Mantle Melting at Subduction Zones

(an experimental petrologist's view)

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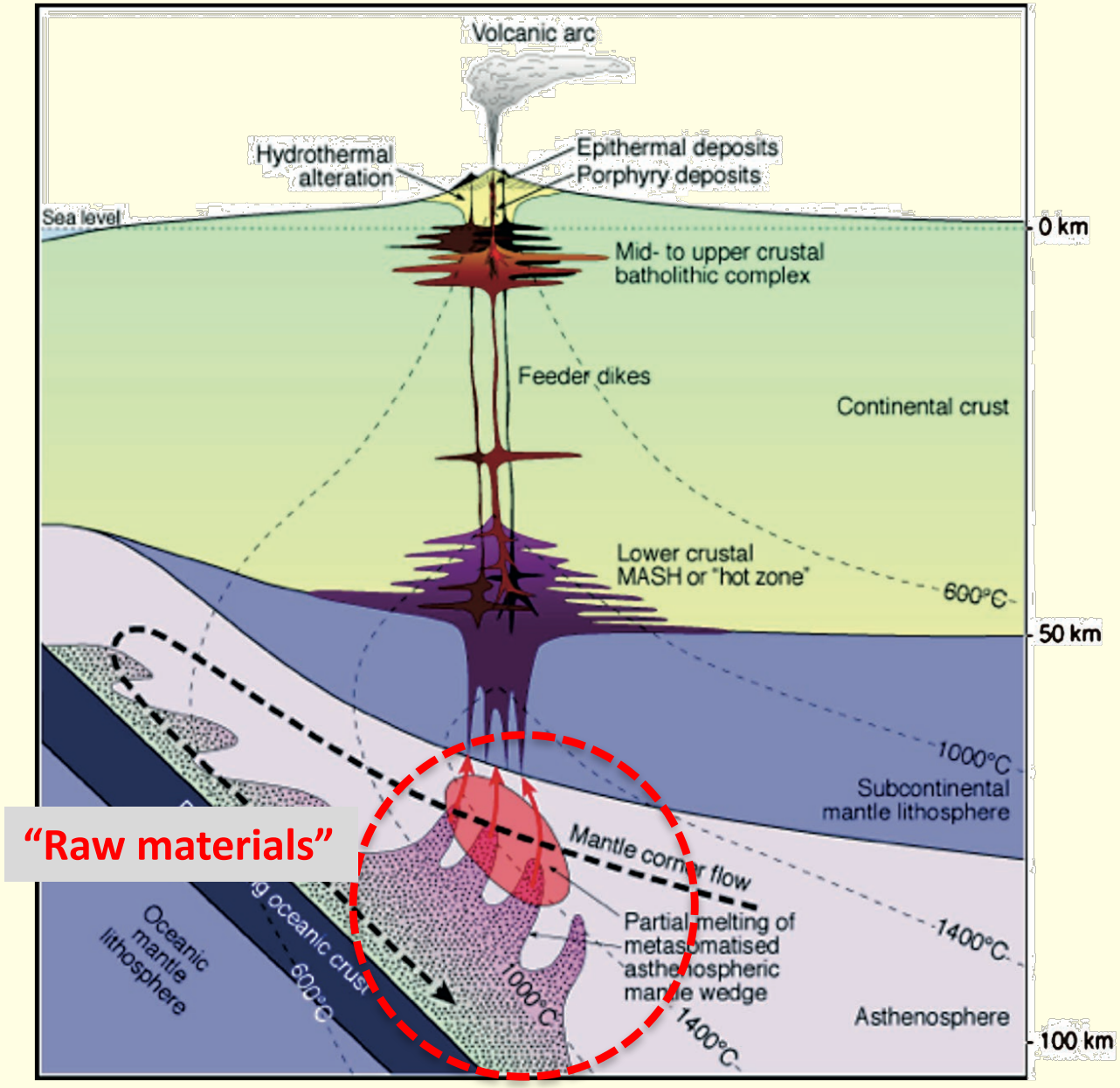
NSF



Richards, 2011

- Adam Kent (Wednesday Week 1)

The Mantle

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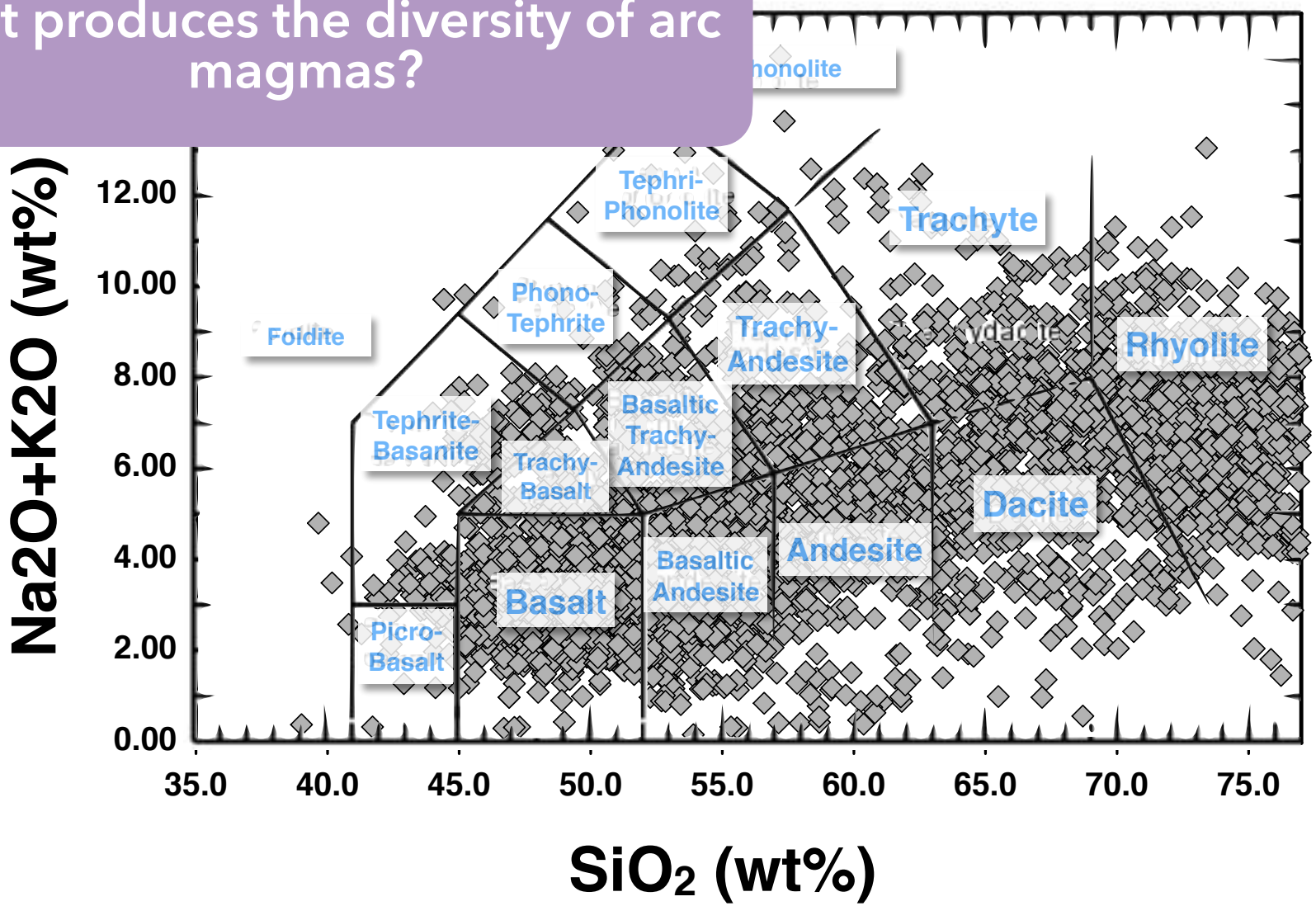
The Mantle

The Mantle

The Mantle

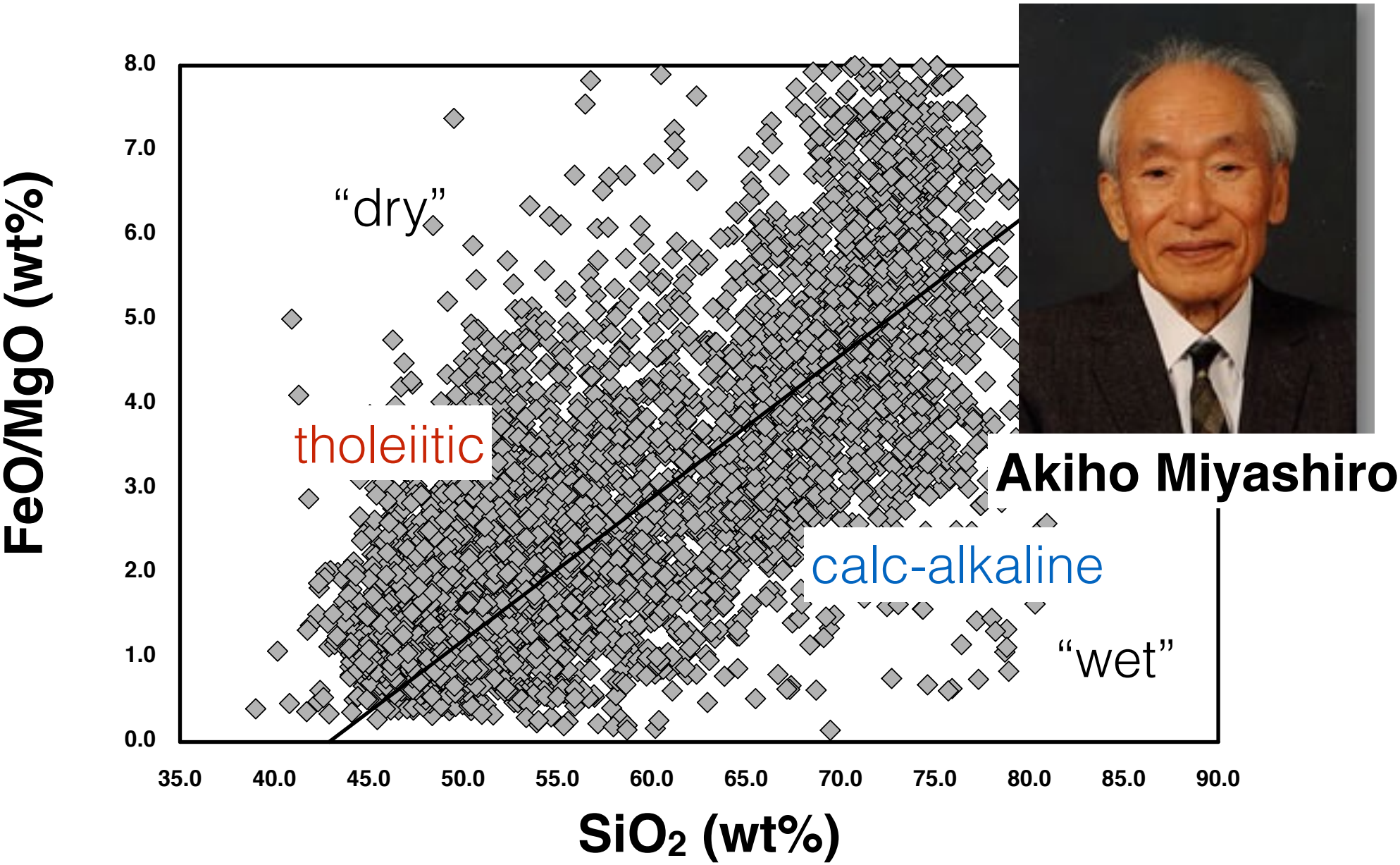
Great diversity in arc magma compositions

What produces the diversity of arc magmas?



Data from GEOROC: 2014 Compilation of Arc Melt Inclusions

Great diversity in arc magma compositions



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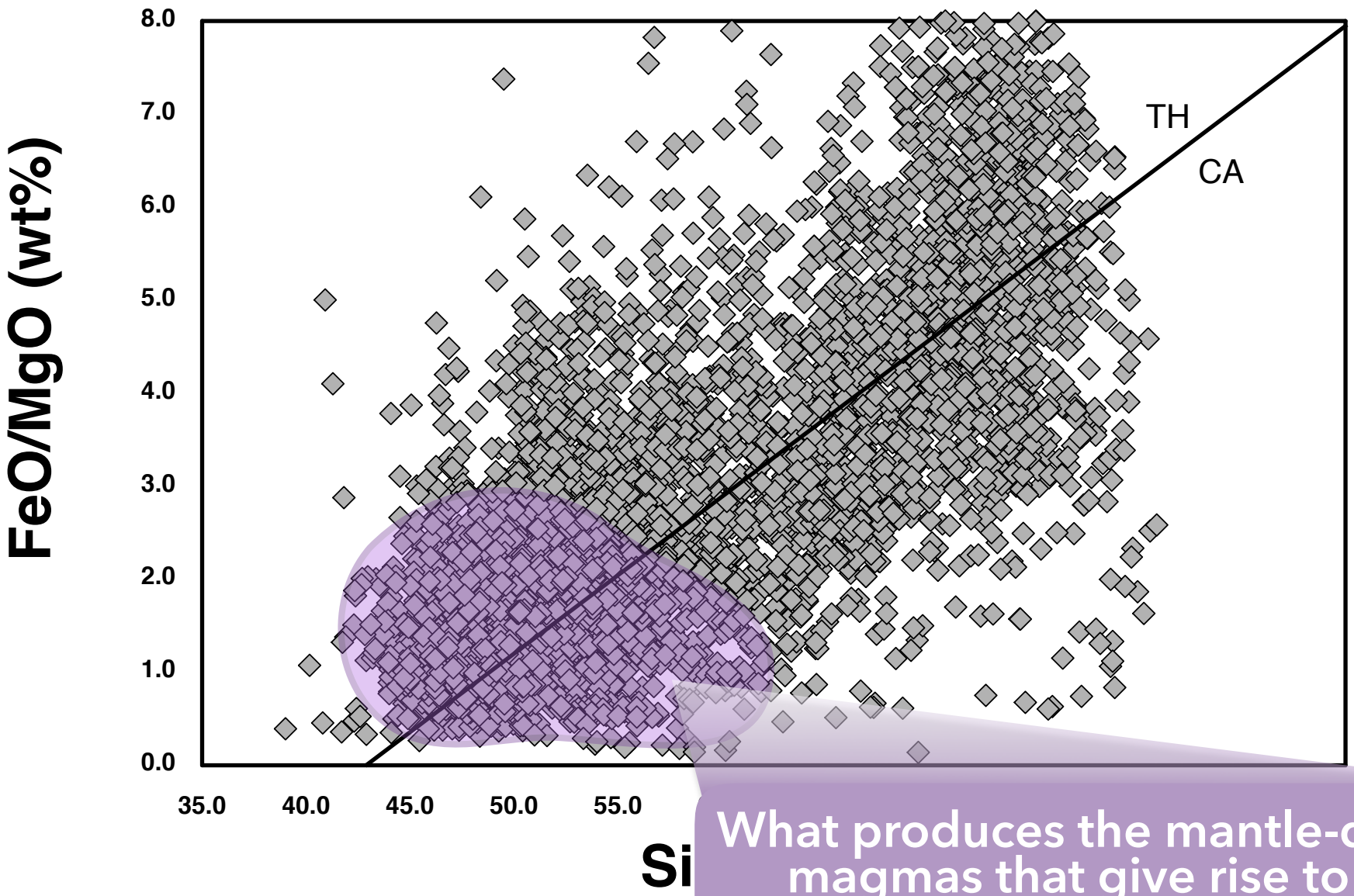


What produces the mantle-derived magmas that give rise to this diversity?

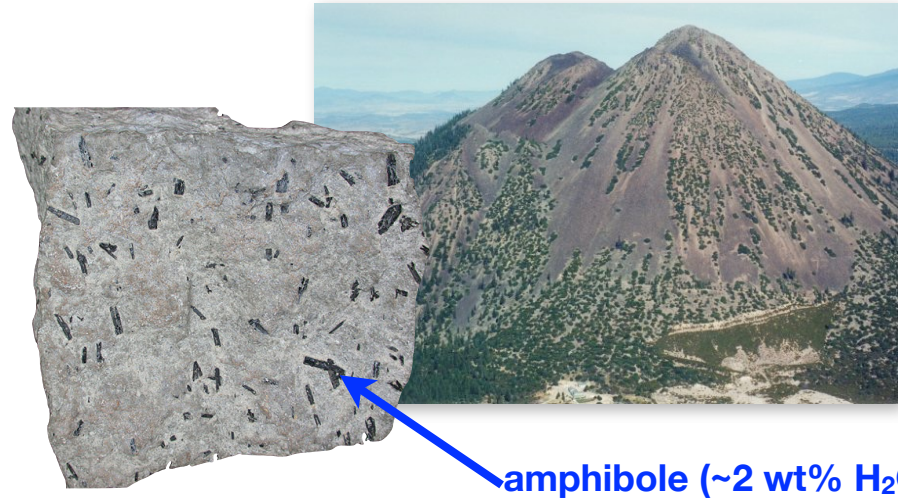
Data from GEOROC: 2014 Compilation of Arc Melt Inclusions

There's H_2O involved in arc magma genesis

1. Petrology of lavas

2. Highly explosive nature of arc volcanoes

3. Melt Inclusions



Physical and chemical analytical data for representative glass inclusions in olivine megacrysts, Mt. Shasta region, California

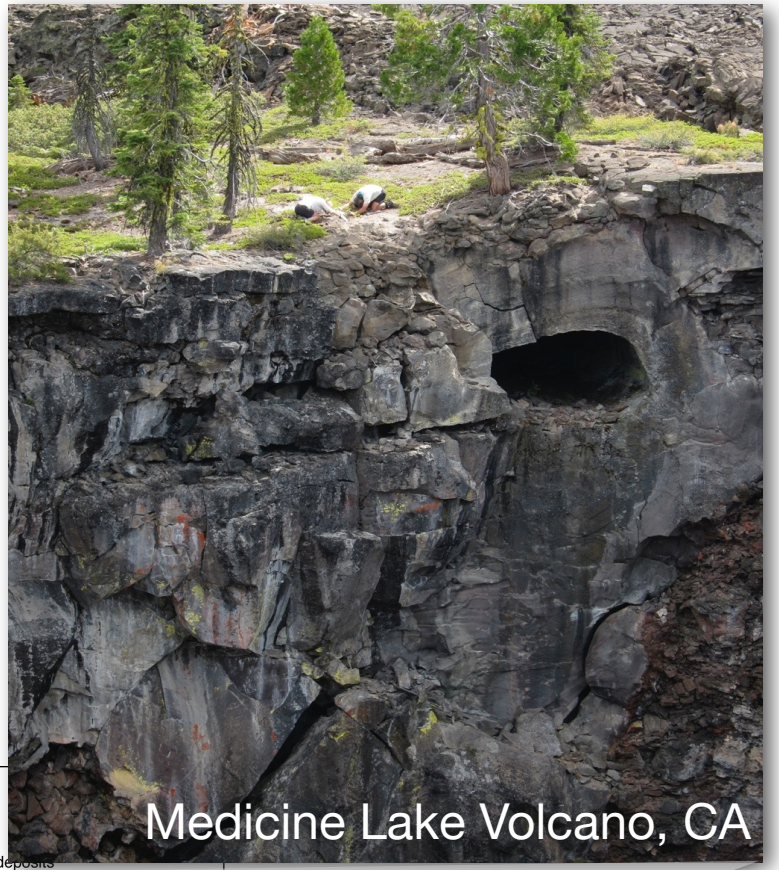
*Locality**	S–1	S–1	S–1	S–7	S–11	S–13	S–17	S–17
Host†	Fo82	Fo87	Fo85	Fo88	Fo90	Fo81	Fo89	Fo94
Diam.‡	40	100	100	200	80	50	60	70
Vapor§	n.o.	7	(3)	(10)	(3)	n.o.	n.o.	8
K_D‖	0·21	0·25	0·18	0·16	0·22	0·25	0·17	0·18
				Weight per cent				
SiO_2	54·1	51·8	56·4	55·8	50·0	55·3	58·9	54·6
Al_2O_3	16·0	18·6	15·1	14·7	17·4	20·1	16·1	15·6
FeO¶‖	7·9	5·3	7·2	8·2	6·1	6·1	5·4	3·8
MgO	4·4	5·0	4·2	5·7	6·8	3·5	4·1	5·3
CaO	8·2	9·9	7·1	9·2	12·2	7·7	7·9	12·6
Na_2O	3·7	3·5	4·0	2·7	2·3	3·8	2·7	2·6
K_2O	0·72	0·52	0·93	0·58	0·25	1·12	1·05	0·49
TiO_2	0·98	0·89	1·20	1·17	0·56	1·13	0·66	0·68
P_2O_5	0·27	0·16	0·24	n.d.	n.d.	n.d.	0·15	0·15
H_2O**	1·7	2·6	1·4	−0·4	2·0	0·7	0·8	2·2
Cl	0·06	0·06	0·06	n.d.	0·07	0·09	0·11	0·19
S	0·02	0·09	0·01	n.d.	0·11	0·04	0·05	0·21
TOTAL	98·0	98·4	97·8	97·6	97·8	99·6	97·9	98·4

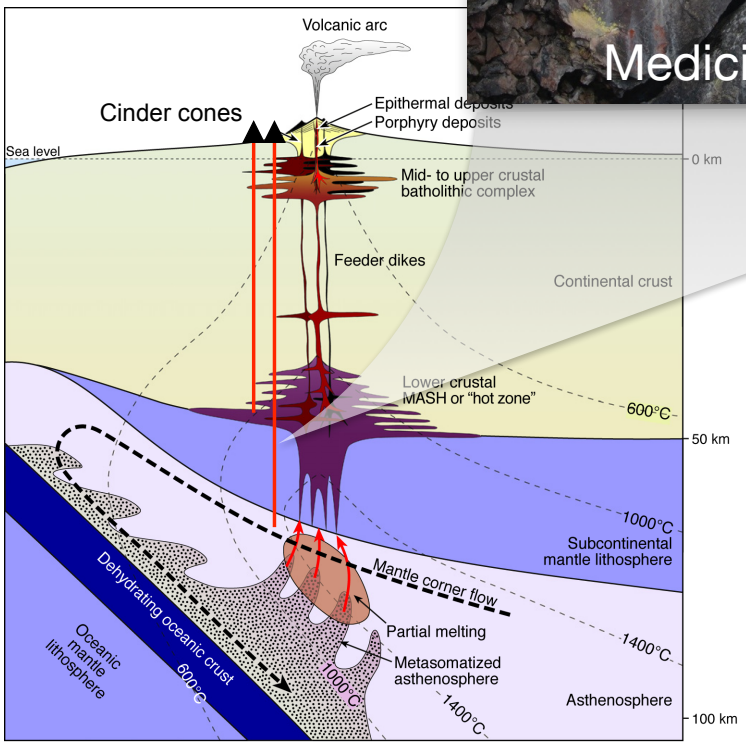
Anderson, 1974

Primitive Magmas

Store information about:

- Temperature of melting
- Pressure of melting
- Bulk composition of mantle
- Extent of melting
- Type of melting process





Modified from Richards (2011)

Many studies have worked on the P-T-X origin of primitive arc magmas in the mantle….

Debate as to origins in early 1990's

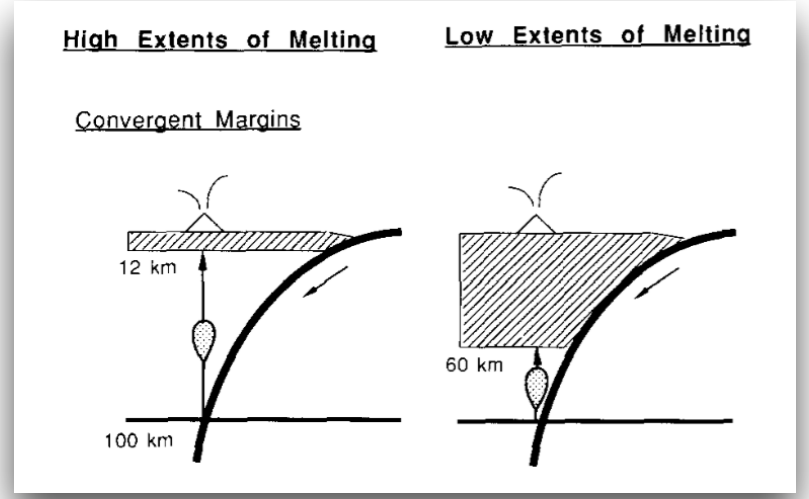
JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 97, NO. B2, PAGES 2037–2070, FEBRUARY 10, 1992

Physical Model of Source Region of Subduction Zone Volcanics

J. HUW DAVIES[1]
Seismological Laboratory, California Institute of Technology, Pasadena

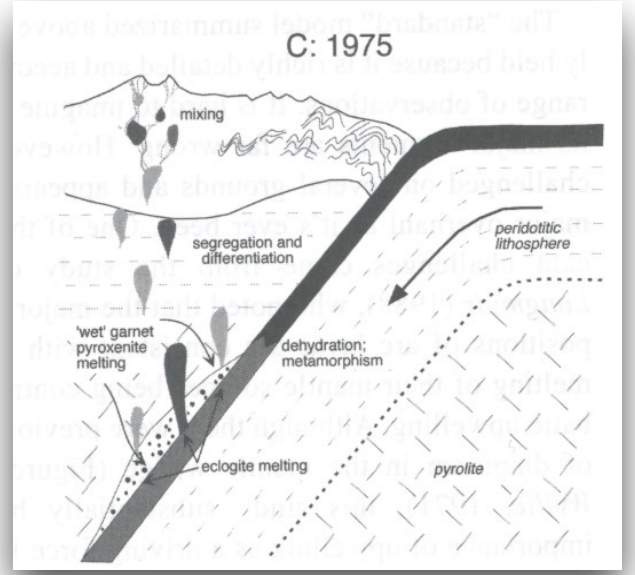
D. J. STEVENSON
Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena

Dry decompression melting of the mantle



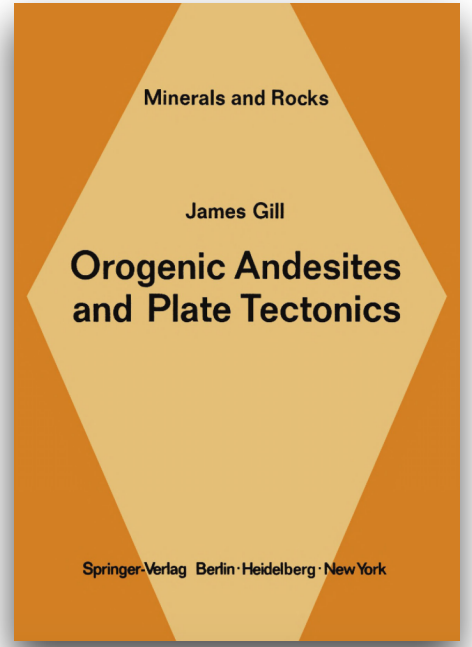
e.g., *Plank & Langmuir, 1988; Sisson and & Bronto, 1998*

Slab eclogite melts



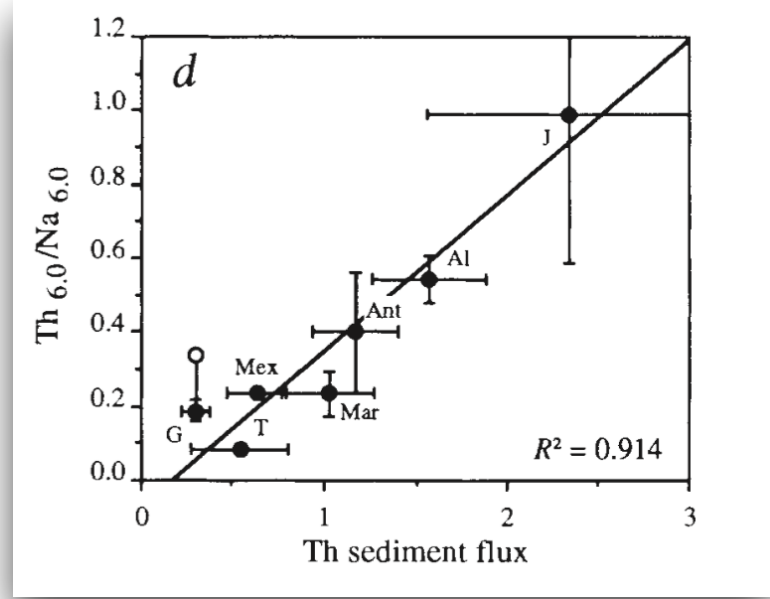
e.g., *Ringwood, 1975, Marsh, 1979*

Flux melting of mantle wedge



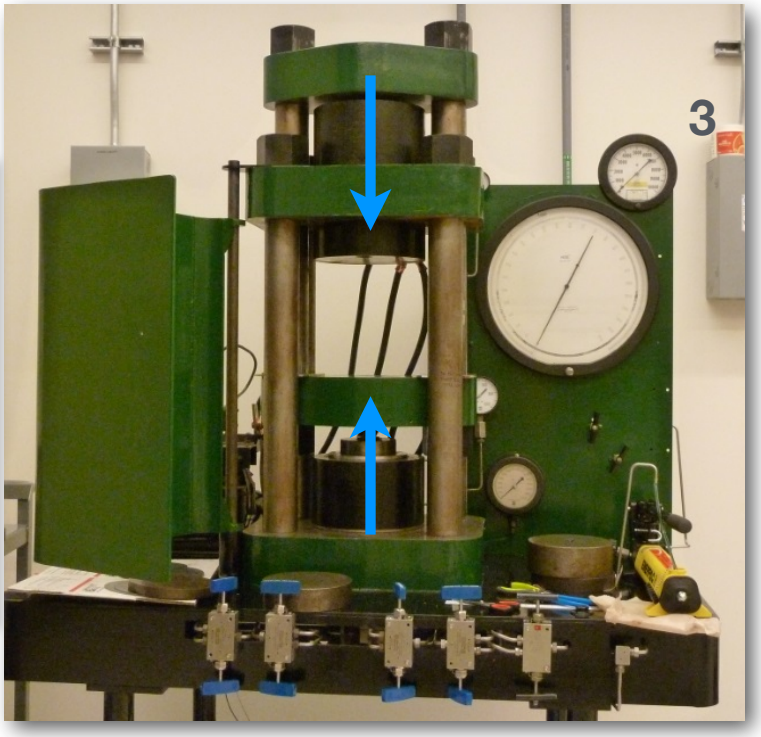
e.g., *Kushiro, 1968; Gill, 1981; Sisson and Grove, 1993a,b*

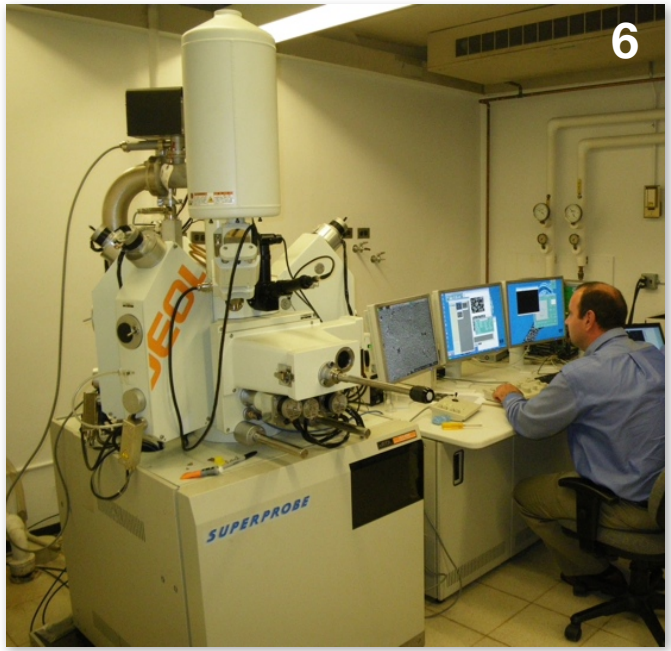
Sediment flux is a key player



Plank & Langmuir, 1993

How we do an phase equilibria experiment





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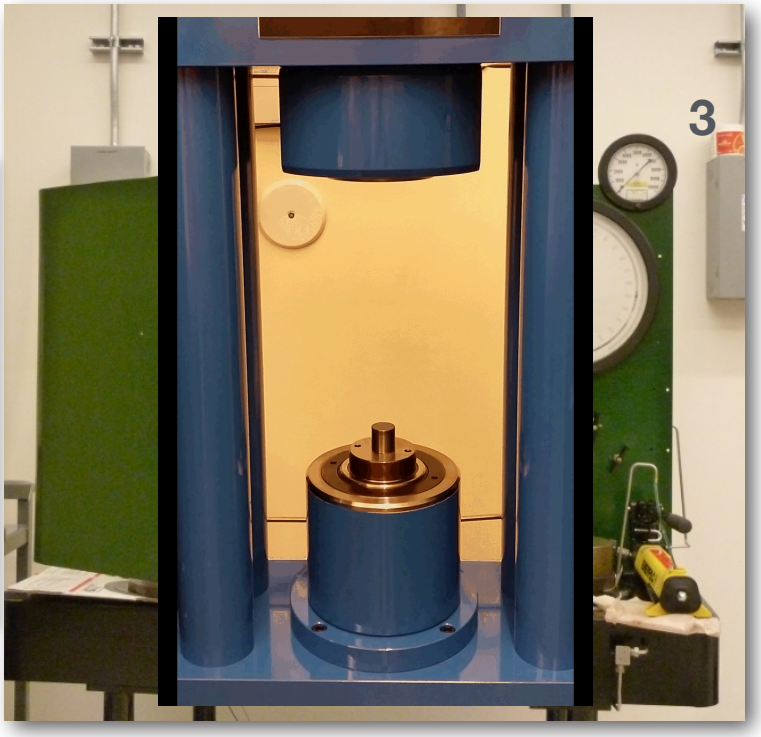
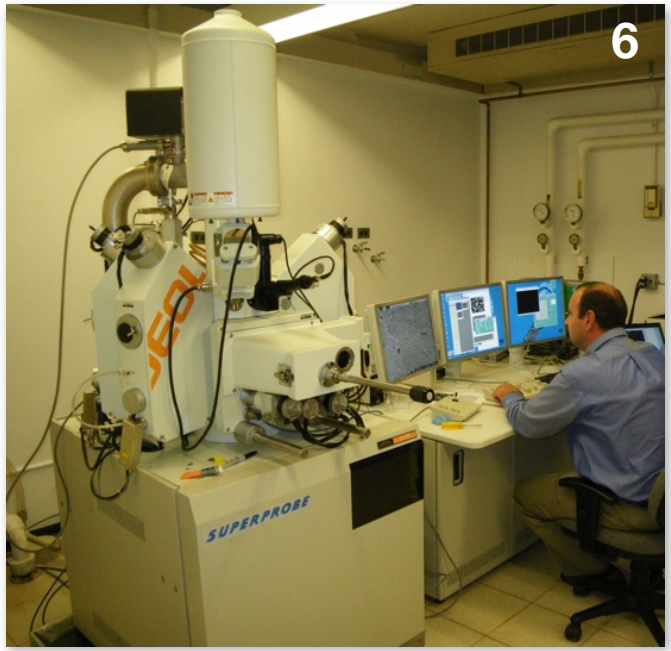
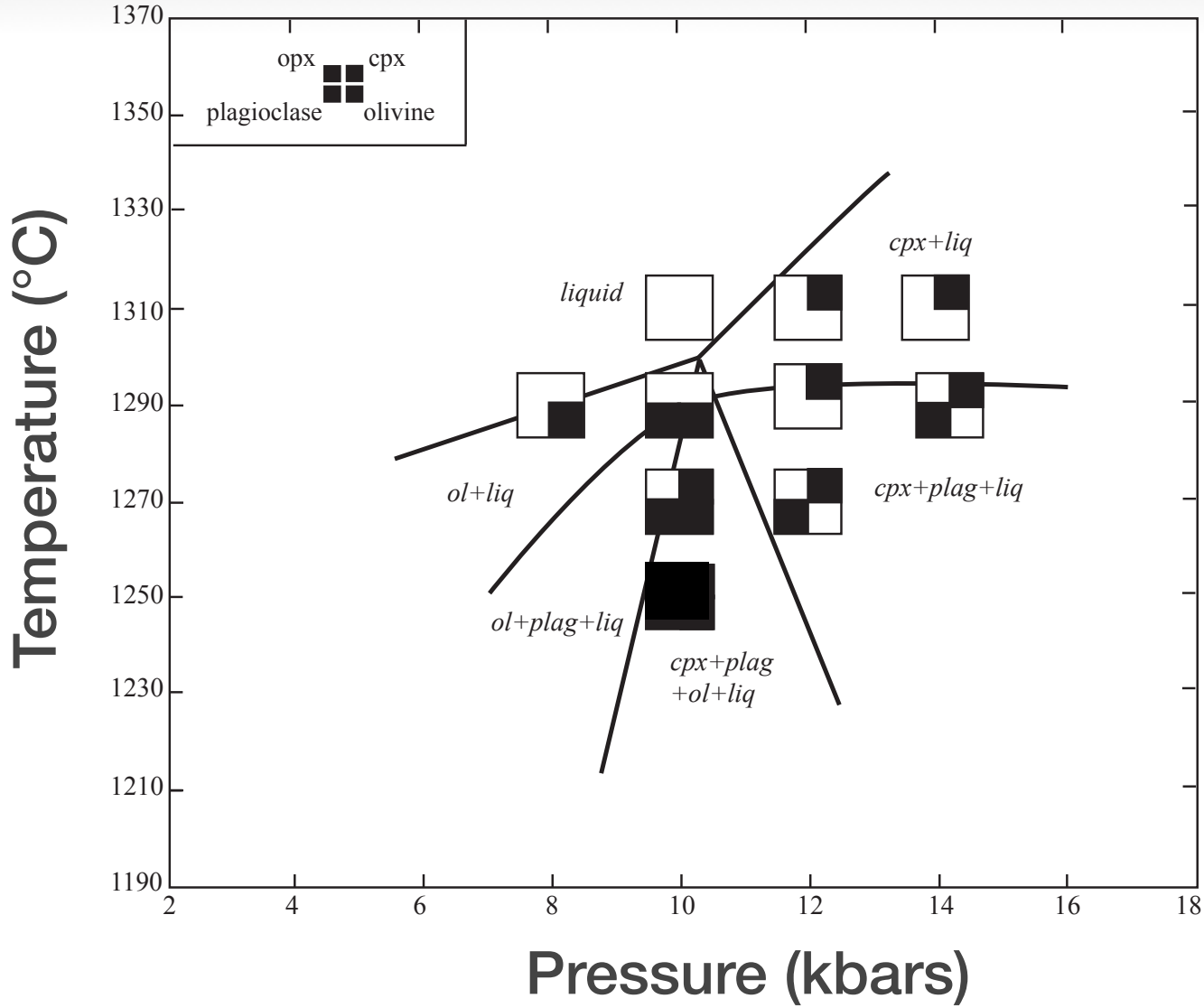


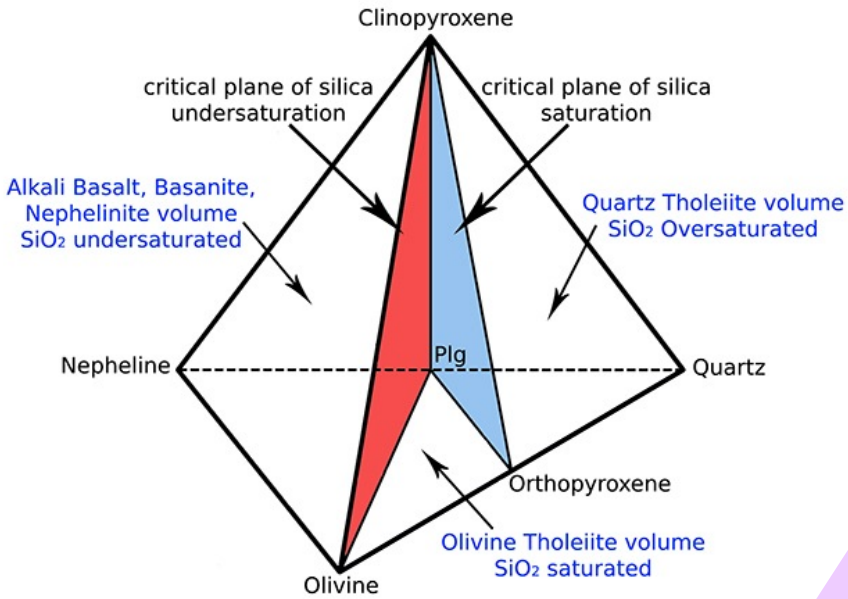


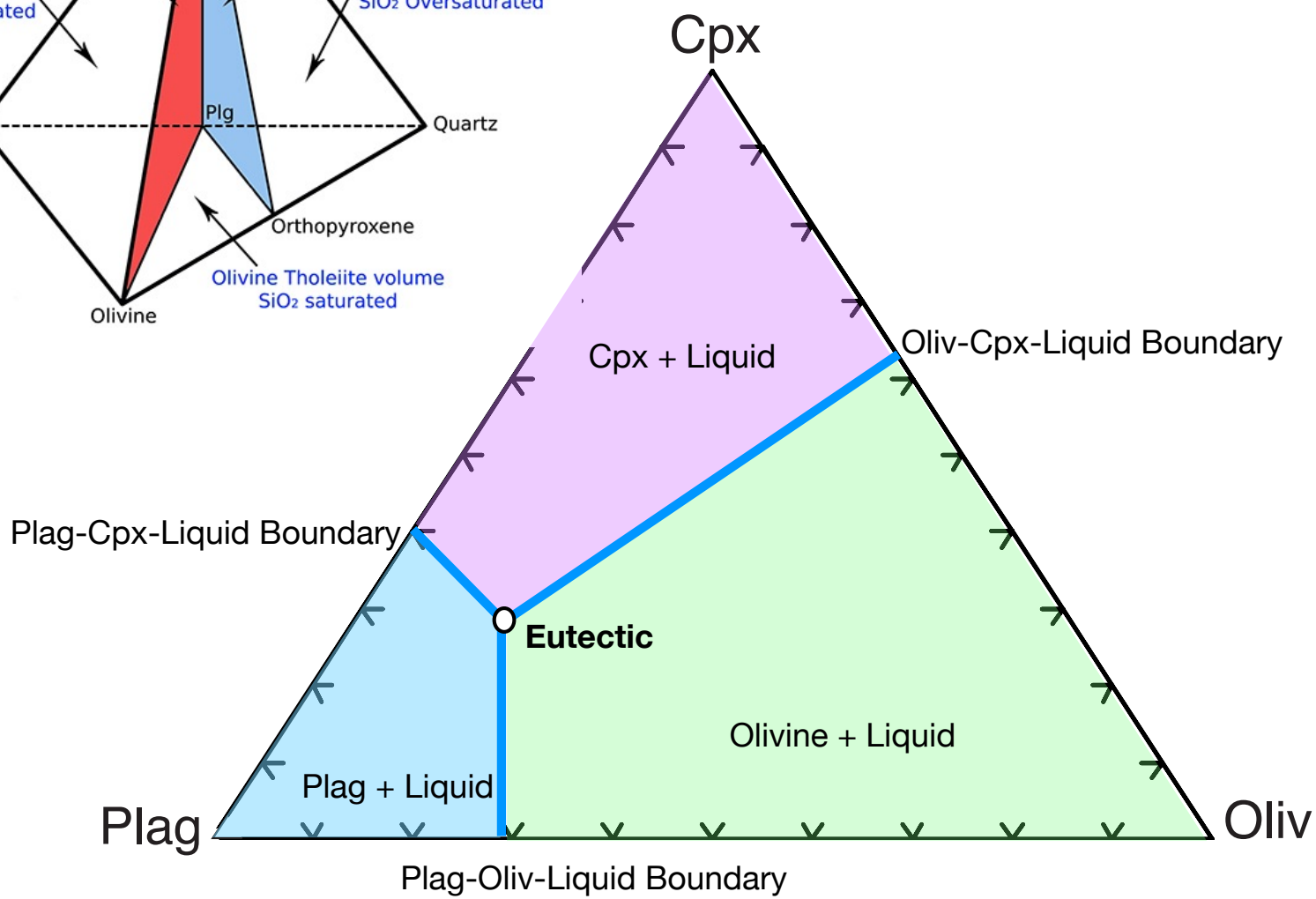
Tools: Experiments and Phase Equilibria



- At a pressure and temperature: what mineral assemblage ± melt is stable?
- What is the chemical composition of the phases in equilibrium with each other?

Melt-Mantle Equilibria from High P-T Experiments





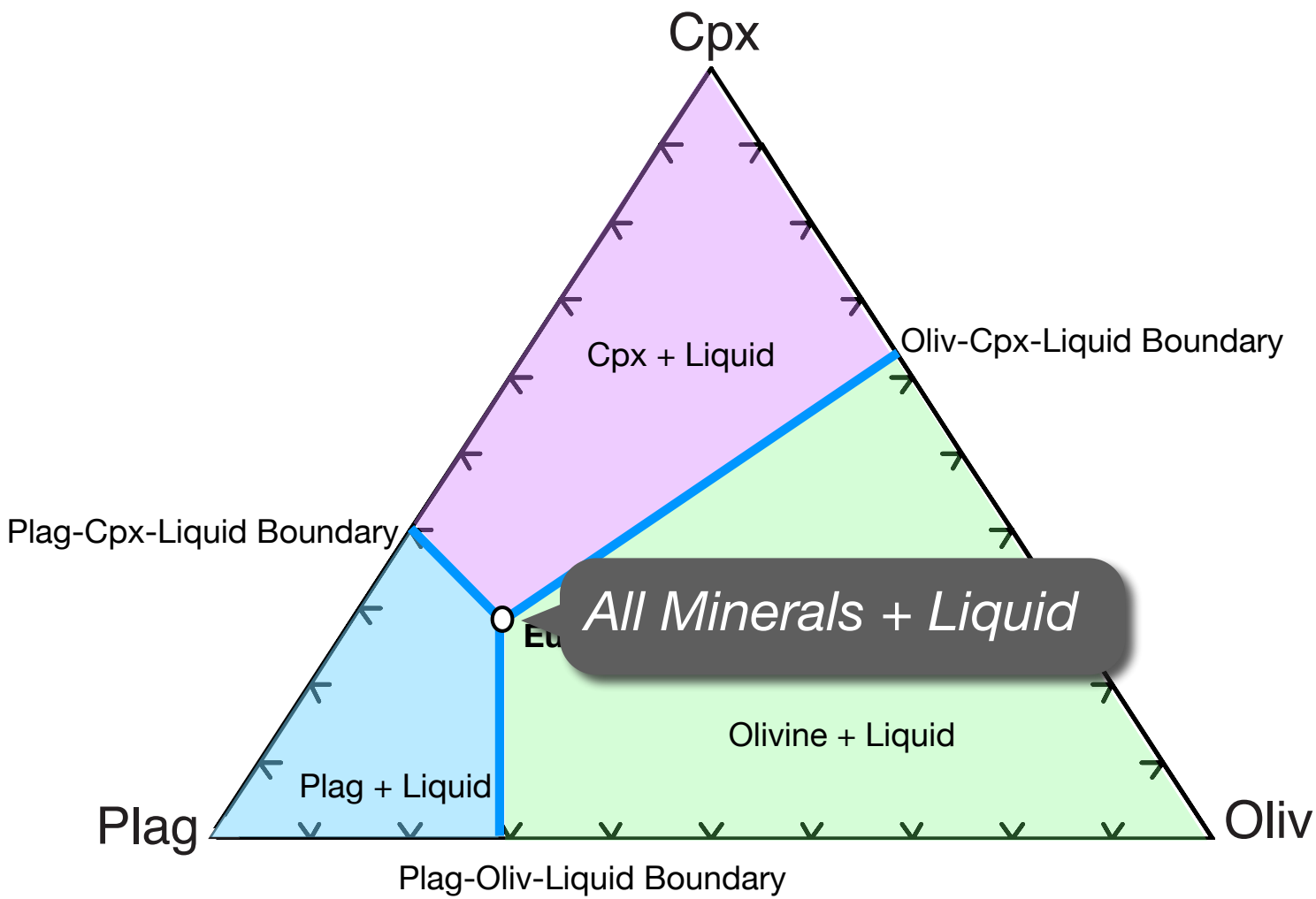
Till et al., JGR, 2012

Melt-Mantle Equilibria from High P-T Experiments

An example:

- Undepleted Mantle Lherzolite Composition

- 4 kilobars



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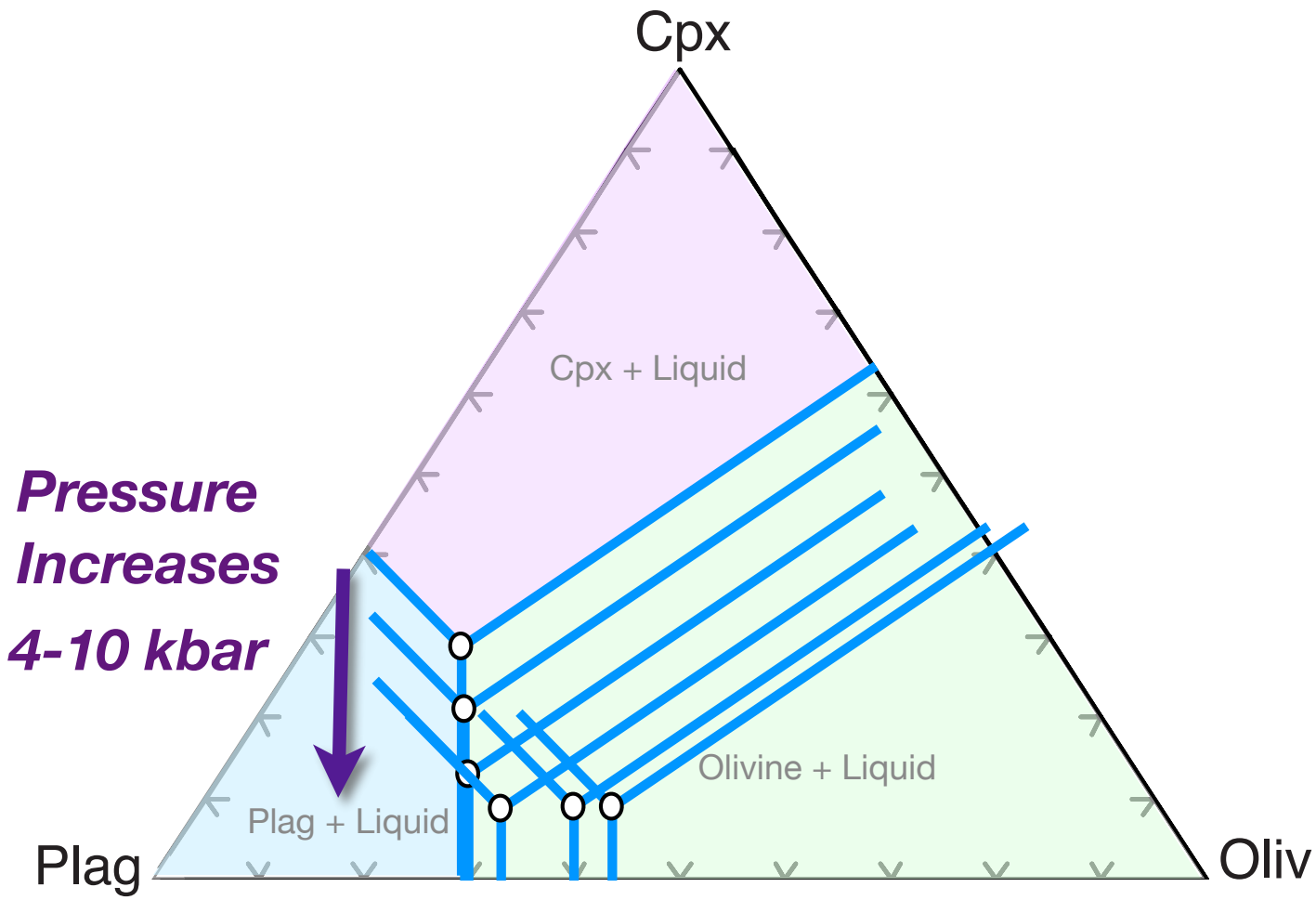

Till et al., JGR, 2012

Melt-Mantle Equilibria from High P-T Experiments

An example:

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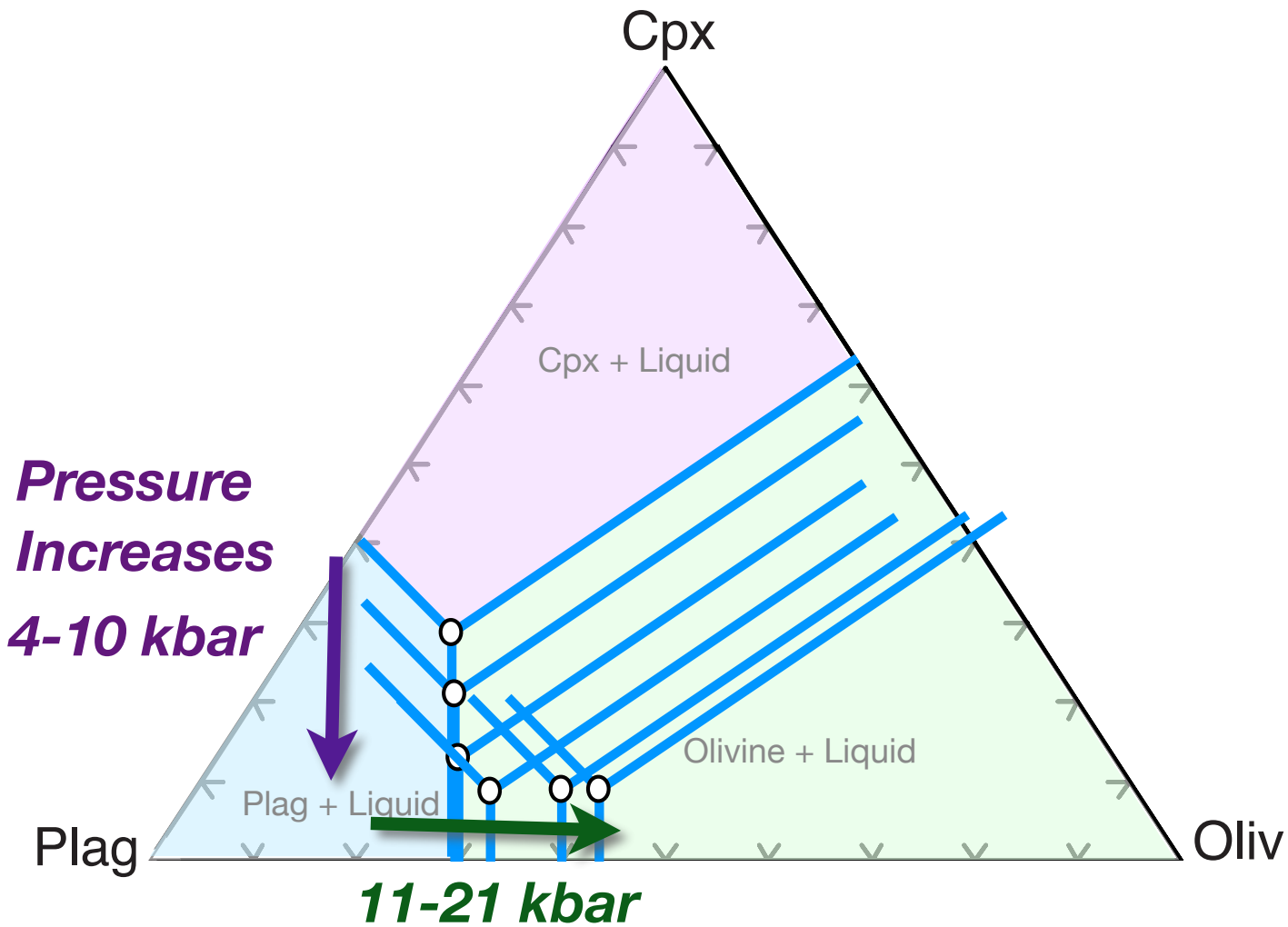
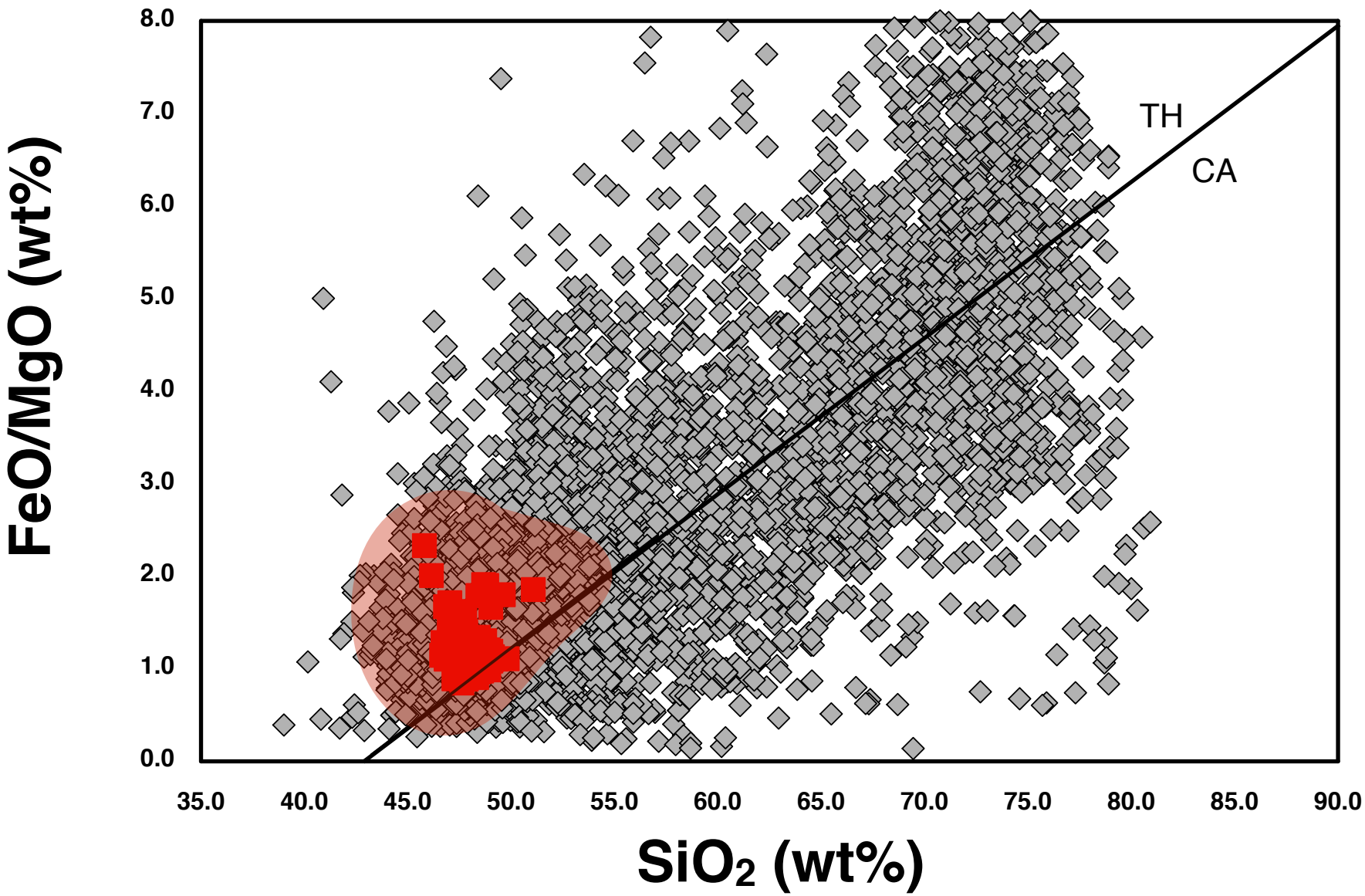


Till et al., JGR, 2012

Great diversity in arc magma compositions



Red Data Points Nominally Anhydrous Primitive Basalts from Cascades + IBM (Till, 2017)

Gray Data Points from GEOROC: 2014 Compilation of Arc Melt Inclusions

Changes in Melt Composition with Pressure-Temperature-Melt Fraction

More recent experiments on melting of fertile mantle lherzolite (initially garnet-bearing) confirm that:

alkaline basalts are favored by **higher P** and **low F** (as a result **higher T**)

whereas **tholeiites** are favored **by higher F** and **lower P** **(**as a result **lower T**)

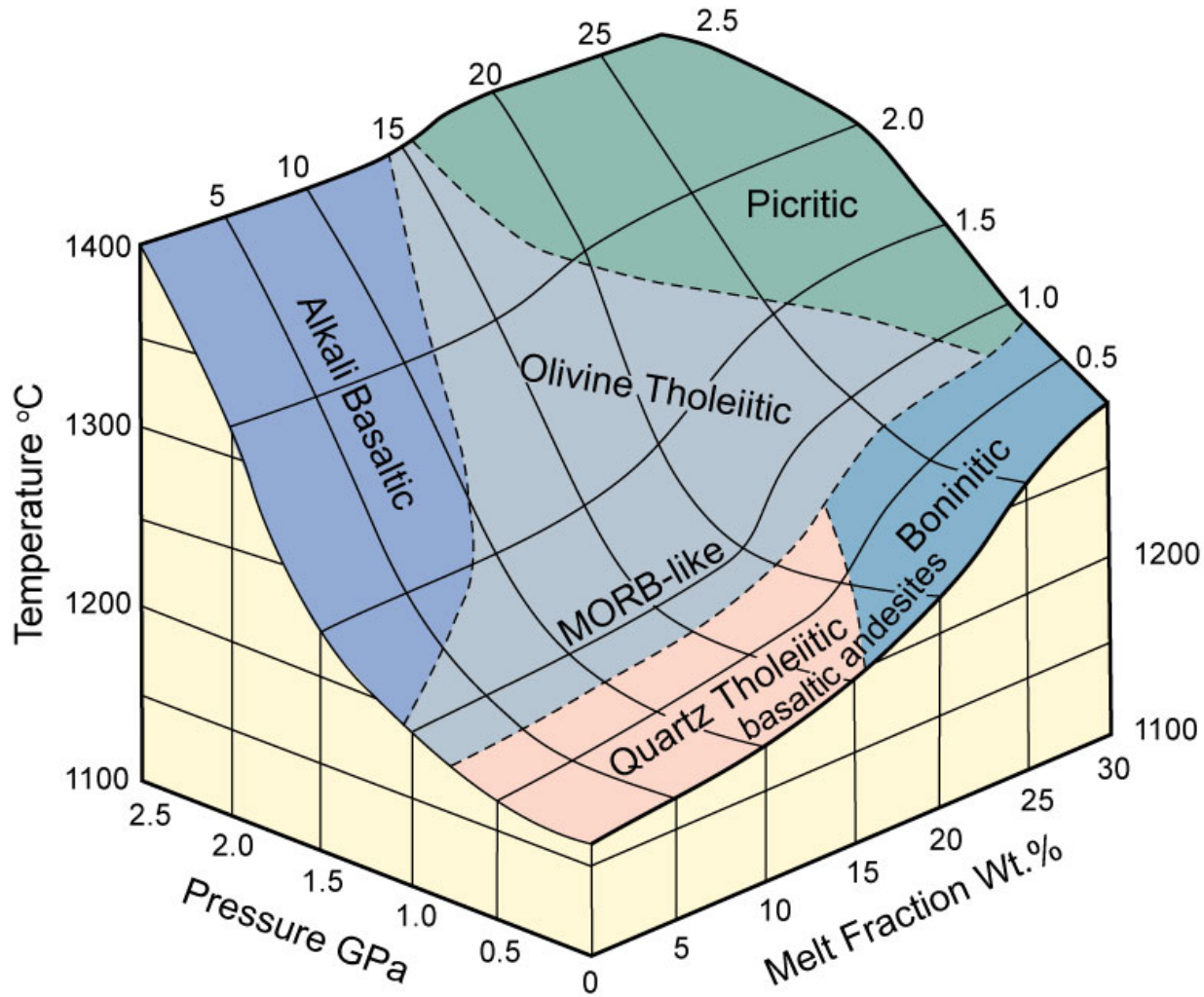
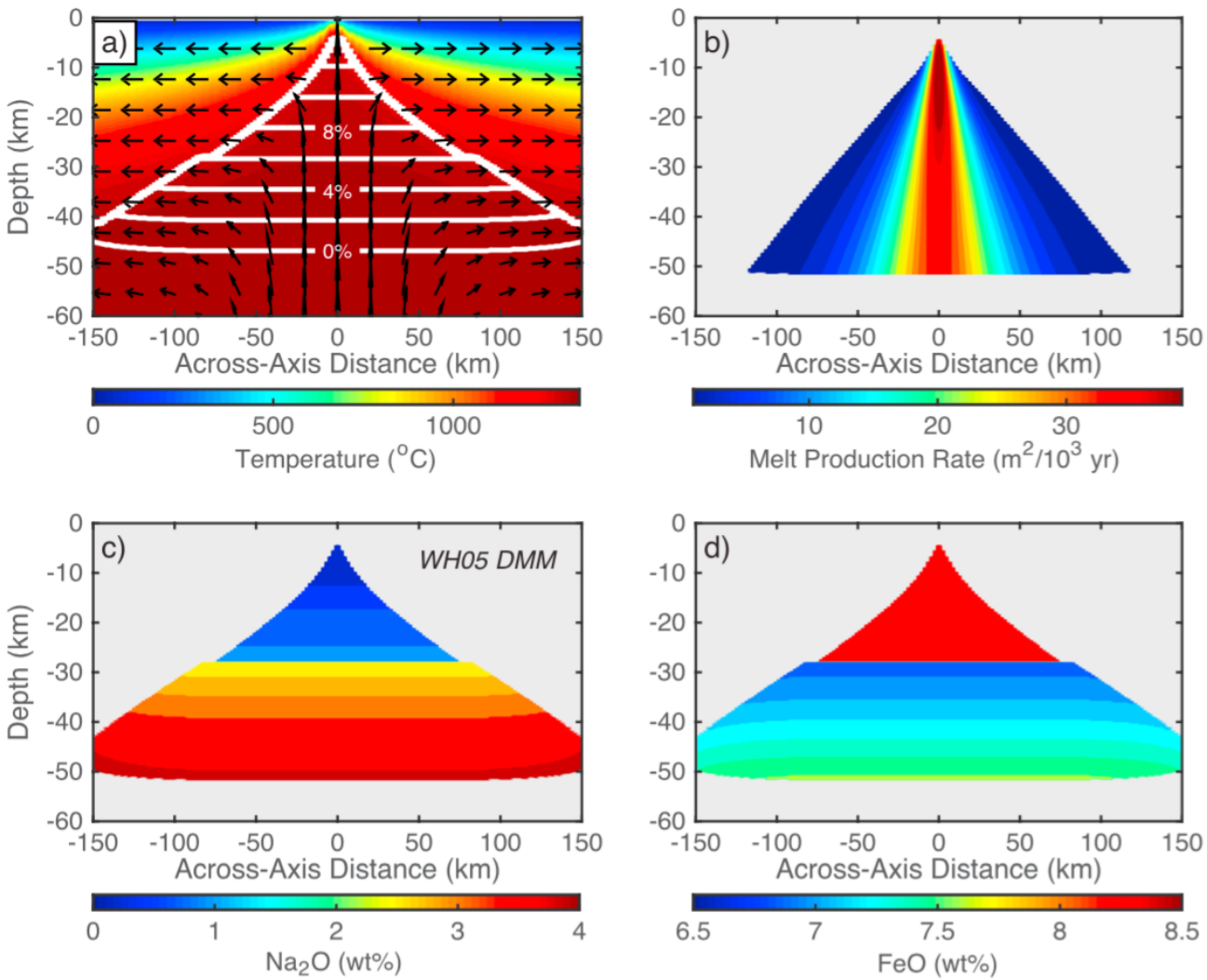


Figure after Kushiro (2001)

Good forward geochemical models of dry mantle melting

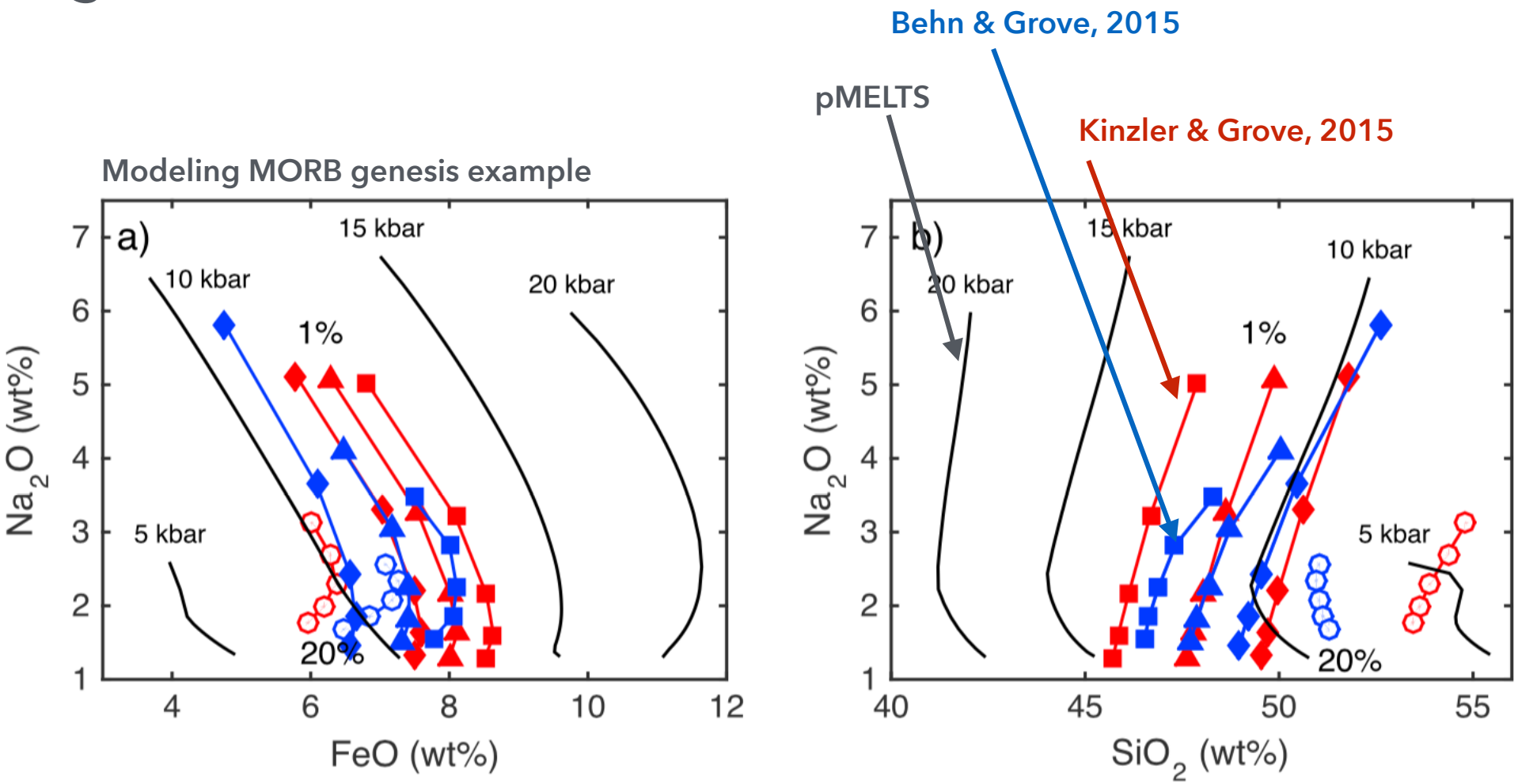


Behn & Grove, 2015

Grove et al., 2013; Till et al., 2012; Ghiorso et al., 2002; Kinzler & Grove, 1992

Forward geochemical models of dry mantle melting don't all agree

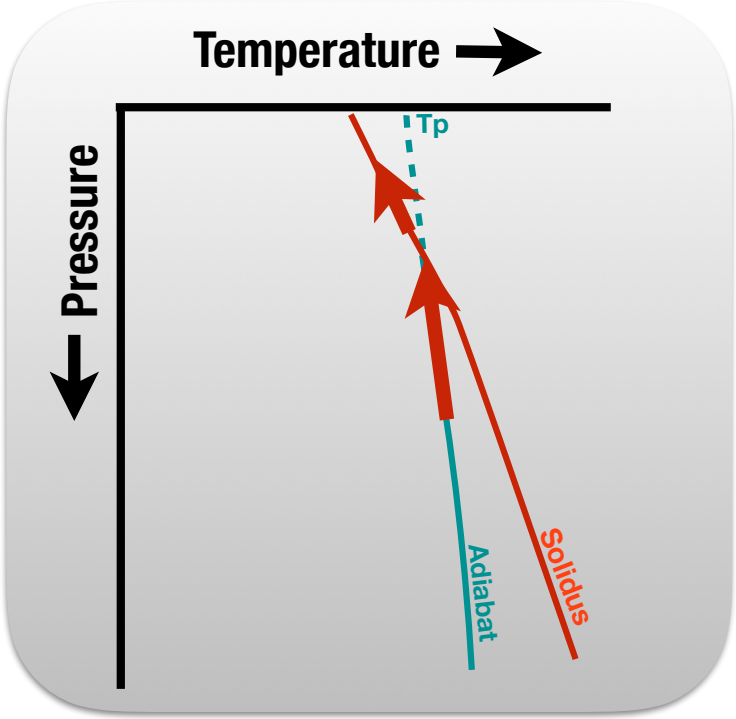
Modeling MORB genesis example

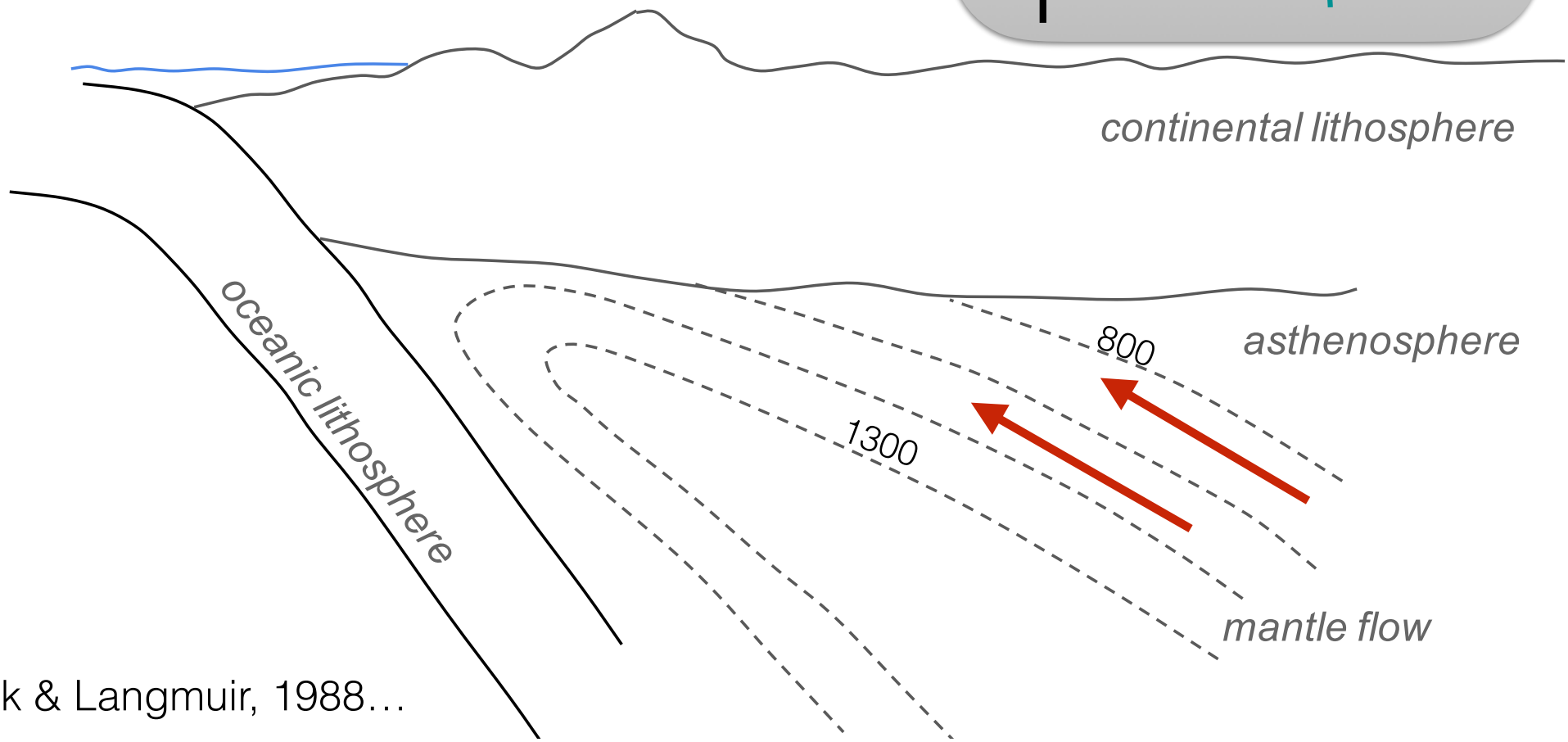


Behn & Grove, 2015

Grove et al., 2013; Till et al., 2012; Ghiorso et al., 2002; Kinzler & Grove, 1992

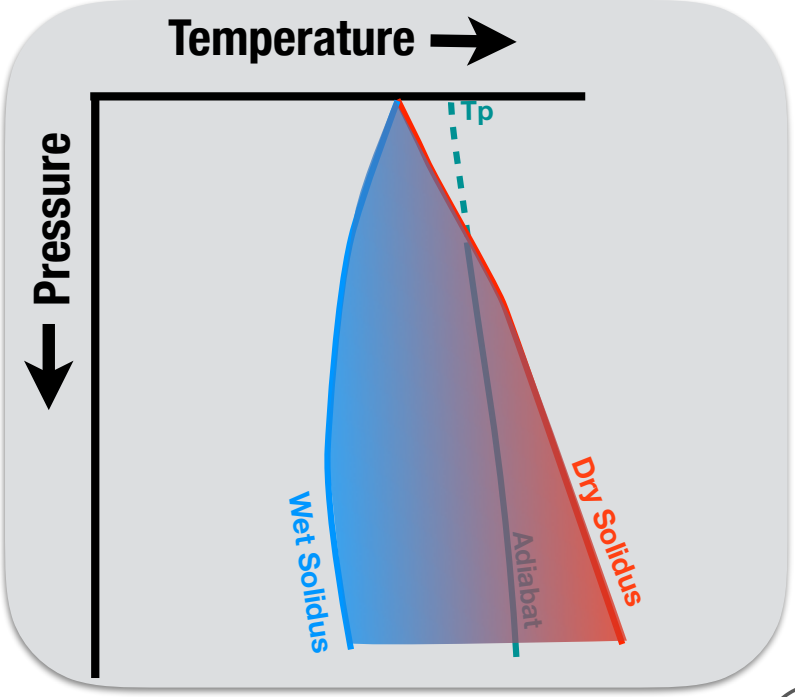
Adiabatic Decompression or "Dry" Mantle Melting (Tholeiites)



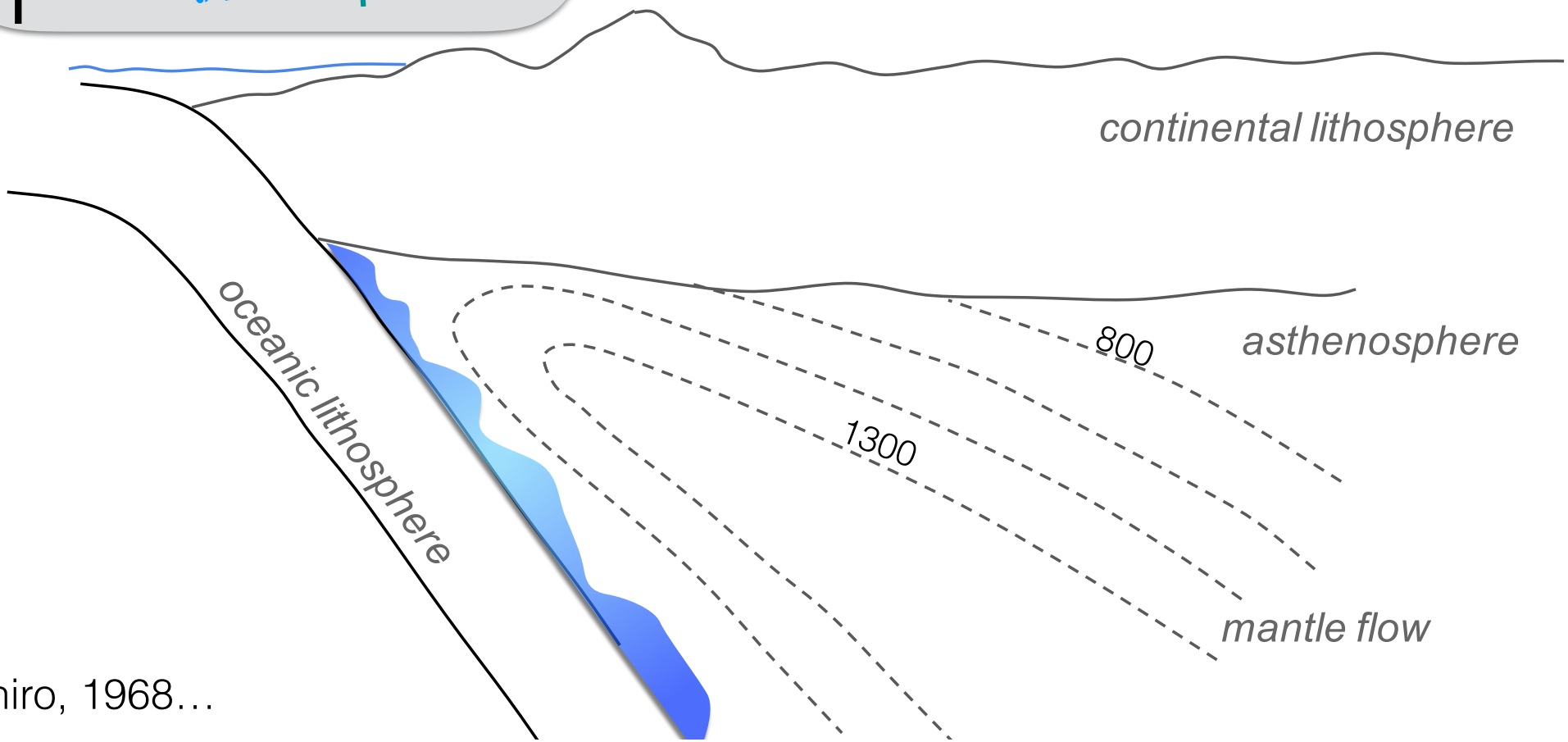


Plank & Langmuir, 1988…

Now what happens if H_2O added…

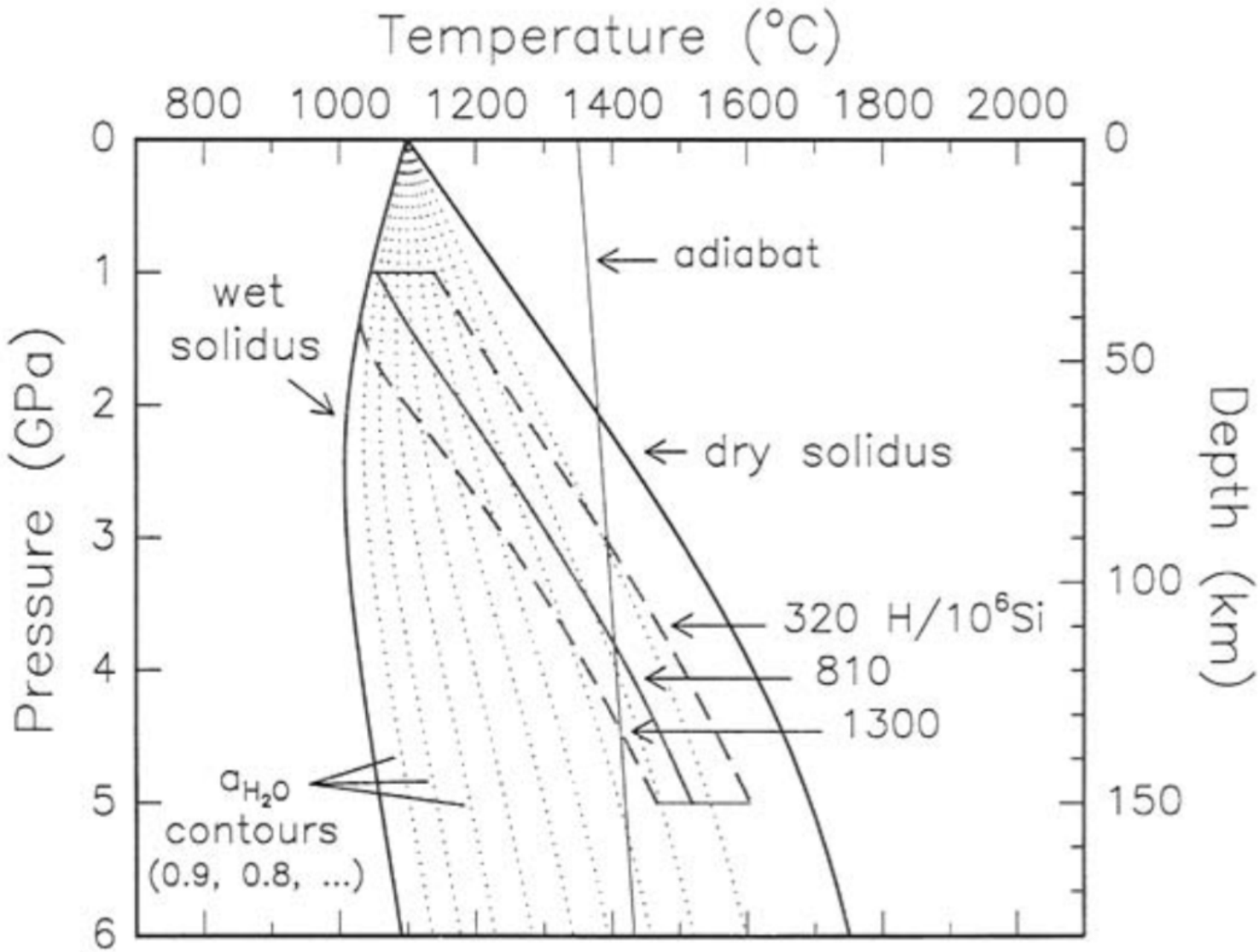


Flux or "Wet" Mantle Melting (Calc-Alkaline Magmas)



Kushiro, 1968…

H_2O added —-> Depress solidus temps

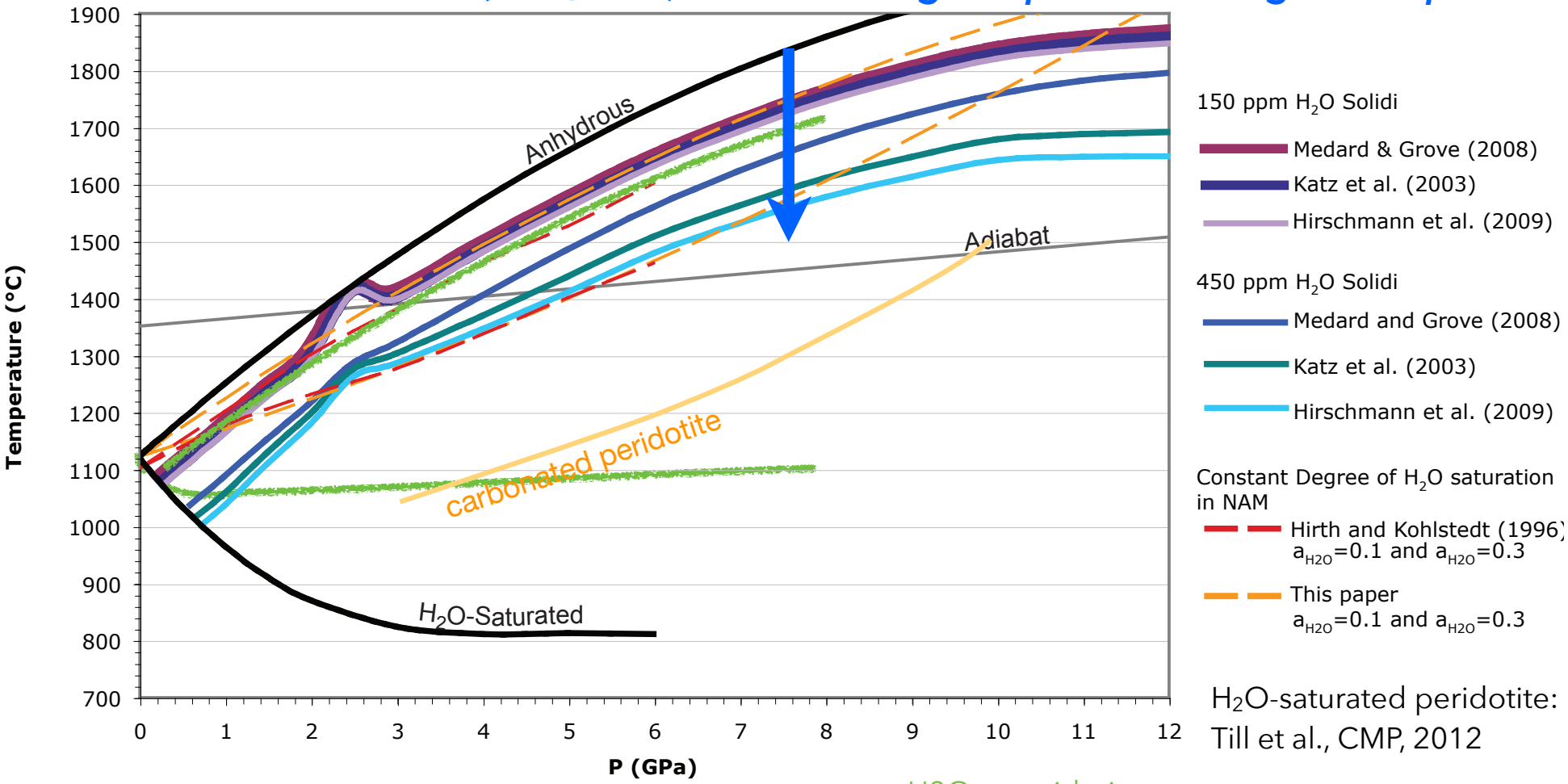


Hirth & Kohlstedt, 1996

H_2O added –-> Depress solidus temps

…but by how much?

volatiles (H_2O, CO_2) lower melting temperature at a given depth

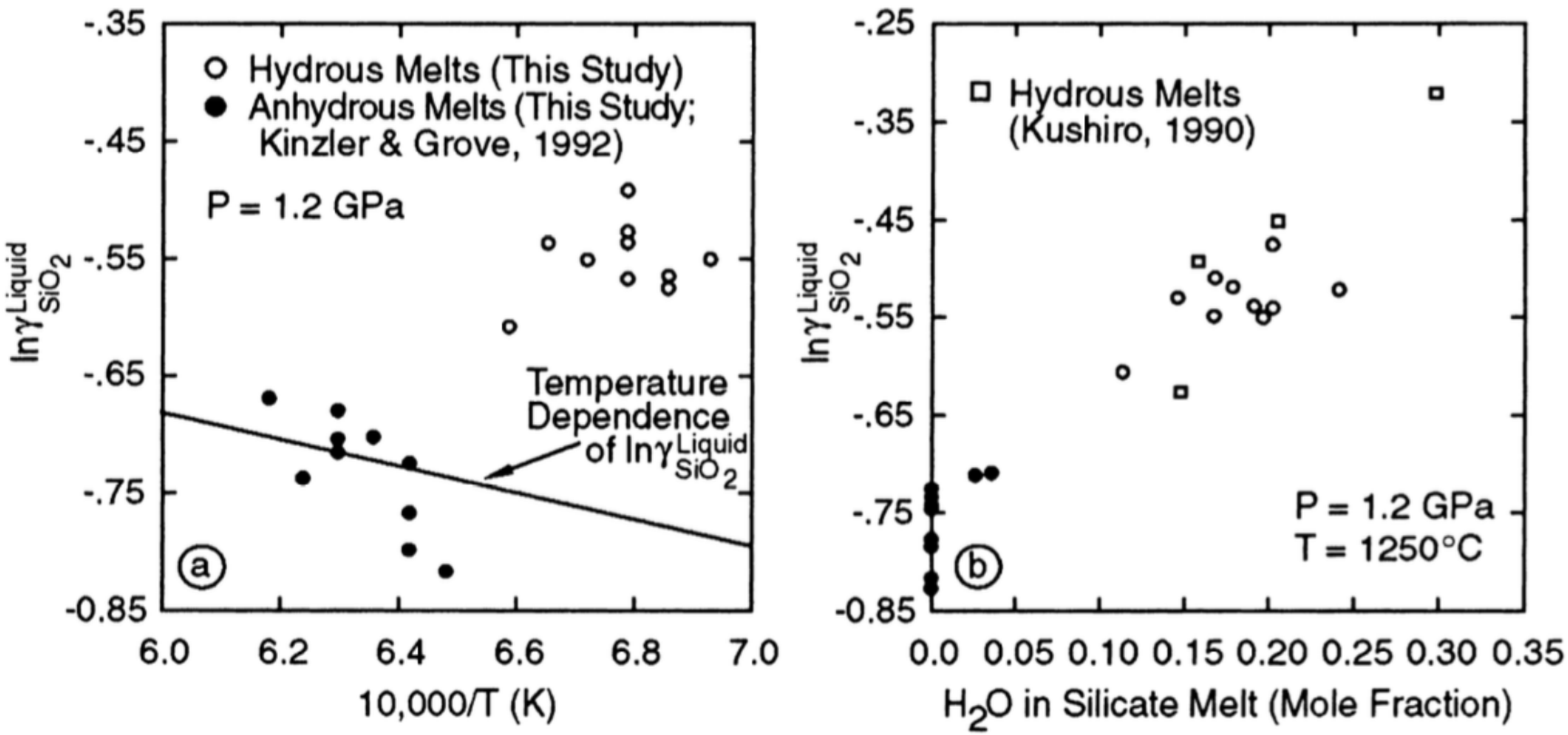


H_2O-saturated peridotite: Till et al., CMP, 2012

H2O + peridotite: Katz et al, 2003

carbonated peridotite: Dasgupta & Hirschmann, 2006

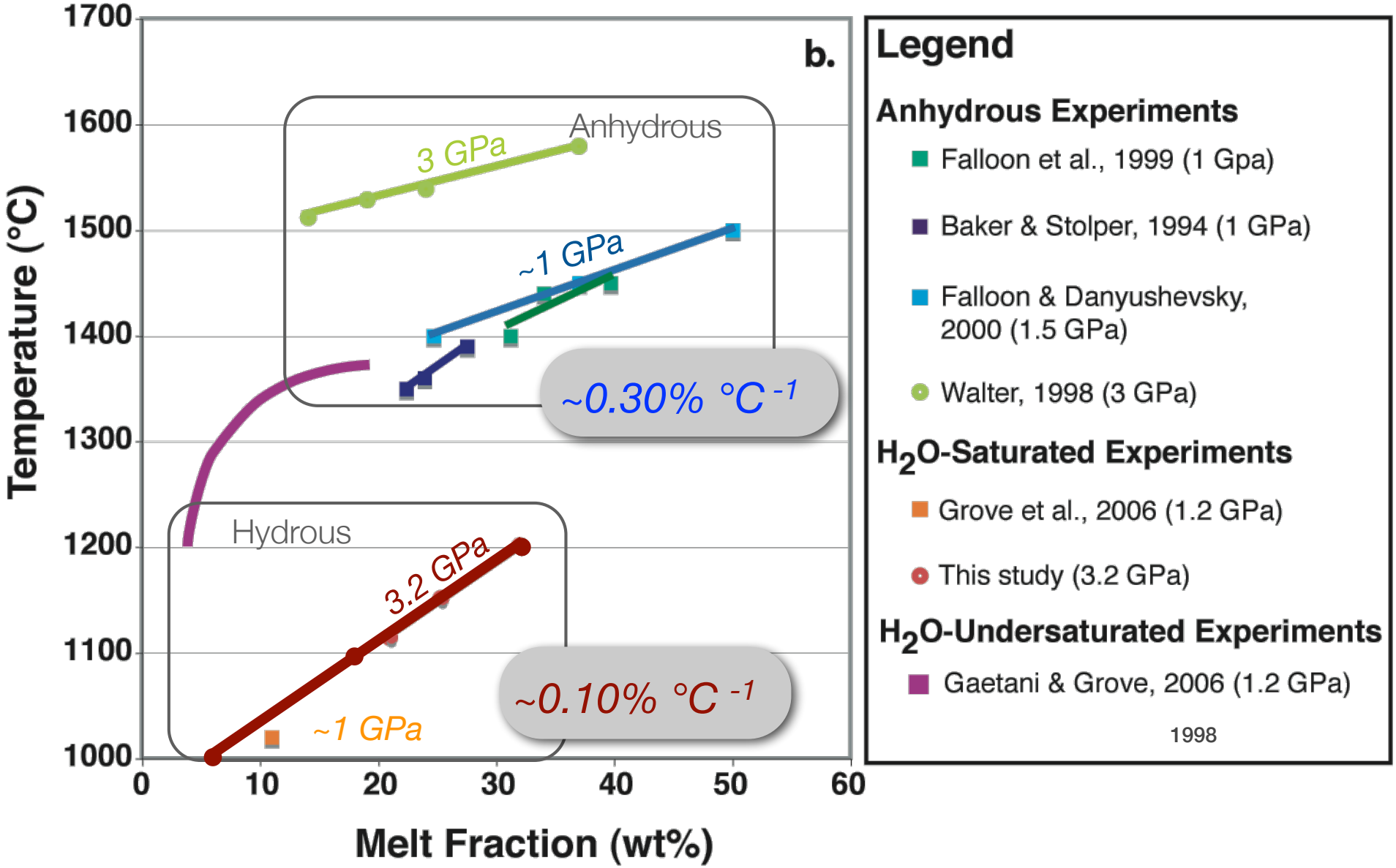
Melting in the presence of H_2O changes melt composition



"…produce elevated SiO2/(MgO + FeO) in hydrous peridotite partial melts, mkaing them relatively SiO2-rich compared to anhydrous melts. The lower FeO + MgO concentrations result from the lower temperatures at which H2O-bearing melts coexist with mantle minerals."

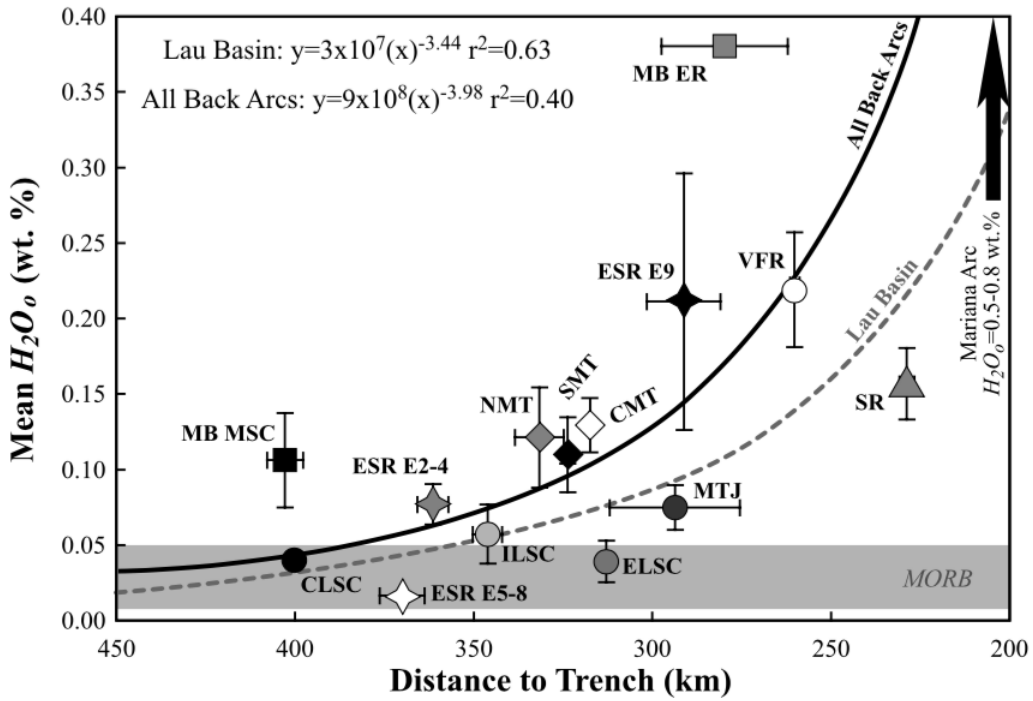
Gaetani and Grove, 1998

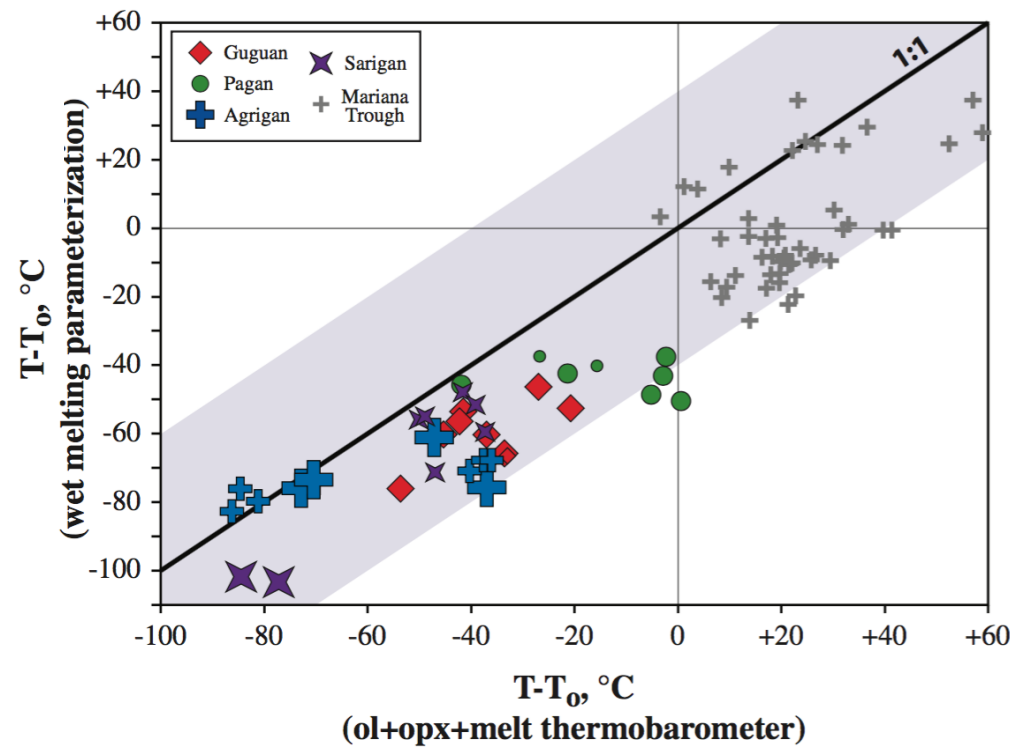
Melting in the presence of H_2O changes melt productivity



Till & Grove, in prep.

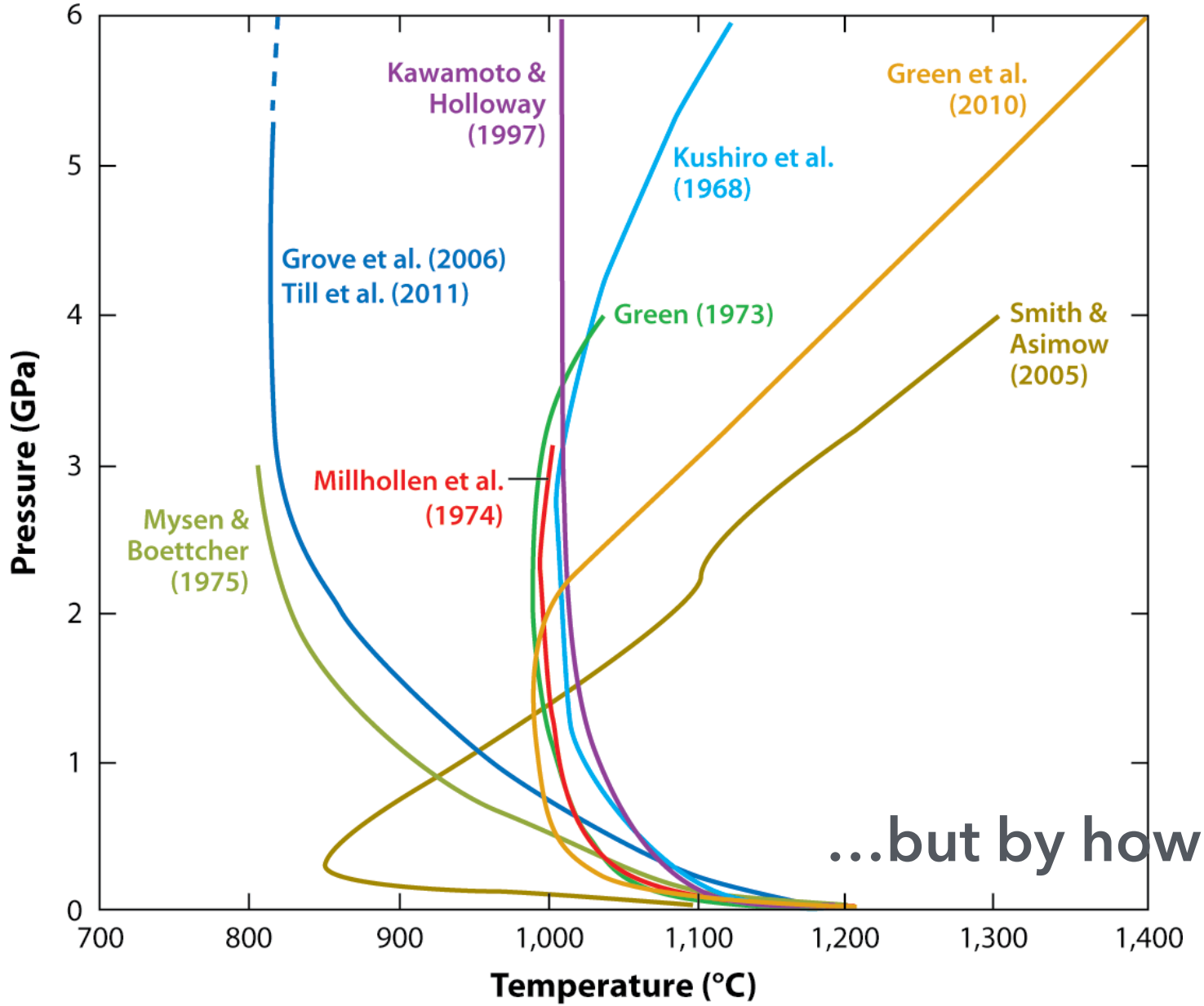
Also relevant to back-arc basins





Kelley et al., 2006; Kelley et al., 2010

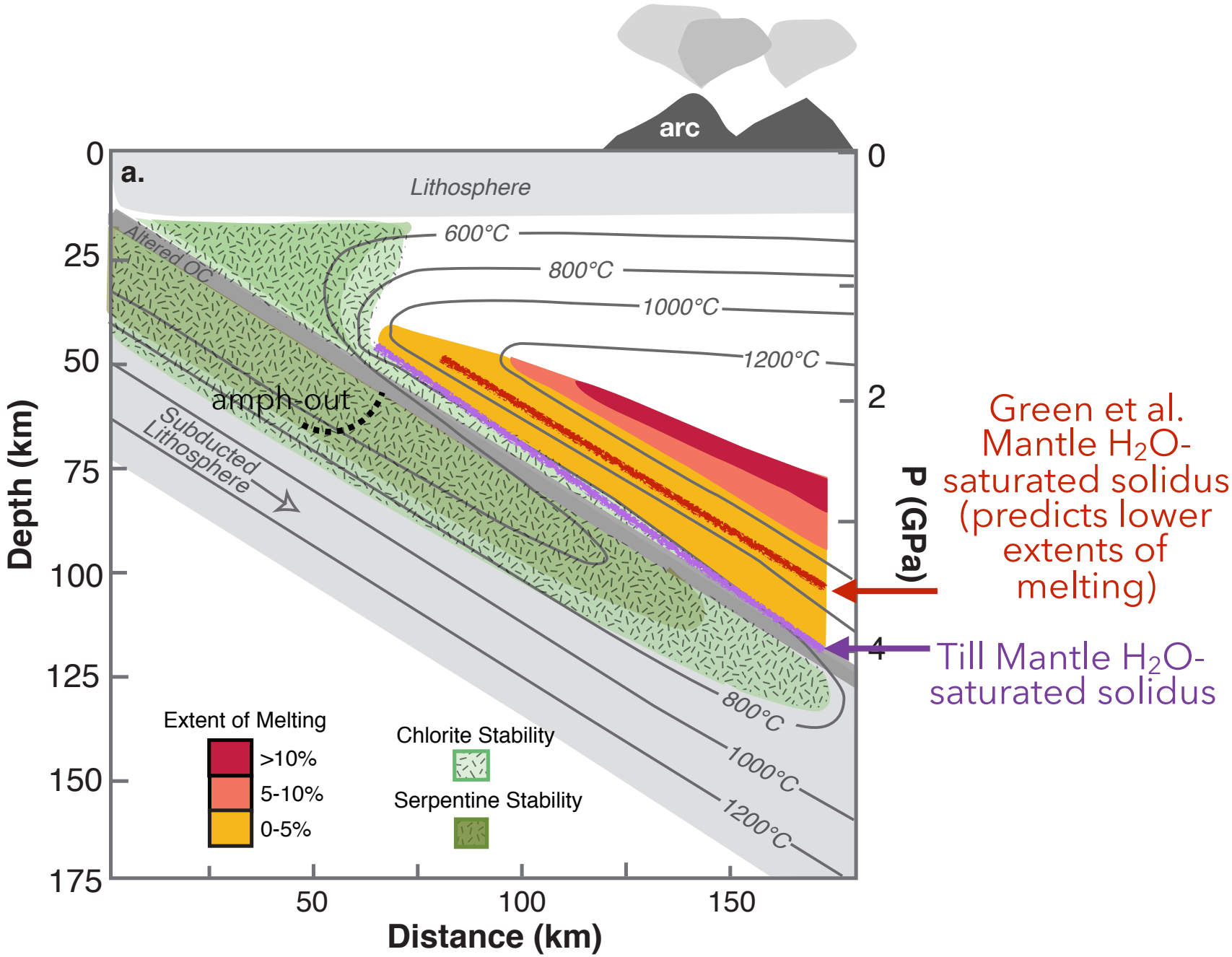
Now what happens if a *lot of* H_2O added? Depress solidus temps…



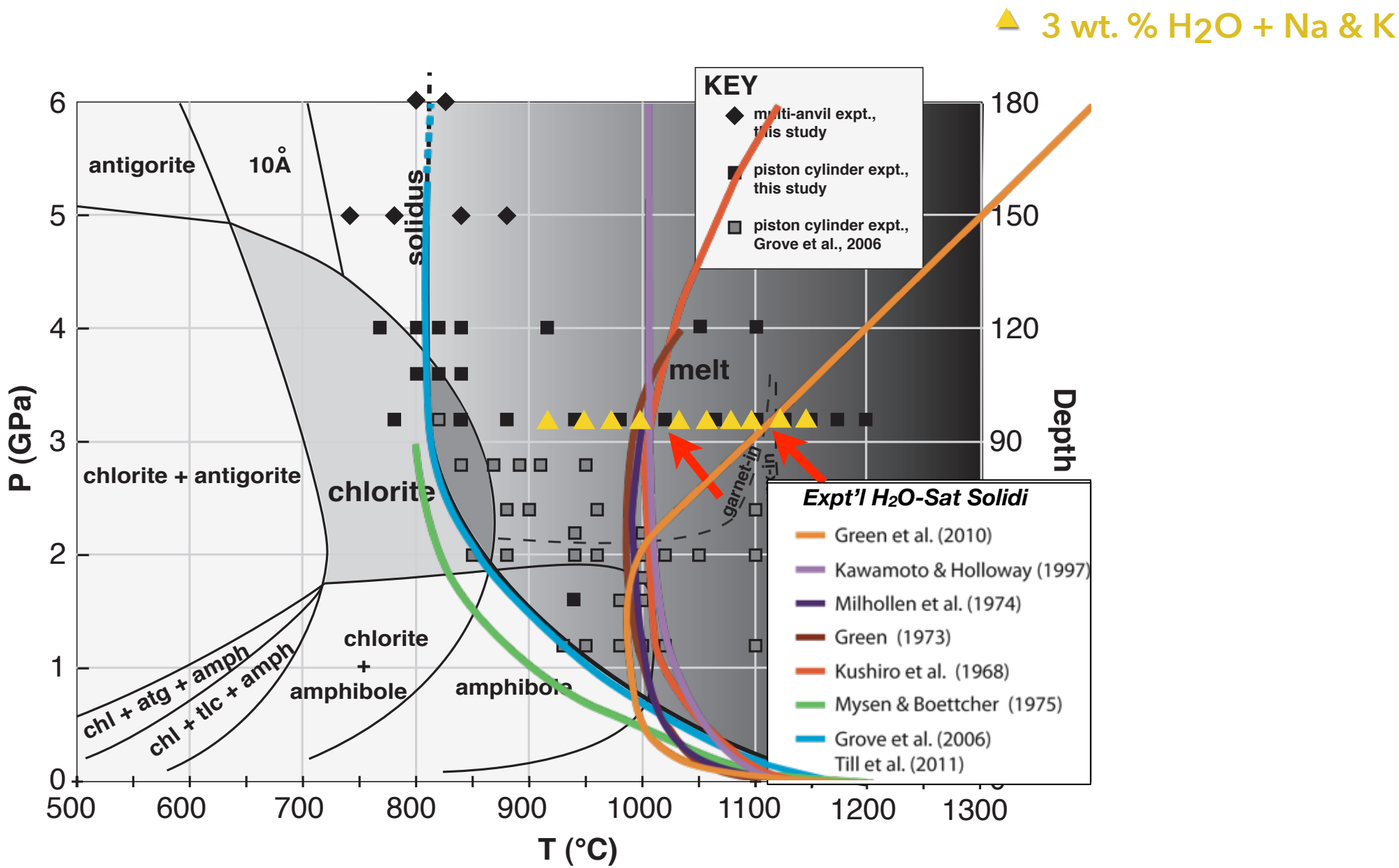
…but by how much?

Grove et al., 2012

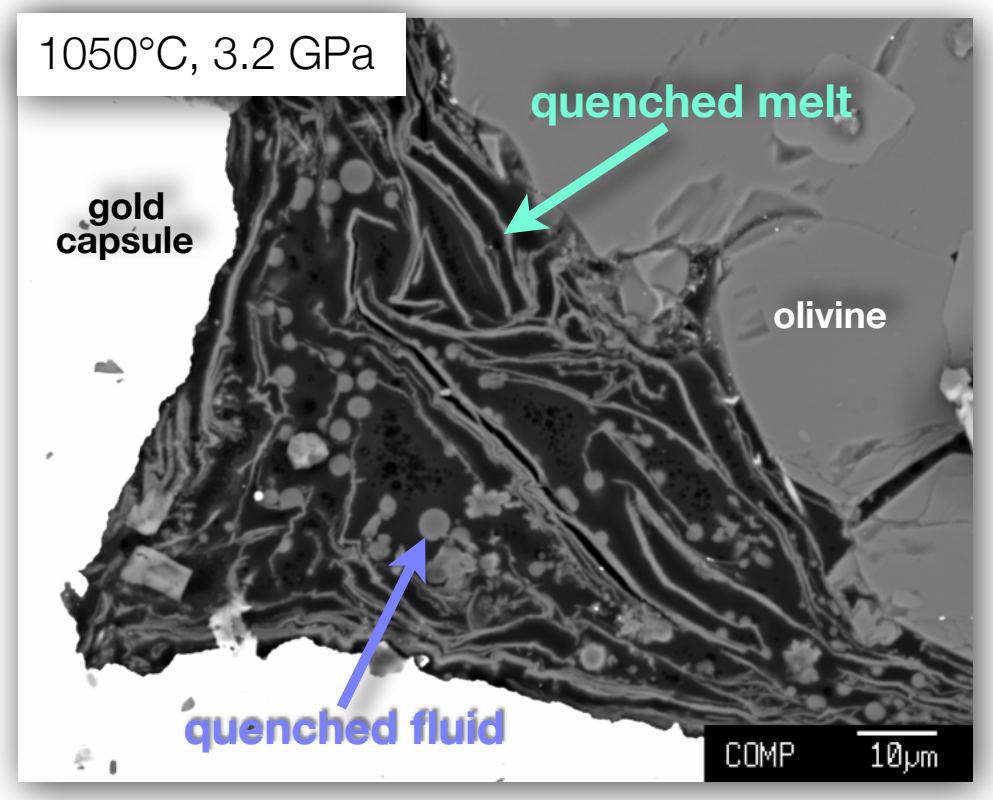
Where does wet melting begin in the mantle wedge?

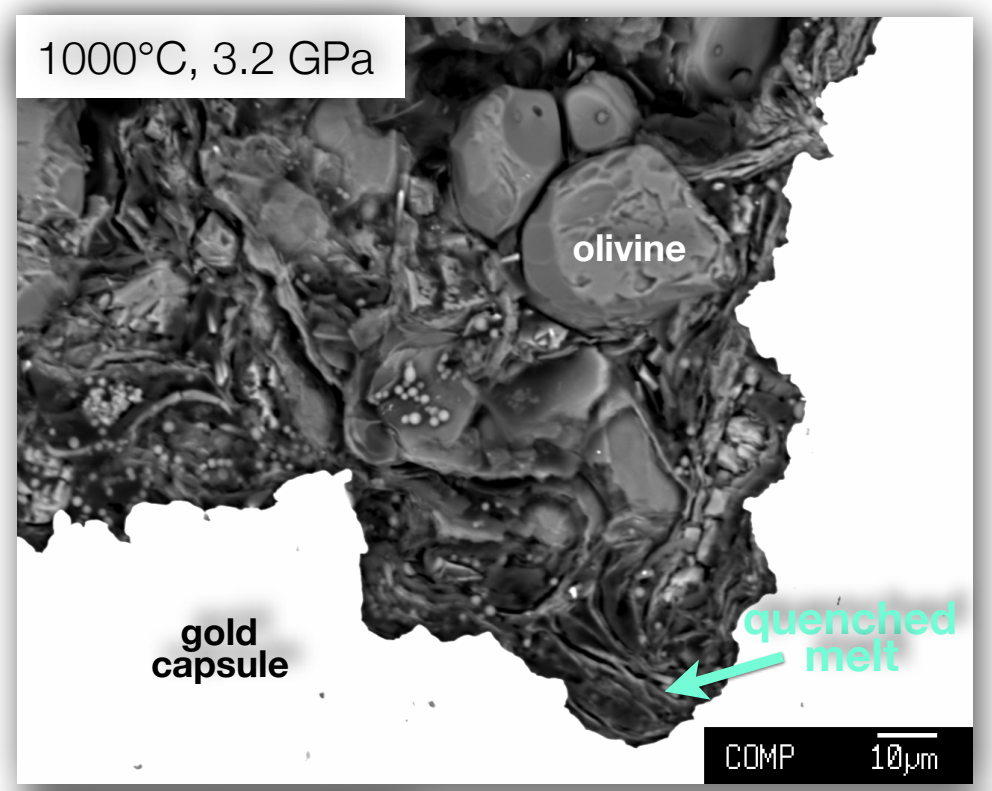


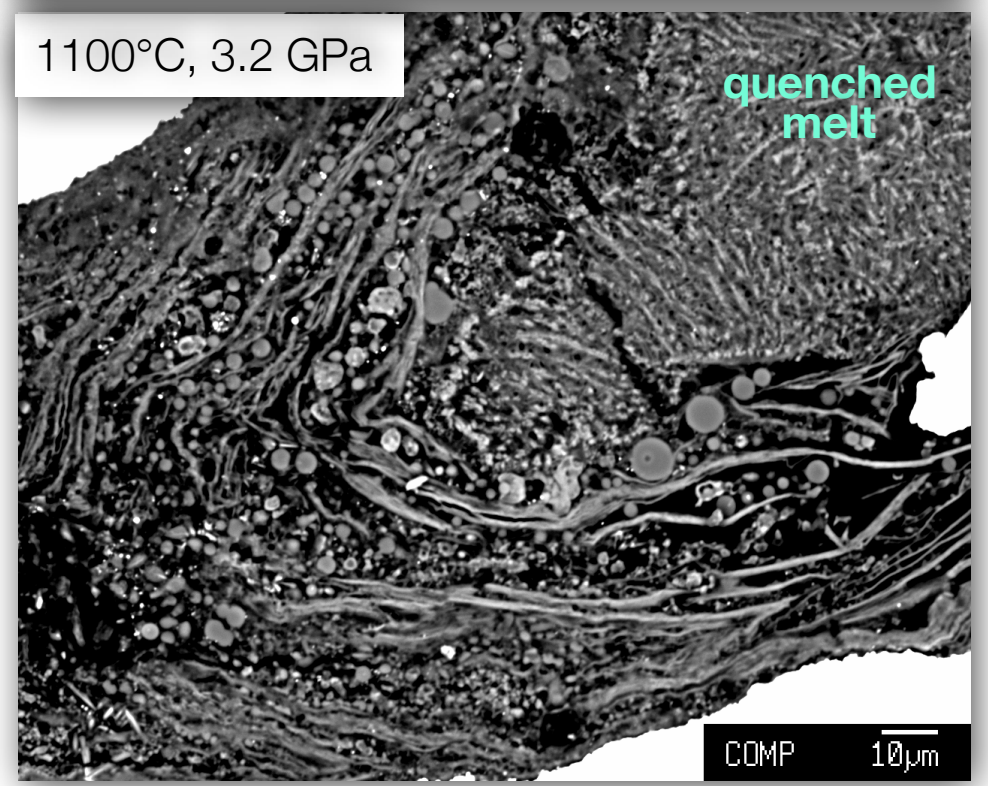
What is the composition of early wet melts?



Quenched Melt & Fluid

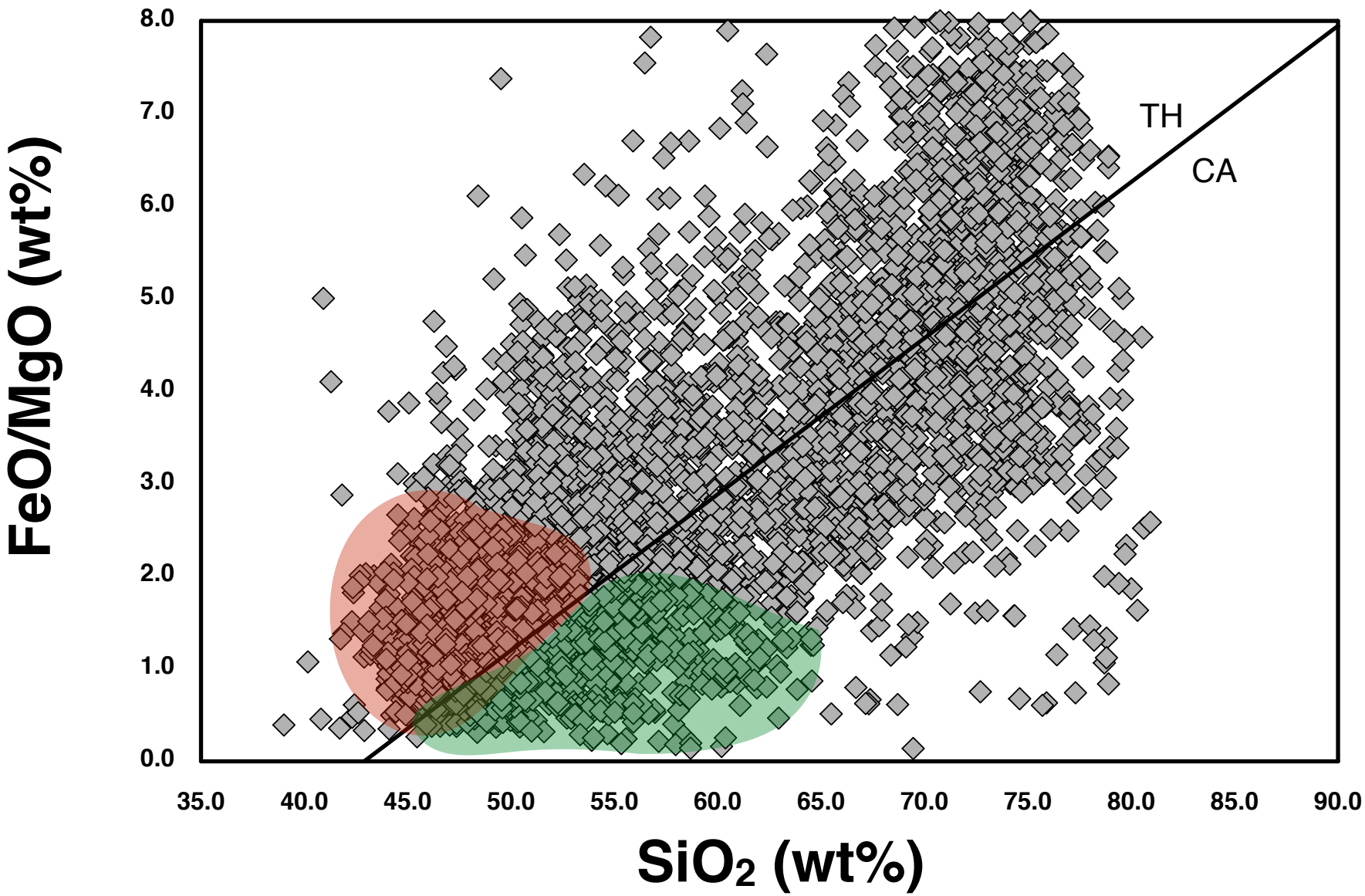






(Till et al.,Cont. Min. Pet., 2012)

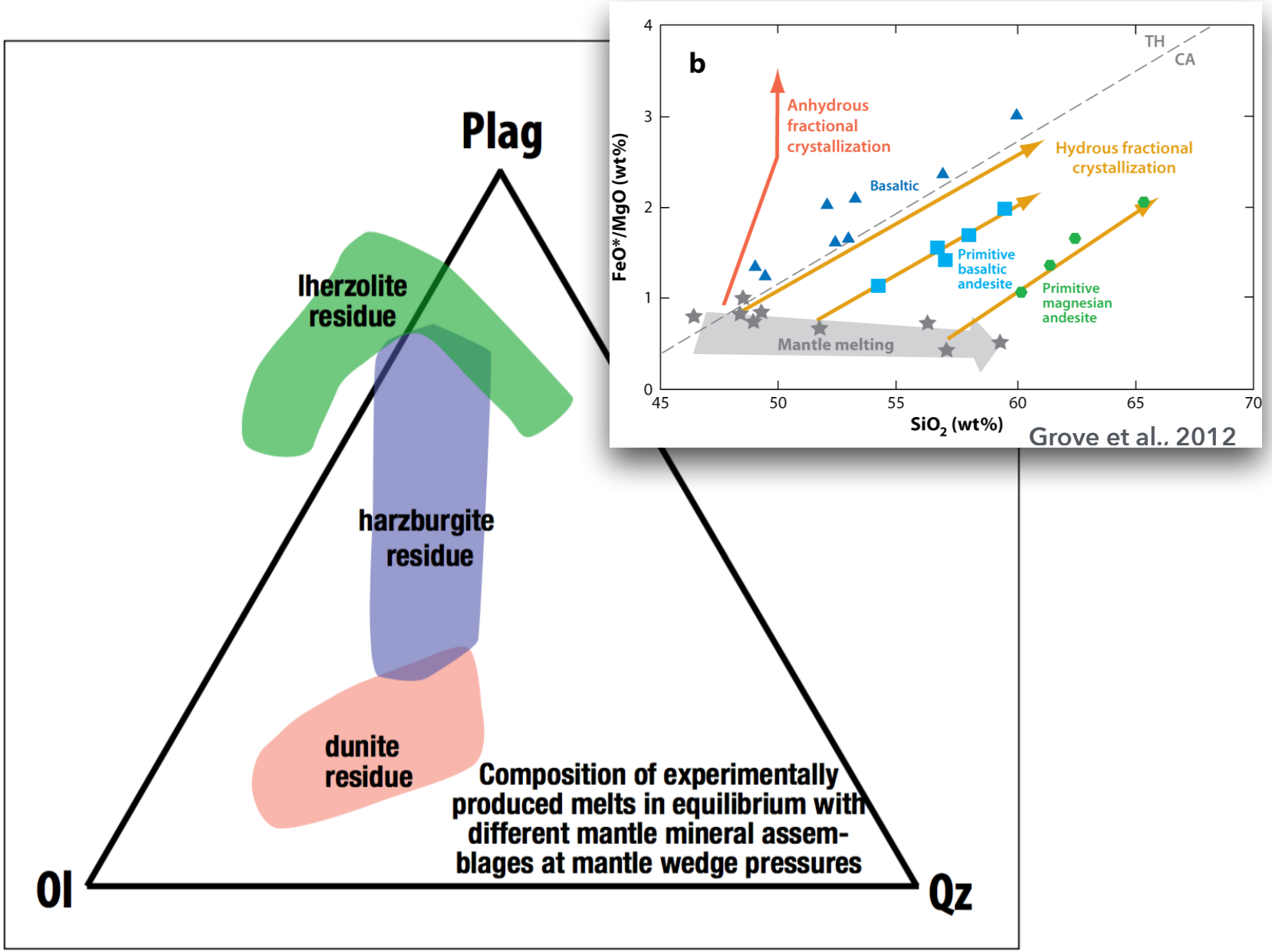
What primitive compositions explained by wet melting….



Green Data Points Hydrous Primitive Basalts from Cascades + IBM (Till, 2017)

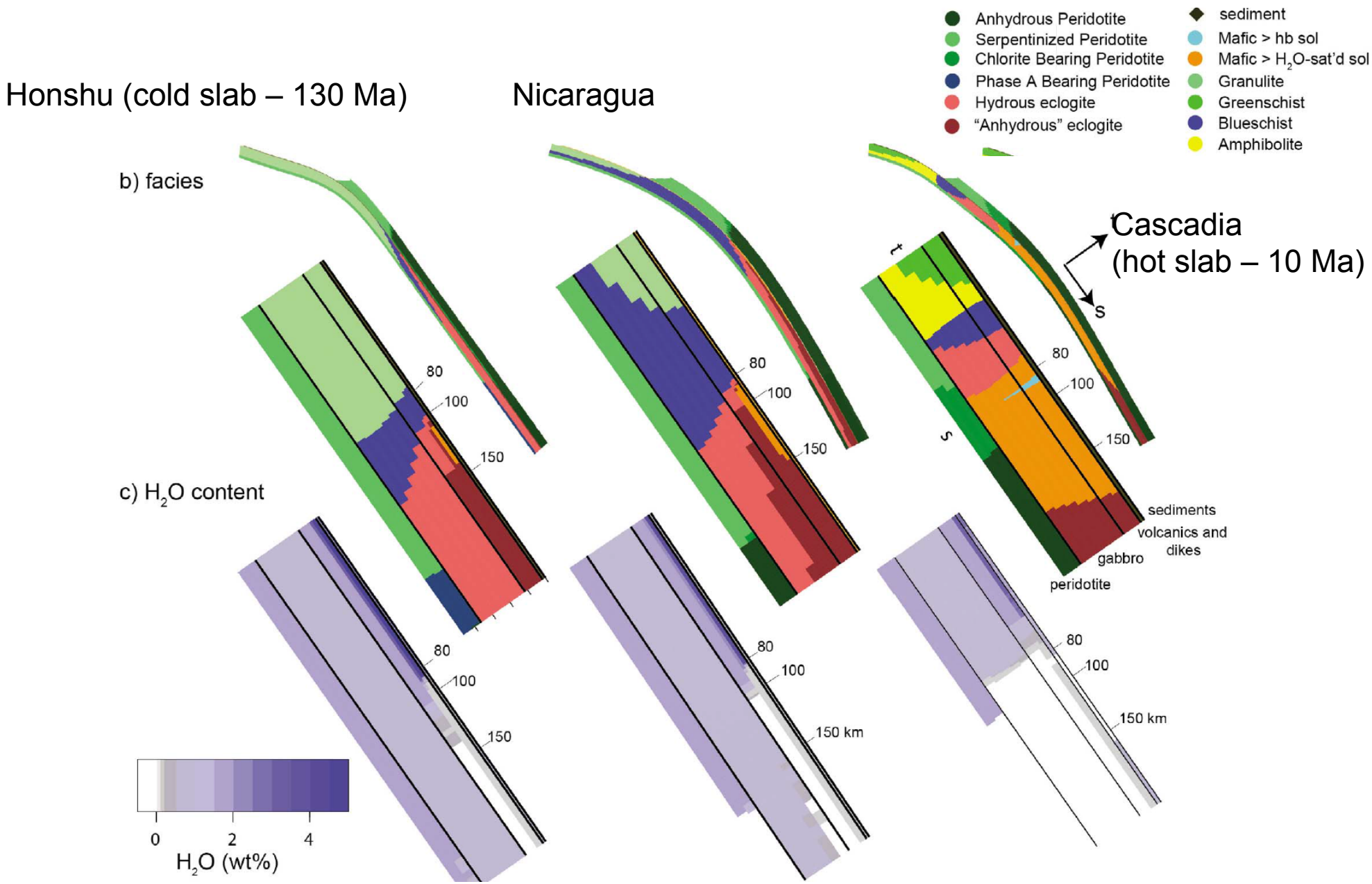
Gray Data Points from GEOROC: 2014 Compilation of Arc Melt Inclusions

Effect of mantle residue composition



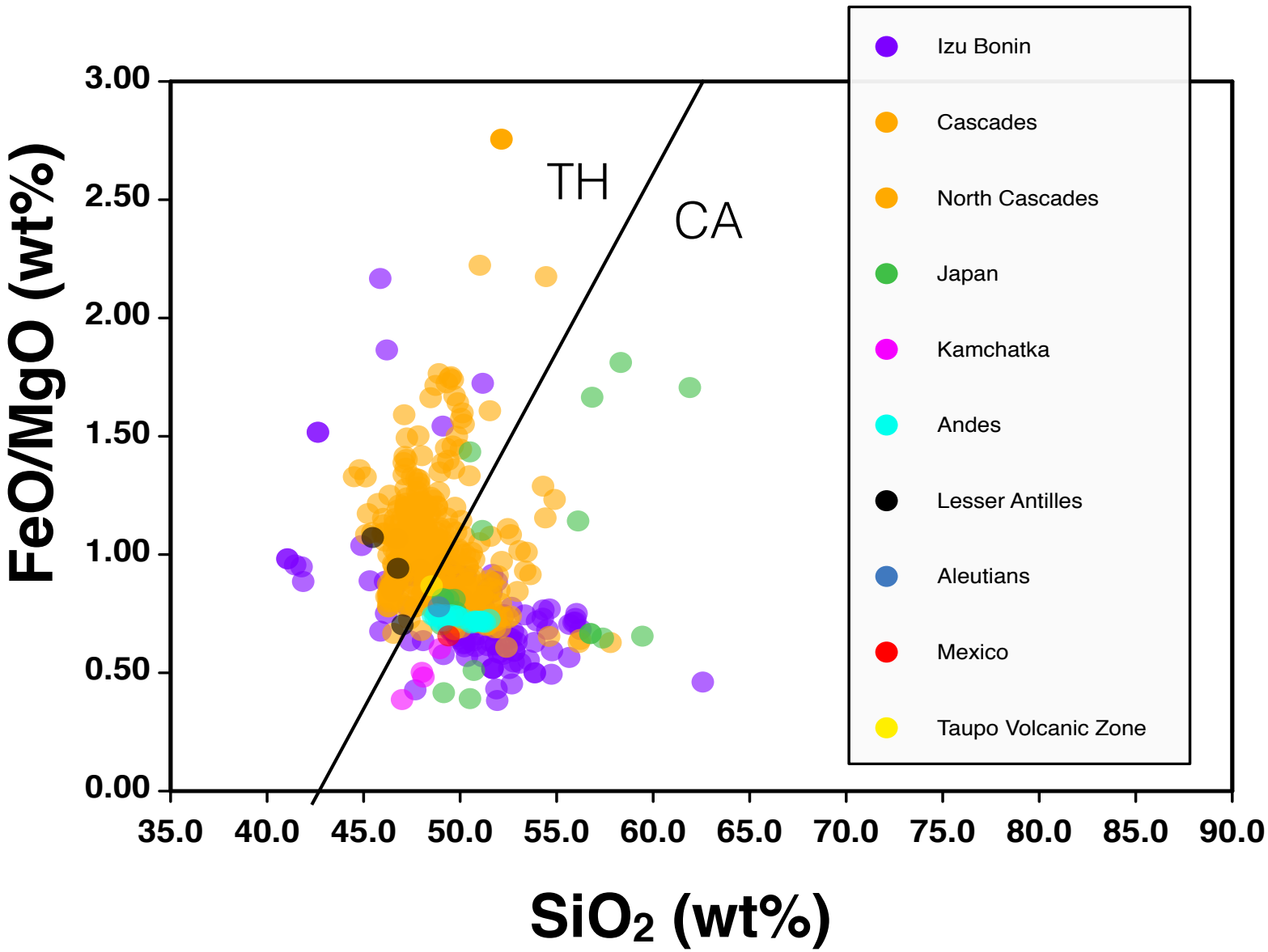
Liquids in equilibrium with lherzolite based on the work of Till et al. (2012a, 2013).
Liquids in equilibrium with harzburgite based on the work of Mitchell and Grove (2015).
Liquids in equilibrium with dunite based on the work of Mitchell and Grove (2016).

Global Variation in Input + Thermal Structure



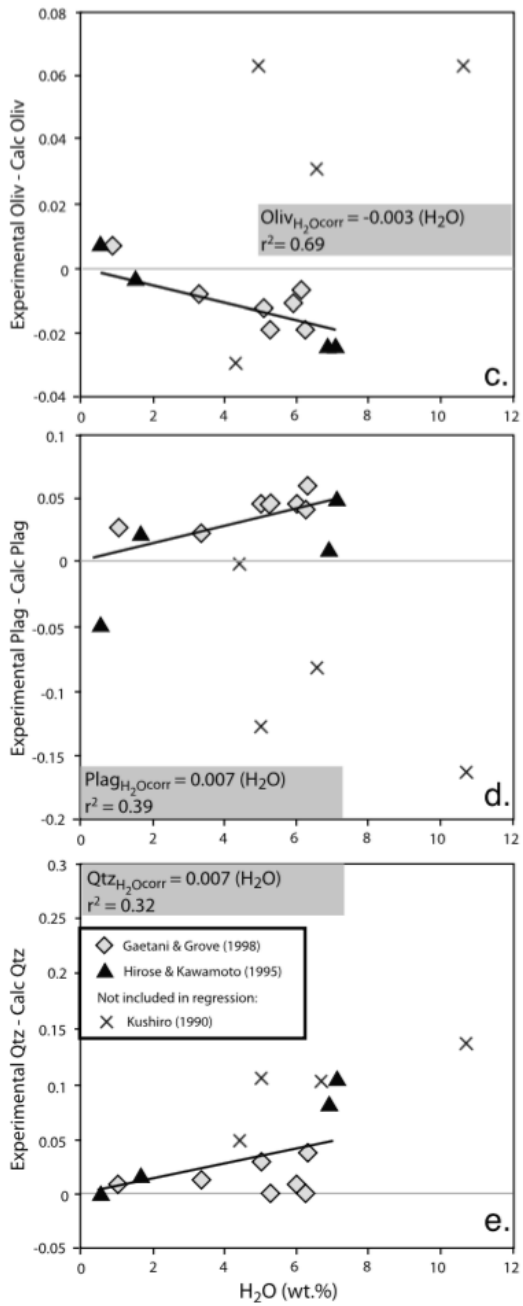
van Keken et al., 2011

There's regional variability in the composition of primitive melts (variations in residue + thermal state + flux from slab)



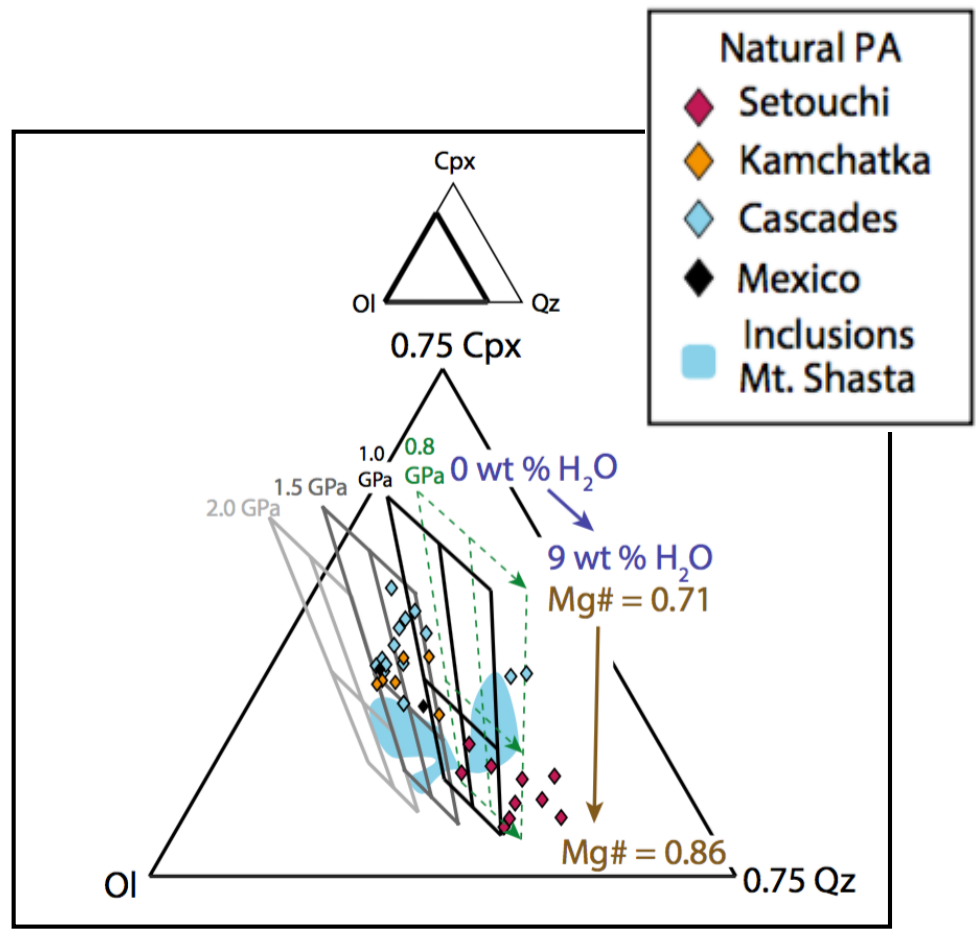
Limited forward geochemical models of wet mantle melting

lherzolite melting at 0-6 wt% H2O



Till et al., 2012

harzburgite melting at 0–7 wt% H2O

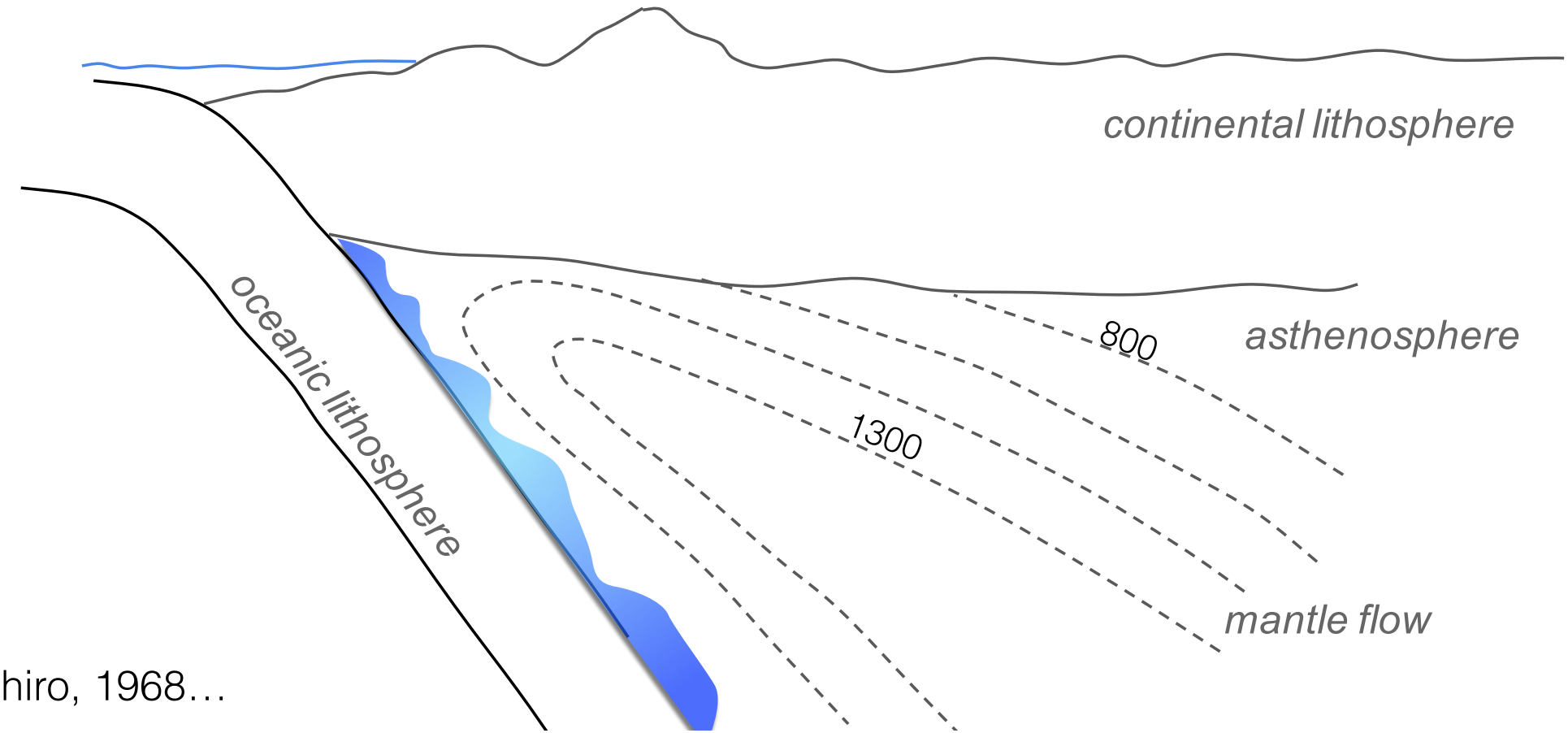


Mitchell & Grove, 2015

But flux of material from the subducting plate to the mantle may not be simply an aqueous fluid…

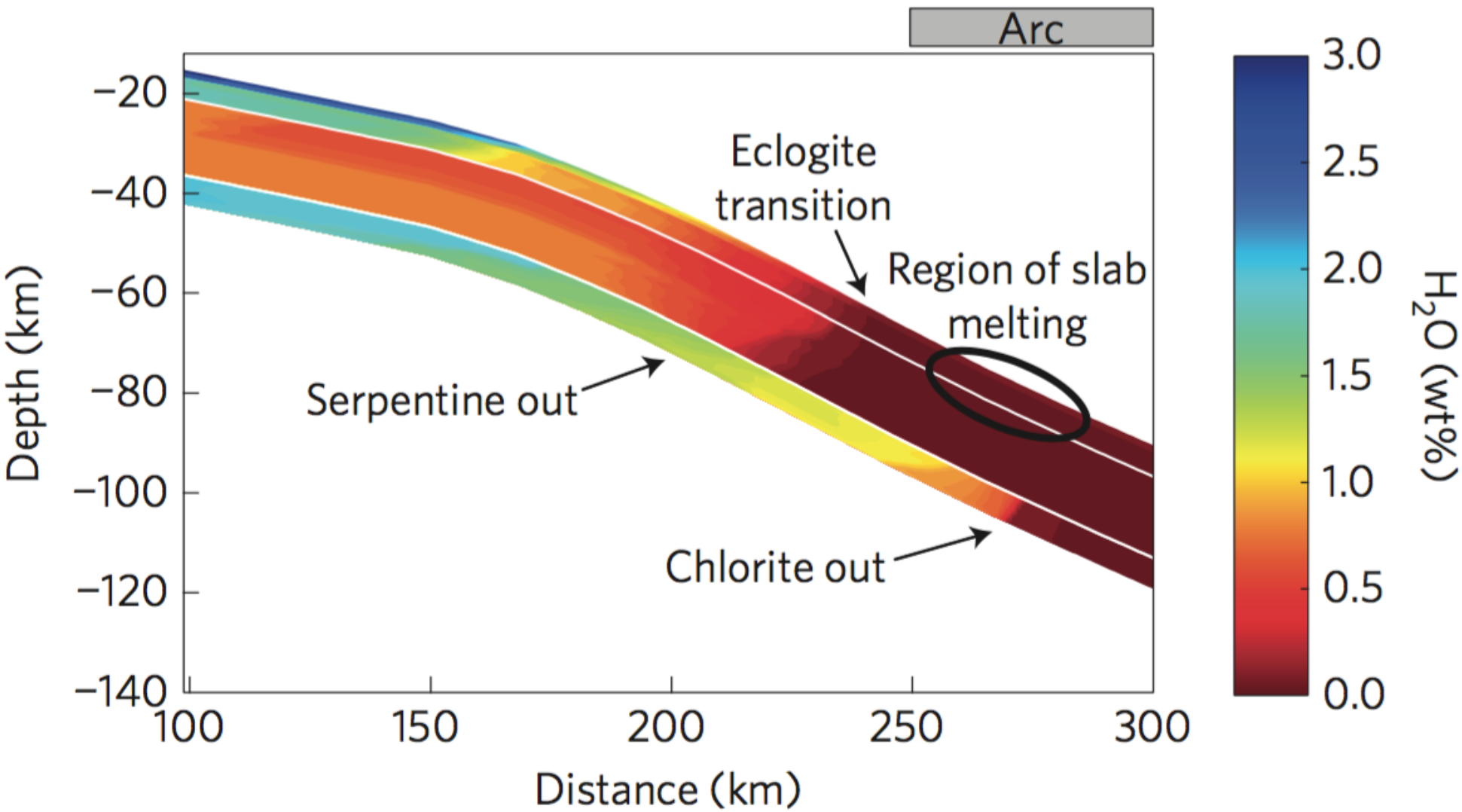
Other possibilities include include:

- *Sediment diapirs*
- *Melts of sediments*
- *Melts of oceanic crust*
- *Combination of these (supercritical fluid)*



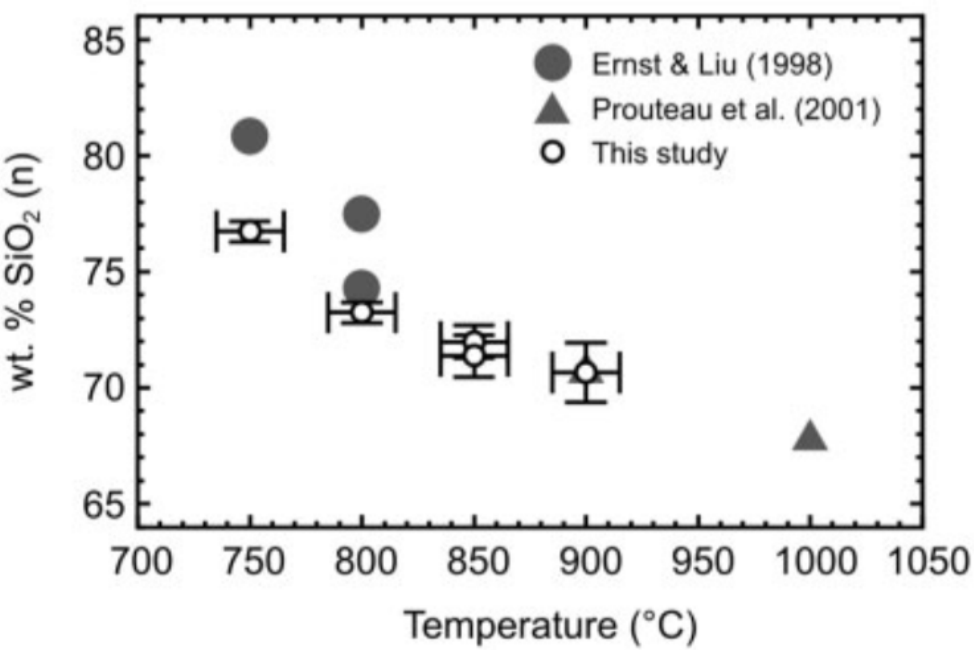
Kushiro, 1968…

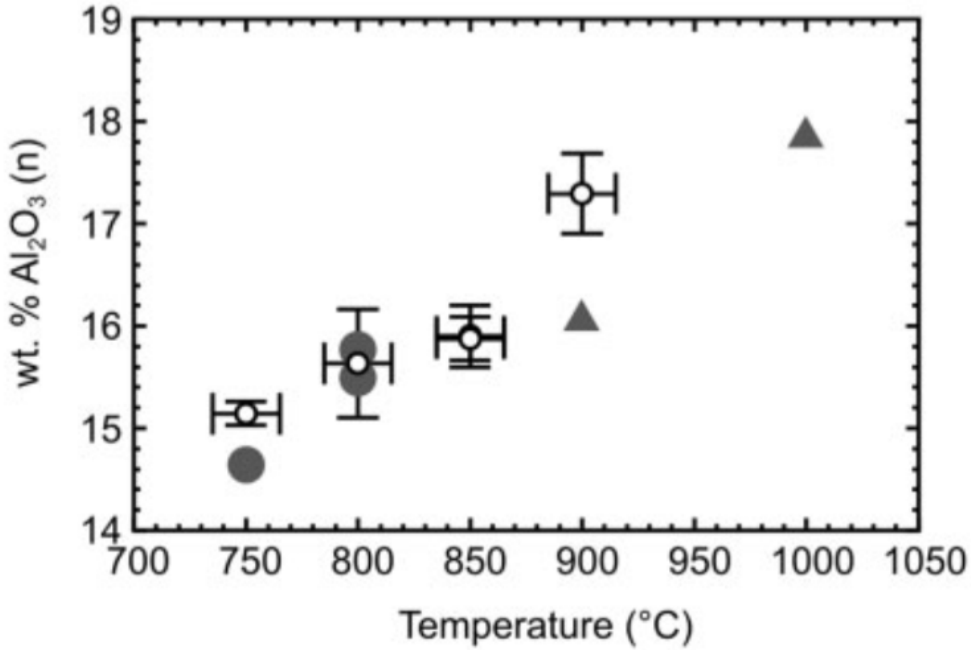
Compelling Arguments for Slab Melt below Lassen



Walowski et al., 2016

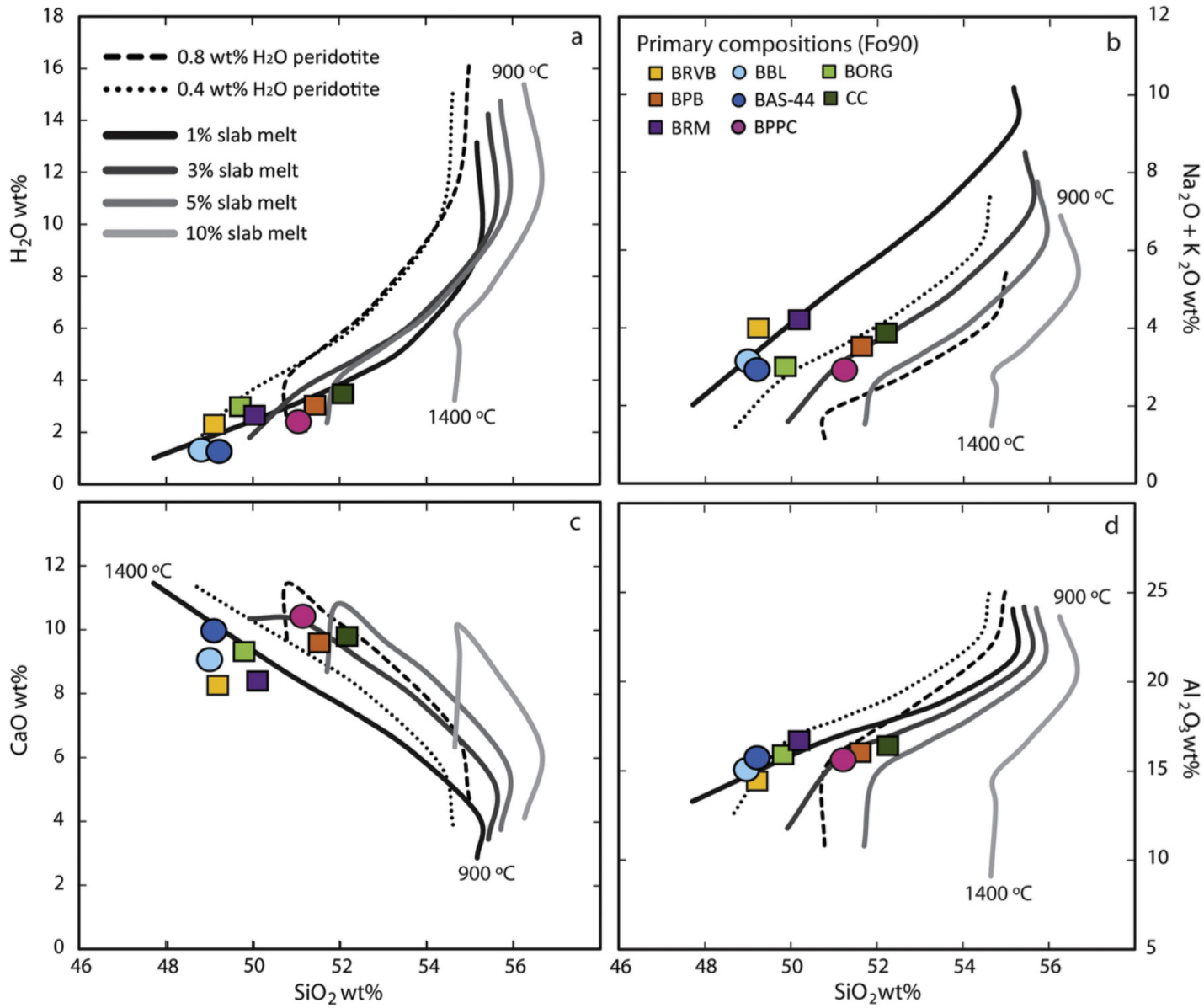
Experimental H2O-saturated eclogite melts = dacite





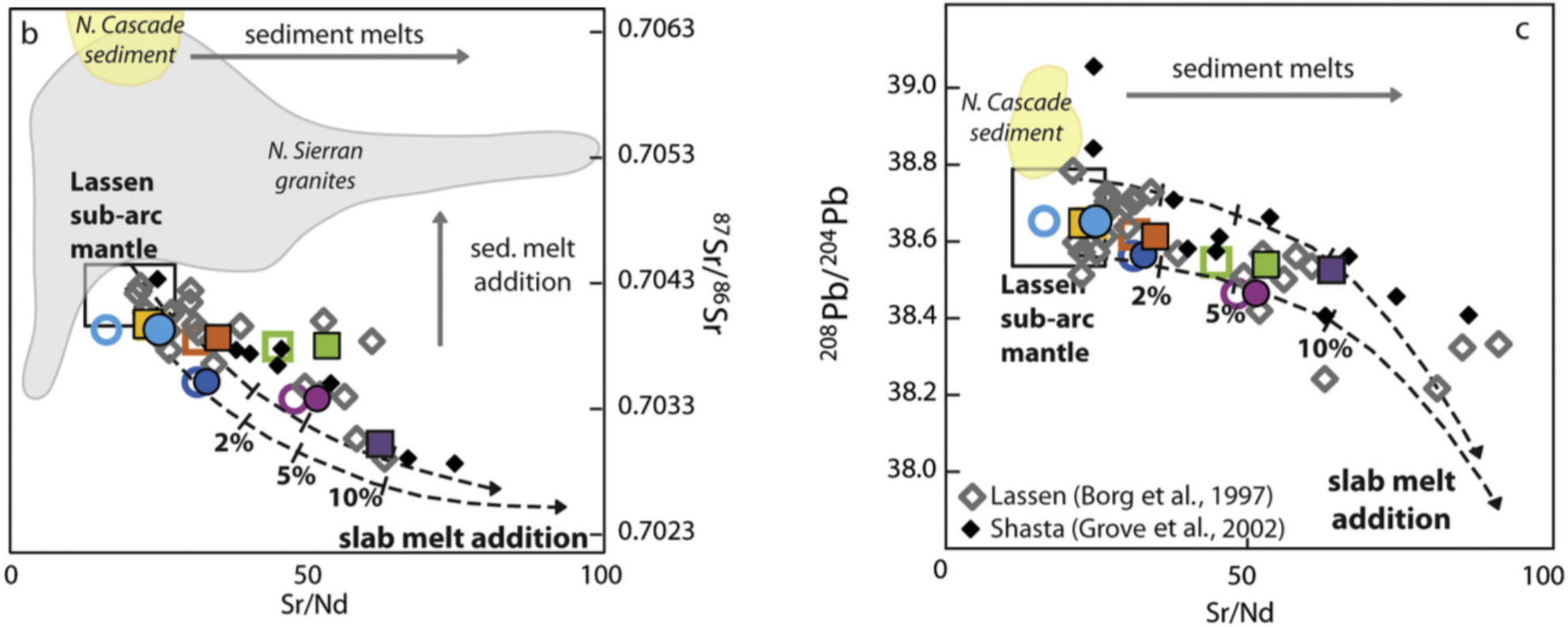
Klimm et al., 2008

Lassen Major Elements Consistent with Slab Melt



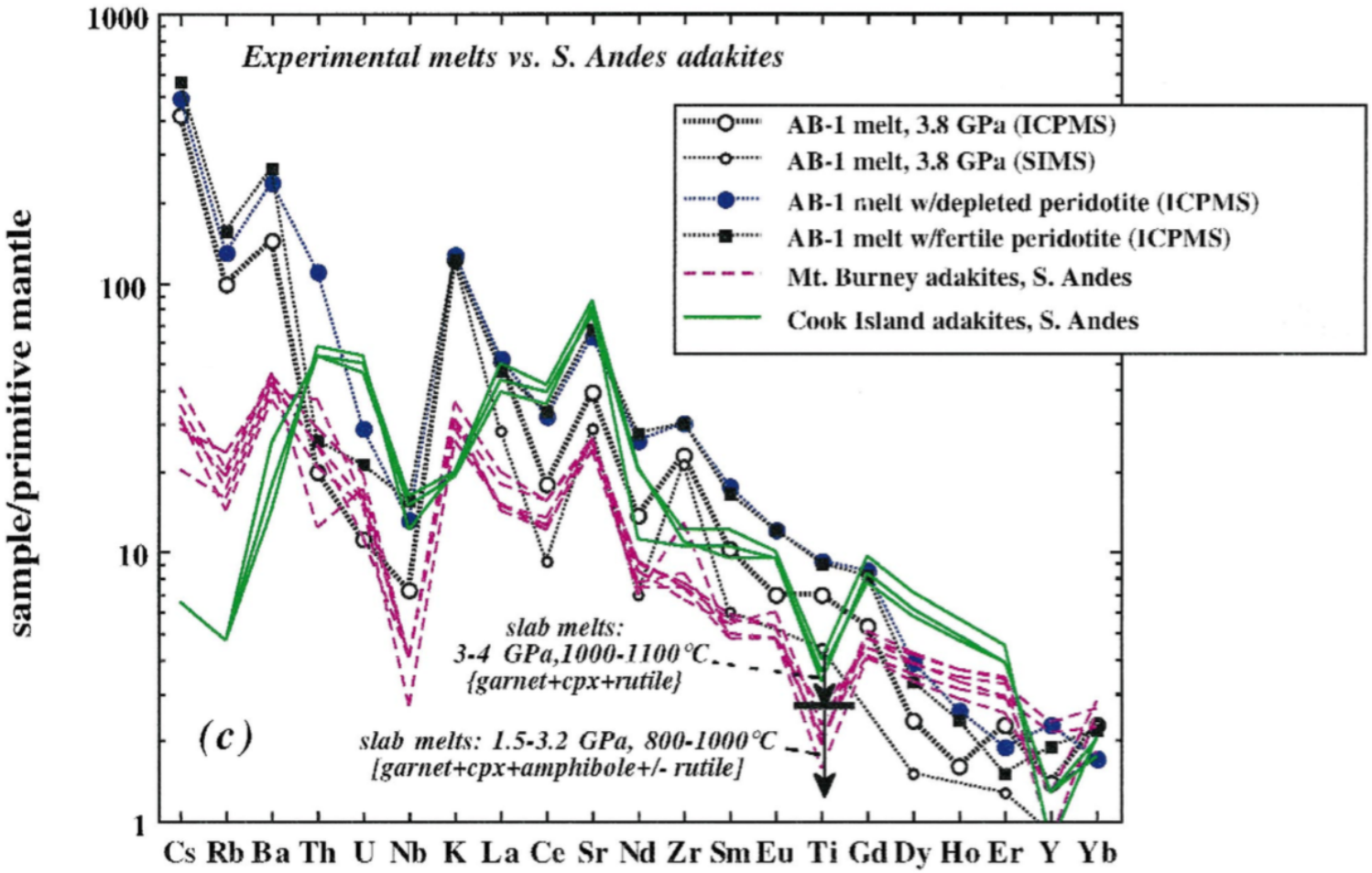
Walowski et al., 2016

Lassen Isotopic Composition Consistent with Slab Melt



Walowski et al., 2016

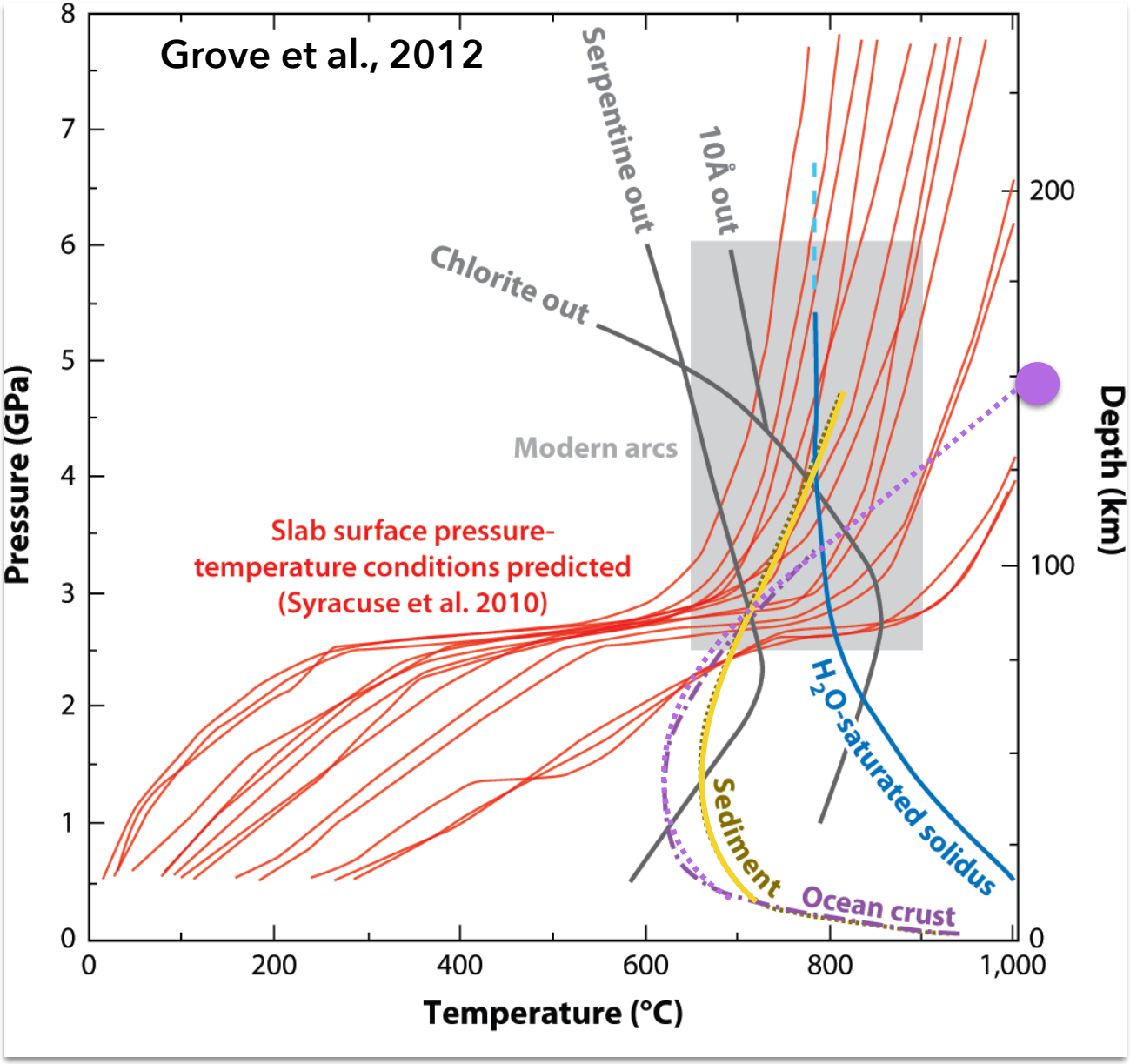
Experiments of eclogite melts reacted with mantle reproduce major + trace element composition of "adakites"



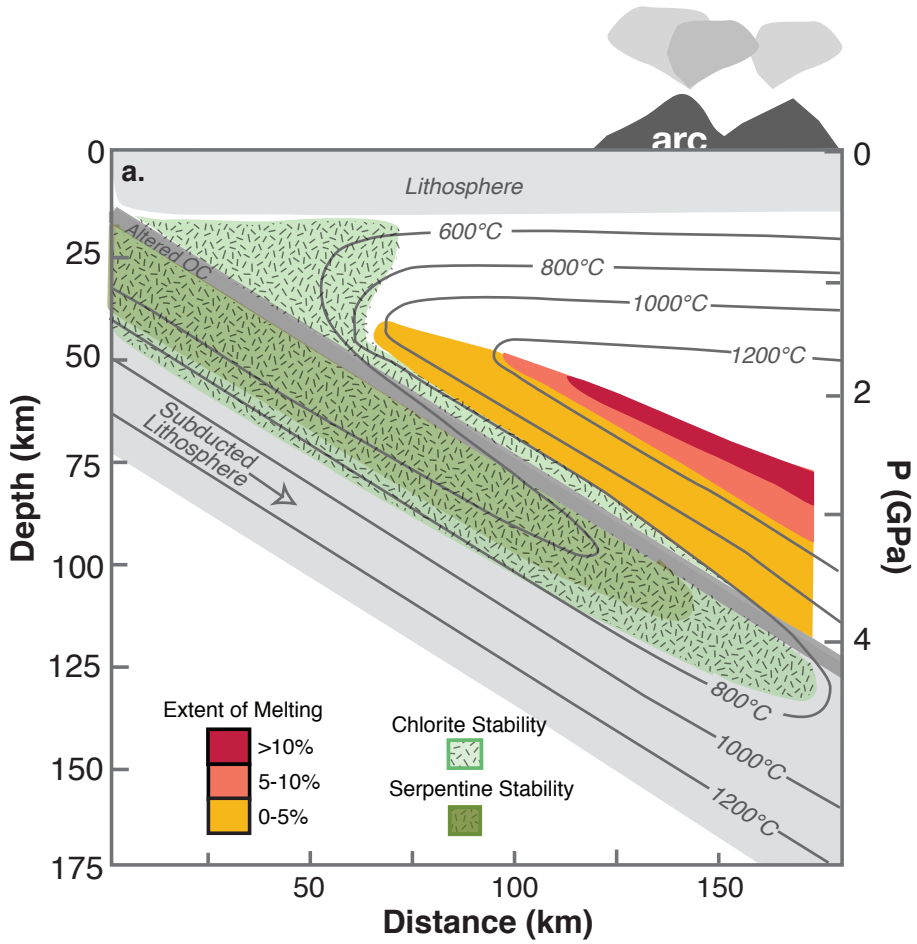
"Analysis of both the pristine and hybridized slab melts for a range of trace elements indicates that, although abundances of most trace elements in the melt increase during assimilation because melt is consumed, trace element ratios remain relatively constant"

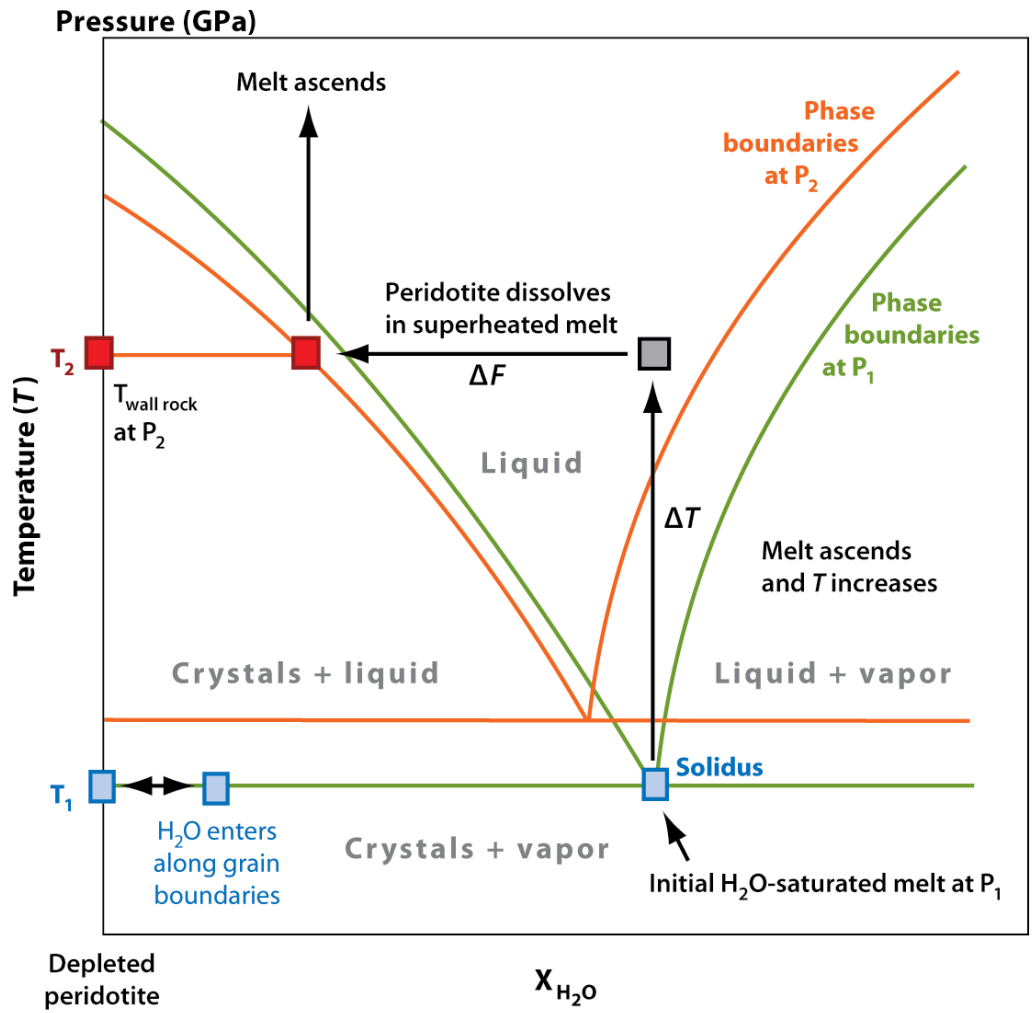
Rapp et al., 1999

Flux of material from the subducting plate=?



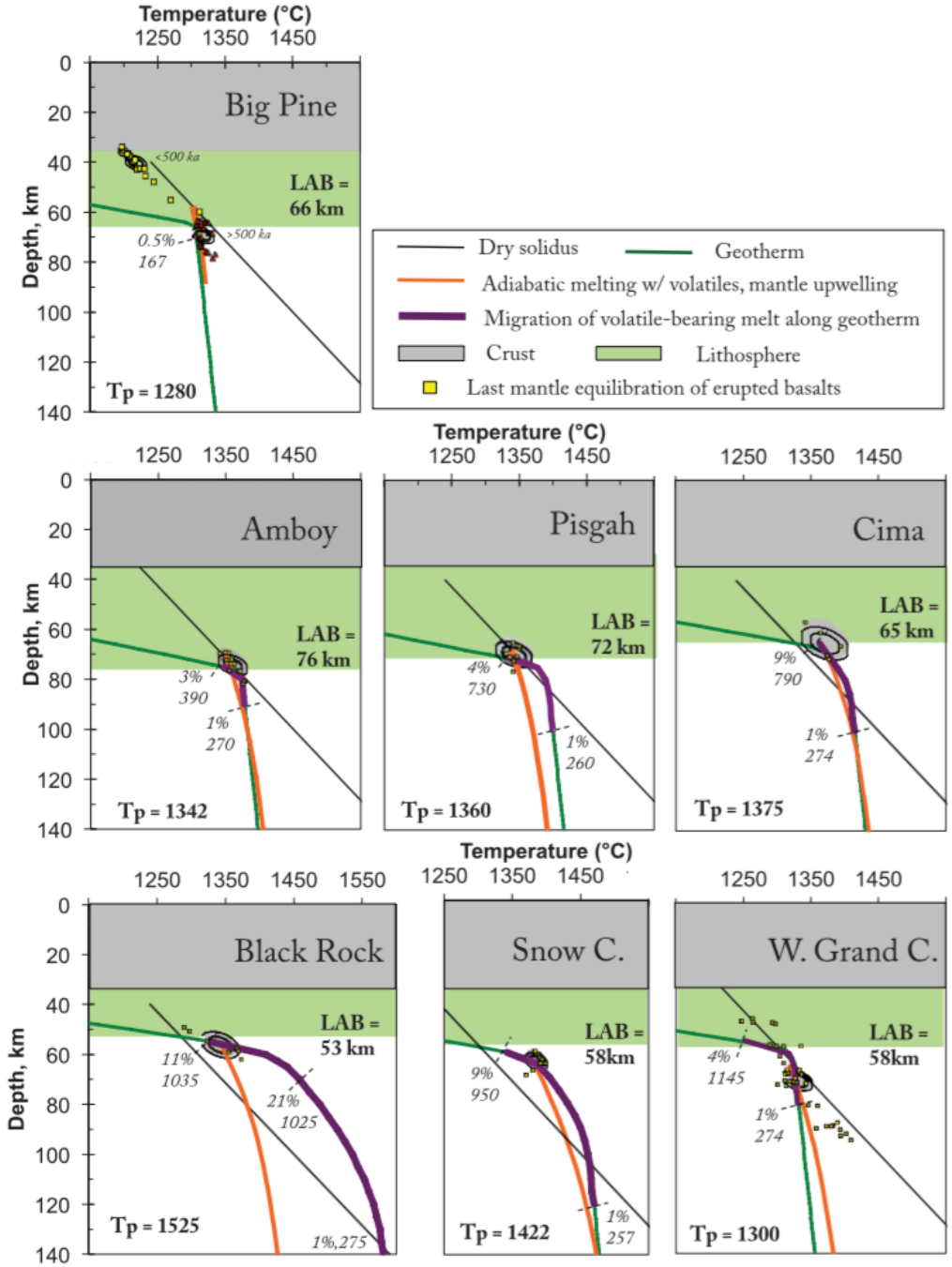
Reaction with mantle as melt rises



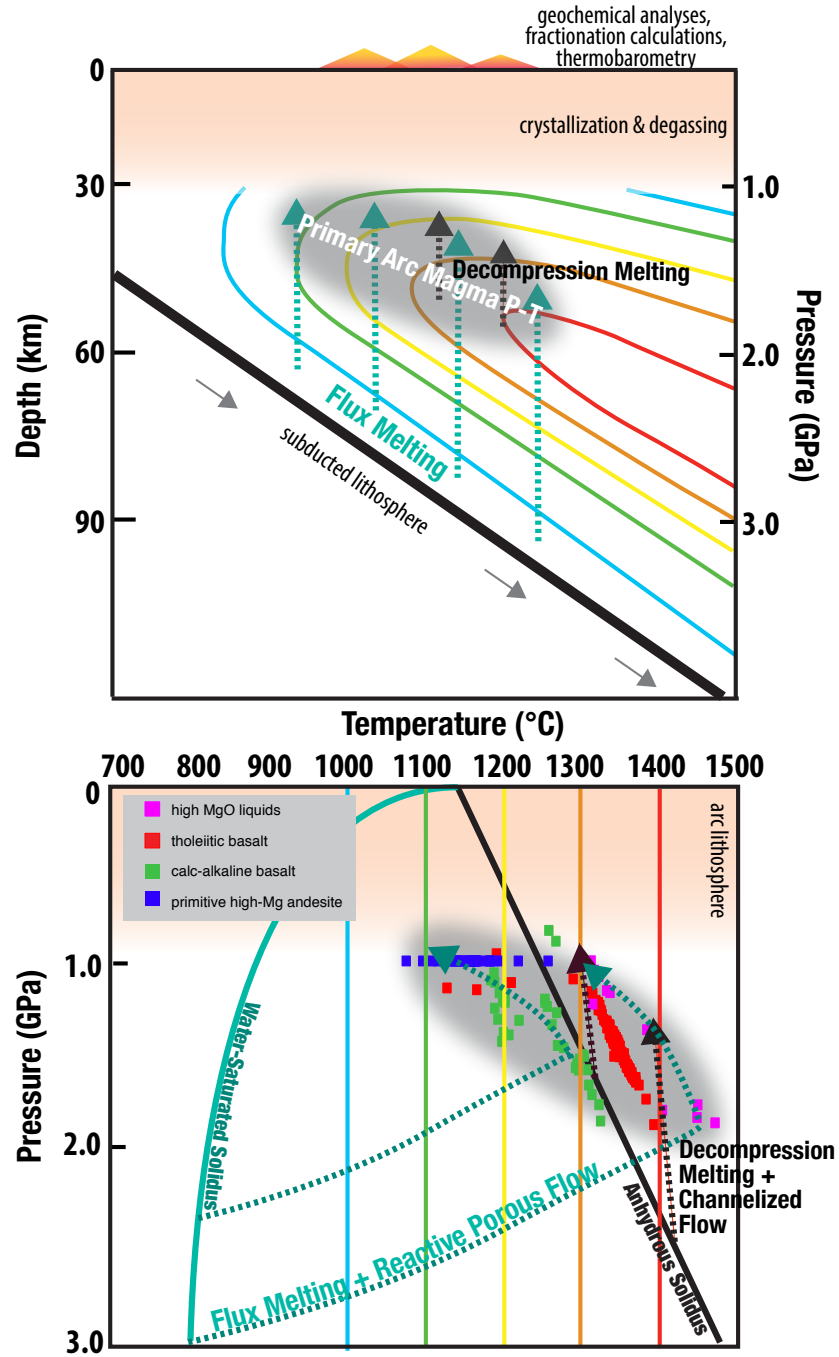


Grove et al., 2012

Mantle melts seem to last equilibrate near the LAB

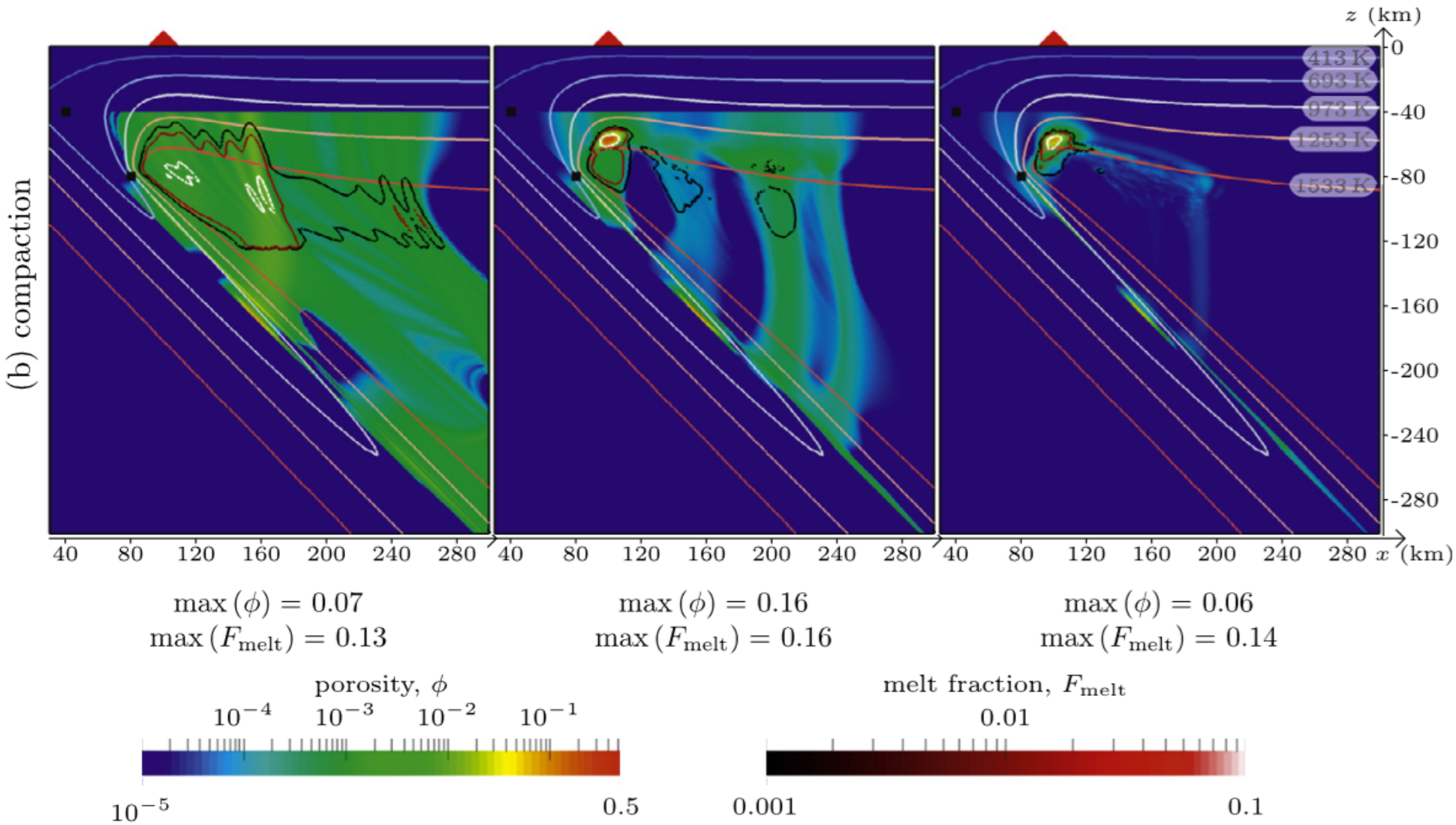


Plank & Forsyth, 2016



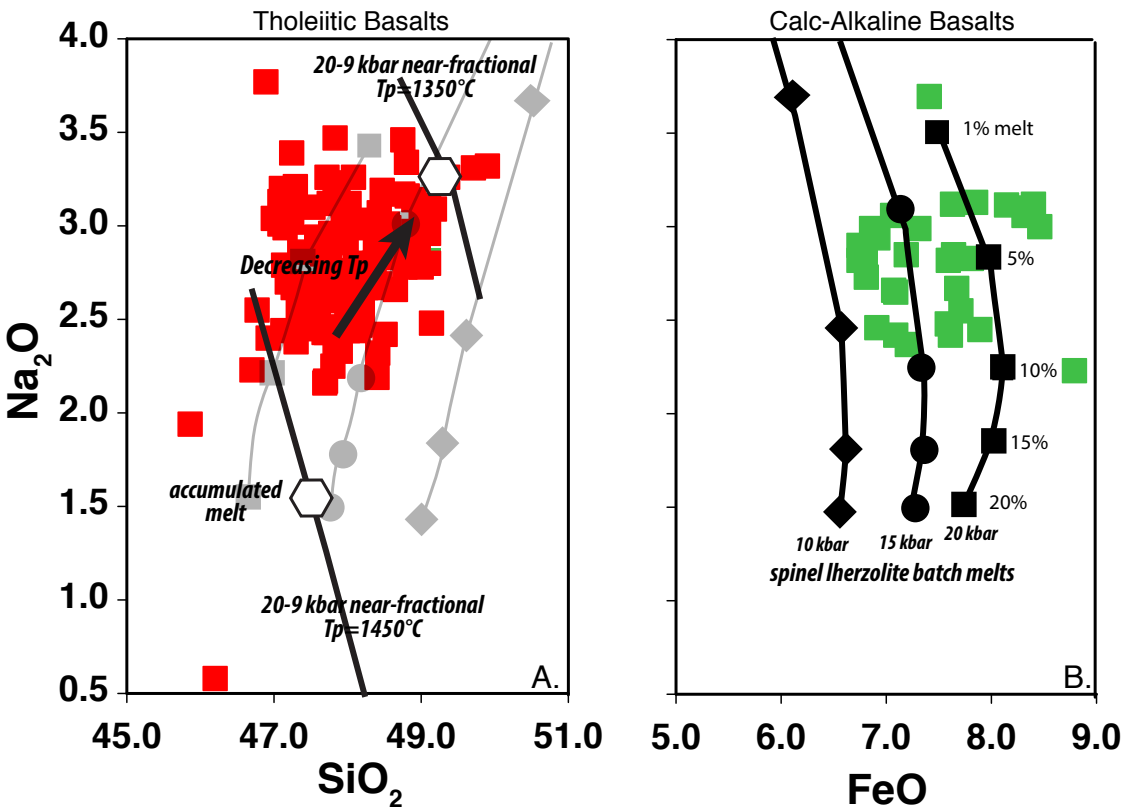
Till, 2017

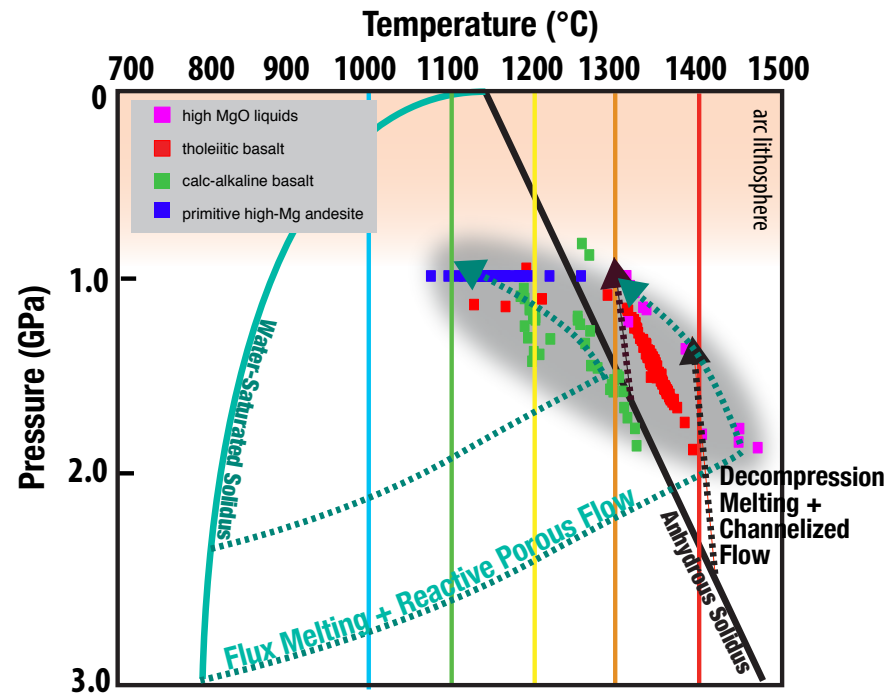
P-T in the Context of Arc Flow Models



Wilson et al., 2014

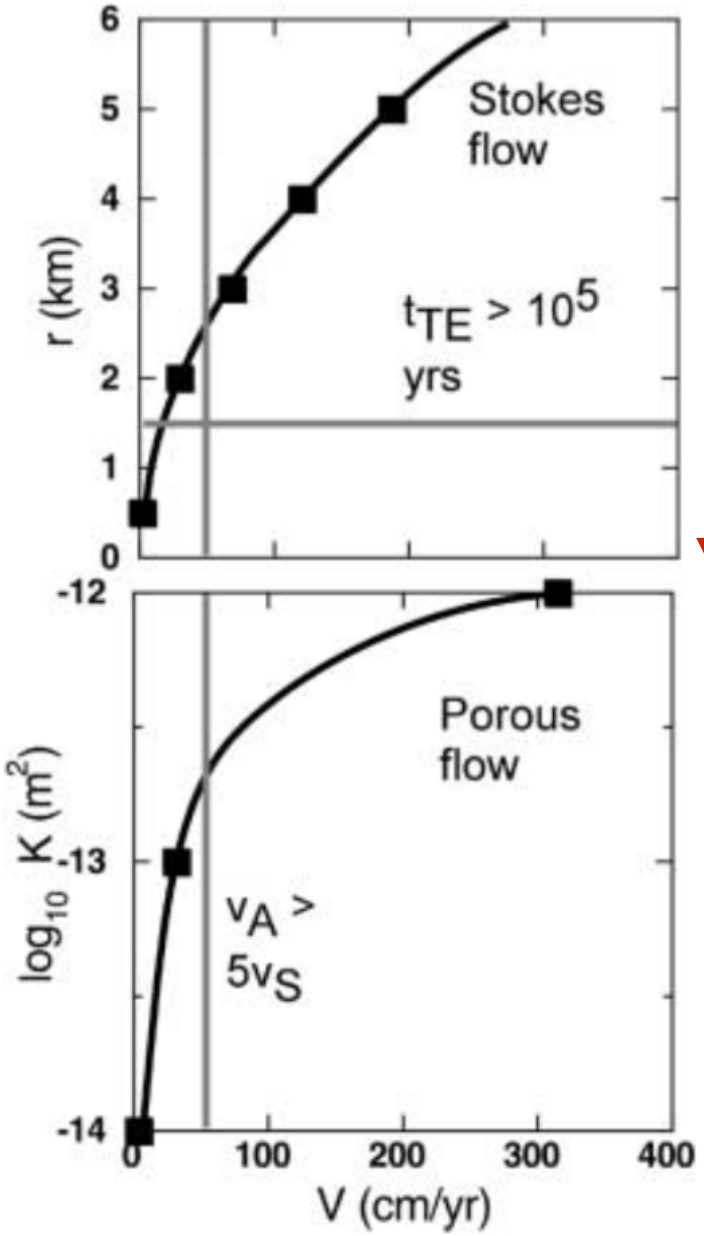
Likely Melt Ascent Paths





Till, 2017

Constraints on Porous vs. Channelized Flow

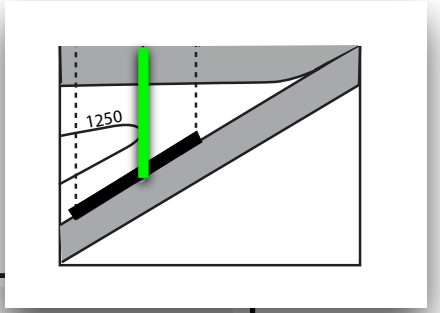


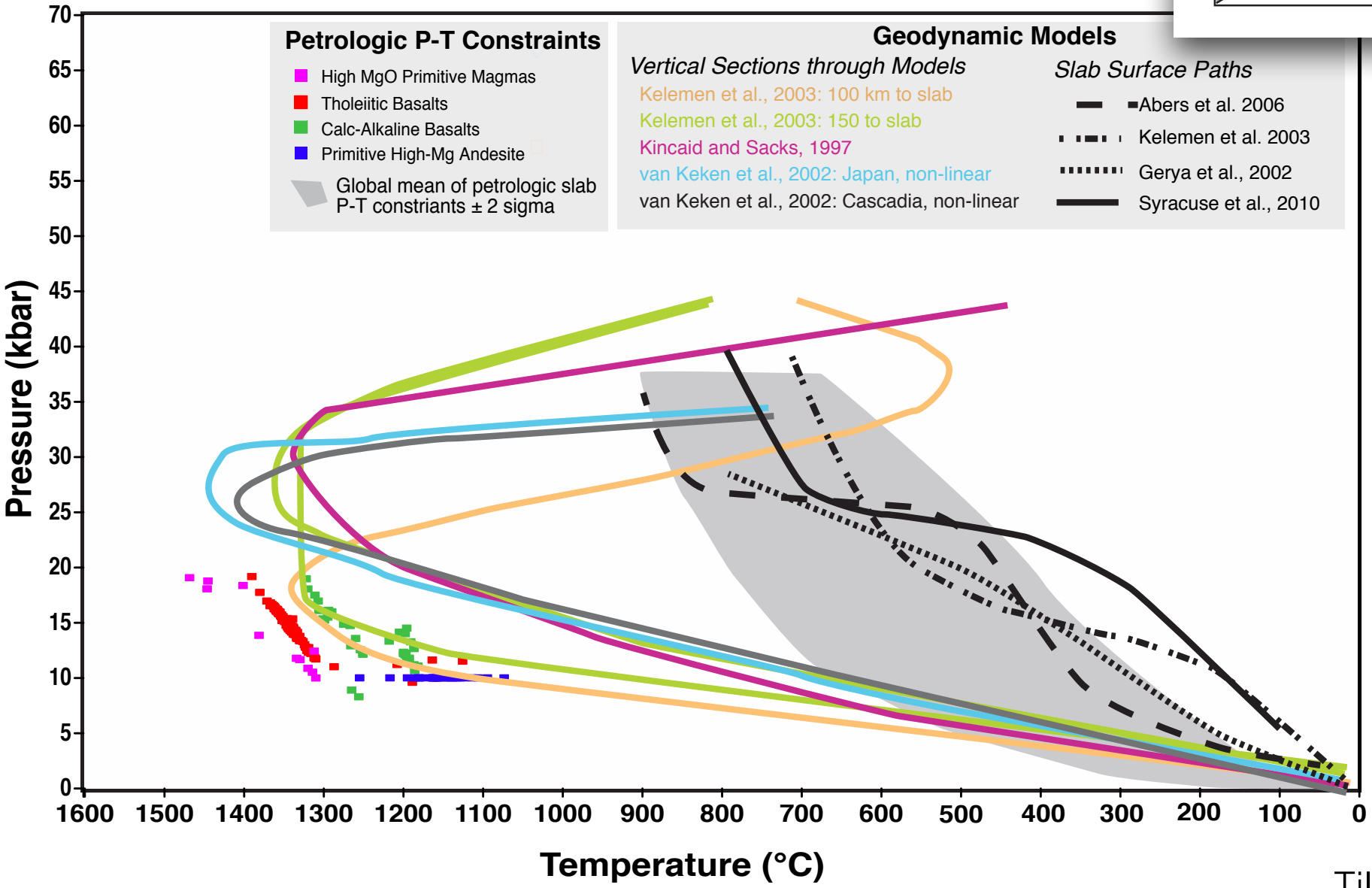
Thermal req-equilibration of diapir happens in $<10^5$ years

Ascent velocity >5x sub rate (such that ascend rather than subduct)

Grove et al., 2002

Comparison to thermal models

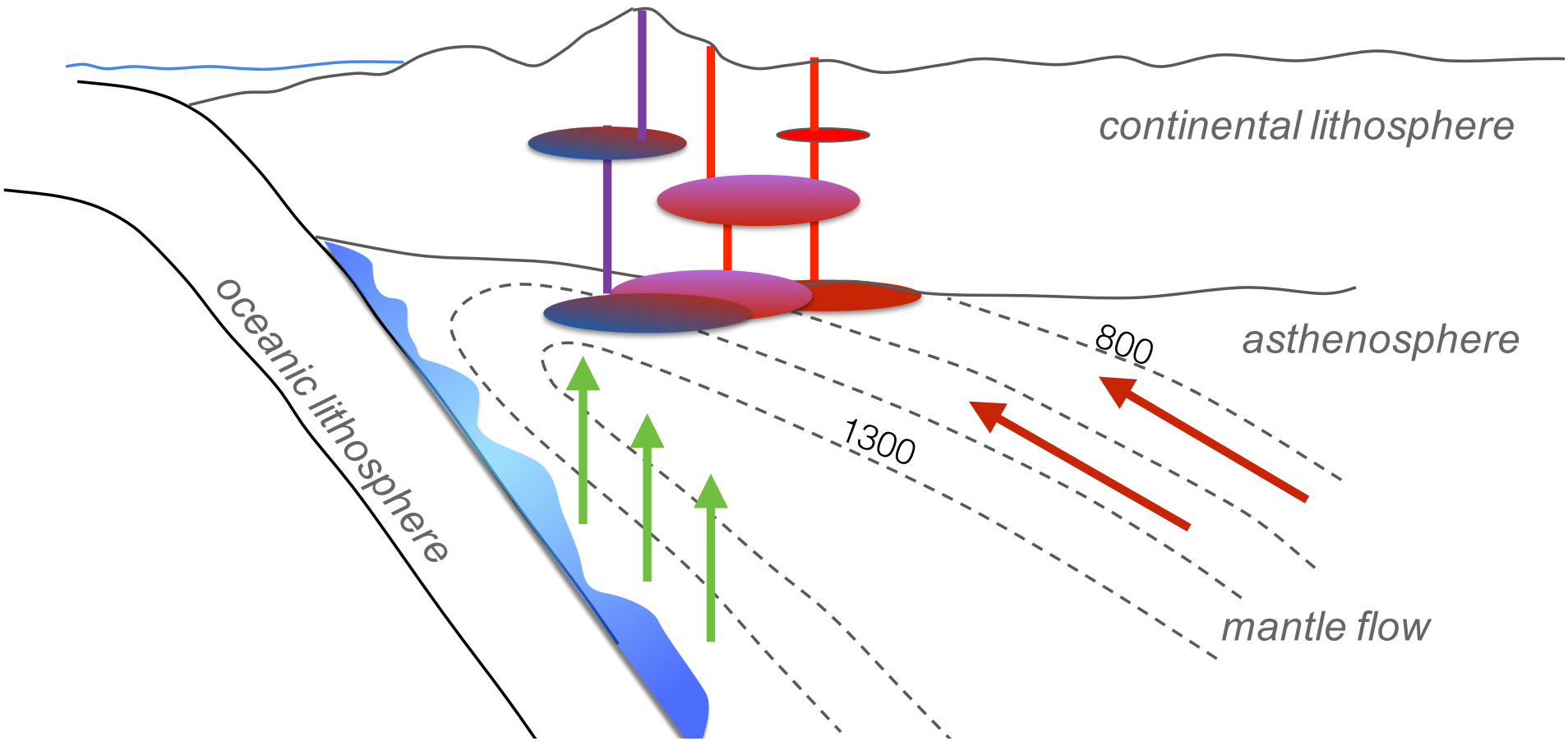




Till, 2017

Major element Occam's razor model for an "average" subduction zone

Primitive magma Type	Melting Mechanism	Mantle Residue
Calc-alkaline basalts-andesites	Flux Melting	Lherzolite
Tholeiites	Decompression Melting	Lherzolite
Primitive High-Mg andesites	Flux Melting	Harzburgite
High MgO liquids	? Damp ? Melting	Harzburgite



Debate as to origins in early 1990's

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 97, NO. B2, PAGES 2037–2070, FEBRUARY 10, 1992

Physical Model of Source Region of Subduction Zone Volcanics

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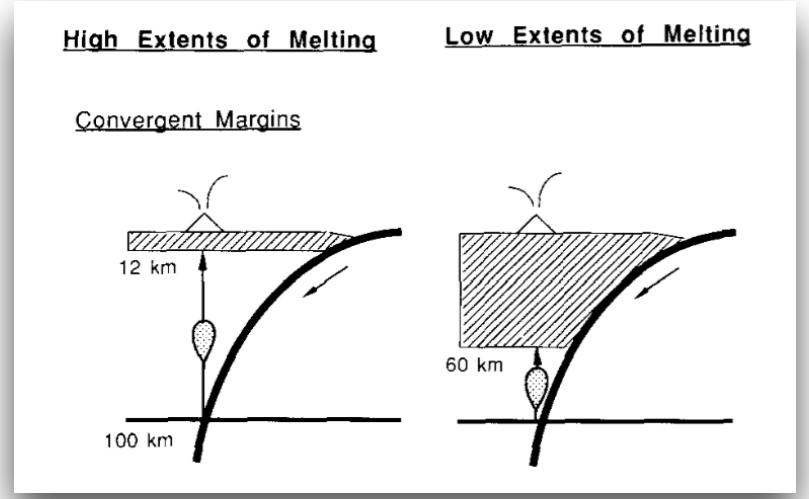
Seismological Laboratory, California Institute of Technology, Pasadena

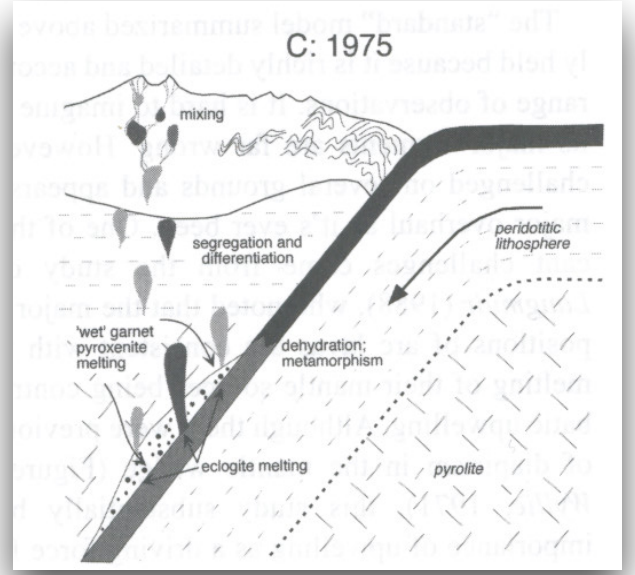
D. J. STEVENSON
Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena

Dry decompression melting of the mantle



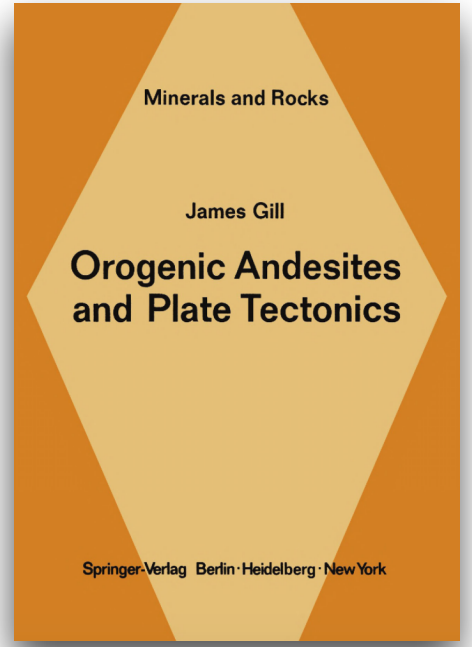
e.g., *Plank & Langmuir, 1988; Sisson and & Bronto, 1998*

Slab eclogite melts



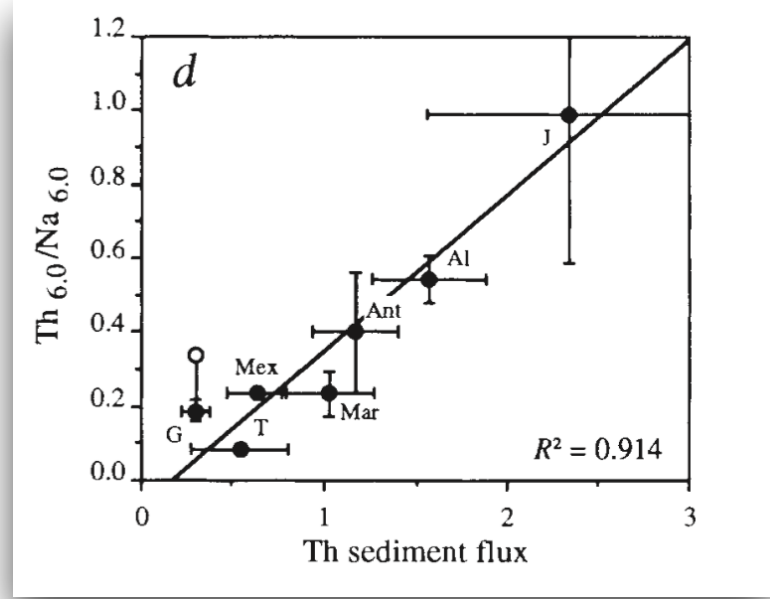
e.g., *Ringwood, 1975, Marsh, 1979*

Flux melting of mantle wedge



e.g., *Kushiro, 1968; Gill, 1981; Sisson and Grove, 1993a,b*

Sediment flux is a key player



Plank & Langmuir, 1993

Future Opportunities

- integrated quantitative slab to surface evolution of melts
- major + trace element + isotopic constrained models
- quantitative forward models of melt composition as a function of H_2O content for range of intensive variables (X, P, T, fO_2)