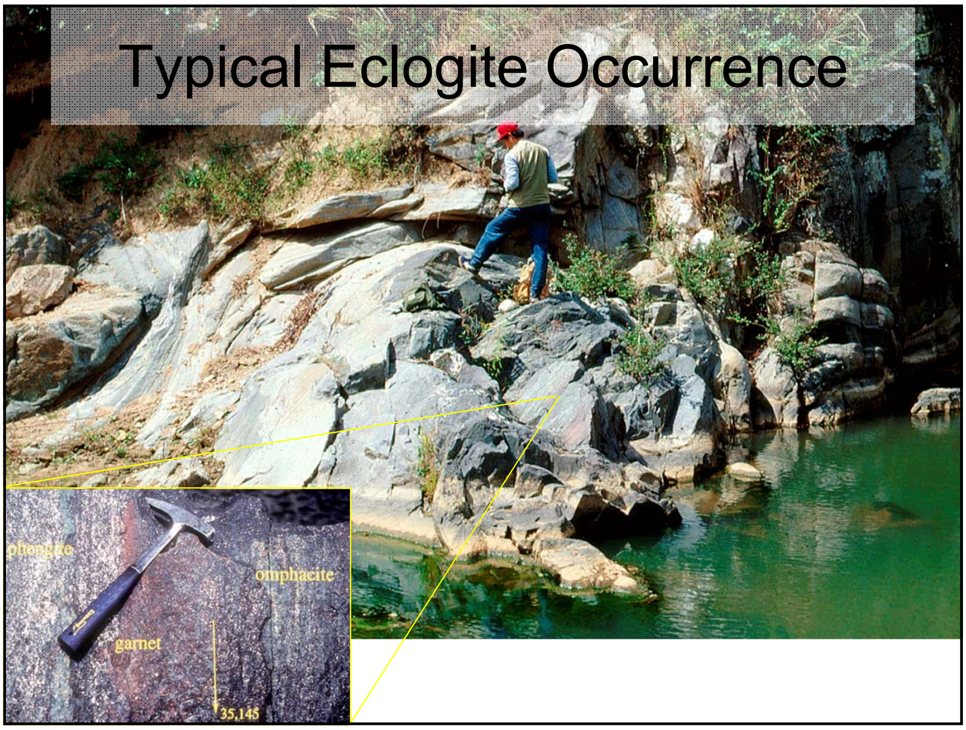
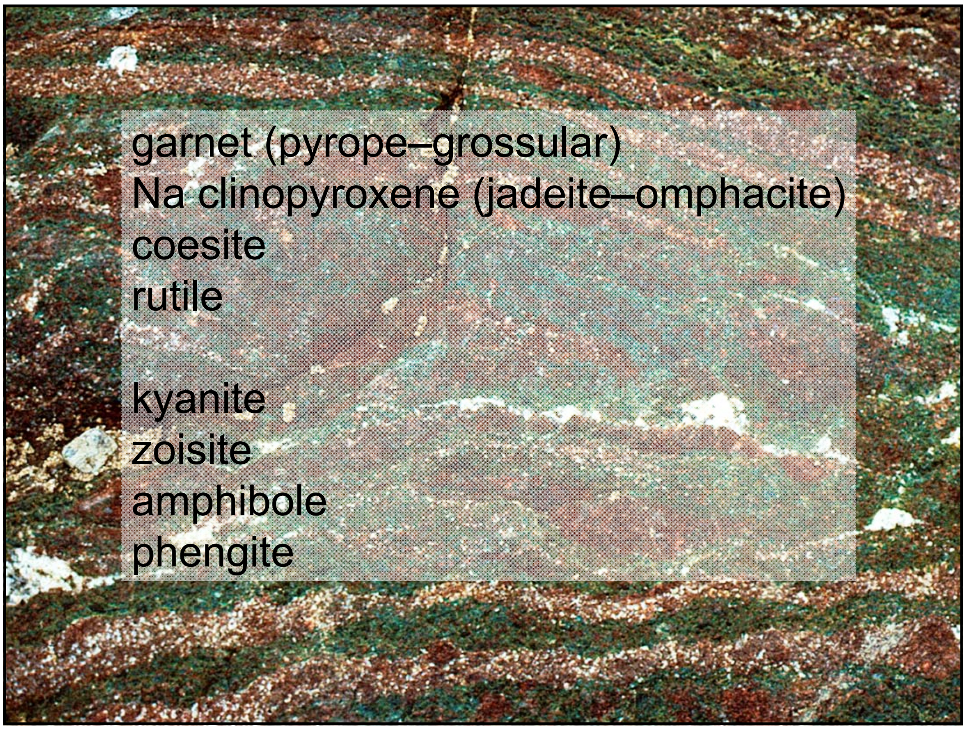
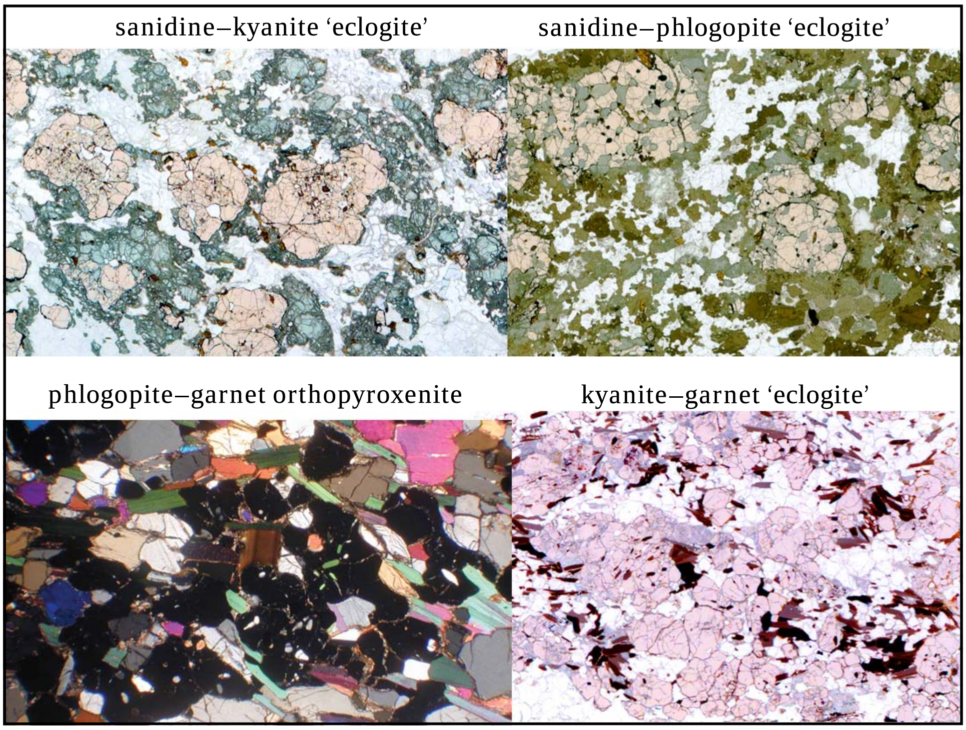
Petrology at Ultrahigh Pressure

- phase relations at high P & T
- coesite recognition & textures
- diamond recognition & textures
- other UHP phases
- thermobarometry of eclogite
- P & T of record from UHP terranes
- retrogression of UHP rocks

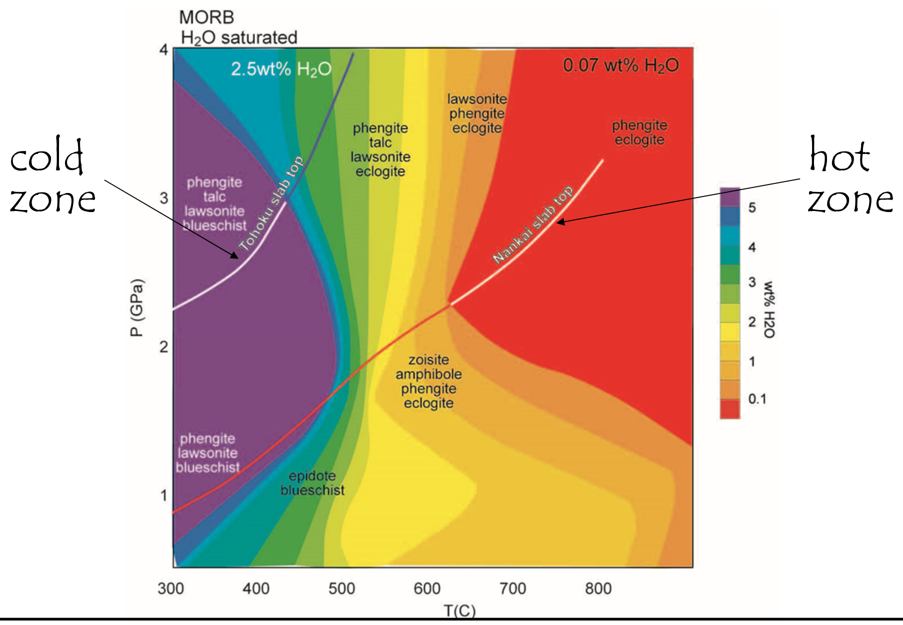
Typical Eclogite Occurrence




garnet (pyrope–grossular)
Na clinopyroxene (jadeite–omphacite)
coesite
rutile
kyanite
zoisite
amphibole
phengite


sanidine–kyanite 'eclogite'
sanidine–phlogopite 'eclogite'
phlogopite–garnet orthopyroxenite
kyanite–garnet 'eclogite'

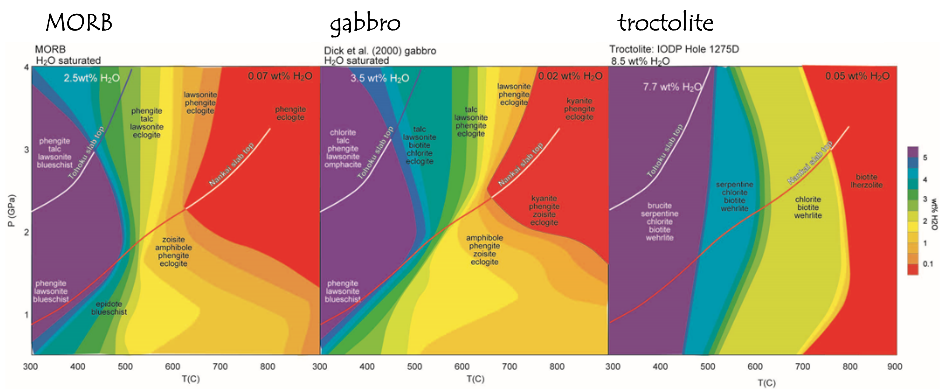
MORB



Unmetasomatized Mafic Crust

cold zones: very wet; hot zones: dry

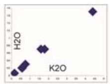
troctolite best suited for carrying H_2O because serpentine stable

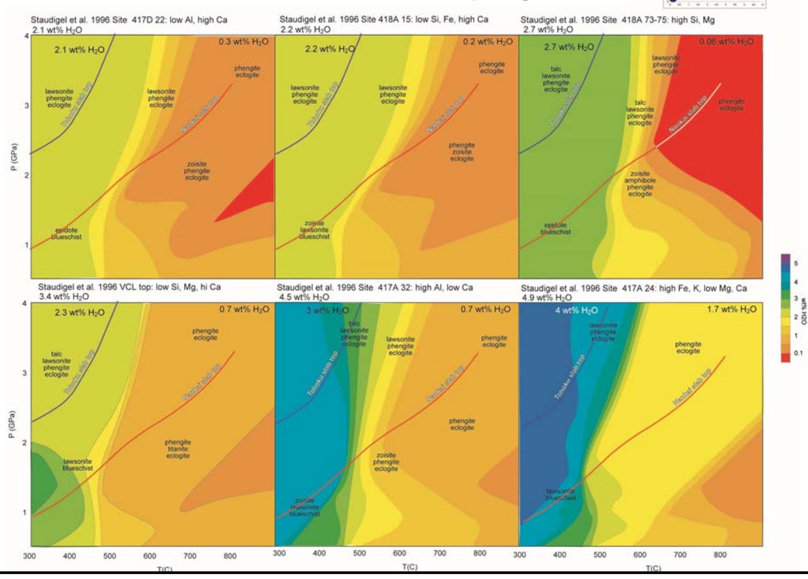


Typical Oceanic Volcanic Rocks

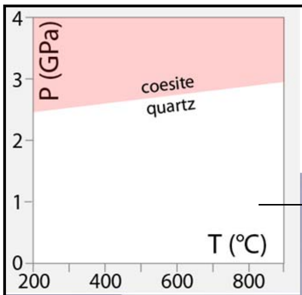
cold zones: H_2O scales with bulk-rock H_2O because lawsonite

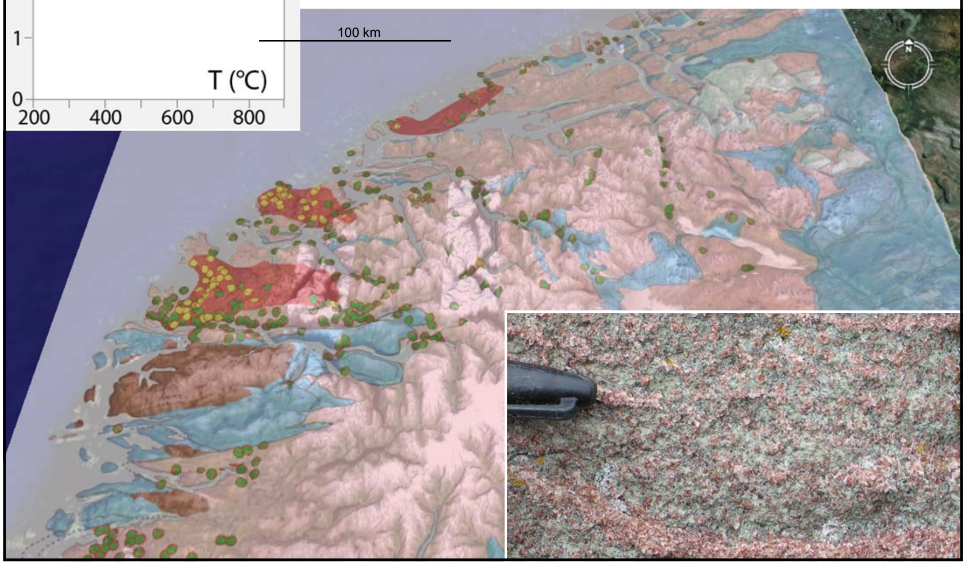
hot zones: H_2O scales with K_2O content because phengite





Western Gneiss Region, Norway



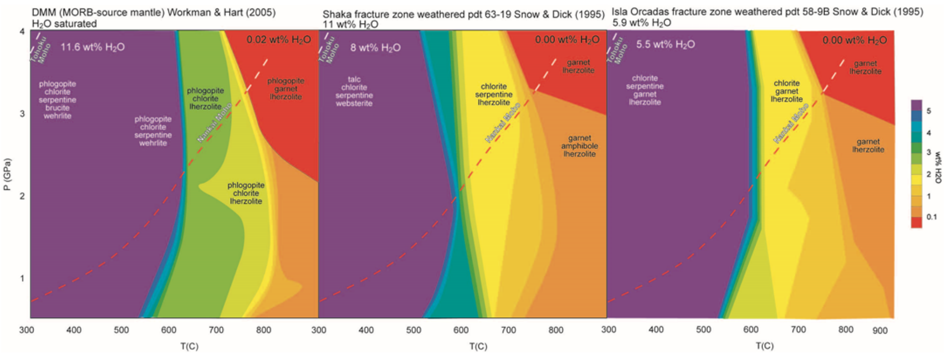


Oceanic Mantle

cold zones: scales with bulk rock H_2O; serpentine & brucite are key

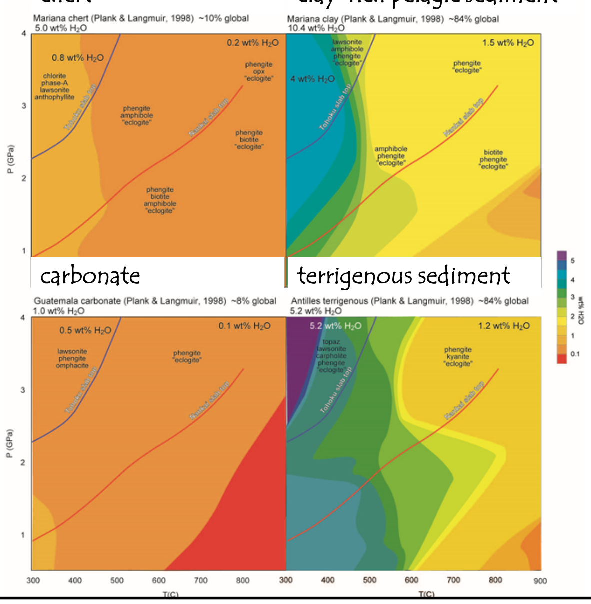
hot zones: no H_2O

depleted mantle | fracture-zone rock | fracture-zone rock



Oceanic Sediments

chert | clay-rich pelagic sediment



chert & carbonate carry some $H_2O > 0$

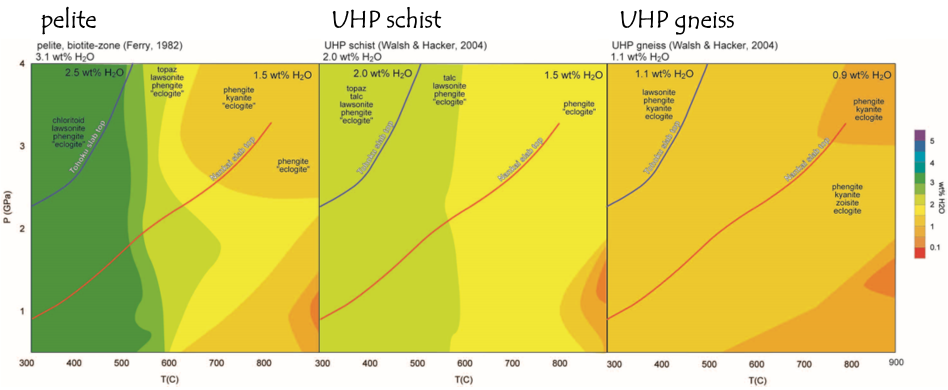
terrigenous sediments, clay-rich pelagics have significant H_2O

Continental Schist & Gneiss

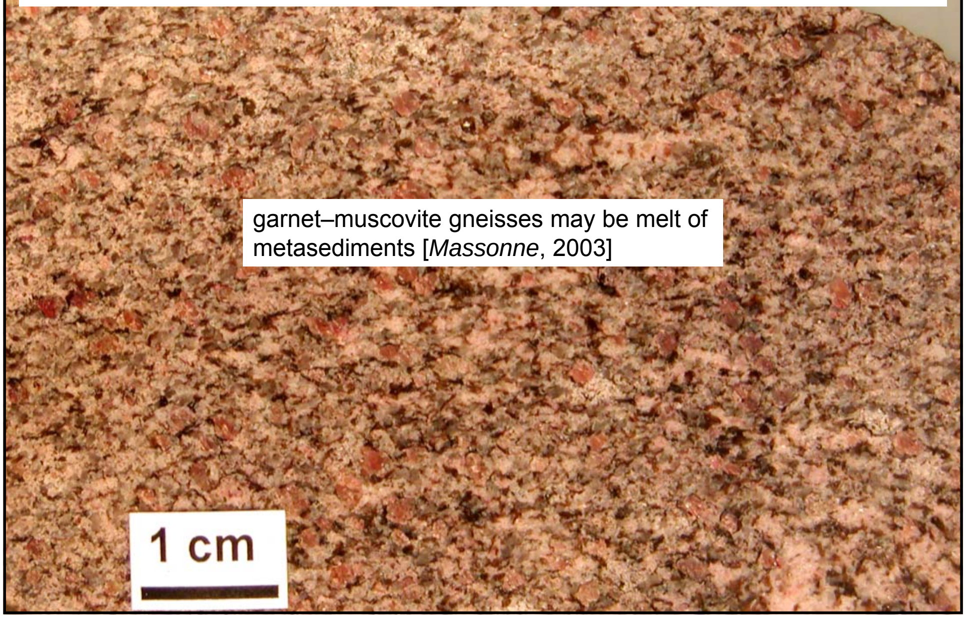
important carrier of H_2O

cold zone: H_2O scales with bulk-rock H_2O

hot zones: H_2O scales with bulk-rock K_2O

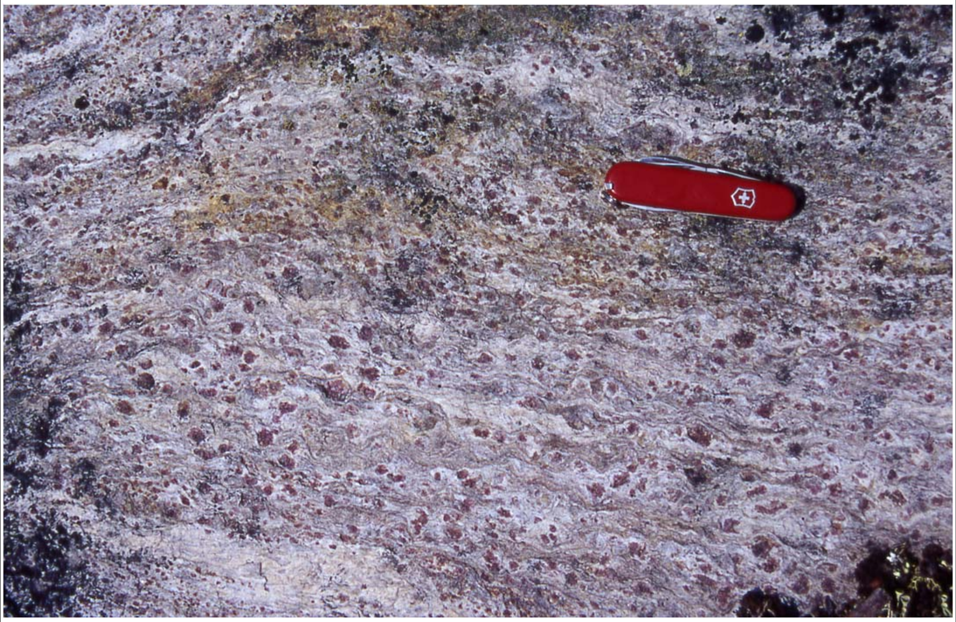


Diamondiferous quartzofeldspathic gneiss from Saidenbach Reservoir



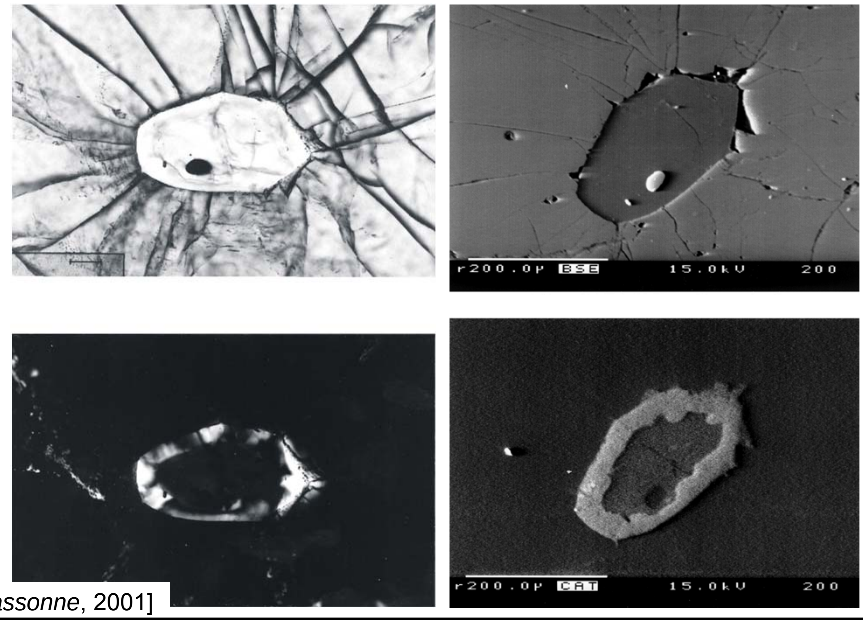
Garnet-kyanite gneiss

Julie Baldwin



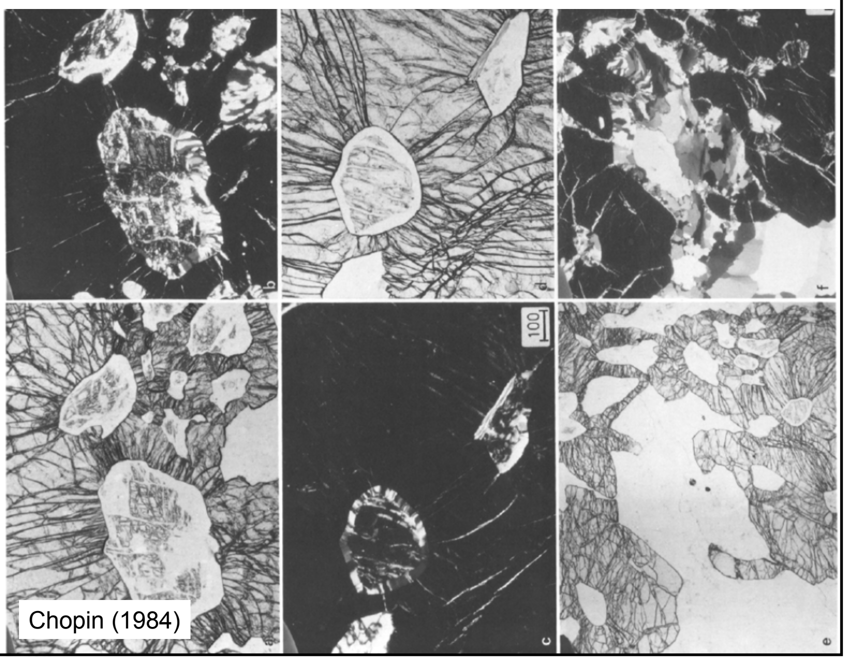
Julie Baldwin

Coesite Eclogite, Erzgebirge



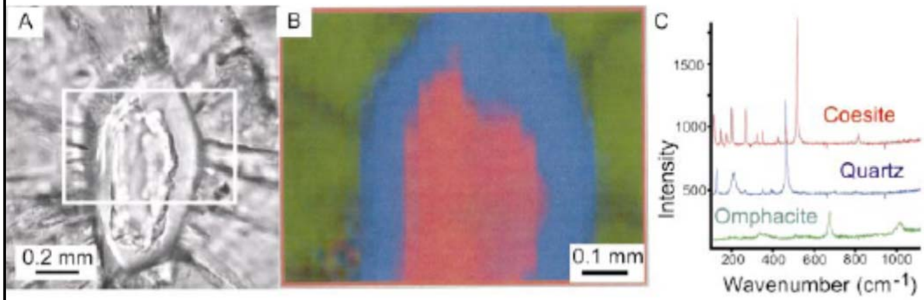
[*Massonne*, 2001]

Dora Maira



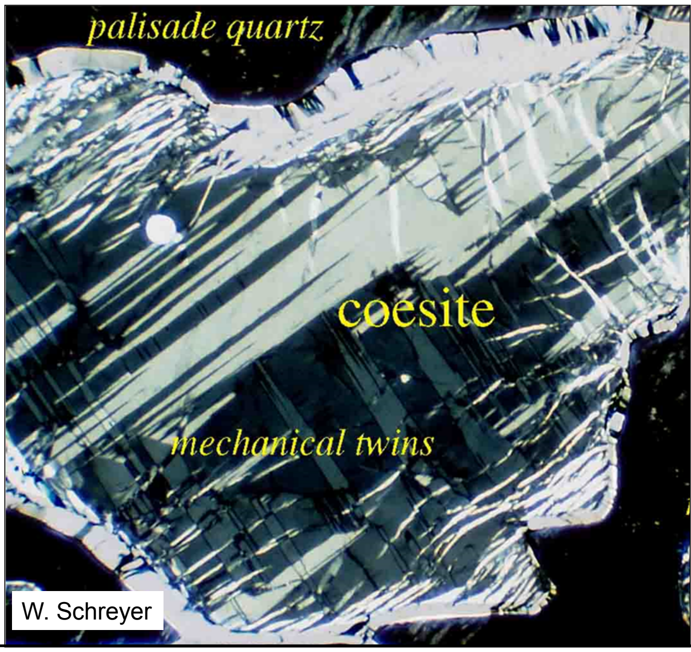
Chopin (1984)

Kaghan Valley, Pakistan

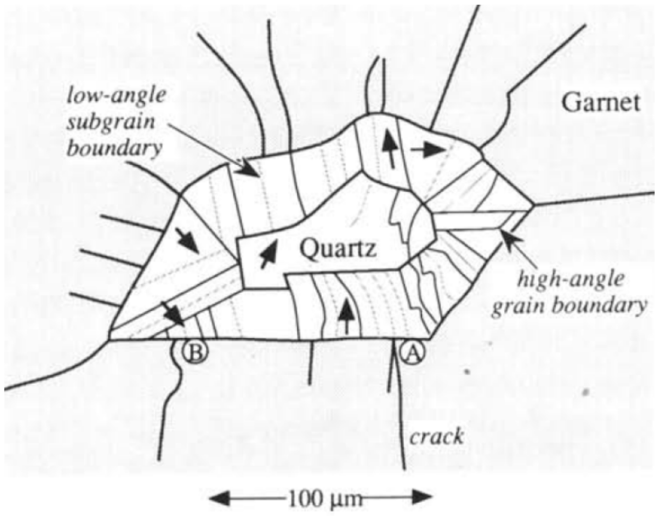


O'Brien et al. (2001)

Dora Maira

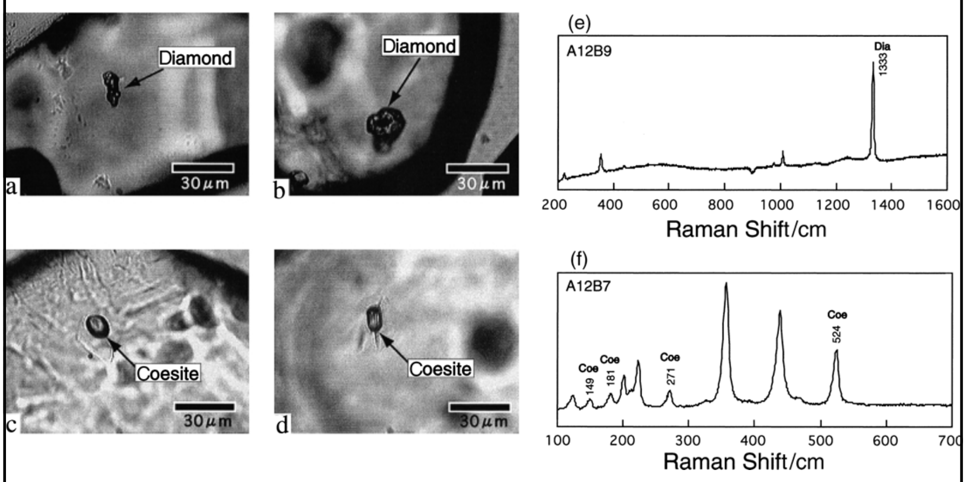


Palisade Quartz



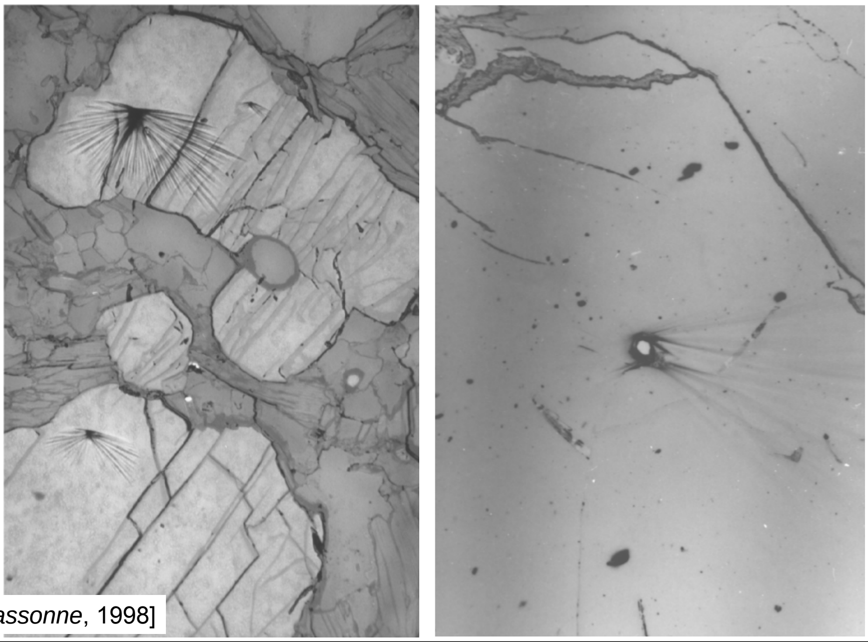
Hacker & Peacock (1994)

Kokchetav Massif

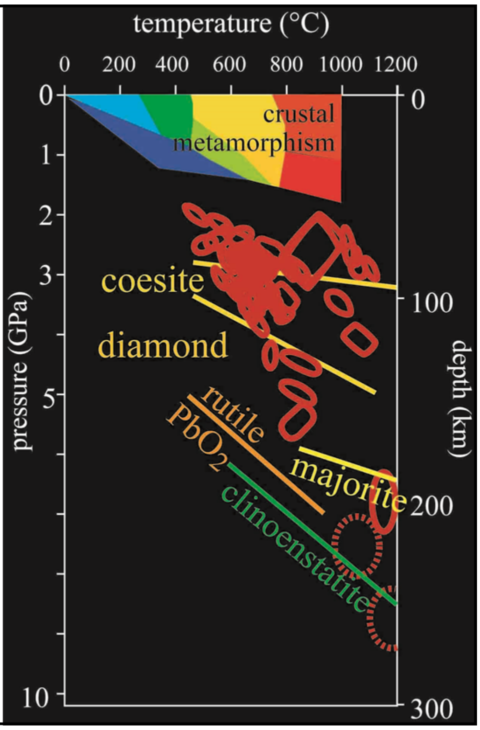


Katayama et al. (2000)

Diamondiferous quartzofeldspathic gneiss, Erzgebirge



[*Massonne*, 1998]

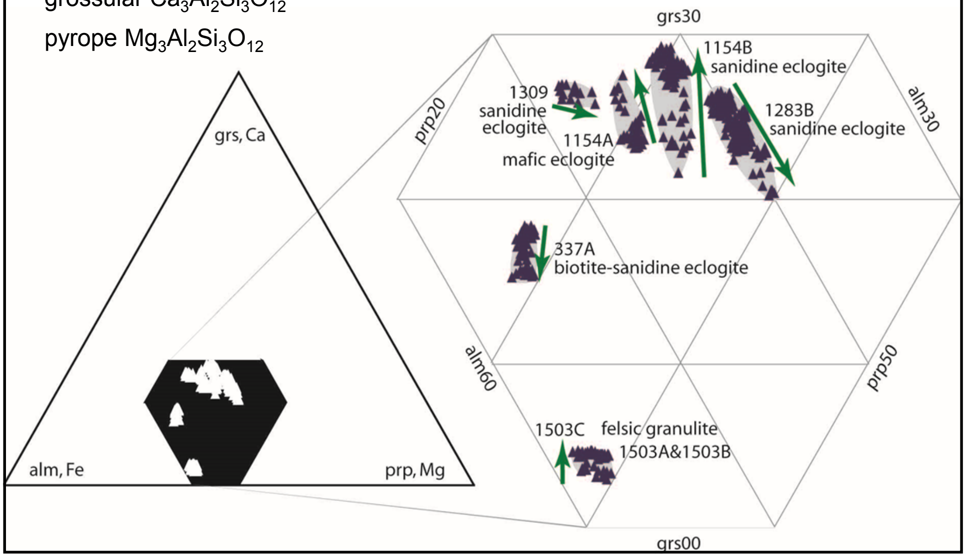


UHP Garnet

almandine $Fe_3Al_2Si_3O_{12}$

grossular $Ca_3Al_2Si_3O_{12}$

pyrope $Mg_3Al_2Si_3O_{12}$



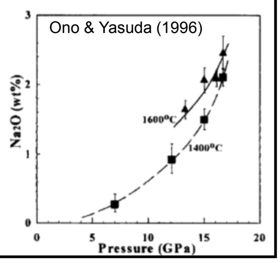
Na Garnet

trace elements in African kimberlites (ppm)

Bishop et al. (1978)	Na_2O	P_2O_5	K_2O	TiO_2
	Lherzolite and ultramafic rocks			
Garnet	150–790(340)	200–1040(460)	<20	160–5190(1470)
Olivine	40–130(90)	50–200(130)	<20	0–390(130)
Orthopyroxene	530–1900(1070)	0–90(50)	10–110(30)	10–1650(480)
	Eclogites and cpx megacryst			
Garnet	100–1420(610)	160–940(530)	<20	210–7800(2000)

$Na^+ + Ti^{4+} = Ca^{2+} + Al^{3+}$ (Chopin & Ferraris, 2003)

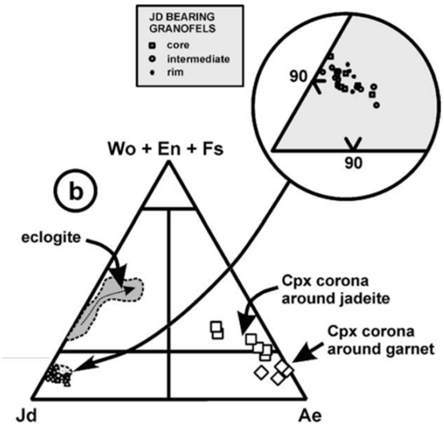
$Na^+ + P^{5+} = Mg^{2+} + Si^{4+}$



UHP Clinopyroxene

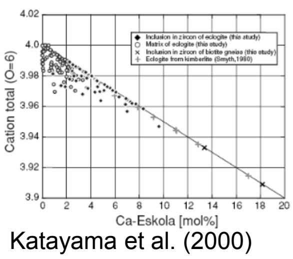
jadeite $NaAlSi_2O_6$

acmite $NaFe^{3+}Si_2O_6$

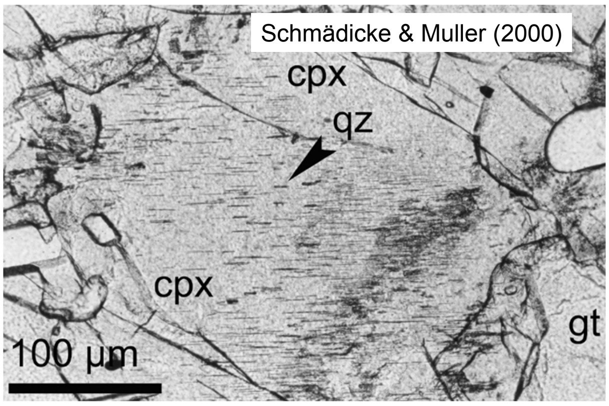


Rolfo et al. (2004)

Clinopyroxene with octahedral vacancies



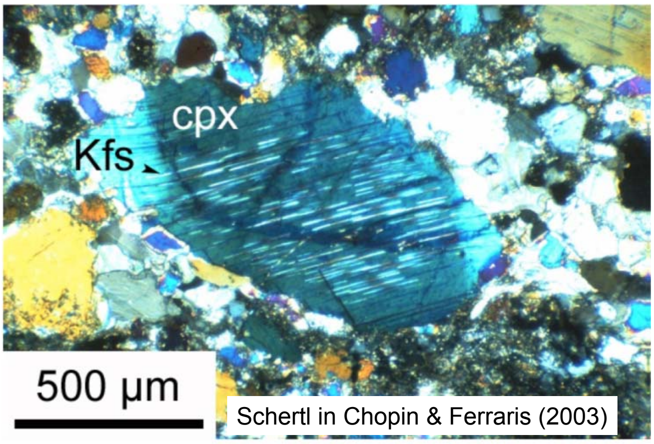
Katayama et al. (2000)



Schmädicke & Muller (2000)

Ca-Eskola $Ca_{0.5}AlSi_2O_6$

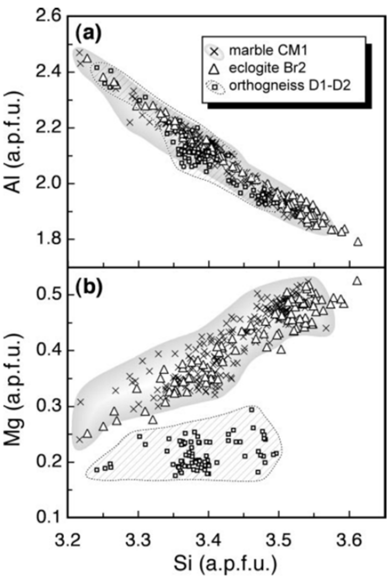
Potassic Clinopyroxene

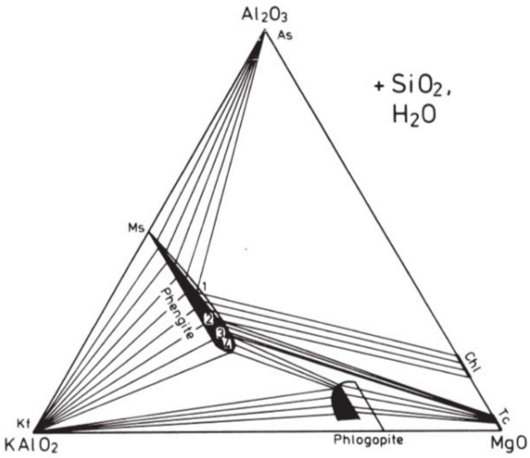


0.23 K pfu

$K^+ + Al^{3+} = Ca^{2+} + Mg^{2+}$ (Bindi et al., 2003)

Phengite



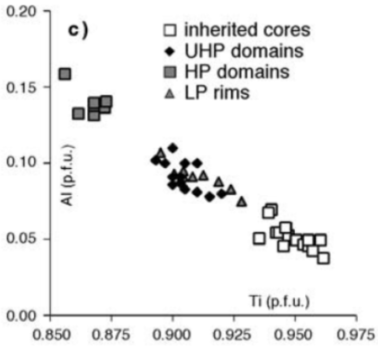


Chopin & Ferraris (2003)

Al Sphene

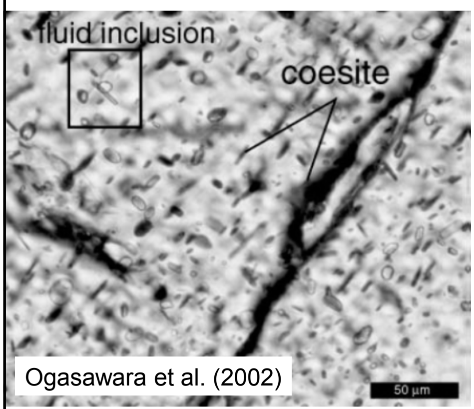
$(Al, Fe)^{3+} + (OH, F)^{-} = Ti^{4+} + O^{2-}$
0.535 Å + 1.33 Å < 0.605 Å + 1.40 Å

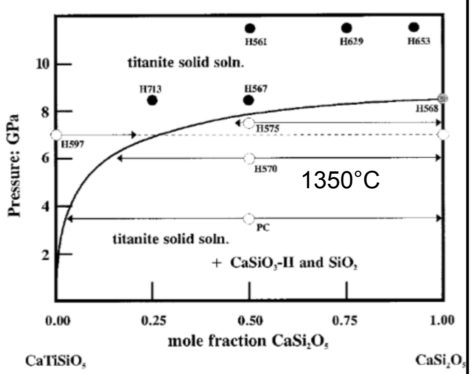
Chopin & Ferraris (2003)



Rubatto et al. (2003)

Si Sphene

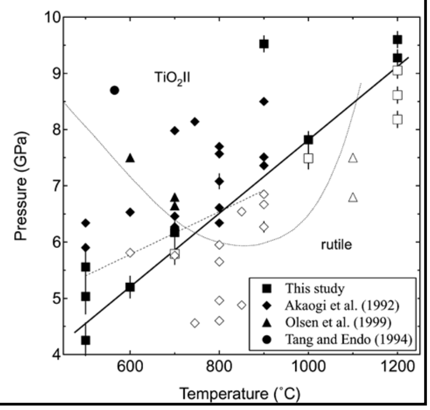




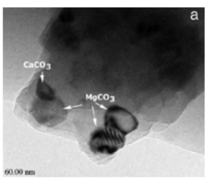
Ti = Si substitution produces $CaSi_2O_5$ (Knoche et al., 1998)

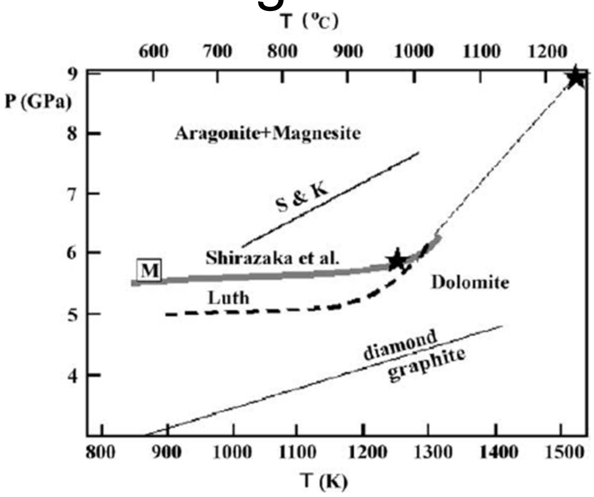
αPbO_2 TiO_2

α-PbO_2 Ries impact crater (El Goresy et al., 2001)
Erzgebirge nm film (Hwang et al., 2000)



Aragonite + Magnesite





aragonite + magnesite in diamond from Kokchetav interpreted to indicate >6 GPa

Dobrzhinetskaya et al. (2006)

P-T Determinations from UHP Terranes

Motivation

Comprehensive & accurate *P-T* determinations for

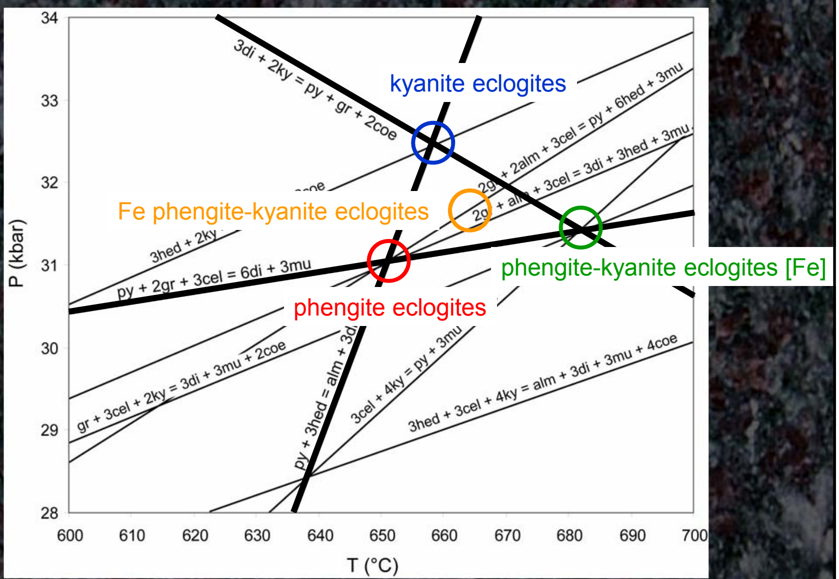
- degree of structural disruption
- maximum depth of subduction/exhumation
- temperatures in subduction zones
- whether subducting sediment/crust adds to arc magmatism
- exchange of material between crust & mantle

Problem

- most eclogites bimineralic
- diffusional re-equilibration of Fe–Mg likely
- cannot easily measure Fe^{3+}/Fe^{2+}
- uncertainties in Fe^{3+}/Fe^{2+} leads to ±100°C

[e.g., *Krogh Ravna & Paquin*, 2003; *Proyer et al.*, 2004]

Eclogite Thermobarometry



[*Sharp et al.*, 1992; *Waters & Martin*, 1993; *Ravna & Terry*, 2004]

Ti in zircon

• experimentally & empirically calibrated [*Watson & Harrison*, 2005; *Watson et al*., 2006]

• stated uncertainty ~10 °C (2σ), however, effect of P (50°C/GPa) only theoretical [*Ferry & Watson,* 2007]

• returns 700–800°C for Norway, China, & Greenland, similar to other estimates

• run-to-run precision is 2.7% (2σ) or ±11–21°C

Ti in quartz

• *Wark & Watson* [2006]

• 1 GPa experimental calibration; P effect unknown

• solubility of Ti in *coesite* unknown

• peak temperatures of 750–791°C for Norway & 941–998°C for Pamir

• run-to-run precision is 1.7% (2σ) or ±11–18°C

Zr in rutile

- empirically & experimentally calibrated [*Zack et al.*, 2004; *Ferry & Watson,* 2007; *Tomkins et al.,* 2007]
- minor analytical & calibration inaccuracy, 20–40 °C (2σ), theoretical P dependence 50–75°C/GPa [*Ferry & Watson*, 2007; *Tomkins et al*., 2007]
- Greenland HP rocks return 700– 850°C (Scott Johnston, pers. comm.)

Zr in garnet

- experimentally calibrated in almandine [*Donohue et al*., 2001; *Donohue*, 2002; *Tomkins et al*., 2007]
- uncertainties, e.g., solubility of Zr in grossular & pyrope, not quantified & expected to be large, based on models by *Brandelik* [2004] & *Massonne* [pers. comm.].
- run-to-run precision is 0.7% (2σ) or ±5–15°C

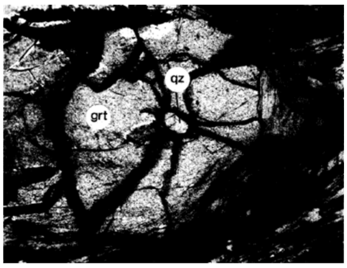
Oxygen-isotope thermometry

• uncertainties of 50–100°C [e.g., *Sharp et al.*, 1992; *Sharp et al.*, 1993; *Zhang et al.*, 1998; *Zheng et al.*, 1998; *Leech & Ernst*, 2000; *Zheng et al.*, 2002; *Masago et al.*, 2003; *Zheng et al.*, 2003].

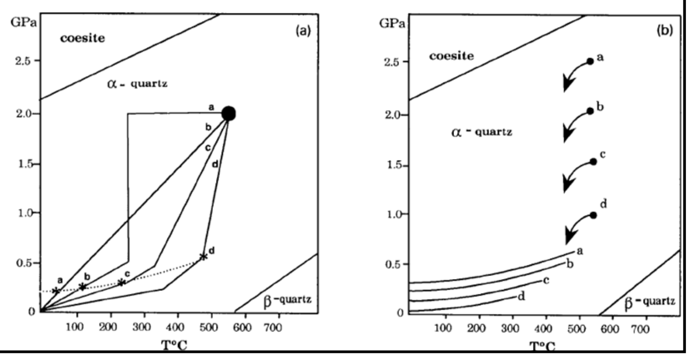
• when minerals *are* in isotopic equilibrium, is a powerful complement to other thermometers – or may constitute only thermometer

• when oxygen isotopes are *not* in equilibrium among minerals, indicates that distributions of other isotopes or elements are suspect

Inclusion Barometry

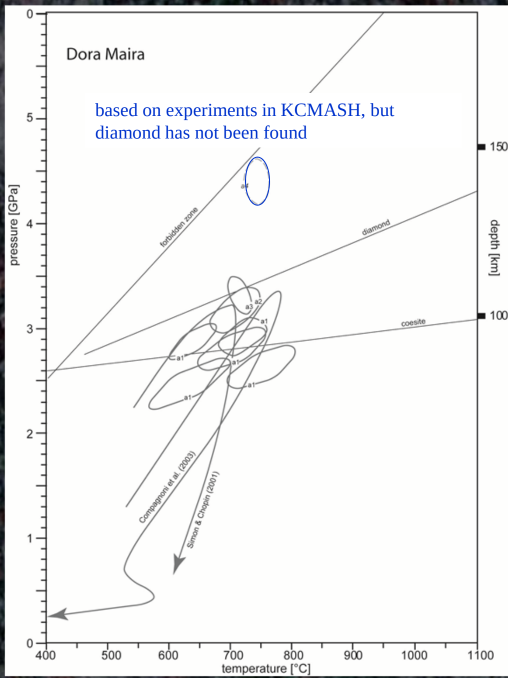


>2 GPa at 550°C



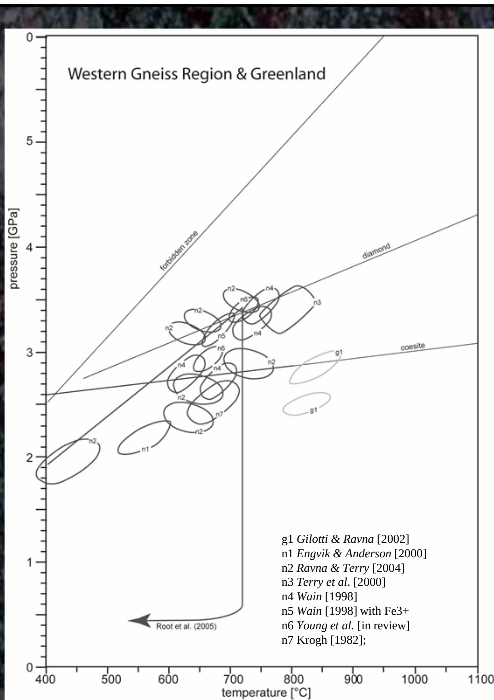
Wendt et al. (1993)

Dora Maira

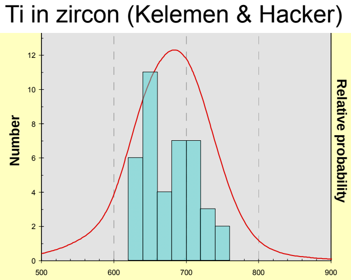


a1 *Nowlan* [1998],
a2 *Kienast et al*. [1991],
a3 *Coggon & Holland* [2002],
a4 *Hermann* [2003]

Norway & Greenland

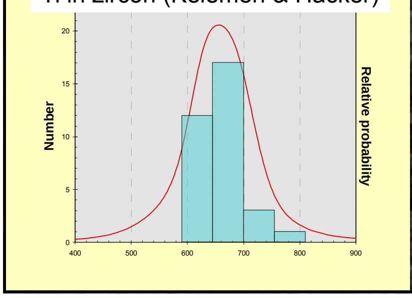


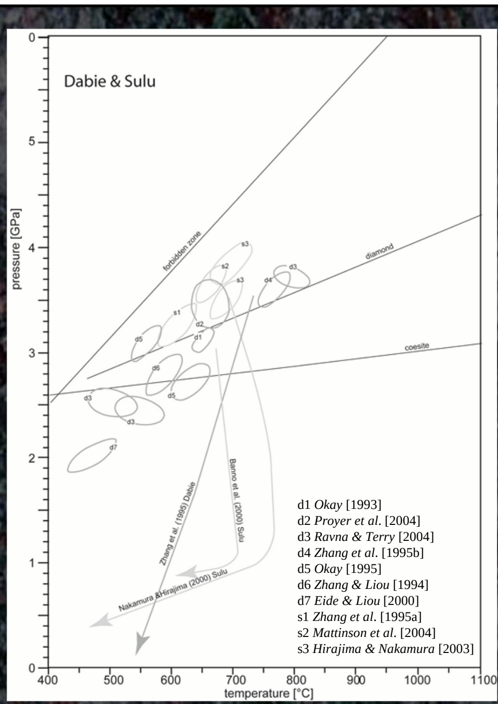
Ti in zircon (Kelemen & Hacker)



Dabie & Sulu

Ti in zircon (Kelemen & Hacker)





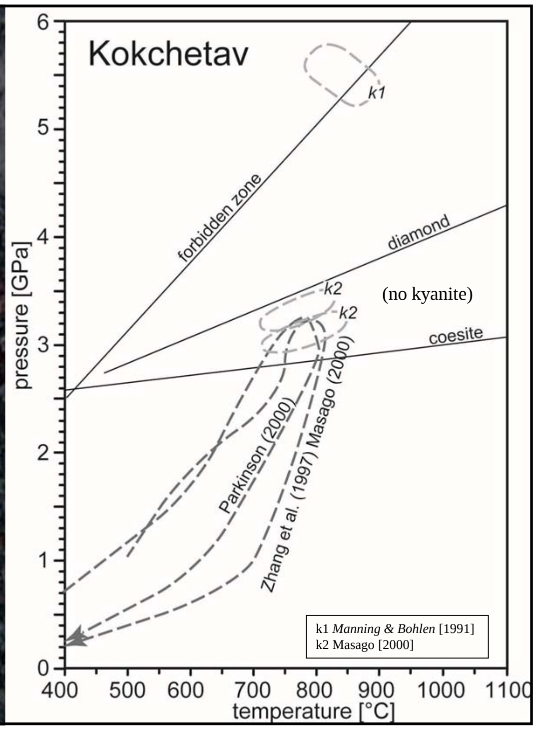
Kokchetav

1st regional metamorphic diamond

5–8 GPa estimated from
Si-sphene [*Ogasawara et al.*, 2002]
K-cpx [*Bindi et al.*, 2003]
TARK [*Manning & Bohlen*, 1991]

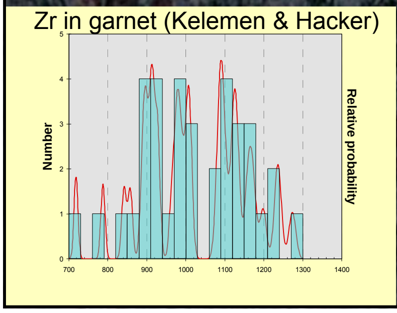
>1000°C from Ti solubilities in garnet [*Massonne*, 2003]

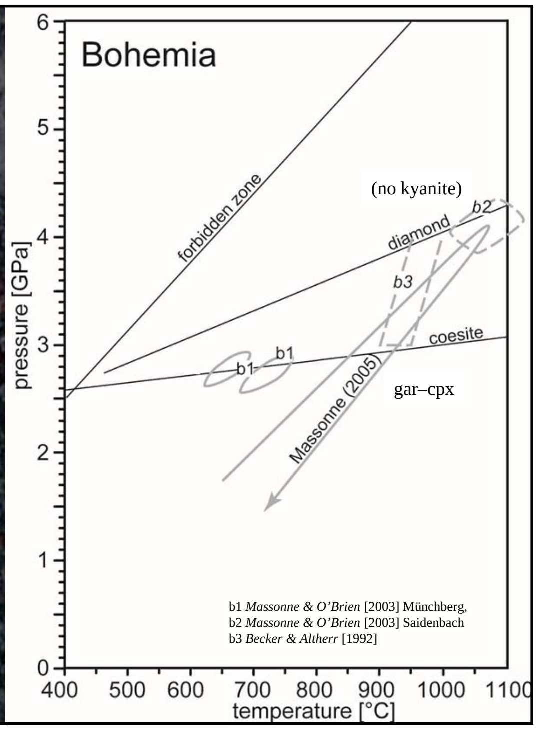
but large extrapolation of solubility data or thermodynamic properties



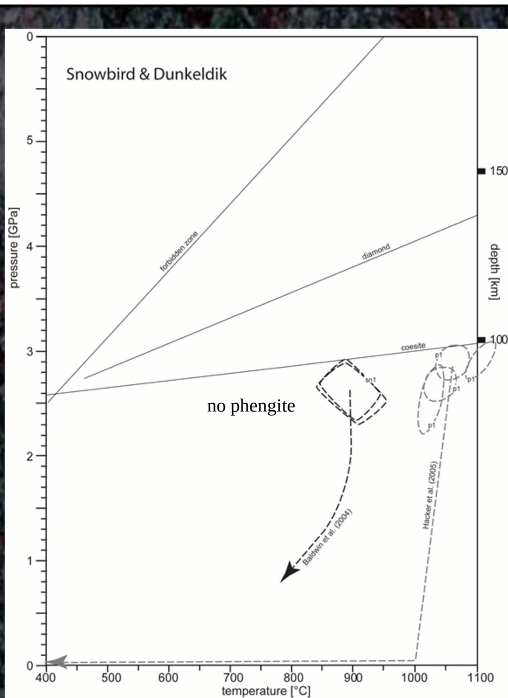
Bohemian Massif

nm αPbO_2 TiO_2 [*Hwang et al.*, 2000] prompted suggestions of 7 GPa [*Massonne*, 2003], but affect of interfacial free energies makes 4 GPa more likely *Hwang et al.* [2000]

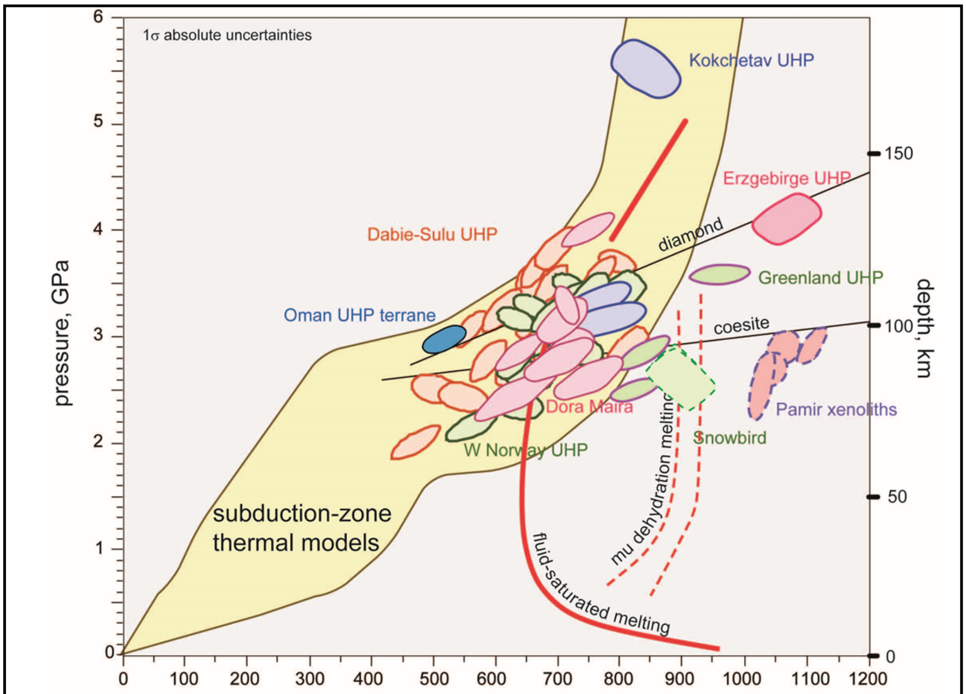




Snowbird T.Z. & Dunkeldik Xenoliths



p1 *Hacker et al.* [2005]
sn1 *Baldwin et al.* [2004]

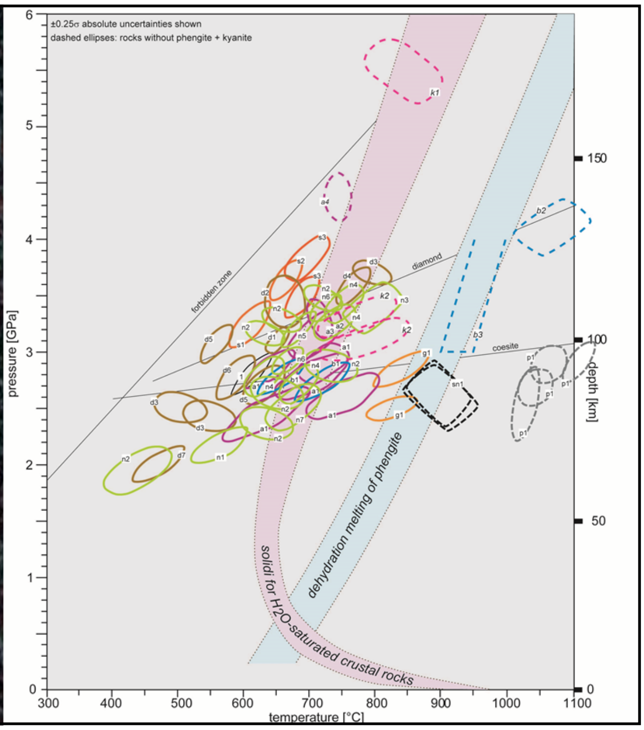


Ravna & Terry (2004)

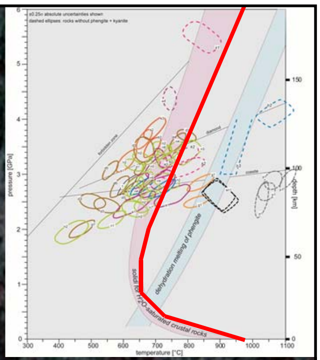
Pinned by Solidus?

solidi [*Stern et al.*, 1975; *Nichols et al.*, 1994; *Kessel et al.*, 2005]

phengite dehydration [*Hermann & Green*, 2001]

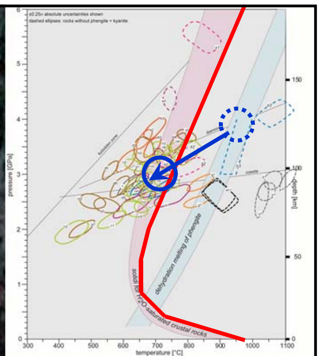


Pinned by Solidus?



- UHP rocks rarely experience hypersolidus temperatures
- UHP rocks that experience hypersolidus T recrystallize in the presence of melt during cooling & "freeze in" when crossing back below the solidus
- UHP rocks that experience hypersolidus T rarely exhumed because UHP terrane disaggregates as a result of melt-induced weakening

Pinned by Solidus?



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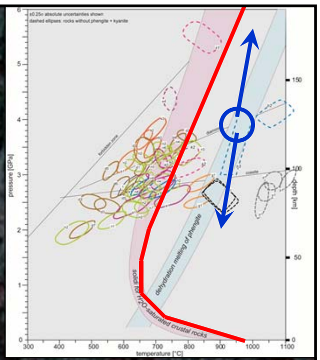
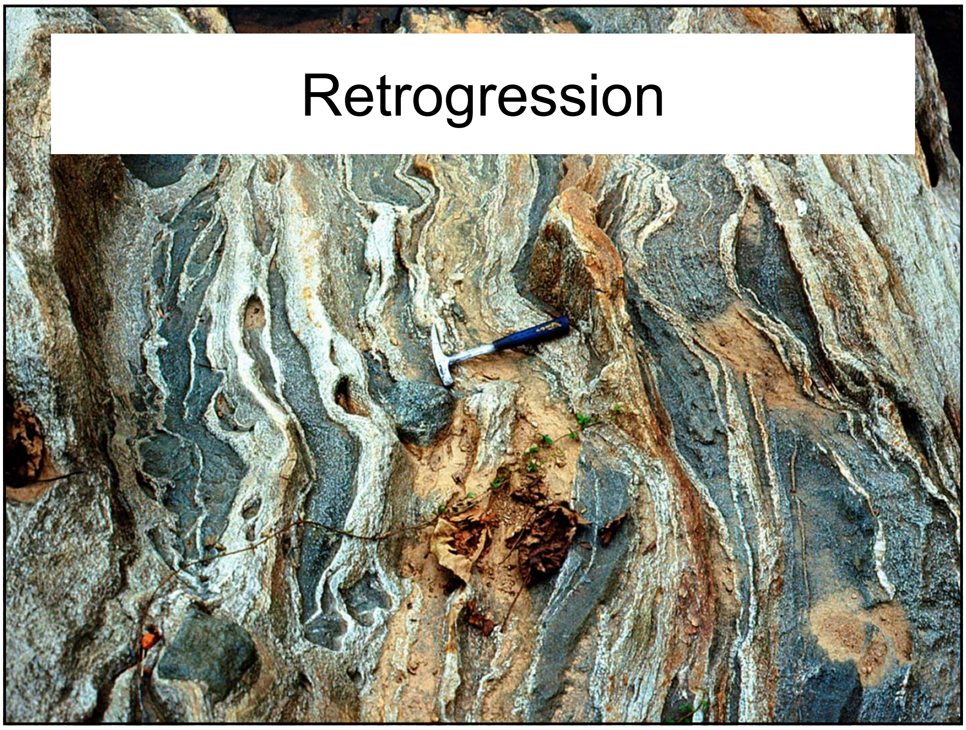
- UHP rocks that experience hypersolidus T rarely exhumed because UHP terrane disaggregates as a result of melt-induced weakening

Pinned by Solidus?

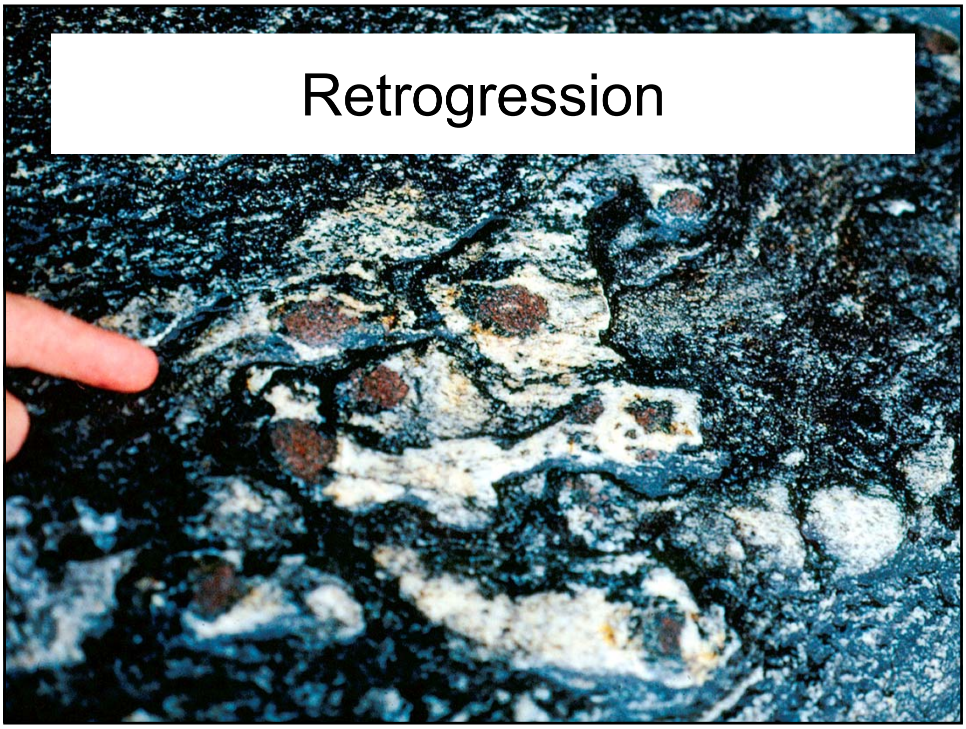


- UHP rocks rarely experience hypersolidus temperatures
- UHP rocks that experience hypersolidus T recrystallize in the presence of melt during cooling & "freeze in" when crossing back below the solidus
- UHP rocks that experience hypersolidus T rarely exhumed because UHP terrane disaggregates as a result of melt-induced weakening

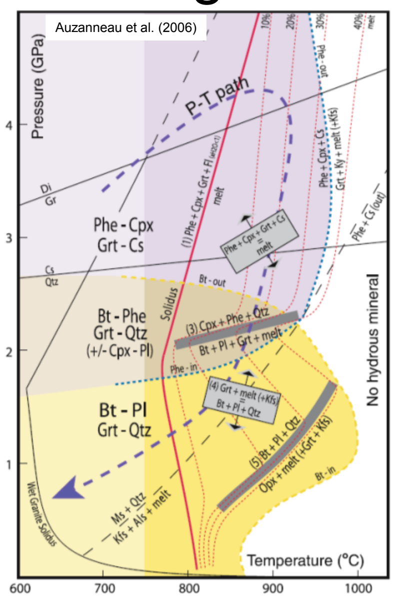
Retrogression



Retrogression



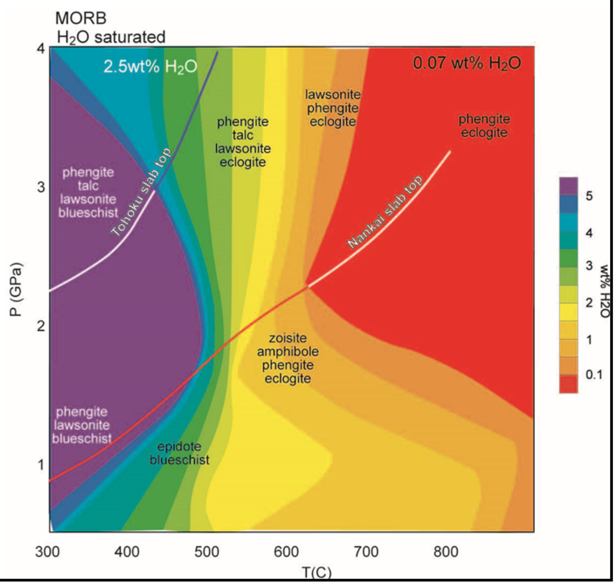
Decompression Melting



Retrogression

retrogression of eclogite requires hydration

∴ eclogites are preserved

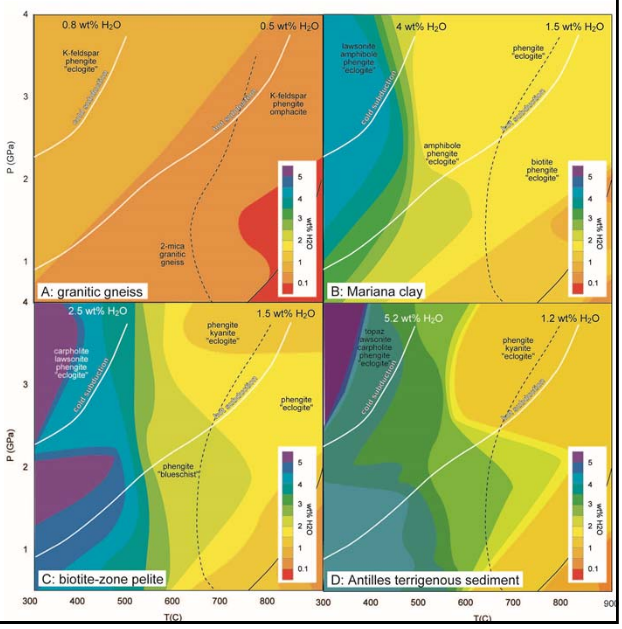


Heinrich (1982)

Retrogression

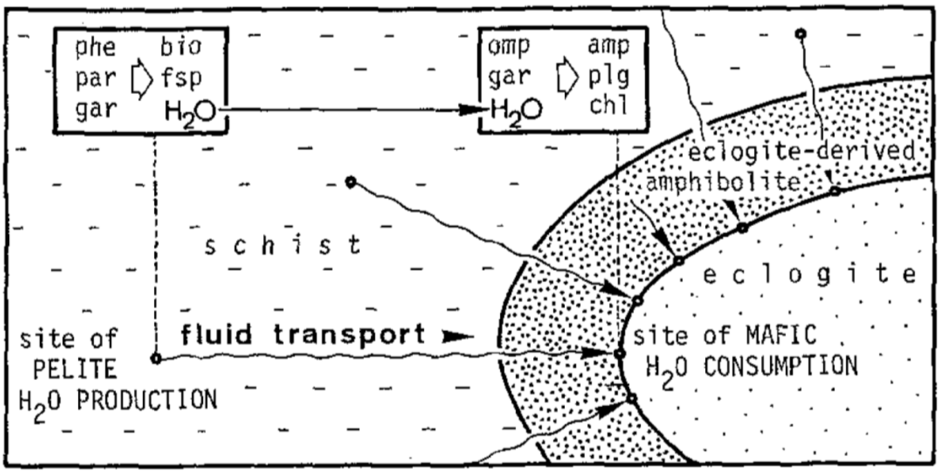
retrogression of pelite does *not* require hydration (in fact, liberates H_2O)

∴ HP pelites are destroyed



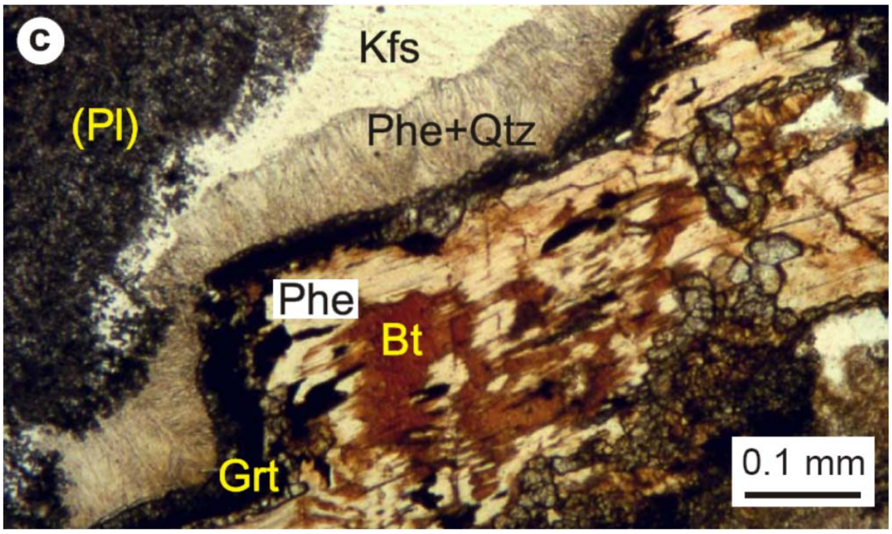
Heinrich (1982)

Retrogression



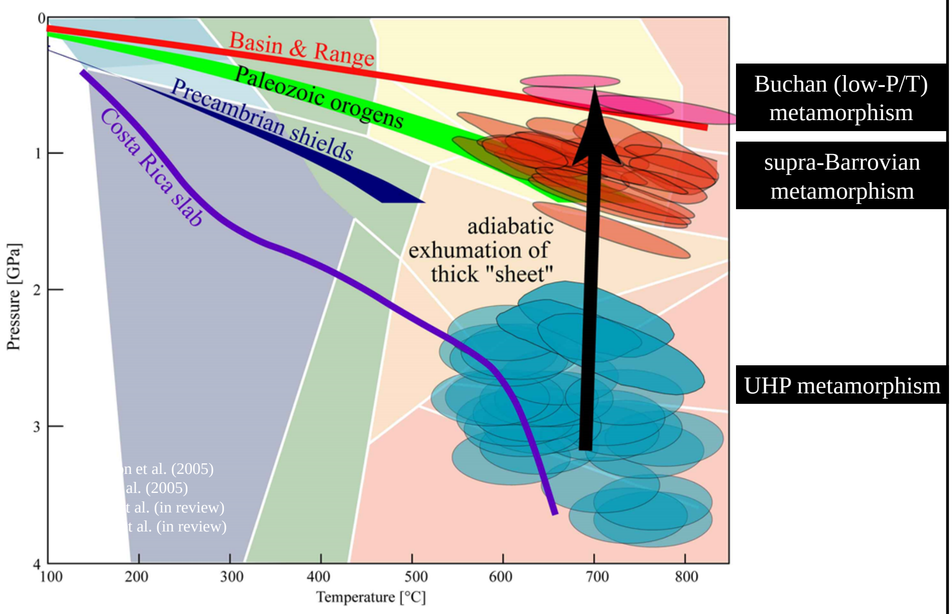
Heinrich (1982)

Retrogression

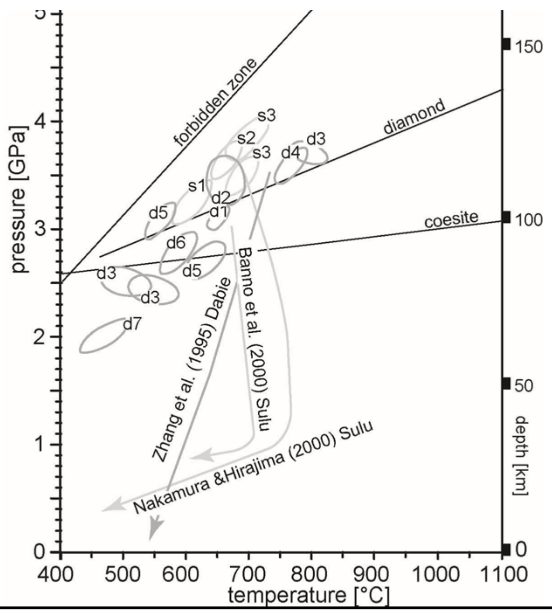


Compagnoni & Rolfo (2003)

UHP → (supra-)Barrovian → Buchan @ 650–750°C



Retrograde Paths



Hacker (2006)

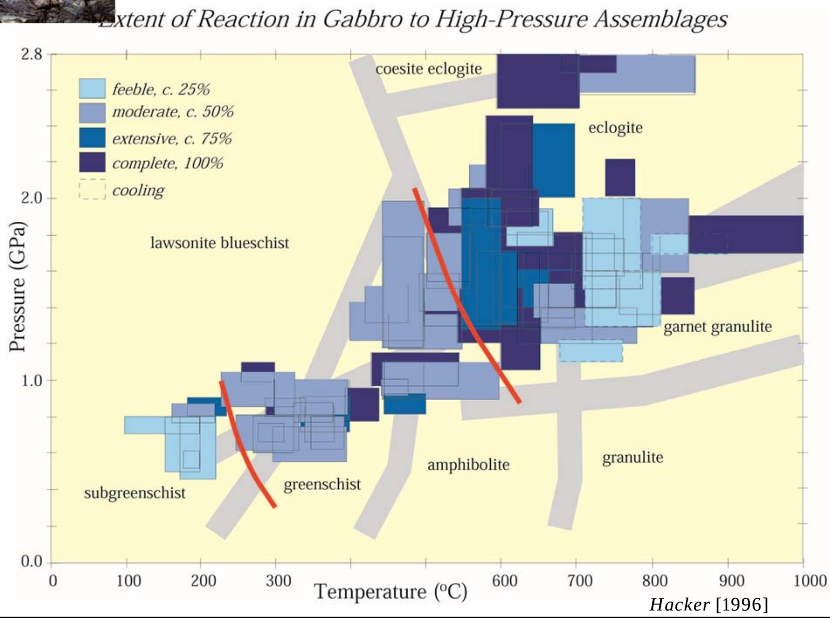
Rates of Phase Transformations

- general field evidence of sluggish
  reactions
- general geophysical evidence of sluggish
  reaction
- slow reactions in UHP terranes

Rates of Phase Transformations

- dehydration reactions are fast
- growth rates measured experimentally
- diffusivities measured experimentally

Extent of Reaction



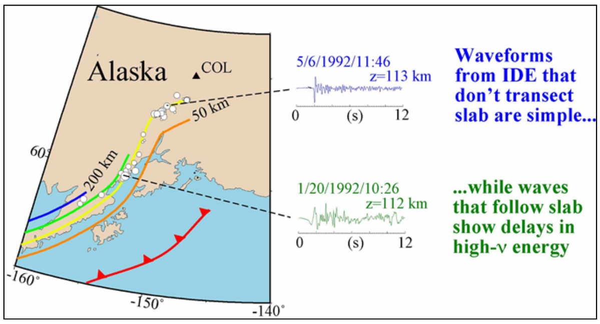
Hacker [1996]

Slow Waveguides

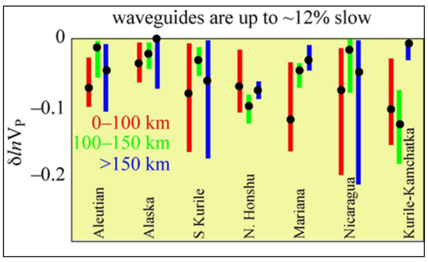
slow waveguides
imply slow reaction

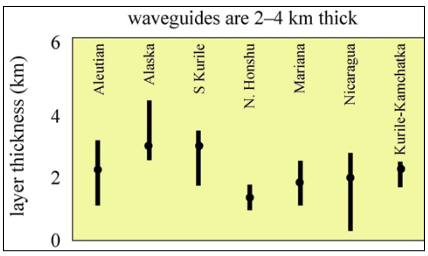
Pacific slabs:

- <12% slow layer
- 2–4 km thick
- 100–250 km depth



Abers [2000, 2003, 2005], following *Matsuzawa et al.* [1986]



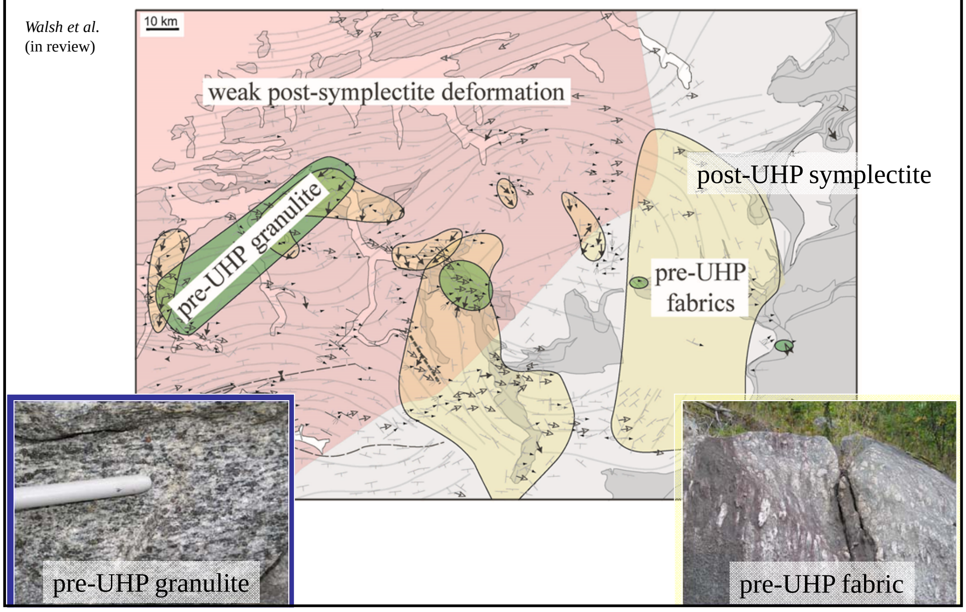


Transformation at (U)HP

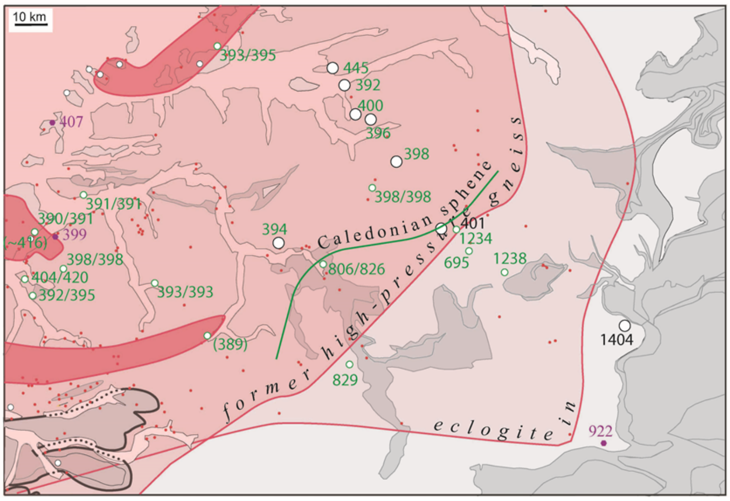
- expectations of transformation at high *P* & *T*, but contrary examples

Incomplete Transformation

Walsh et al. (in review)



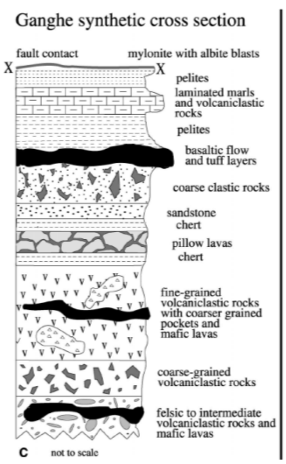
Incomplete UHP–HP Transformation Indicated by Geochronology

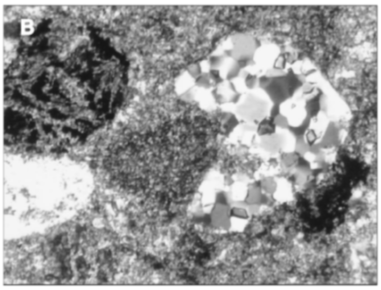


sphene U/Pb: *Andrew Kylander-Clark et al.* (in review)

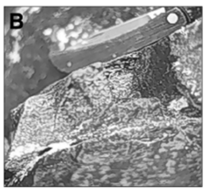
garnet Sm/Nd: *Emily Peterman et al.* (5:00 PM in 709/711)

Incomplete UHP–HP Transformation Indicated by Geochronology





preserved ash texture



Oberhänsli et al. (2002)

preserved variolitic texture