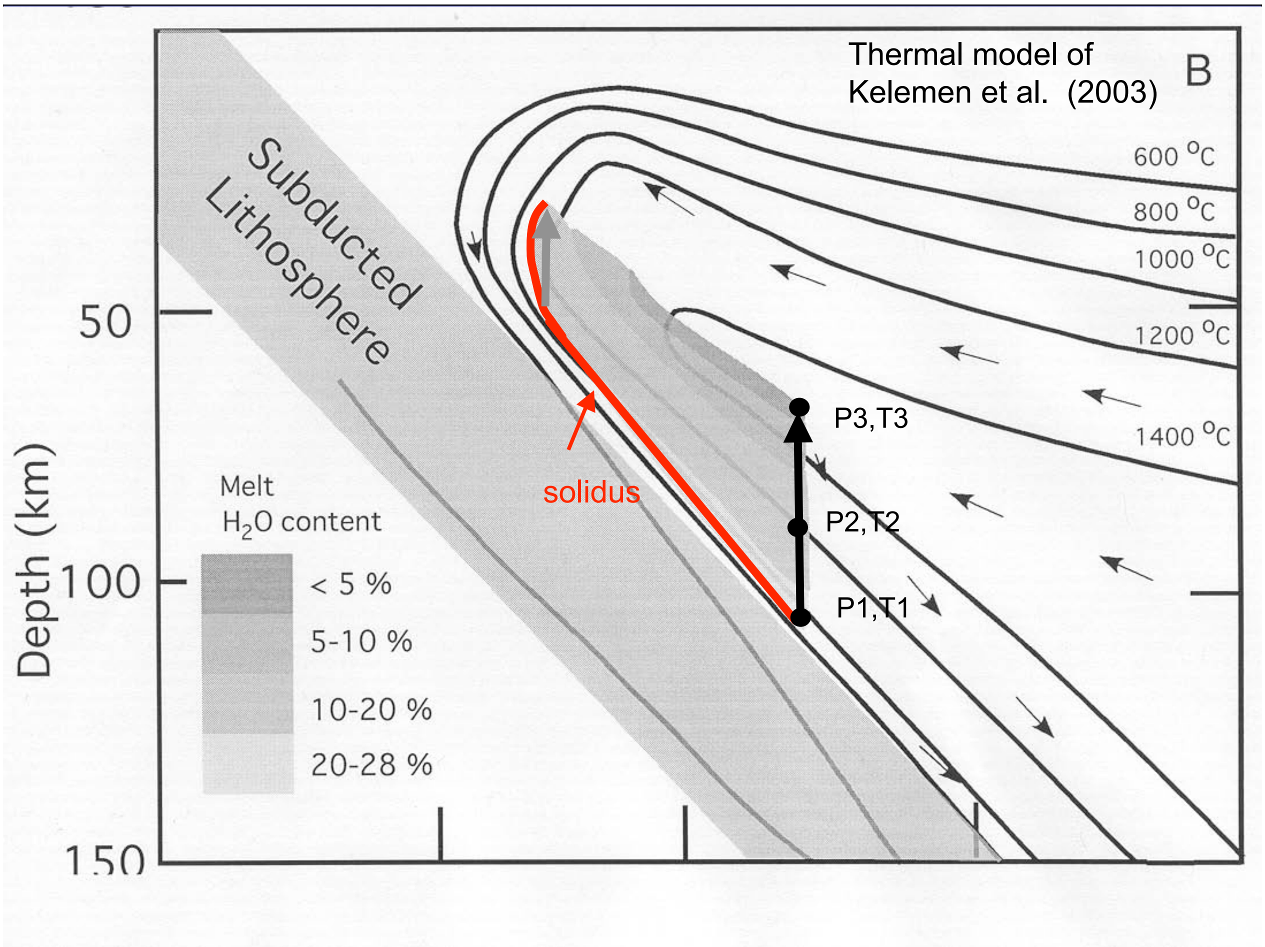
The melting model:
Melting paths calculated wherever vapor-saturated melting could occur – no assumptions about melt connectivity Mibe et al. (1999).

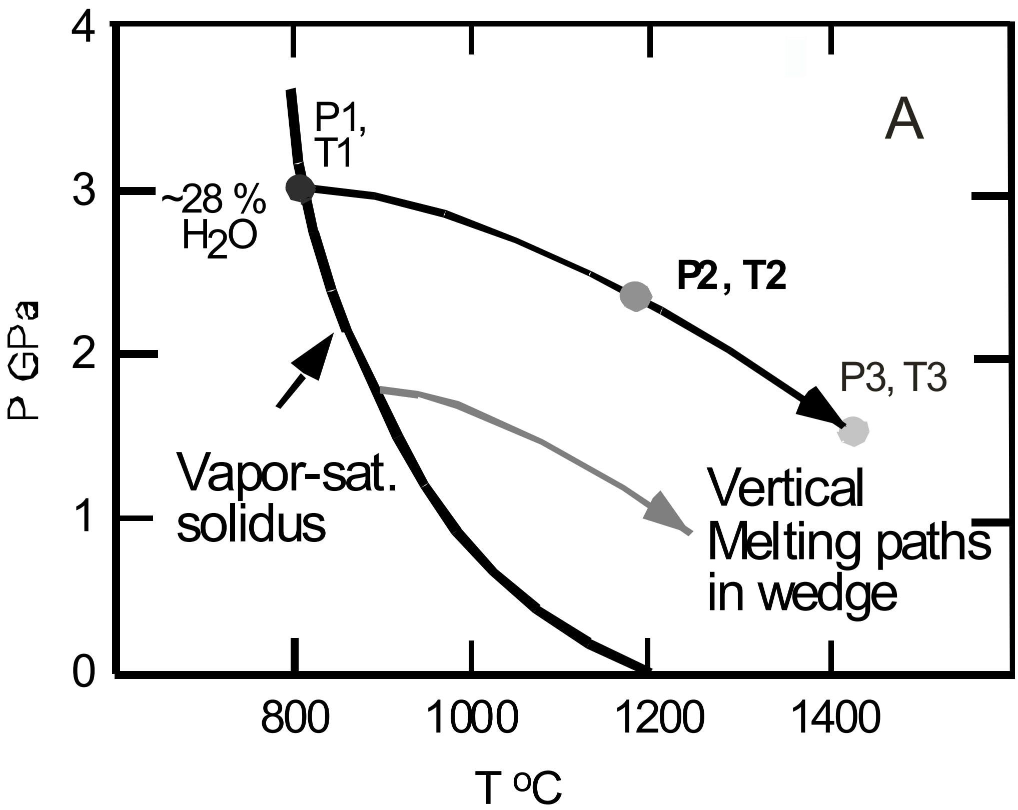
Buoyant hydrous melts leave the base of wedge and ascend into the overlying mantle by porous flow.

Melt volume equilibrates with mantle at each step –both thermally and chemically – reactive porous flow

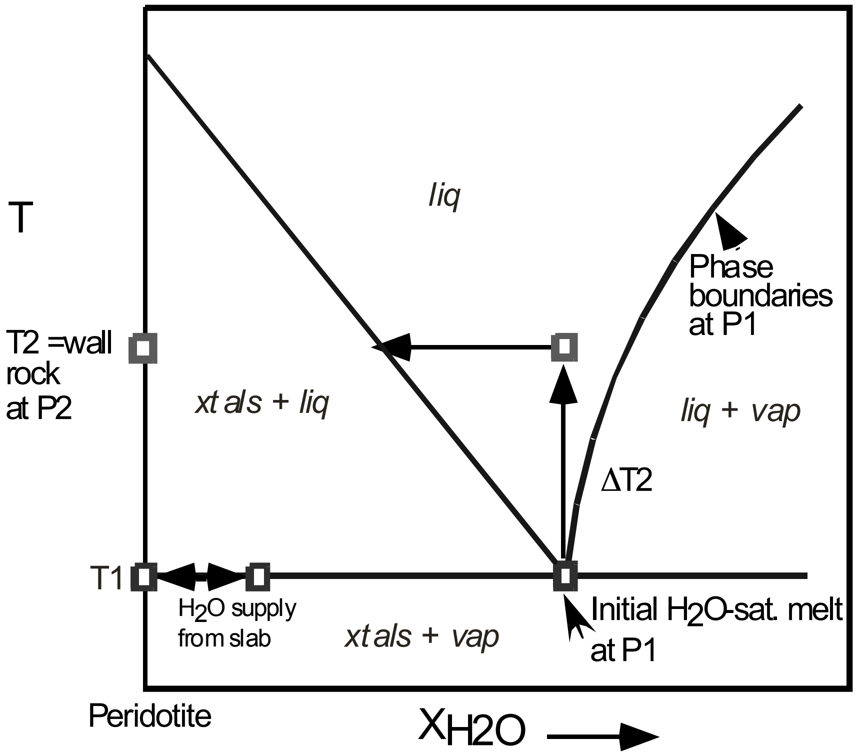
Assumptions: initial critical melt fraction – F_{crit}= 2.5 wt. % values range from < 0.1 (Kohlstedt, 1992) to 8 % Fujii et al. (1986)

Chlorite peridotite, Shikoku, Japan f.o.v.=2mm



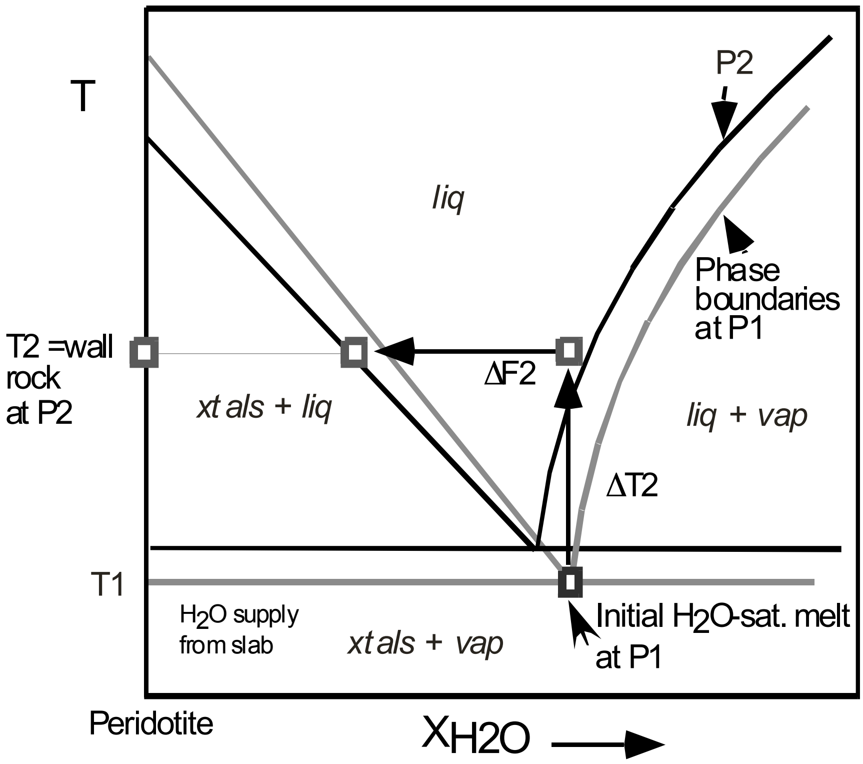


T distribution with depth determines melting processes in wedge

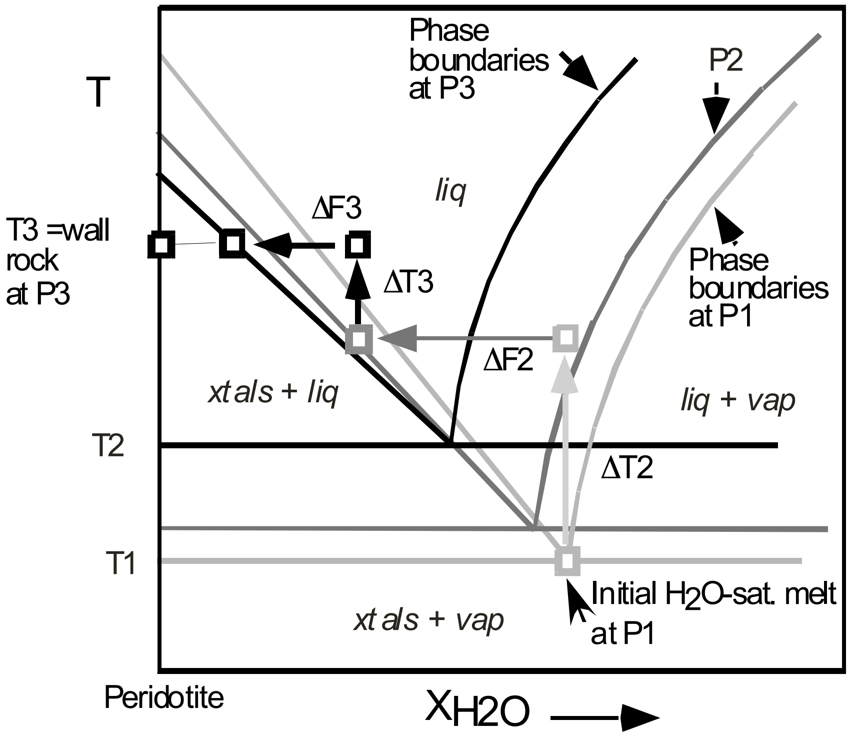


Melt ascends into hotter, shallower part of wedge. Melt reacts with and dissolves mantle, lowering H_2O in melt.

Reactive porous flow melting or Flux-Melting

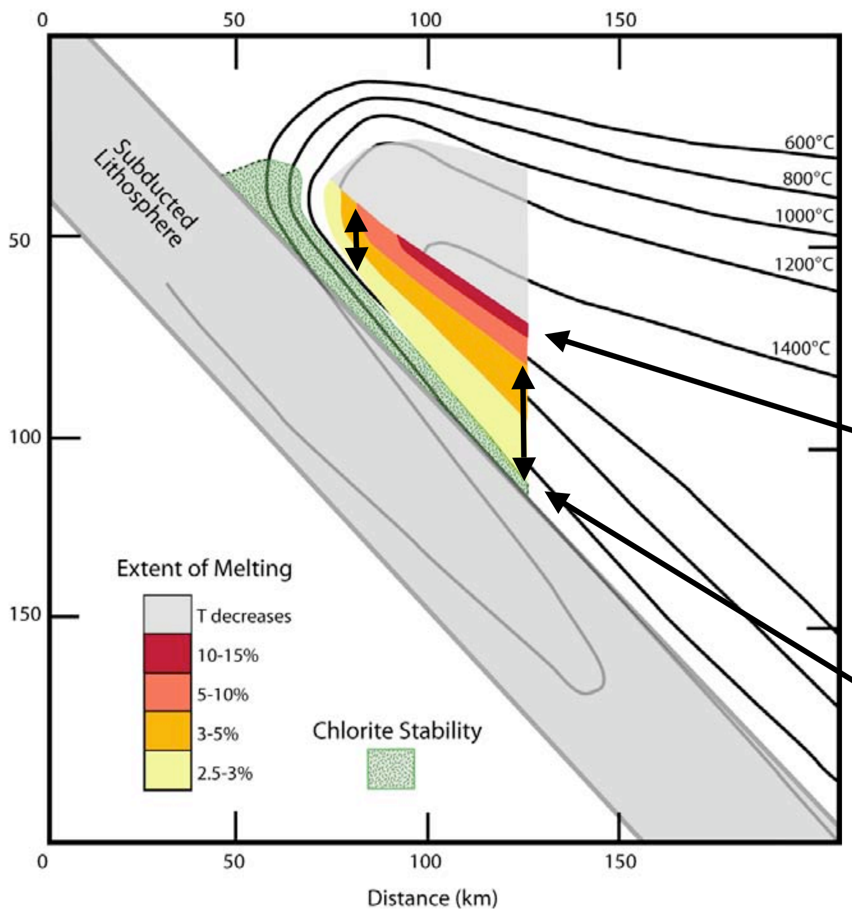


Melt reacts with and dissolves mantle, lowering H_2O in melt at coming into equilibrium with mantle at P2, T2.



Melt ascends again into hotter, shallower wedge at T3, P3. Melt reacts with and dissolves mantle, lowering H_2O in melt even more and increasing melt fraction..

Flux –melting process = melt extent increases and H_2O in melt decreases – melting process controlled by phase equilibria

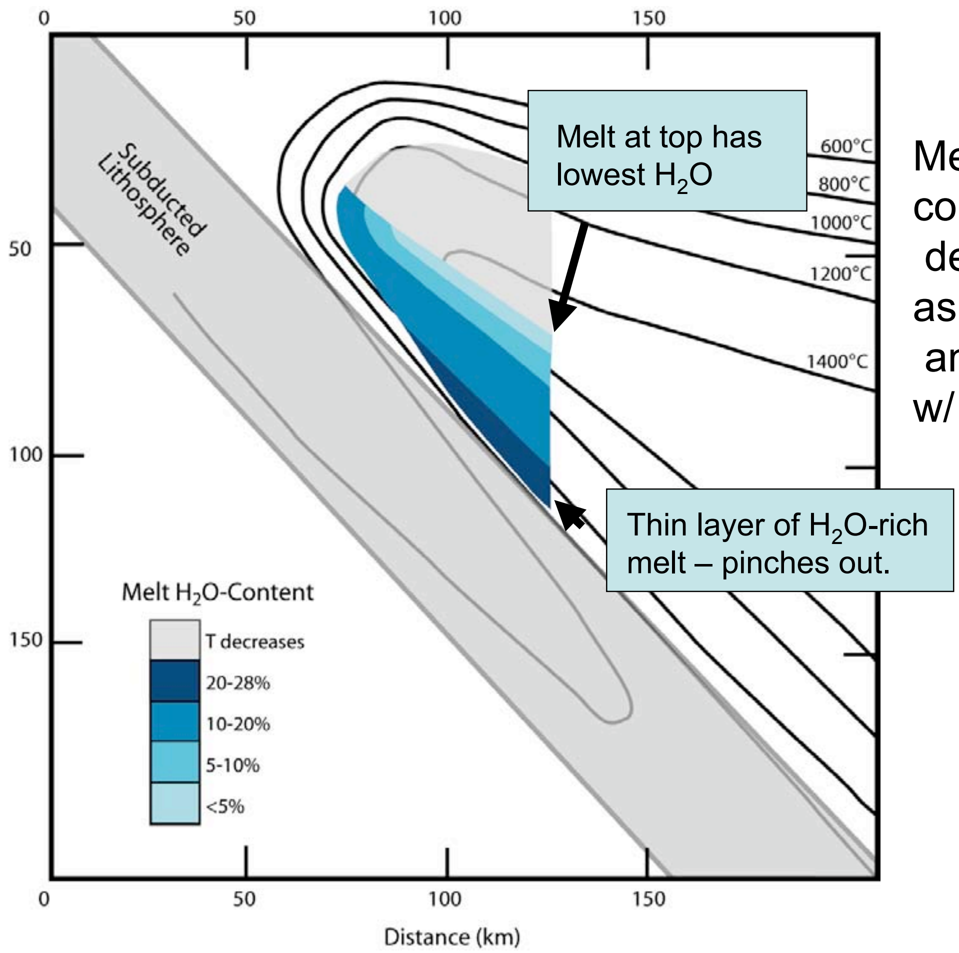


Maximum melt % occurs in a thin layer in hot core of the wedge

Highest melt fraction achieved in a very thin layer.

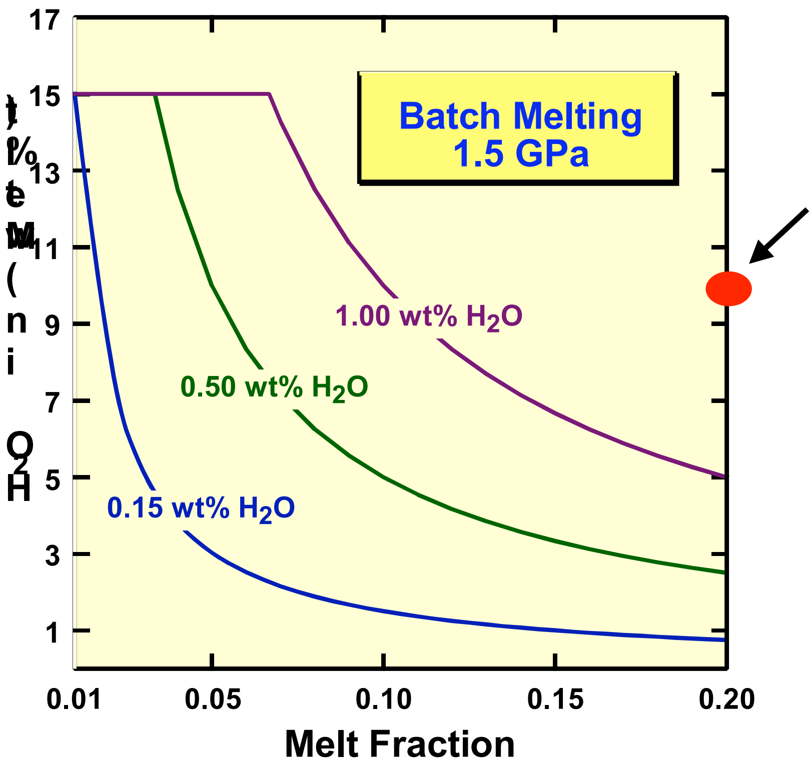
Most of wedge contains < 5% melt (double arrows).

Chlorite is transported down into the wedge ABOVE the slab and gives up its H_2O at solidus.



Melt H_2O content continuously decreases as melt ascends and reacts w/ hotter mantle

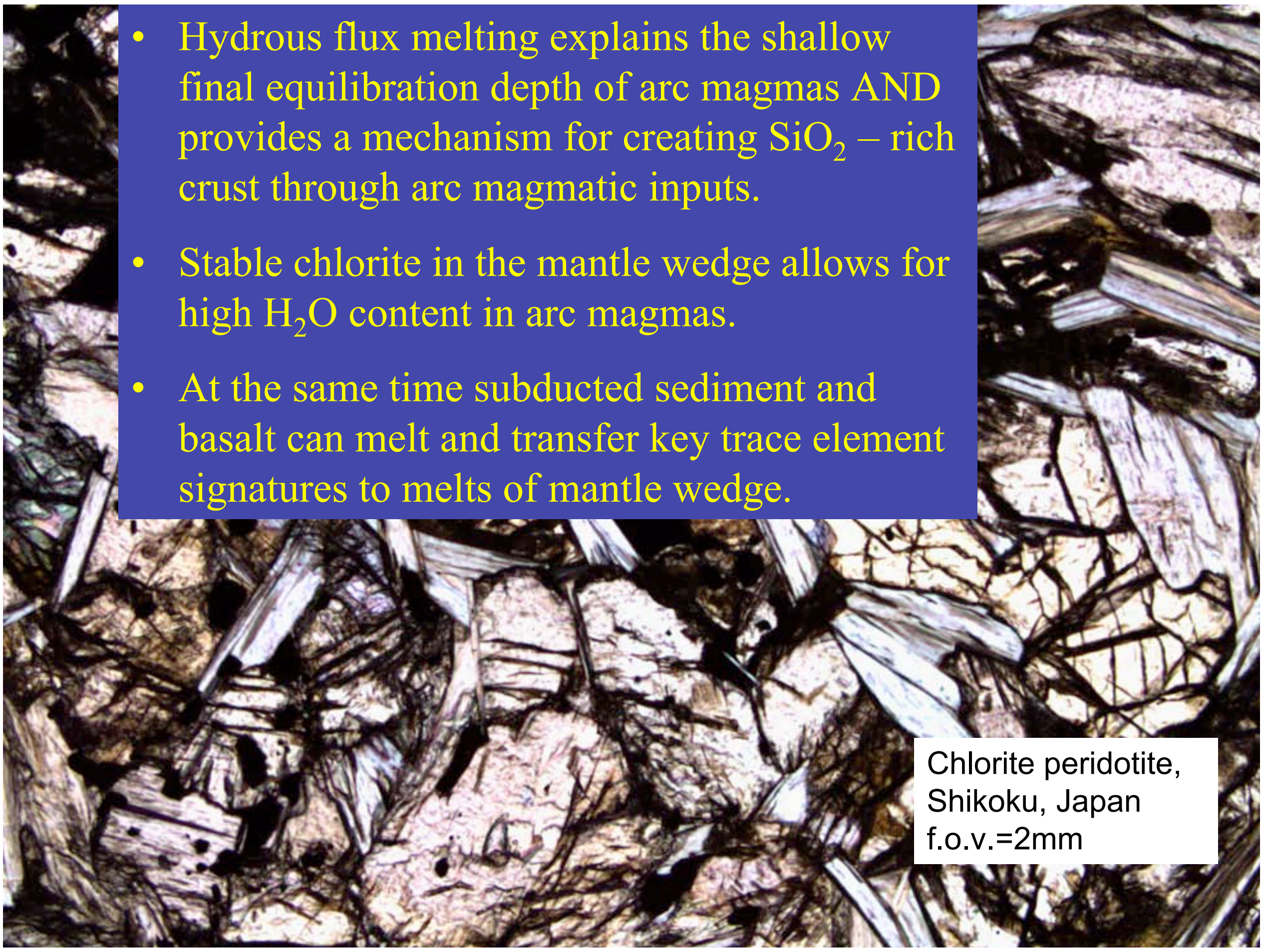
When mantle peridotite is hydrated it contains 13 % chlorite. Bulk H_2O of solid is 2 wt. % .



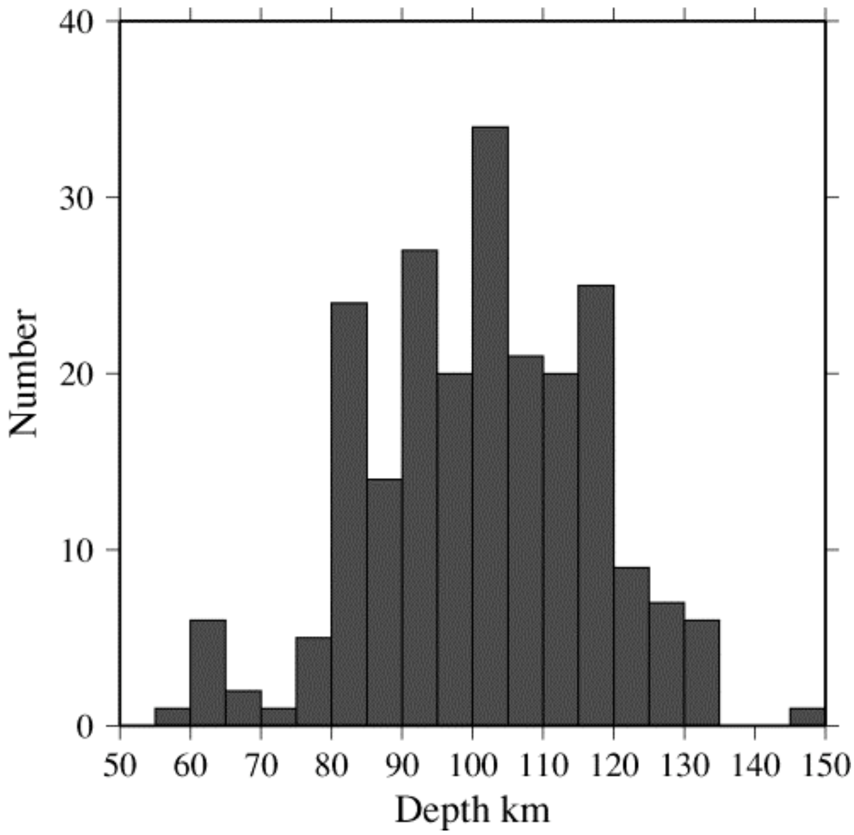
Bulk perid. = 2 wt. % H_2O. H_2O content of melt could exceed 10 wt. %.

High H_2O contents are possible.

- Hydrous flux melting explains the shallow final equilibration depth of arc magmas AND provides a mechanism for creating SiO_2 – rich crust through arc magmatic inputs.
- Stable chlorite in the mantle wedge allows for high H_2O content in arc magmas.
- At the same time subducted sediment and basalt can melt and transfer key trace element signatures to melts of mantle wedge.



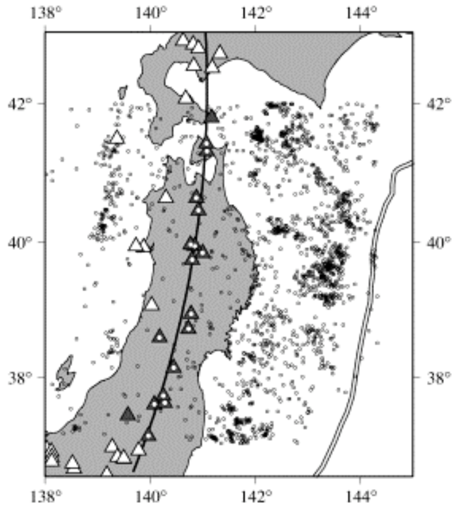
Chlorite peridotite,
Shikoku, Japan
f.o.v.=2mm

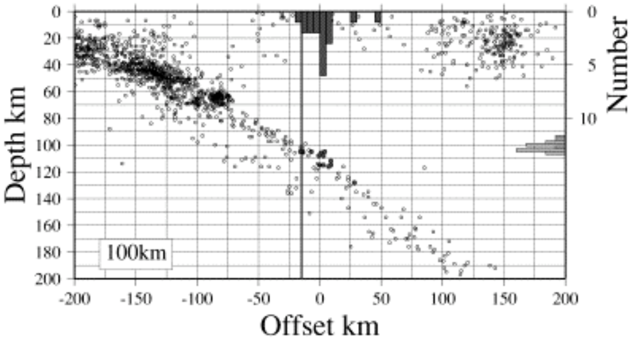


What controls the location of volcanoes in subduction zones?

From England et al. 2004.

Average depth to slab beneath an arc volcano is ~ 108 km.





From England et al. 2004.

Distribution of arc volcanoes and intermediate depth seismicity.

Perhaps these earthquakes show the zone of subducted serpentinite - chlorite mantle.

England et al. (2004) and Syracuse and Abers (2006) explore the global variations of depth to slab below volcanic fronts.

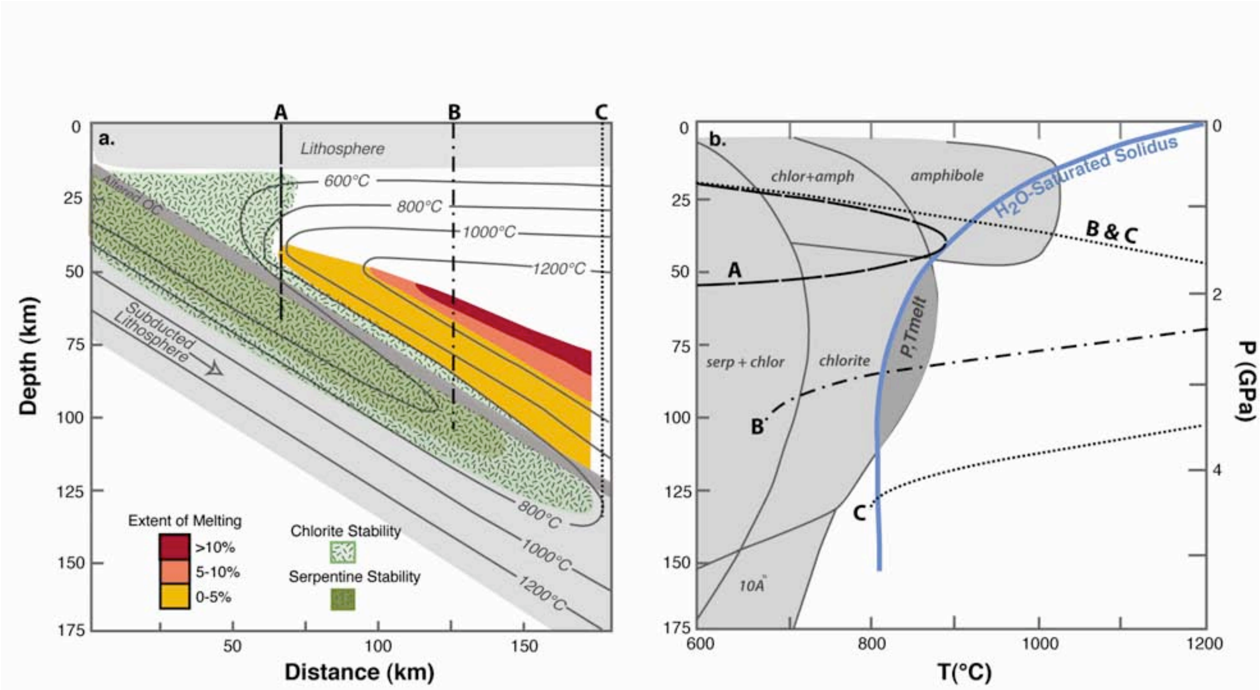
England et al. find a systematic variation of depth to the slab

Attributed to the product of convergence rate (V) and angle of descent of slab (sin δ)

We develop a model to test importance of down dip velocity and convergence rate on temperature structure

We find that sin δ has the dominant control. As dip angle increases hotter mantle is drawn to shallower depths in the nose of the wedge.

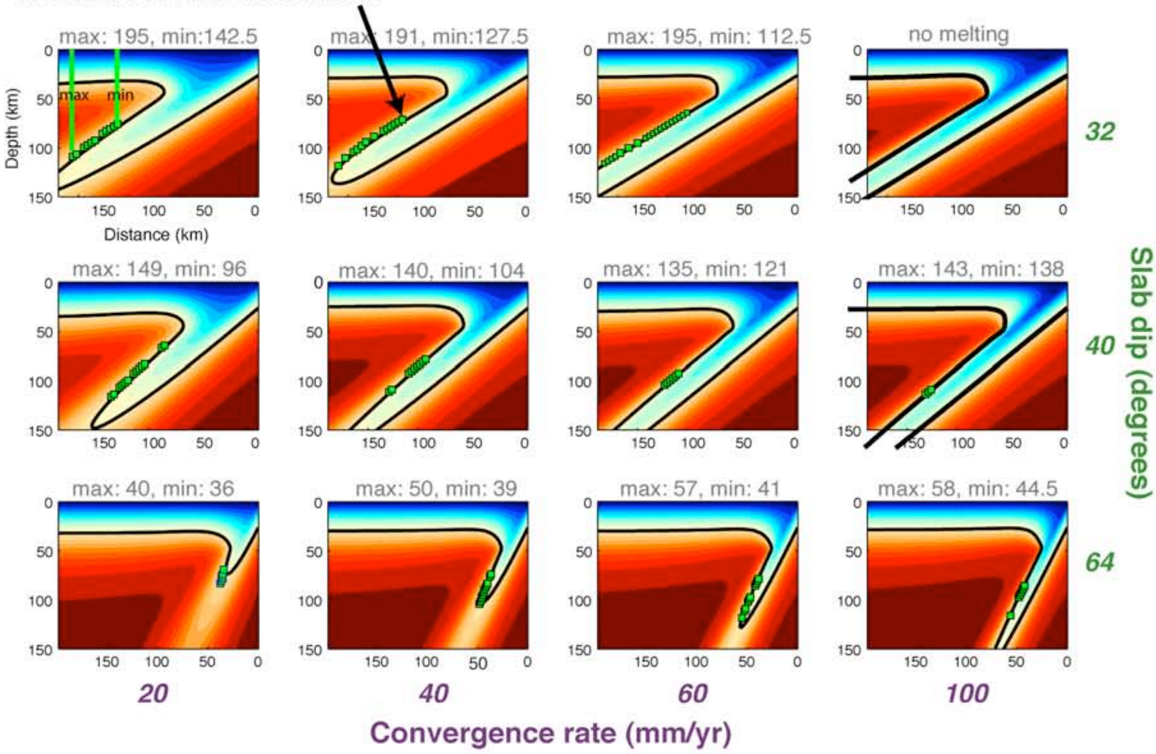
Petrologic controls are temperature structure and supply of H_2O from chlorite breakdown

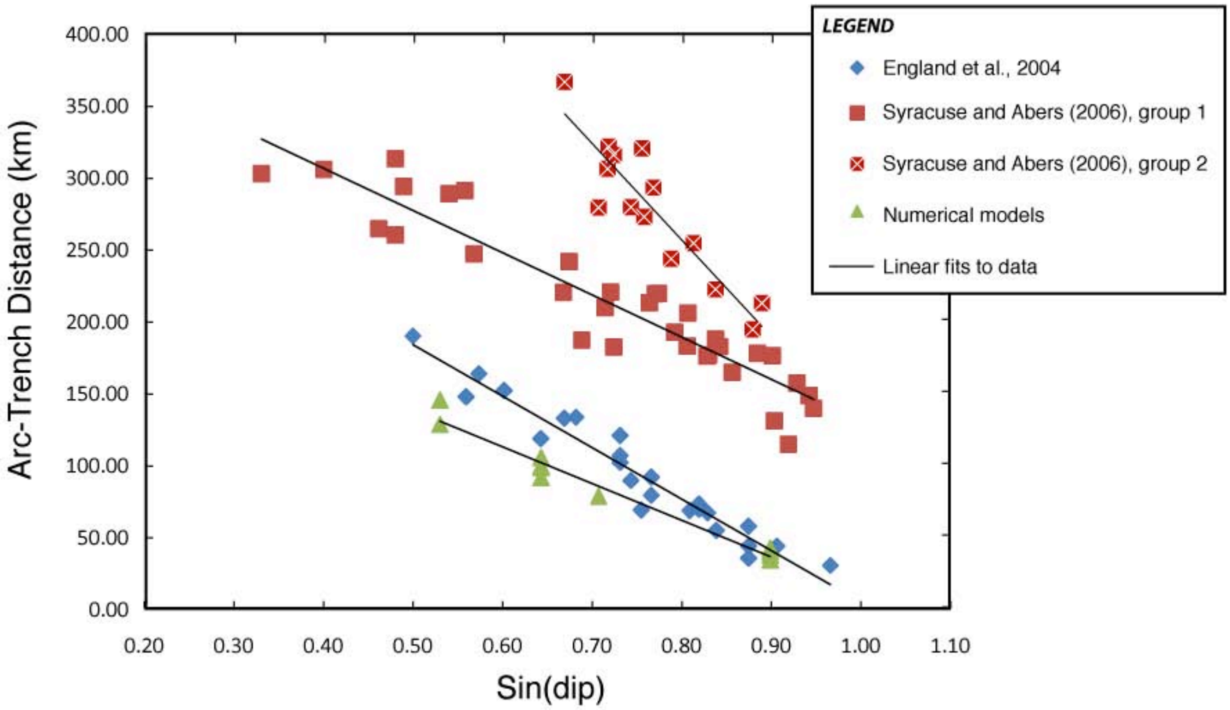


Primary petrologic controls on hydrous melt generation:

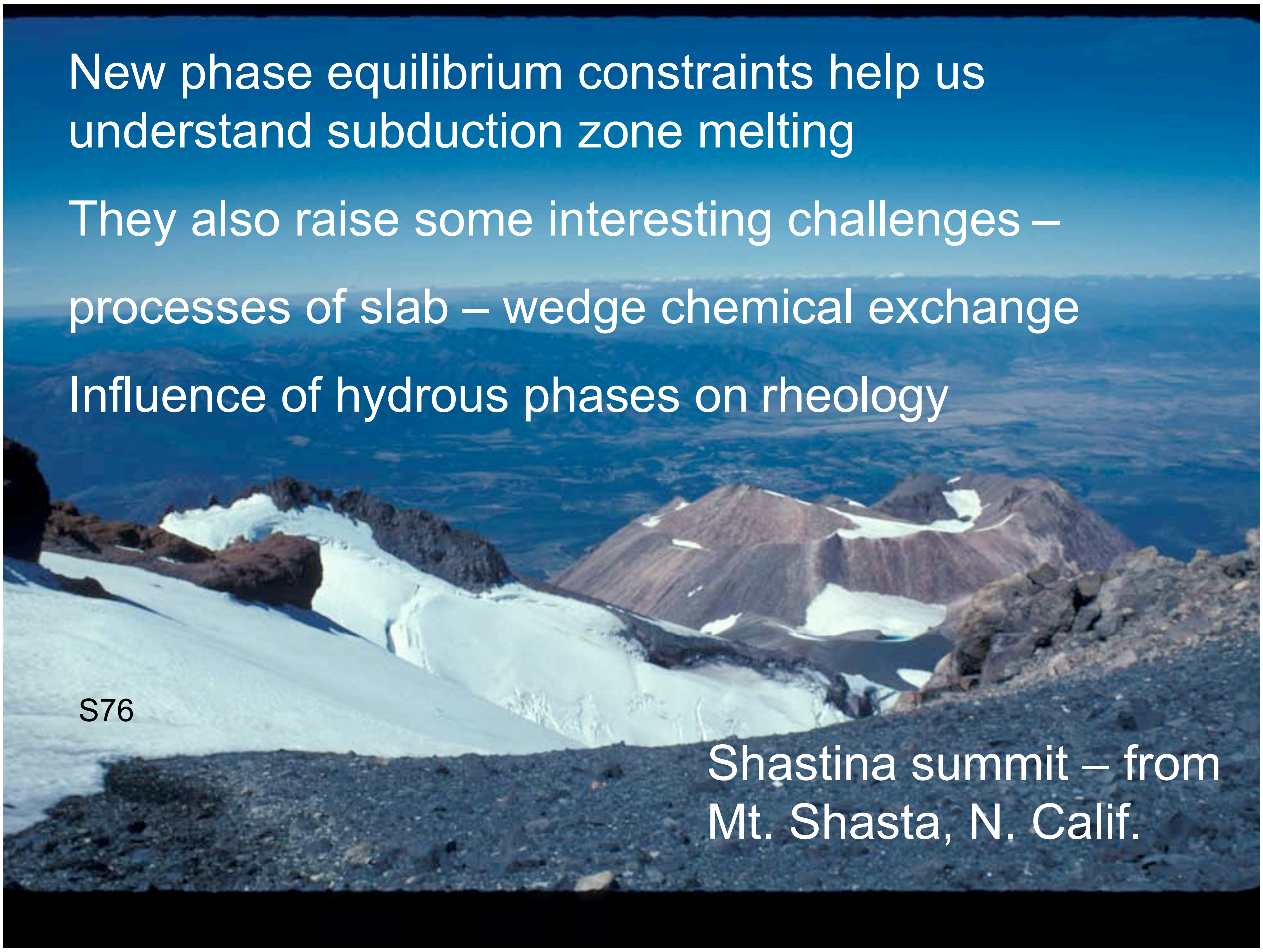
1) Temperature – Pressure distribution in the mantle wedge and the vapor-saturated peridotite solidus.
2) Breakdown of hydrous minerals at the base of mantle wedge.

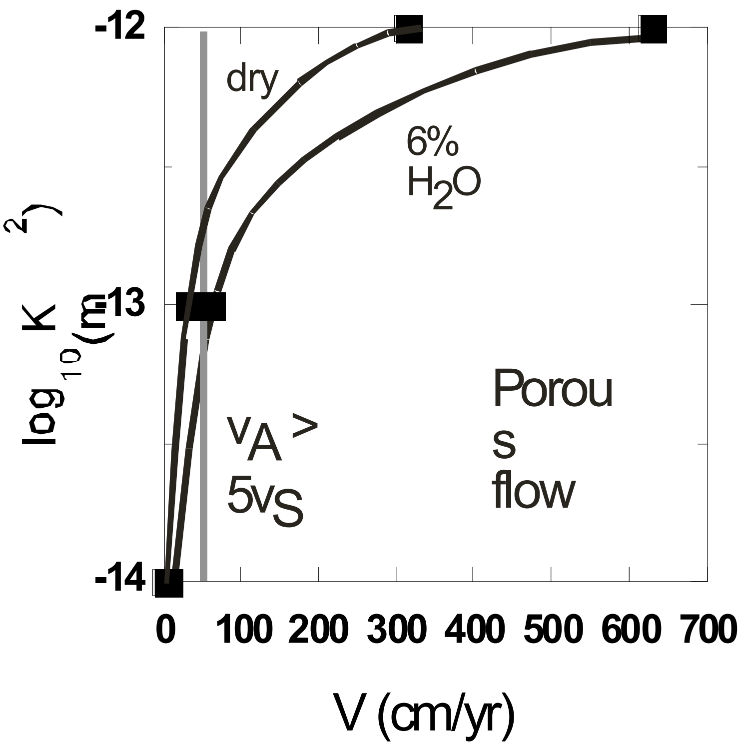
Location of the initiation of melting where temperature is greater than the wet solidus and less than chlorite breakdown





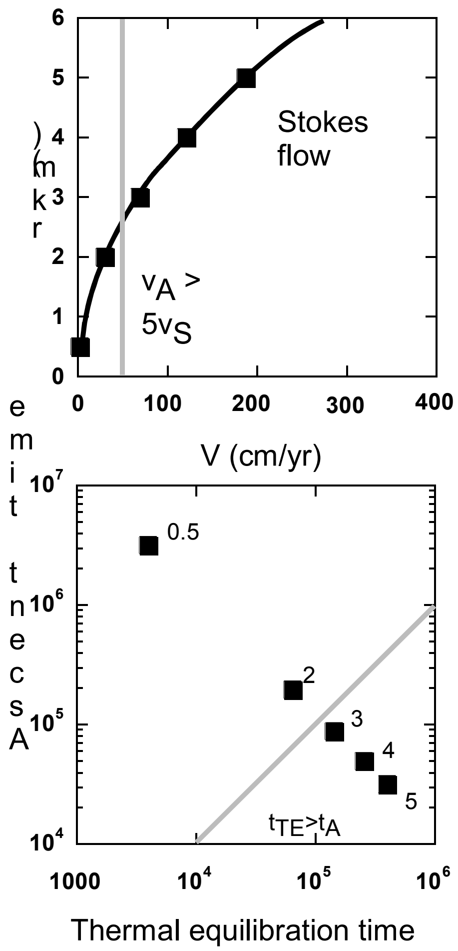
Comparison of numerical model results and observations of the distance between the arc front and trench vs. sin (dip).





Melt ascends into overlying mantle wedge rapidly

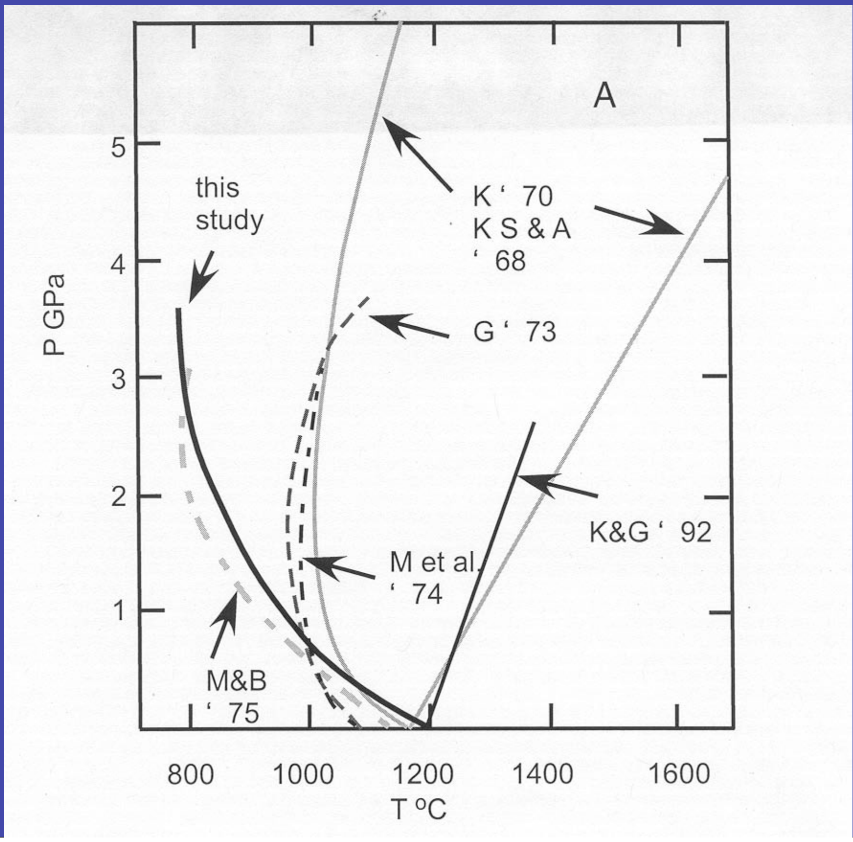
(< 25,000 years)



Diapiric ascent of crystal + hydrous melt

For ascent to be sufficiently rapid, diapir will cool wedge

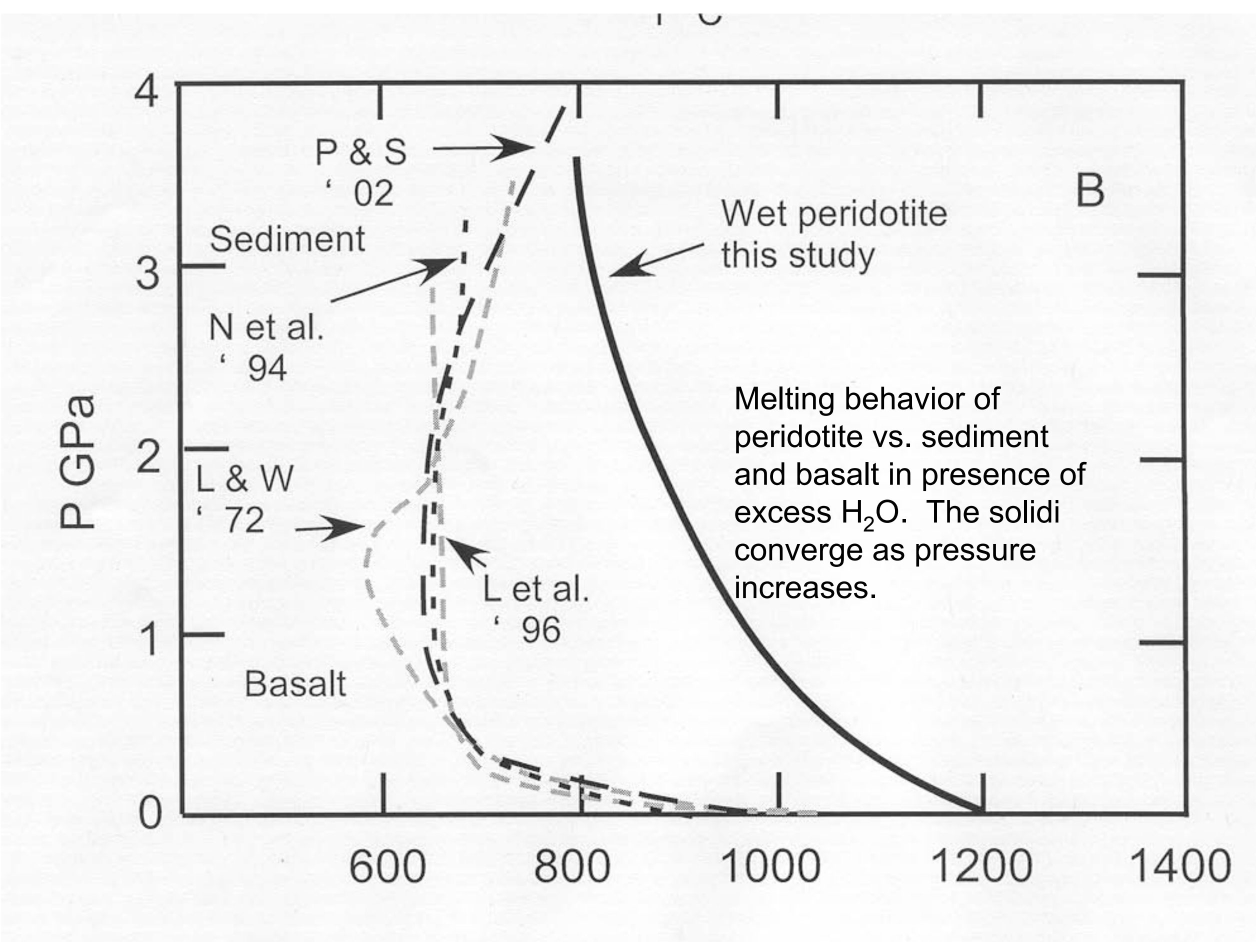
Old & New Expts. Why the difference? – melting kinetics

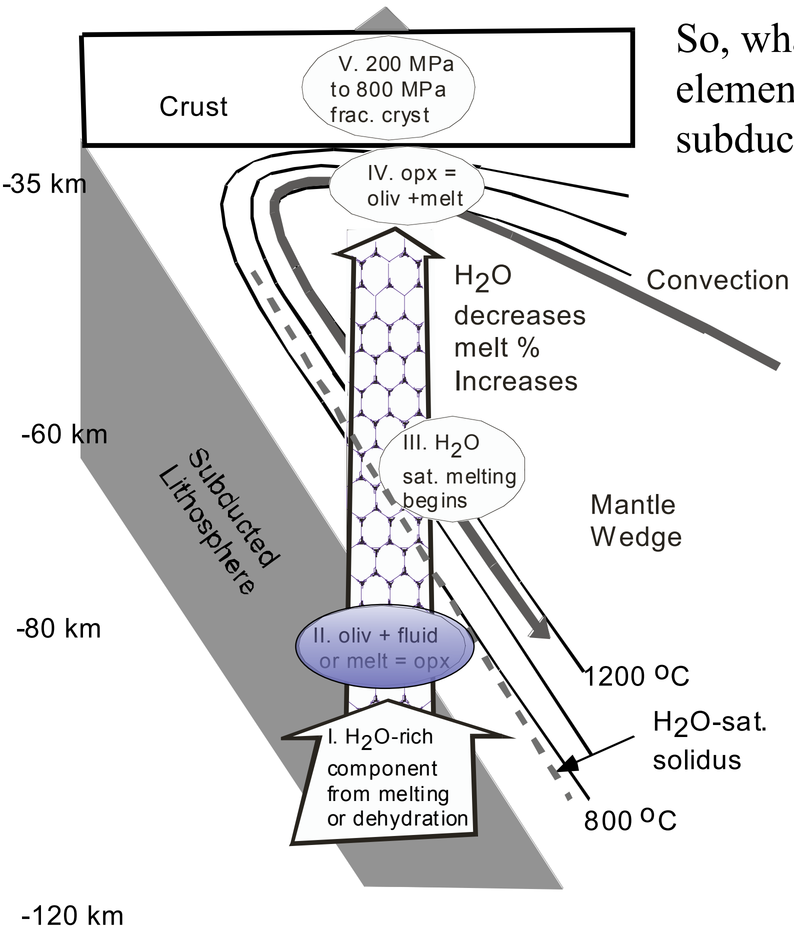


Olivine melting rate is slower than that of pyroxene

-Olivine also melts at a lower Temperature by about 200 °C

- In the short run time expts pyroxene melted first





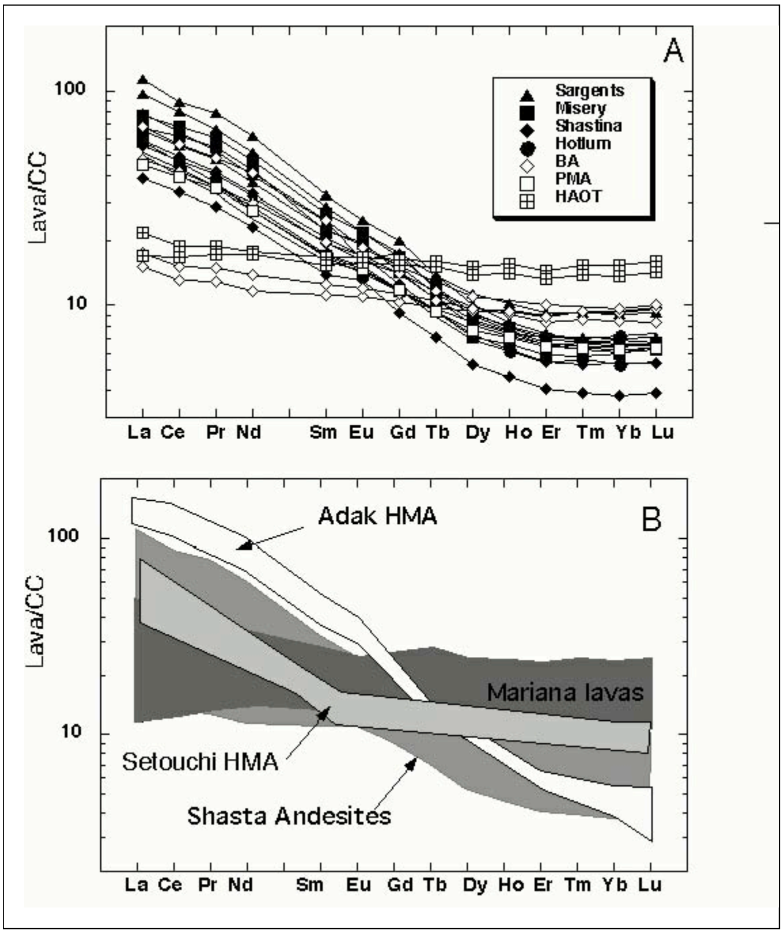
So, what medium transfers elements from hot, young subducted lithosphere?

Is it a melt?? A fluid??

Looks most like a low degree melt of sediment/MORB eclogite.

Fluid – not a good match.

Mantle wedge / slab melt interaction improves model.

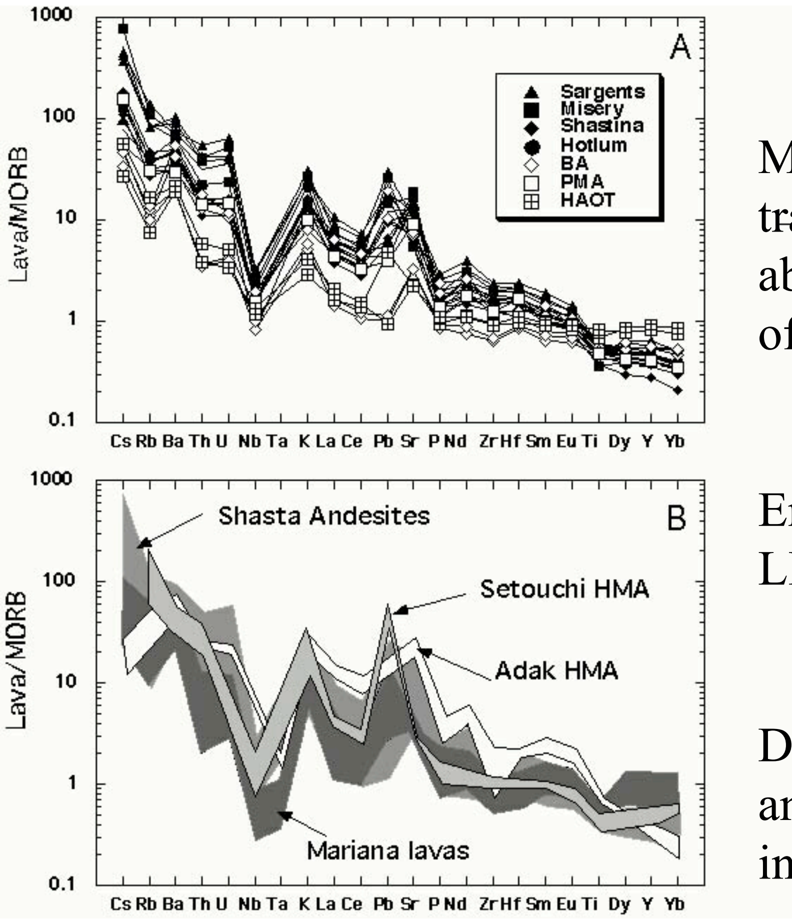


Shasta lava trace elements in hydrous PMA & BA

Model estimates contributions from

Mantle Wedge

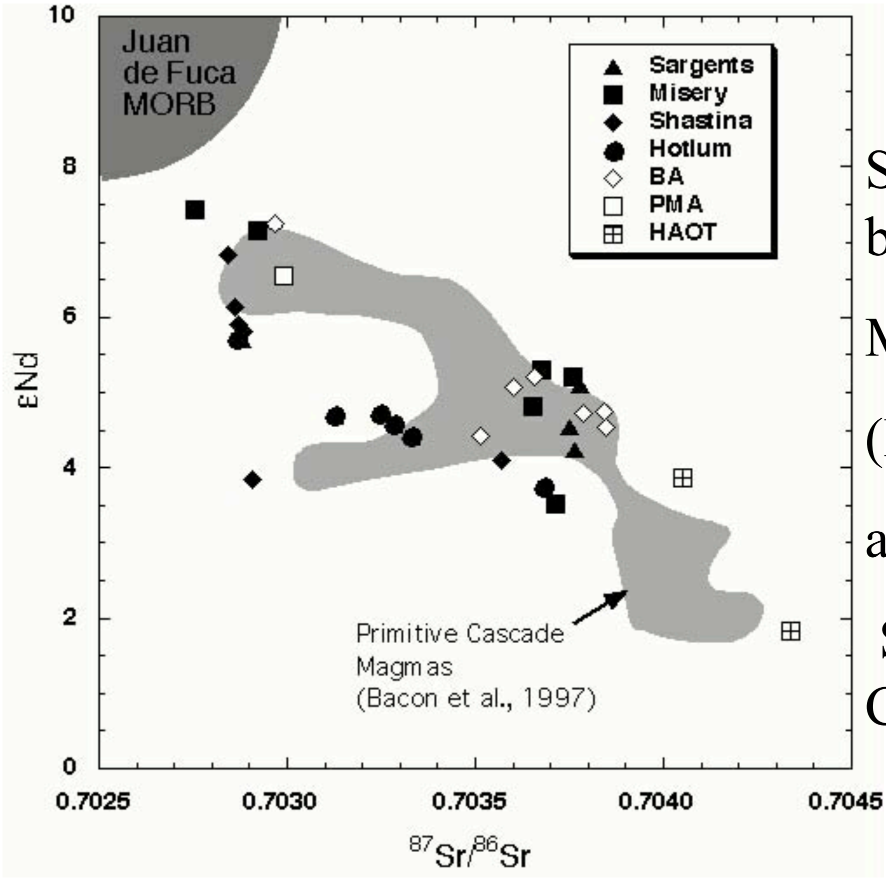
& Subducted Lithosphere.



MORB-normalized trace element abundances typical of arc magmas

Enrichments in LILE

Depletions in HFSE and the less incompatible TE



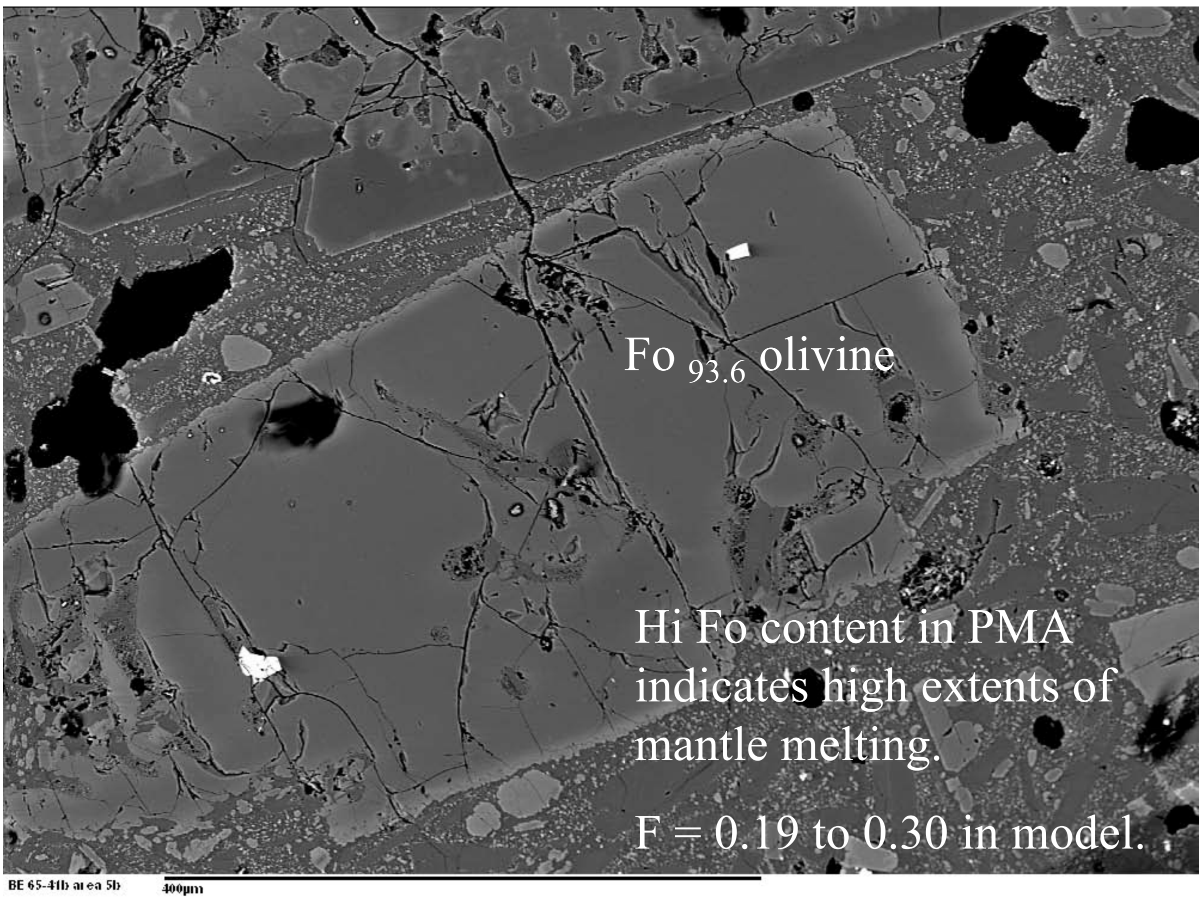
Signatures of both:

MORB

(High La/Sm)

and

Sediment Components

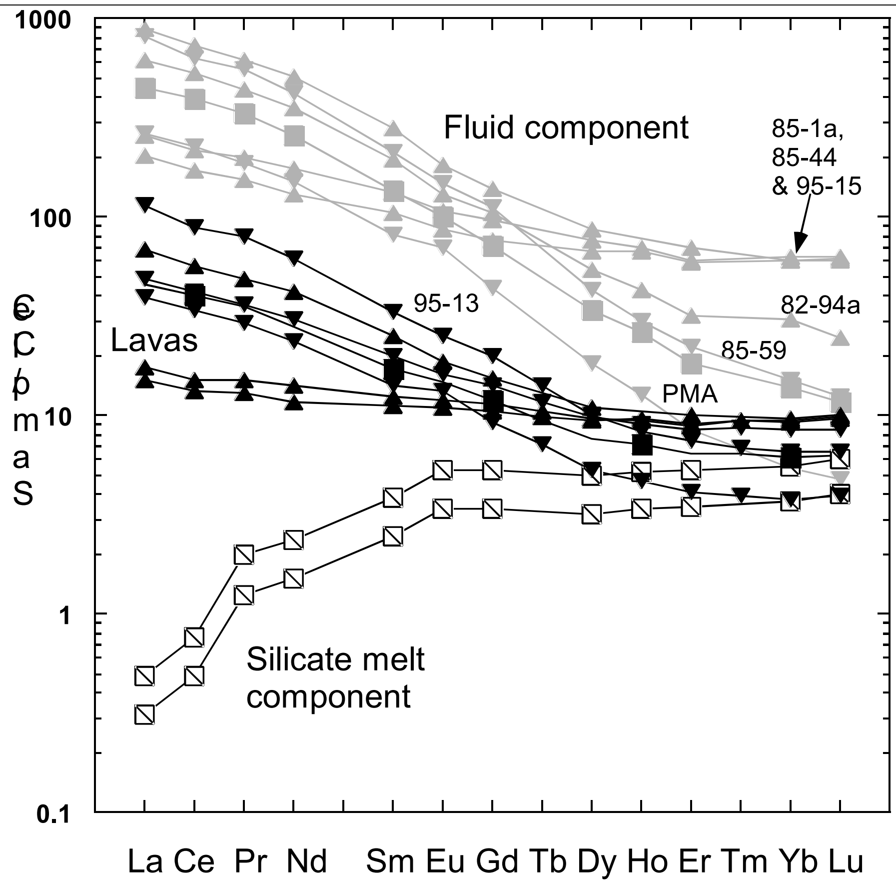


Mass Balance Model

$$C_{fluid} = (C_{lava} - X_{melt}\, C_{melt})/(X_{fluid})$$

- Substitute batch melting equation for C_{melt}
- F is fraction of mantle melt and
- D is bulk distribution coefficient
- C_0 element abundance in mantle source
- α is a correction for other elements in fluid

$$C_{fluid} = (C_{lava} - (1 - X_{H2O}/\alpha)C_0/[F+D(1-F)])/(X_{H2O}/\alpha)$$



Estimated fluid component = gray

Lavas = solid black

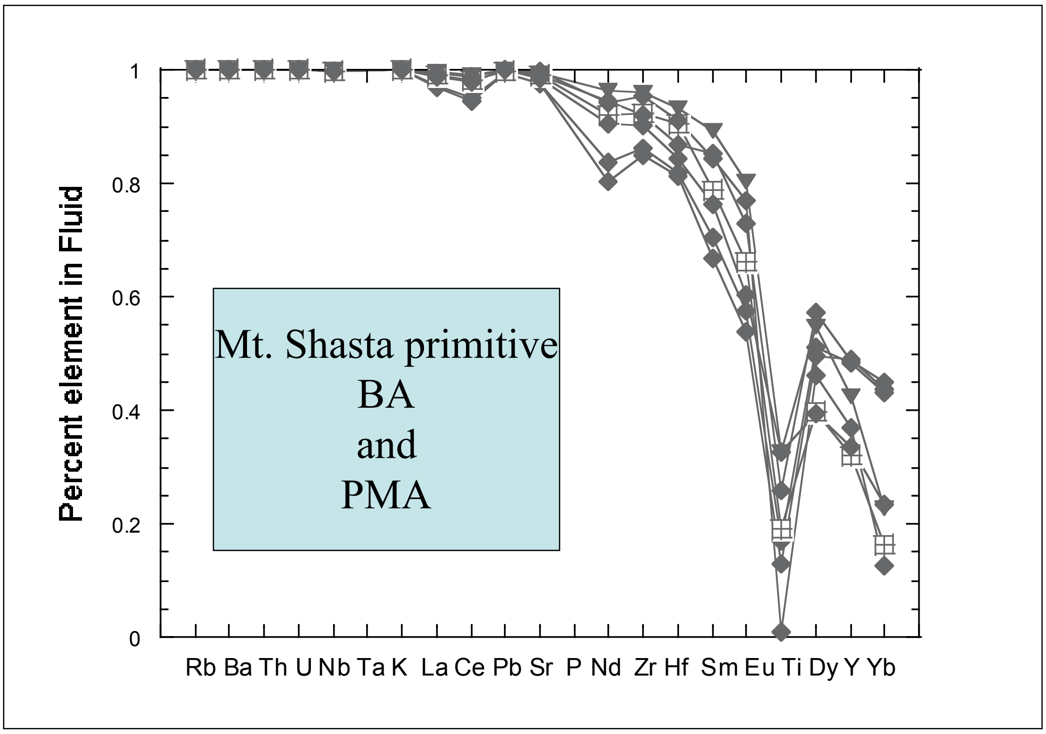
Silicate melt of mantle = open square.

Note the dichotomy in La/Sm_N

and

Dy/Yb_N

Estimated Slab Contribution



Major element characteristics of the fluid-rich Mt. Shasta component

- Na_2O = 25 to 33 wt.% of the "fluid"
- K_2O = 5 to 13 wt. % of "fluid"
- SiO_2 = 0 wt. %
- H_2O = 54 to 70 wt. %
- Similar to finding of Stolper & Newman (1994).

So, what is it? A melt or a fluid?

Any H_2O rich slab fluid/melt is likely to interact with the wedge

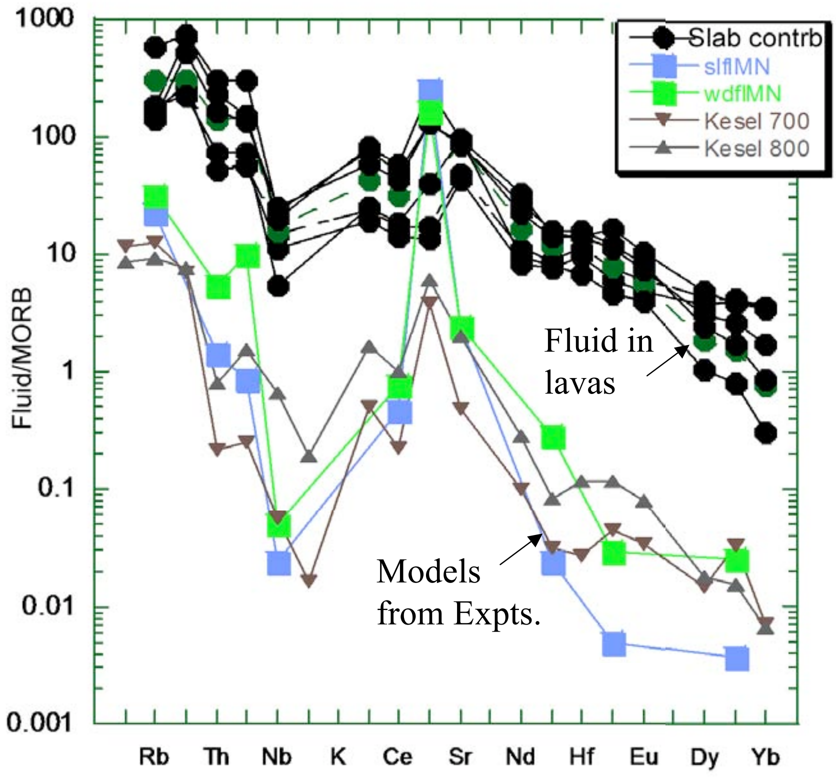
- SiO_2 solubility in an H_2O-rich fluid will be low -Zhang & Franz (2000) Newton and Manning (2003)
  Olivine + SiO_2(fluid) = orthopyroxene

- Bell et al (2005) characterize chemical interaction between wedge & subduction added component in Kaapvaal harzburgites. Metasomatic reaction is:

1.25 Oliv +1 liquid = 1.0 Opx +0.08 Gar+ 0.17 Phlog

Let's further react the slab melt with the wedge. The result is Distilled Essence of Slab Melt.

H_2O-rich component a fluid? No…



Estimated fluid-rich component (black circles)

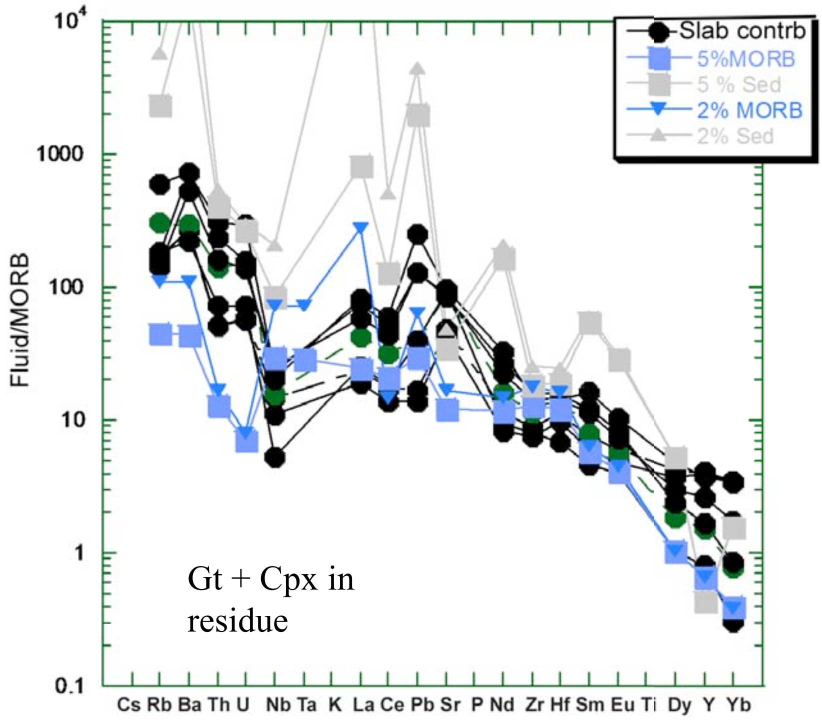
Least similar to a hydrous fluid saturated with eclogitic residue

Slfl = slab fluid
Ds from Ayers, Brenan, Kogiso, Stalder, etc.

Wdfl =wedge fluid

Kesel (2005) = fluid inMORB at 4 GPa

H_2O-rich component a silicate melt?
Much closer….

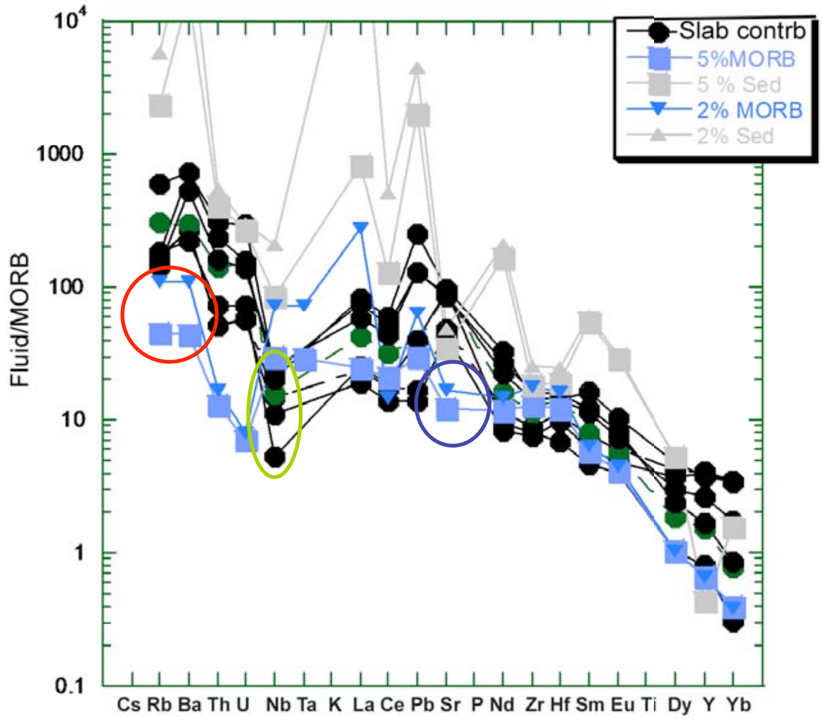


Estimated fluid-rich component (black circles)

Most similar to a mix of hydrous low degree melt of eclogitic residue

n-MORB (Hofmann) and Sediment (Ben Otham)

eclogite melt Ds from Green et al. (2000)



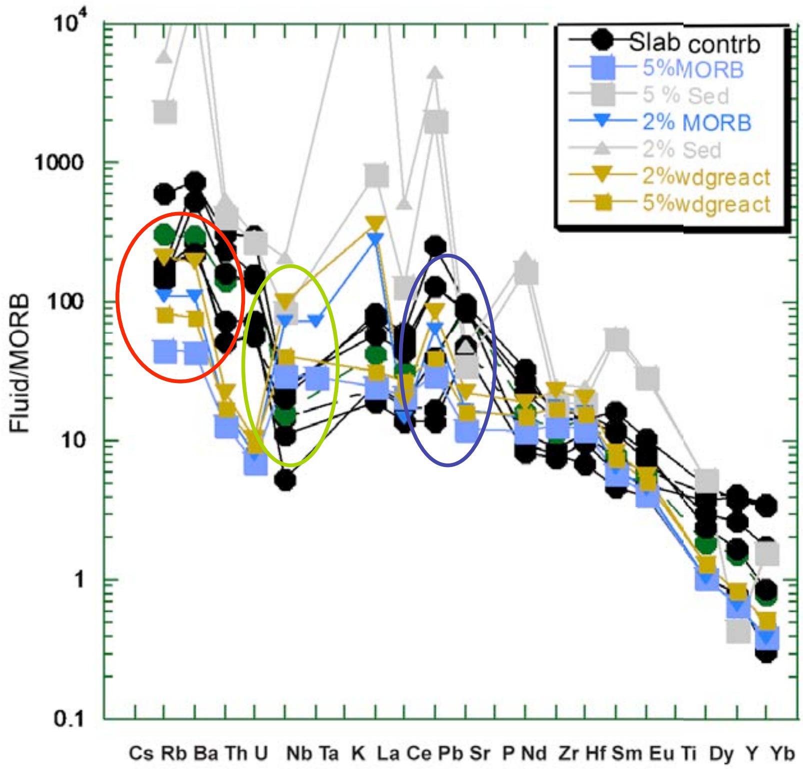
But the eclogite melt model of MORB & Sediment are not perfect fits.

Misfits:

Highly incompatible elements

&HFSE

& Fluid mobile



Brown symbols show effect of wedge peridotite + slab melt interaction at base of wedge using reaction inferred by Bell et al. (2005).

highly incompatible elements -better

HFSE -worse

Fluid mobile - better

So, what medium transfers elements from subducted lithosphere?

- Is it a melt? Is it a fluid? Are minerals also involved? Yes , No, Yes – IF the melt is REALLY H_2O-rich and MODIFED
- A low degree melt of sediment or MORB eclogite looks OK - sort of…
- Match is closer than it is for “H_2O”
- But there are mismatches – in HFSE, highly incompatible elements and fluid mobile.