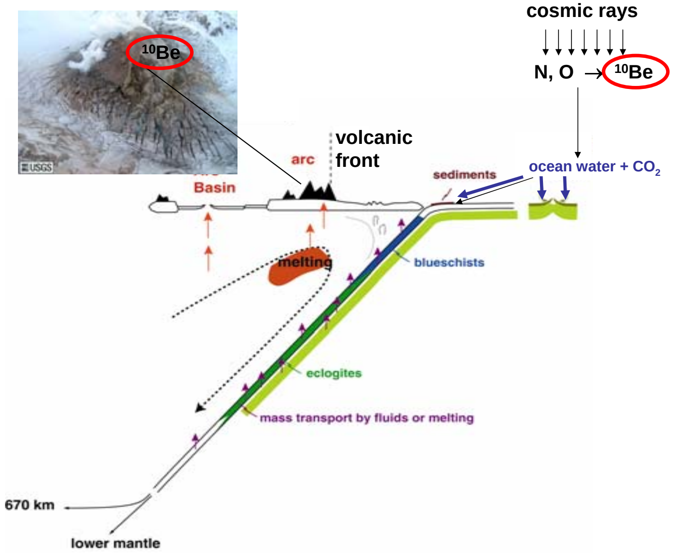
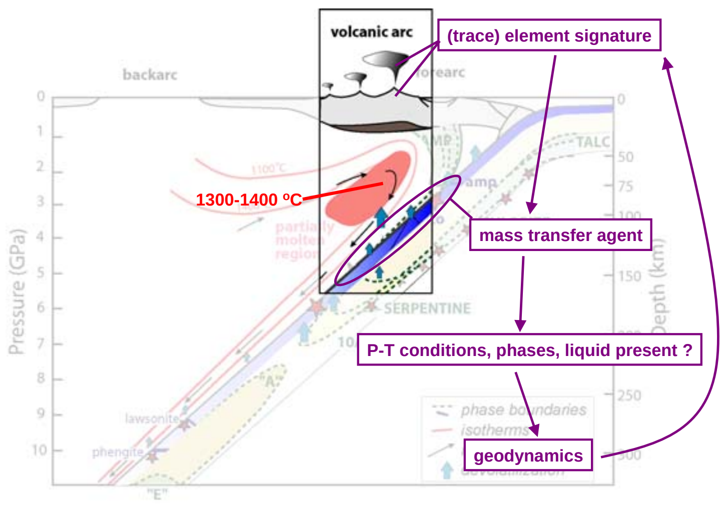
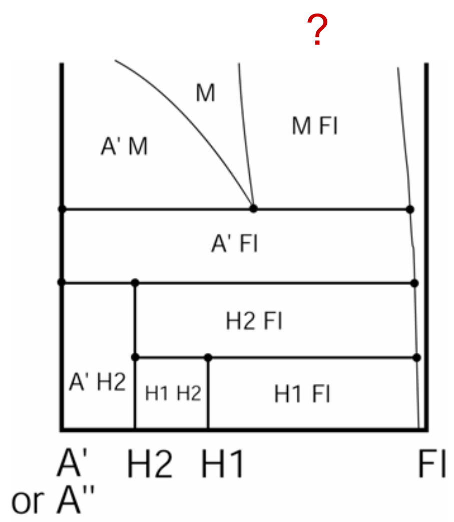
Fluids, melts, and supercriticality in the MSH system and element transport in subduction zones

tracing petrologic and geotectonic processes





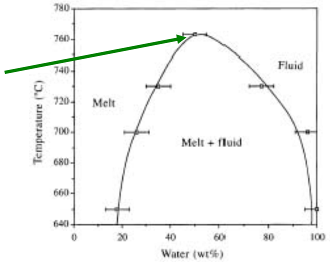


Fluids, melts, and supercritical liquids

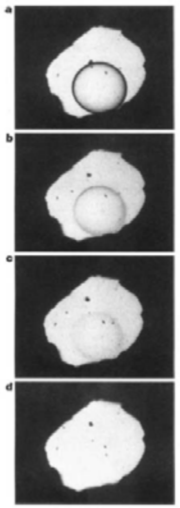
Fluids = rich in volatile component, low in solute
Melts = rich in silicate component, moderate in volatiles
Supercritical liquids = a continuum from volatile to silicate component

- predicted by Ricci (1951),
- experimentally proven for geological systems (quartz+H2O) by Kennedy et al. (1962)
- brought back to our attention by Shen and Keppler (1997)

critical point



Shen and Keppler (1997)



Silicate – H_2O system **without** hydrous phase

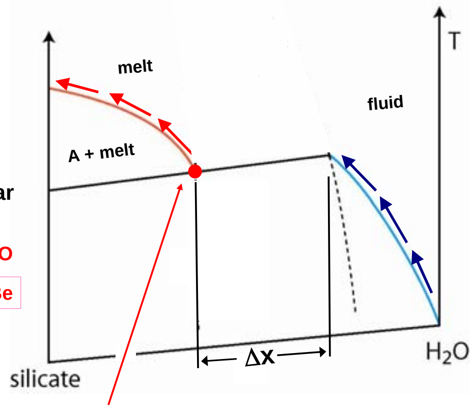
U>Th, high Li,B; low Be

80-95 wt% H_2O

cpx + fluid = melt ± gar

10-20 wt% H_2O

Th>U, high Be



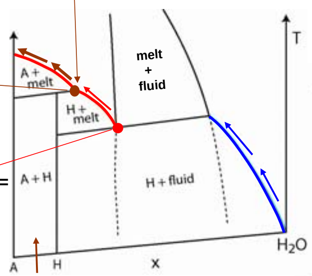
fluid-saturated solidus

Silicate – H_2O system **with** hydrous phase

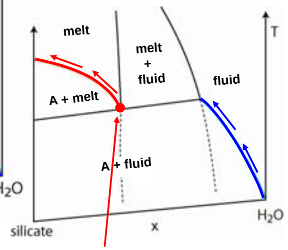
"fluid"-absent solidus

cpx + phengite = melt + gar

cpx + phengite + fluid = melt ± gar



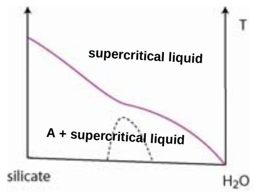
Silicate – H_2O system **without** hydrous phase



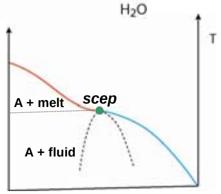
fluid-saturated solidus

Silicate – H_2O system without hydrous phase

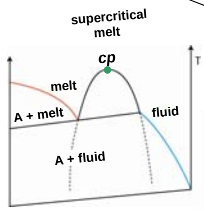
All of this was laid out by Ricci (1951)



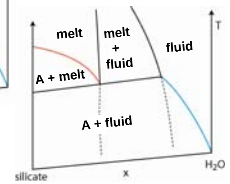
+ P

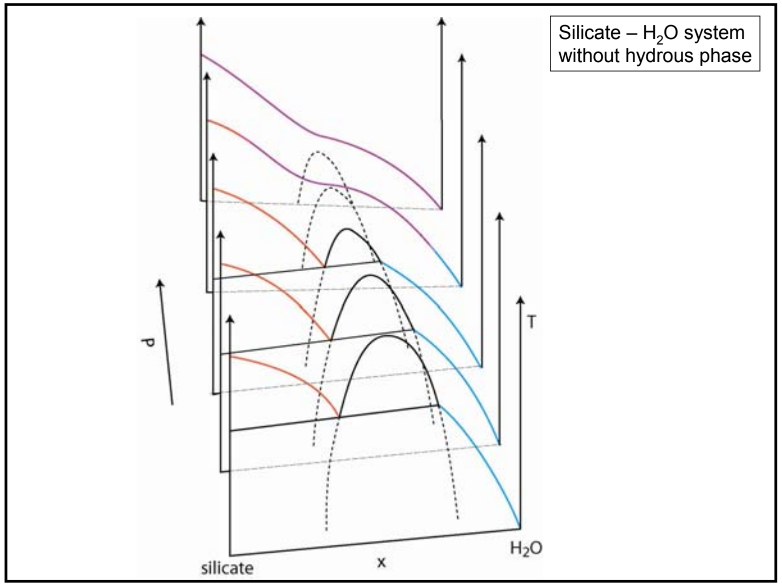


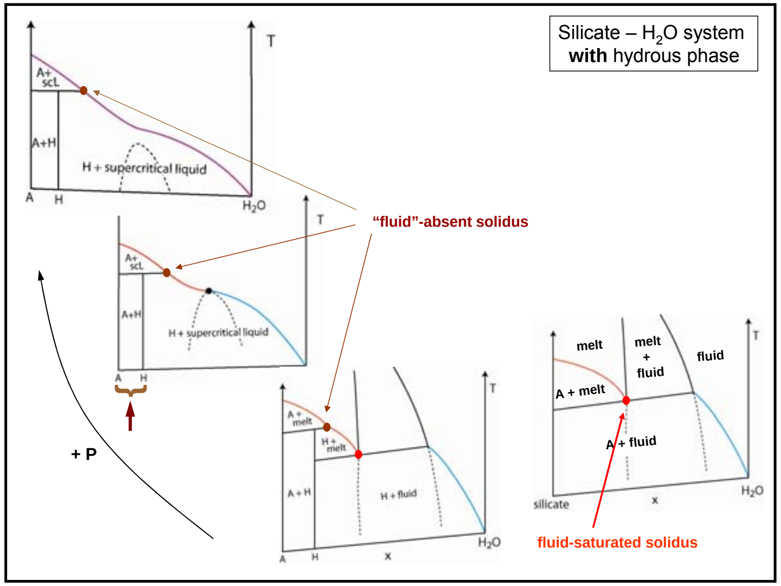
scep = second critical endpoint

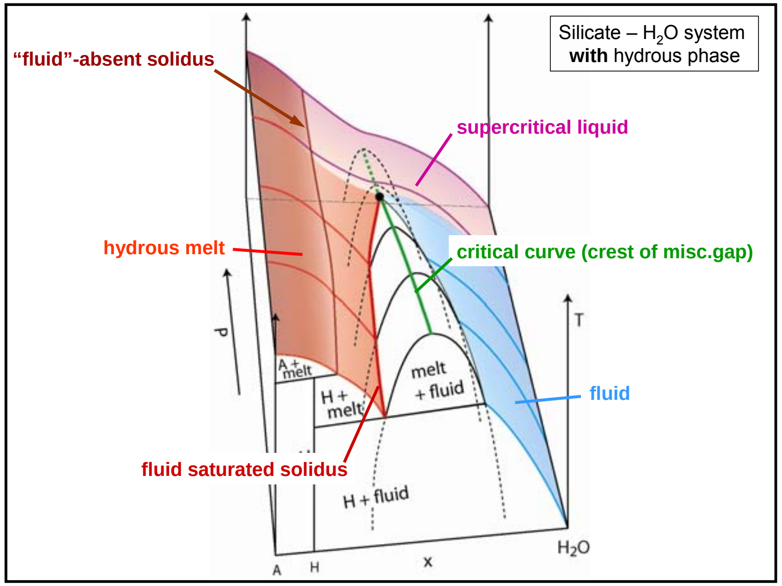


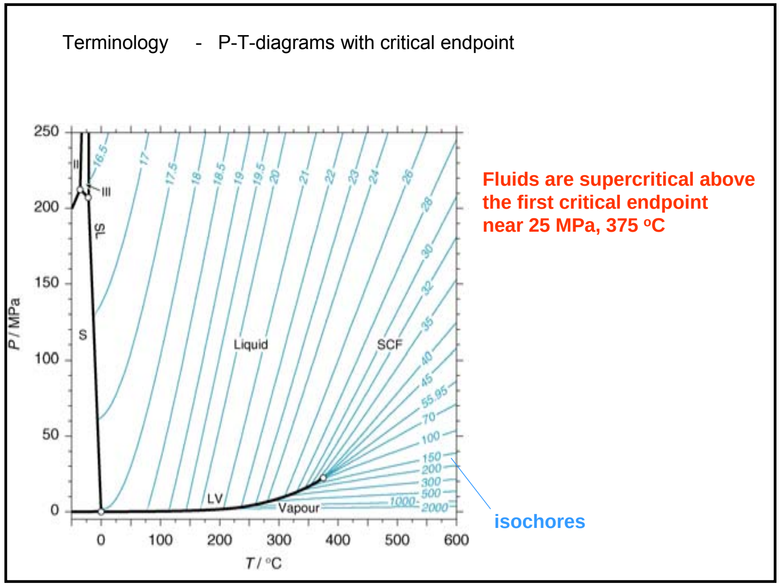
cp = critical point



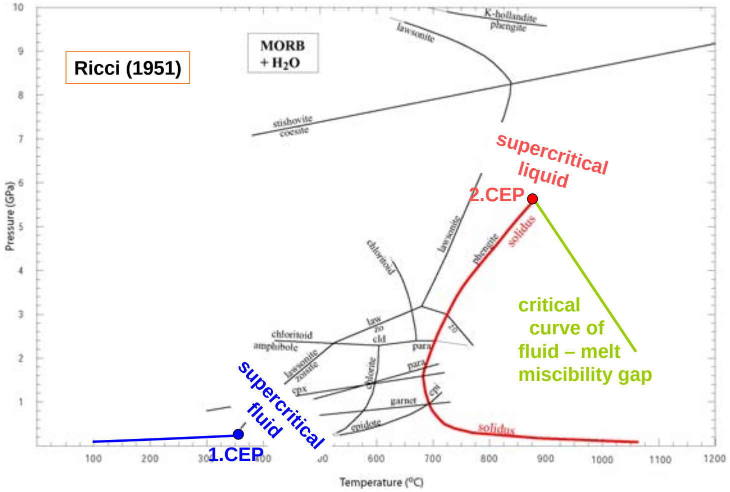

Silicate – H_2O system
without hydrous phase
p
T
silicate
x
H_2O


Silicate – H_2O system
with hydrous phase
T
A+ scL
A+H
H + supercritical liquid
A
H
H_2O
"fluid"-absent solidus
+ P
A+melt
H+melt
H + fluid
melt
melt + fluid
fluid
A + melt
A + fluid
silicate
x
fluid-saturated solidus


Silicate – H_2O system
with hydrous phase
"fluid"-absent solidus
supercritical liquid
hydrous melt
critical curve (crest of misc.gap)
fluid
p
T
A + melt
H + melt
melt + fluid
fluid saturated solidus
H + fluid
A
H
x
H_2O

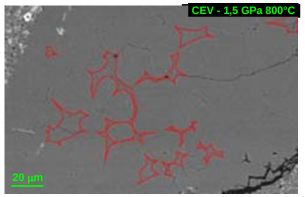

Terminology - P-T-diagrams with critical endpoint
Fluids are supercritical above the first critical endpoint near 25 MPa, 375 ºC
P / MPa
T / °C
Liquid
SCF
Vapour
LV
S
SL
isochores

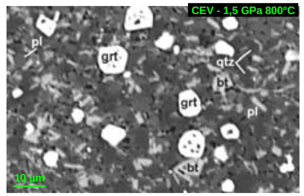
Terminology (not just pure semantics) - P-T-diagrams with critical endpoint



Metagreywacke

Technique for the extraction of silicate melt (or fluid)





- Inert trap
- liquid-matrix connexion ⇒ chemical equilibrium
- works even for low melt fractions
- allows the precise P-T location of the solidus
- Defocused electron beam ⇒ reduces losses of Na
- A single contamination source : quartz ⇒ easy correction

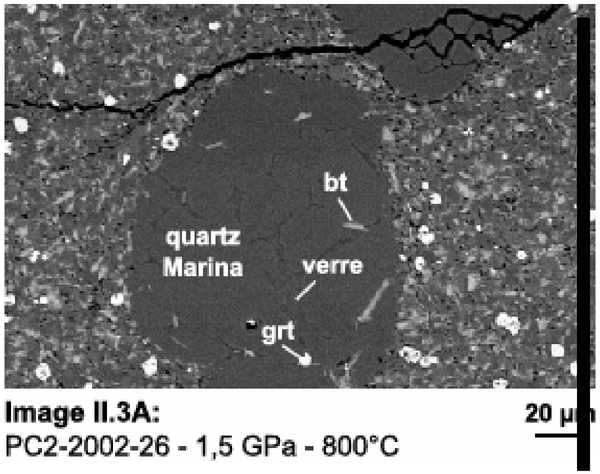
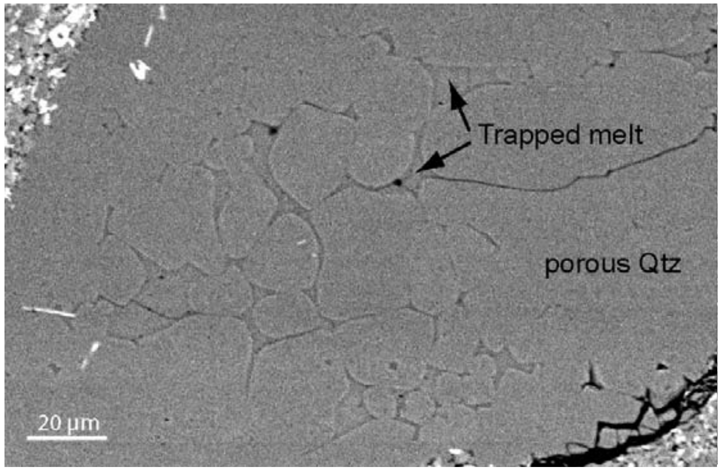
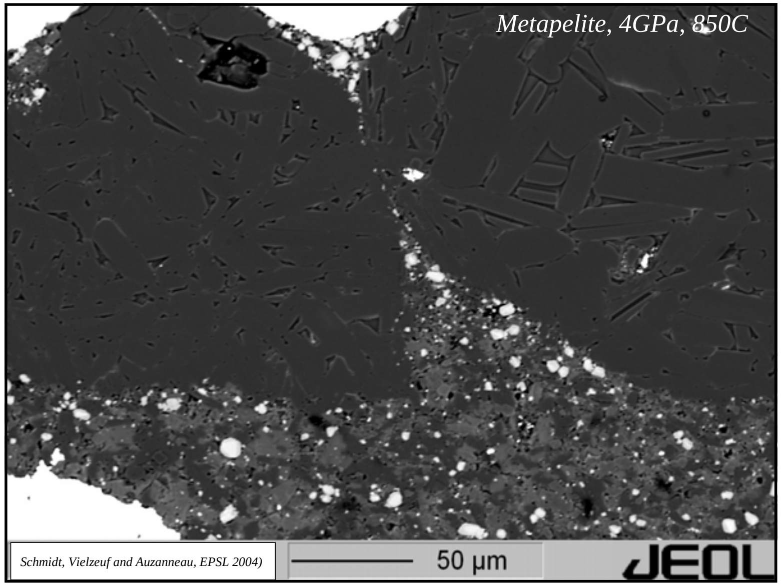
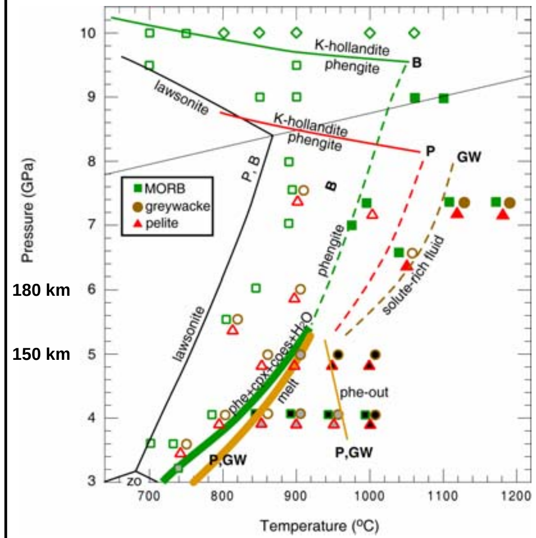


Image II.3A:
PC2-2002-26 - 1,5 GPa - 800°C



1.5 GPa, 800°C





At > 100 km, clastic sediments and basaltic rocks have the same eclogitic mineralogy:

garnet+cpx+phengite +rutile+quartz

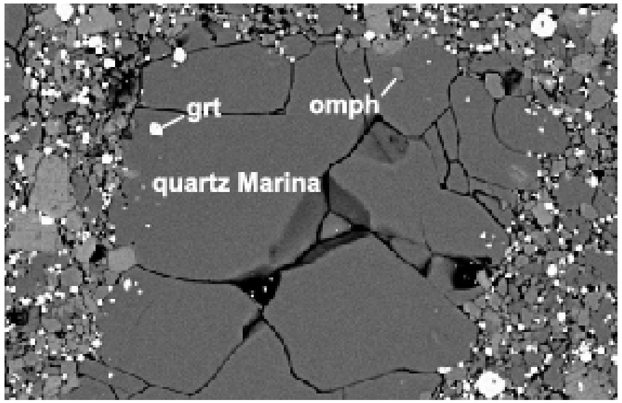


Image II.3B: 20 µm
ME219 - 6 GPa - 900°C

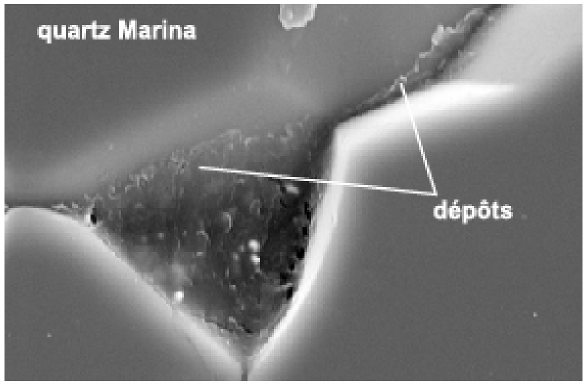
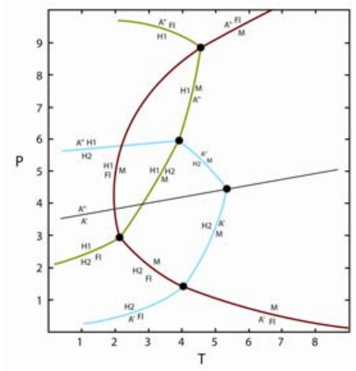
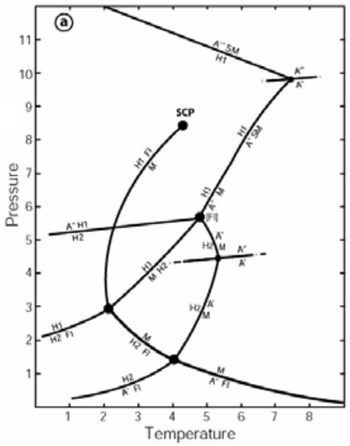


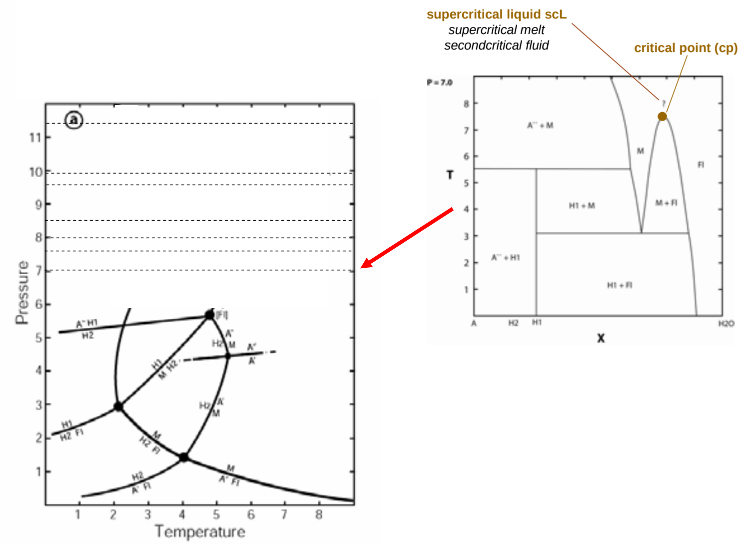
Image II.3C: 2 µm
ME219 - 6 GPa - 900°C

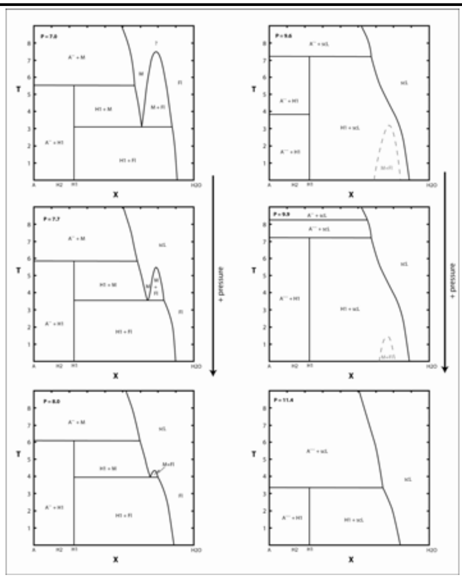
back to our little A-H2-H1-H_2O - diagram ....

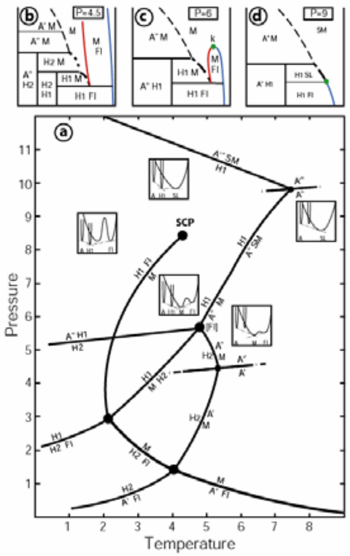
For meta-granite/greywacke/pelite:
H1 = phengite
H2 = biotite

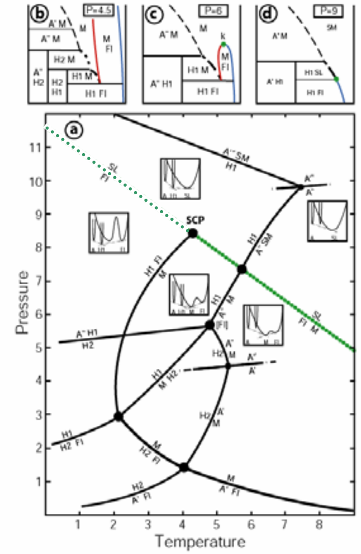


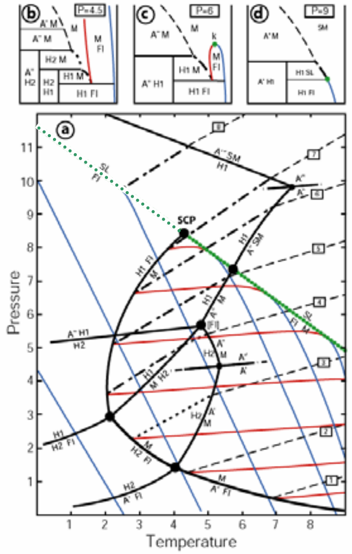


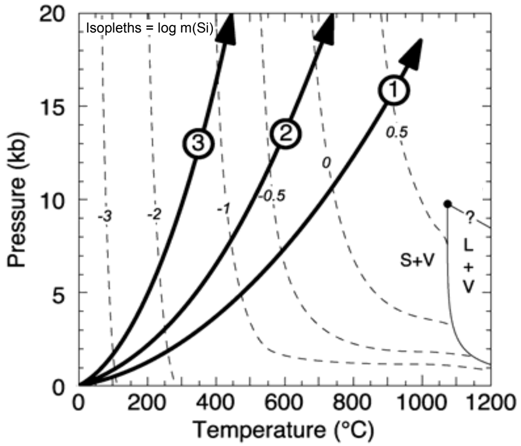




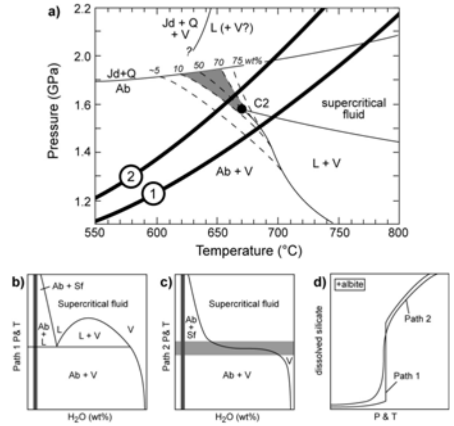




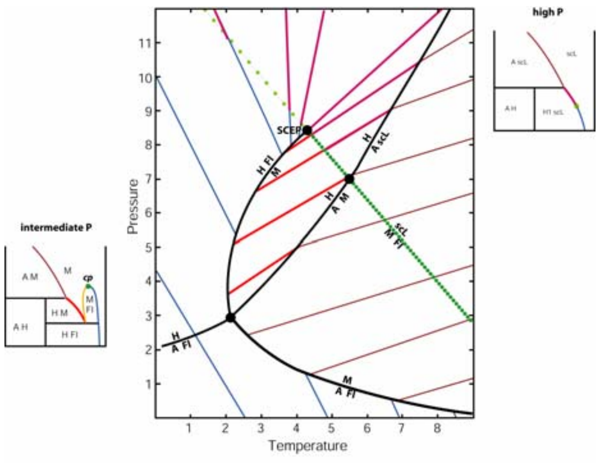




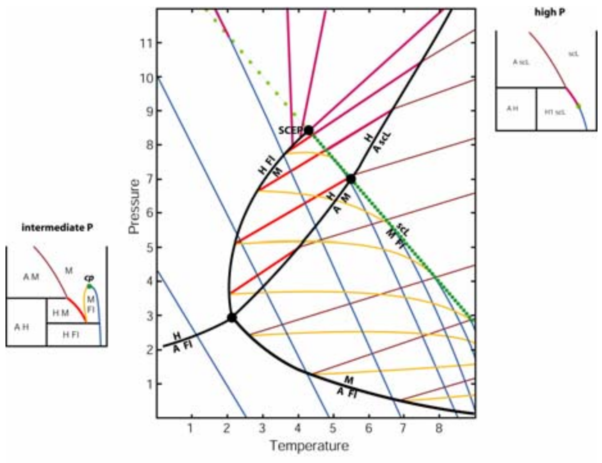
Kennedy et al. (1962), Peacock (1993), Manning (1994)



After Shen & Keppler (1997), Stalder et al. (2000)



Up to 3 sets of H_2O-isopleths possible



Up to 3 sets of H_2O-isopleths possible

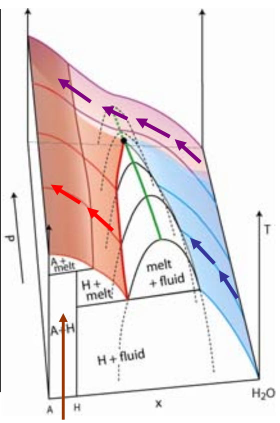
Hydrous melt + fluid vs. supercritical liquids

Temperatures above the critical point (at a given P) of the hydrous melt - fluid immiscibility gap imply a continuum in physical and chemical properties of the supercritical liquid (e.g. solubilities, density, viscosity etc…)

Pressures above the intersection of the critical P-T-curve of the immiscibility gap with the fluid-saturated solidus imply

- the continuum spans the entire temperature range
- nevertheless, isopleths of constant H_2O and composition of an scL in equilibrium with silicates are still defined

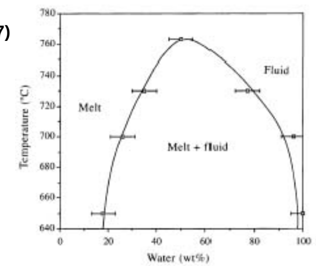
"Fluid"-absent melting continues beyond pressures of the solidus' critical endpoint

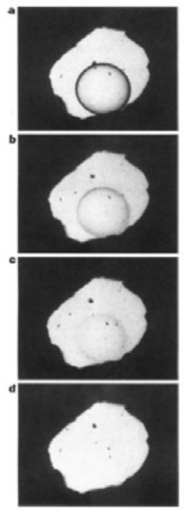


How to determine critical phenomena:

- direct observation (DAC, synchrotron)

Shen and Keppler (1997)





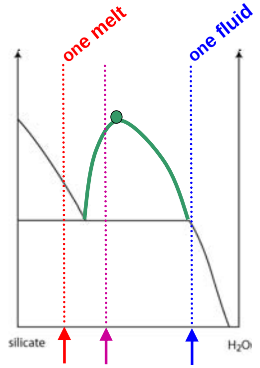
+ very sensitive on 2 phase / 1 phase transition

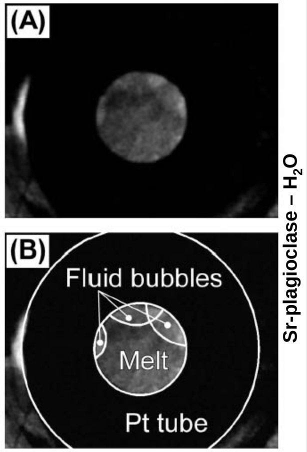
- limited in temperature and thus chemical system (external heated DAC)
- Pressure somewhat uncertain

not explored for partially crystallized systems

How to determine critical phenomena:

- direct observation (DAC, synchrotron)



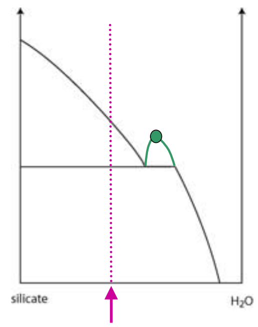


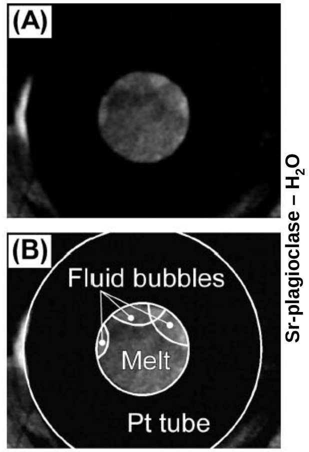
+ potentially large P-T range
- Few experiments possible (synchrotron)
- Run durations limited
- Limit of detection (ΔZ) ?
- Depends on formation of bubbles

Mibe et al. (2004)

How to determine critical phenomena:

- direct observation (DAC, synchrotron)

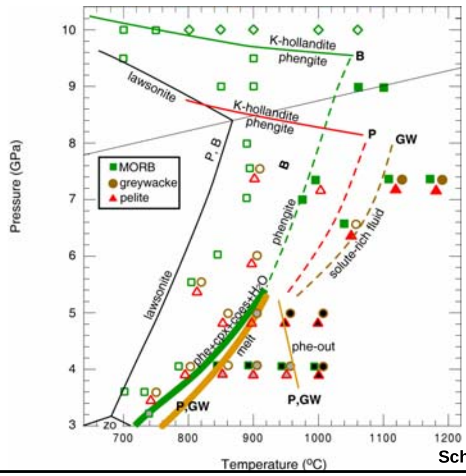




+ potentially large P-T range
- Few experiments possible (synchrotron)
- Run durations limited
- Limit of detection (ΔZ) ?
- Depends on formation of bubbles

Mibe et al. (2004)

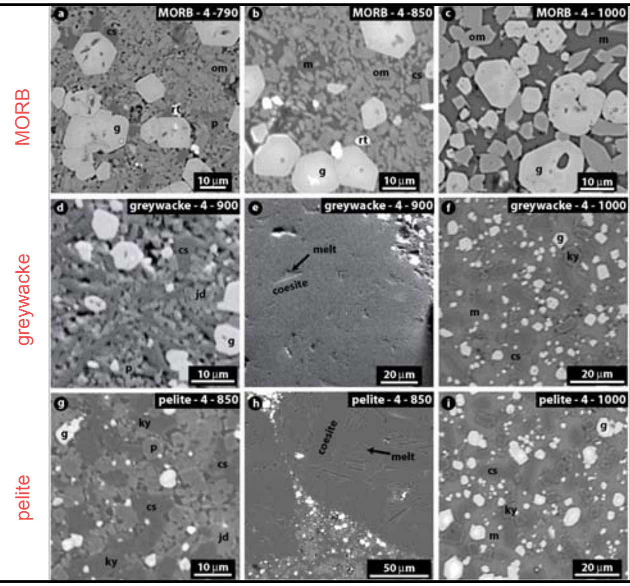
phengite + cpx + coesite + fluid = melt ± garnet



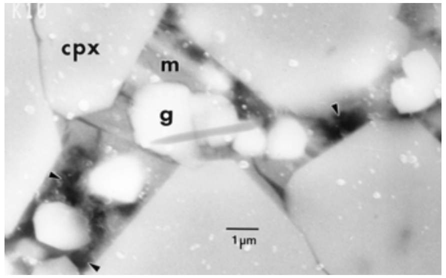
At > 100 km, clastic sediments and basaltic rocks have the same eclogitic mineralogy:

garnet+cpx+phengite +rutile+quartz

Schmidt, Vielzeuf, Auzanneau (2004)



K-enriched (0.5 wt%) MORB at 7 GPa, 1050 °C

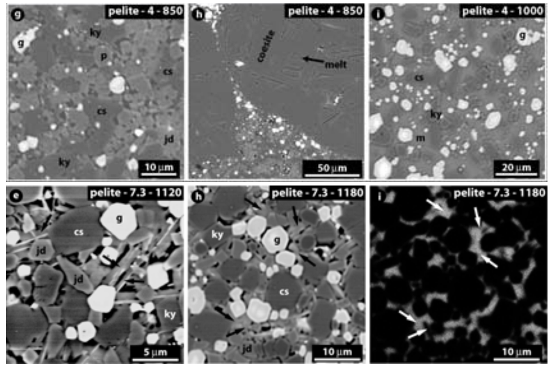


until mid 90's no MORB+H_2O solidus published for > 4 GPa

How to determine critical phenomena:

- textural observation

Pelite at



4 GPa

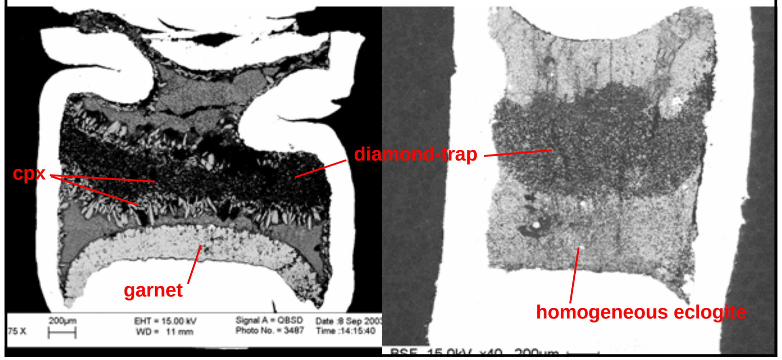
7.3 GPa

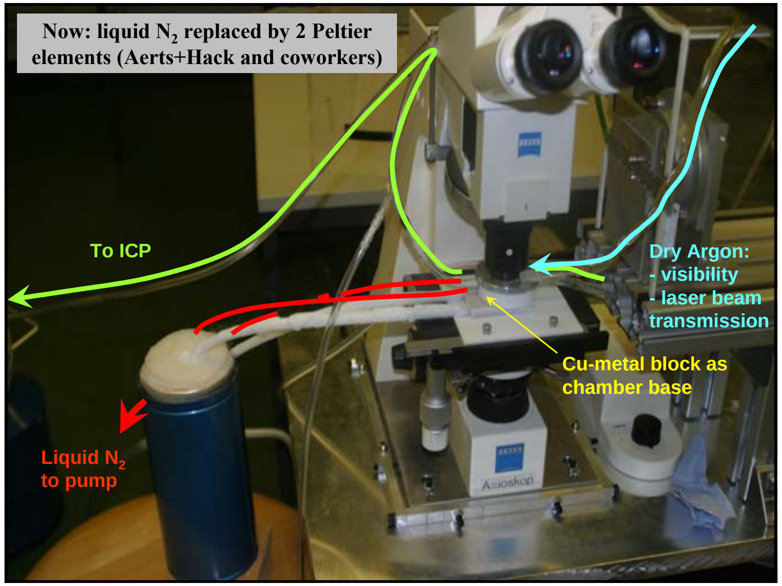
+ equilibrium experiments in complex systems
- only reliable if the melting/dissolution reaction exhausts a phase, and if melts are quenchable (i.e. siliceous)
- no composition of the involved fluids/melts/liquids

How to determine critical phenomena:

- chemical measurement of trapped liquids

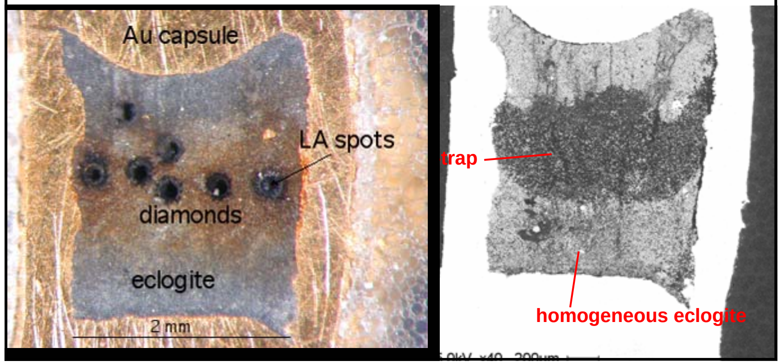
Melting experiments on K-free MORB

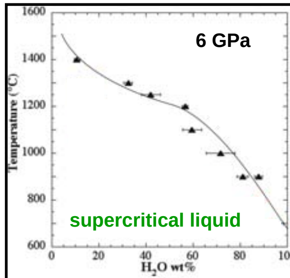




Rocking multi-Anvil diamond-Trap Éxperiment strategy:

- rigid diamonds keep “open space” which is then filled by supercritical melt during the experiment
- after quench and depressurization, capsule is frozen before opening and kept frozen during analyses
- we measure the composition of solidified mud/ ice, that retains all elements (in contrast to letting escape the fluid)

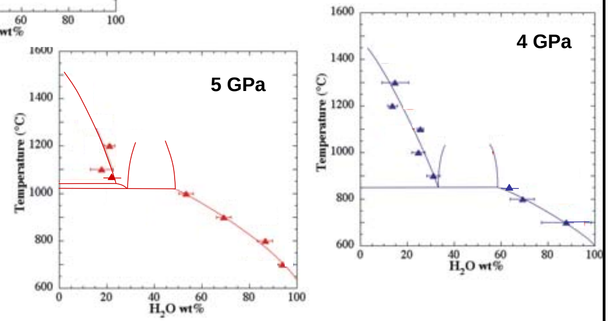


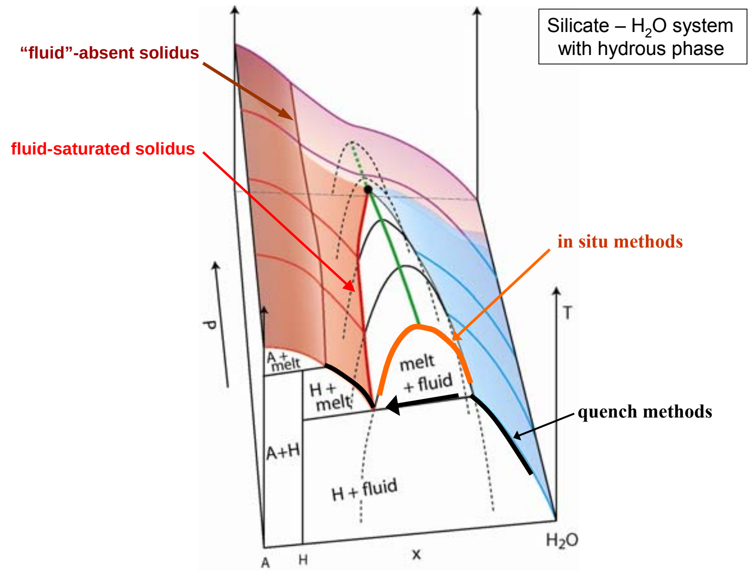


How to determine critical phenomena:

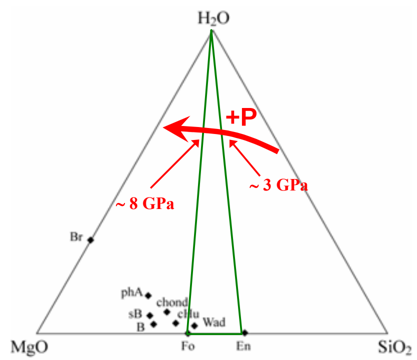
- chemical measurement of trapped liquids

H is not measured but Cs which is to >99% in the fluid
H:Cs ratio in starting material is known
H_2O content calculated from Cs-concentration





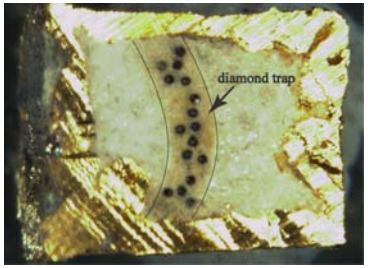
The MgO-SiO_2-H_2O system
and
Dense Hydrous Magnesium silicates

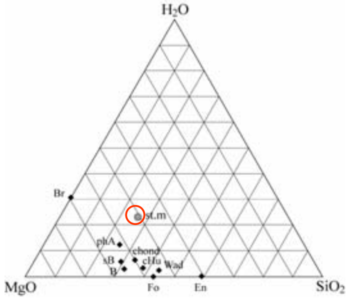


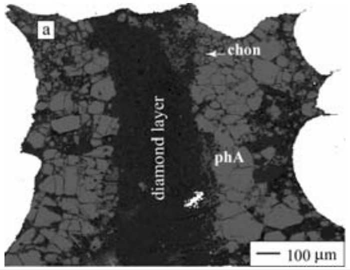
11 and 13.5 GPa - 1000-1350 °C

phase A ($Mg_7Si_2O_8(OH)_6$)
clinohumite ($Mg_9Si_4O_{16}(OH)_2$)
chondrodite ($Mg_5Si_2O_8(OH)_2$)
phase B ($Mg_{12}Si_4O_{19}(OH)_2$)
superhydrous B ($Mg_{10}Si_3O_{14}(OH)_4$)
hydrous wadsleyite ($Mg_{1.89}Si_{0.98}O_{0.37}(OH)_{0.3}$)

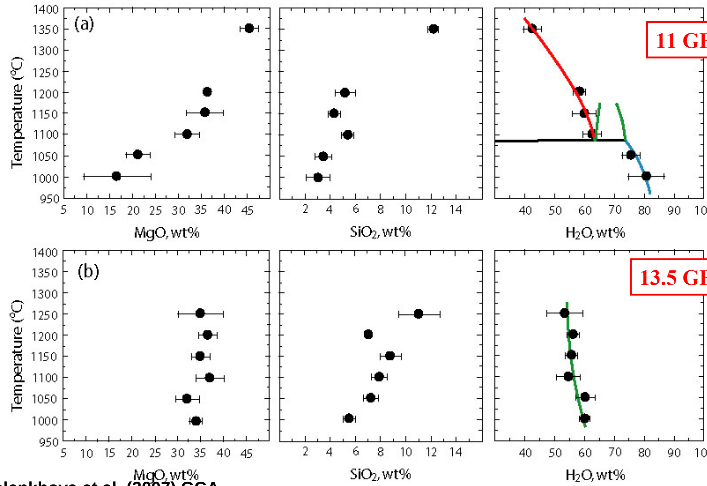
Laser ablation ICP MS



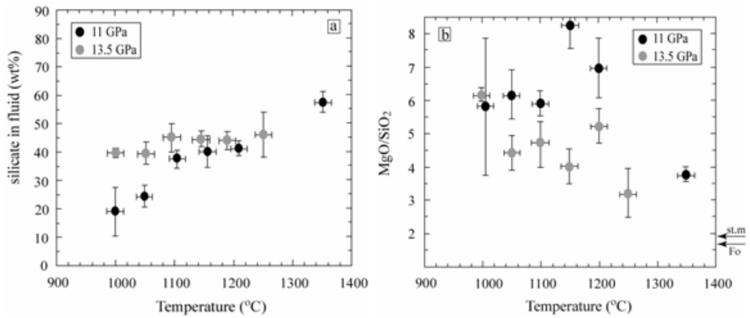




1.0 Phase A + 1.1 Fluid = 0.6 chondrodite + 1.4 Melt



Melenkhova et al. (2007) GCA



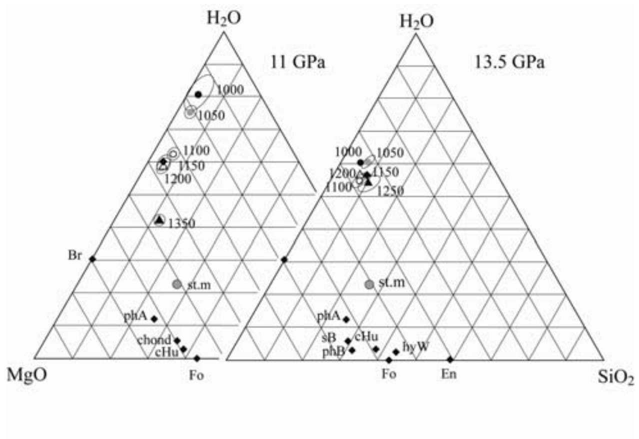
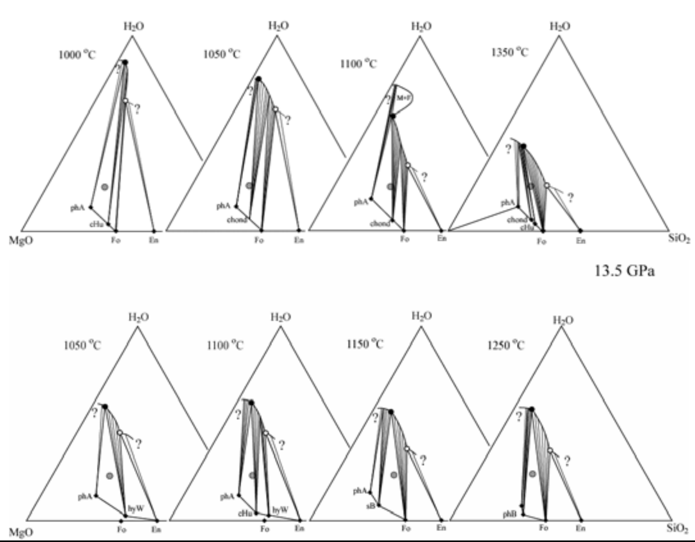
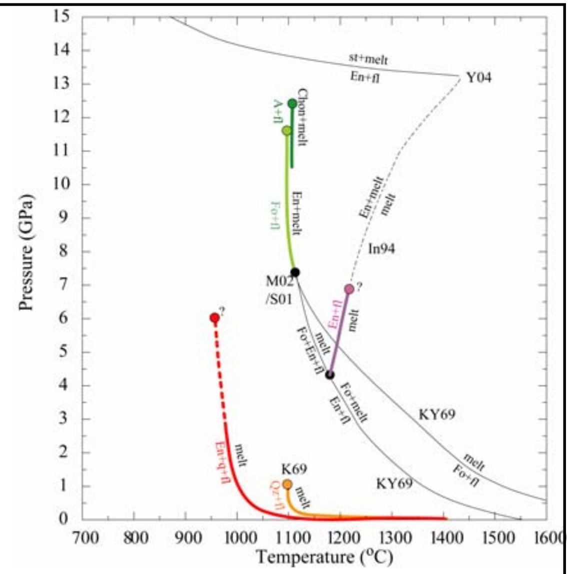


Figure 5

(final) supercriticity in $MgO-SiO_2-H_2O$



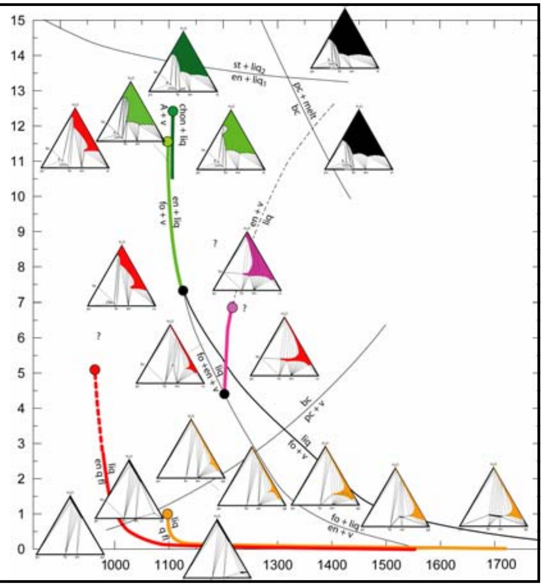
Secondcritical endpoints in $MgO-SiO_2-H_2O$



pressure

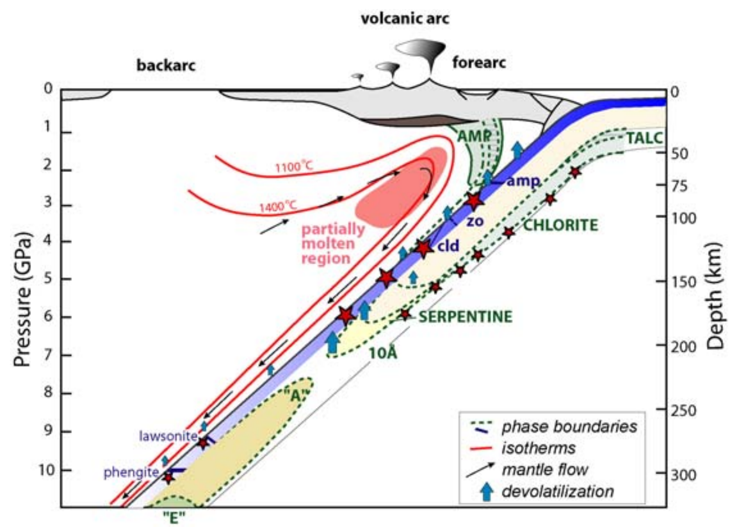
Phase A + Fl
Forsterite + Fl
Enstatite + Fl
Qz + En + Fl
Quartz + Fluid

Liquid volume in $MgO-SiO_2-H_2O$

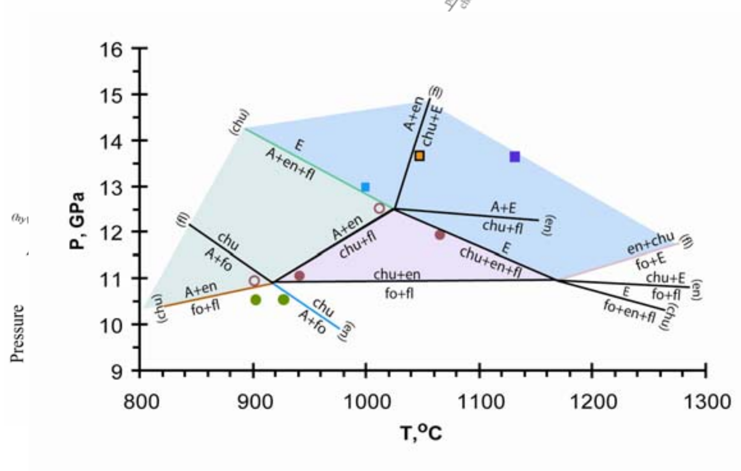


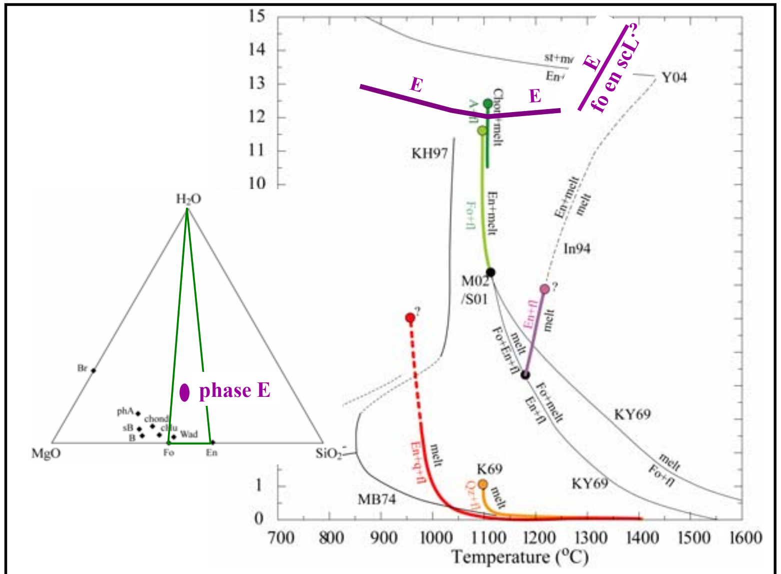
pressure

Phase A + Fl
Forsterite + Fl
Enstatite + Fl
Qz + En + Fl
Quartz + Fluid

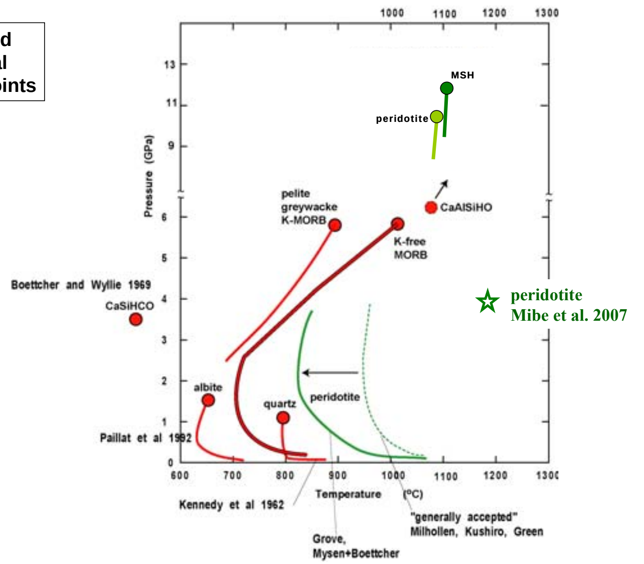


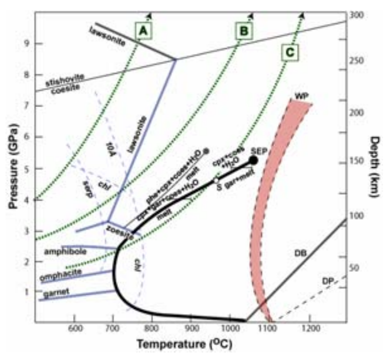
phase A, E, B, superhydrous B, clinohumite, chondrodite, hydrous wadsleyite, forsterite, enstatite, fluid, melt, scL





Second Critical Endpoints





The H_2O-saturated solidus for K-free MORB lies between **850 and 900°C** at **4 GPa** and between **1000 and 1050°C** at **5 GPa**. No solidus at **6 GPa**.

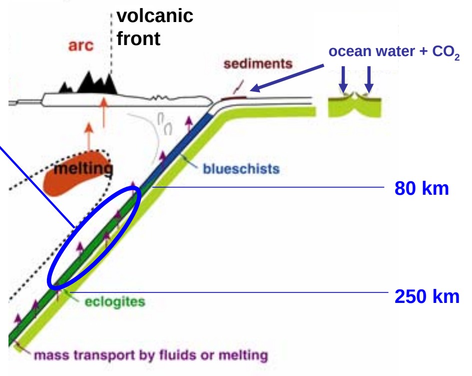
The dichotomy of dissolution vs. melting at 4-5 GPa is expressed through contrasting behaviour of many trace elements (U/Th, Sr, Ba, Be, LREE).

Problem:

What transport capacities does the "mobile" phase have (e.g. how much Be is transferred under what conditions) ?

What do the observed trace Element (Be) concentrations in arcs allow to deduce about transfer conditions ?

→ Investigate experimentally element distribution minerals/mobile phase



Plank and coworkers:
>50% Be are transfered to arc magmas, thus, slabs must melt,
thus temperatures of the subducted crust below the arcmust be >750 °C

Trace element signature of supercritical liquids

Why fluid-saturated melting ?

In subducting lithosphere serpentine dehydration is a huge fluid source just at the right temperature for wet melting

To what depth does classical fluid-present melting exist ?

To some pressure, the fluid-melt dichotomy with clearly distinguished chemical charcteristics of the mobile phase exists, what happens at higher pressure ?

The above question does not concern fluid-absent melting, i.e. melting without external fluid source

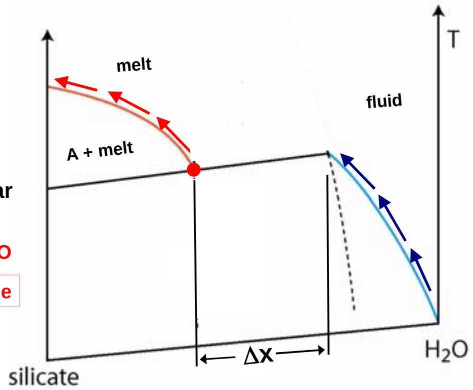
U>Th, high Li,B; low Be

80-95 wt% H_2O

cpx + fluid = melt ± gar

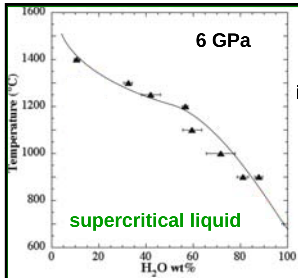
10-20 wt% H_2O

Th>U, high Be



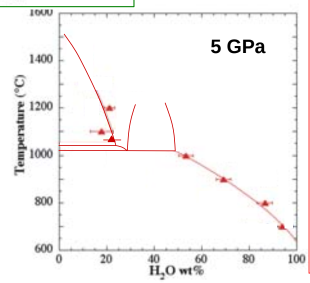
sediment melting signature

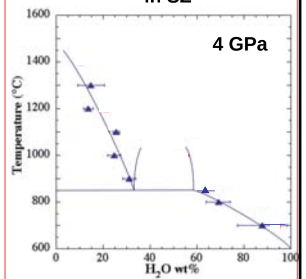
- high recycling rates of > 60% of the subducted Be, La, and Th in many arcs, including e.g. Tonga
- these elements are mostly insoluble in crustal fluids, thus sediment melting was proposed to generally occur (Plank et al.)



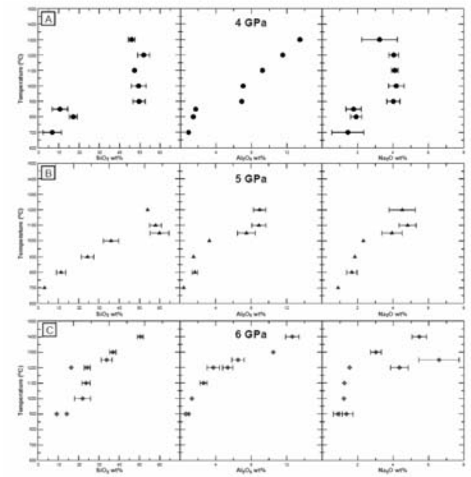
Chemical continuum with a supercritical liquid in SZ at > 160 km depth

dichotomy of fluid vs. melt production in SZ





phase compositions for a K-free meta-MORB eclogite

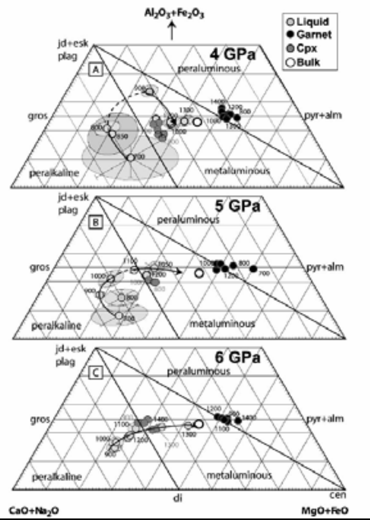


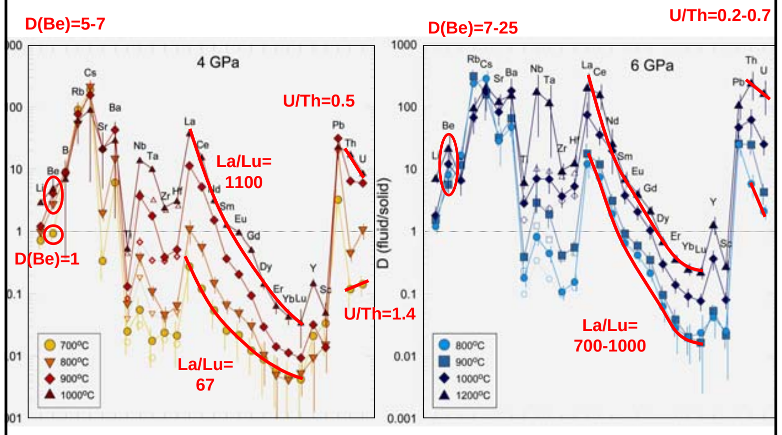
phase compositions for a K-free meta-MORB eclogite

peralkaline:
Na+K >> Al

metaaluminous:
Na+K ~ Al = feldspar

peraluminous:
Na+K << Al
→ excess Al-phases such as garnet, muscovite





fluid-melt dichotomy **melt-like supercritical liquids**

Conclusions

- Supercritical liquids in subducted crust at ≥ 160 km depth
- MSH becomes entirely supercritical at P > 11 GPa
- Fluid-absent melting in crust and mantle take place to higher P
  phengite in crust, phase E possibly in mantle
- The “sediment melting signature” (Ba-La-Th mobility) is identical to the supercritical liquid signature
  → no direct temperature implication
- A lot of work is still needed to understand the systematics and geochemical consequences of supercriticality