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.
The subduction interface is more complex than we usually draw.
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

- Subduction zone metamorphism
- Mid-ocean ridge metamorphism
- Contact metamorphism around plutons
- Regional metamorphism during collision
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

Garnet garnet
Aluminosilicate kyanite
Silica quartz
Plagioclase anorthite

\[
\text{Ca}_3\text{Al}_2\text{Si}_3\text{O}_{12} + 2\text{Al}_2\text{SiO}_5 + \text{SiO}_2 = 3\text{CaAl}_2\text{Si}_2\text{O}_8
\]

Mineral compositions are measured and used to determine equilibrium 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** $\text{NaAlSi}_3\text{O}_8-\text{CaAl}_2\text{Si}_2\text{O}_8$
- **Clinopyroxene** $\text{Ca(}\text{Mg,Fe})\text{Si}_2\text{O}_6$
- **Orthopyroxene** $(\text{Mg,Fe})_2\text{Si}_2\text{O}_6$
- **Olivine** $(\text{Mg,Fe})\text{SiO}_4$

Color coding:
- Si, Al, O
- Fe, Mg
- Ca
- Na
- H, C, K (elements added during seafloor alteration)
Metamorphic facies and tectonic environment

- Subduction zone metamorphism
- Mid-ocean ridge metamorphism
- Contact metamorphism around plutons
- Regional metamorphism during collision
- Not found on Earth
- 5 degrees C/km
- High P/T
- Intermediate P/T
- Low P/T
- Eclogite
- Blueschist
- Amphibolite
- Granulite
- Zeolite
- Hornfels
Zeolite facies minerals

- Zeolite group minerals
  - Analcime \( \text{NaAlSi}_2\text{O}_6\cdot\text{H}_2\text{O} \)
  - Laumontite \( \text{CaAl}_2\text{Si}_4\text{O}_{12}\cdot4\text{H}_2\text{O} \)
  - Heulandite \( \text{CaAl}_2\text{Si}_7\text{O}_{18}\cdot6\text{H}_2\text{O} \)
  - Stilbite \( \text{CaAl}_2\text{Si}_4\text{O}_{12}\cdot7\text{H}_2\text{O} \)
  - Wairakite \( \text{CaAl}_2\text{Si}_4\text{O}_{12}\cdot2\text{H}_2\text{O} \)

- Albite \( \text{NaAlSi}_3\text{O}_8 \)

- Clays - smectite (Fe-Mg bearing), kaolinite, illite (K-bearing)

- Quartz \( \text{SiO}_2 \)

- Calcite \( \text{CaCO}_3 \)

Added to rocks through alteration on the seafloor:

- \( \text{H}_2\text{O} \)
- \( \text{CO}_2 \)
- \( \text{K}_2\text{O} \)

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

- Subduction zone metamorphism
- Mid-ocean ridge metamorphism
- Contact metamorphism around plutons
- Regional metamorphism during collision
- Typical metamorphic assemblages:
  - Prehnite-Pumpellyite
  - Zeolite
  - Hornfels
  - Eclogite
  - Blueschist
  - Amphibolite
  - Granulite

Temperature (°C) vs. Pressure (GPa) diagram with various mineral assemblages and metamorphic zones.
<table>
<thead>
<tr>
<th>Mineral</th>
<th>Chemical Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prehnite</td>
<td>$\text{Ca}_2\text{Al}_2\text{Si}<em>3\text{O}</em>{10}(\text{OH})_2$</td>
</tr>
<tr>
<td>Pumpellyite</td>
<td>$\text{Ca}_2(\text{Mg,Fe})\text{Al}_2\text{Si}<em>3\text{O}</em>{11}(\text{OH})_2\cdot\text{H}_2\text{O}$</td>
</tr>
<tr>
<td>Albite</td>
<td>$\text{NaAlSi}_3\text{O}_8$</td>
</tr>
<tr>
<td>Chlorite</td>
<td>$(\text{Fe,Mg})<em>{4.5}\text{Al}<em>3\text{Si}</em>{2.5}\text{O}</em>{10}(\text{OH})_8$</td>
</tr>
<tr>
<td>Clays</td>
<td>smectite, kaolinite, illite</td>
</tr>
<tr>
<td>Quartz</td>
<td>$\text{SiO}_2$</td>
</tr>
<tr>
<td>Aragonite</td>
<td>$\text{CaCO}_3$</td>
</tr>
</tbody>
</table>
Carbonates at high P/T:

Calcite $\rightleftharpoons$ Aragonite

$\text{CaCO}_3 \rightleftharpoons \text{CaCO}_3$

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!
Metamorphic facies and tectonic environment

- Subduction zone metamorphism
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- Regional metamorphism during collision

Pressure (GPa) vs. Temperature (°C) diagram showing:
- Zeolite
- Prehnite-Pumpellyite
- Greenschist
- Amphibolite
- Eclogite
- Granulite
- Hornfels
- Not found on Earth

Legend:
- 5 degrees C/km
- High P/T
- Intermediate P/T
- Low P/T
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

Lawsonite

Glaucophane

Garnet

Calcite

Phengite

Epidote
Blueschist facies minerals

- **Glaucophane**: $\text{Na}_2\text{Mg}_3\text{Al}_2\text{Si}_8\text{O}_{22}(\text{OH})_2$
- **Lawsonite**: $\text{CaAl}_2(\text{Si}_2\text{O}_7)(\text{OH})_2 \cdot \text{H}_2\text{O}$
- **Jadeite/Omphacite**: $\text{NaAlSi}_2\text{O}_6$
- **Phengite**: $\text{K(Al,Mg)}_3(\text{Al, Si})_3\text{O}_{10}(\text{OH})_2$
- **Pumpellyite**: $\text{Ca}_2(\text{Mg,Fe})\text{Al}_2\text{Si}_3\text{O}_{11}(\text{OH})_2 \cdot \text{H}_2\text{O}$
- **Epidote**: $\text{Ca}_2\text{Al}_2\text{FeSi}_3\text{O}_{12}(\text{OH})$
- **Garnet**: $(\text{Ca,Mg,Fe})_3\text{Al}_2\text{Si}_3\text{O}_{12}$
- **Chlorite**: $(\text{Fe,Mg})_{4.5}\text{Al}_3\text{Si}_{2.5}\text{O}_{10}(\text{OH})_8$
- **Quartz**: $\text{SiO}_2$
- **Aragonite**: $\text{CaCO}_3$

(source: wikimedia)
Phase diagram showing High P/T mineral stabilities

Lawsonite
\[ \text{CaAl}_2(\text{Si}_2\text{O}_7)(\text{OH})_2 \cdot \text{H}_2\text{O} \]
Phase diagram showing High P/T mineral stabilities

Lawsonite
\[ \text{CaAl}_2(\text{Si}_2\text{O}_7)(\text{OH})_2 \cdot \text{H}_2\text{O} \]

Glaucophane
\[ \text{Na}_2\text{Mg}_3\text{Al}_2\text{Si}_8\text{O}_{22}(\text{OH})_2 \]
Phase diagram showing High P/T mineral stabilities

Lawsonite: $\text{CaAl}_2\text{(Si}_2\text{O}_7\text{)(OH)}_2\text{•H}_2\text{O}$

Glaucophane: $\text{Na}_2\text{Mg}_3\text{Al}_2\text{Si}_8\text{O}_{22}\text{(OH)}_2$

Jadeite/Omphacite: $\text{NaAlSi}_2\text{O}_6$

Liou, 1987
These minerals tell us that subduction zones are cooler than other settings!
Facies can be subdivided – for example lawsonite blueschist facies (LBS) and epidote blueschist facies (EBS)

Grove and Bebout, 1995
Metamorphic facies and tectonic environment

- Subduction zone metamorphism
- Mid-ocean ridge metamorphism
- Contact metamorphism around plutons
- Regional metamorphism during collision
- Not found on Earth

Diagram shows a pressure-temperature (P-T) phase diagram with various metamorphic facies and tectonic environments.

- Zeolite
- Prehnite-Pumpellyite
- Greenschist
- Hornfels
- Blueschist
- Eclogite
- Granulite

Arrows indicate temperature and pressure conditions for each facies transition.
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

- Subduction zone metamorphism
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- Regional metamorphism during collision

The graph shows the relationship between pressure (GPa) and temperature (°C) for different metamorphic facies. Key metamorphic zones include:

- Blueschist
- Amphibolite
- Greenschist
- Eclogite
- Hornfels
- Granulite

Legend:
- Zeolite
- Prehnite-Pumpellyite
- 5 degrees C/km
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Eclogite
Eclogite

The mineral assemblage that defines an eclogite is garnet and omphacite pyroxene.
Eclogite facies minerals

- Garnet \((\text{Ca, Mg, Fe})_3\text{Al}_2\text{Si}_3\text{O}_{12}\)
- Omphacite \((\text{Na, Ca})(\text{Mg, Fe, Al})\text{Si}_2\text{O}_6\)
- Phengite \(\text{K}(\text{Al, Mg})_3(\text{Al, Si})_3\text{O}_{10}(\text{OH})_2\)
- Glaucophane \(\text{Na}_2\text{Mg}_3\text{Al}_2\text{Si}_8\text{O}_{22}(\text{OH})_2\)
- Lawsonite \(\text{CaAl}_2(\text{Si}_2\text{O}_7)(\text{OH})_2\cdot\text{H}_2\text{O}\)
- Epidote/Zoisite \(\text{Ca}_2\text{Al}_2\text{FeSi}_3\text{O}_{12}(\text{OH})\)
- Quartz \(\text{SiO}_2\)
- Kyanite \(\text{Al}_2\text{SiO}_5\)
- Aragonite \(\text{CaCO}_3\)
Eclogite facies mineral stability

Experimental results for MORB bulk composition

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

Omphacite: \((\text{Na, Ca})(\text{Mg, Fe, Al})\text{Si}_2\text{O}_6\)

Almandine garnet: \(\text{Fe}_3\text{Al}_2\text{Si}_3\text{O}_{12}\)

(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: \((\text{Na,Ca})(\text{Mg,Fe,Al})\text{Si}_2\text{O}_6\)

Almandine garnet: \(\text{Fe}_3\text{Al}_2\text{Si}_3\text{O}_{12}\)

(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 \(< 750 \text{ Ma}\)
- 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
Water is released during prograde metamorphism

**ALTERED MORB**

- Heulandite
- Stilbite
- Kaolinite
- Illite

**BLUESCHIST**

- Glaucophane:
  - $\text{Na}_2\text{Mg}_3\text{Al}_2\text{Si}_8\text{O}_{22}(\text{OH})_2$
- Lawsonite:
  - $\text{CaAl}_2(\text{Si}_7\text{O}_{22})(\text{OH})_2\cdot\text{H}_2\text{O}$

**ECLOGITE**

- Omphacite
- Almandine: garnet
  - $(\text{Na,Ca})(\text{Mg,Fe,Al})\text{Si}_2\text{O}_6$
  - $\text{Fe}_3\text{Al}_2\text{Si}_3\text{O}_{12}$
Evidence for fluid flow: Veins
Evidence for fluid flow: Reaction zones and rinds

Block core

Block rind

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)

Typically 1-2.5 wt.% LOI

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)
- rutile

Typically 1-2.5 wt.% LOI
Pieces of mafic blocks breaking off

Early garnet growth in block cores. Foliation develops in rinds.

Fluid infiltration and accompanying diffusion alters garnets in rinds in more static environment

Continued garnet growth in block cores, garnet growth in rinds

Penniston-Dorland et al., 2014
Isotopic evidence for fluid flow

Bebout and Barton 1989
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 \( \text{H}_2\text{O} \)

0.3 to 0.4 wt.% \( \text{H}_2\text{O} \) loss during garnet growth over <1 Ma
Study of fluid-related features tells us about the duration of fluid infiltration events (~100 years) during subduction.

Evidence for timescales of fluid flow

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 (~200 years) during subduction.

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

Rock from Chinese Tianshan
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)
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 mélangé

Bebout and Barton 2002

Amphibolite facies mélangé 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

Mélange

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

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

\[
\text{ZrO}_2 \text{ (in rutile)} + \text{SiO}_2 \text{ (quartz)} \rightleftharpoons \text{ZrSiO}_4 \text{ (zircon)}
\]

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

Uncertainty (2σ) on mean max is the range of values for filled symbols or analytical uncertainty, whichever is greater.

Penniston-Dorland et al. (in review)
Samples within individual facies record distinctly different $T_s$. Penniston-Dorland et al. (in review)
Map of amphibolite facies $T$ estimates

Temperature contours (°C) at 1 GPa
- 640-649
- 650-659
- 660-669
- 670-679
- 680-689
- 690-699
- 700-709
- 710-719
- 720-729

Penniston-Dorland et al. (in review)
Development of rheologically stiffer matrix minerals inhibits scale of flow

Sedimentary rocks
- Basalt
- Gabbro

Subducted lithosphere
- Continental crust
- Mantle wedge

Metamorphic grade
- Low
- High

Low-grade (sheet silicates)
- High-grade (amphiboles, pyroxenes)

Mélange 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.

Duration of crack sealing ~7 days
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
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.