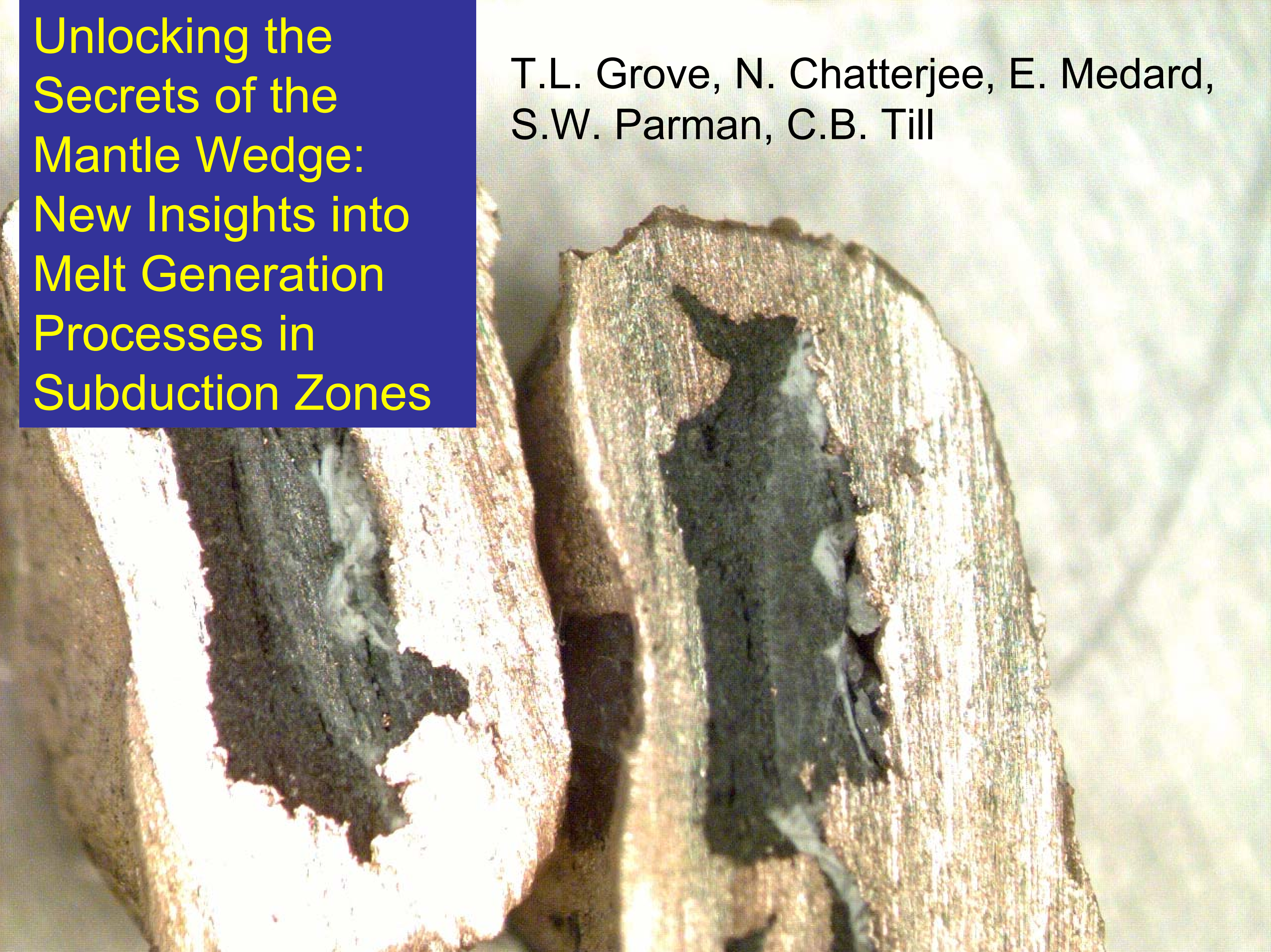
Unlocking the Secrets of the Mantle Wedge: New Insights into Melt Generation Processes in Subduction Zones

T.L. Grove, N. Chatterjee, E. Medard,
S.W. Parman, C.B. Till



Reginald Aldworth Daly (1871 – 1957) :

Bowie Medalist (1946)

The Quintessential AGU member

- Igneous petrology
- Volcanology
- Paleo-climate
- Mineral Physics
- Geodynamics

Let us take a moment to recount some of Daly's thoughts and contributions to the subject of today's lecture.

On island arcs in subduction zones:

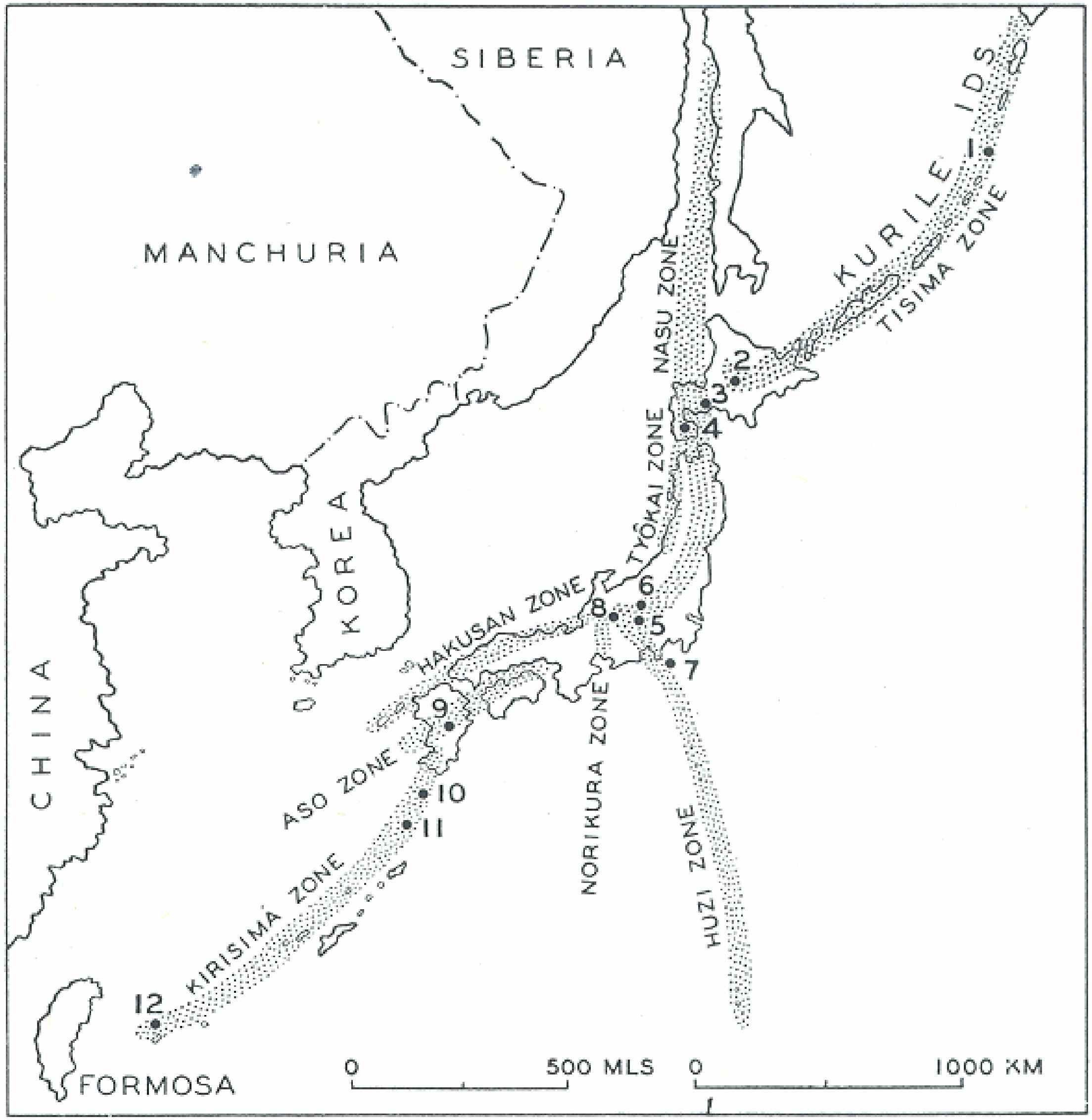


FIG. 74.—Neovolcanic cone chains of Japan and (numbered) localities of volcanic activity during the period 1924–1931. 1, Matuwa Zima; 2, Tokati Dake; 3, Tarumai San; 4, Komaga Take; 5, Asama Yama; 6, Kusatusirane; 7, Osima Mihara Yama; 8, Yake Dake; 9, Aso San; 10, Kutinoerabu Zima; 11, Suwanose Zima; 12, Hatoma Zima. (*After H. Tanakadate, Japanese Jour. Astr. and Geophysics, vol. 9, No. 1, 1931,*

Daly wrote about these features in his 1933 book “Depths of the Earth and Origin of Magmas”

“Each of these areal groupings of units clearly represents and important genetic problem”

He also endorsed DuToit’s theory of continental drift (1927)

On the importance of H_2O in magma generation:

Daly wrote the following about the solubility of H_2O in his 1933 book “Depths of the Earth and Origin of Magmas”

Between 500 bars and 2000 bars the solubility increases nearly as the *square root* of the pressure, a rule that applies also to the solubility

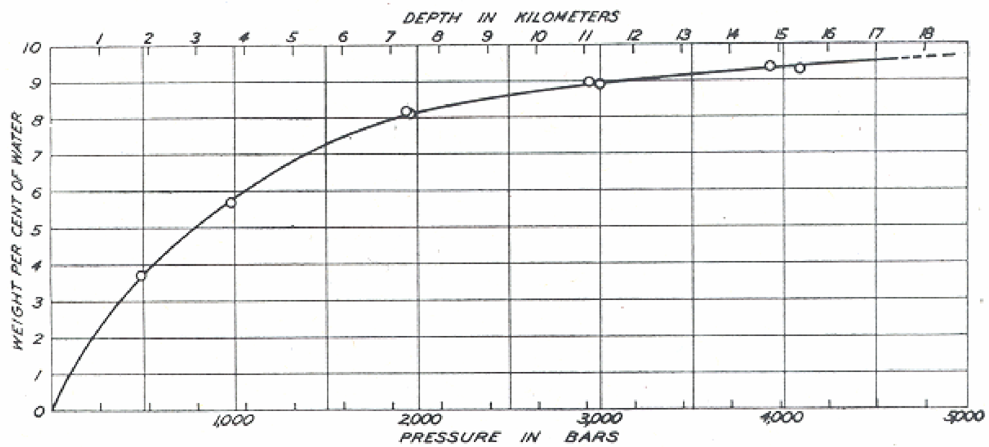


FIG. 123.—Solubility of water in granite glass, as a function of pressure within the earth at the 900° C. isotherm.

of hydrogen in some molten metals, within, however, a different range of pressures. Above 2000 bars the solubility of the water increased

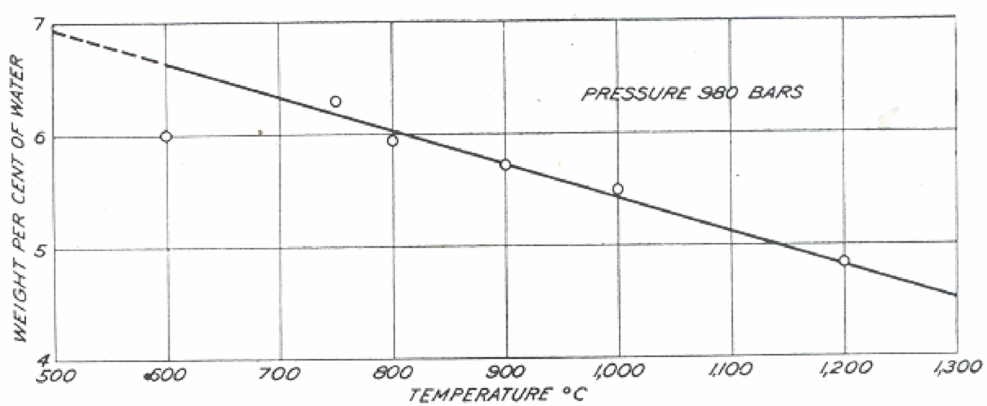


FIG. 124.—Solubility of water in granite glass, as a function of temperature at the pressure of 900 bars (metric atmospheres).

still more slowly with pressure. Goranson's pressure-solubility curve indicates at zero pressure an increase of solubility per bar of 0.0108 per cent of water. Extrapolation to 10,000 bars gives saturation at about 10 per cent of water by weight, instead of about 100 per cent as

He also noted:

“Other experiments are needed on the solubility of water in basic melts, these representing the dominant magmas in volcanoes of long life.”

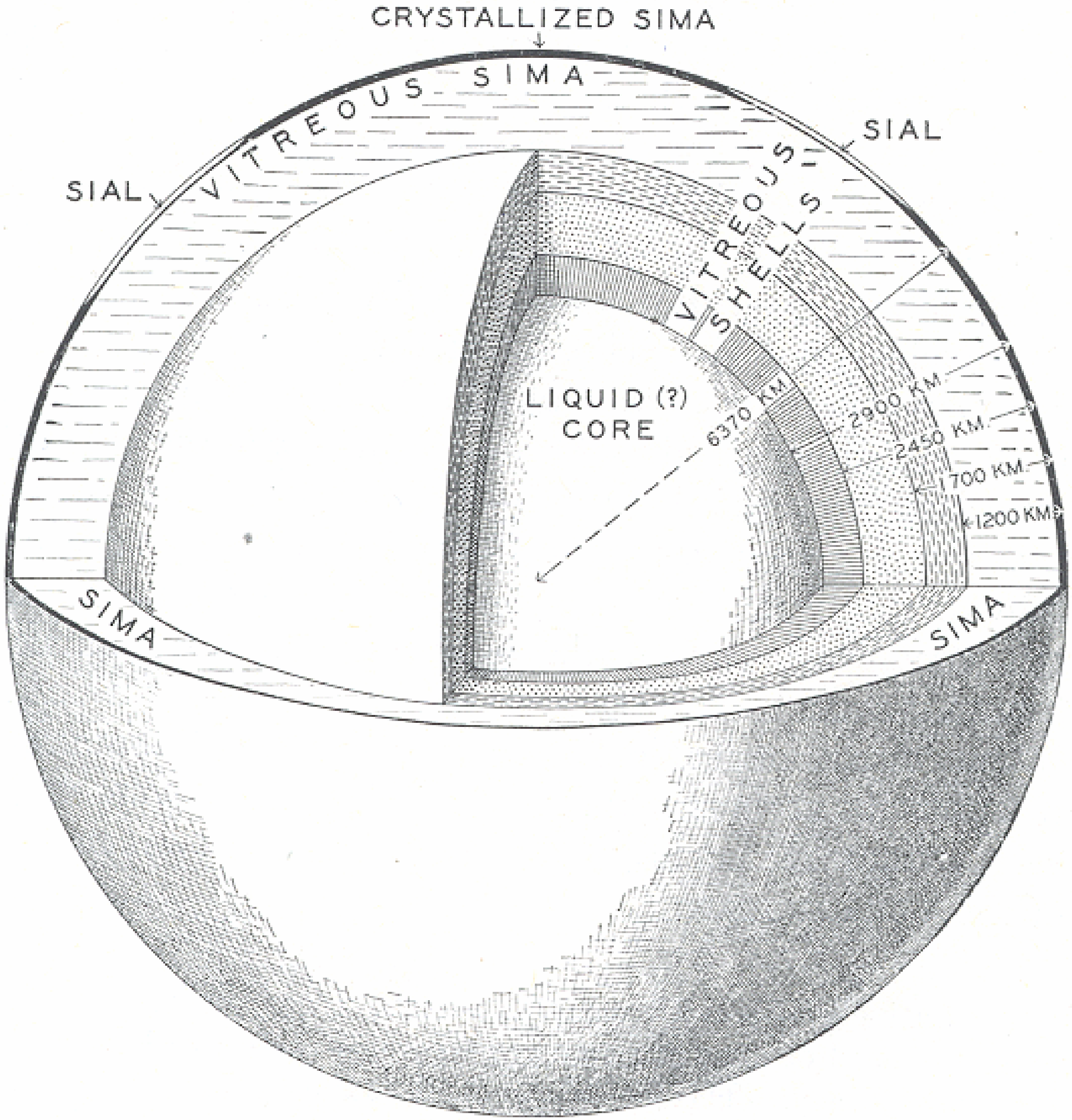


Fig. 91.—Diagram illustrating the shelled nature of the earth. The crystallized Sima below the Sial is thin; thicker elsewhere (heavier exterior line in the sections). Six discontinuities of material are shown, with shell thicknesses nearly to true scale. (*After E. A. Hodgson, Smithsonian Rep. for* 1931, *p.* 358.)

He also developed a theory of the characteristics of the Earth's deep interior structure –

"The Glassy Shells"

One of the first systematic efforts to relate geophysical measurements to Earth material properties

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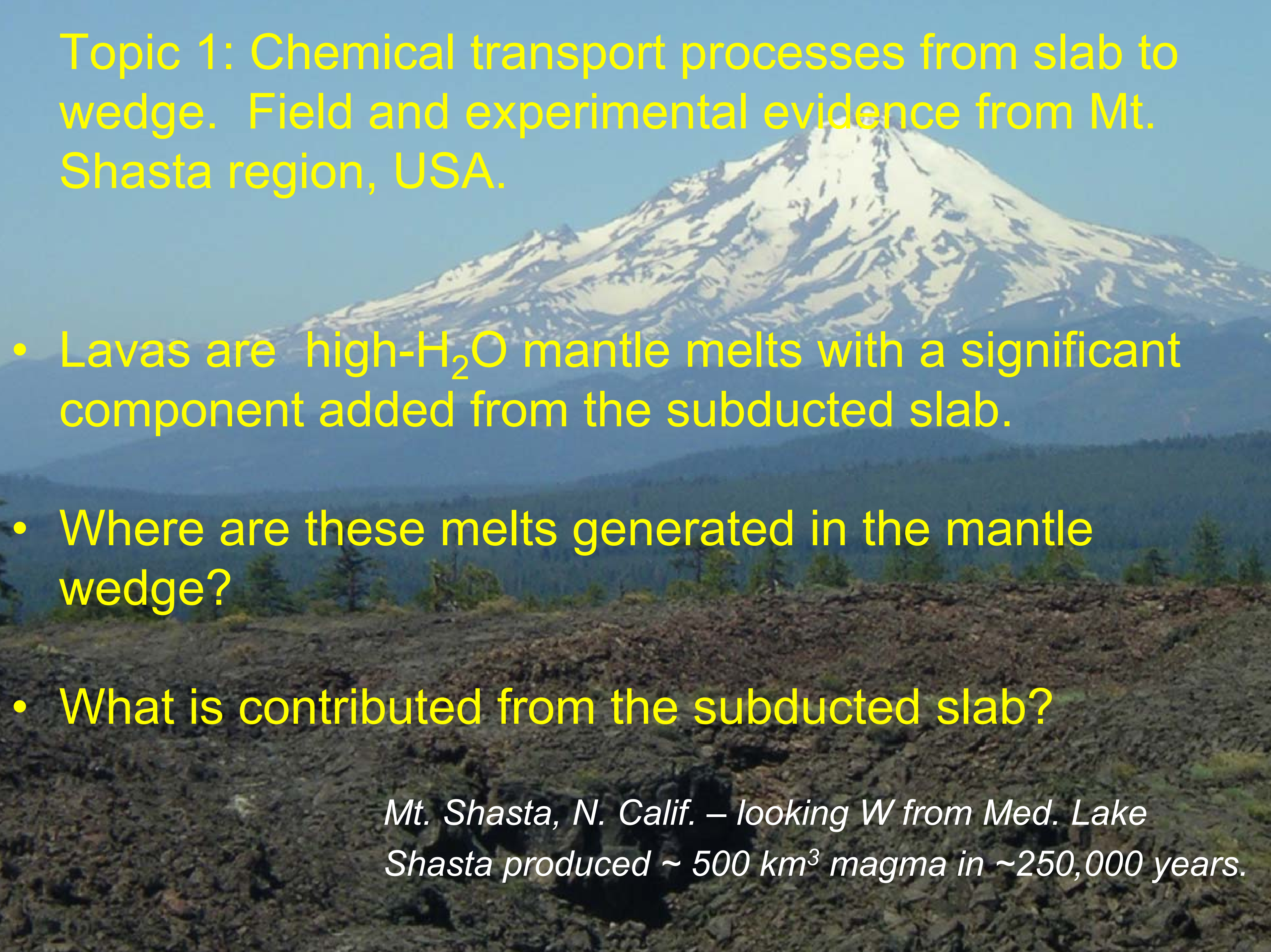
1) Chemical transport processes from subducted slab to the overlying wedge. Melting from top to bottom in the wedge. Field and experimental evidence.

2) Element transport from slab to wedge > Melts? Fluids ? Or more complex processes?

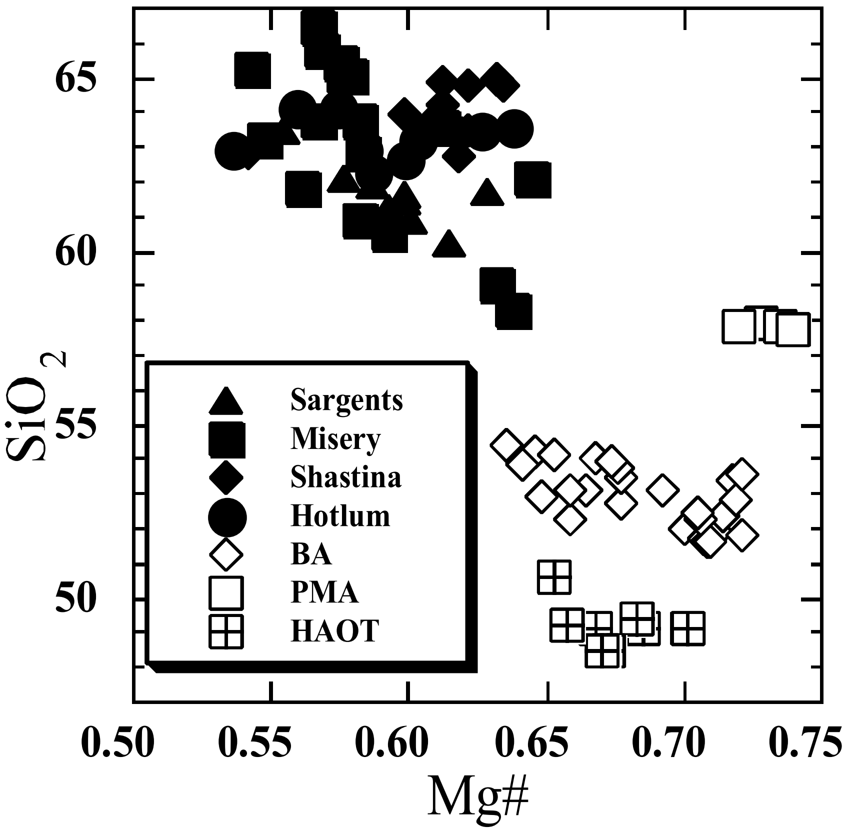
3) Insights into subduction zone processes. New experimental constraints.

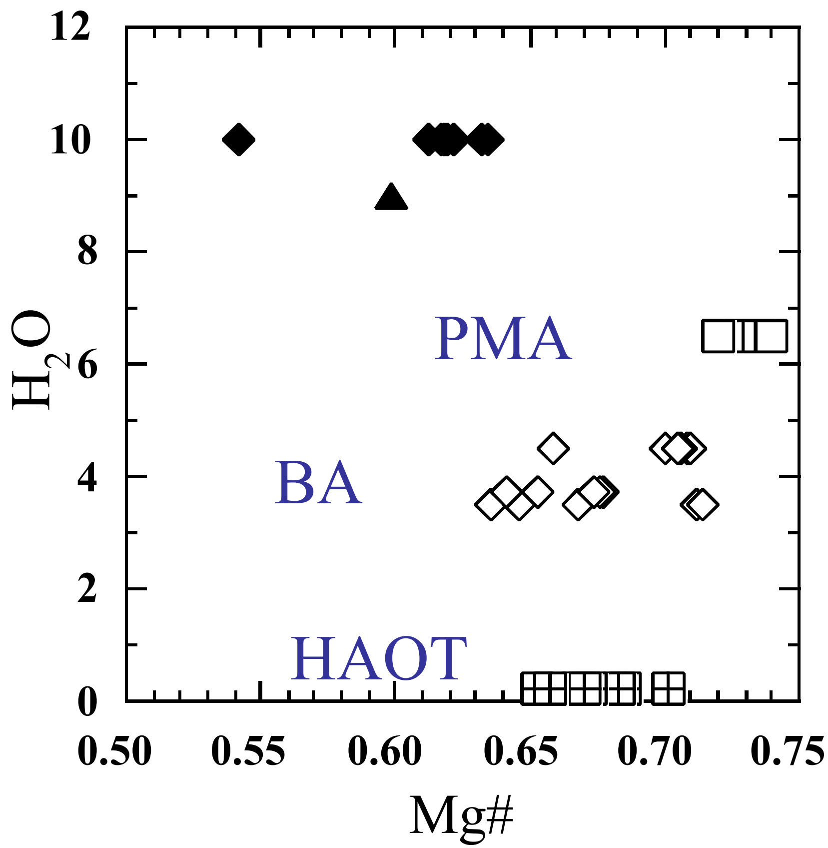


Mt. Shasta, N. Calif. – looking W from Med. Lake
Shasta produced ~ 500 km^3 magma in ~250,000 years.

Major elements and H_2O

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





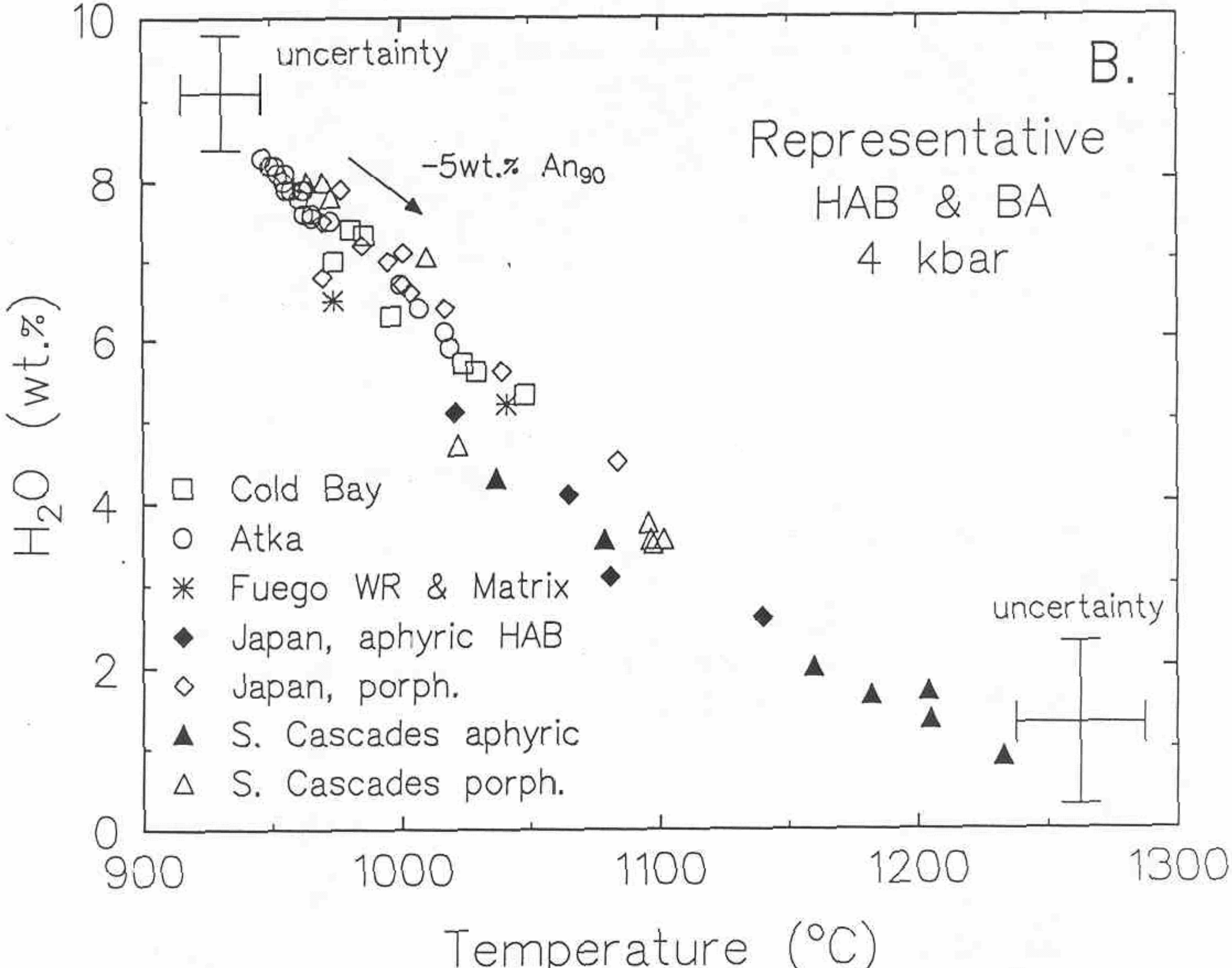
Estimates of Pre-eruptive H_2O

- H_2O solubility in silicate melts is P-dependent and goes to ~ 0 at P = 1 bar.

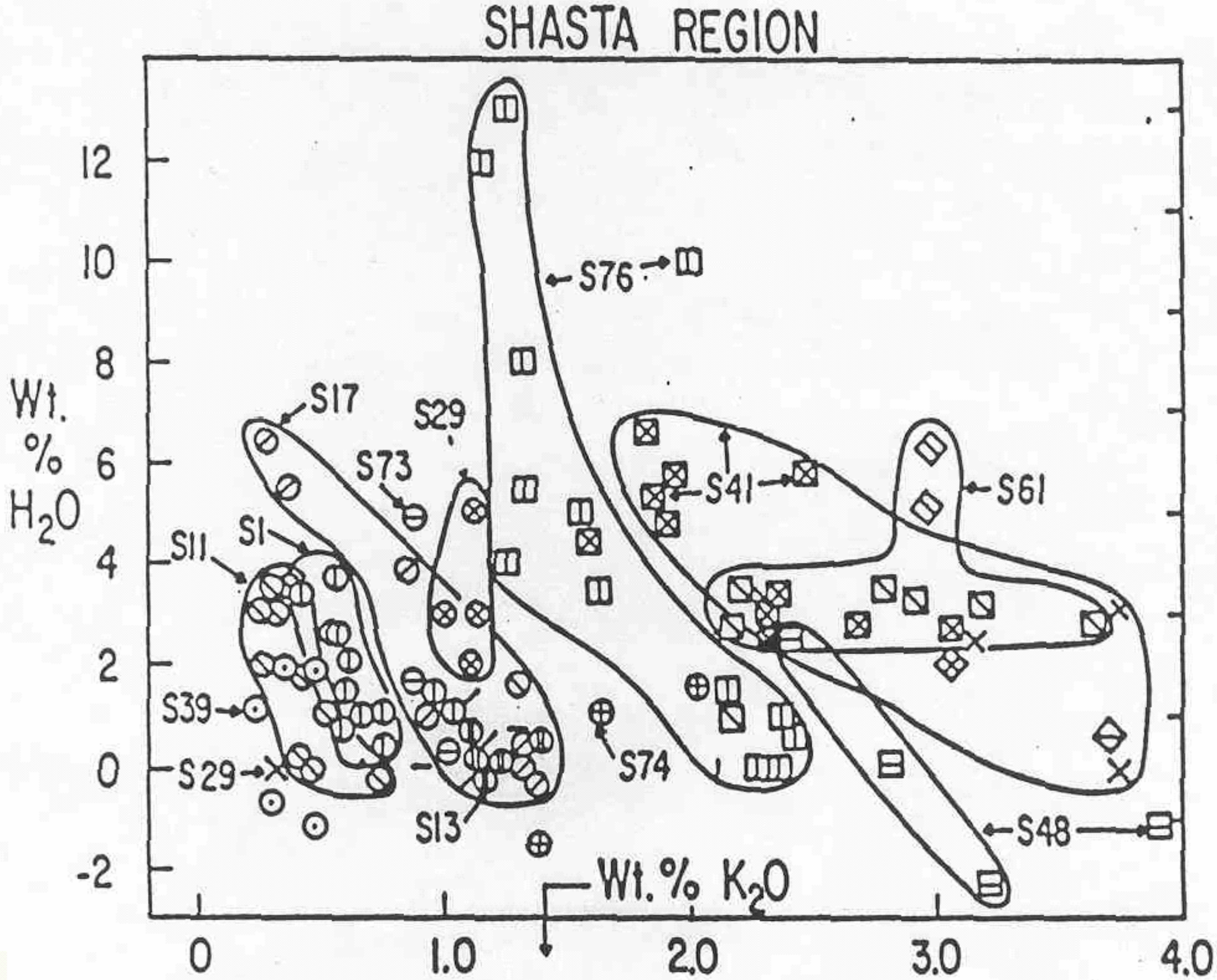
- So, H_2O is often lost as a gas phase

- 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.

Sisson & Grove (1993)



Estimation of pre-eruptive H_2O content

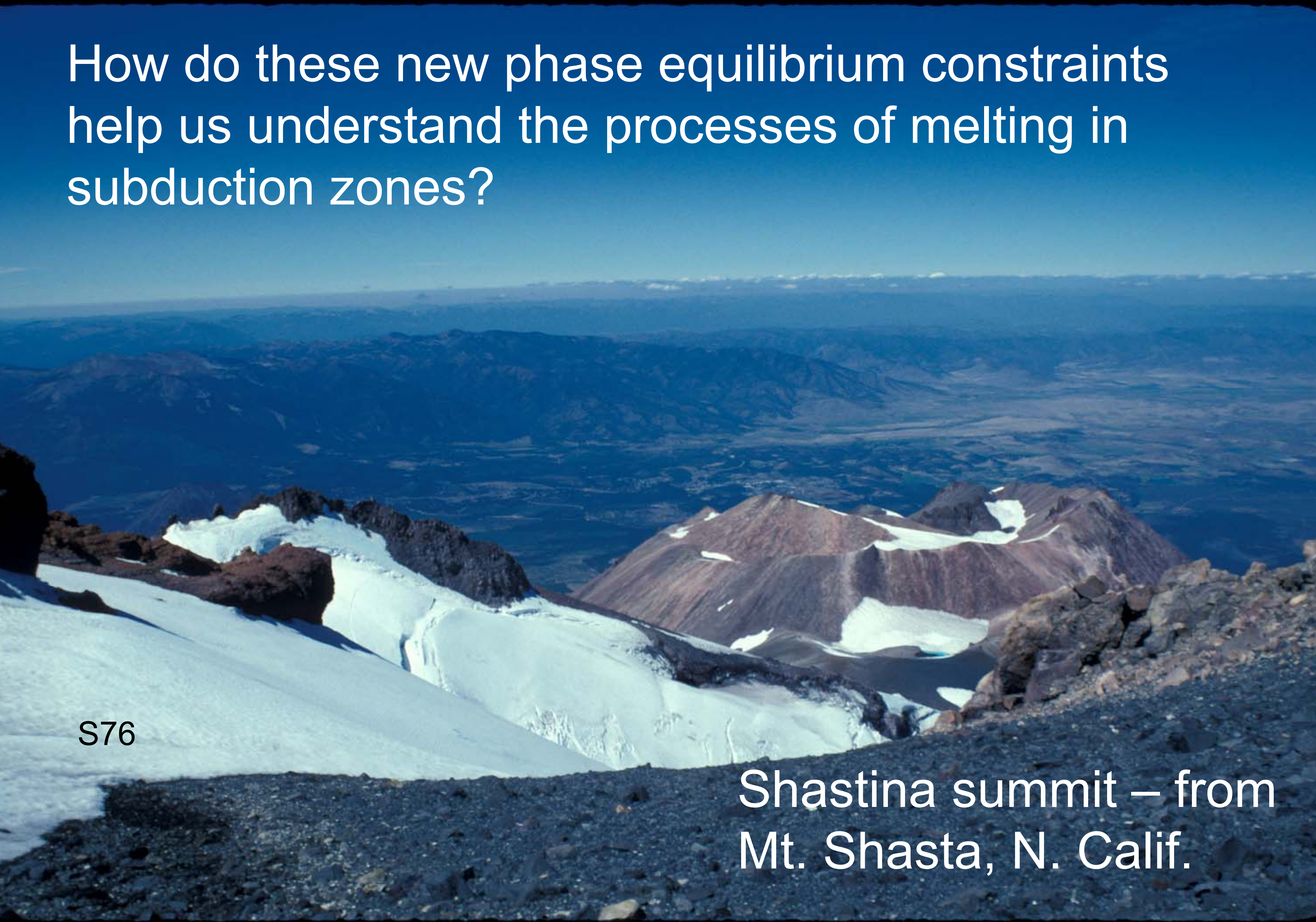


Direct measurement of H_2O in Shasta melt inclusions (Anderson, 1979).

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.

How do these new phase equilibrium constraints help us understand the processes of melting in subduction zones?

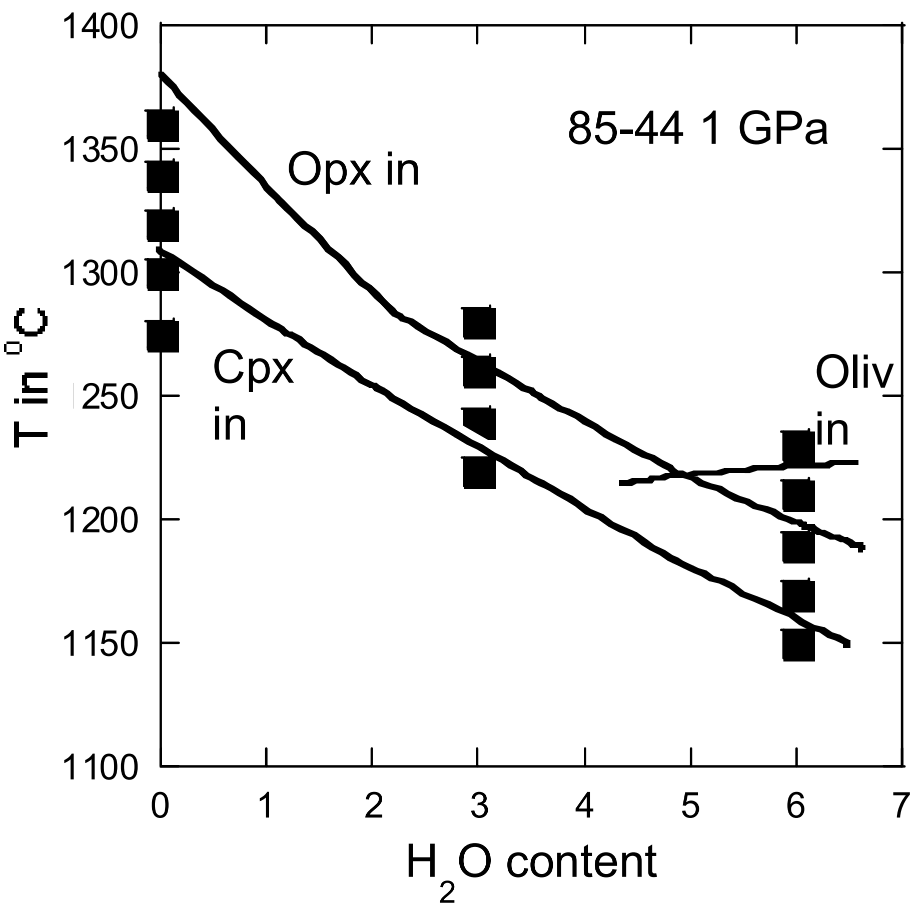


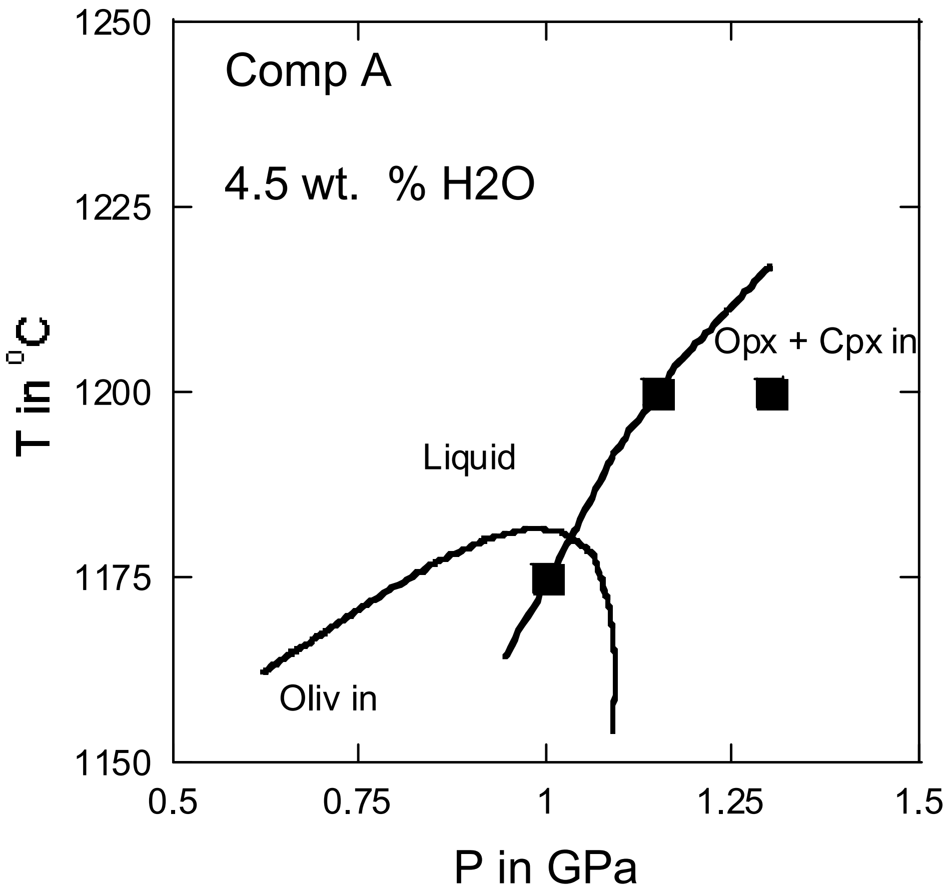
S76

Shastina summit – from Mt. Shasta, N. Calif.


Cinder Cone
Basaltic Andesite –
85-44 and S-1

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





Topic 2: Estimating the chemical composition of the fluid-rich component.

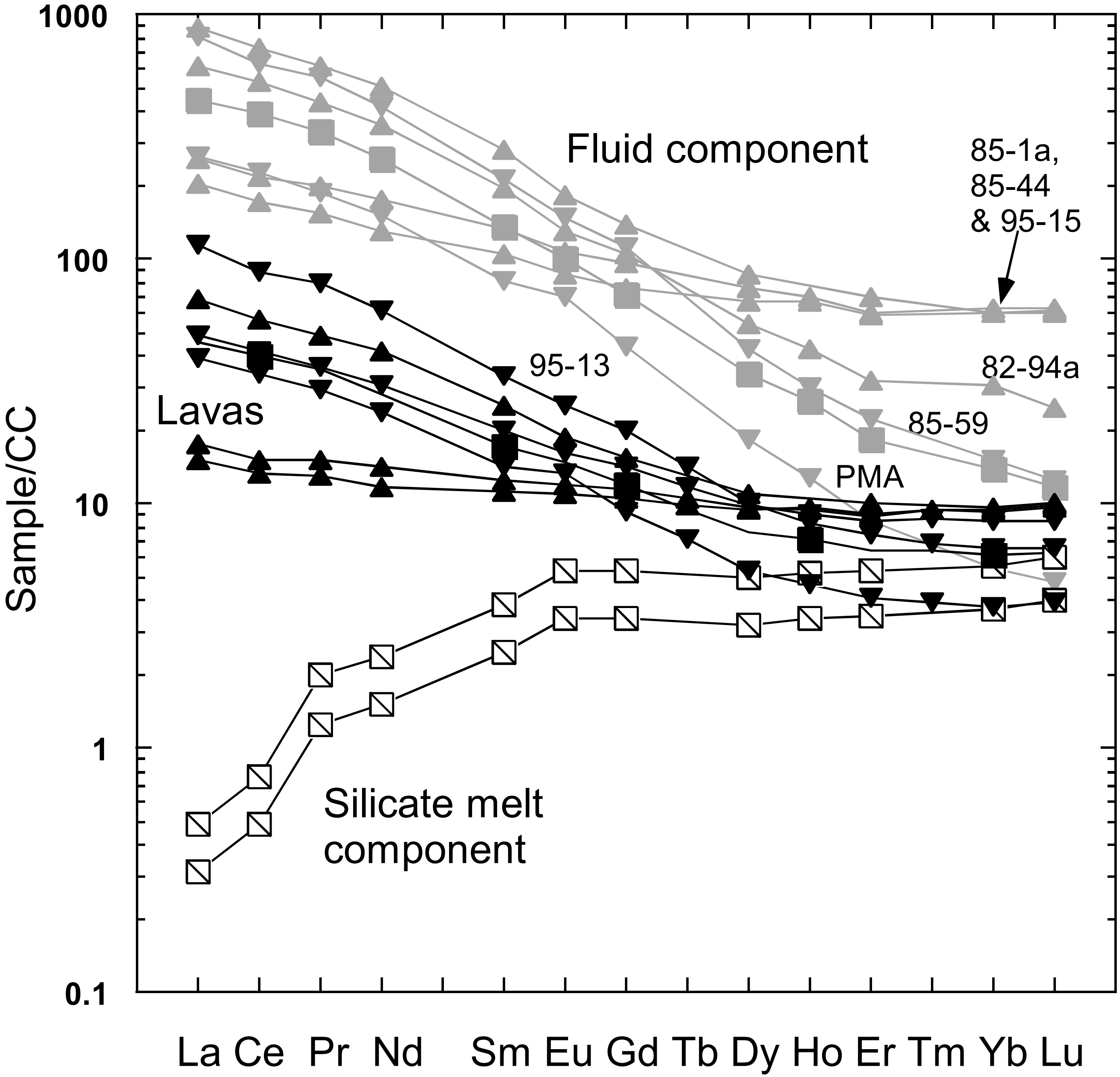
- We will model this by assuming 2 components: 1) a silicate melt from a harzburgite residue (wedge) 2) a fluid-rich component from the subducted lithosphere (slab).
- Use mass balance. Calculate elemental contribution from mantle melting
- Use H_2O content of lava to estimate the composition of the H_2O-rich component.

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

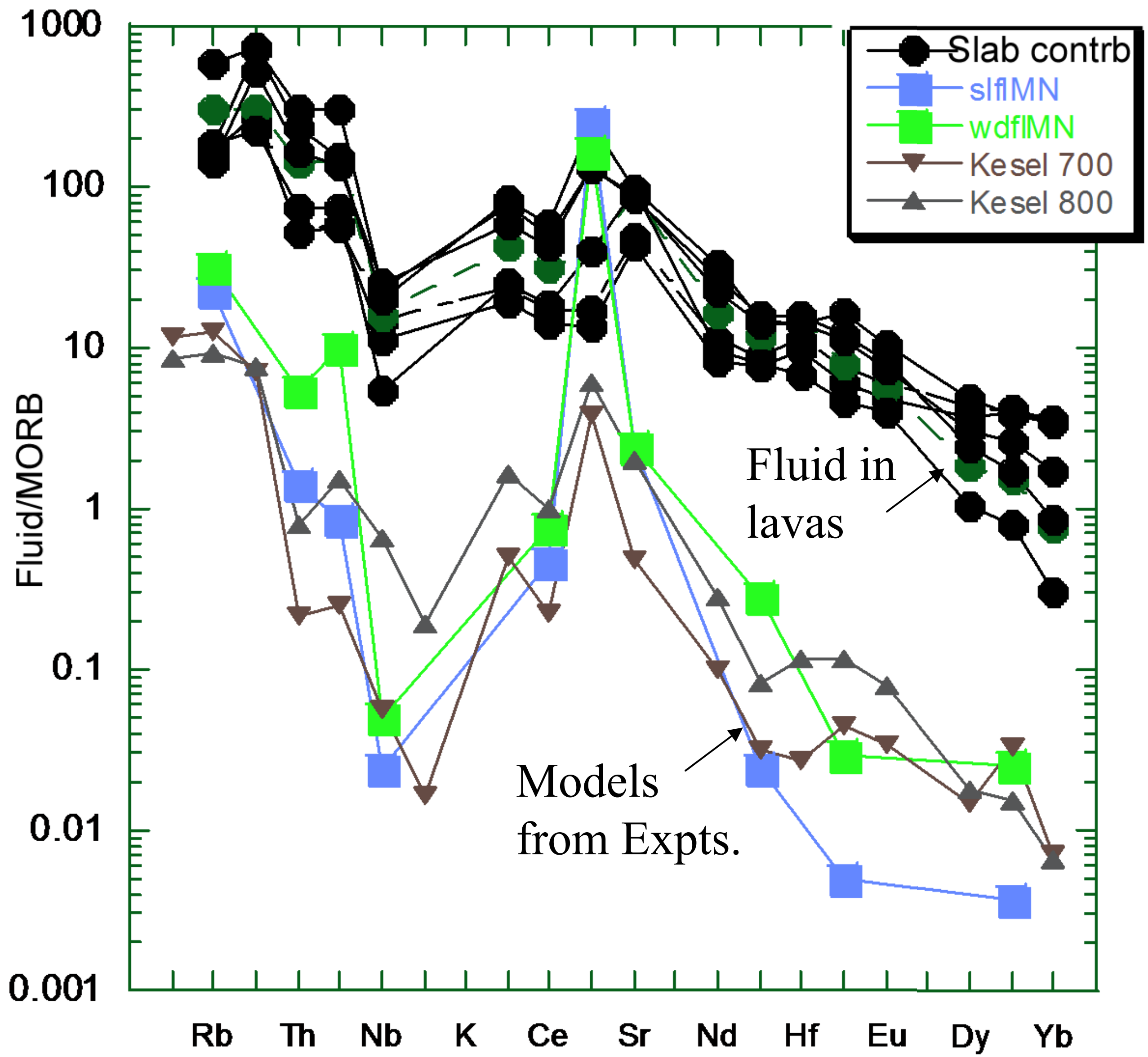
Silicate melt of mantle = open square.

Note the dichotomy in La/Sm_N

and

Dy/Yb_N

H_2O-rich component a fluid? No…



Estimated fluid-rich component (black circles)

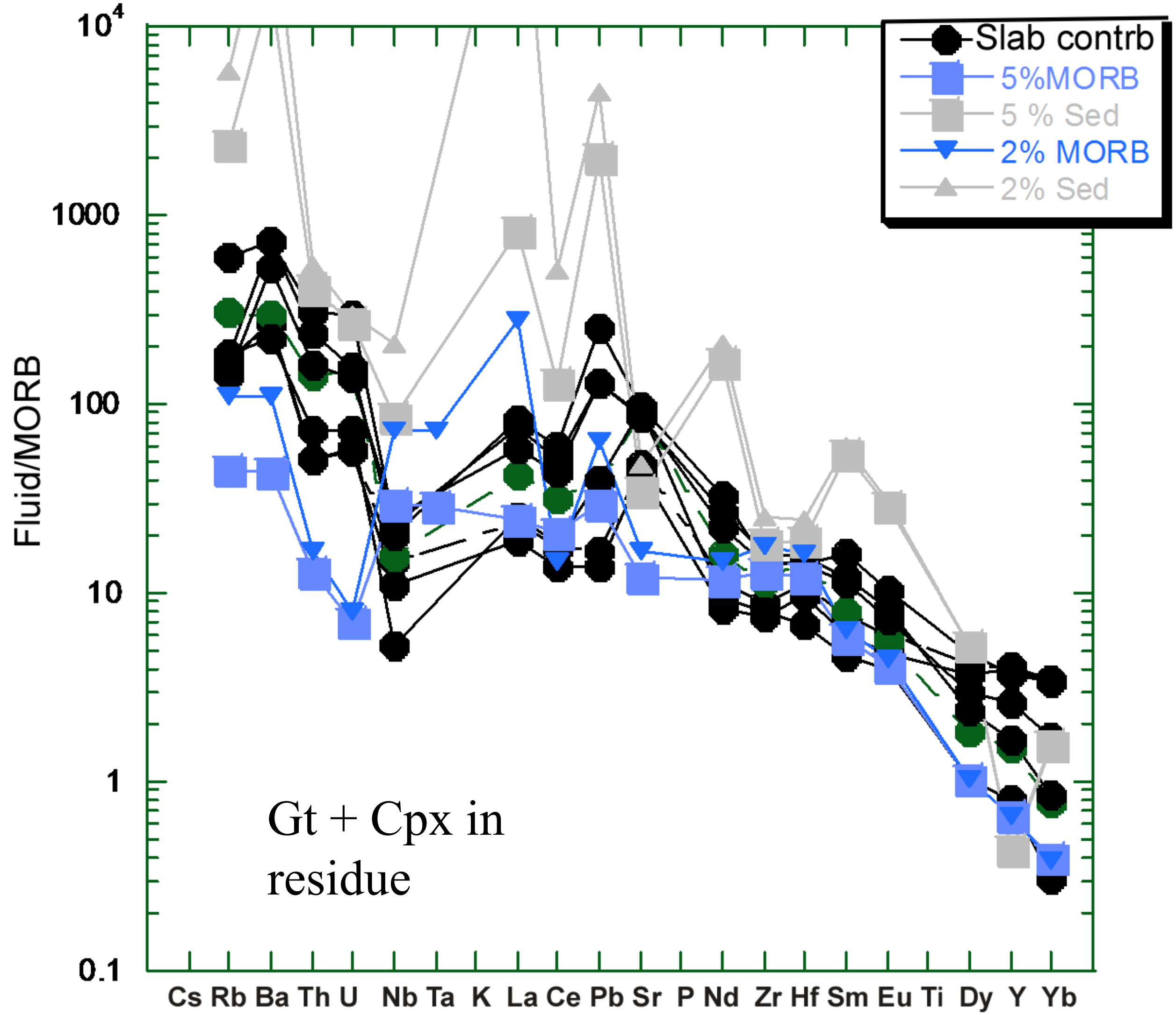
Least similar to a hydrous fluid saturated with eclogitic residue

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….

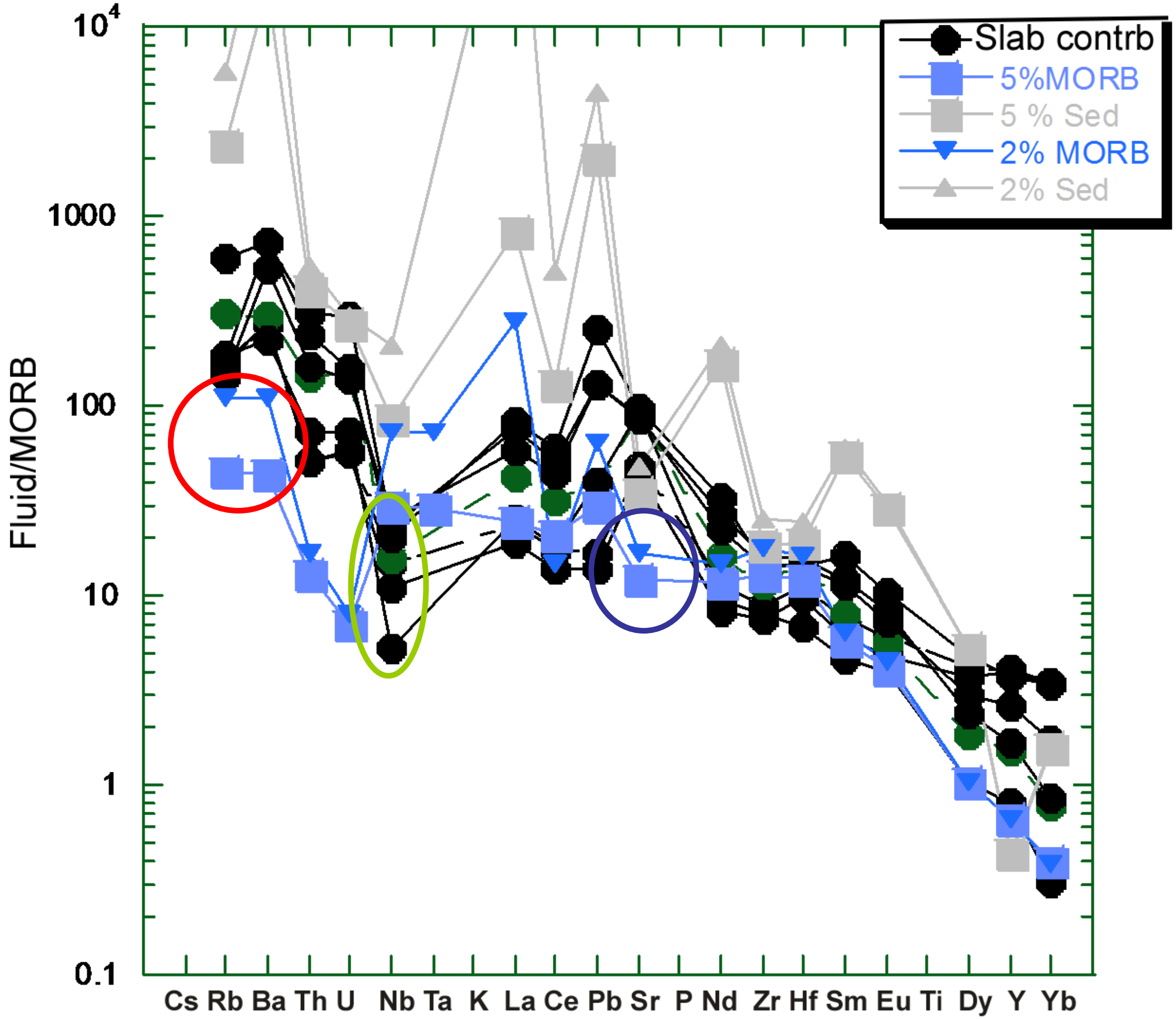


Estimated fluid-rich component (black circles)

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

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

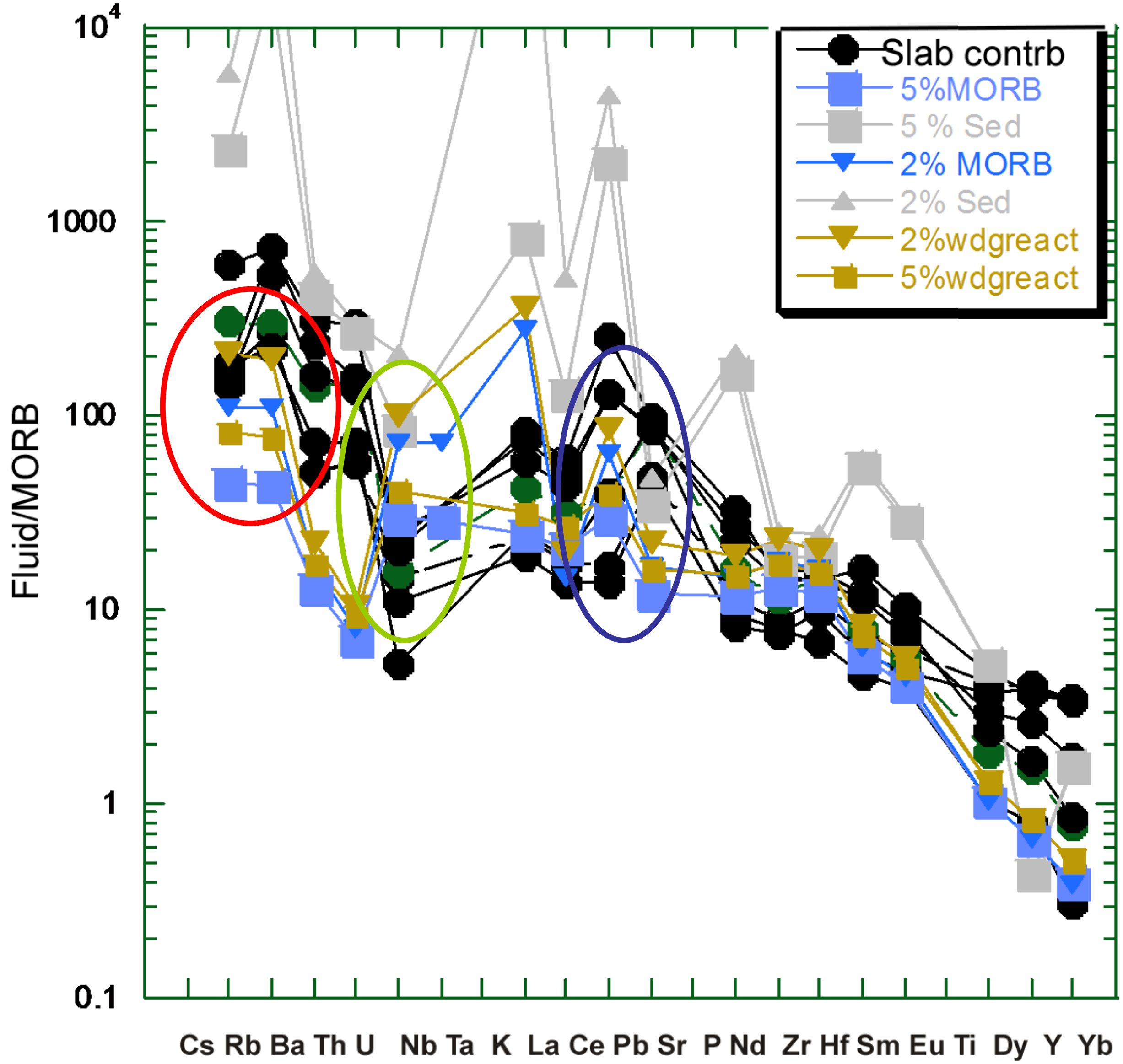
- SiO_2 solubility in an H_2O-rich fluid will be low -Zhang & Franz (2000) Newton and Manning (2003)

  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.

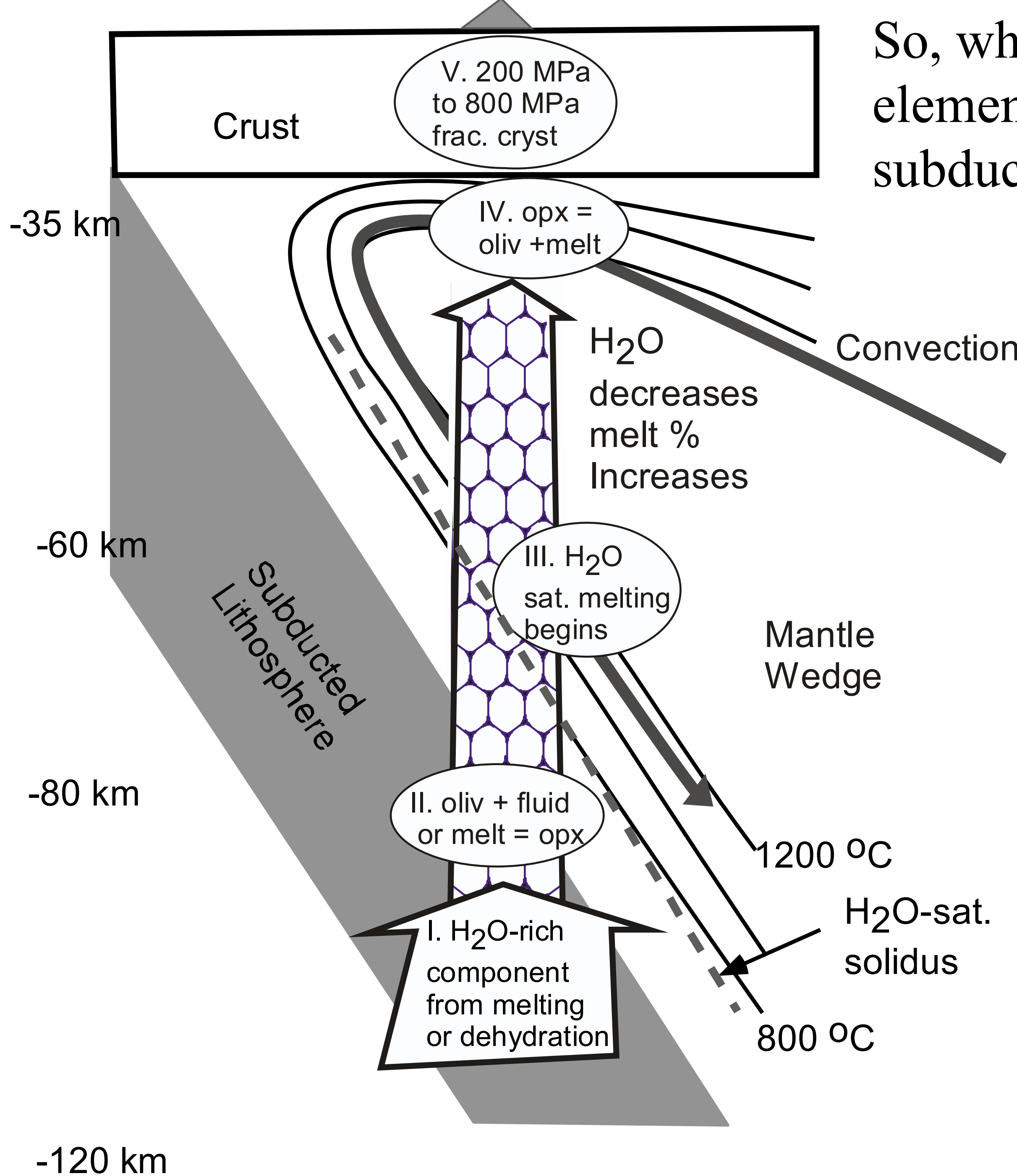


Brown symbols show effect of wedge peridotite + slab melt interaction at base of wedge using reaction inferred by Bell et al. (2005).

highly incompatible elements -better

HFSE -worse

Fluid mobile - better



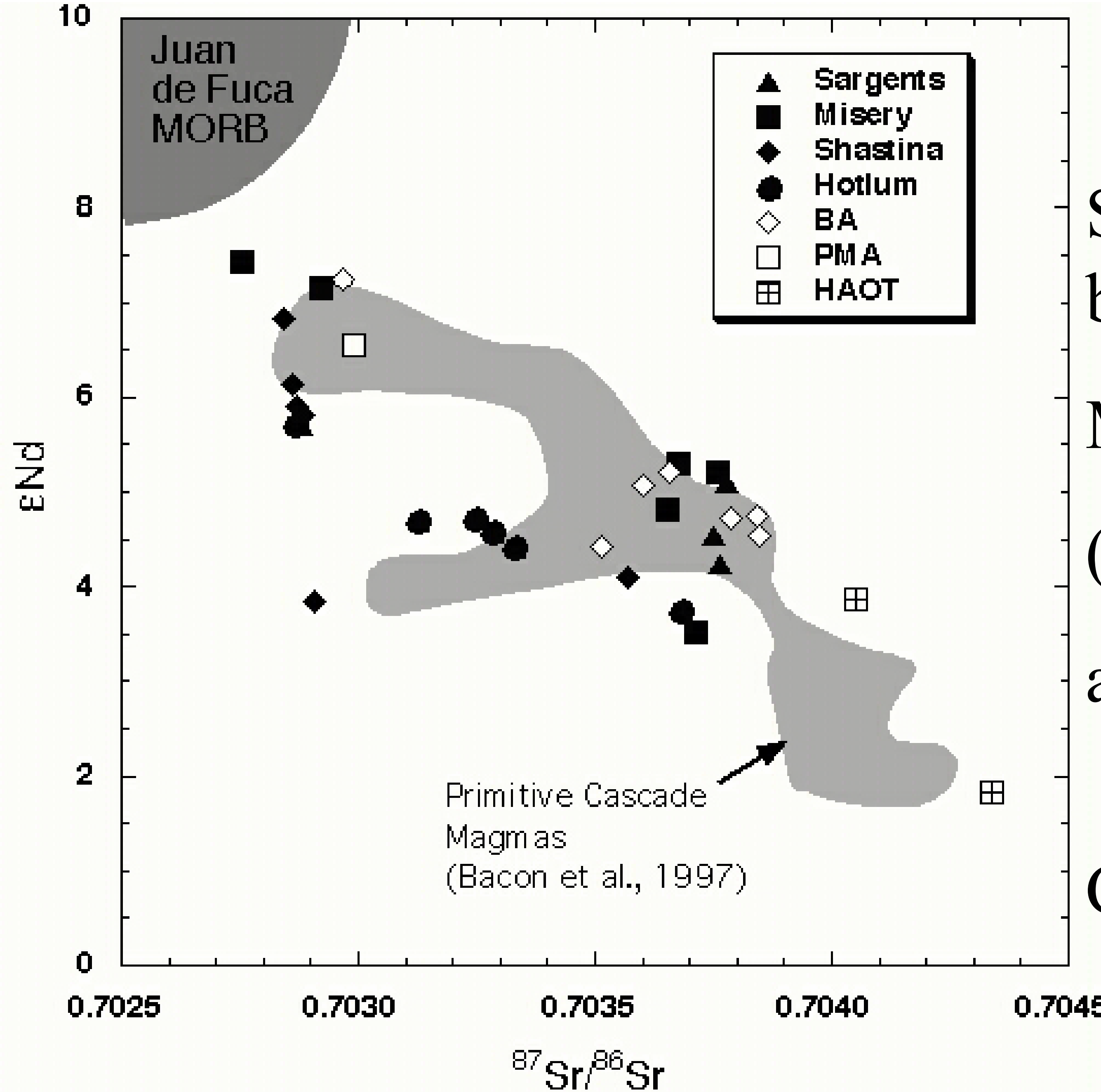
So, what medium transfers elements from hot, young subducted lithosphere?

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.



Signatures of both:

MORB

(High La/Sm)

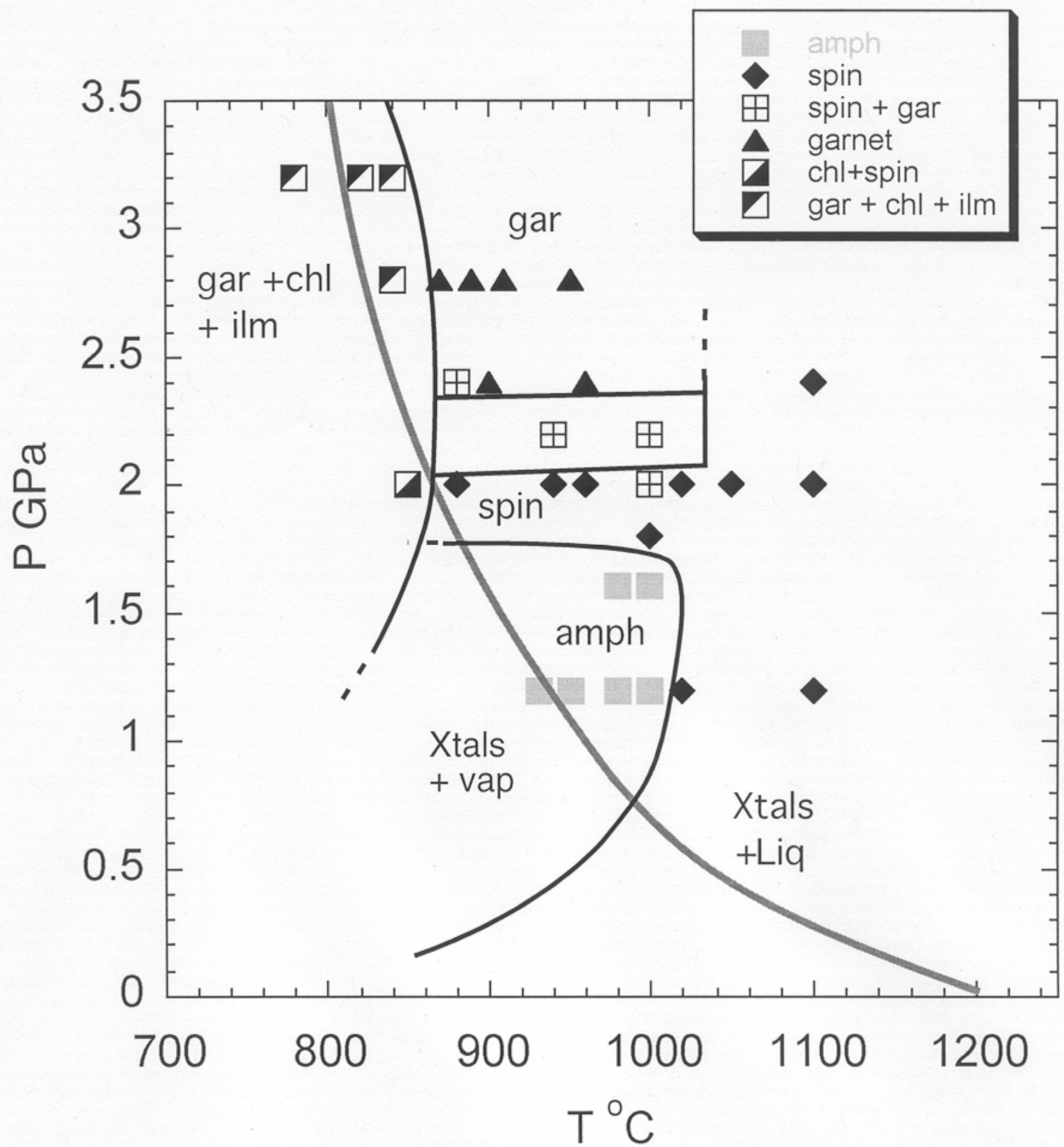
and

Sediment Components

Topic 3: New experimental constrainst on subduction zone melting processes.

- Can the slab and the wedge BOTH melt?
- Can we understand the high pre-eruptive H_2O contents of arc magmas?

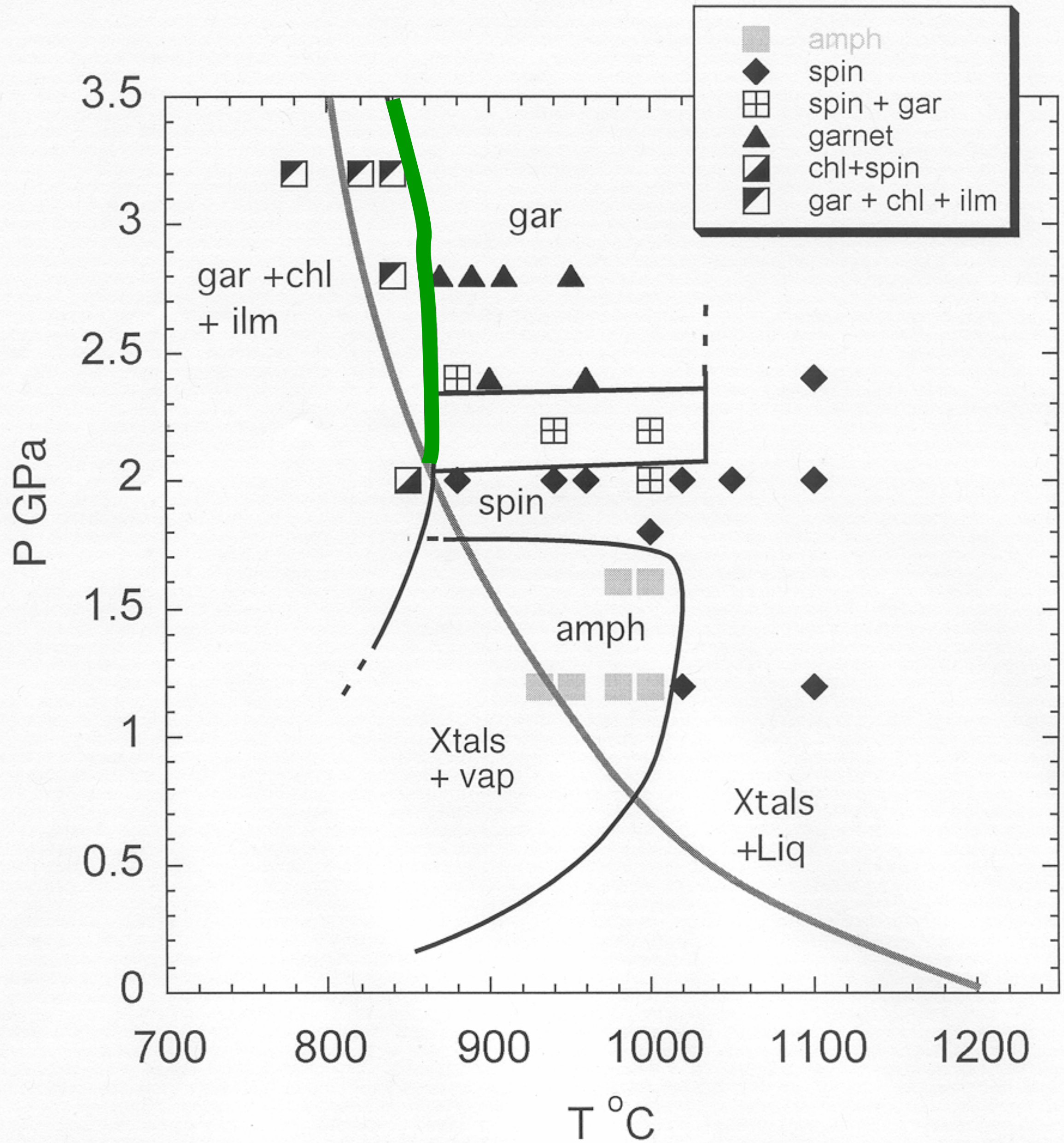
Mt. Shasta, . Calif. – looking South from US 97.



3) New 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.



Chlorite on the vapor - saturated solidus

– a way to transport H_2O deep into the wedge

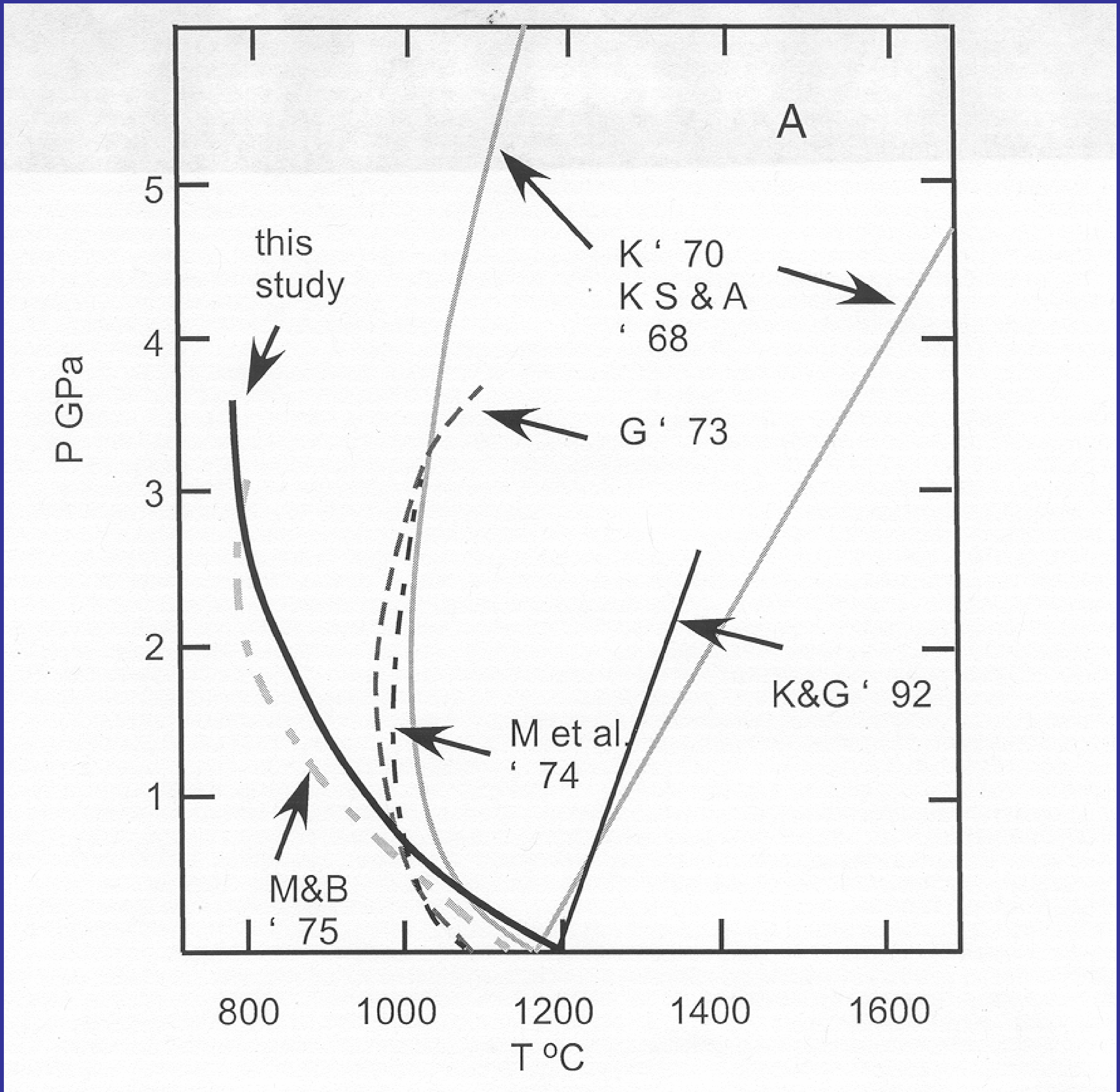
Also, Ilmenite,

Rutile &

Ti-clinohumite

are stable.

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

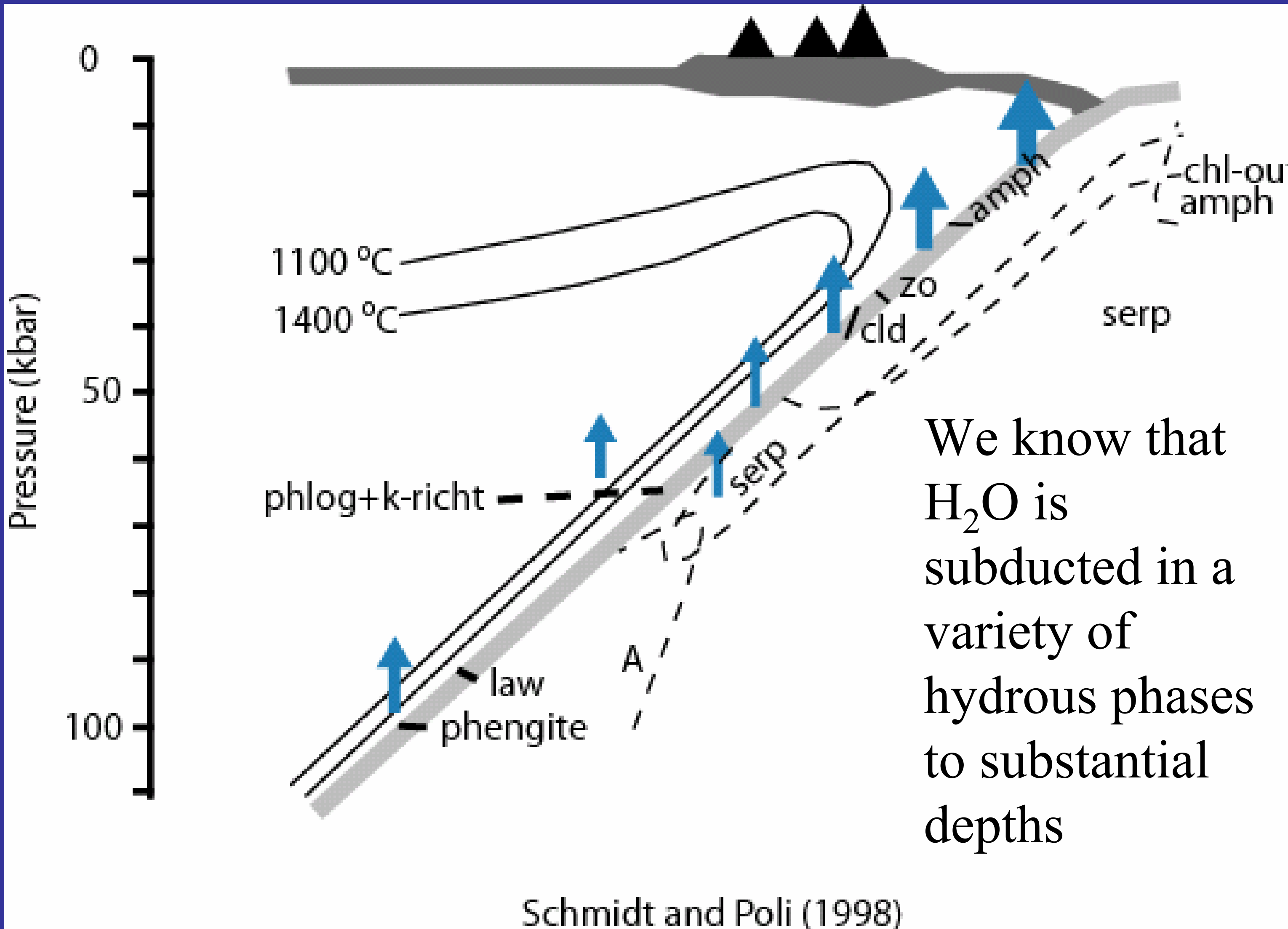


Olivine melting rate is slower than that of pyroxene

-Olivine also melts at a lower Temperature by about 200 ºC

- In the short run time expts pyroxene melted first

Serpentine and chlorite dehydration as a source for H_2O.

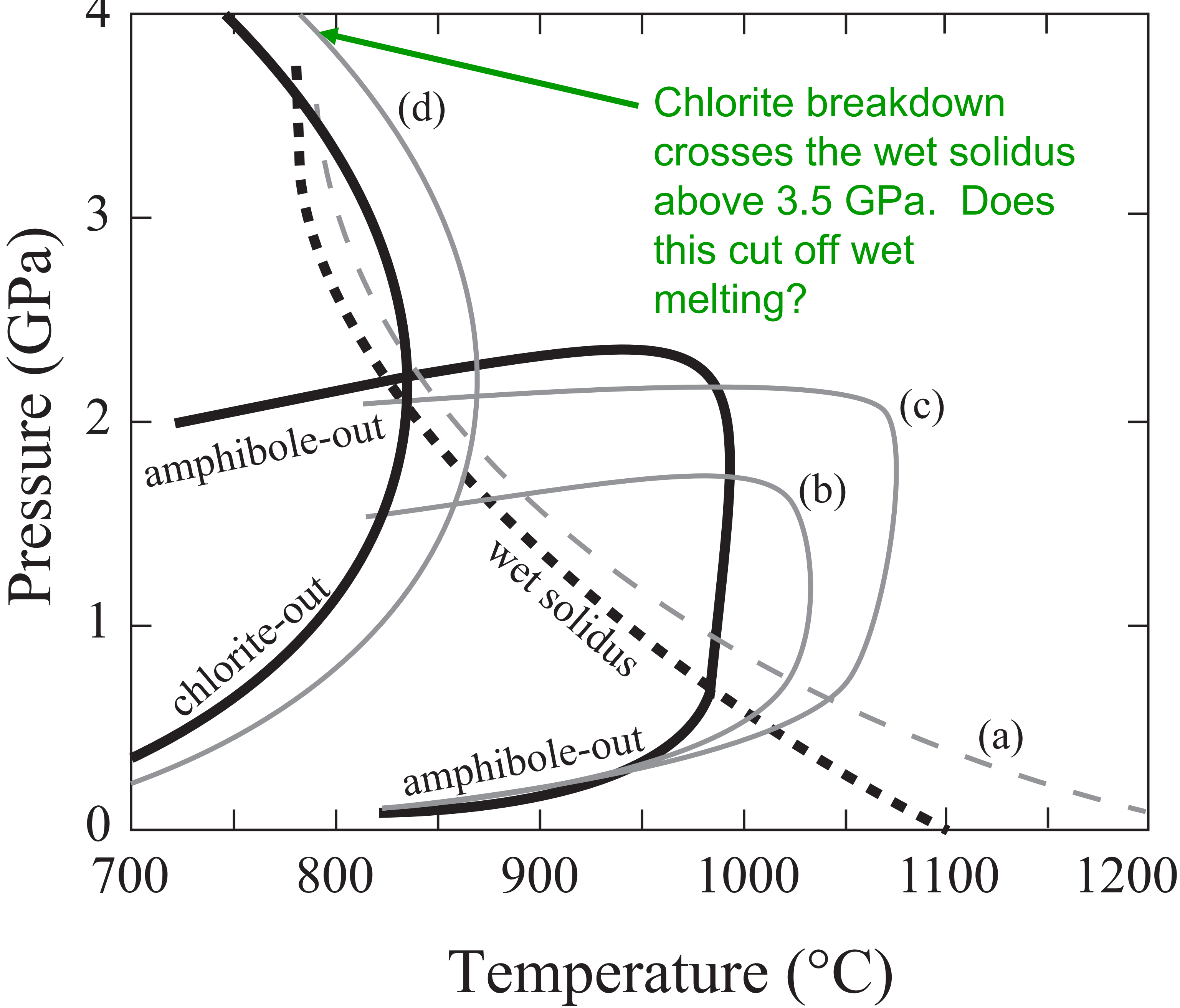


Schmidt and Poli (1998)

We know that H_2O is subducted in a variety of hydrous phases to substantial depths

How do these phases interact with the wet peridotite solidus?

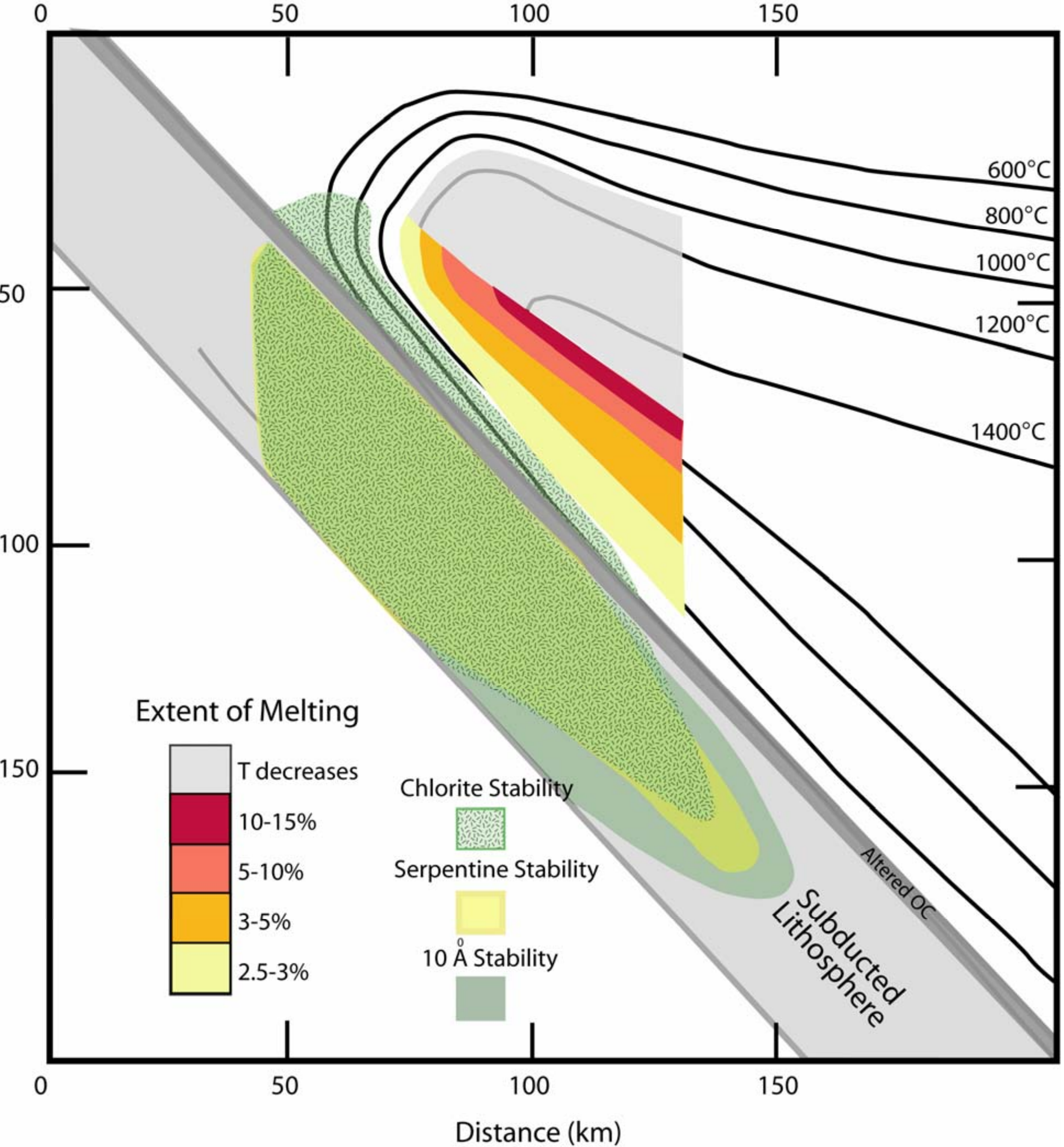
Medard & Grove (2006), Fumigali & Poli (2005), Pawley (2003)



Black is Martian mantle

Grey is Earth's mantle

Where is water stored in the wedge? Thermal model of Kelemen et al. (2003)



Hydrous phases in the mantle wedge & subducted slab.

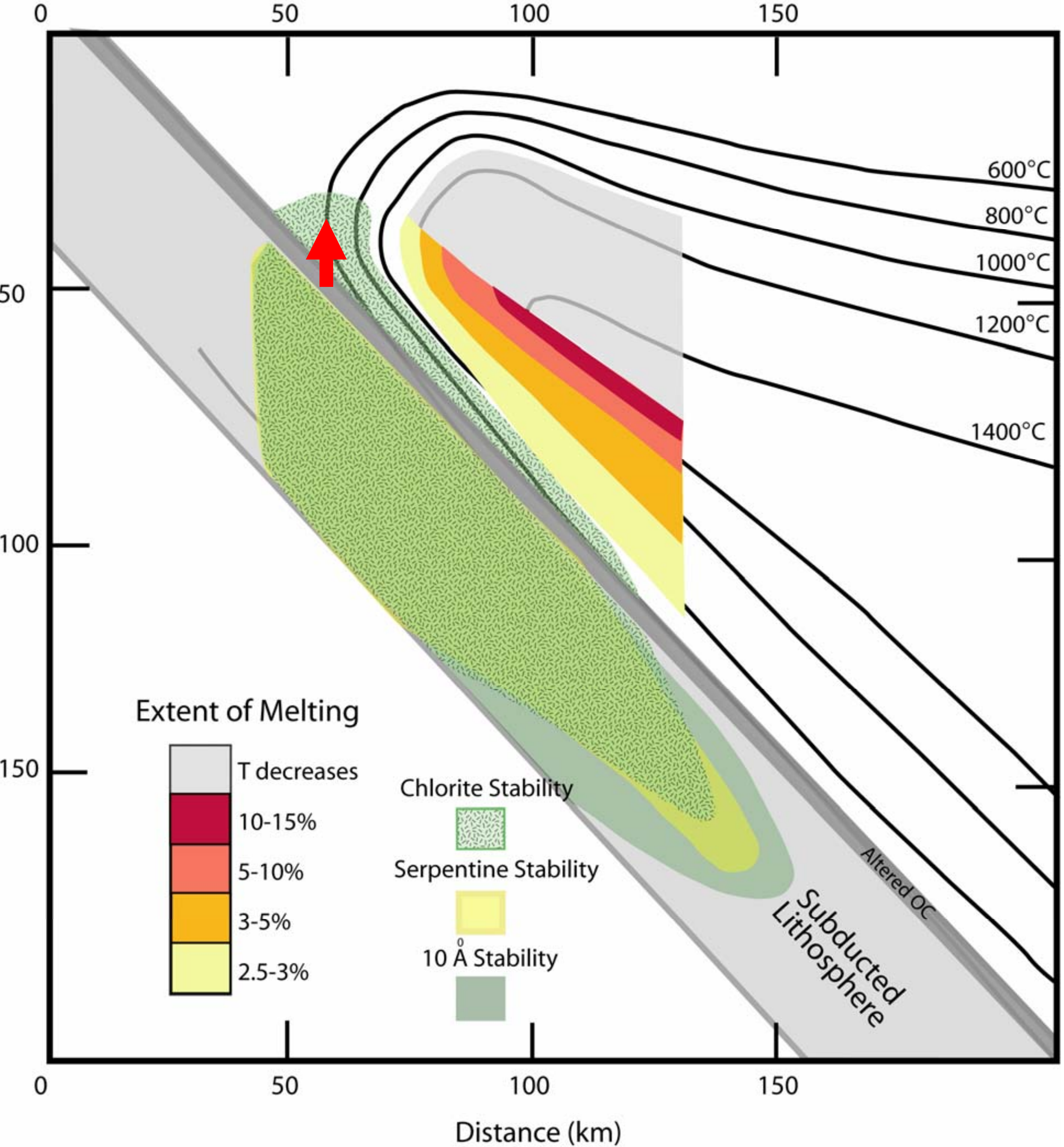
Chlorite provides a source of H_2O for wet arc melting that is above the slab.

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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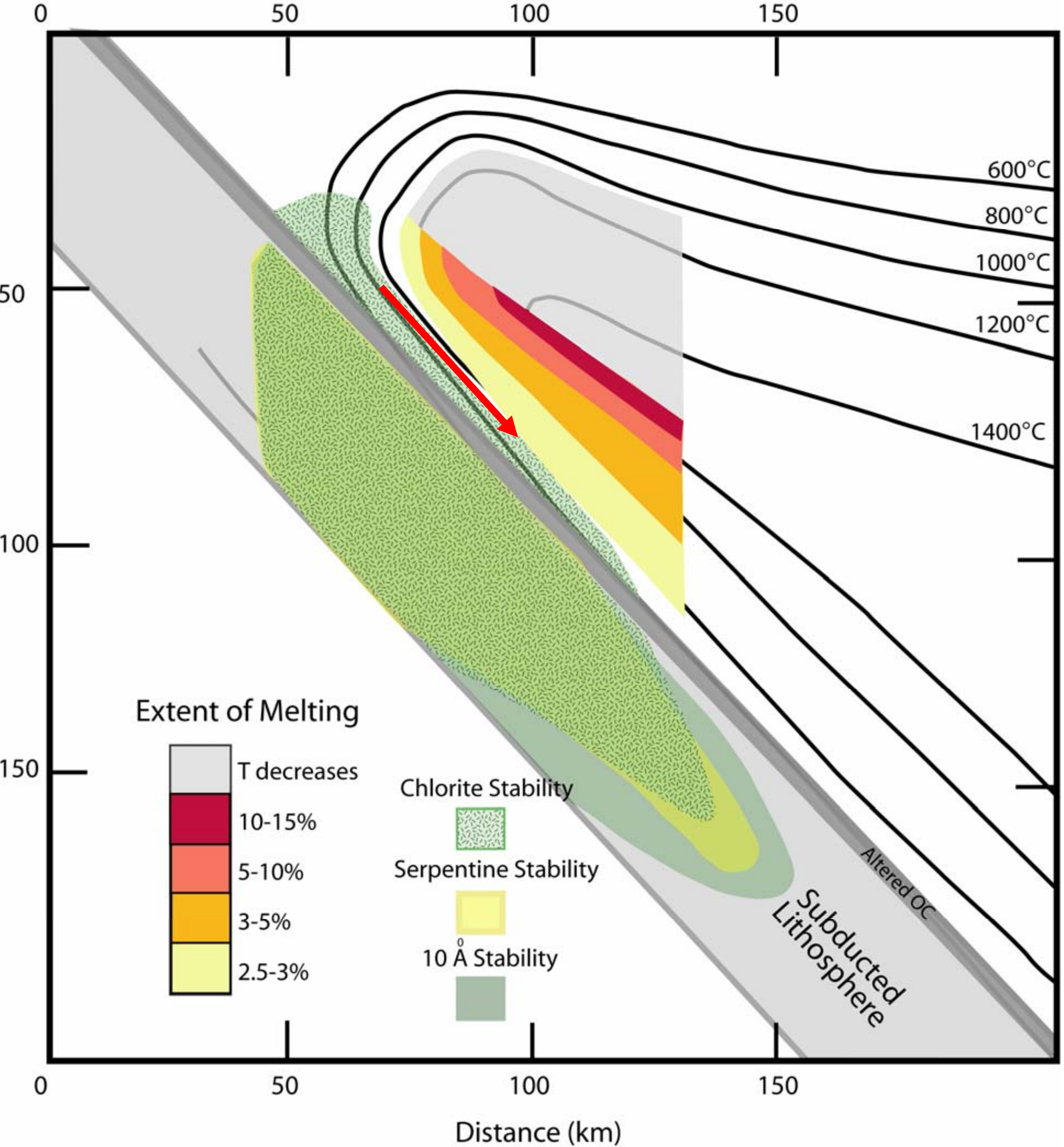

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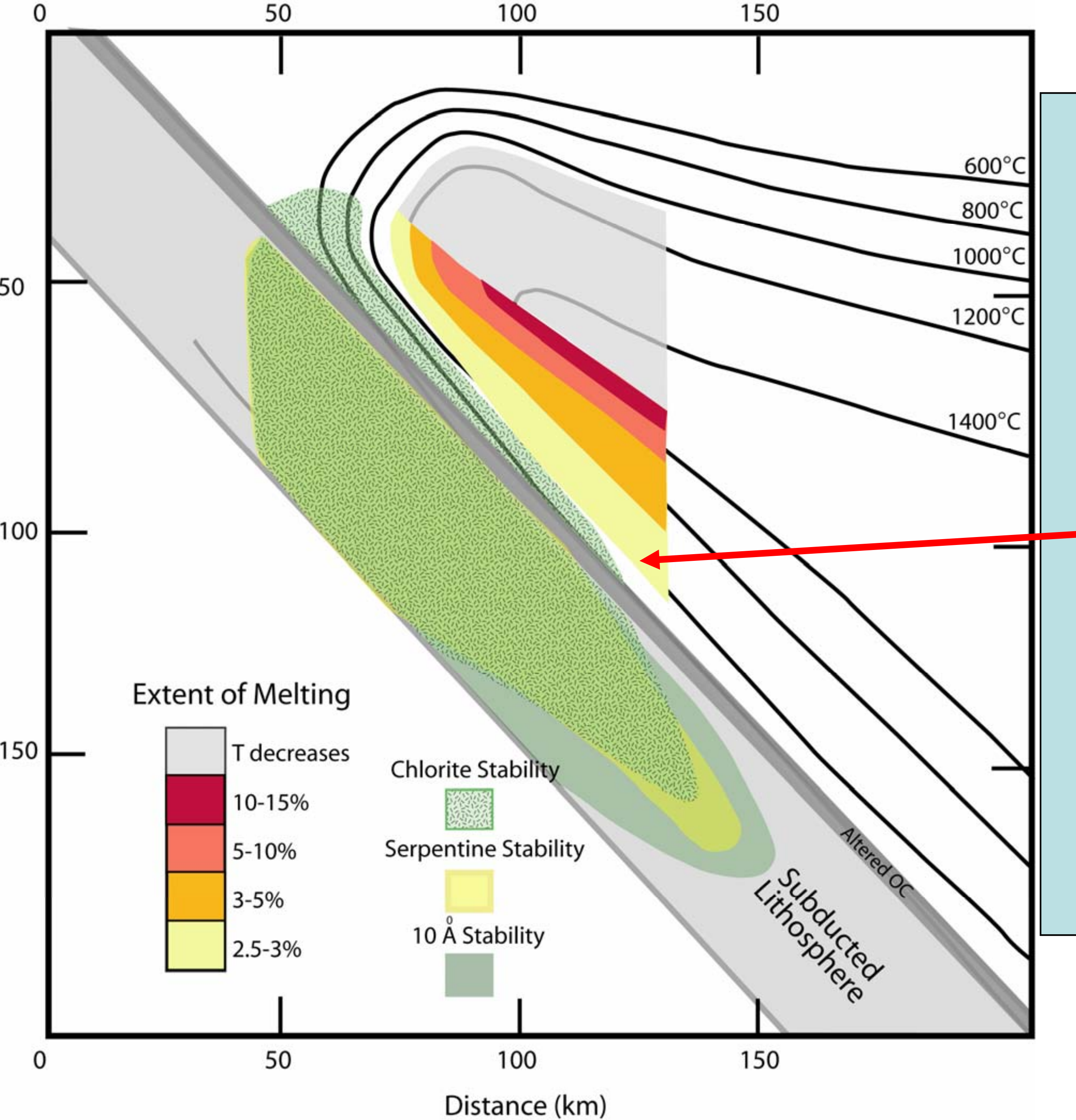
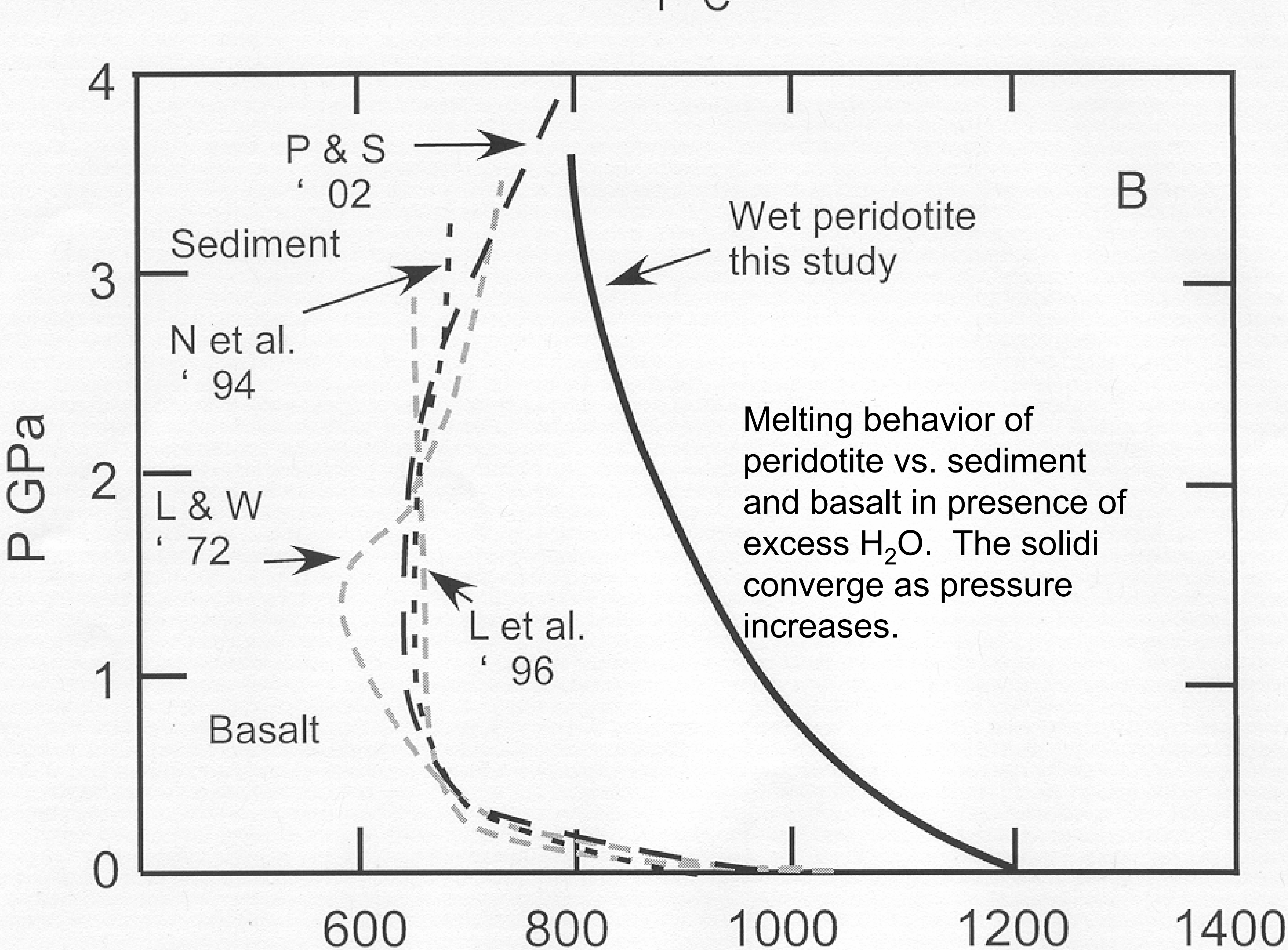


Chlorite breaks down as pressure increases.

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.



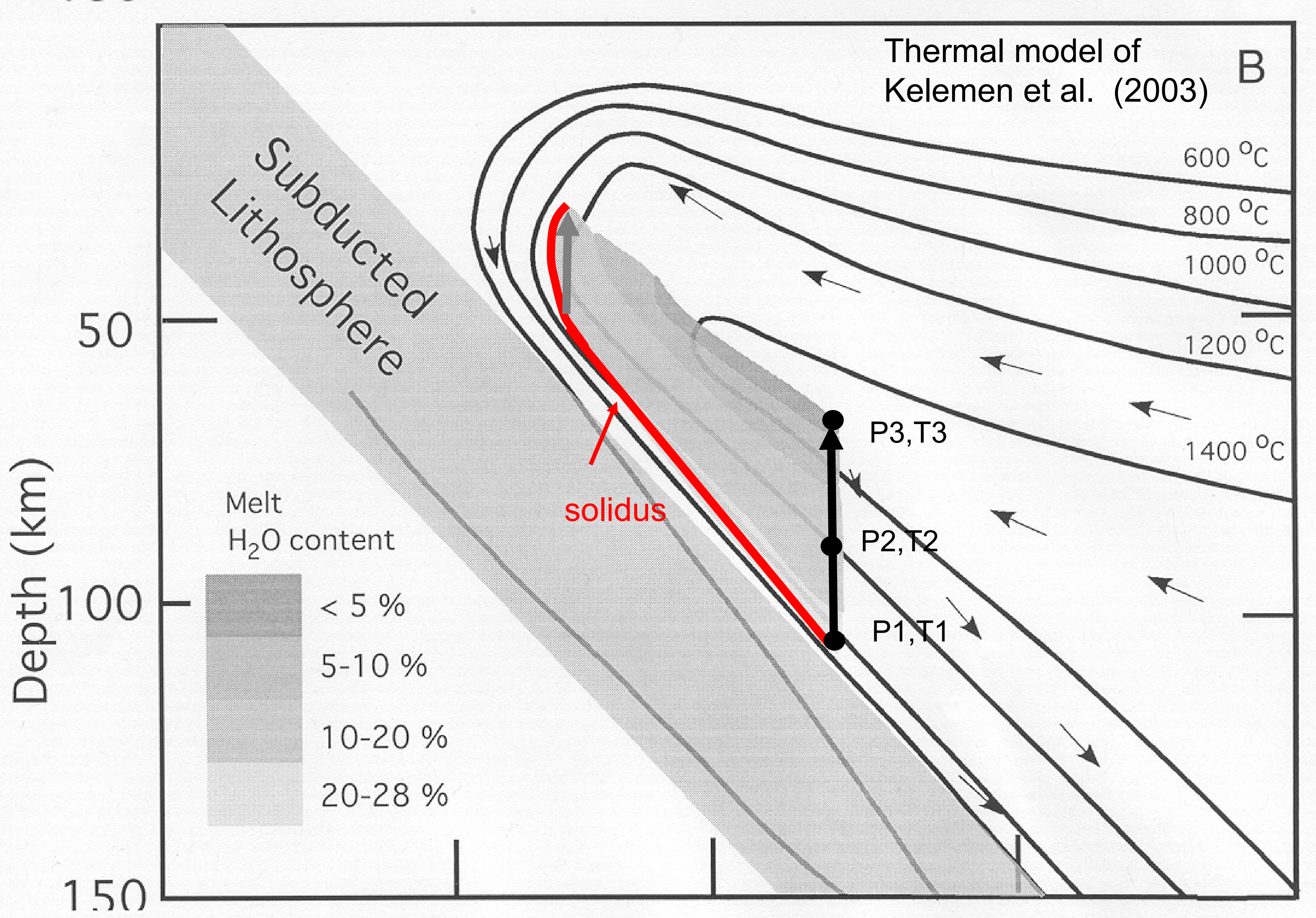
Melting behavior of peridotite vs. sediment and basalt in presence of excess H_2O. The solidi converge as pressure increases.

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

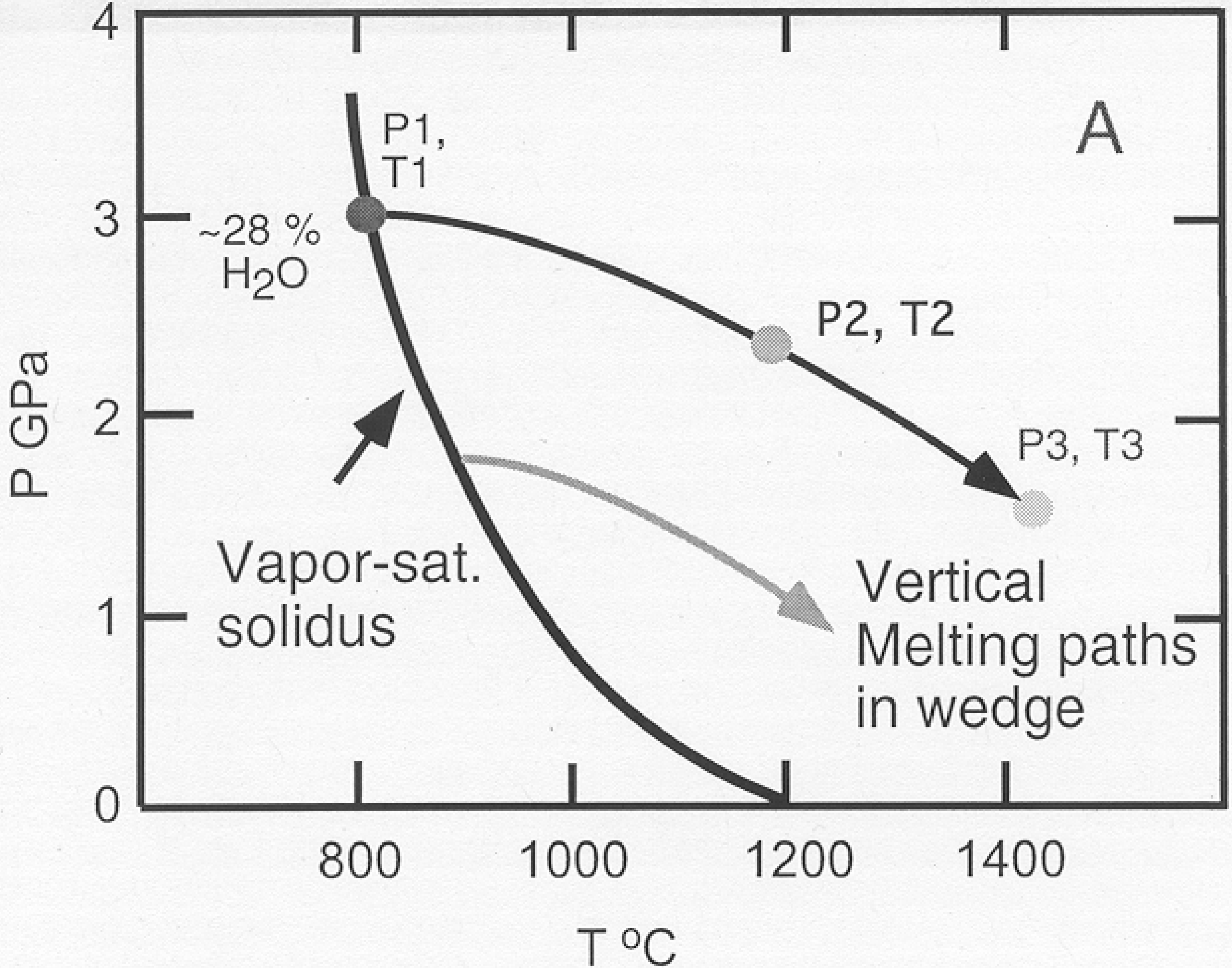
Buoyant hydrous melts leave the base of wedge and ascend into the overlying mantle by porous flow.

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

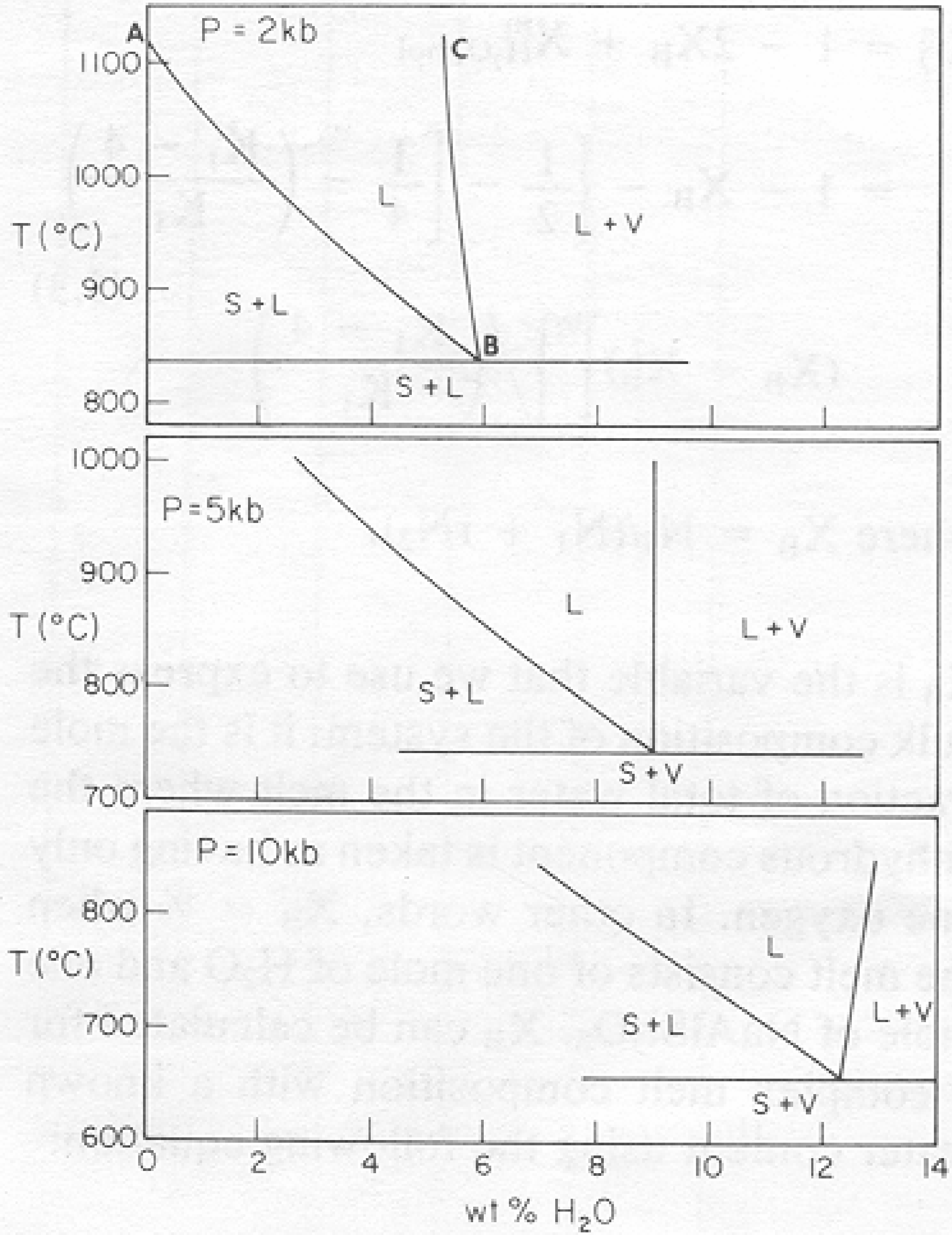
Assumptions: initial critical melt fraction –
F_{crit}= 2.5 wt. % values range from < 0.1 (Kohlstedt, 1992) to 8 % Fujii et al. (1986)



Thermal model of
Kelemen et al. (2003)
B
Subducted
Lithosphere
600 °C
800 °C
1000 °C
1200 °C
1400 °C
P3,T3
P2,T2
P1,T1
solidus
Melt
H2O content
< 5 %
5-10 %
10-20 %
20-28 %
Depth (km)
50
100
150



P GPa
4
3
2
1
0
800
1000
1200
1400
T °C
A
P1,
T1
~28 %
H2O
P2, T2
P3, T3
Vapor-sat.
solidus
Vertical
Melting paths
in wedge

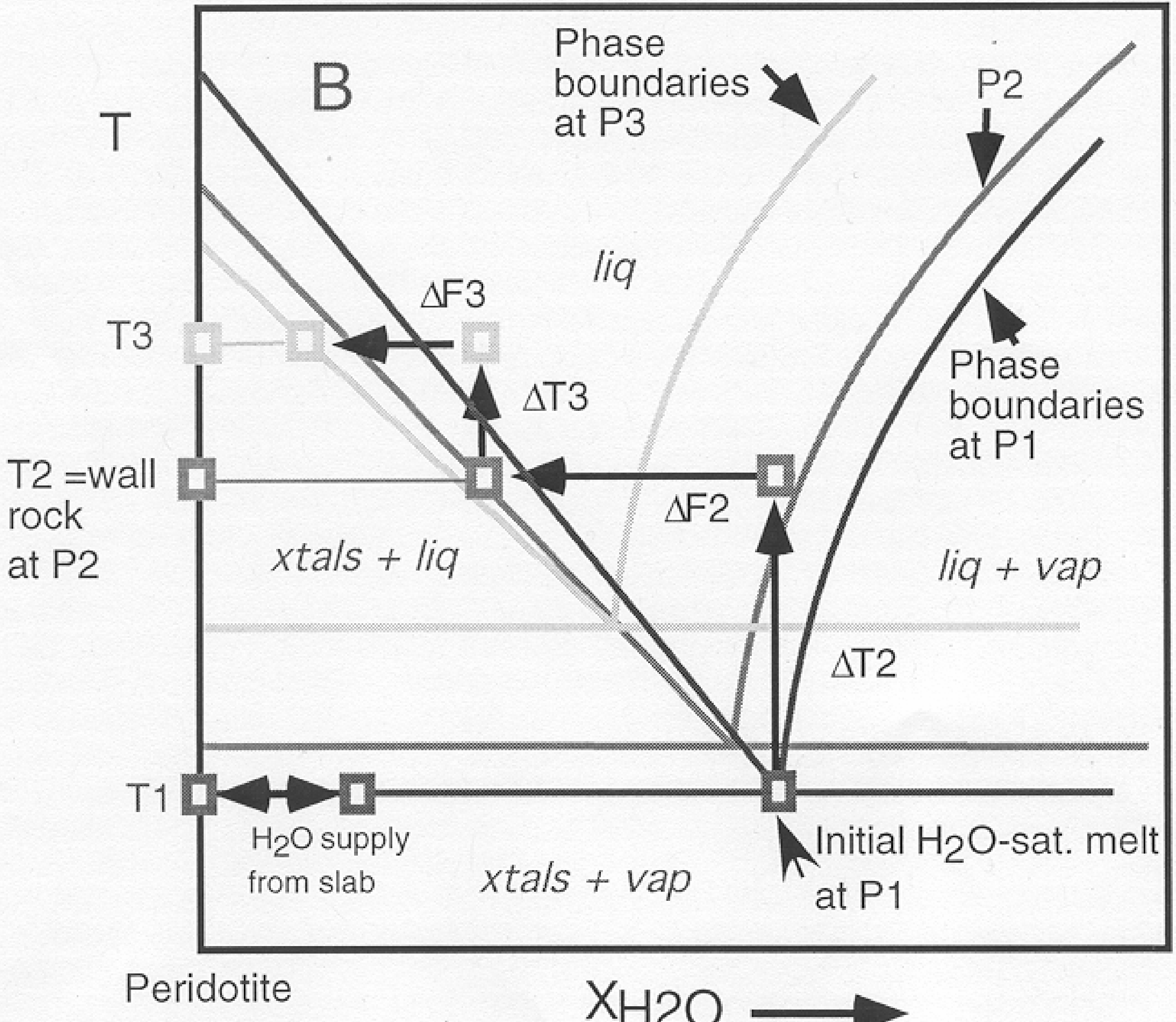


Silver and Stolper (1985) speciation model for melting in simple two component systems mineral – H_2O

Includes molecular H_2O – OH speciation and leads to a planar T – P – X_{H2O} solid – melt boundary

Note linearity of liquidus boundary.

This melting behavior is "adjusted" for perid.



Melt H_2O content is strongly influenced by the lever rule effect –

melt % increases rapidly as bulk composition

Approaches liquidus.

Reactive porous flow melting = melt volume must come into equilibrium with mantle at each step –both thermally and chemically

The melting model:

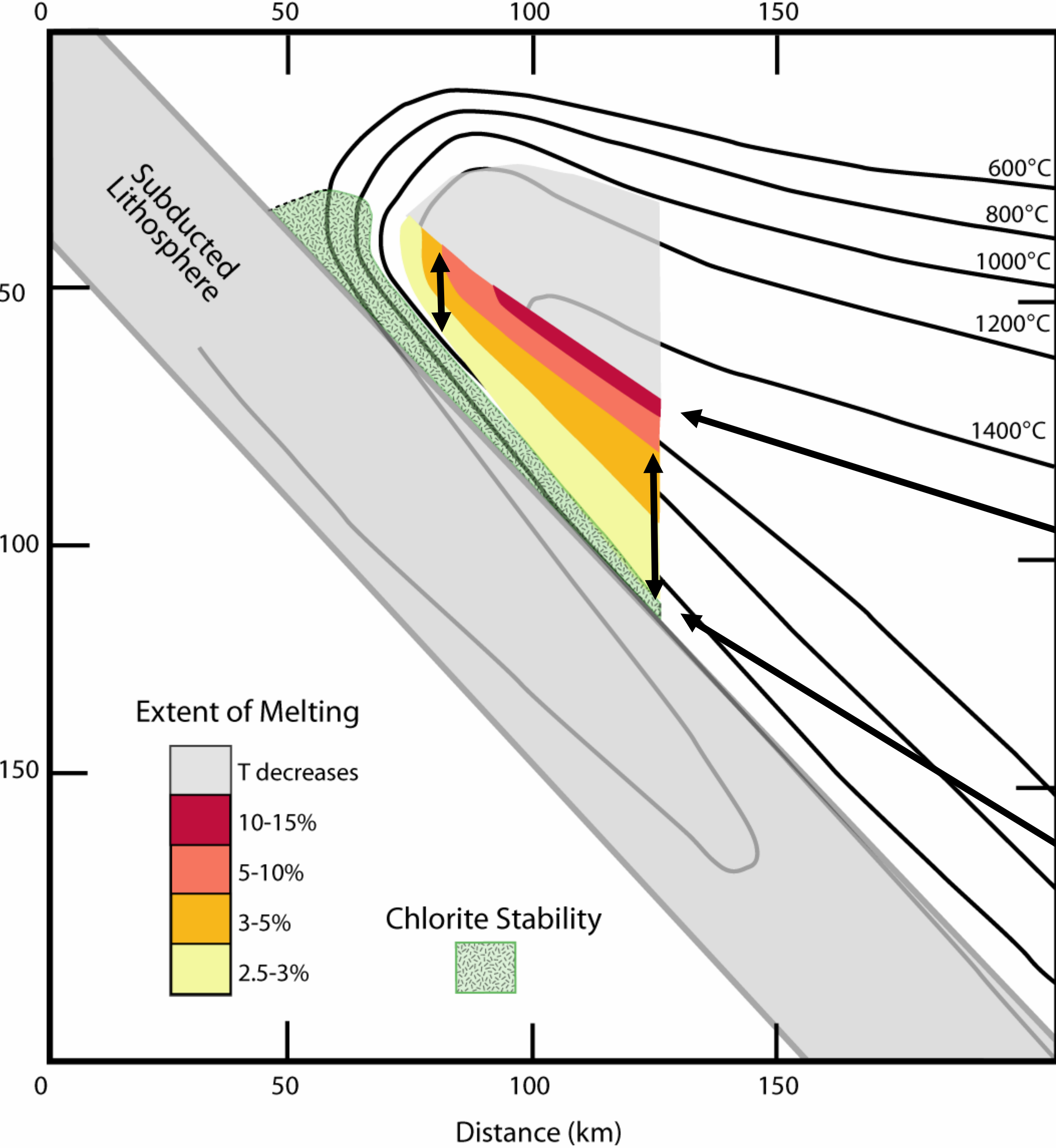
. We use our phase diagram & measured H_2O solubility vs. pressure in forsterite – H_2O to predict the peridotite – melt boundary in T – P – XH_2O space. The expression is:

$$7290*P - 810*T - 24600*H_2O + 1093500 = 0$$

where T is in ^oC, P is in kilobars and H_2O content is in wt. %.

At P2, T2 the amount of melt ($F_{P2,T2}$) is given by:

$$F_{P2,T2} = ((X_{init} - X_{P2,T2})/X_{init}) * F_{init} + F_{init}$$

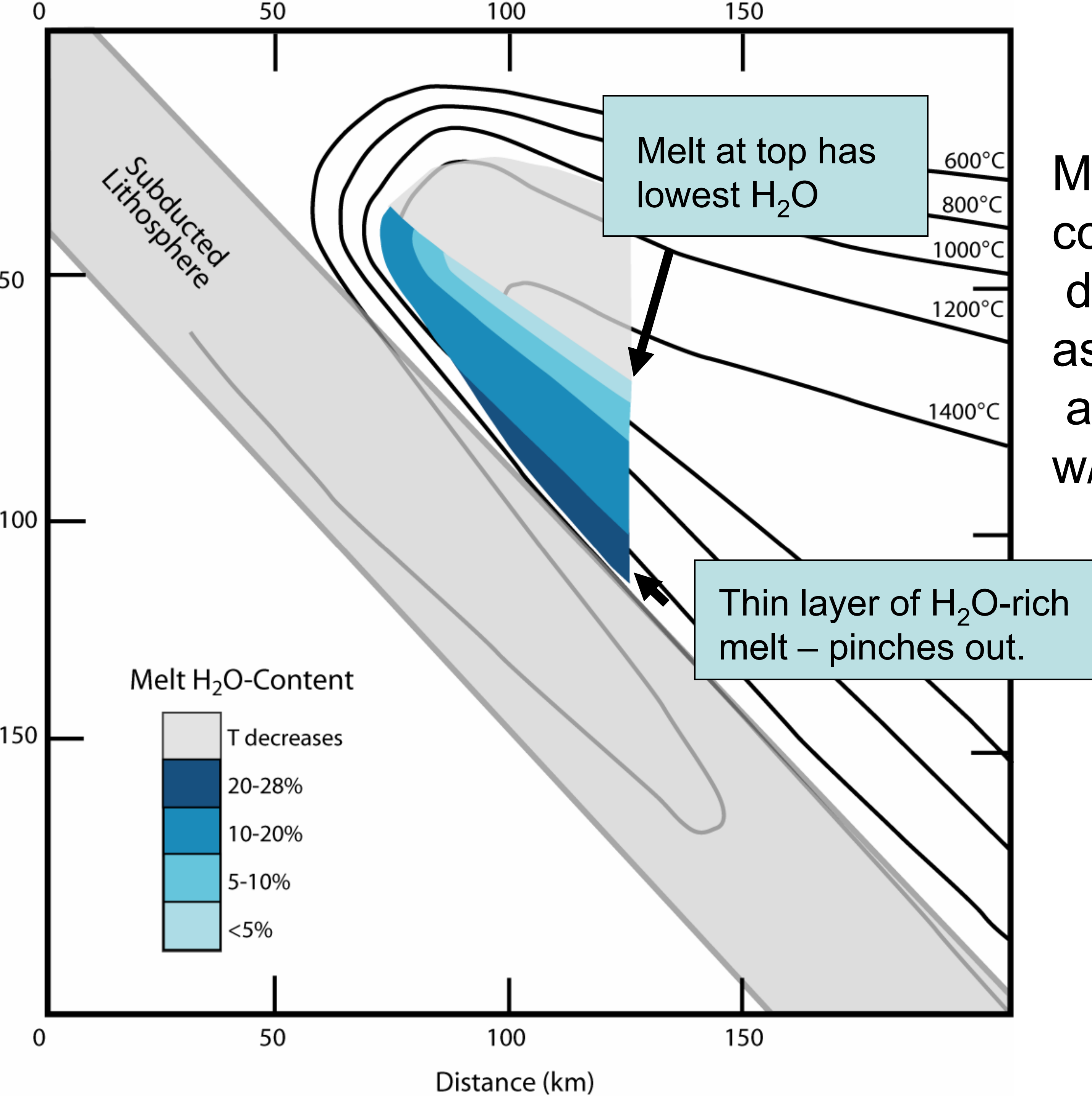


Maximum melt % occurs in a thin layer in hot core of the wedge

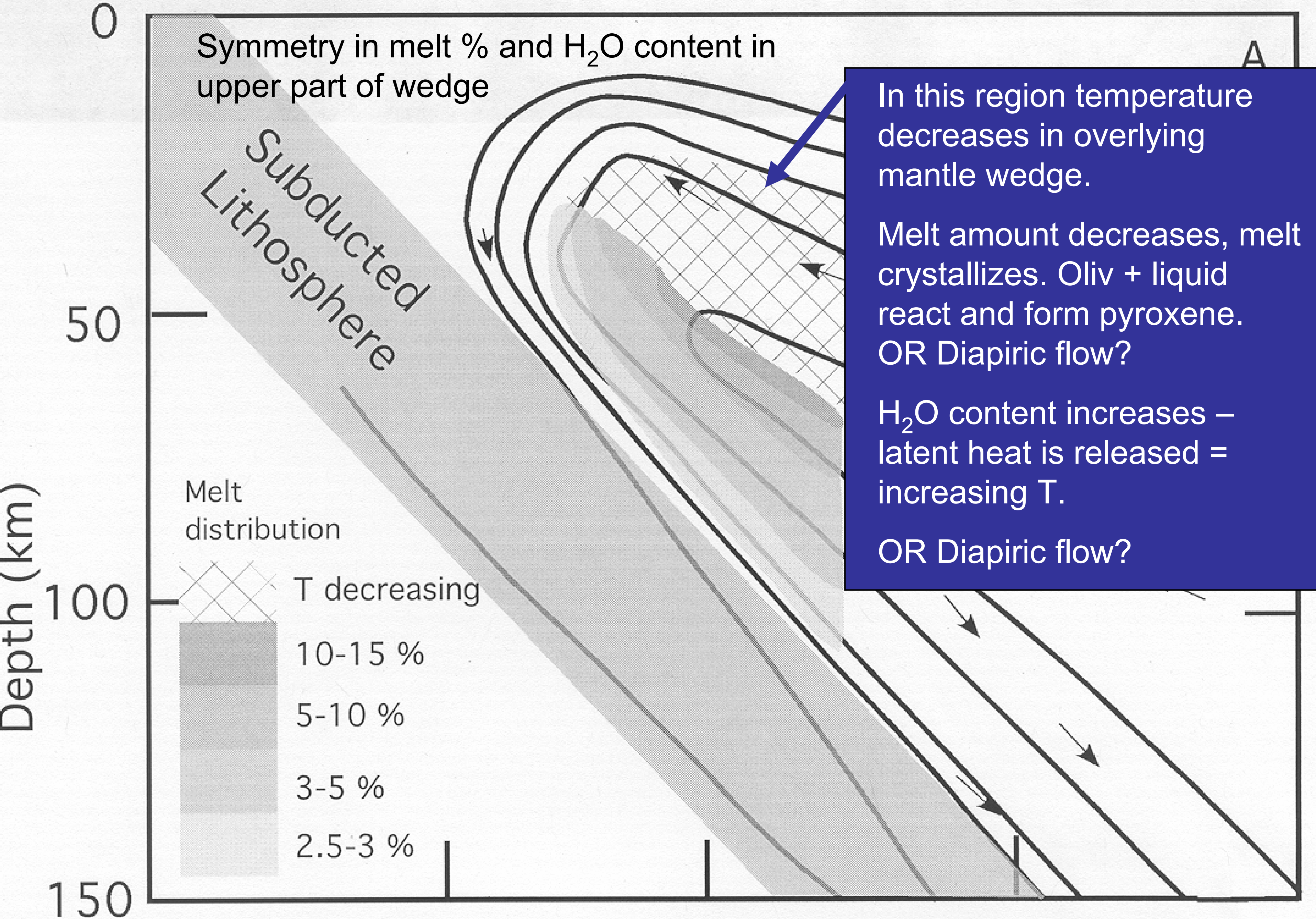
Highest melt fraction achieved in a very thin layer.

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

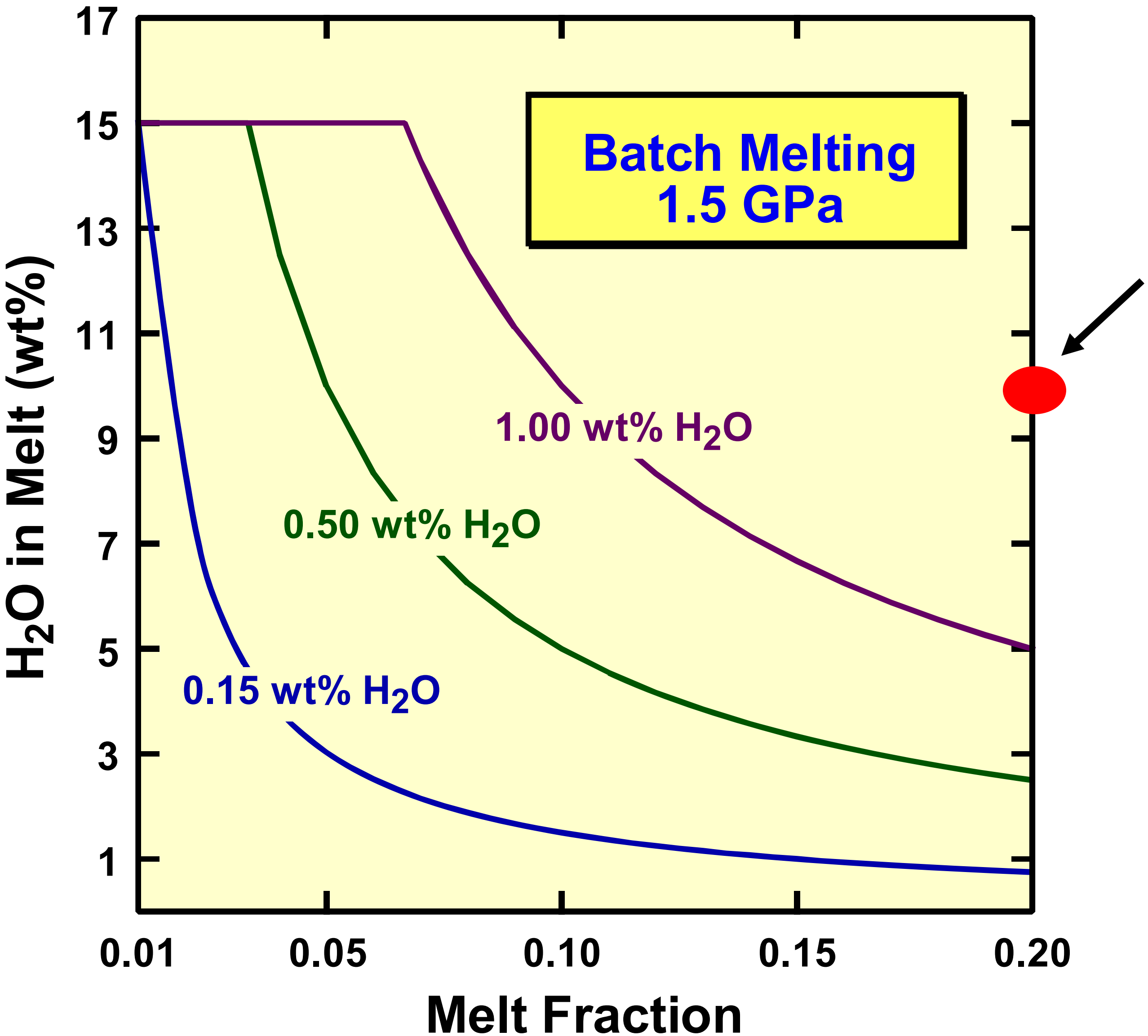
Chlorite is transported down into the wedge ABOVE the slab and gives up its H_2O at solidus.



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


Symmetry in melt % and H_2O content in upper part of wedge
In this region temperature decreases in overlying mantle wedge.
Melt amount decreases, melt crystallizes. Oliv + liquid react and form pyroxene. OR Diapiric flow?
H_2O content increases – latent heat is released = increasing T.
OR Diapiric flow?
Subducted Lithosphere
Melt distribution
T decreasing
10-15 %
5-10 %
3-5 %
2.5-3 %
Depth (km)
0
50
100
150
A

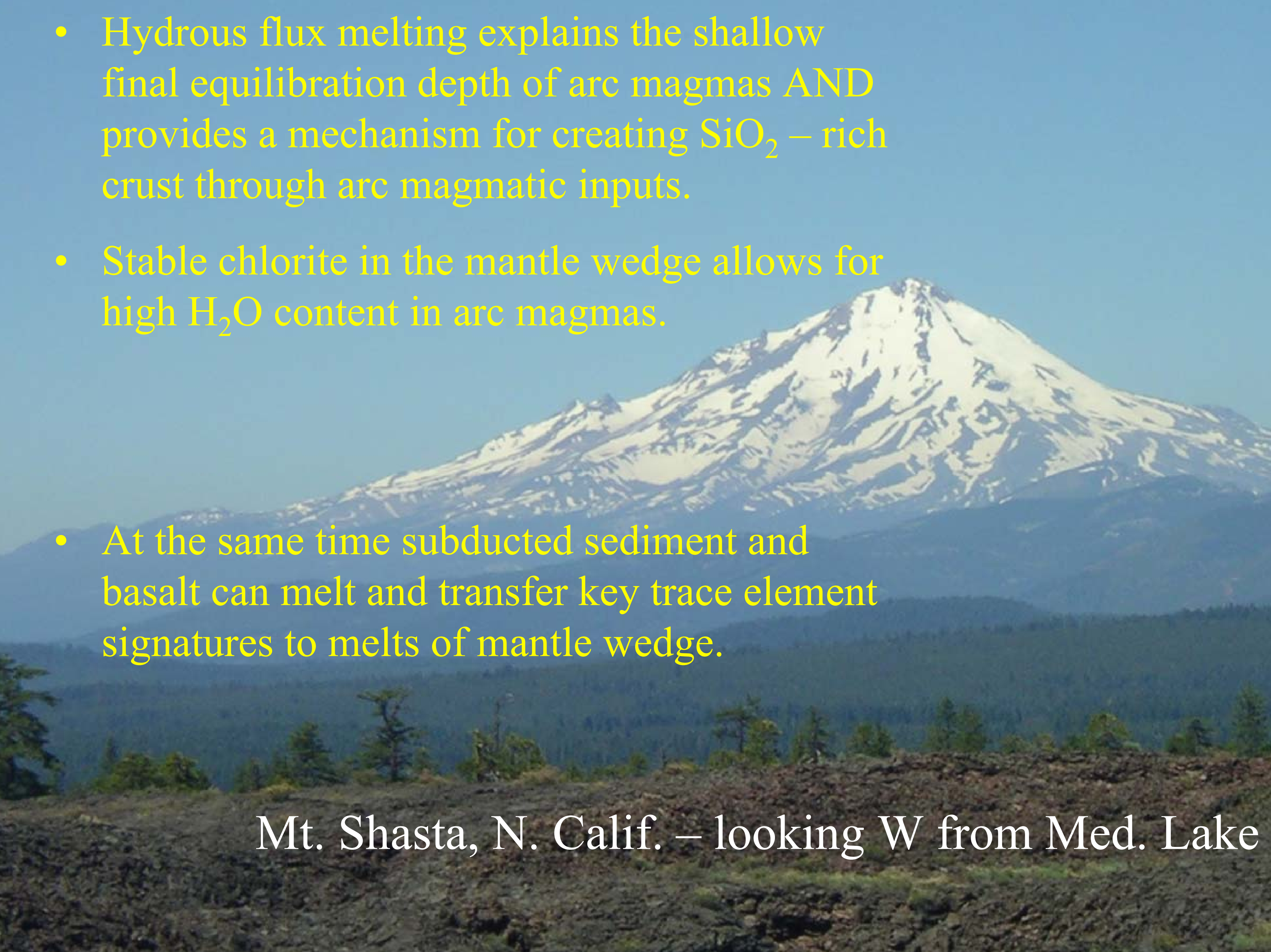
When mantle peridotite is hydrated it contains 13 % chlorite. Bulk H_2O of solid is 2 wt. % .



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.



Mt. Shasta, N. Calif. – looking W from Med. Lake

Experimental Details

Au capsules – Piston cylinder - 1.2 – 3.2 GPa

Hart & Zindler Primitive Mantle

Oxide starting mix

With MgO added as $Mg(OH)_2$ = 14 wt. % H_2O

Run Duration

96 – 140 hours (a few at 24 hrs)

Experimental Products

Homogeneous olivine, opx, cpx, spinel and/or garnet

Melt or vapor phase (supercritical fluid)

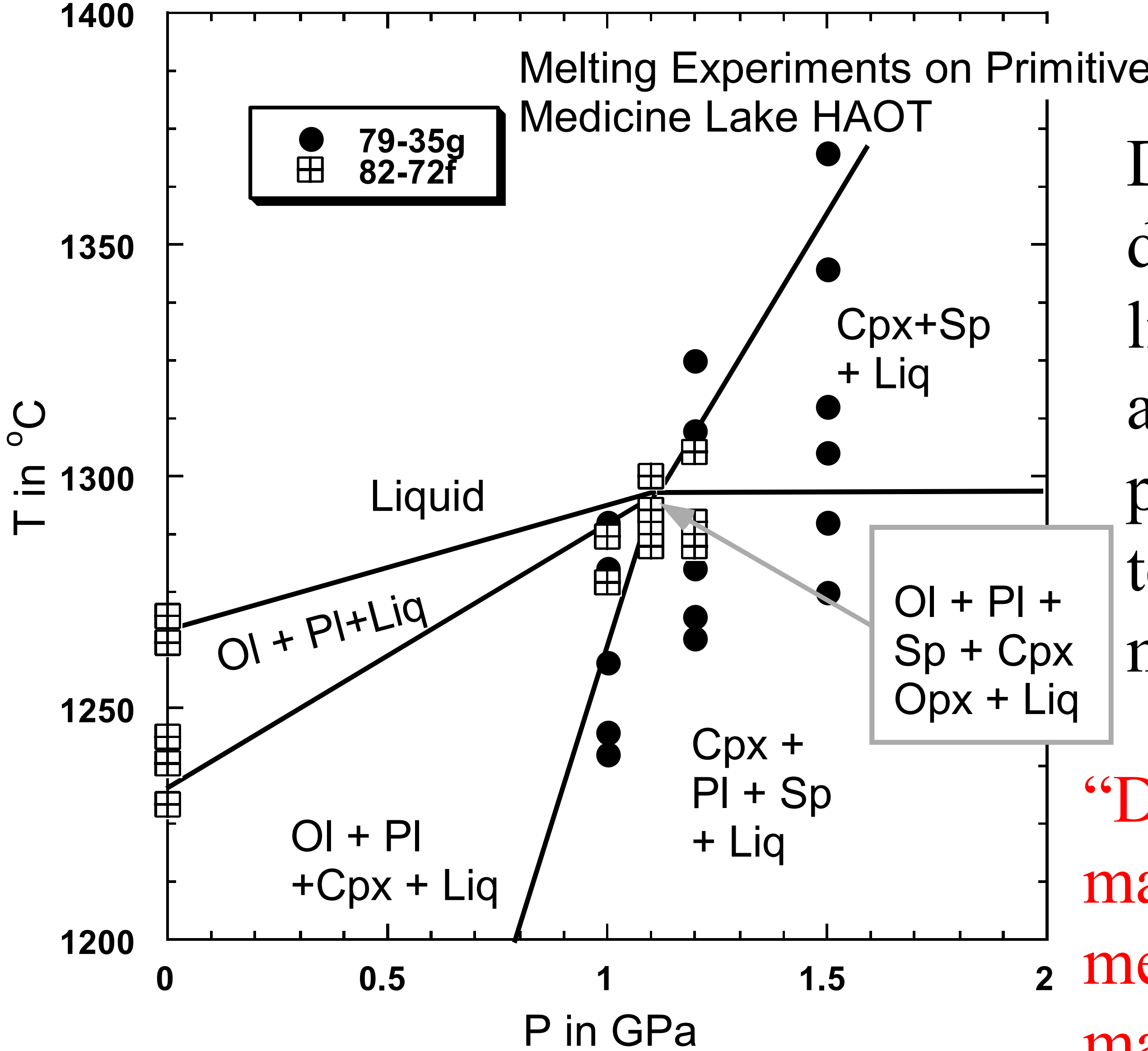
Equilibrium

QUILF used to check Temp. from Opx-Cpx – within 1 sigma of uncertainty

and f_{O2} from oliv-opx-spinel (Ballhaus et al., 1994) =QFM + 0.8

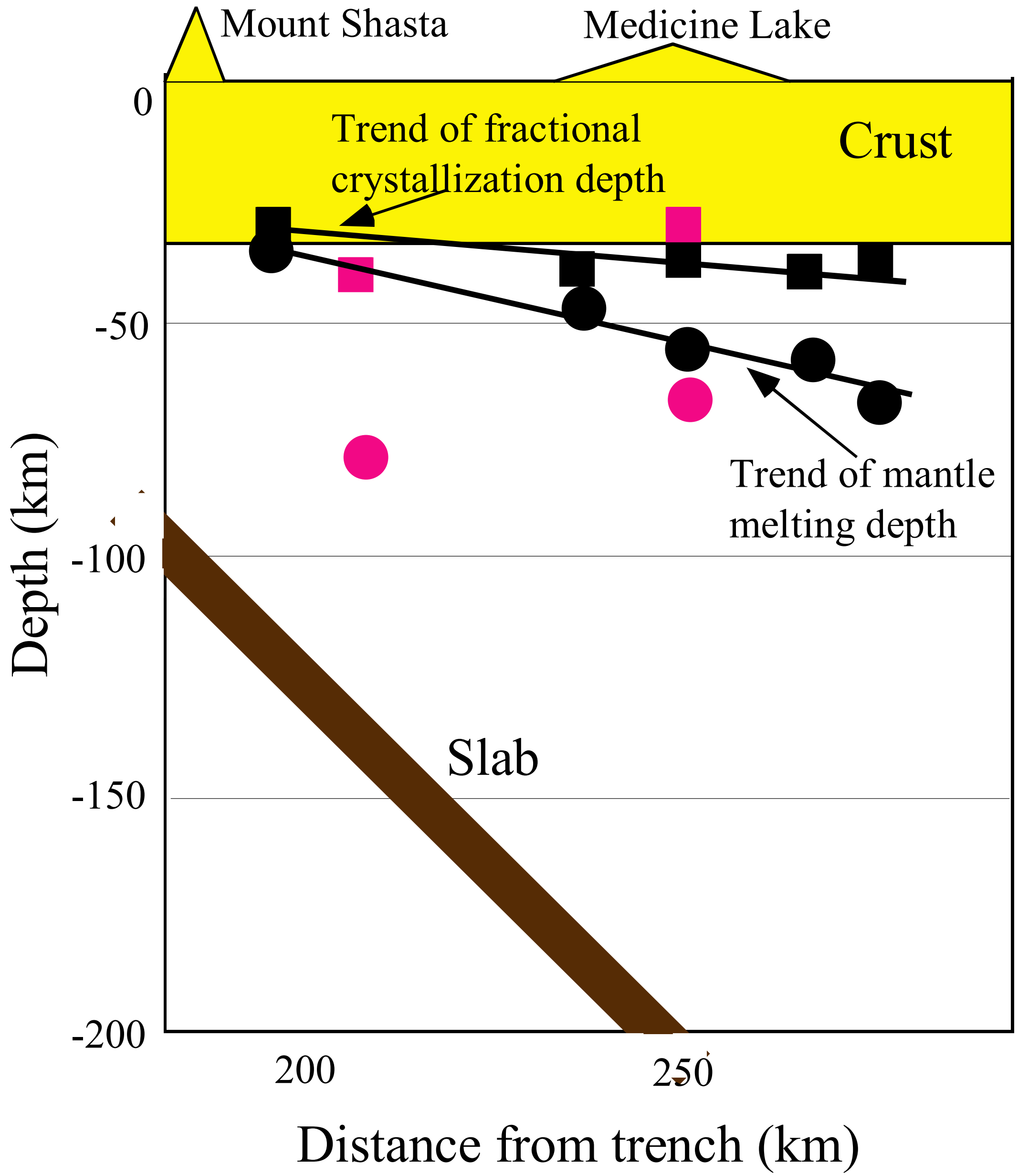
PREVIOUS STUDIES

Run Times	*H_2O added*	*Capsule*
High – T melting		
Kushiro et al. (1968)		
5 – 30 min	*30%*	*Mo & Pt*
Millhollen et al. (1974)		
0.5 – 3 hrs.	*5.7 %*	*Pt*
Green (1973)		
1 – 6 hrs.	*10 %*	*AgPd alloy*
Low – T melting		
Mysen and Boettcher (1975)		
24 – 64 hrs.	*20- 30 %*	*AgPd alloy*
THIS STUDY		
48 – 120 hrs	*14 –30 %*	*Au*



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

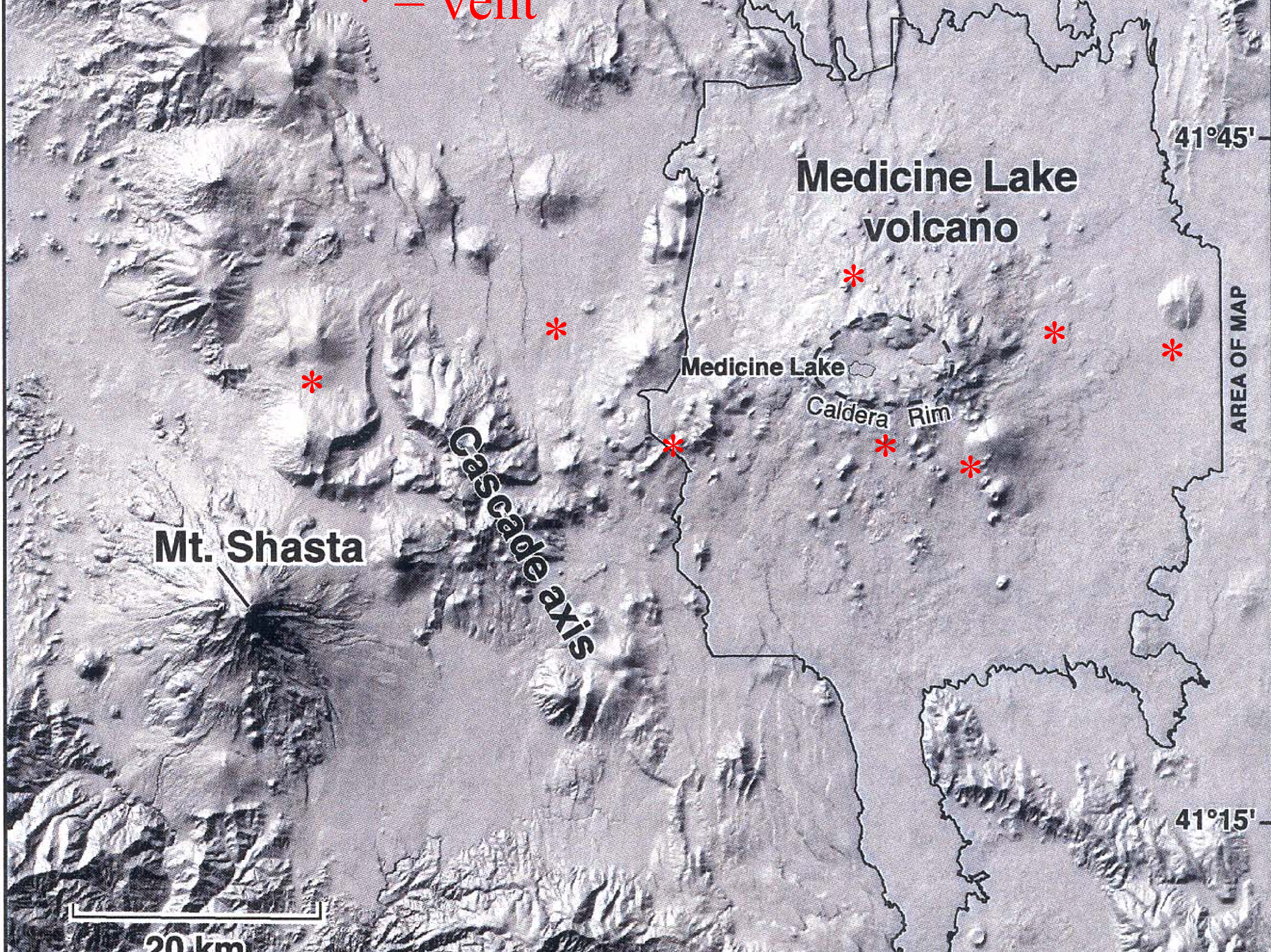


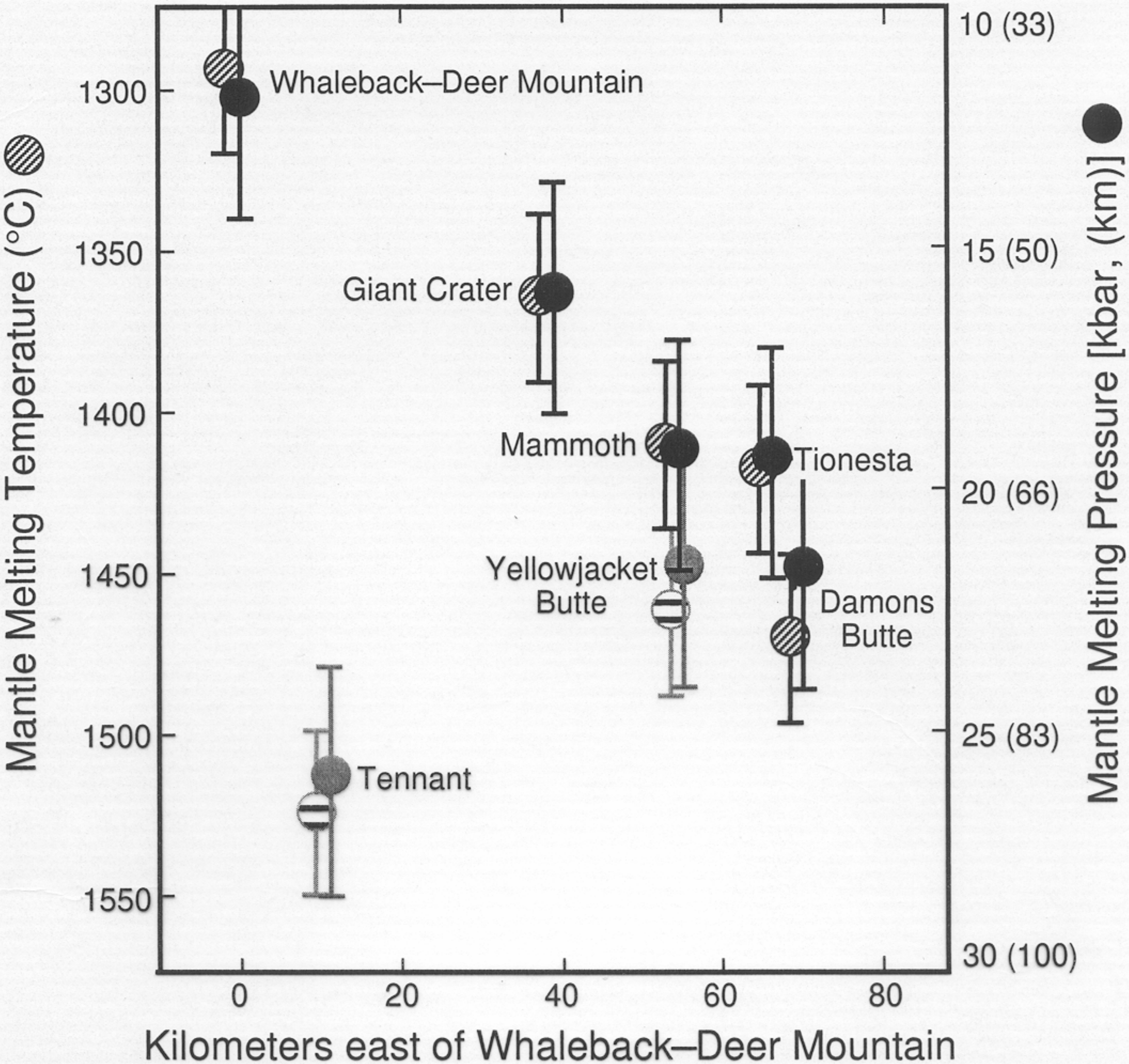
Shallow, hot mantle melting beneath the Cascades

Inferred from Pressure of multiple saturation.

T = 1300 – 1450 ^{o}C.

Elkins-Tanton et al. (2001)


* = vent
Medicine Lake volcano
Medicine Lake
Caldera Rim
Cascade axis
Mt. Shasta
41°45'
41°15'
AREA OF MAP
20 km



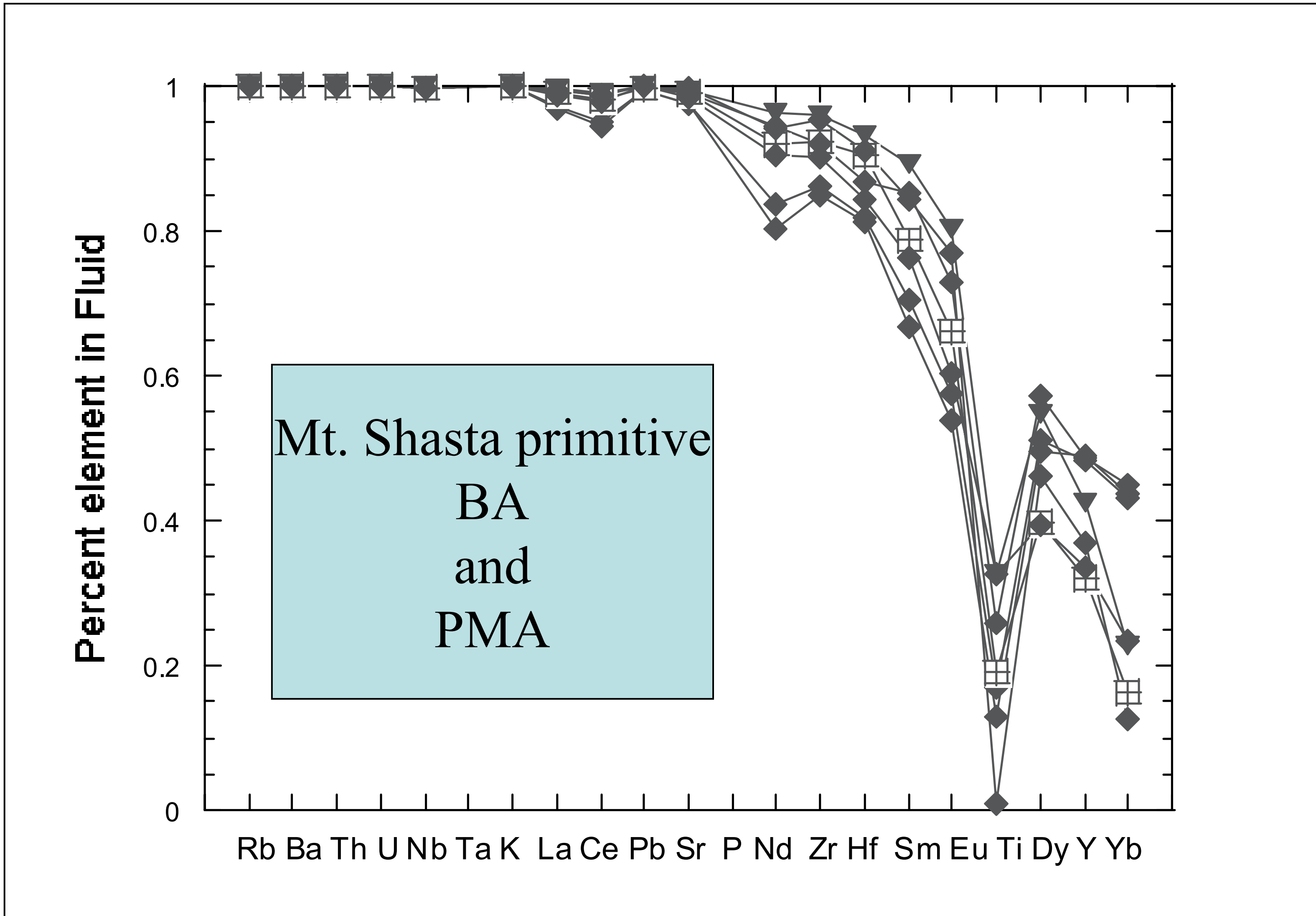
Whaleback–Deer Mountain
Giant Crater
Mammoth
Tionesta
Yellowjacket Butte
Damons Butte
Tennant
1300
1350
1400
1450
1500
1550
Mantle Melting Temperature (°C)
10 (33)
15 (50)
20 (66)
25 (83)
30 (100)
Mantle Melting Pressure [kbar, (km)]
0
20
40
60
80
Kilometers east of Whaleback–Deer Mountain

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

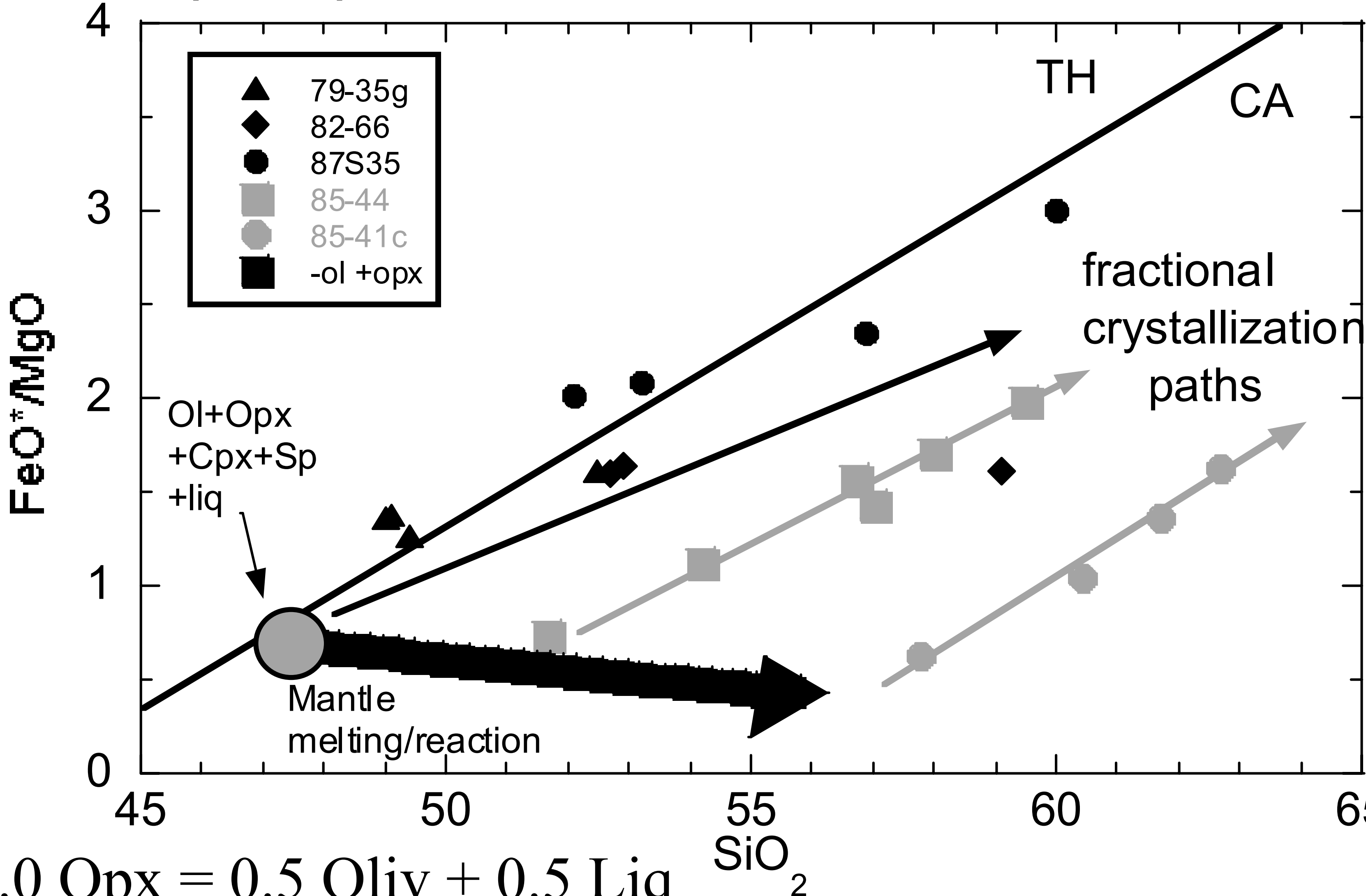
- Na_2O = 25 to 33 wt.% of the "fluid"
- K_2O = 5 to 13 wt. % of "fluid"
- SiO_2 = 0 wt. %
- H_2O = 54 to 70 wt. %
- Similar to finding of Stolper & Newman (1994).

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

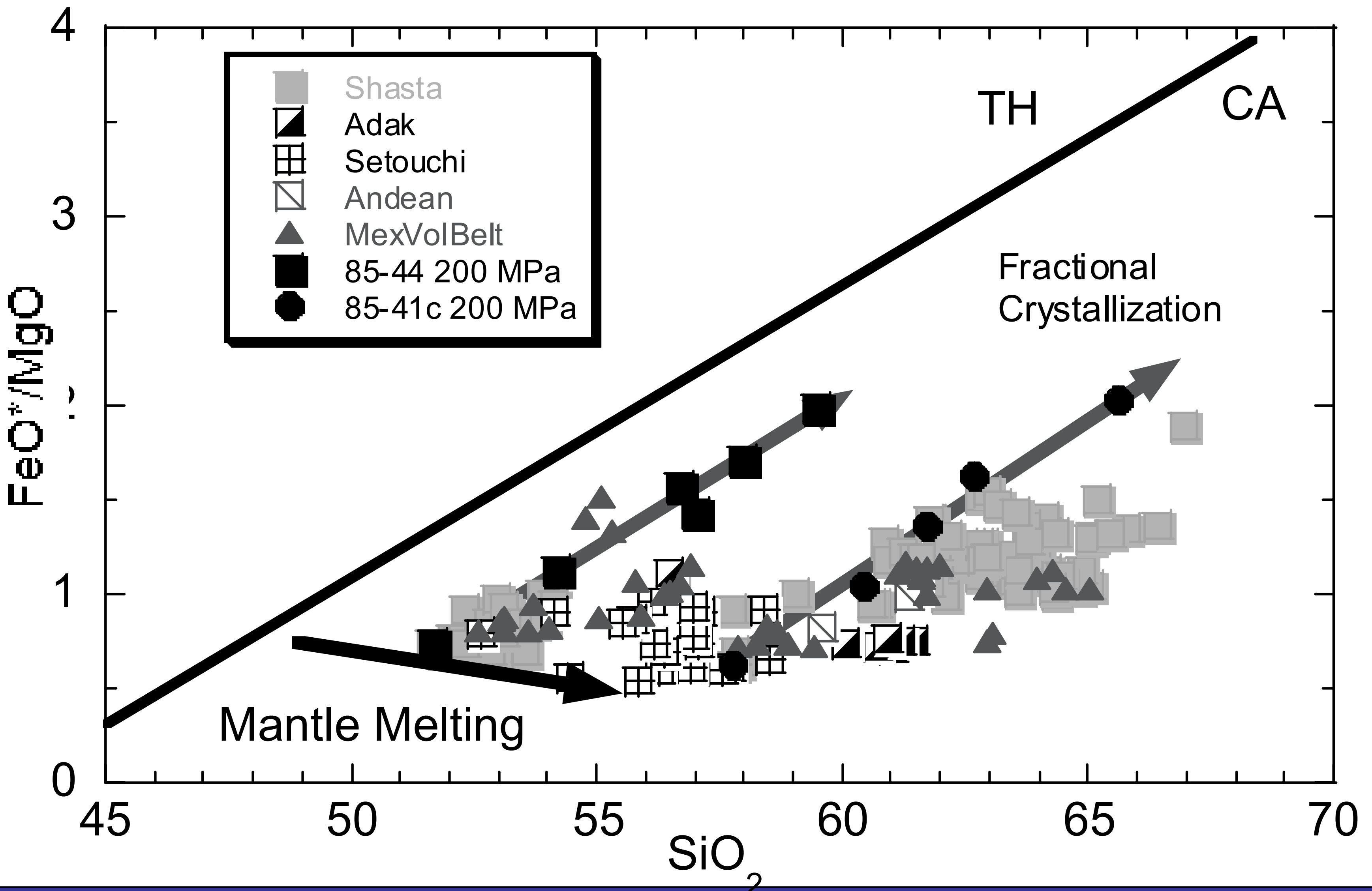
Estimated Slab Contribution



Mantle melting trend to high-SiO_2 - low FeO^*/MgO is controlled by the reaction relation oliv + liq → opx.



1.0 Opx = 0.5 Oliv + 0.5 Liq



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.