What we know about subduction zones from the metamorphic rock record

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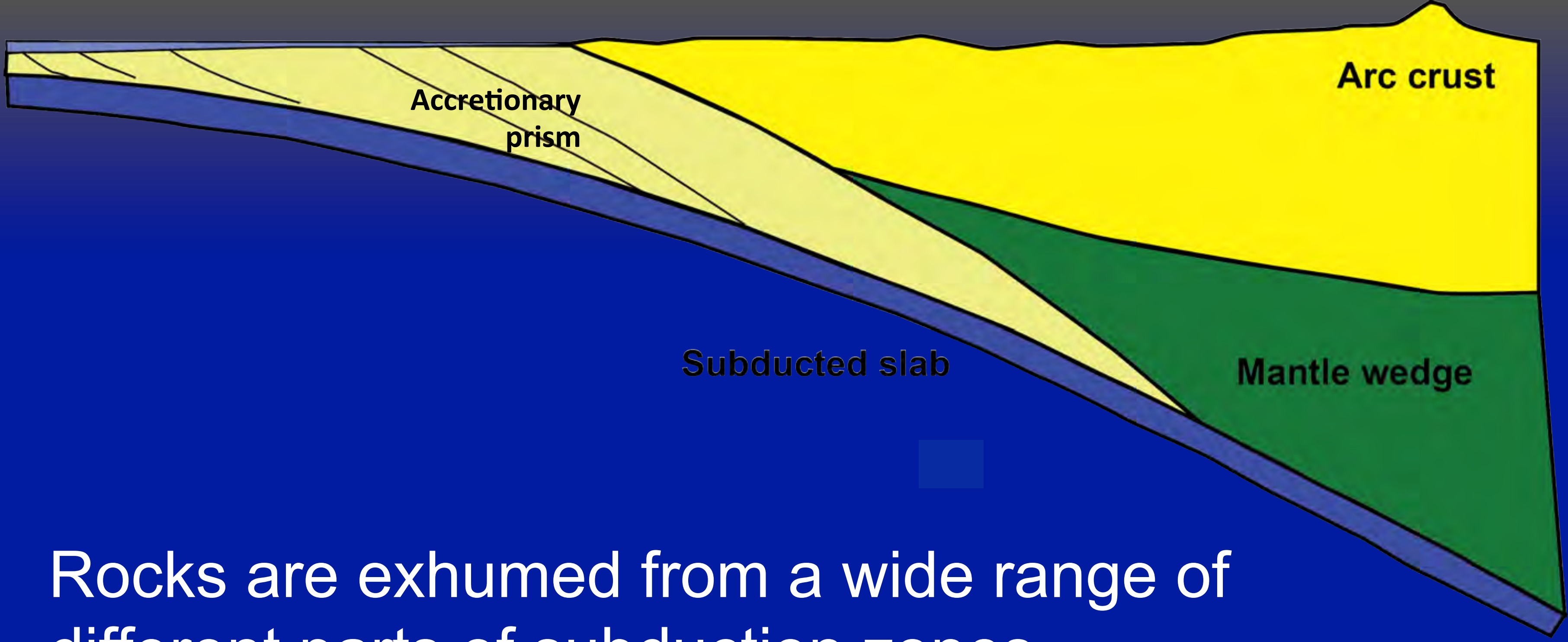
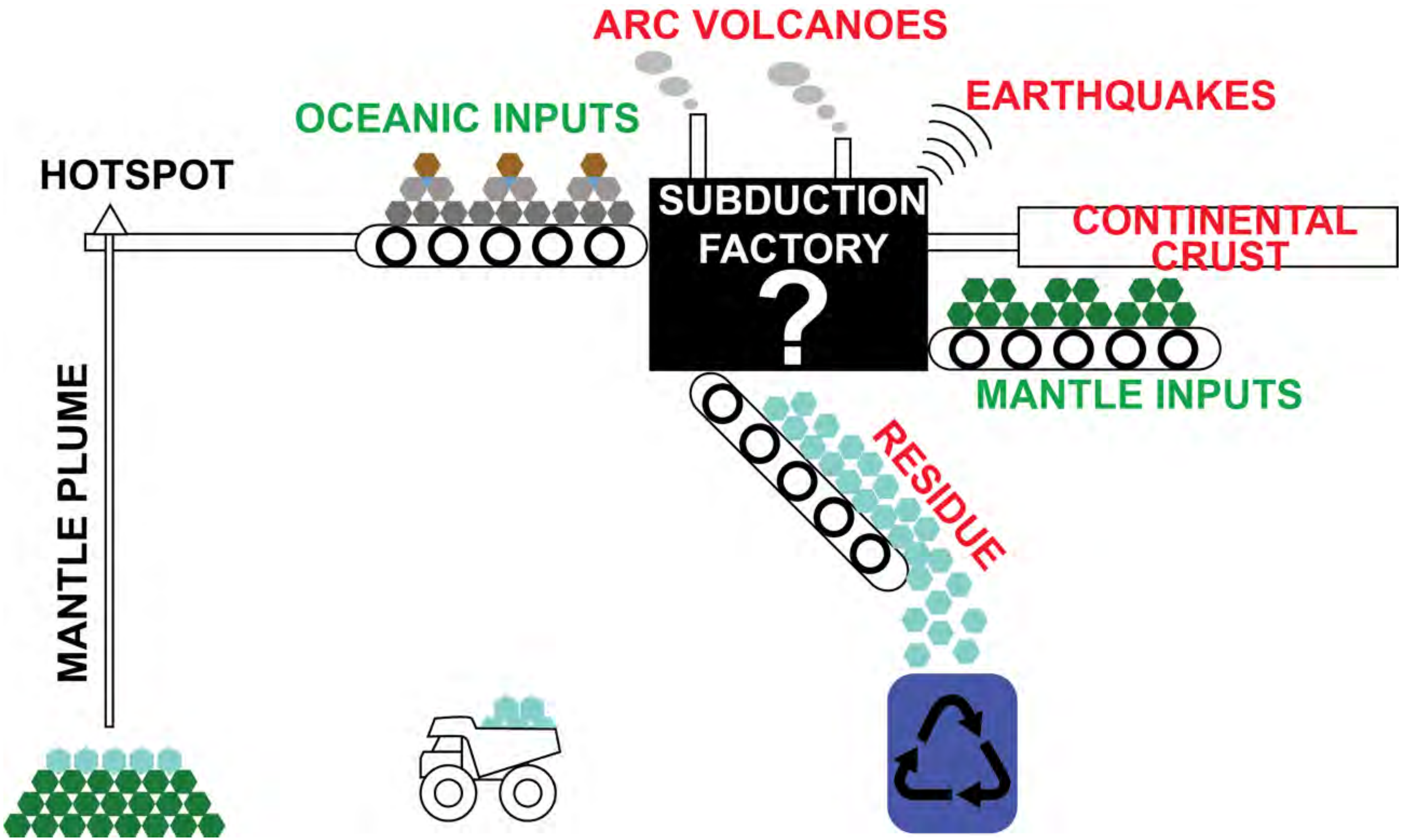
Subduction zones are complex

We can learn a lot about processes occurring within active subduction zones by analysis of metamorphic rocks exhumed from ancient subduction zones

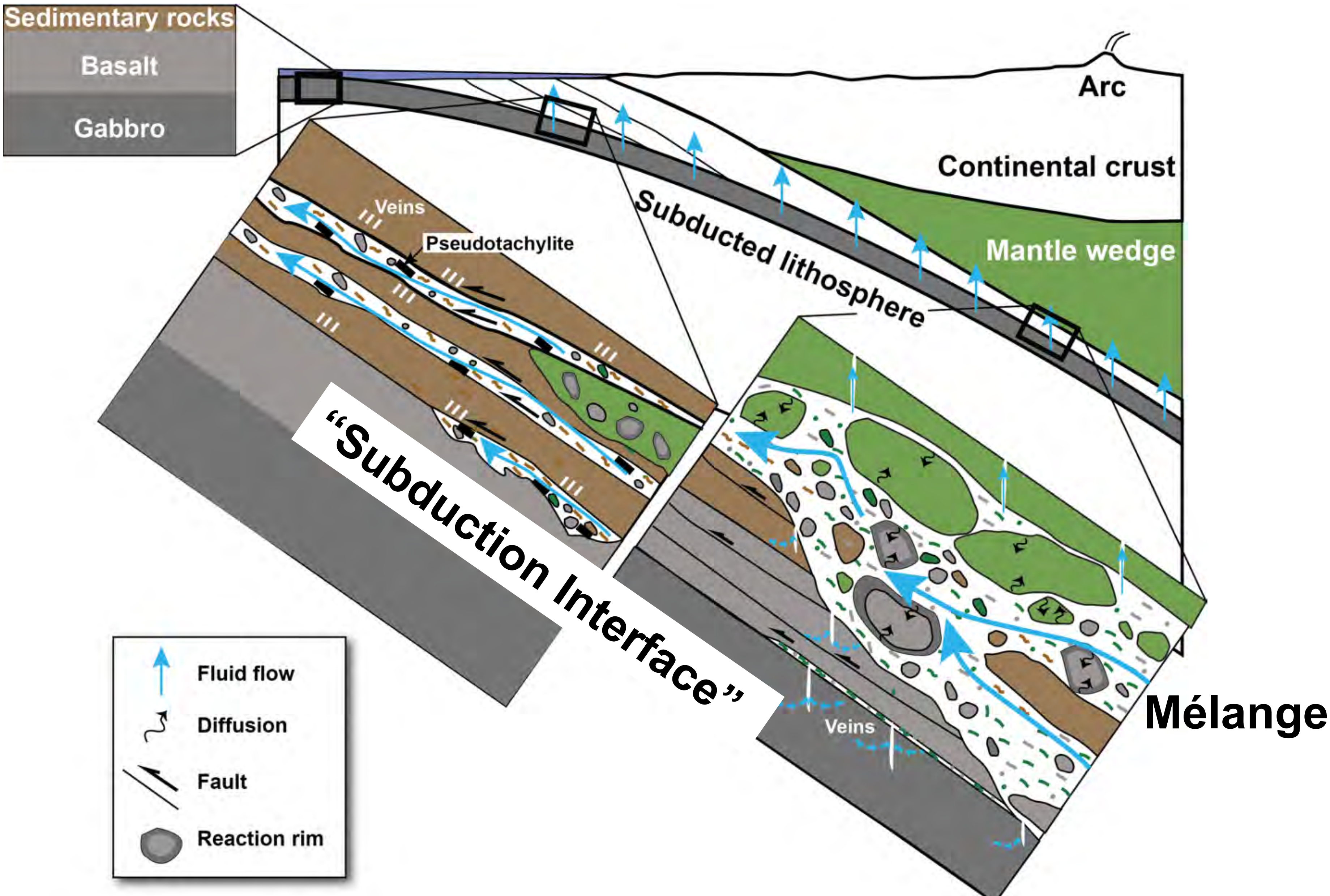


- Rocks are exhumed from a wide range of different parts of subduction zones.
- Exhumed rocks from fossil subduction zones tell us about materials, conditions and processes within subduction zones
- They provide complementary information to observations from active subduction systems



Tatsumi, 2005

The subduction interface is more complex than we usually draw



(Bebout, and Penniston-Dorland, 2015)

Information from exhumed metamorphic rocks

1. Thermal structure
The minerals in exhumed rocks of the subducted slab provide information about the thermal structure of subduction zones.

2. Fluids
Metamorphism generates fluids. Fossil subduction zones preserve records of fluid-related processes.

3. Rheology and deformation
Rocks from fossil subduction zones record deformation histories and provide information about the nature of the interface and the physical properties of rocks at the interface.

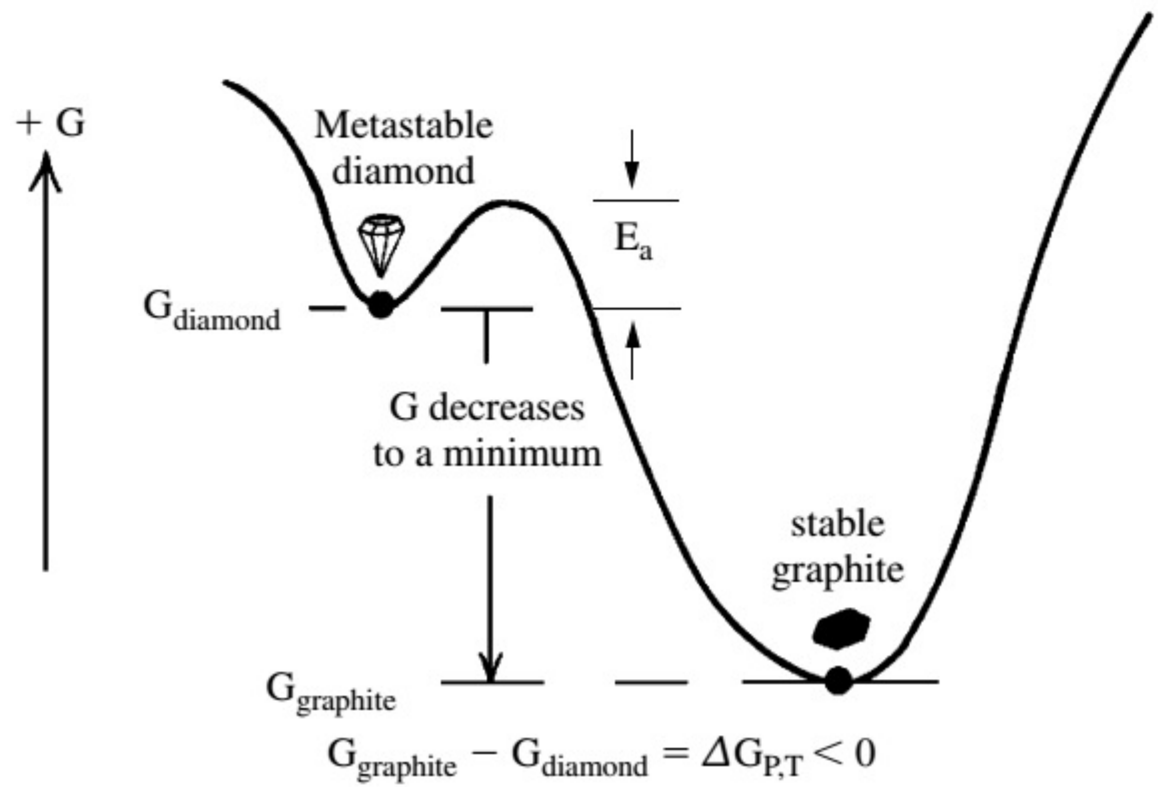
4. Geochemical cycling
Metamorphism of the subducting slab plays a key role in the cycling of various elements through subduction zones.


Thermal structure

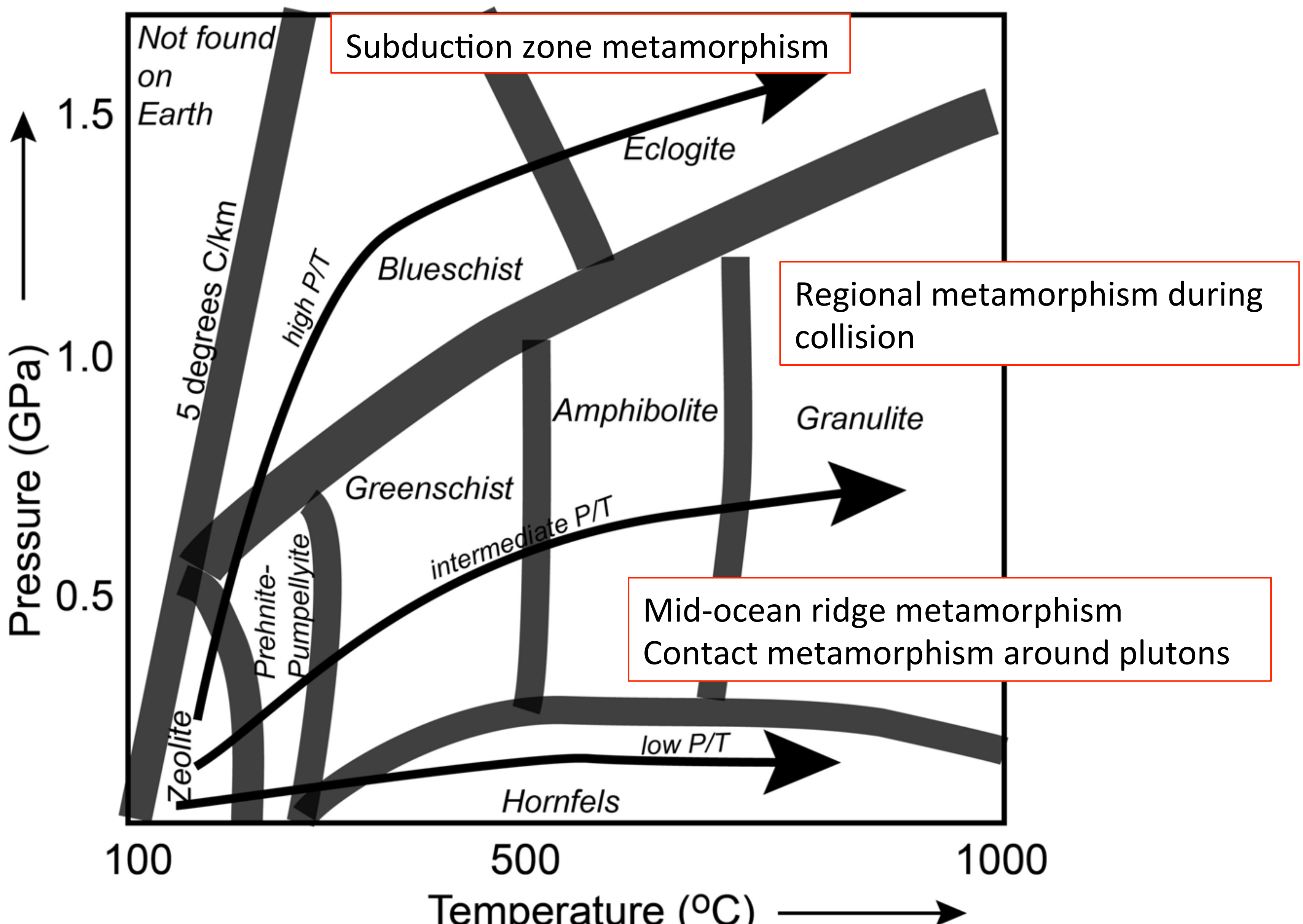
Equilibrium Thermodynamics

provides the basis for estimating *P-T* conditions using mineral assemblages and compositions

Systems act to minimize Gibbs Free Energy (chemical potential energy)



Metamorphic facies and tectonic environment



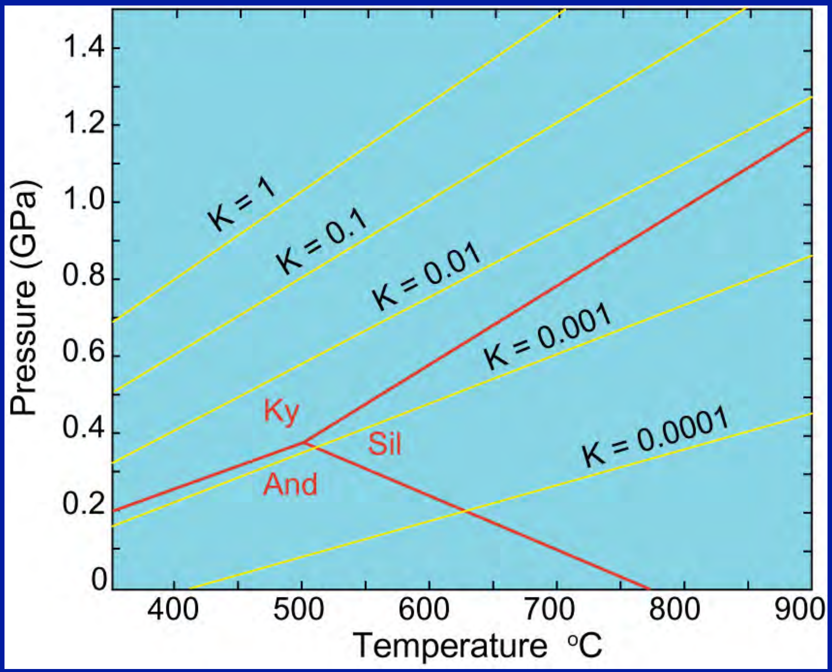
Determining P-T conditions from metamorphic rocks
Assumption of chemical equilibrium

Classic thermobarometry

Based on equilibrium reactions for minerals in rocks, uses the compositions of those minerals and their thermodynamic properties

e.g. GASP barometer	**G**arnet garnet	**A**luminosilicate kyanite	**S**ilica quartz	**P**lagioclase anorthite

$$Ca_3Al_2Si_3O_{12} + 2Al_2SiO_5 + SiO_2 = 3CaAl_2Si_2O_8$$

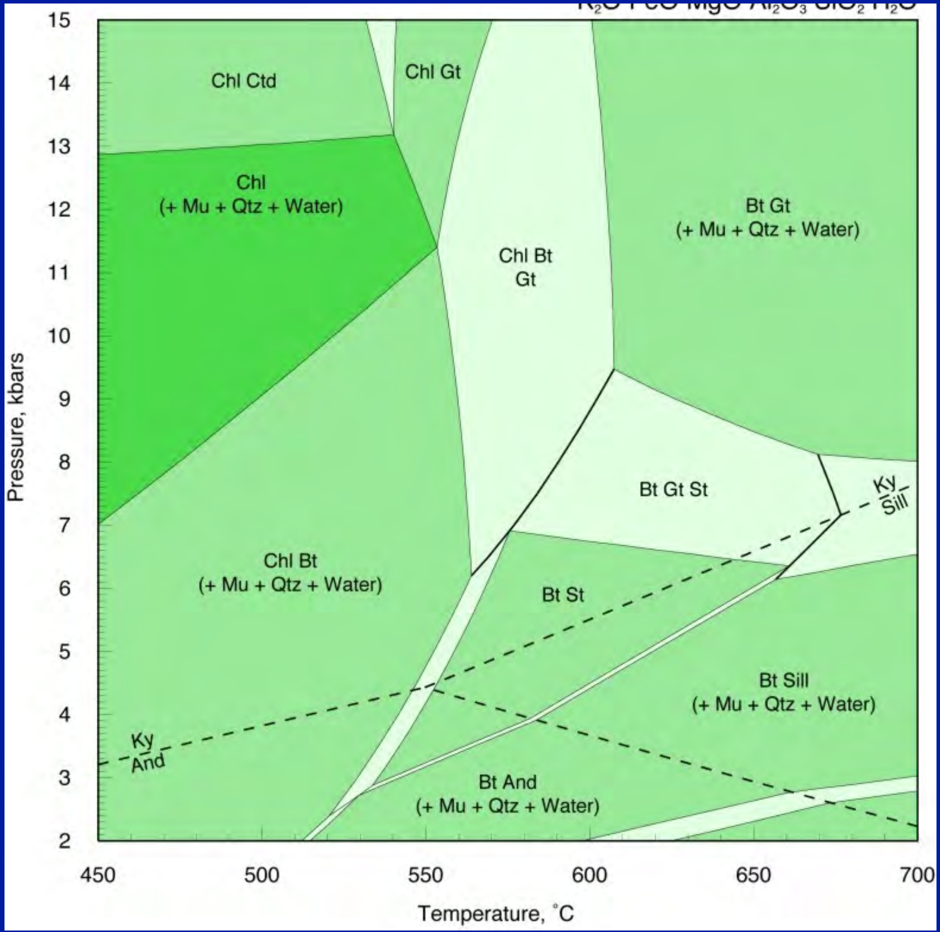


Mineral compositions are measured and used to determine eequilibrium constant for reaction. The compositions along with mineral entropies, enthalpies, heat capacities and other thermodynamic data allow plotting of mineral reactions on phase diagrams.

Determining P-T conditions from metamorphic rocks
Assumption of chemical equilibrium

Pseudosections/Mineral Assemblage Diagrams (MADS)

Uses bulk composition and thermodynamic database to determine equilibrium mineral assemblages

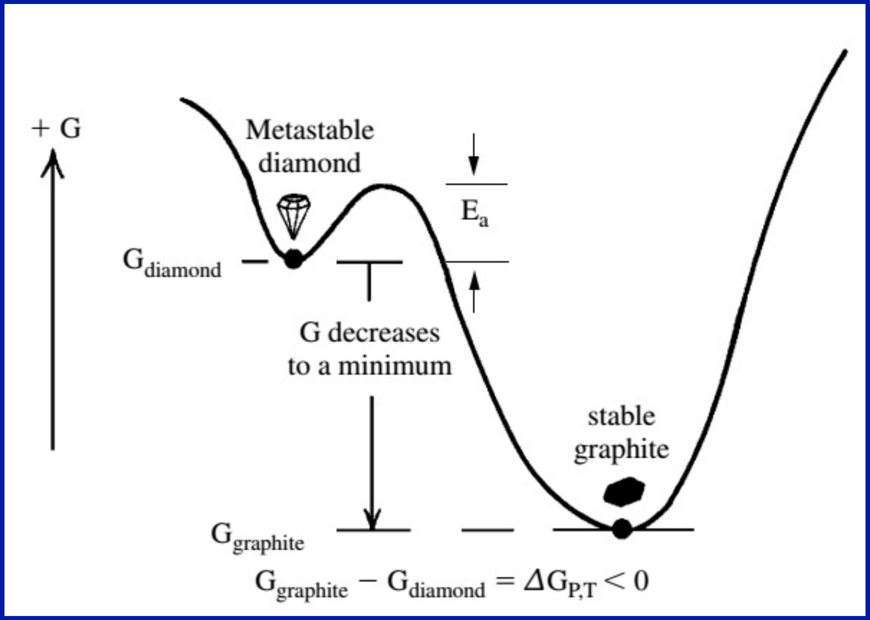


Determining P-T conditions from metamorphic rocks
Assumption of chemical equilibrium

Caveats

Equilibrium thermodynamics tells us about which minerals are stable at a given P & T but it does not tell us about rates of reaction.

In general, prograde reactions (increasing T) proceed more rapidly than retrograde reactions (decreasing T). Metamorphic rocks can preserve peak P-T conditions, especially if they are exhumed rapidly.

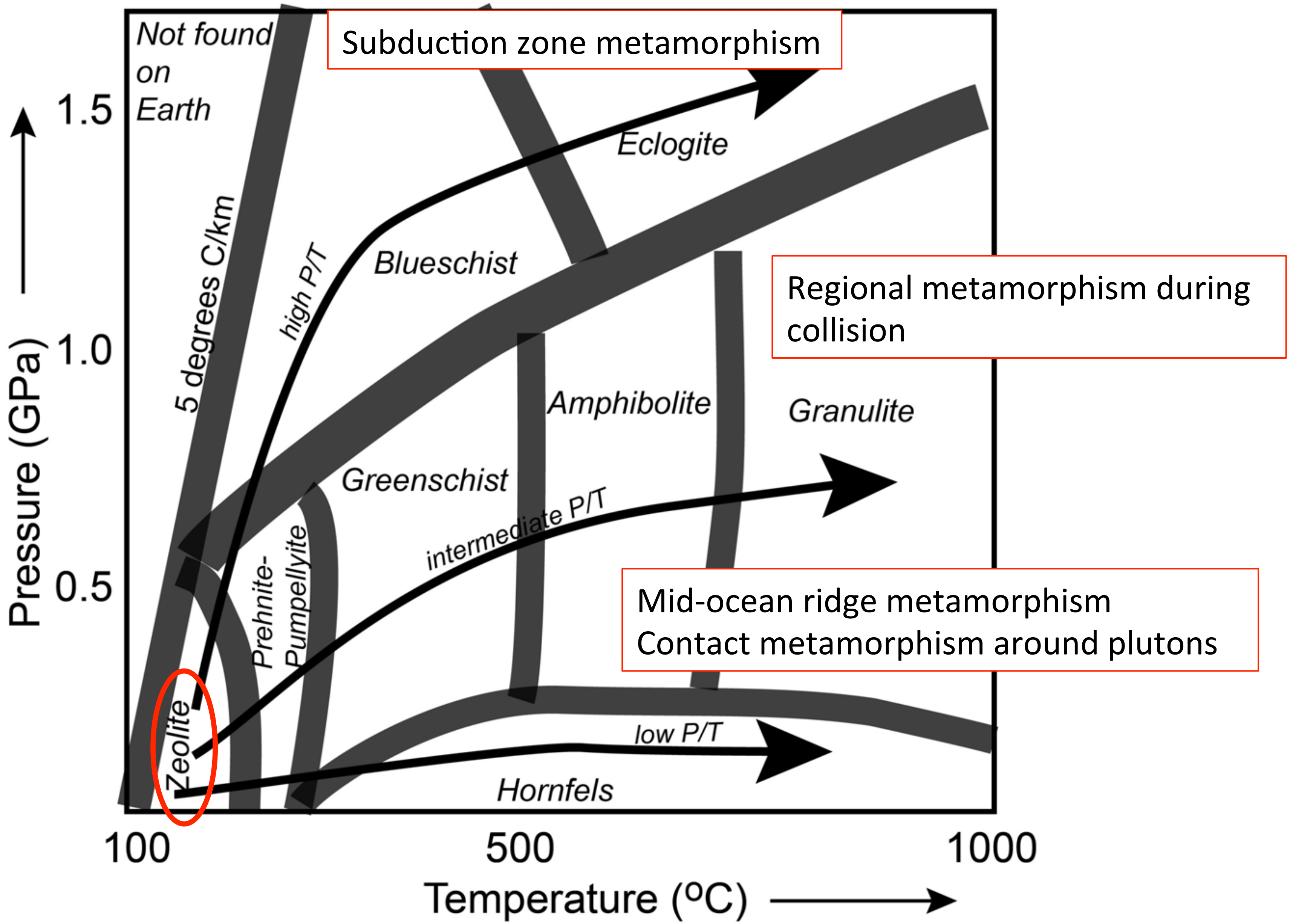


Protolith (Parent rock): Basalt

- Plagioclase $NaAlSi_3O_8$-$CaAl_2Si_2O_8$
- Clinopyroxene $Ca(Mg,Fe)Si_2O_6$
- Orthopyroxene $(Mg,Fe)_2Si_2O_6$
- Olivine $(Mg,Fe)SiO_4$

Color coding:
Si, Al, O
Fe, Mg
Ca
Na
H, C, K (elements added during seafloor alteration)

Metamorphic facies and tectonic environment



Zeolite facies minerals

- Zeolite group minerals
  - Analcime $NaAlSi_2O_6 \cdot H_2O$
  - Laumontite $CaAl_2Si_4O_{12} \cdot 4H_2O$
  - Heulandite $CaAl_2Si_7O_{18} \cdot 6H_2O$
  - Stilbite $CaAl_2Si_4O_{12} \cdot 7H_2O$
  - Wairakite $CaAl_2Si_4O_{12} \cdot 2H_2O$
- Albite $NaAlSi_3O_8$
- Clays - smectite (Fe-Mg bearing), kaolinite, illite (K-bearing)
- Quartz SiO_2
- Calcite $CaCO_3$

Added to rocks through alteration on the seafloor:

H_2O

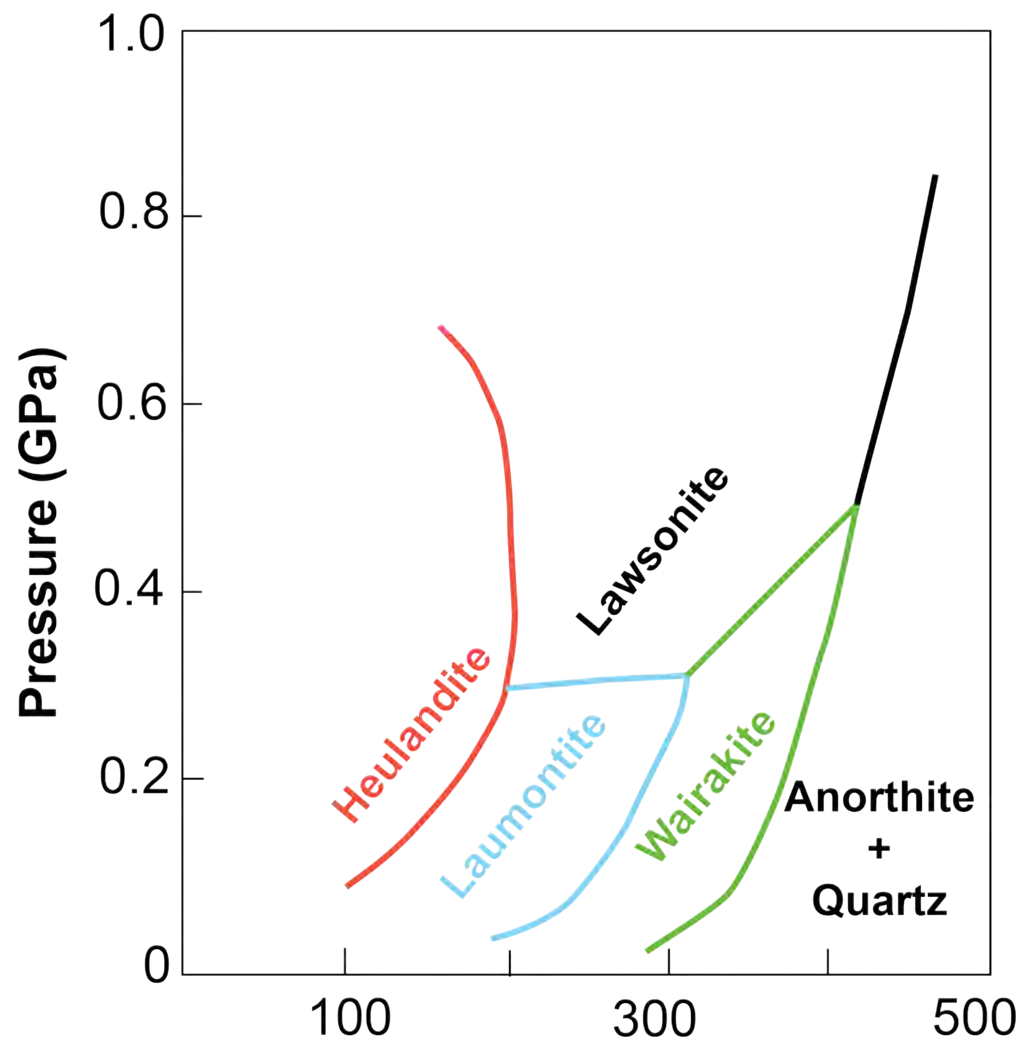
CO_2

K_2O

Vesicle filled with zeolites

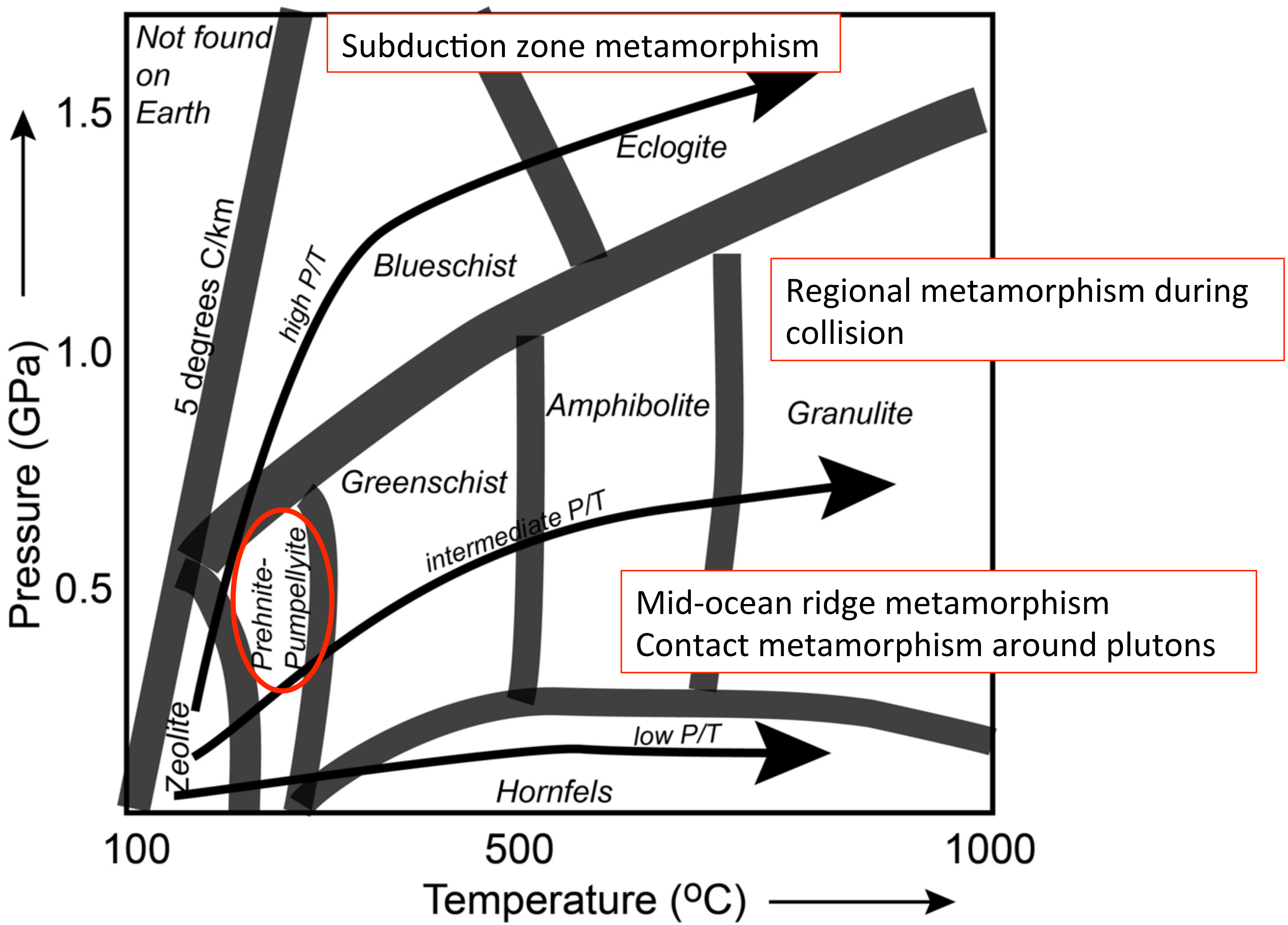
Zeolite P-T conditions

- Zeolites are hydrous calcium-aluminum silicates stable at relatively low-grade conditions



Liou, 1971

Metamorphic facies and tectonic environment



Prehnite-pumpellyite facies minerals

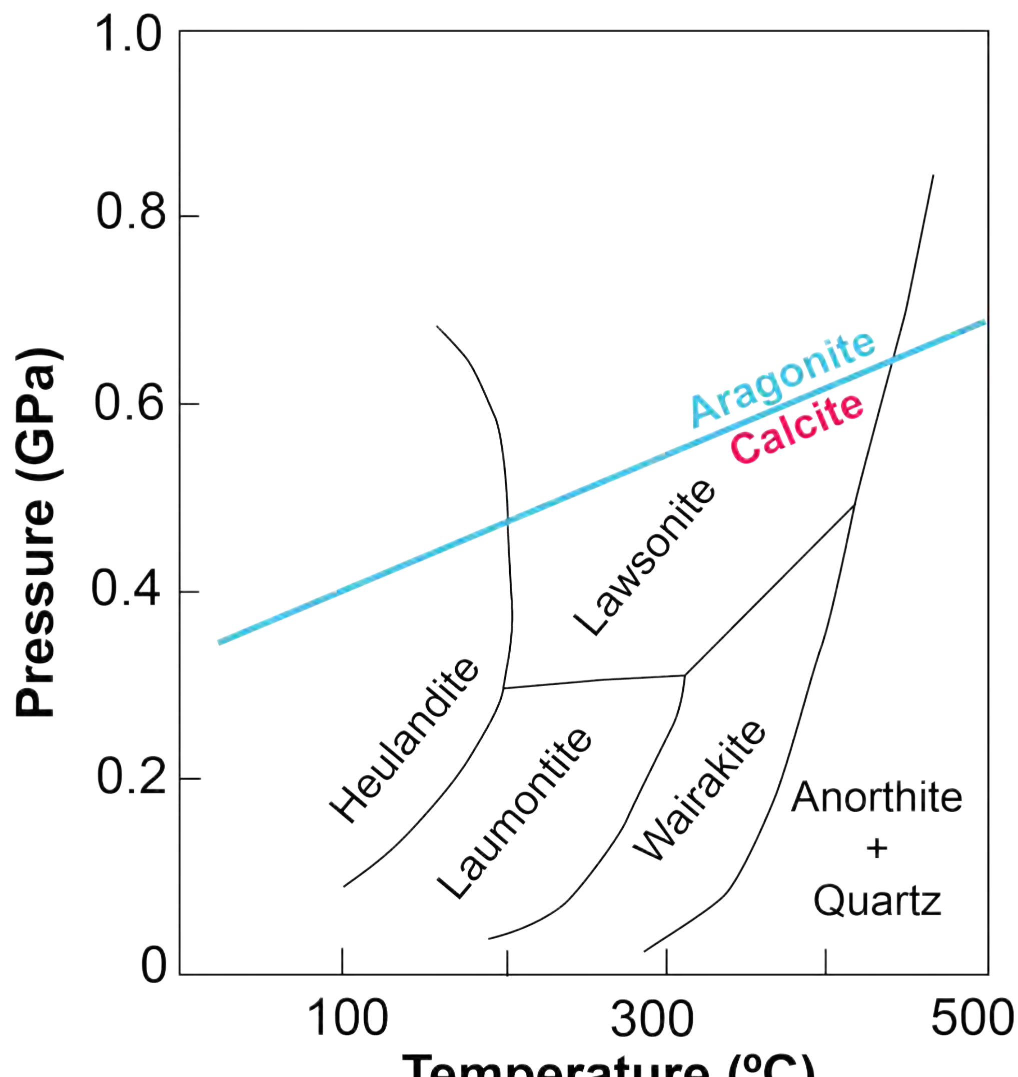
- Prehnite $Ca_2Al_2Si_3O_{10}(OH)_2$
- Pumpellyite $Ca_2(Mg,Fe)Al_2Si_3O_{11}(OH)_2 \bullet H_2O$
- Albite $NaAlSi_3O_8$
- Chlorite $(Fe,Mg)_{4.5}Al_3Si_{2.5}O_{10}(OH)_8$
- Clays smectite, kaolinite, illite
- Quartz SiO_2
- Aragonite $CaCO_3$

Carbonates at high P/T:

Calcite $\rightleftharpoons$ Aragonite

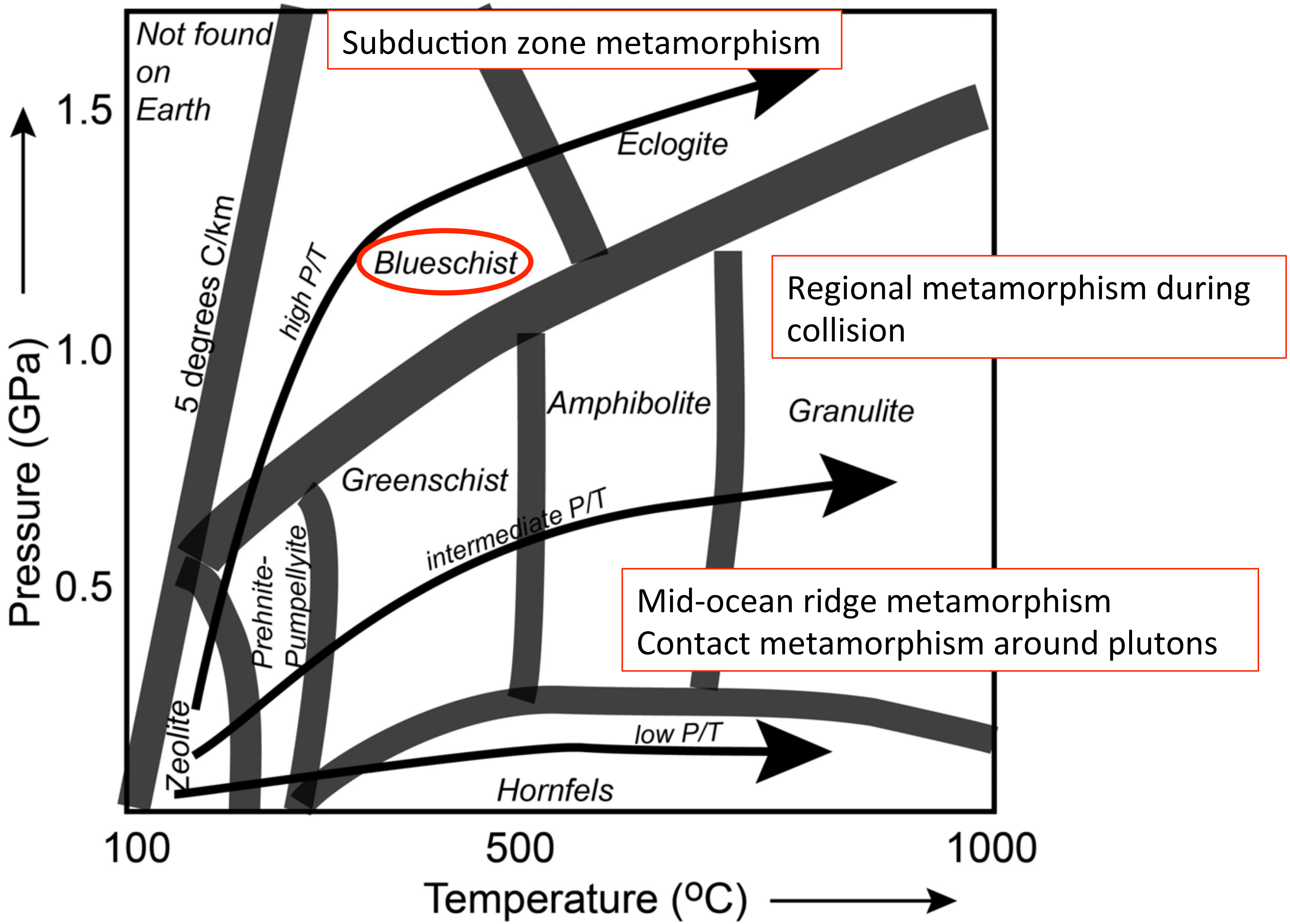
$CaCO_3 \rightleftharpoons CaCO_3$

Note: this reaction proceeds rapidly during retrogression, so in many high-pressure rocks aragonite reverts to calcite. If aragonite is found in high-pressure metamorphic rocks, this provides information about rapid exhumation!



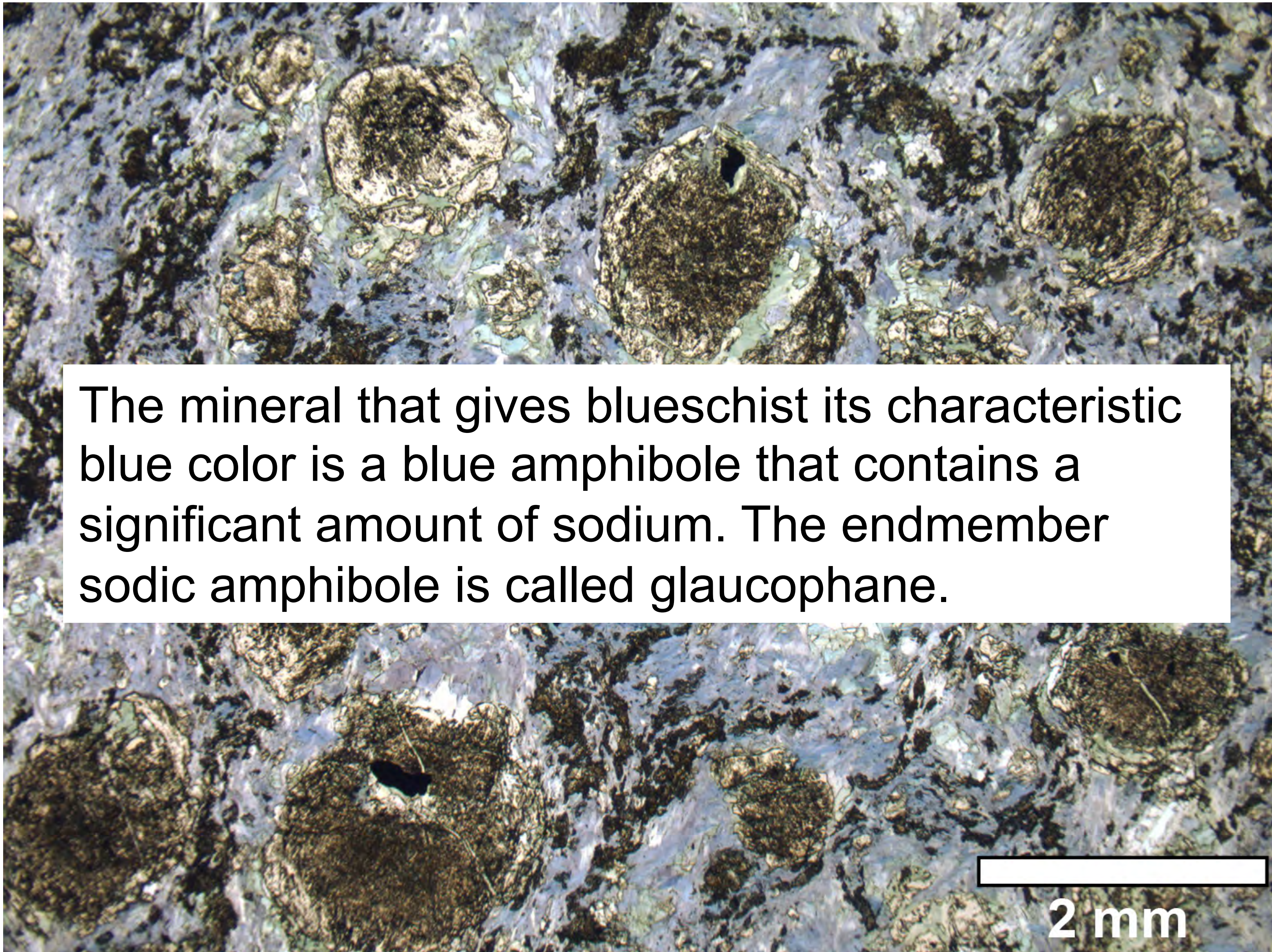
Carlson, 1983

Metamorphic facies and tectonic environment



Blueschist

Blueschist



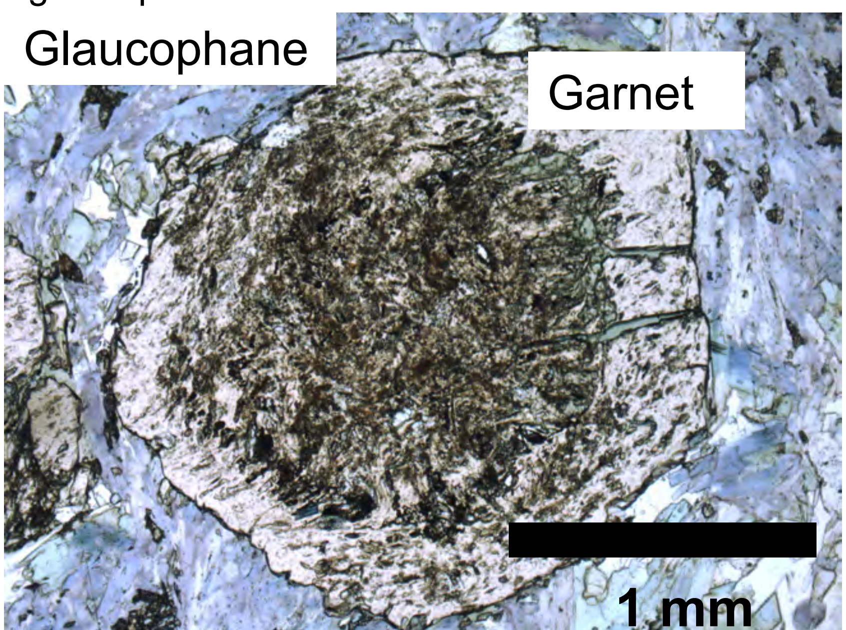
The mineral that gives blueschist its characteristic blue color is a blue amphibole that contains a significant amount of sodium. The endmember sodic amphibole is called glaucophane.

Blueschist

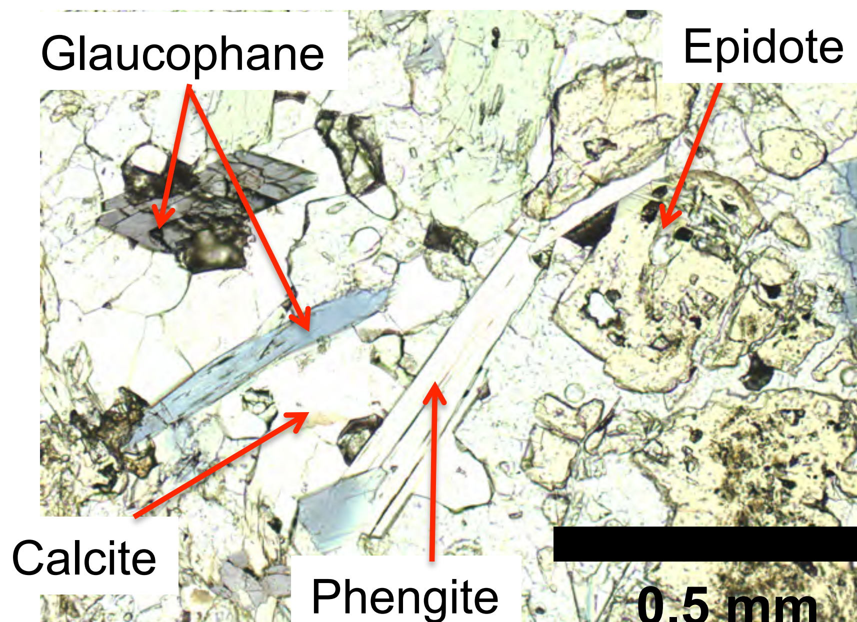
Rhombic lawsonite in foliated blueschist

Garnet porphyroblasts

Garnet with inclusion-rich core surrounded by glaucophane.

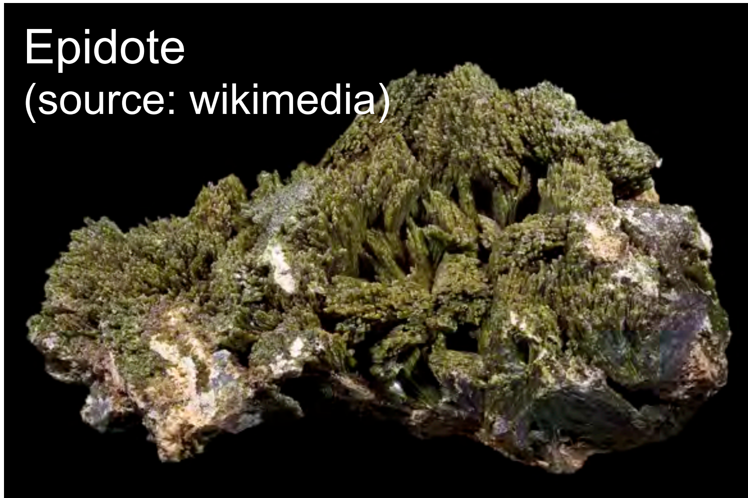


Glaucophane, epidote, phengite and calcite



Blueschist facies minerals

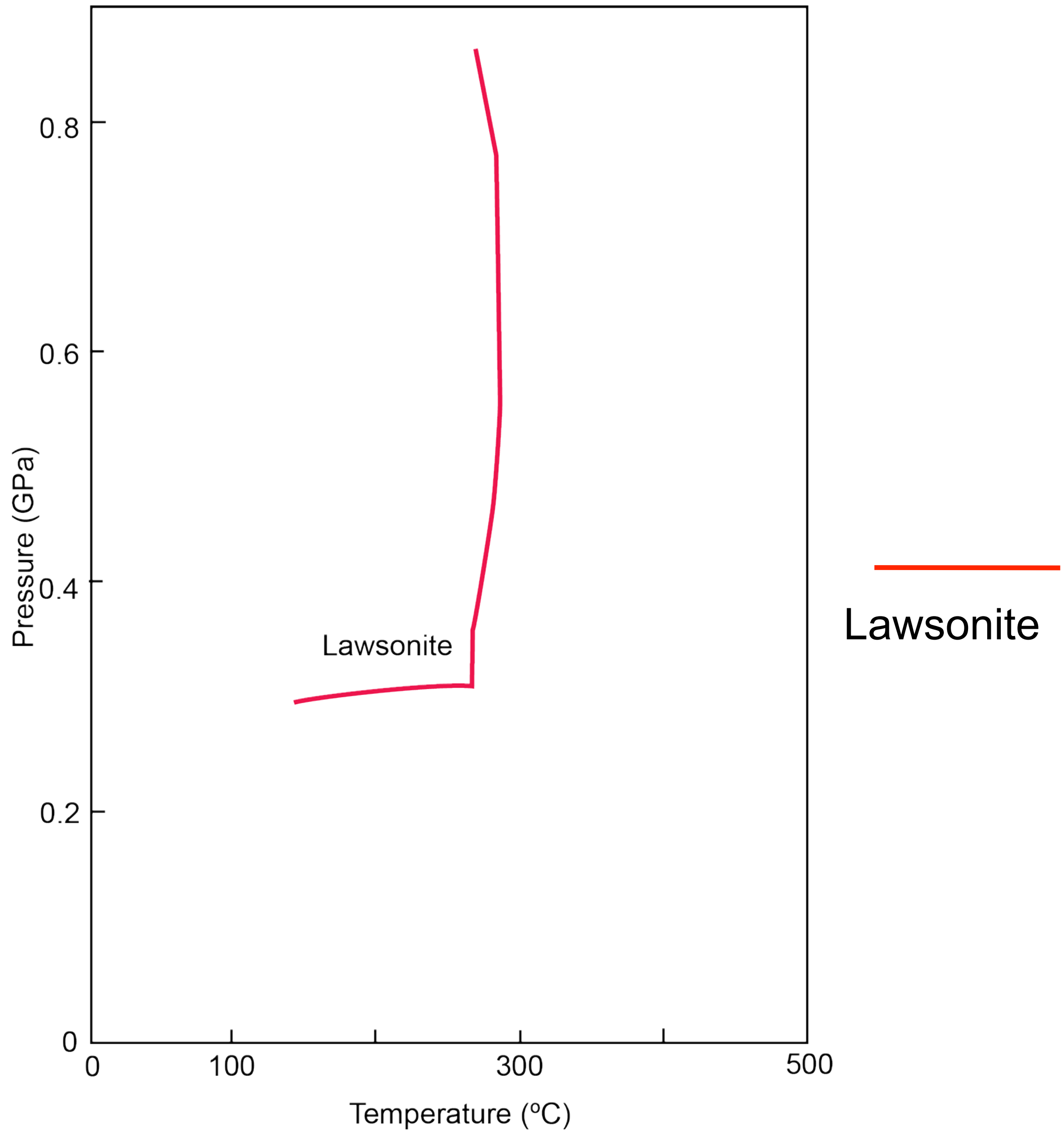
- Glaucophane $Na_2Mg_3Al_2Si_8O_{22}(OH)_2$
- Lawsonite $CaAl_2(Si_2O_7)(OH)_2 \bullet H_2O$
- Jadeite/Omphacite $NaAlSi_2O_6$
- Phengite $K(Al,Mg)_3(Al,Si)_3O_{10}(OH)_2$
- Pumpellyite $Ca_2(Mg,Fe)Al_2Si_3O_{11}(OH)_2 \bullet H_2O$
- Epidote $Ca_2Al_2FeSi_3O_{12}(OH)$
- Garnet $(Ca,Mg,Fe)_3Al_2Si_3O_{12}$
- Chlorite $(Fe,Mg)_{4.5}Al_3Si_{2.5}O_{10}(OH)_8$
- Quartz SiO_2
- Aragonite $CaCO_3$



Phase diagram showing High P/T mineral stabilities

Lawsonite

$CaAl_2(Si_2O_7)(OH)_2 \cdot H_2O$



Liou, 1987

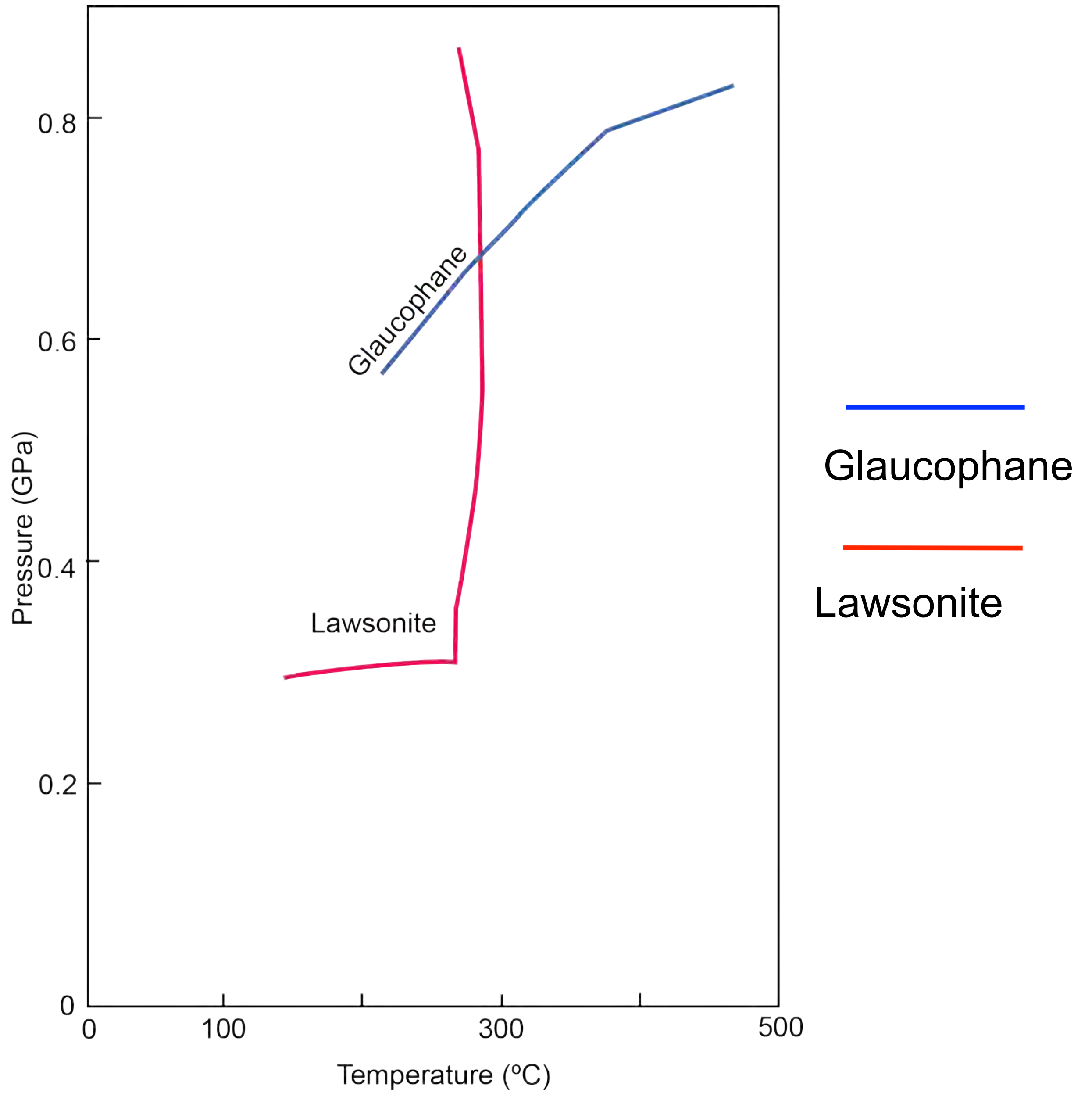
Phase diagram showing High P/T mineral stabilities

Lawsonite

$CaAl_2(Si_2O_7)(OH)_2 \cdot H_2O$

Glaucophane

$Na_2Mg_3Al_2Si_8O_{22}(OH)_2$



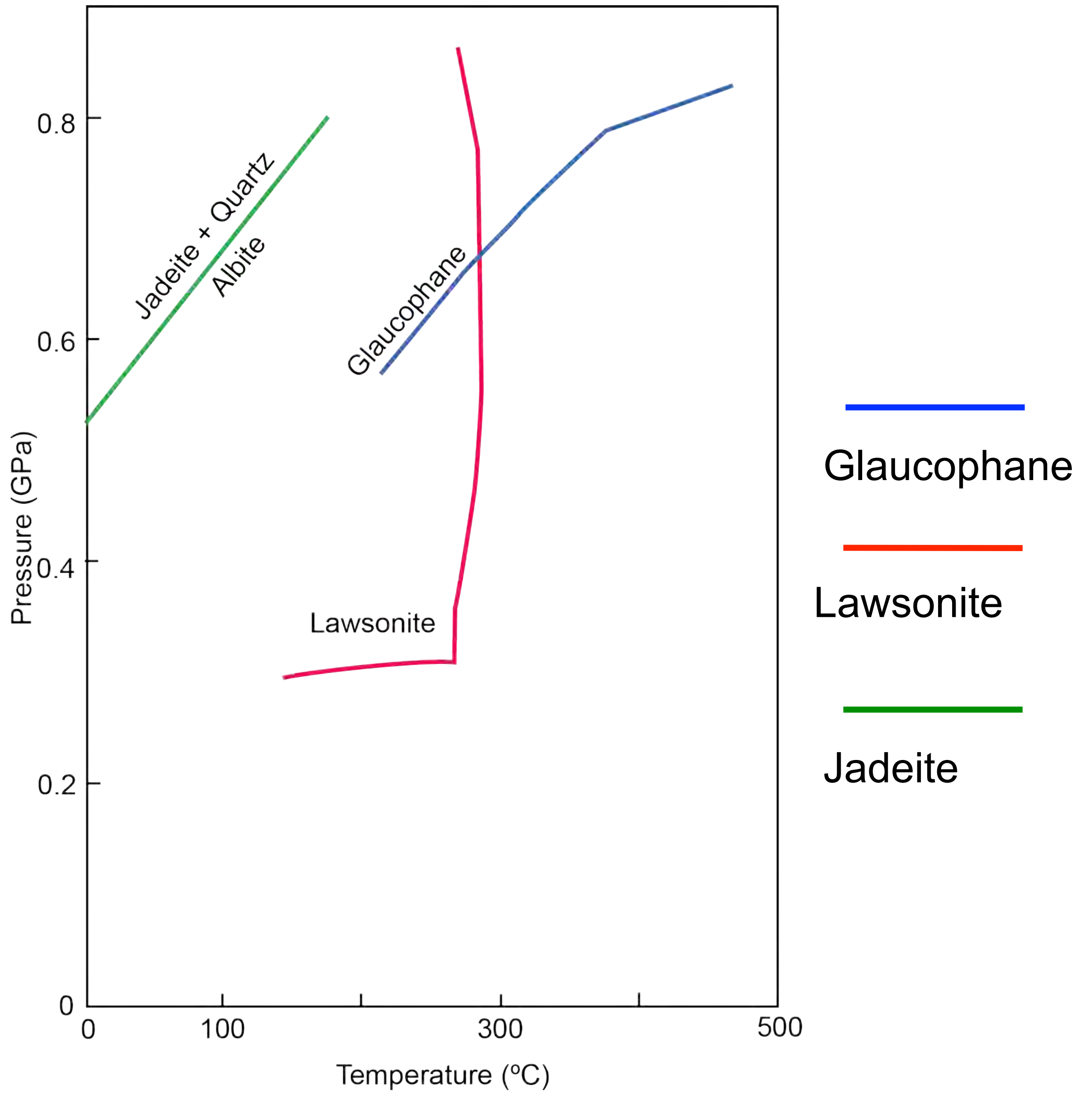
Liou, 1987

Phase diagram showing High P/T mineral stabilities

Lawsonite
$CaAl_2(Si_2O_7)(OH)_2 \bullet H_2O$

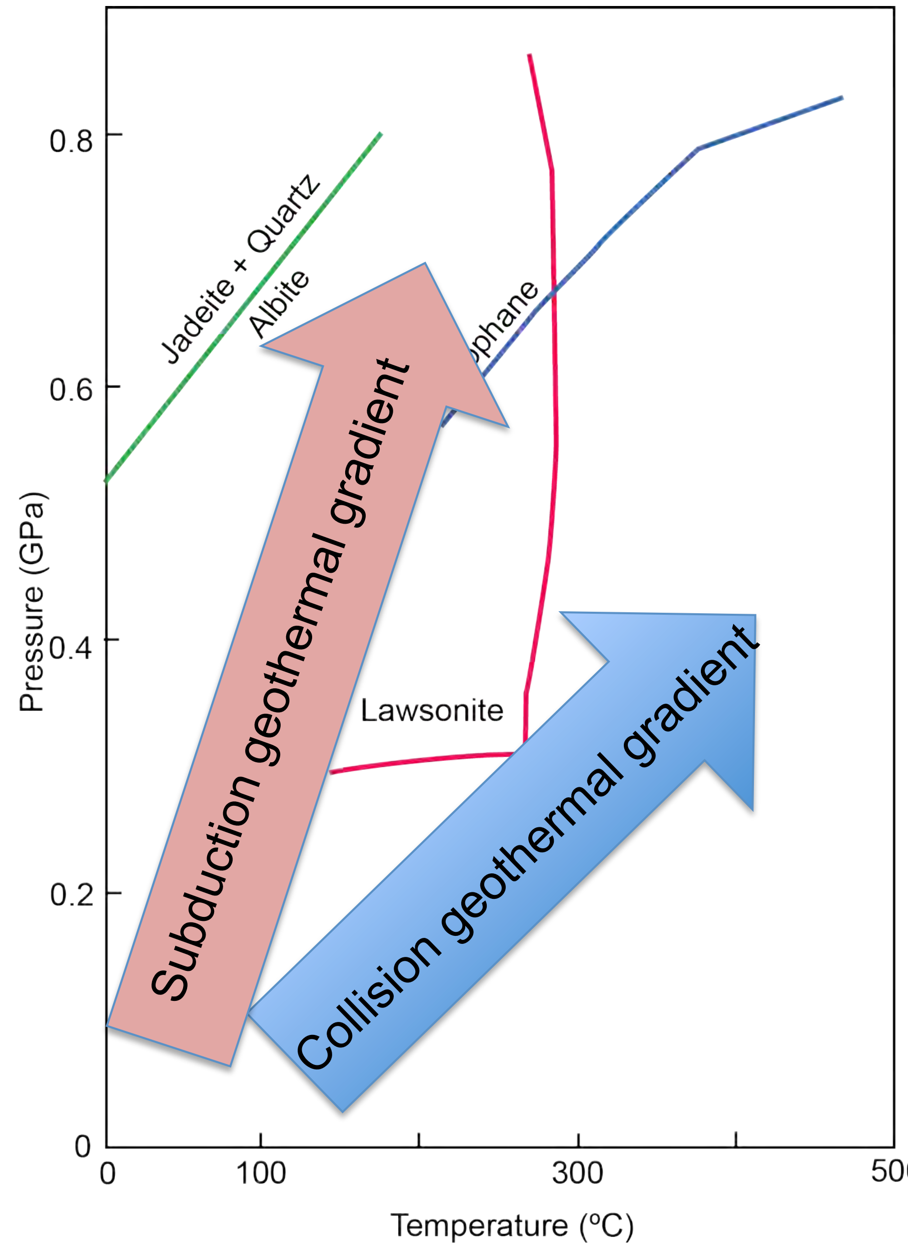
Glaucophane
$Na_2Mg_3Al_2Si_8O_{22}(OH)_2$

Jadeite/Omphacite
$NaAlSi_2O_6$



Liou, 1987

These minerals tell us that subduction zones are **cooler** than other settings!



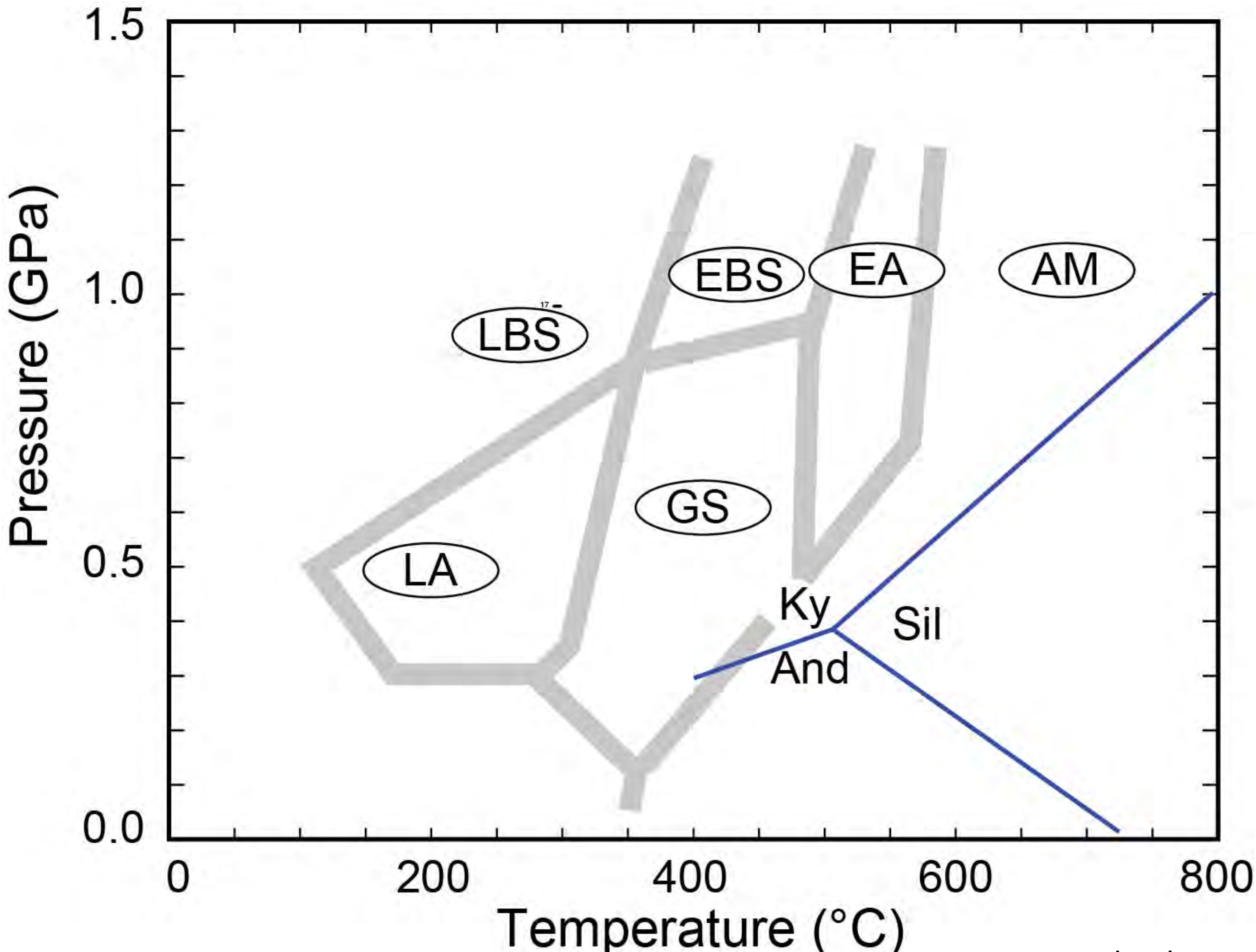
Liou, 1987

Jadeite

Glaucophane

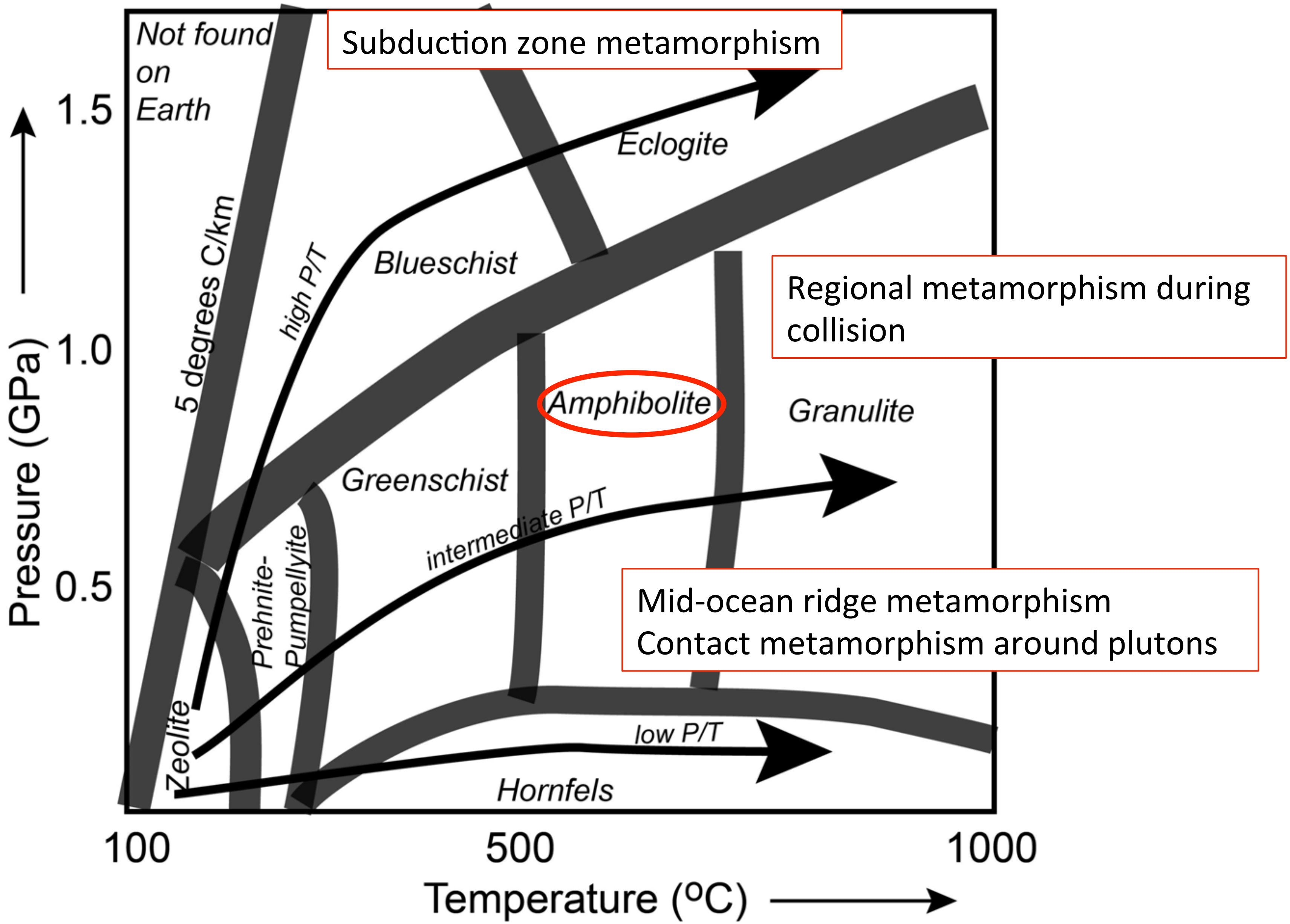
Lawsonite

Facies can be subdivided – for example lawsonite blueschist facies (LBS) and epidote blueschist facies (EBS)



Grove and Bebout, 1995

Metamorphic facies and tectonic environment

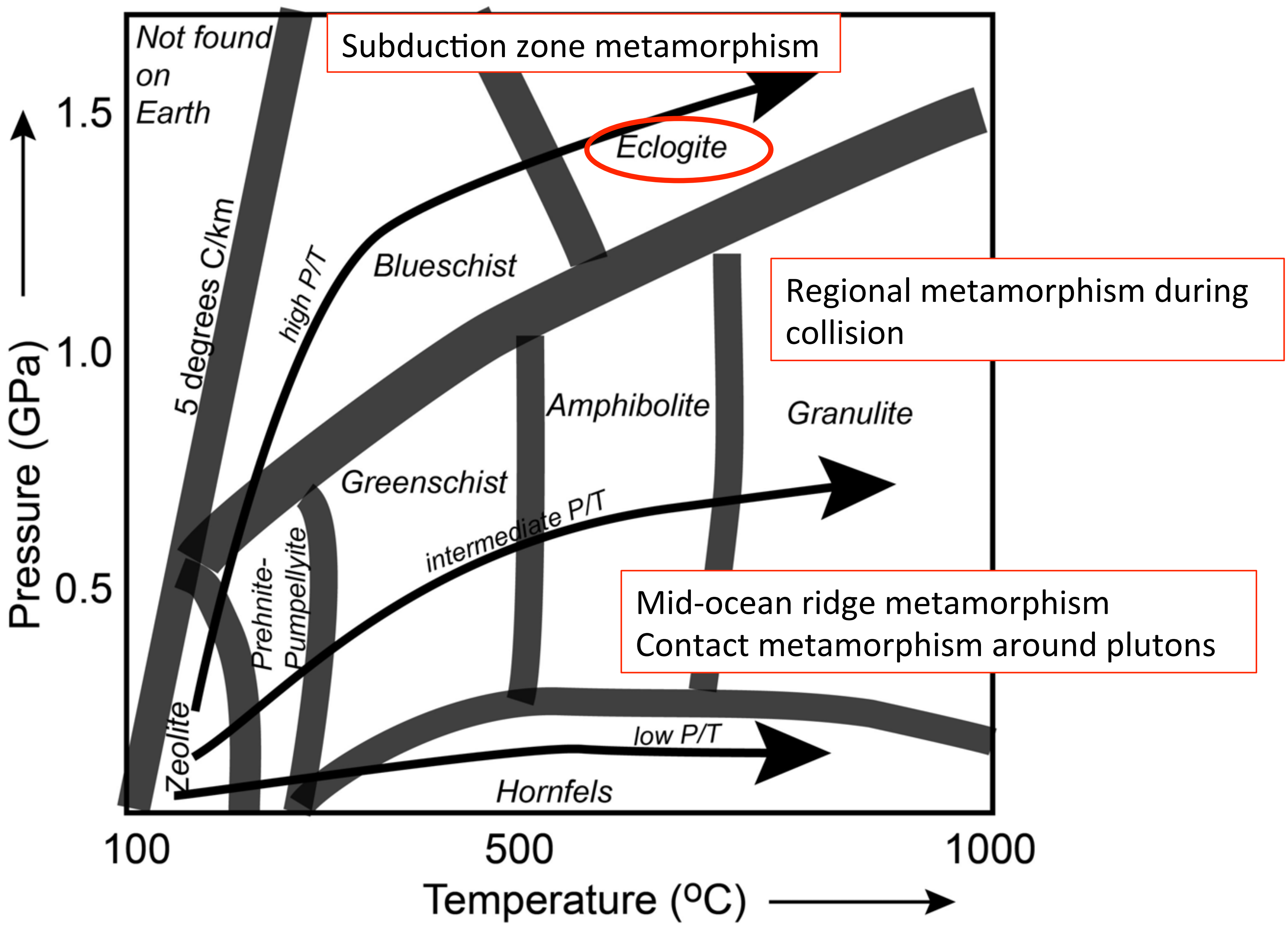


Amphibolite


Amphibolites are found in some subduction complexes and suggest high-temperature processes such as subduction initiation.

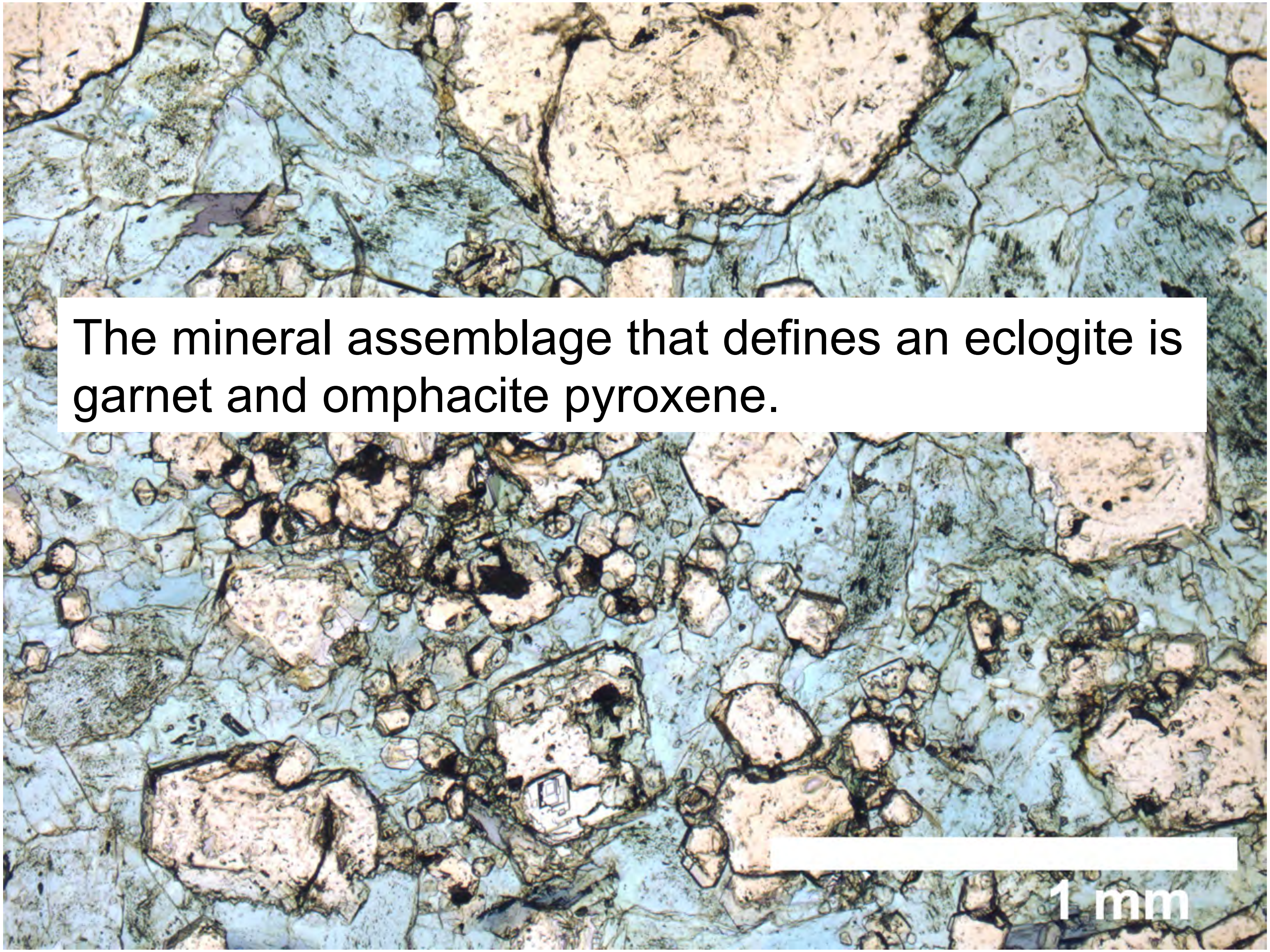
Commonly composed of hornblende amphibole (black) and garnet (red-brown)

Metamorphic facies and tectonic environment



Eclogite

Eclogite



The mineral assemblage that defines an eclogite is garnet and omphacite pyroxene.
1 mm

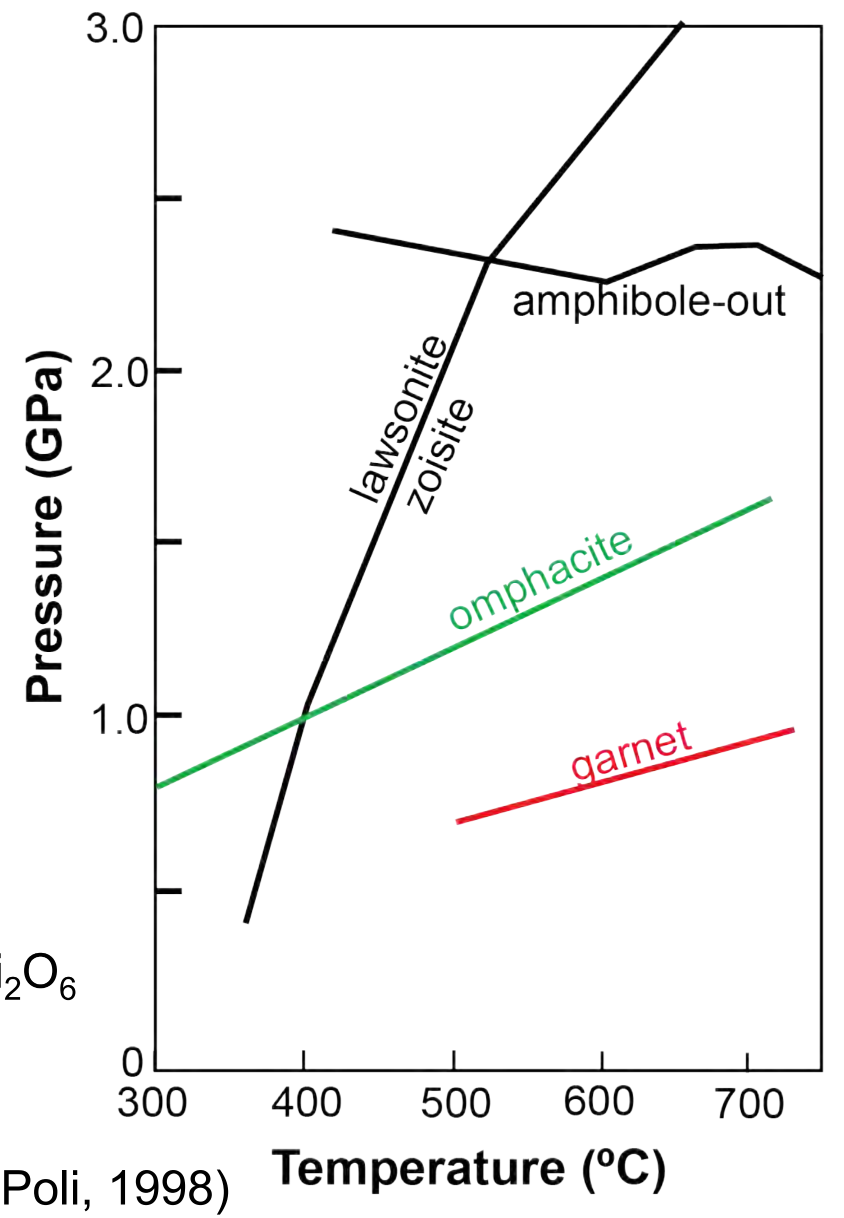
Eclogite facies minerals

- Garnet $(Ca,Mg,Fe)_3Al_2Si_3O_{12}$
- Omphacite $(Na,Ca)(Mg,Fe,Al)Si_2O_6$
- Phengite $K(Al,Mg)_3(Al,Si)_3O_{10}(OH)_2$
- Glaucophane $Na_2Mg_3Al_2Si_8O_{22}(OH)_2$
- Lawsonite $CaAl_2(Si_2O_7)(OH)_2 \bullet H_2O$
- Epidote/Zoisite $Ca_2Al_2FeSi_3O_{12}(OH)$
- Quartz SiO_2
- Kyanite Al_2SiO_5
- Aragonite $CaCO_3$

Eclogite facies mineral stability

Experimental results for MORB bulk composition

Stability fields for key eclogite facies minerals **omphacite** and **garnet**



Omphacite $(Na,Ca)(Mg,Fe,Al)Si_2O_6$

Almandine garnet: $Fe_3Al_2Si_3O_{12}$

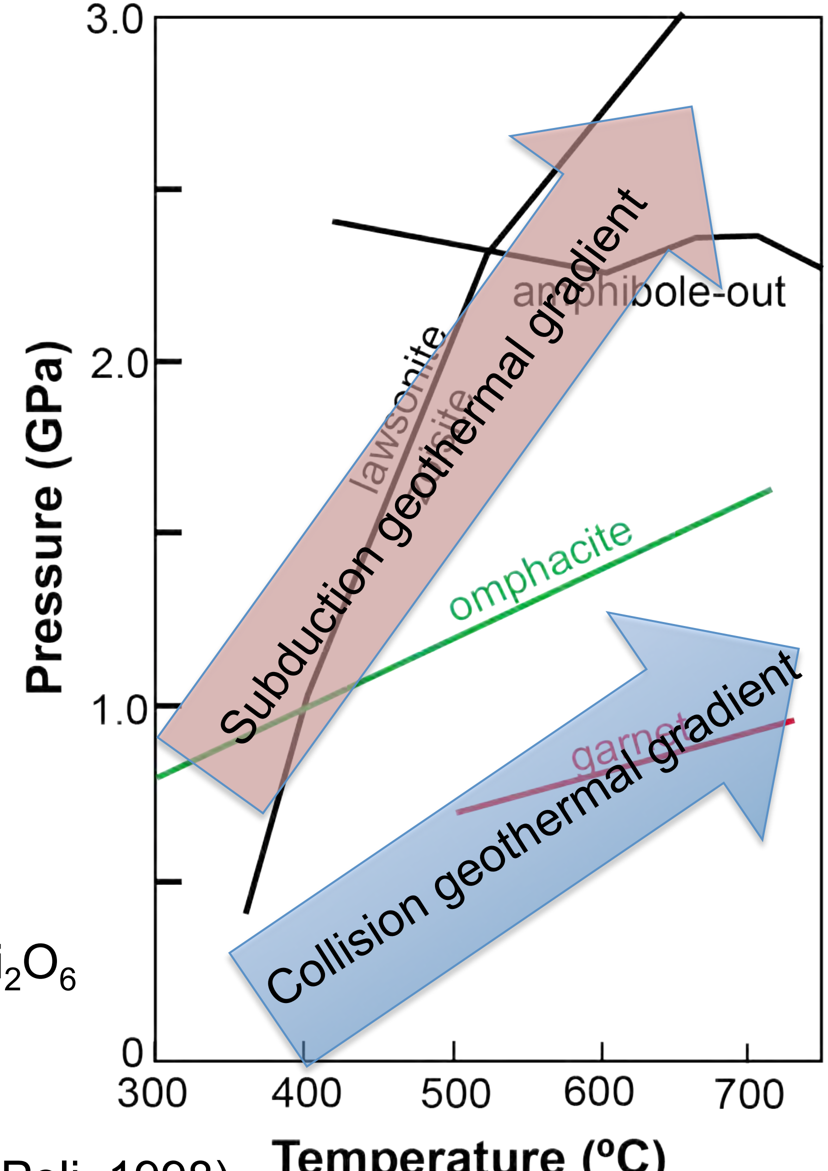
(after Schmidt and Poli, 1998)

Eclogite facies mineral stability

Experimental results for MORB bulk composition

Stability fields for key eclogite facies minerals **omphacite** and **garnet**

Again, these minerals tell us that subduction zones are **cooler** than other tectonic environments.



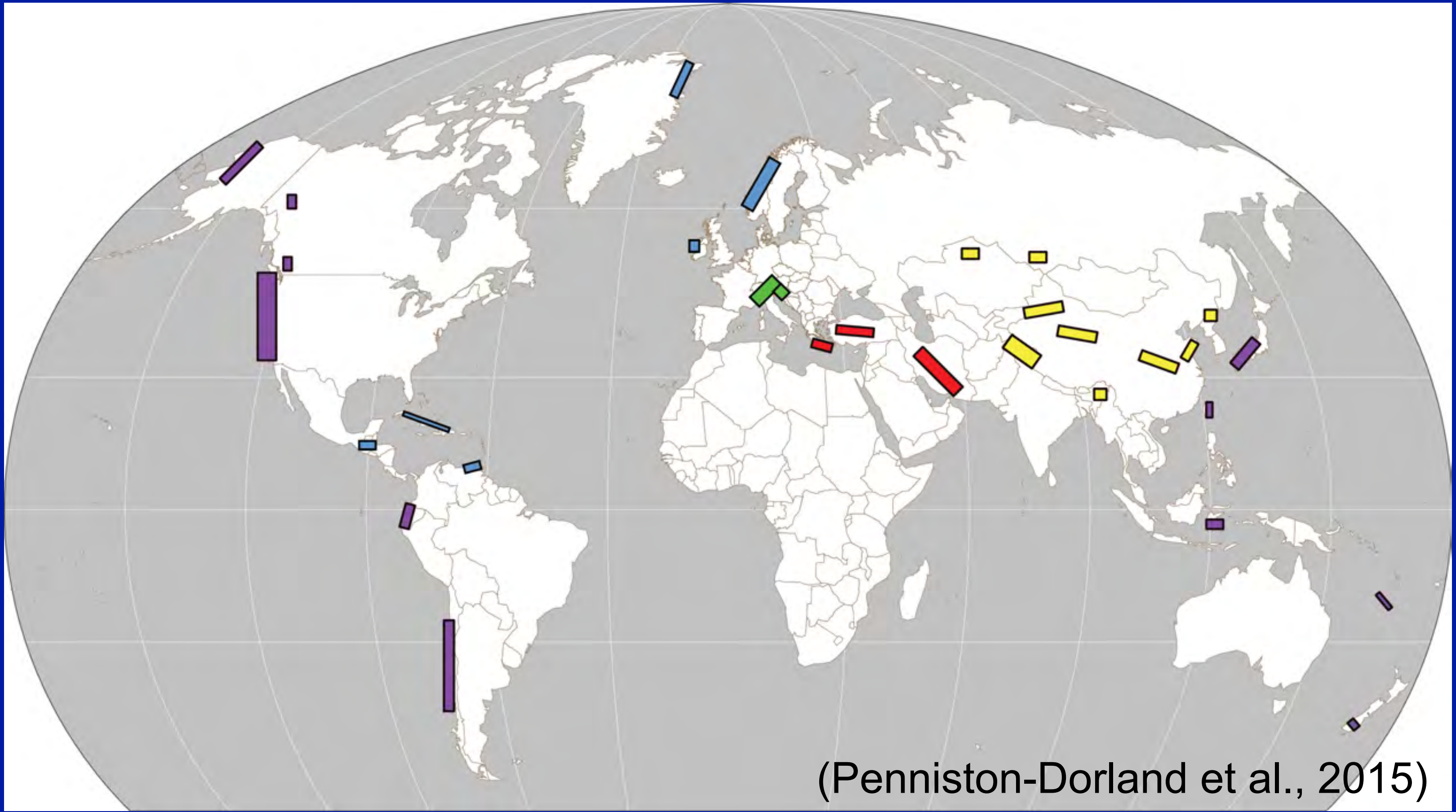
Omphacite	(Na,Ca)(Mg,Fe,Al)Si_2O_6
Almandine garnet:	$Fe_3Al_2Si_3O_{12}$

(after Schmidt and Poli, 1998)

How cold are subduction zones?

Compilation of *P-T* estimates from metamorphic rocks

- Chose *T* at peak *P* of exhumed eclogites and blueschists (prograde)
- Used only studies later than 1990
- Subduction systems < 750 Ma
- Wide range of subduction conditions: all ages of oceanic crust, fast and slow convergence, all angles of subduction

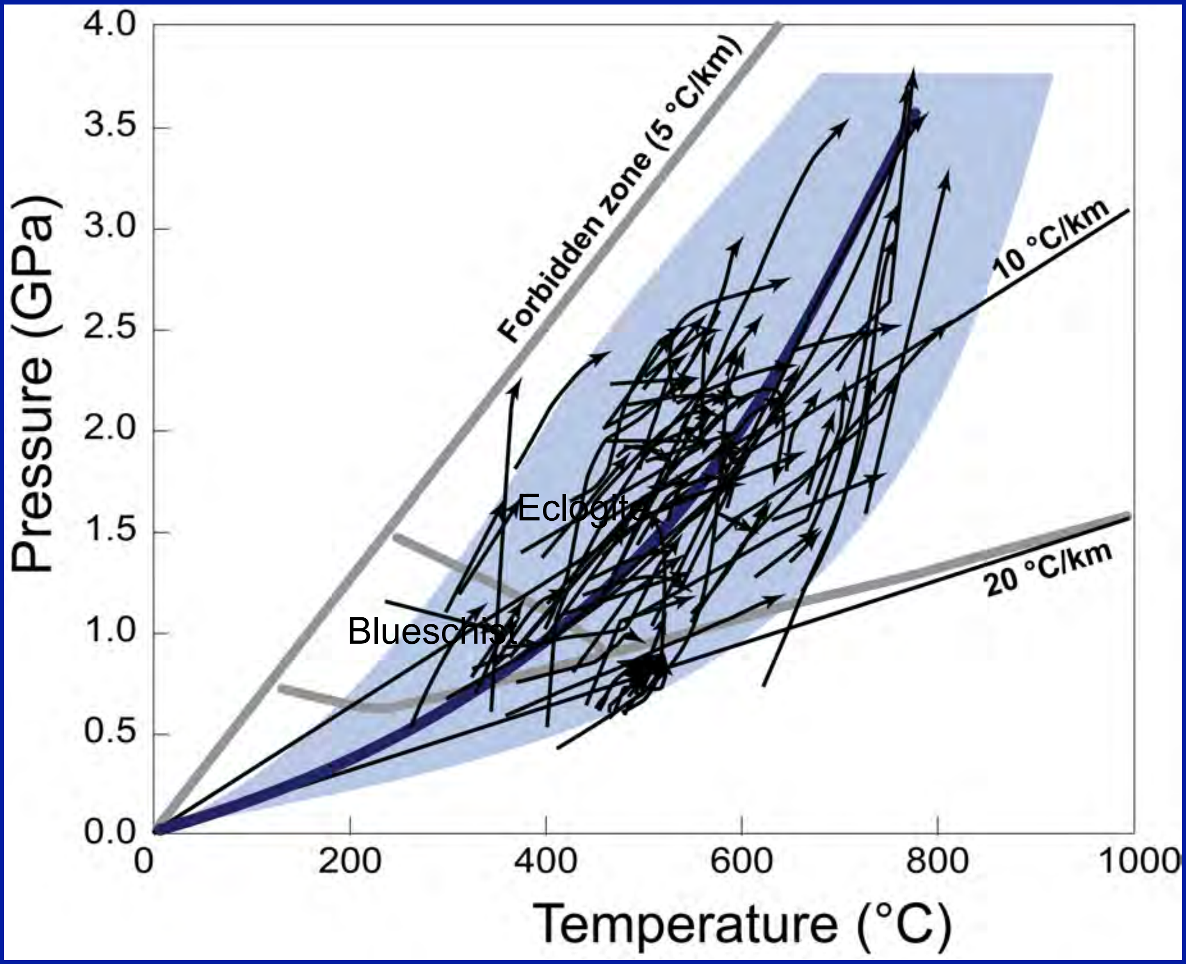


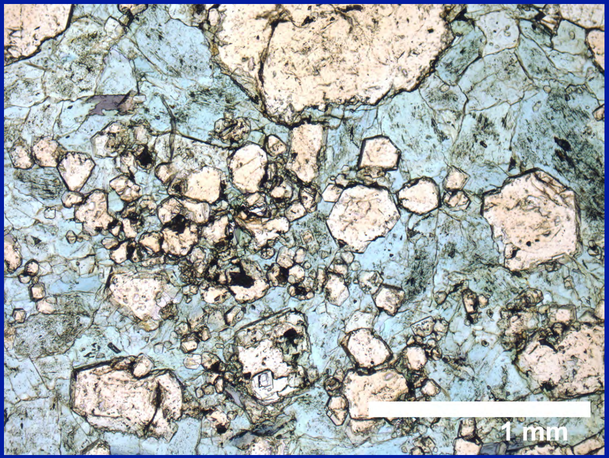
(Penniston-Dorland et al., 2015)

How cold are subduction zones?

Peak *P-T* conditions and prograde paths from exhumed metamorphic rocks provide important constraints on the thermal structure of subduction zones.

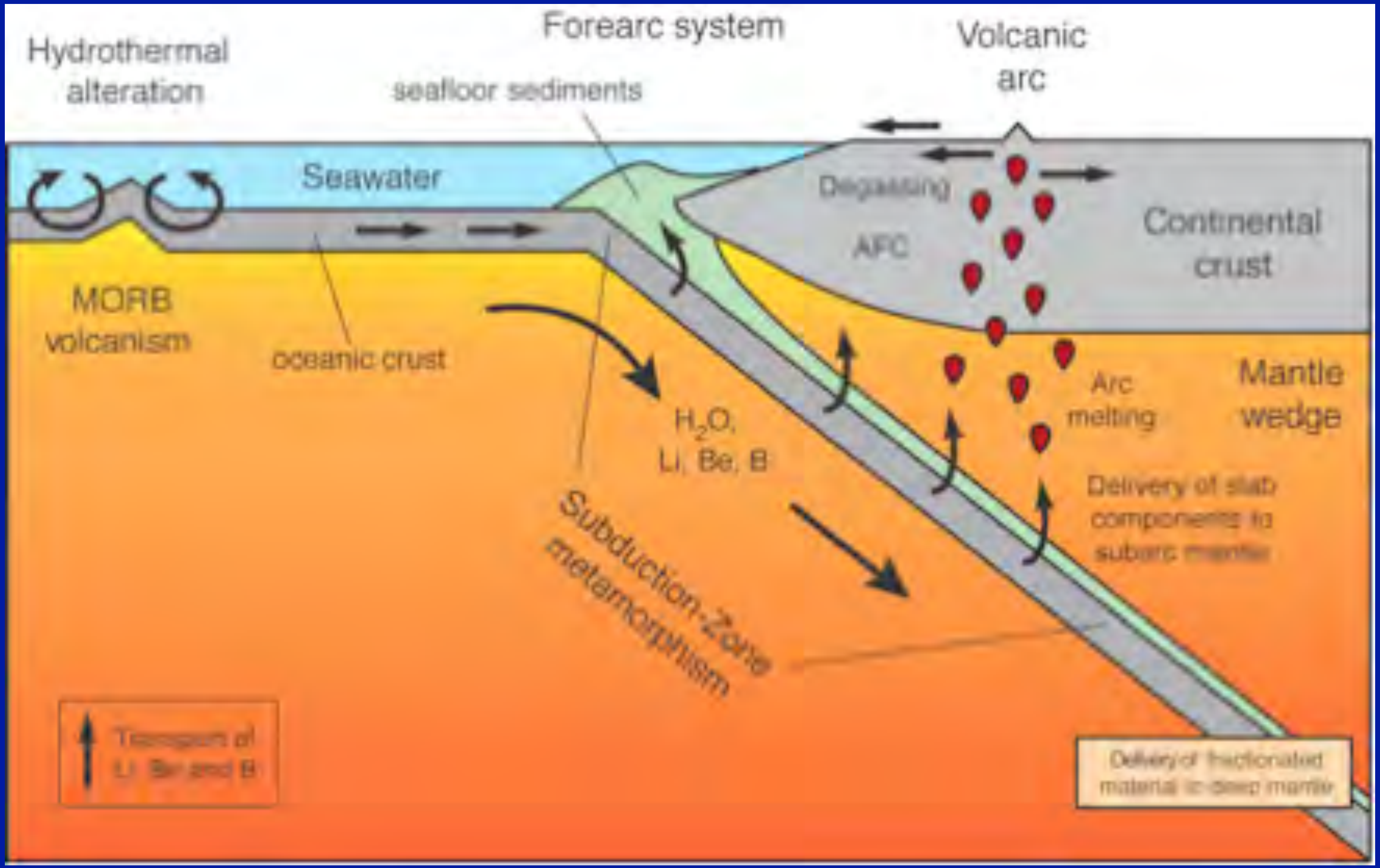
(Penniston-Dorland et al., 2015)






Fluids

Water is released during prograde metamorphism



Marschall, 2005

Water is released during prograde metamorphism

ALTERED MORB

Heulandite	$CaAl_2Si_7O_{18}\bullet 6H_2O$
Stilbite	$CaAl_2Si_4O_{12}\bullet 7H_2O$
Kaolinite	$Al_2Si_2O_5(OH)_4$
Illite	$K_{0.75}Al_2Al_{0.75}Si_{3.25}O_{10}(OH)_2$

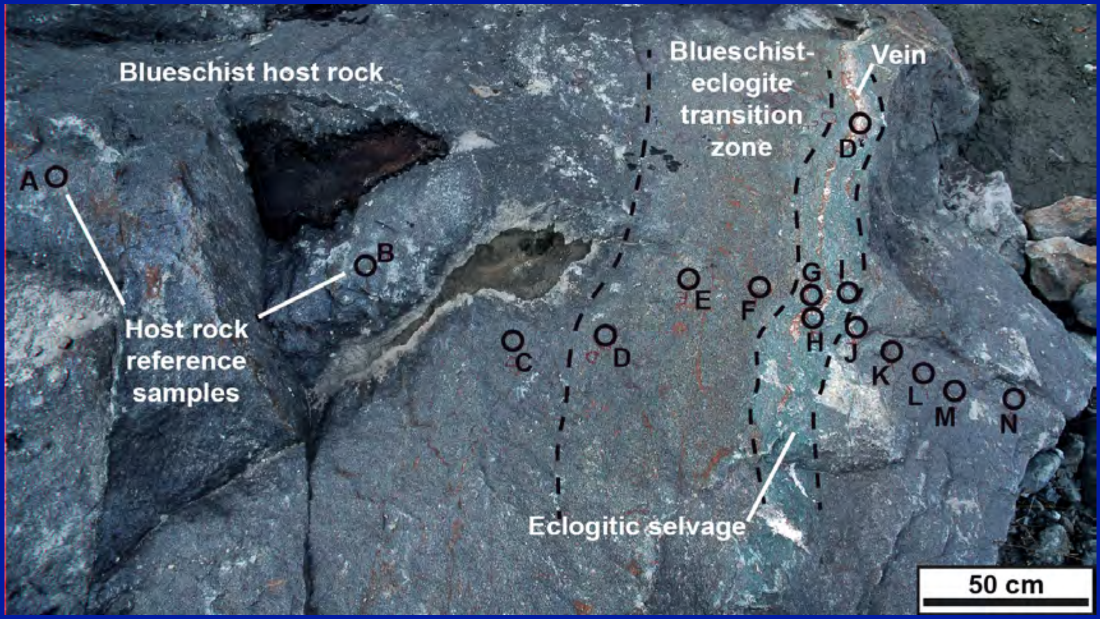
BLUESCHIST

Glaucophane:	$Na_2Mg_3Al_2Si_8O_{22}(OH)_2$
Lawsonite:	$CaAl_2(Si_2O_7)(OH)_2\bullet H_2O$

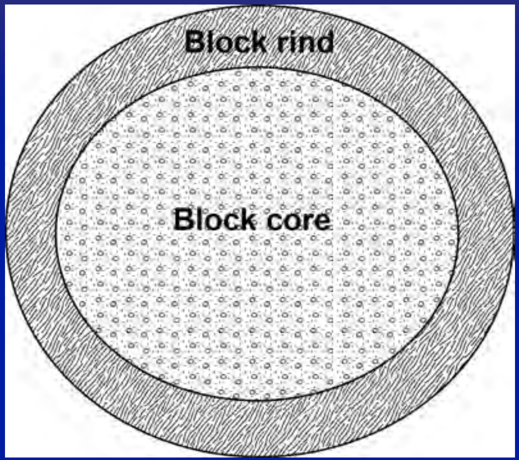
ECLOGITE

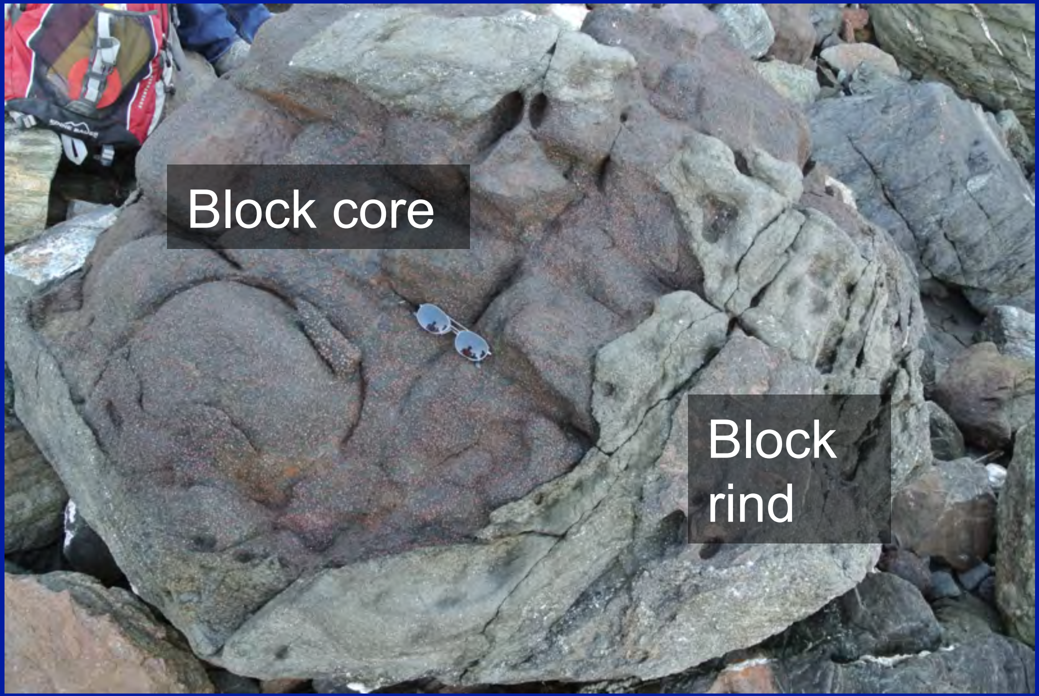
Omphacite	$(Na,Ca)(Mg,Fe,Al)Si_2O_6$
Almandine: garnet	$Fe_3Al_2Si_3O_{12}$

Evidence for fluid flow: Veins



Evidence for fluid flow: Reaction zones and rinds

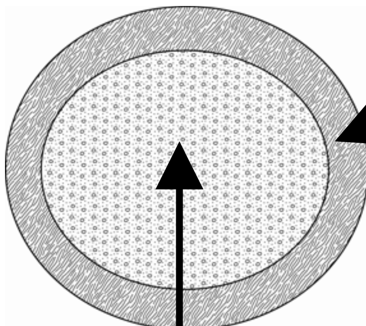


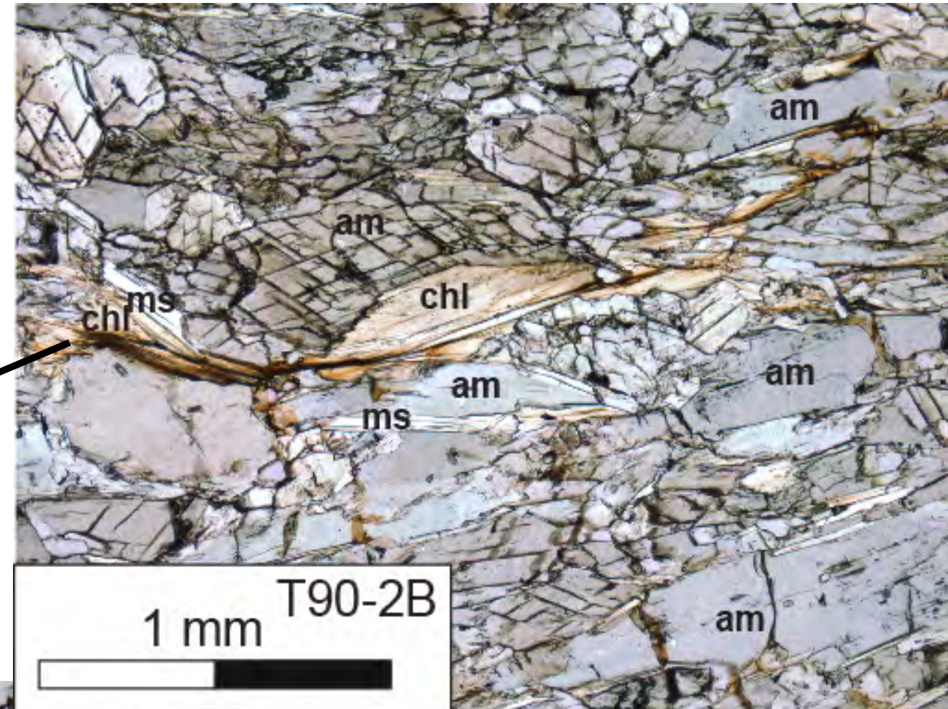


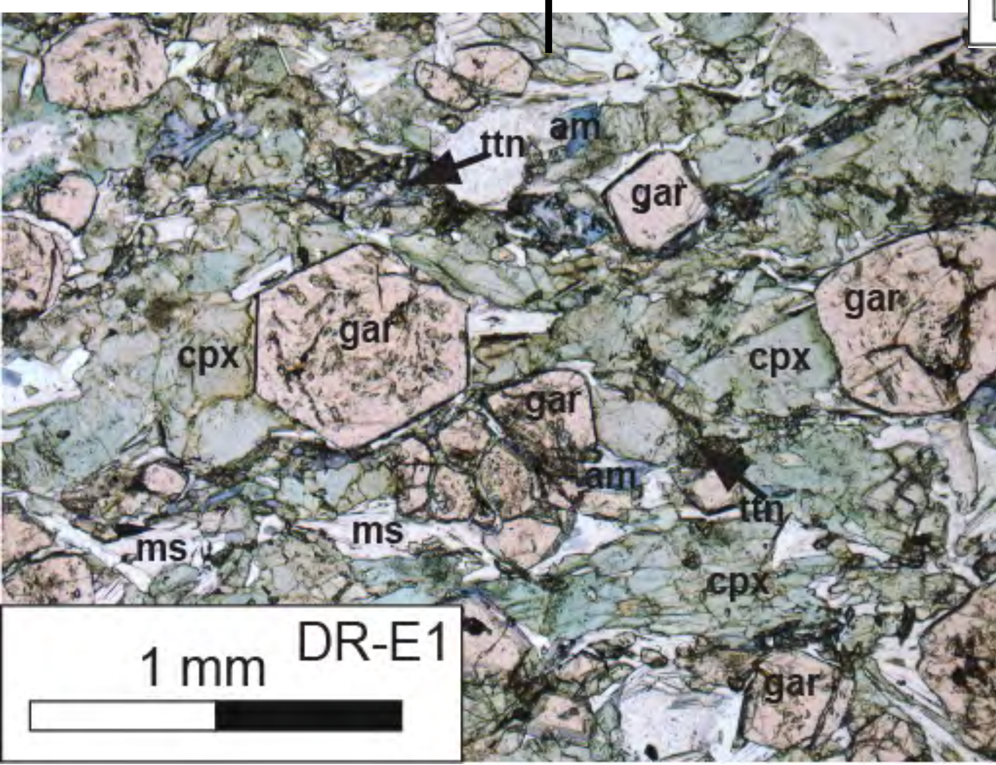
Rind is foliated

Evidence for fluid flow:

Reaction rinds have more hydrous minerals, elevated in concentrations of fluid mobile elements (e.g. Ba, Sr, Th)







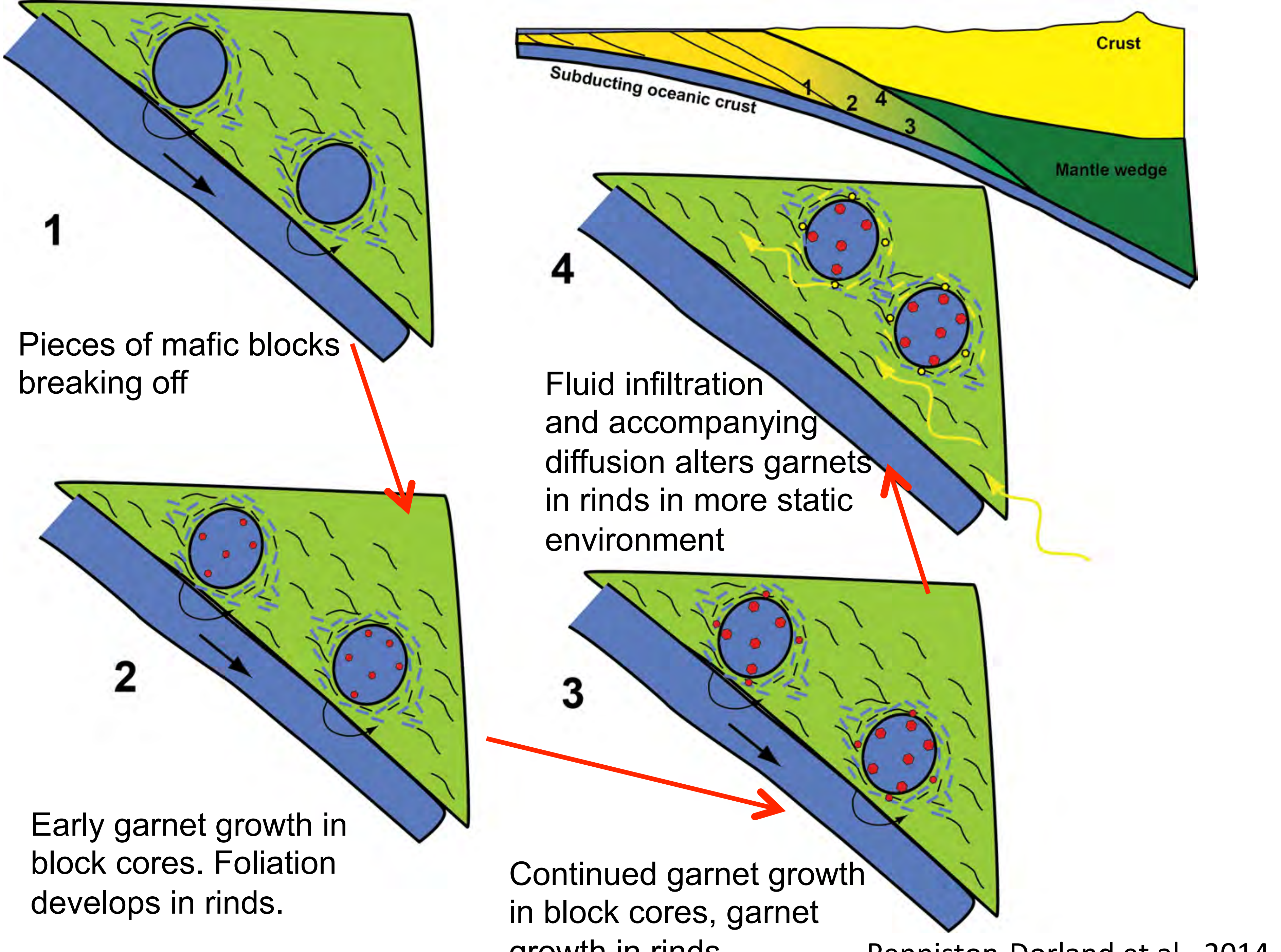
Rind		
	amphibole (am)	quartz
	phengite (ms)	titanite
	chlorite (chl)	talc

Typically 2-3.5 wt.% LOI

Block core (eclogite)

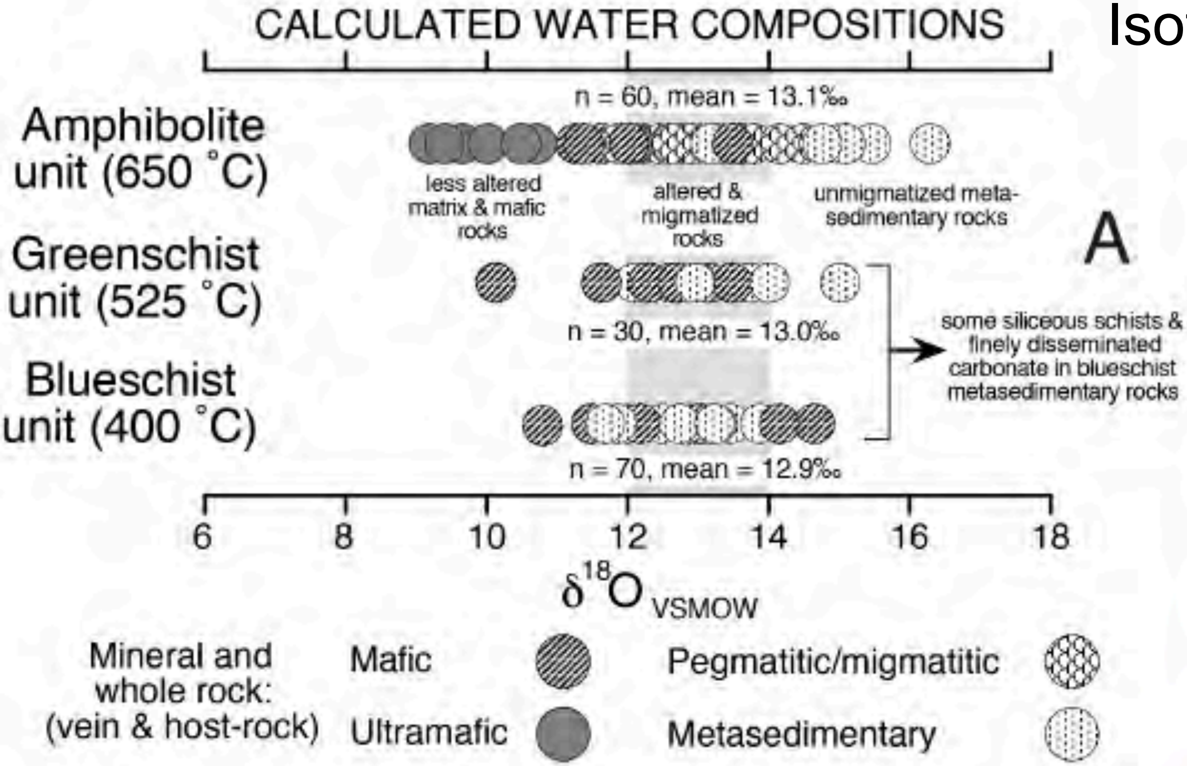
omphacite (cpx)	garnet (gar)
amphibole (am)	phengite (ms)
epidote	titanite (ttn)
chlorite	
rutile	

Typically 1-2.5 wt.% LOI

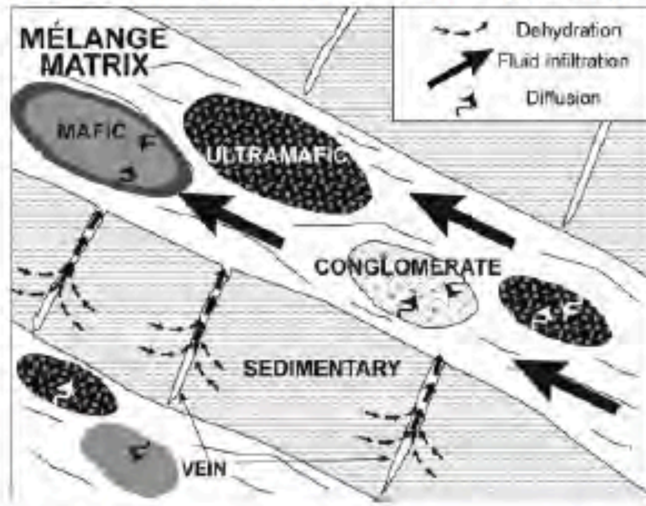


Penniston-Dorland et al., 2014

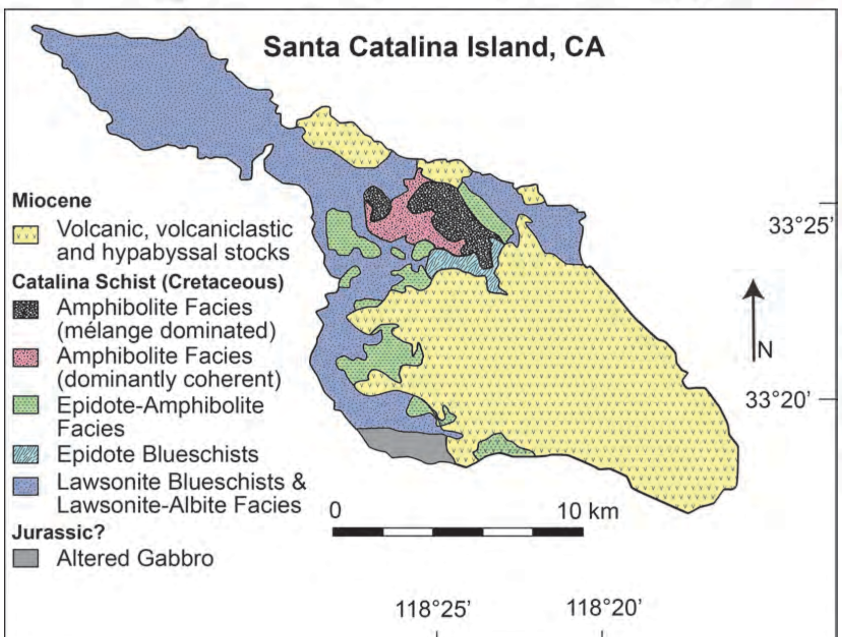
Isotopic evidence for fluid flow



from Penniston-Dorland et al. (2012, *GCA*)

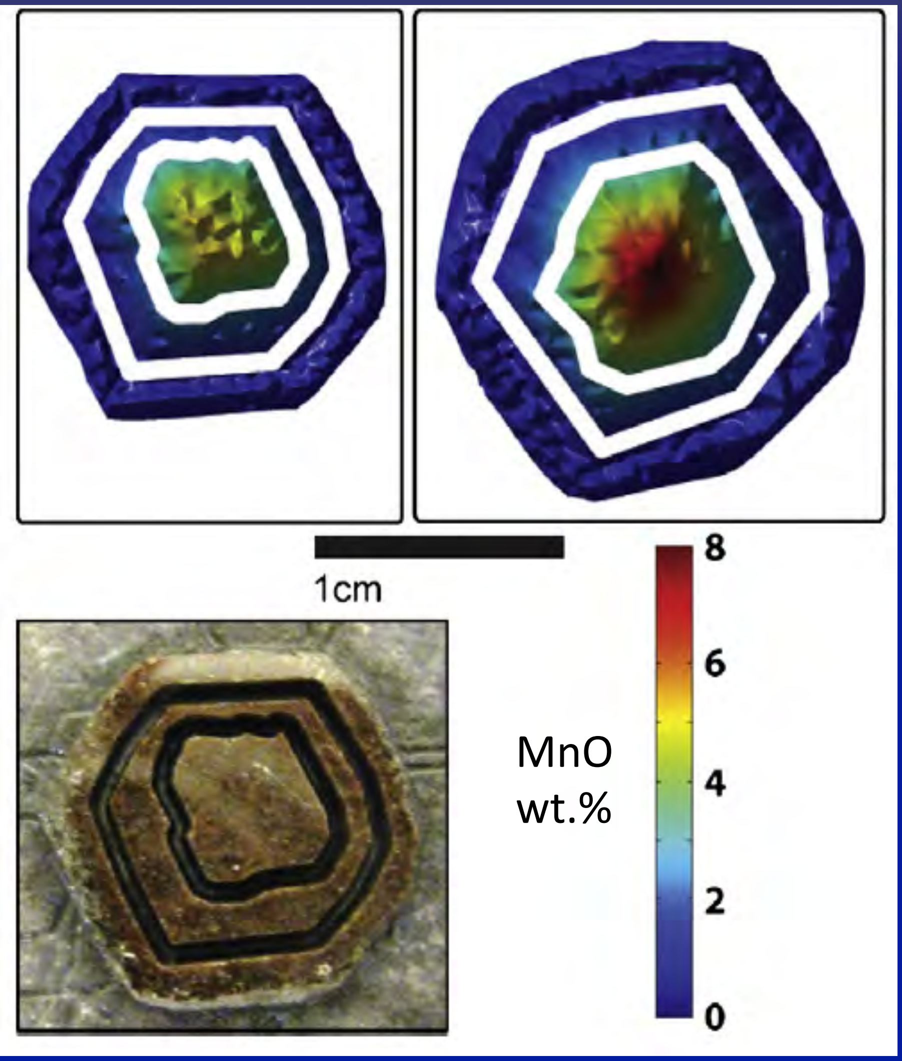


Bebout and Barton 1989

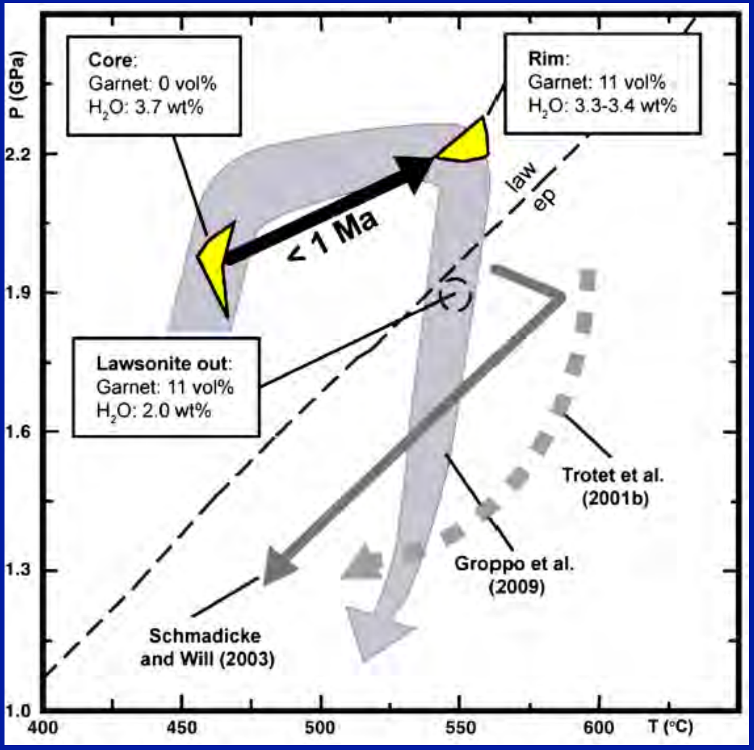


from King et al. (2006; *EPSL*)

Fluid release rates



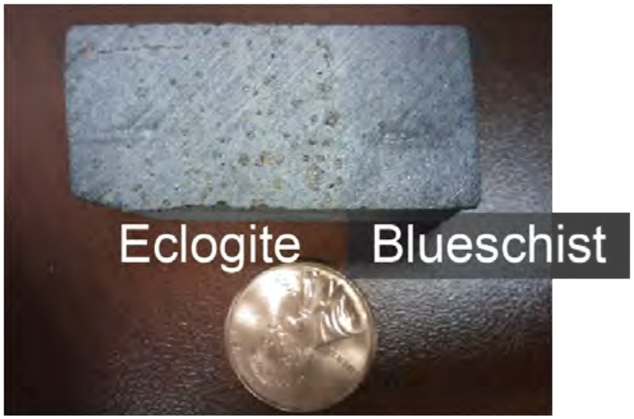
Garnet geochronology + petrology + thermobarometry constrain the amount and duration of the fluid release during garnet-forming reactions
(Dragovic et al., 2012; 2015)



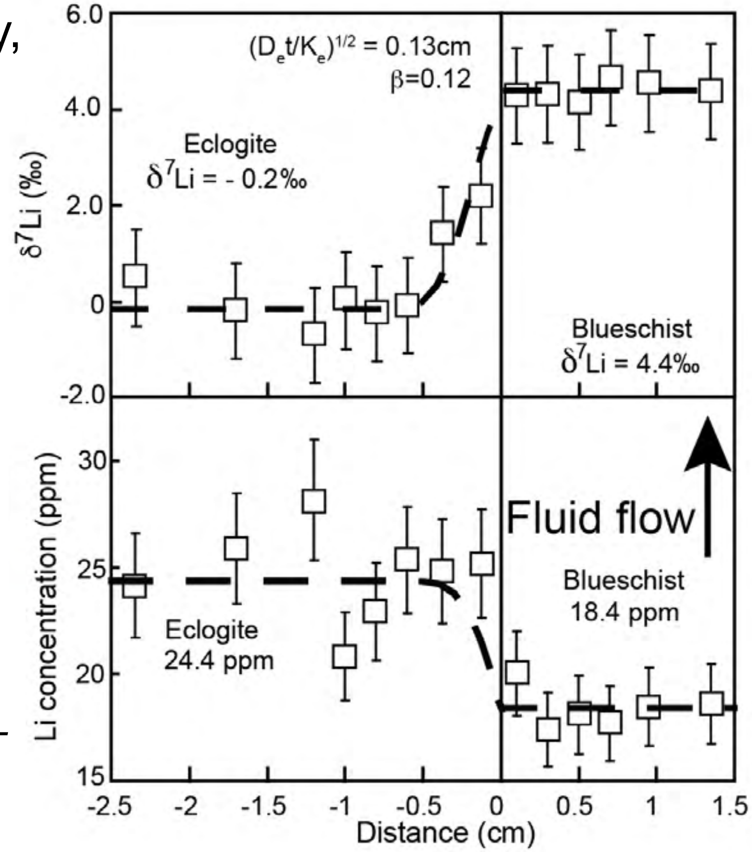
0.02 chlorite + 0.97 glaucophane + 0.10 phengite + 0.06 chloritoid + 0.10 rutile =
1.07 omphacite +0.18 paragonite +0.16 lawsonite + 1.36 quartz + **1.00 garnet** **+ 0.69 H_2O**

0.3 to 0.4 wt.% H_2O loss during garnet growth over <1 Ma

Rock from Field Trip locality, Tiburon
Franciscan Complex

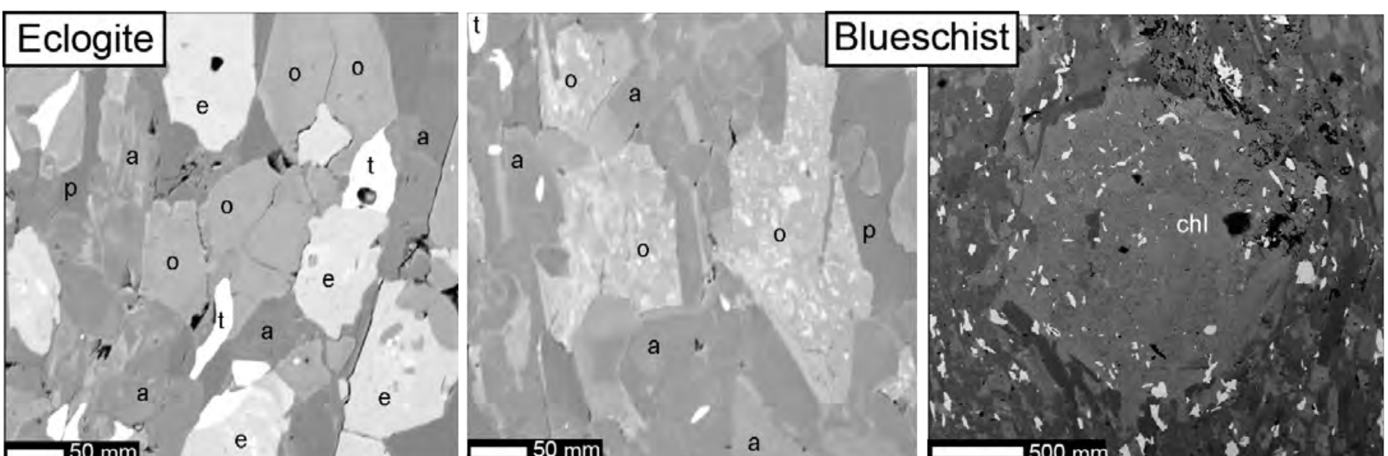


Penniston-Dorland et al., 2010, *EPSL*



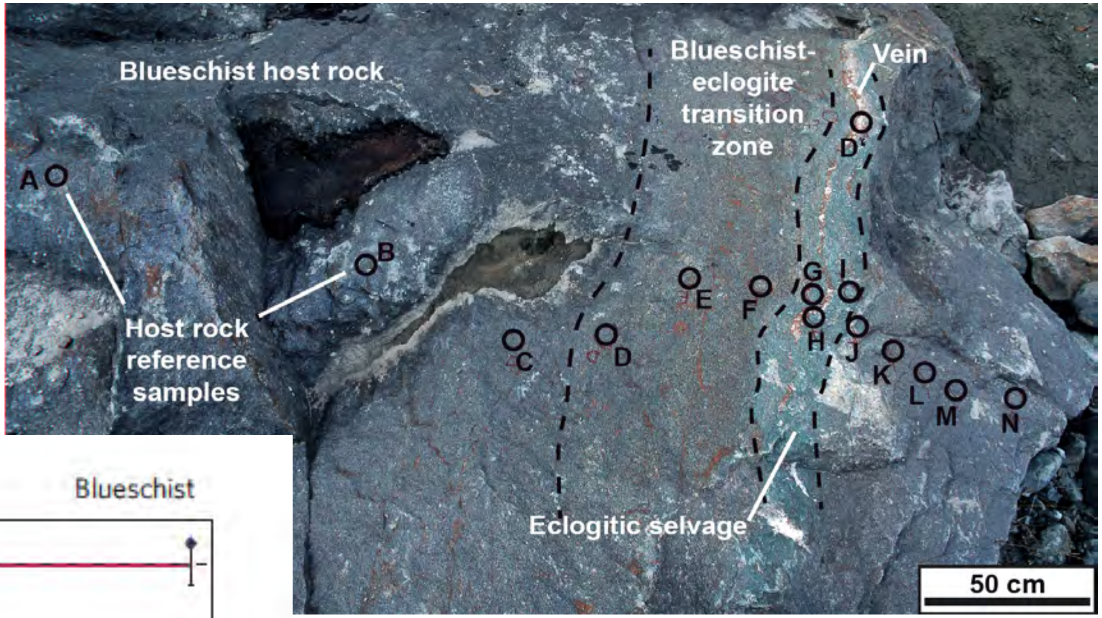
Evidence for timescales of fluid flow

Study of fluid-related features tells us about the duration of fluid infiltration events (<~100 years!) during subduction

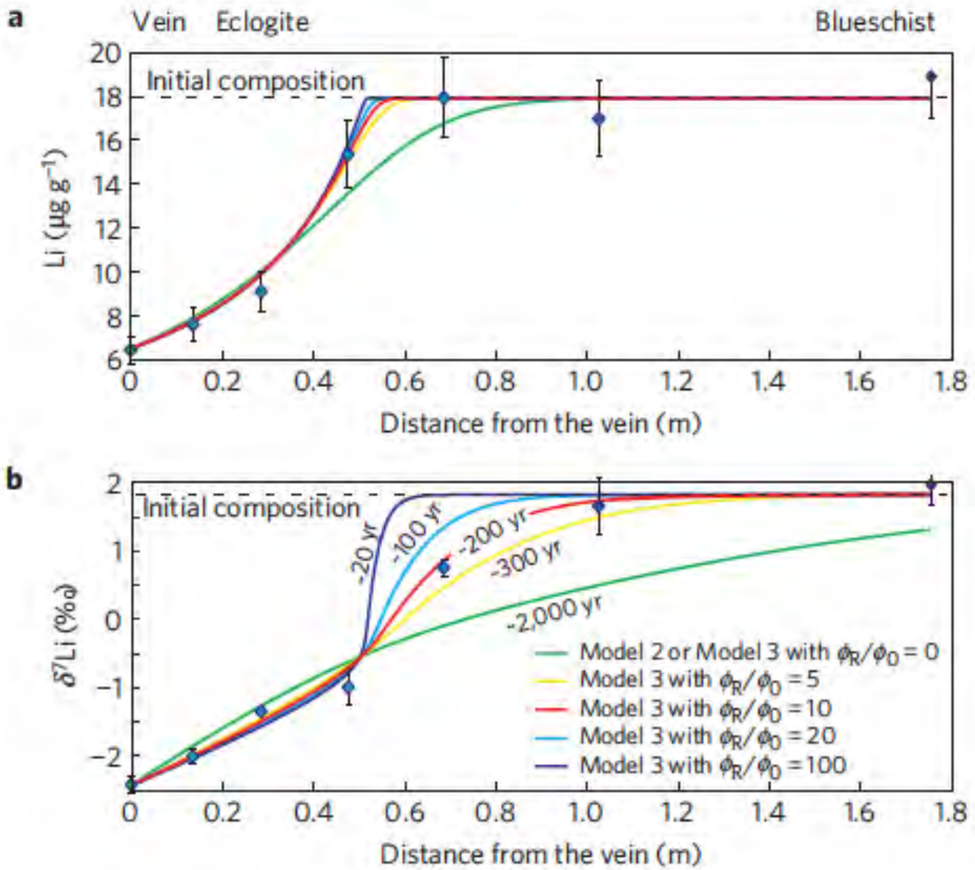


Evidence for timescales of fluid flow

Rock from Chinese Tianshan



John et al., 2012, *Nat. Geoscience*



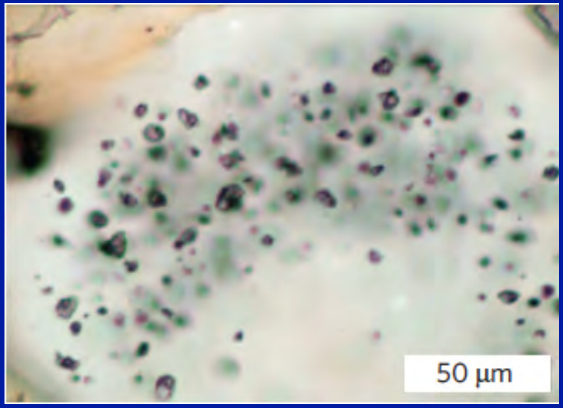
Study of fluid-related features tells us about the duration of fluid infiltration events (<~200 years!) during subduction

Evidence for fluids: fluid inclusions

Aqueous fluid inclusions = homogeneous, low-salinity fluids -> Interpreted as due to flow of large volumes of externally derived sedimentary fluids (Giaramita and Sorensen, 1994)

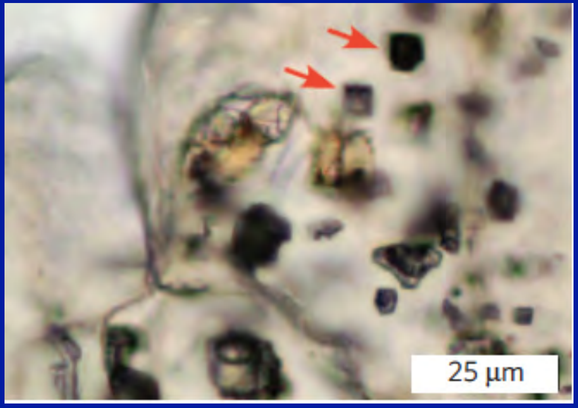
Aqueous fluid inclusions = heterogeneous, wide range of salinities -> suggest *in situ* generation of heterogeneous fluids (Philippot and Selverstone, 1991)

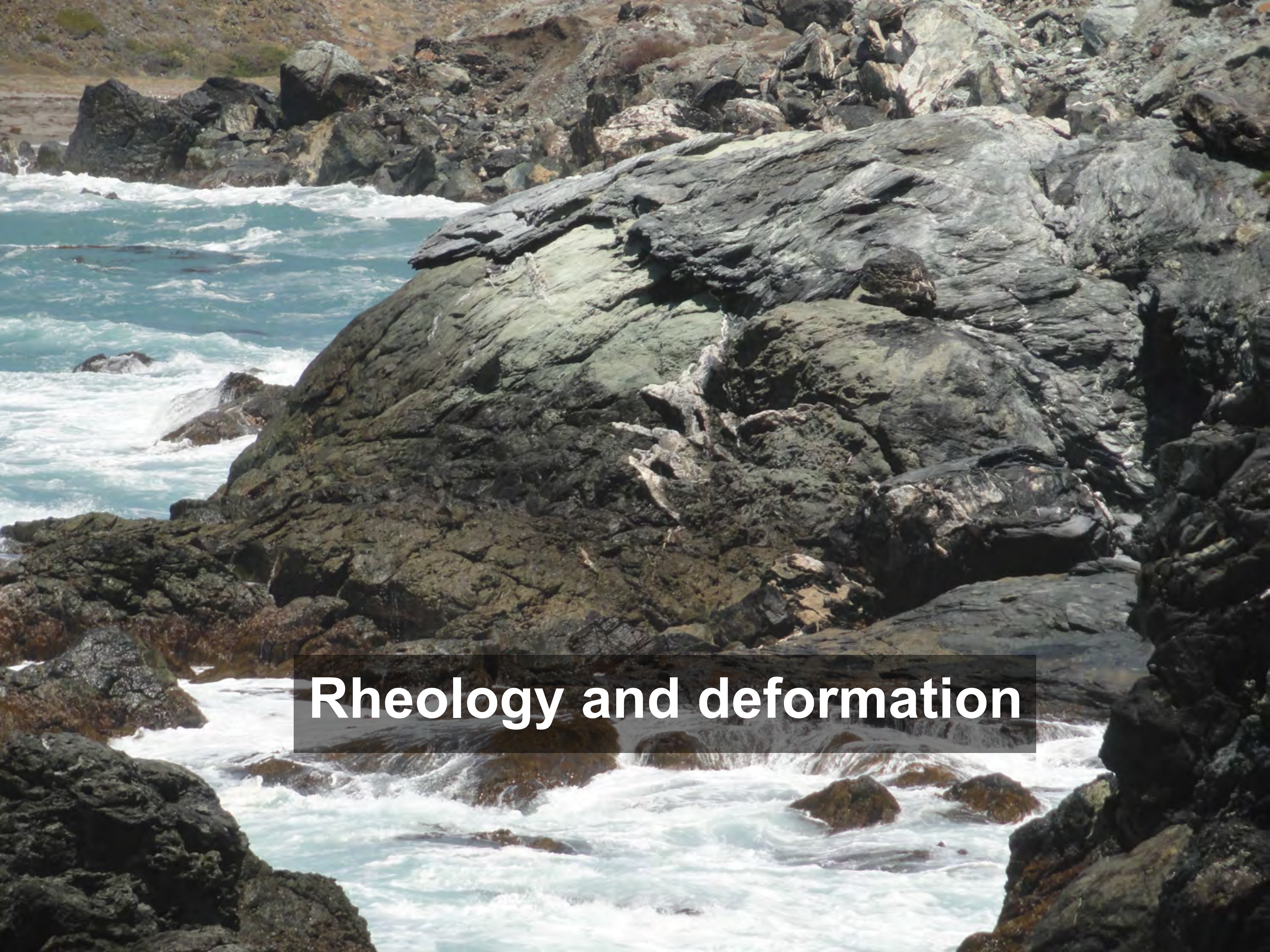
Aqueous fluid containing dissolved carbonate, dissolved silica, and solid ***microdiamonds*** suggests carbonate dissolution may be responsible for carbon release during subduction (Frezzotti et al., 2011)



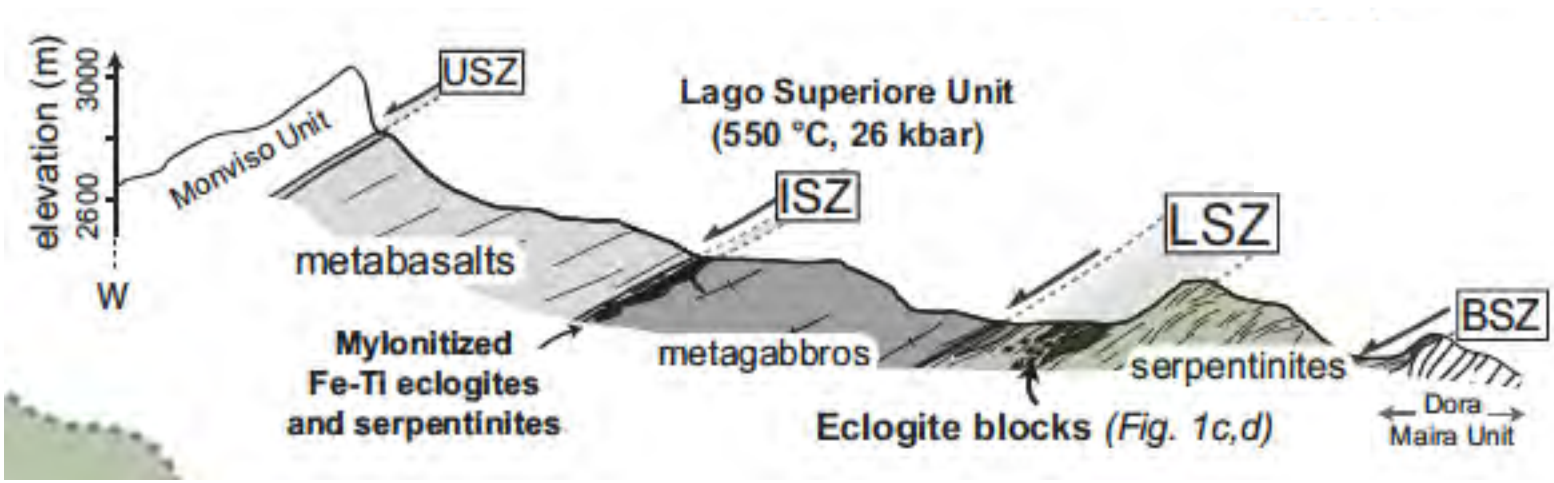
Fluid inclusions in garnet

Microdiamonds




Rheology and deformation

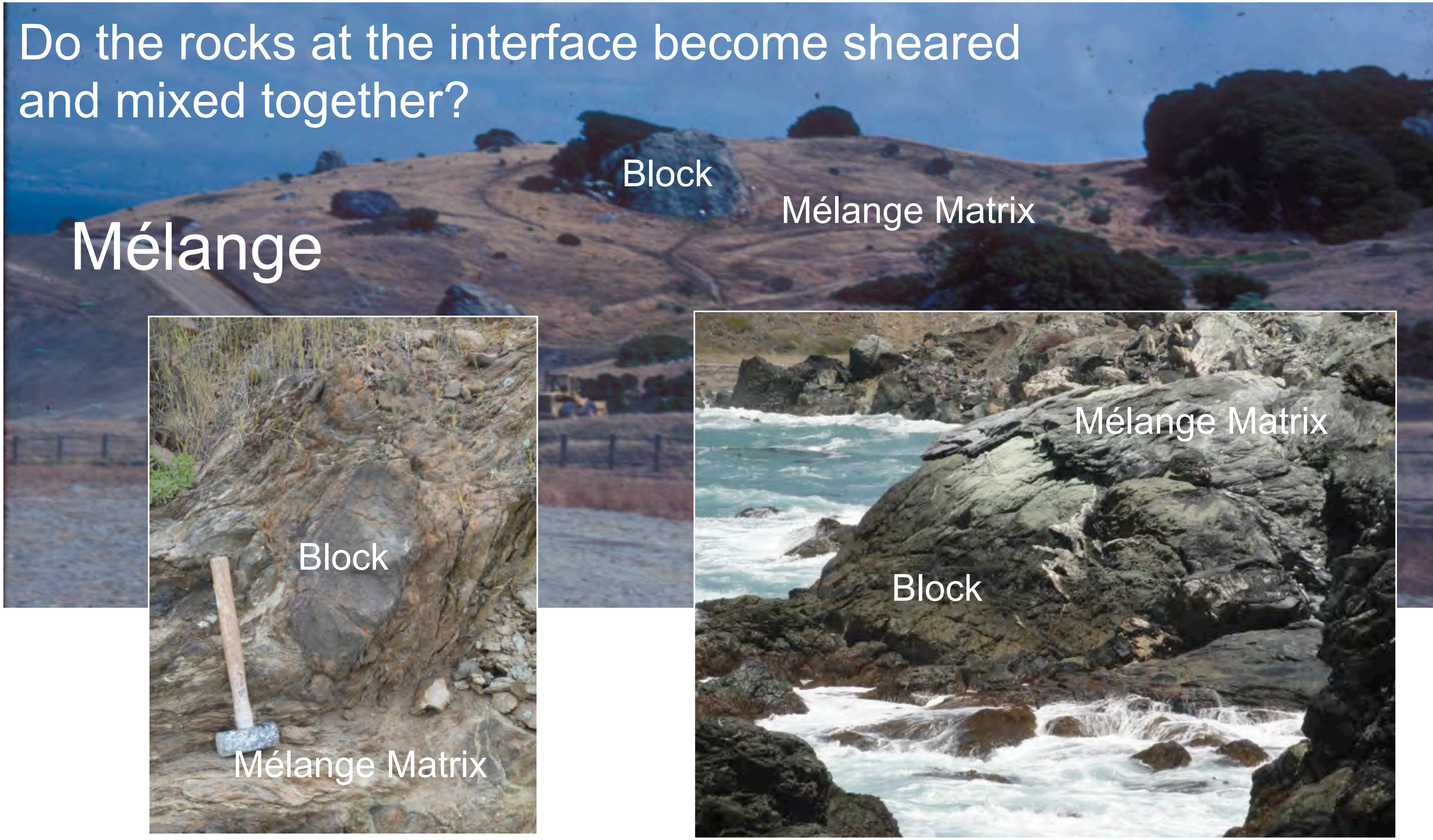
What is the nature of materials at the subduction interface?



Do the rocks on the subducting plate subduct as a relatively coherent sequence of lithosphere?

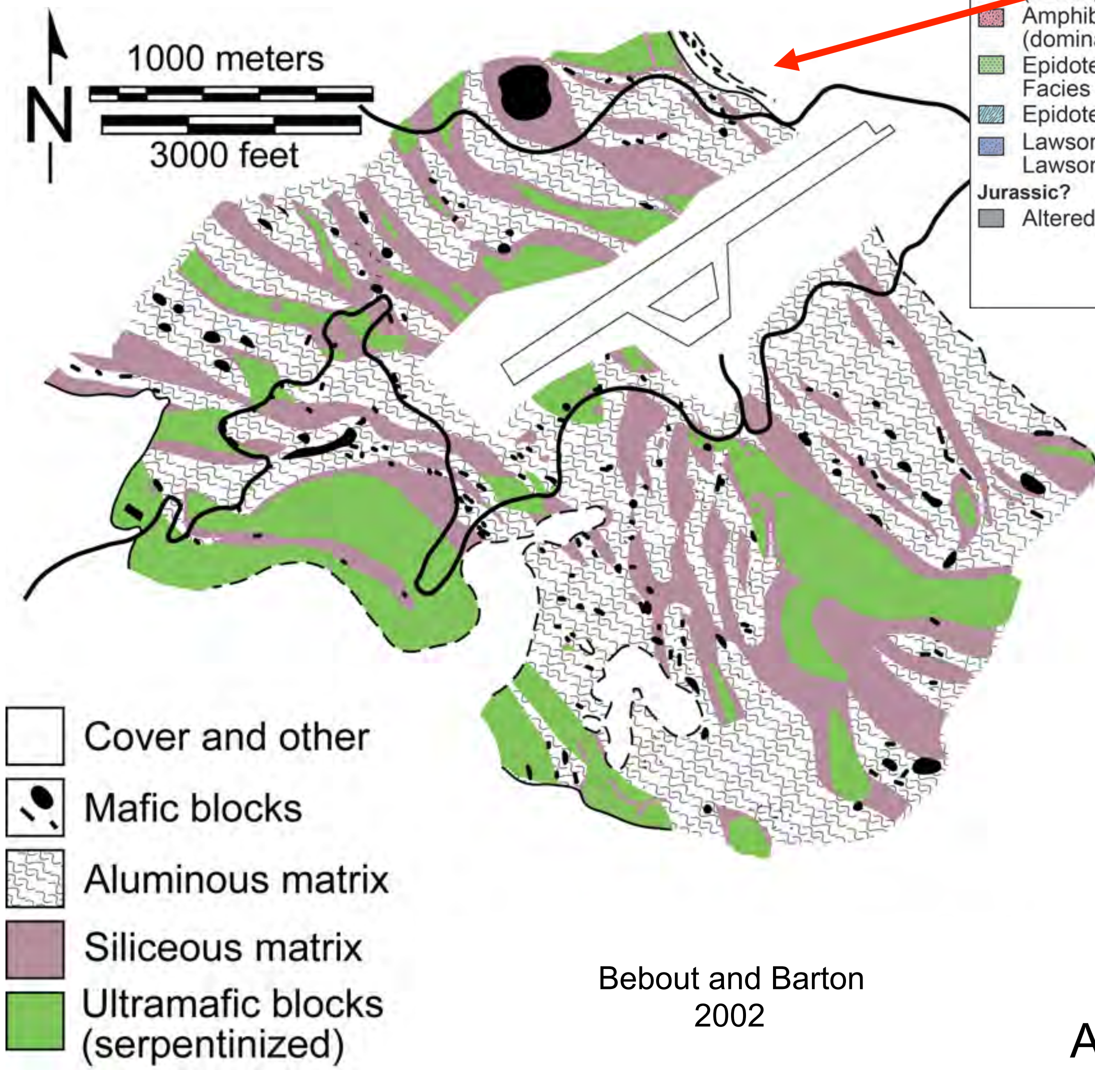
Subduction-related rocks from some localities are found as large sheets of oceanic lithosphere that are fault-bounded.

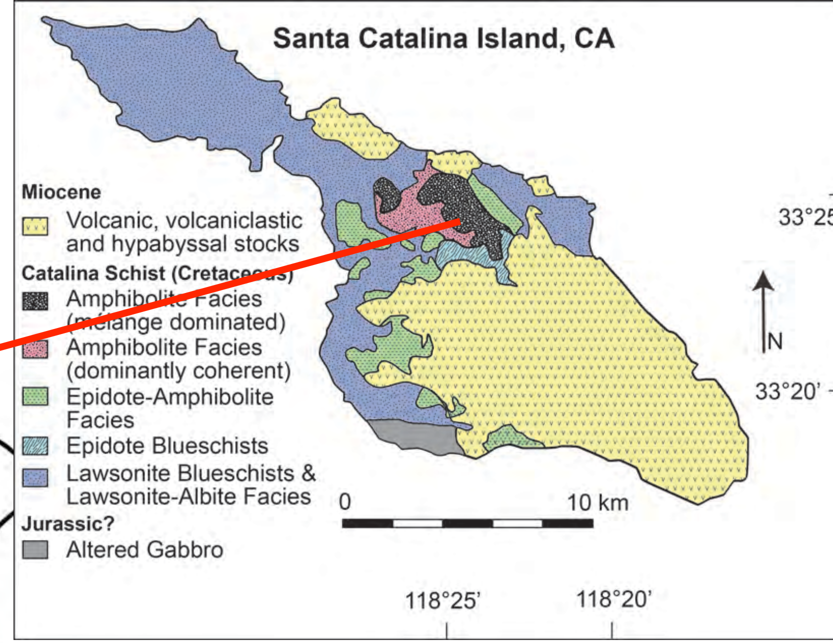
Do the rocks at the interface become sheared and mixed together?



Subduction-related rocks from other localities are found as jumbled mafic, ultramafic, and sedimentary blocks that are surrounded by fine-grained matrix in **mélange zones.**

Kilometer-scale tract of mélange

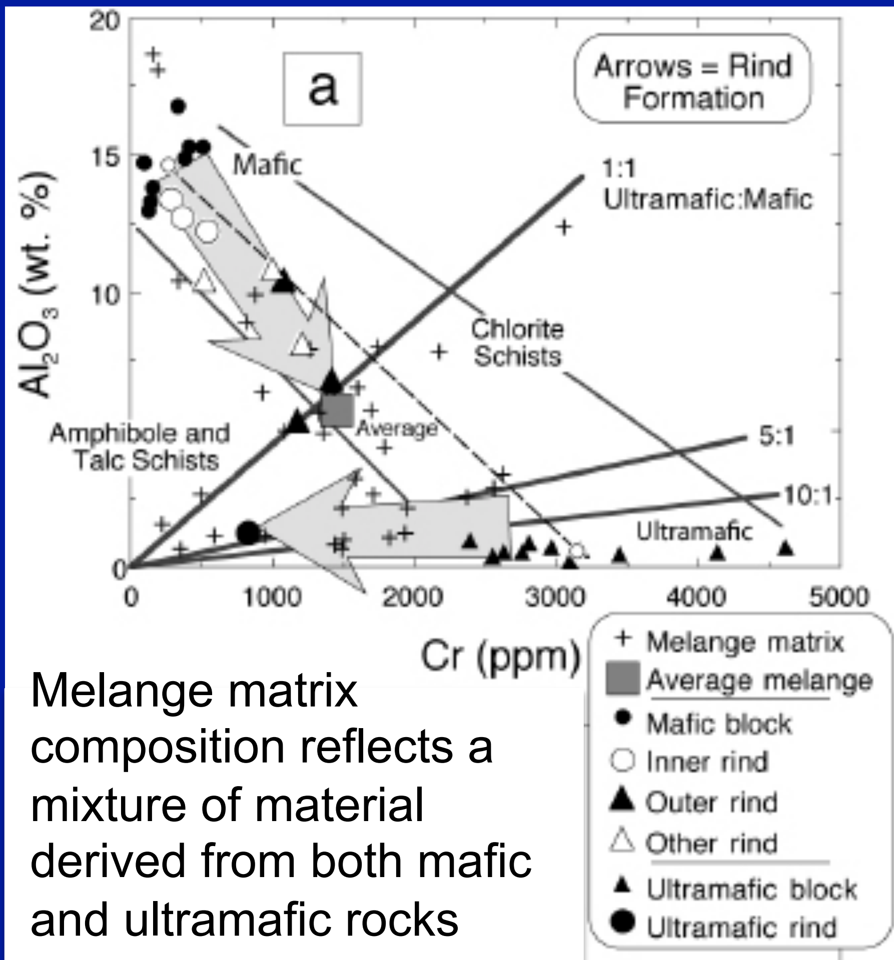




Bebout and Barton 2002

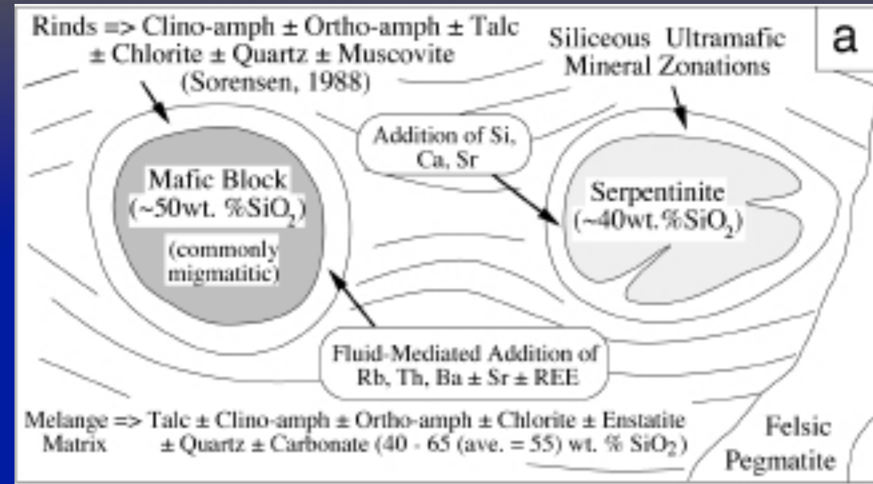
Amphibolite facies mélange matrix

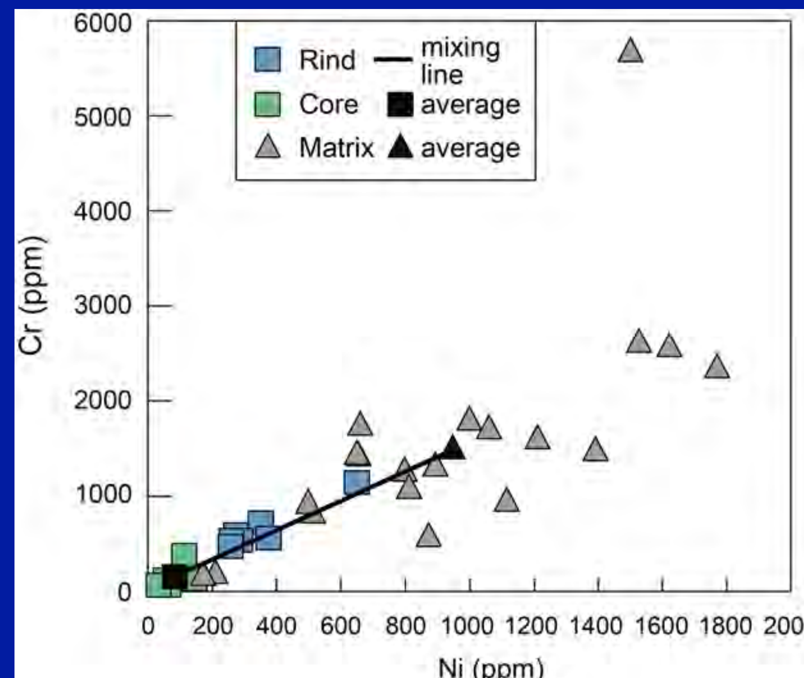
Evidence for physical mixing in mélange and reaction rinds



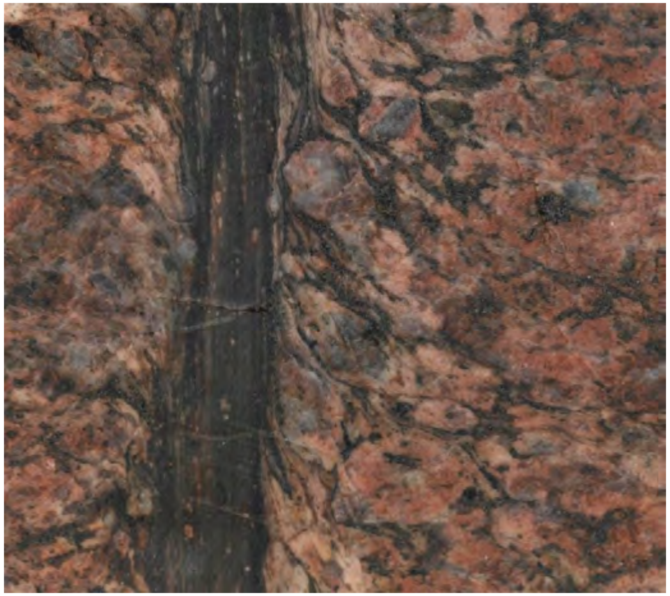
Melange matrix composition reflects a mixture of material derived from both mafic and ultramafic rocks

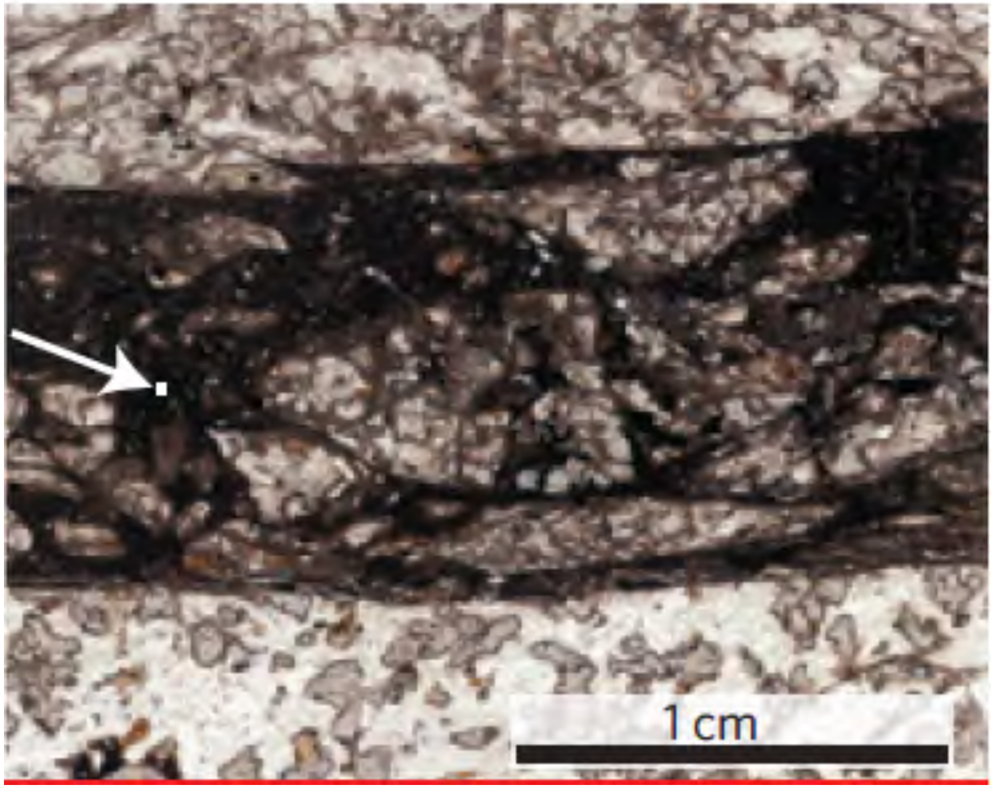
from Bebout and Barton (2002)





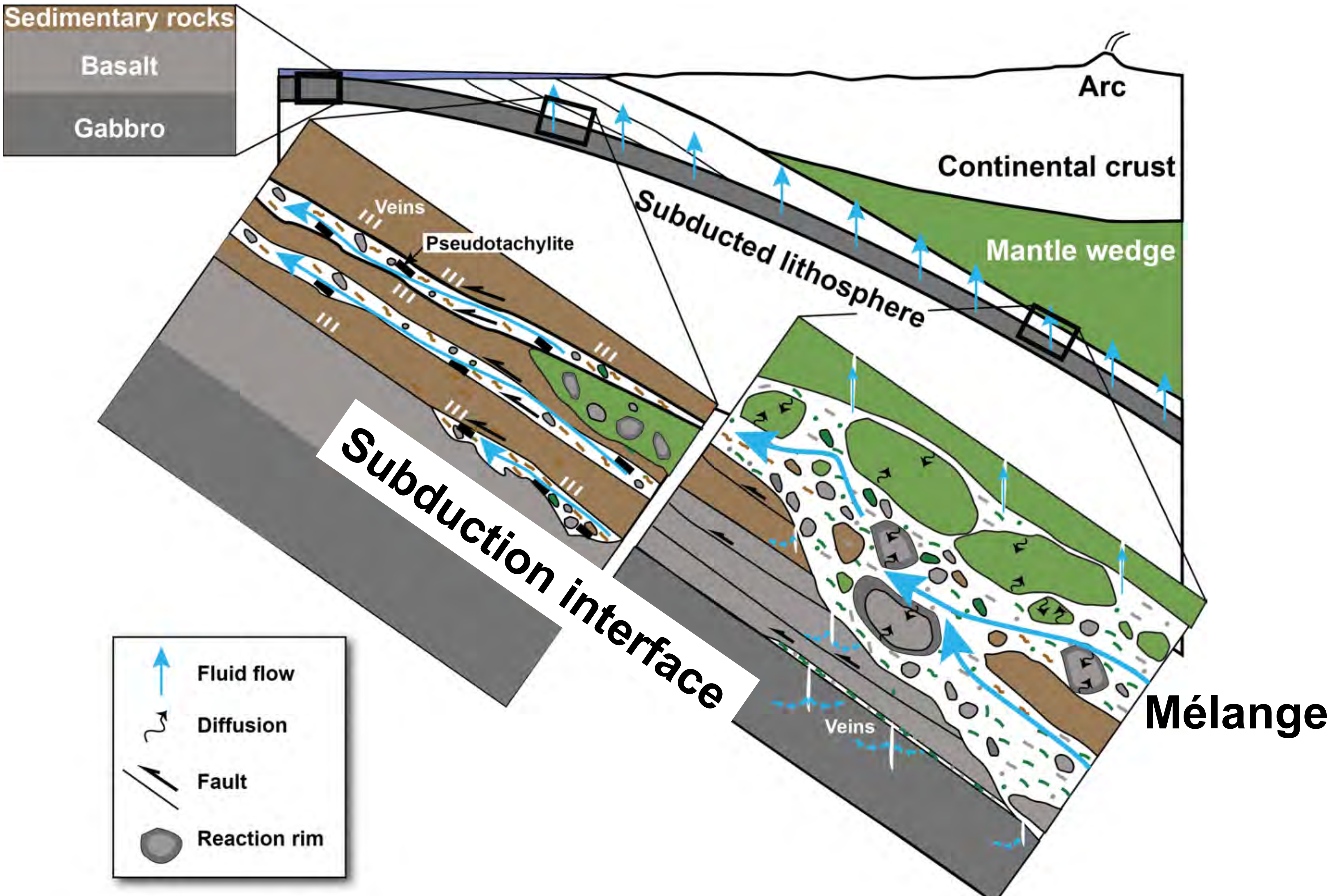
Reaction rinds have higher concentration of Cr and Ni relative to block core reflecting mixing.





Pseudotachylites are fine-grained to glassy rocks that are found in shear zones. They form commonly by frictional melting during rapid movement on faults. They have been found in exhumed subduction-related rocks and are interpreted as direct evidence for **paleo-earthquakes** in ancient subduction zones (e.g. Rowe et al., 2005; John et al., 2009).

Behavior of rocks within subduction zone



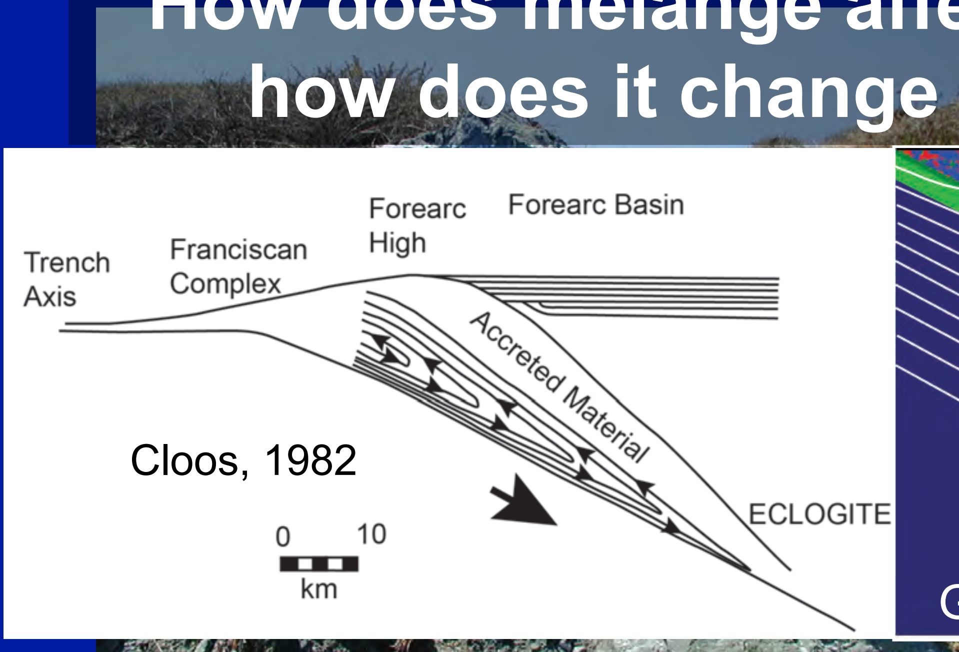
(Bebout and Penniston-Dorland, 2015)

Mélange rheology

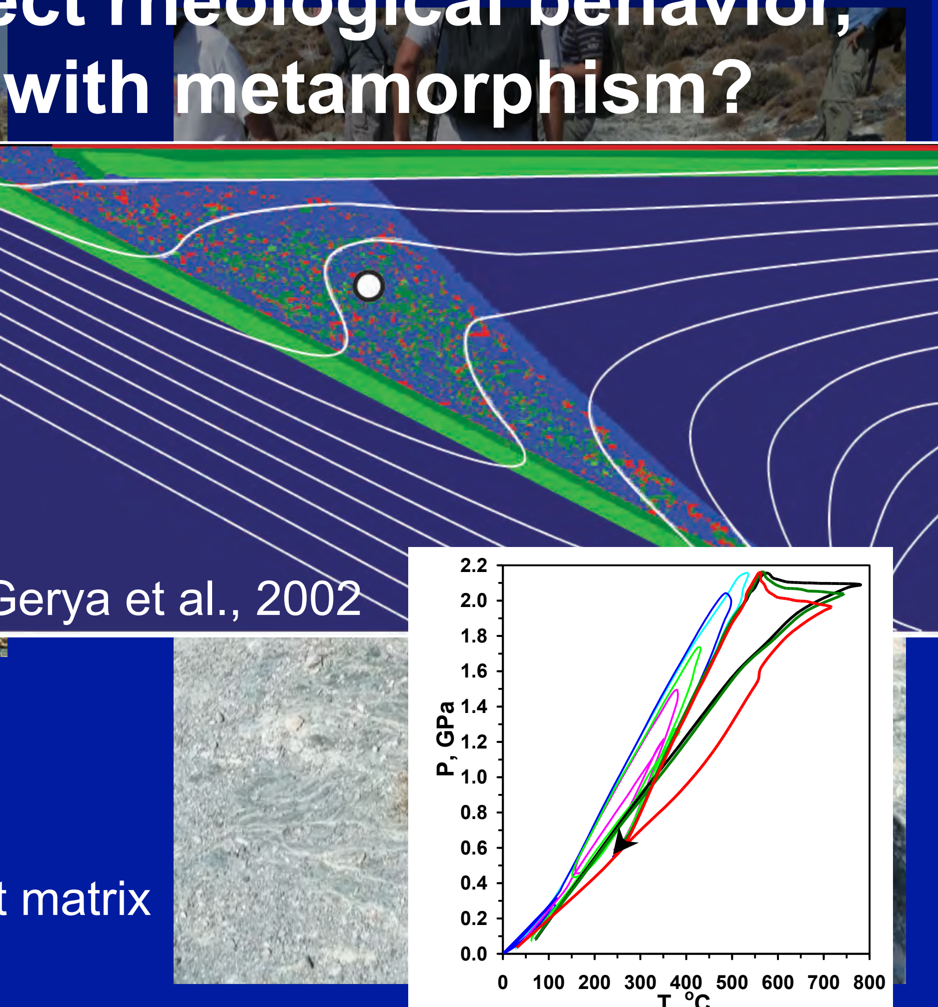
Mélange matrix is commonly made of relatively weak materials

e.g. clay, serpentine, chlorite, talc

How does mélange affect rheological behavior, how does it change with metamorphism?



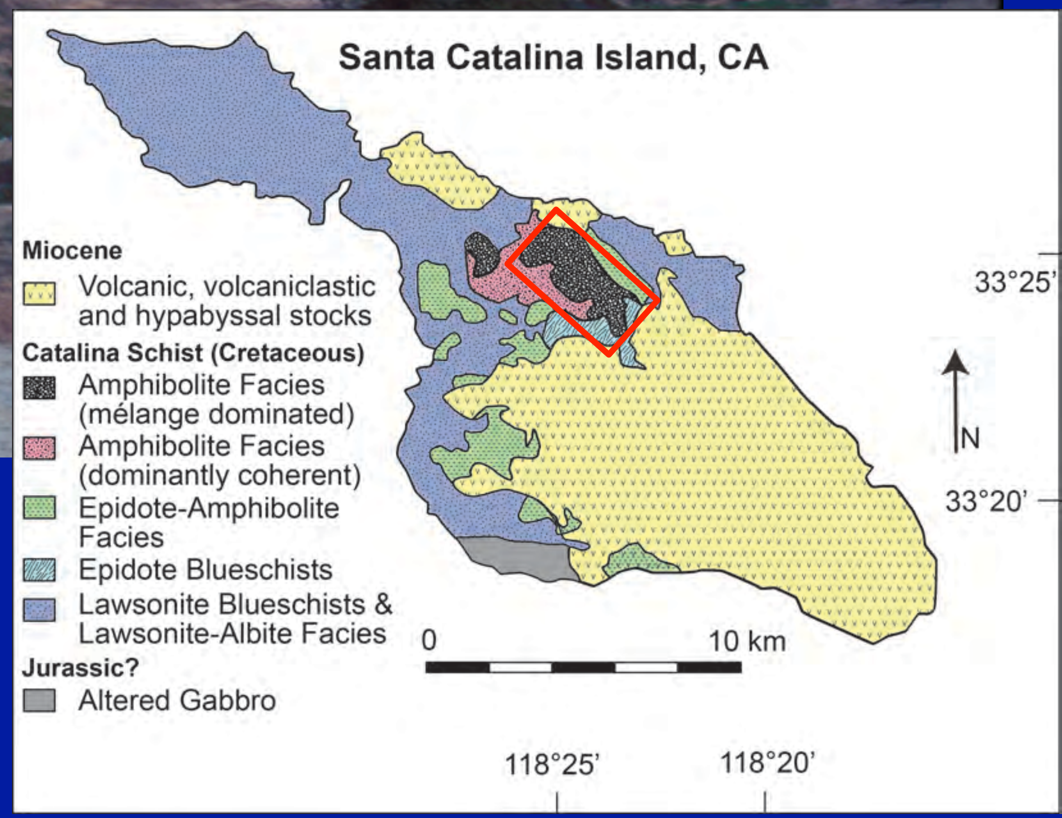
Blueschist block in shale matrix
Franciscan Complex, CA



Chlorite-talc schist matrix
Syros, Greece

How does mélange affect rheological behavior, how does it change with metamorphism?

Coexistence of blueschist, garnet amphibolite, and eclogite blocks at localities such as the Tiburon Peninsula, CA (Franciscan Complex) suggest widely varying *P-T* paths

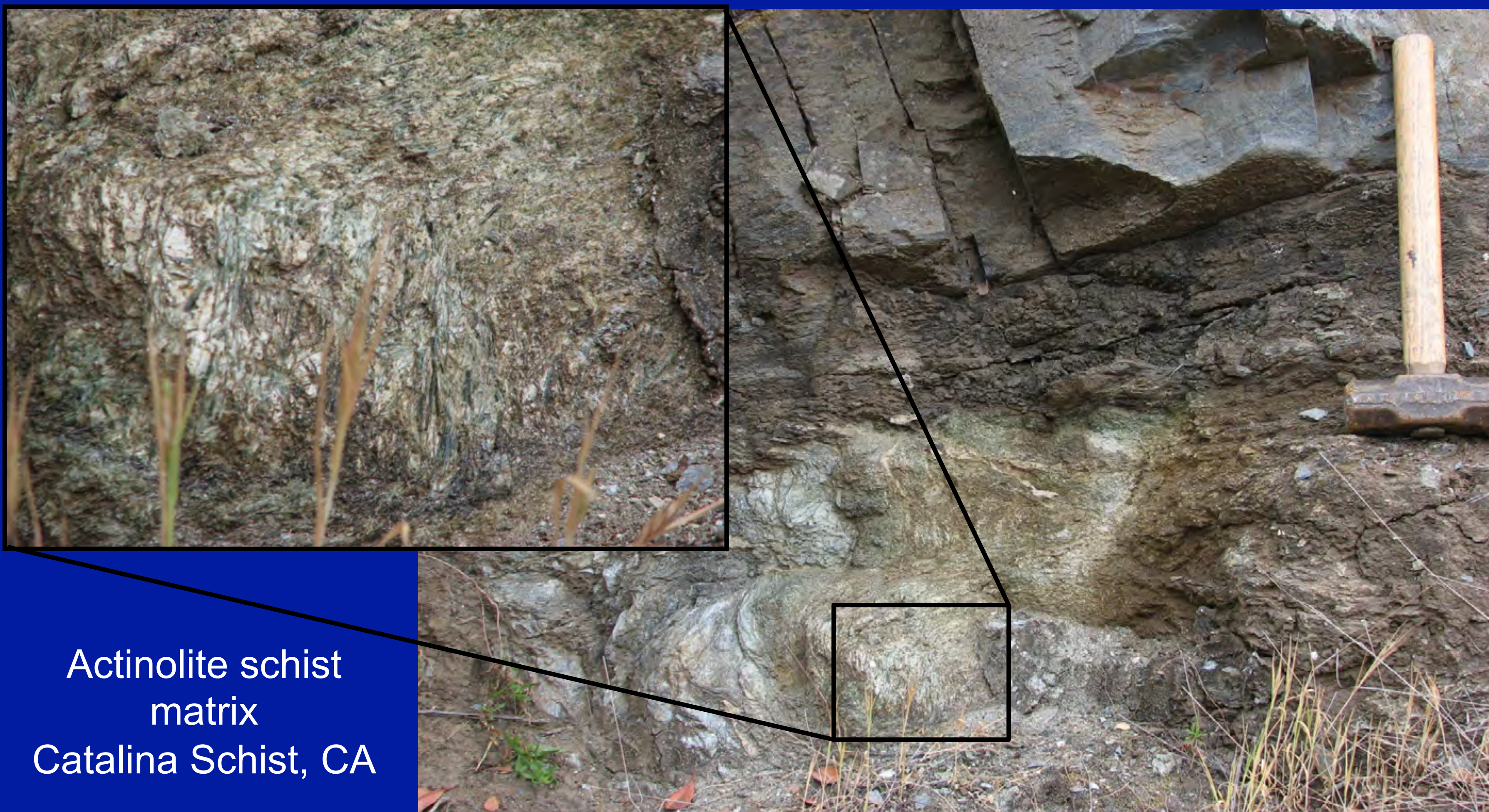


Blocks within each metamorphic facies of the Catalina Schist record similar *P-T* conditions over mappable-scale regions (for the most part)

Why? - Nature of mélange matrix

Metamorphism of chemically complex matrix can form rheologically stiffer minerals

Amphibole, pyroxene

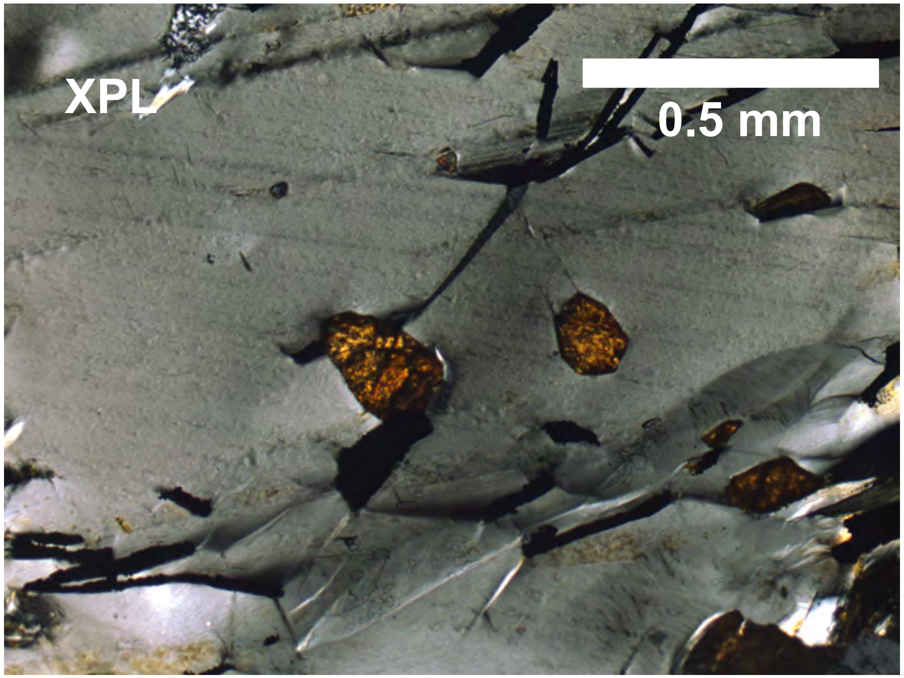


Actinolite schist matrix
Catalina Schist, CA

Zr-in-rutile thermometry

$$ZrO_2 \text{ (in rutile)} + SiO_2 \text{ (quartz)} \rightleftharpoons ZrSiO_4 \text{ (zircon)}$$

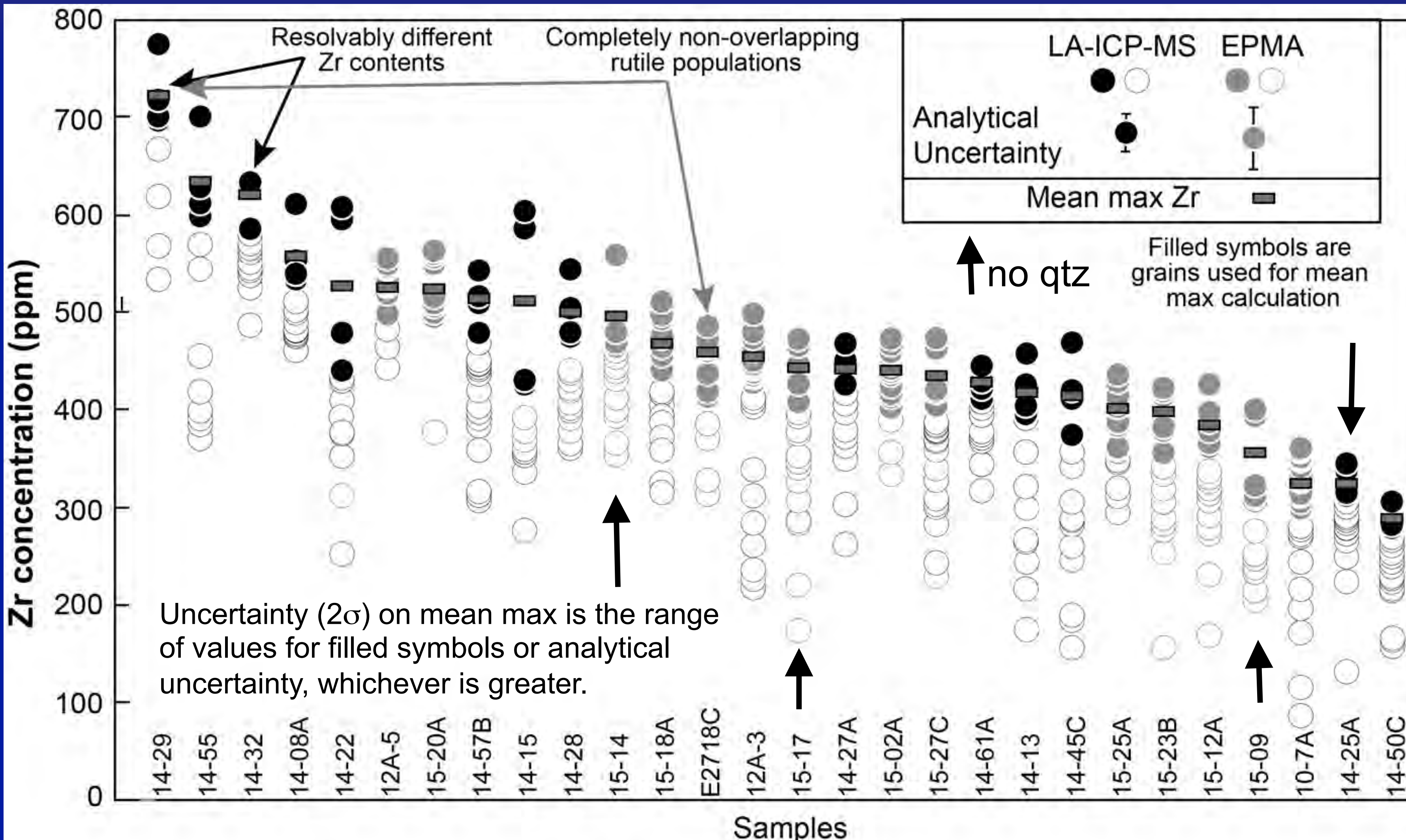
Tomkins et al. (2007)



Samples analyzed:
Garnet amphibolite
Garnet quartzite
Garnet mica schist
Mélange matrix

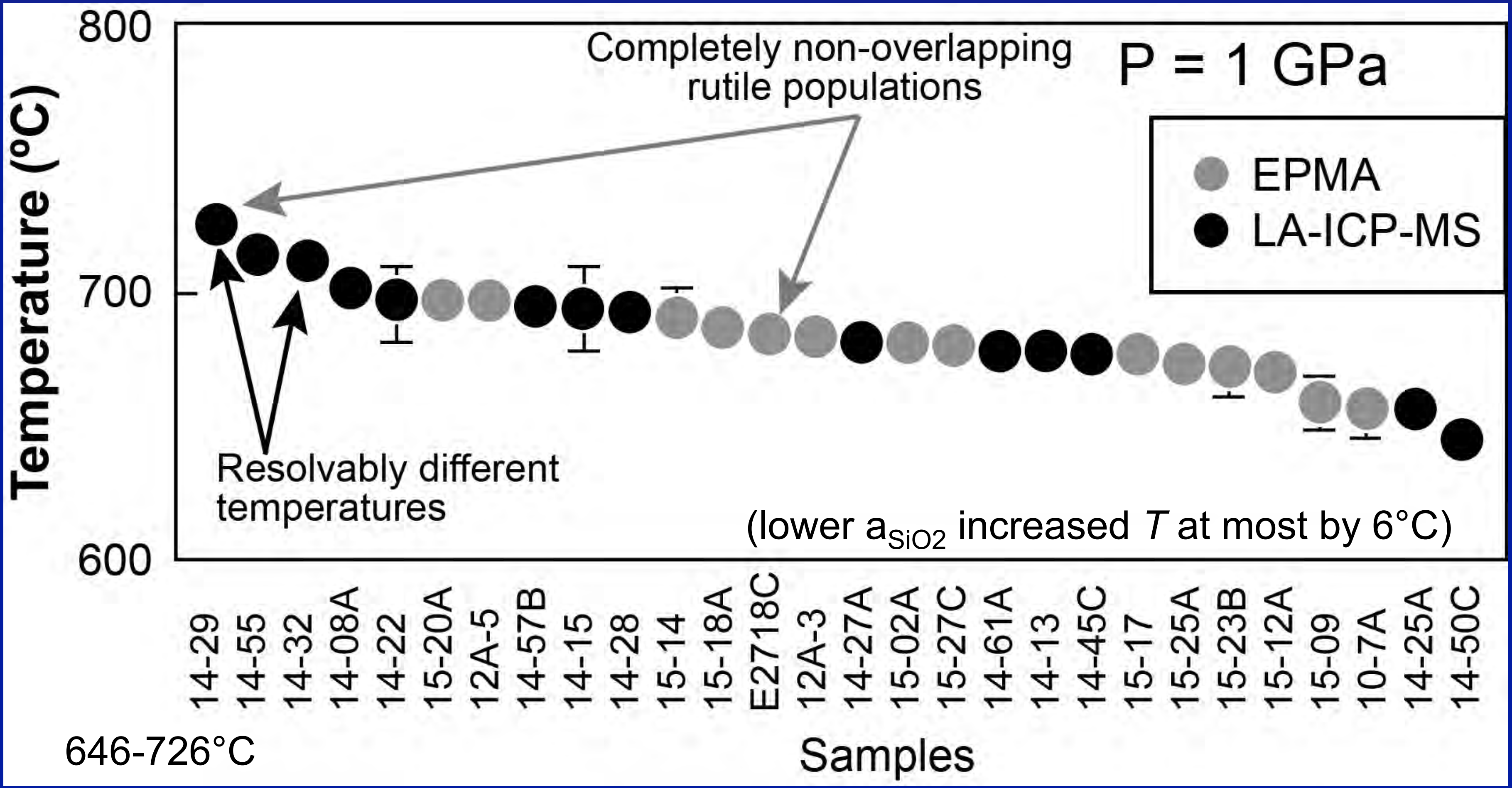
Methods used:
•Electron probe microanalyzer (EPMA)
•Laser ablation inductively coupled plasma mass spectrometer (LA-ICP-MS)

Zr contents of rutile



Penniston-Dorland et al. (in review)

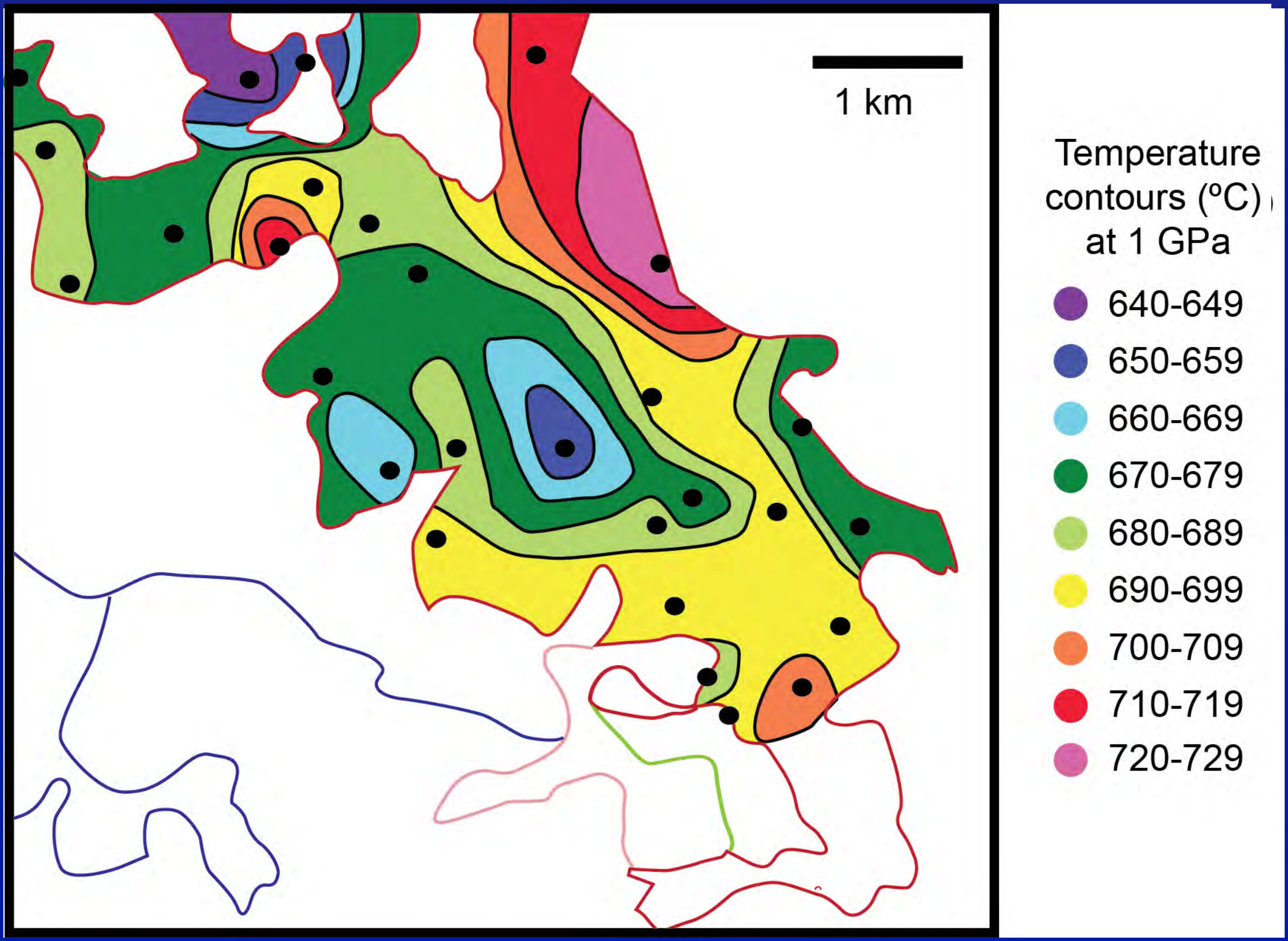
Zr-in-rutile temperatures



Samples within individual facies record distinctly different *T*s.

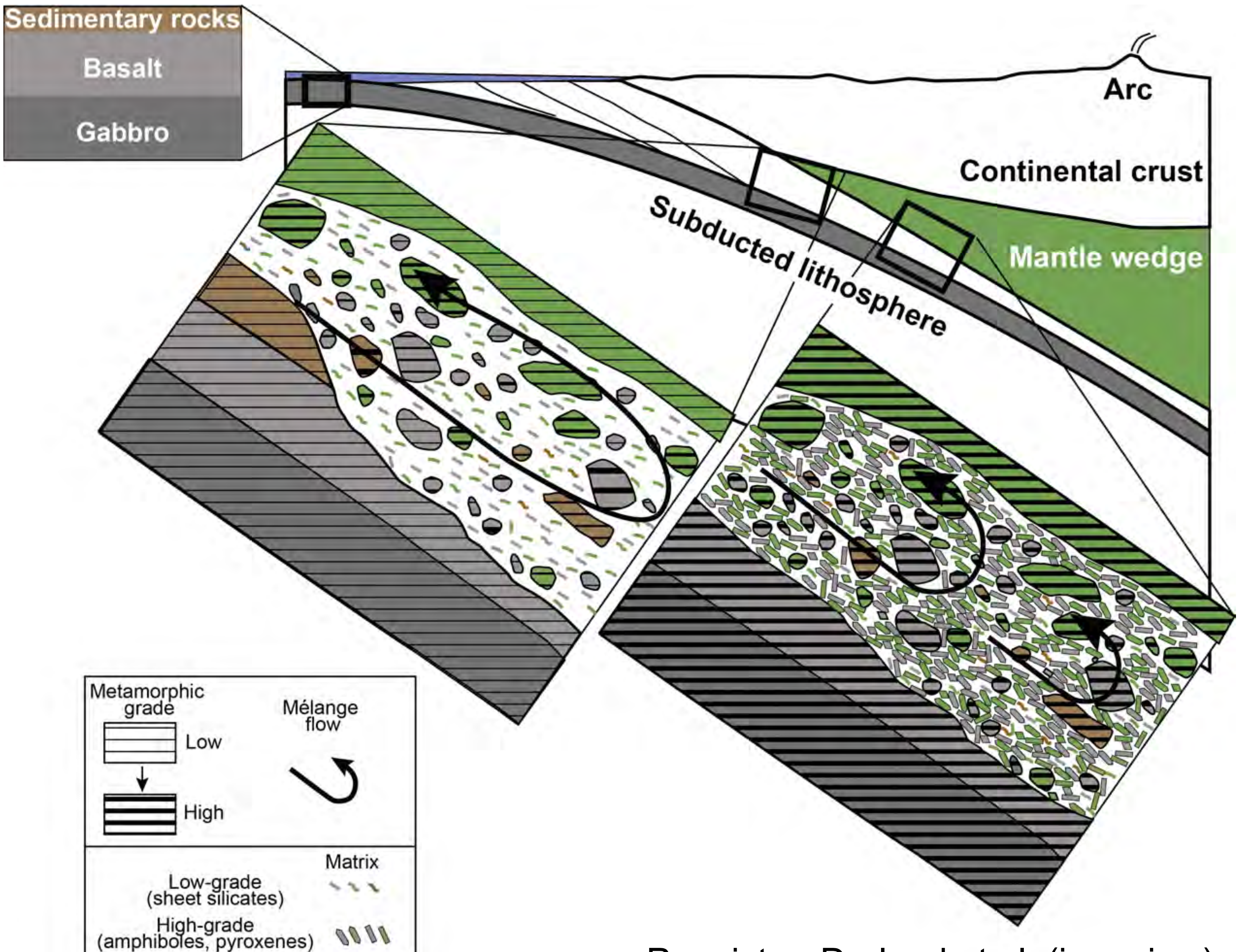
Penniston-Dorland et al. (in review)

Map of amphibolite facies *T* estimates

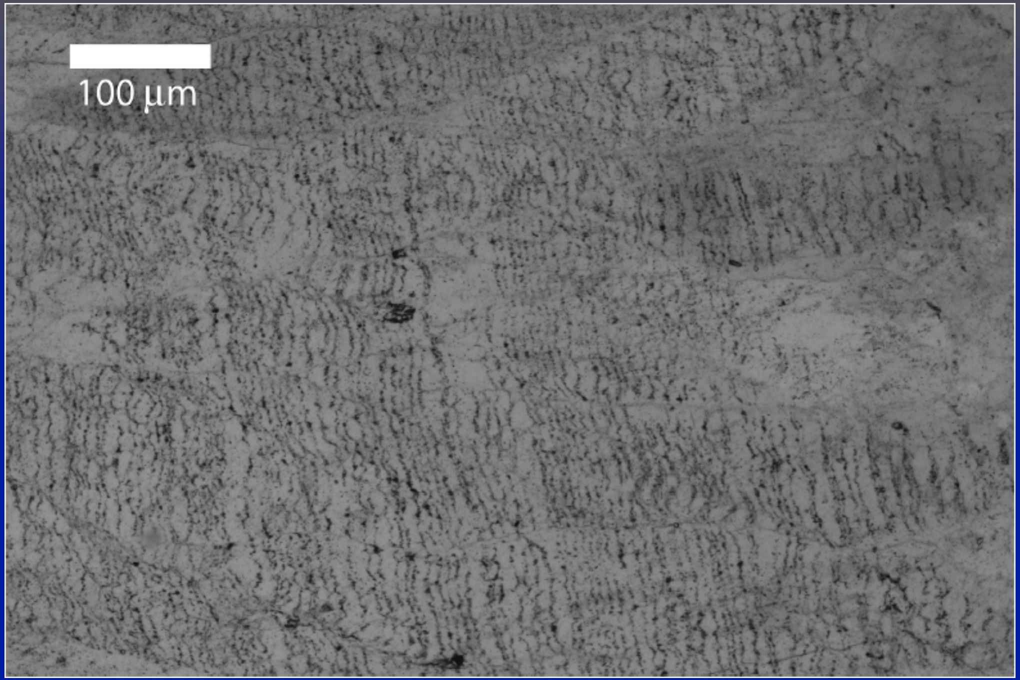


Penniston-Dorland et al. (in review)

Development of rheologically stiffer matrix minerals inhibits scale of flow



Penniston-Dorland et al. (in review)



Relating the rock record of deformation to processes in active subduction

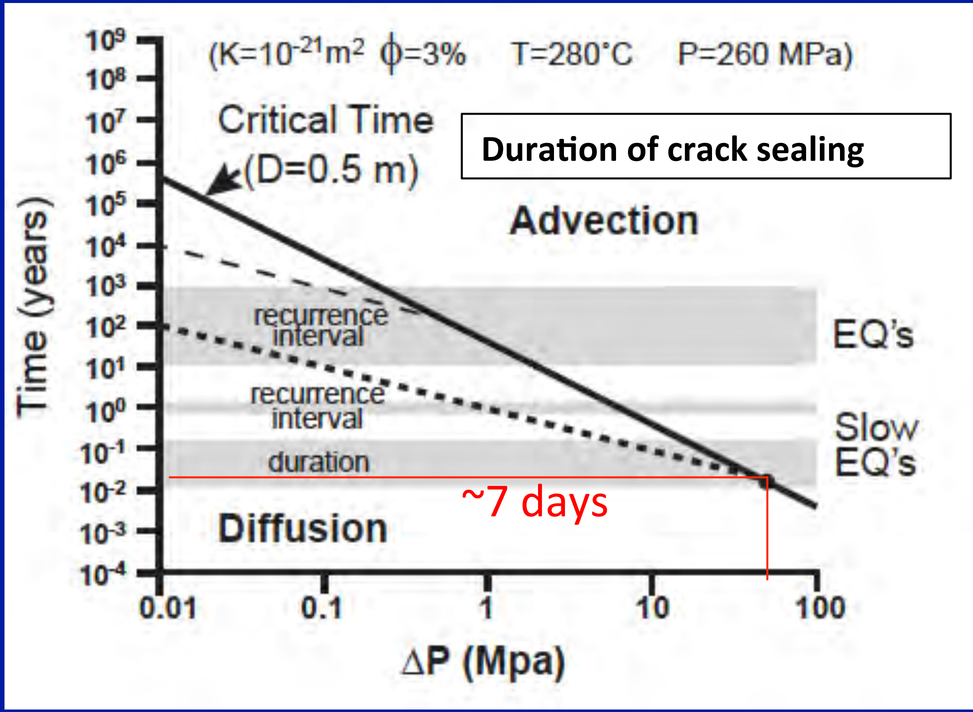
Inclusion bands in quartz in Kodiak, Alaska indicate repeated cycles of fracture opening and sealing.

Silica sourced locally through diffusion from wall rock.

(Fisher and Brantley, 2014)

Diffusive timescales required to source quartz are shorter than recurrence interval of earthquakes, similar to duration of slow earthquakes.

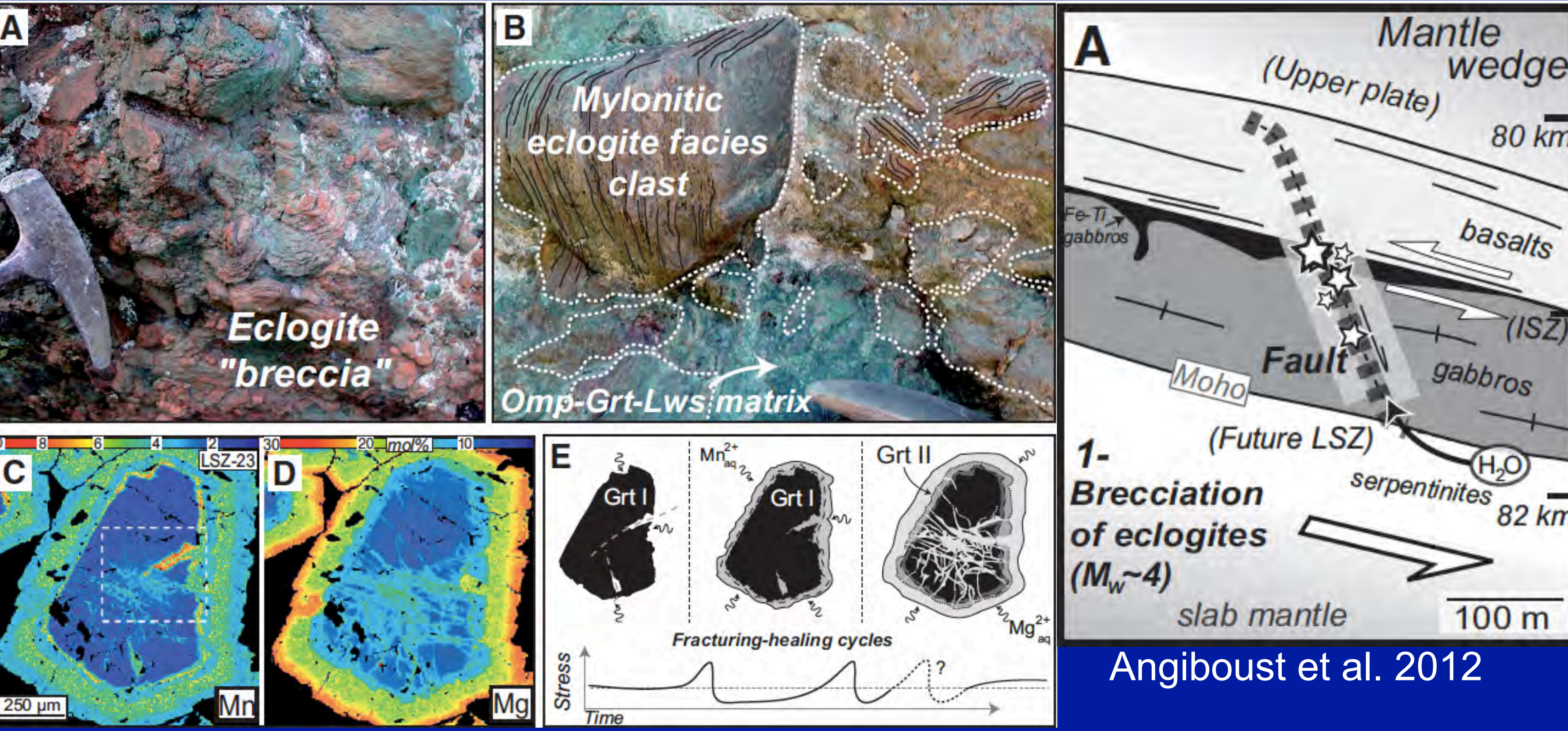
Silica redistribution could play a role in modulating the frequency of plate boundary slip instabilities along convergent plate boundaries



Relating the rock record of deformation to processes in active subduction

Evidence from HP rocks of Monviso (Italy) @ 2.2 to 2.6 GPa (~80 km depth) for brittle fracturing with high-pressure minerals precipitated in fractures.

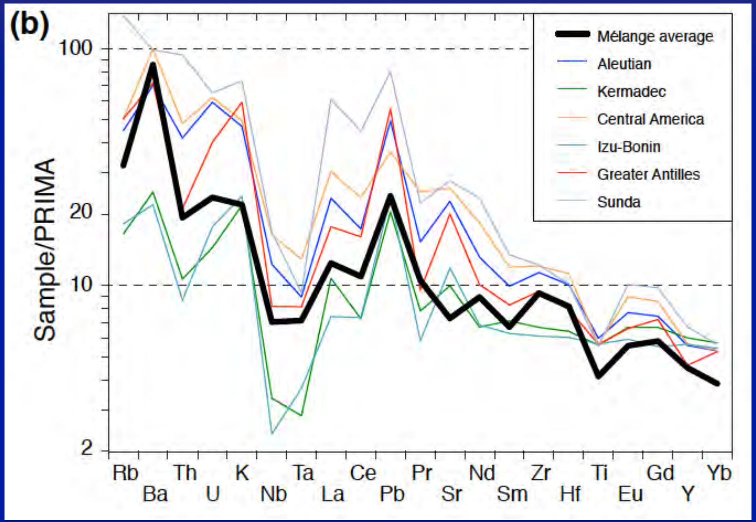
The interpretation of these features is that an intermediate-depth earthquake fractured a large part of the crust.

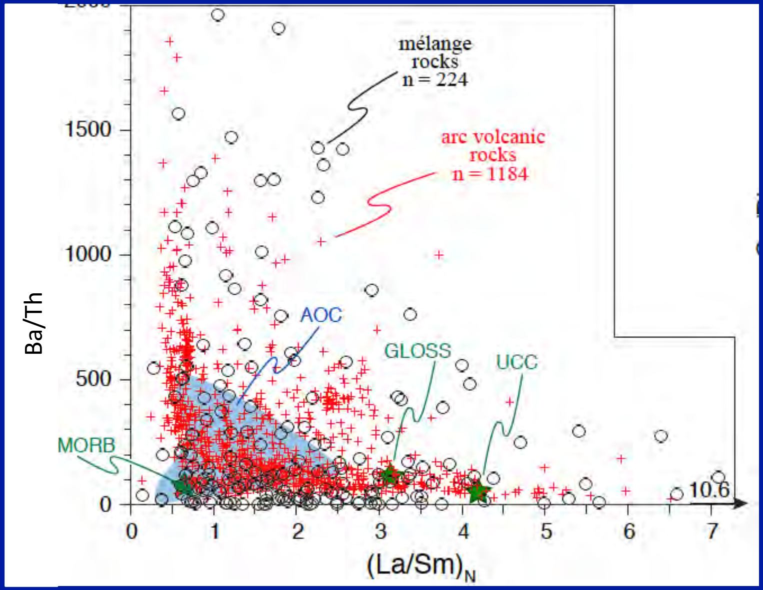


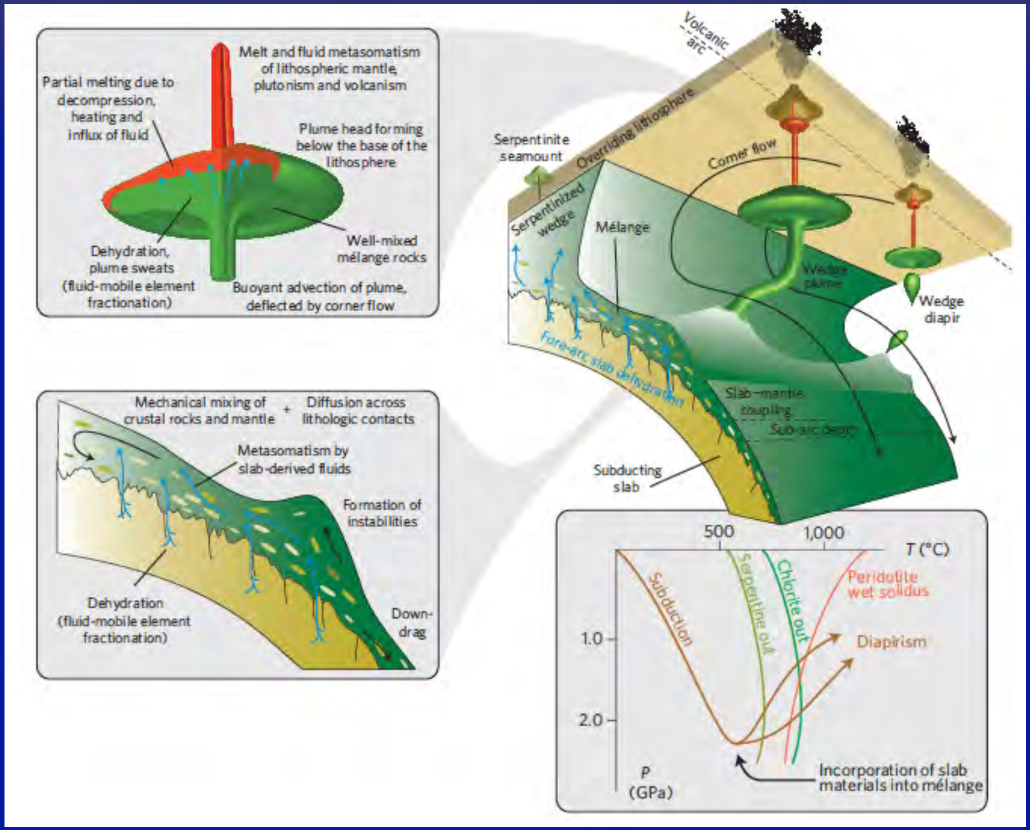
Angiboust et al. 2012

Geochemical cycling

Geochemical cycling



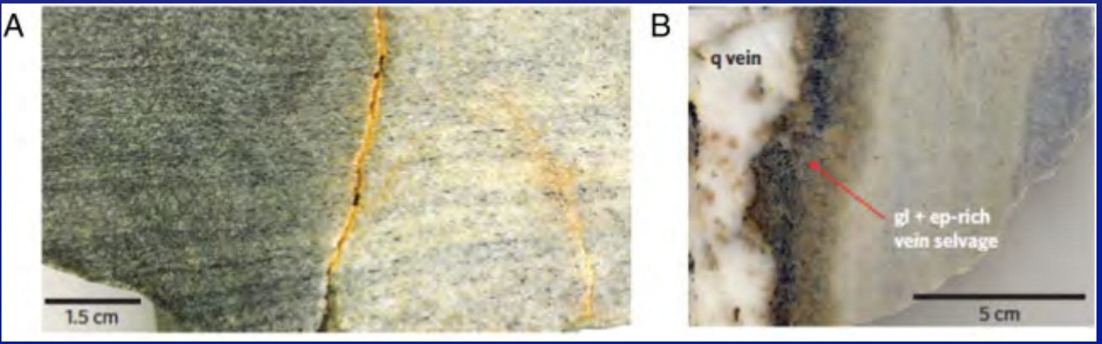


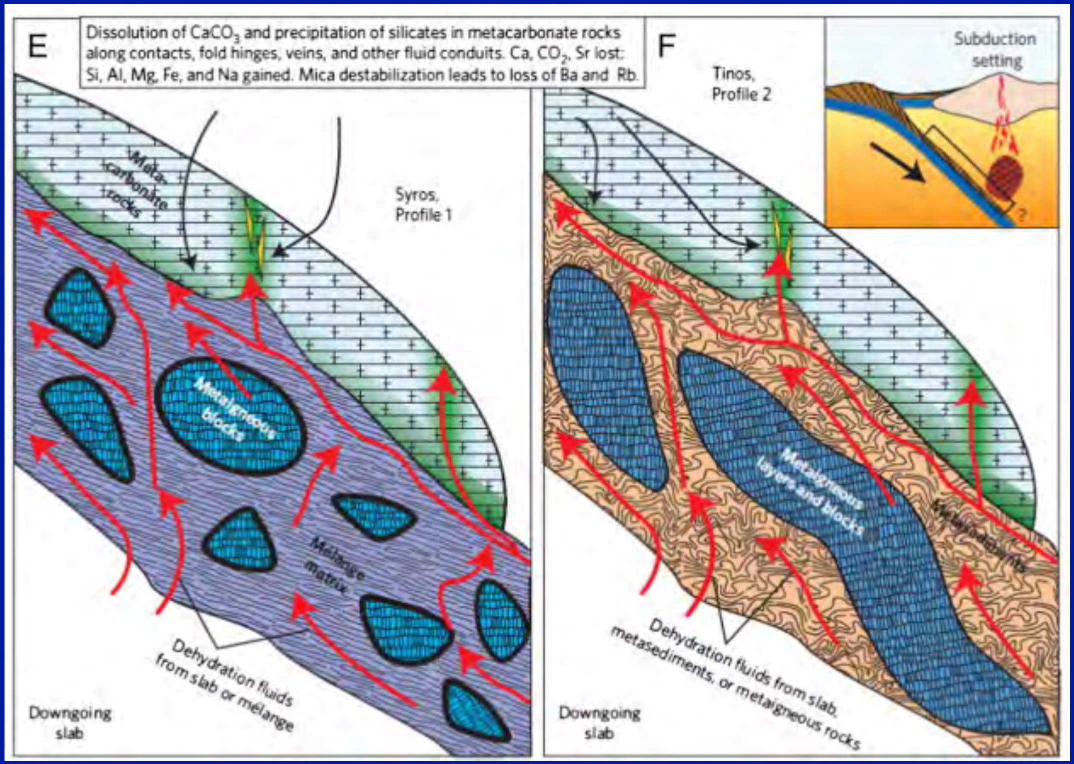


Investigation of the geochemistry of rocks from the subduction interface indicates processes of mixing and fluid infiltration produce trace element compositions similar to arc magmas

(Marschall and Schumacher, 2012)

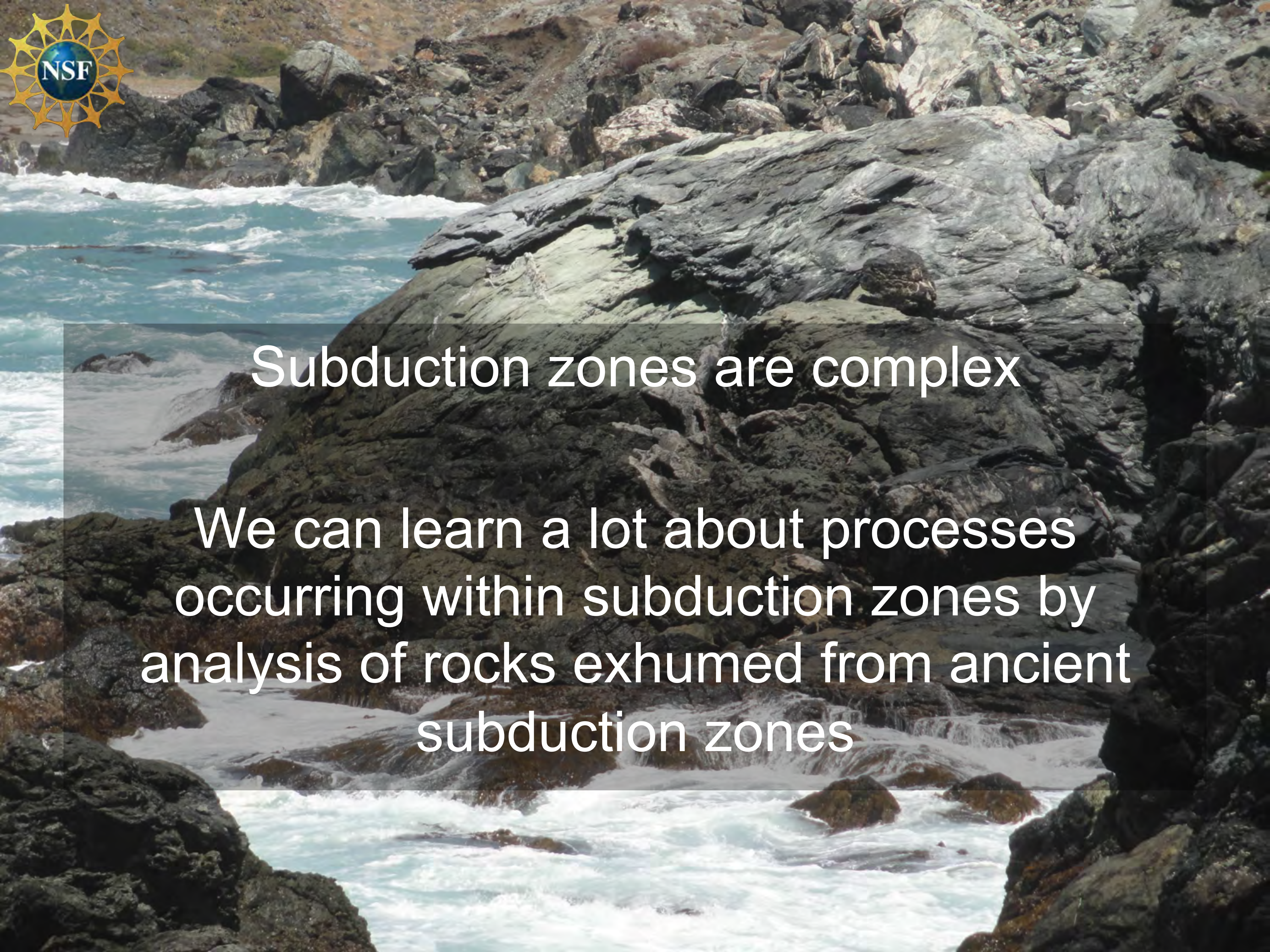
Geochemical cycling





Carbon cycling -
Dissolution of carbonate in high-pressure rocks of Syros, Greece facilitated by fluid flow within the subduction interface may contribute significantly to cycling of carbon within subduction zones

(Ague and Nicolescu, 2014)



Subduction zones are complex

We can learn a lot about processes occurring within subduction zones by analysis of rocks exhumed from ancient subduction zones