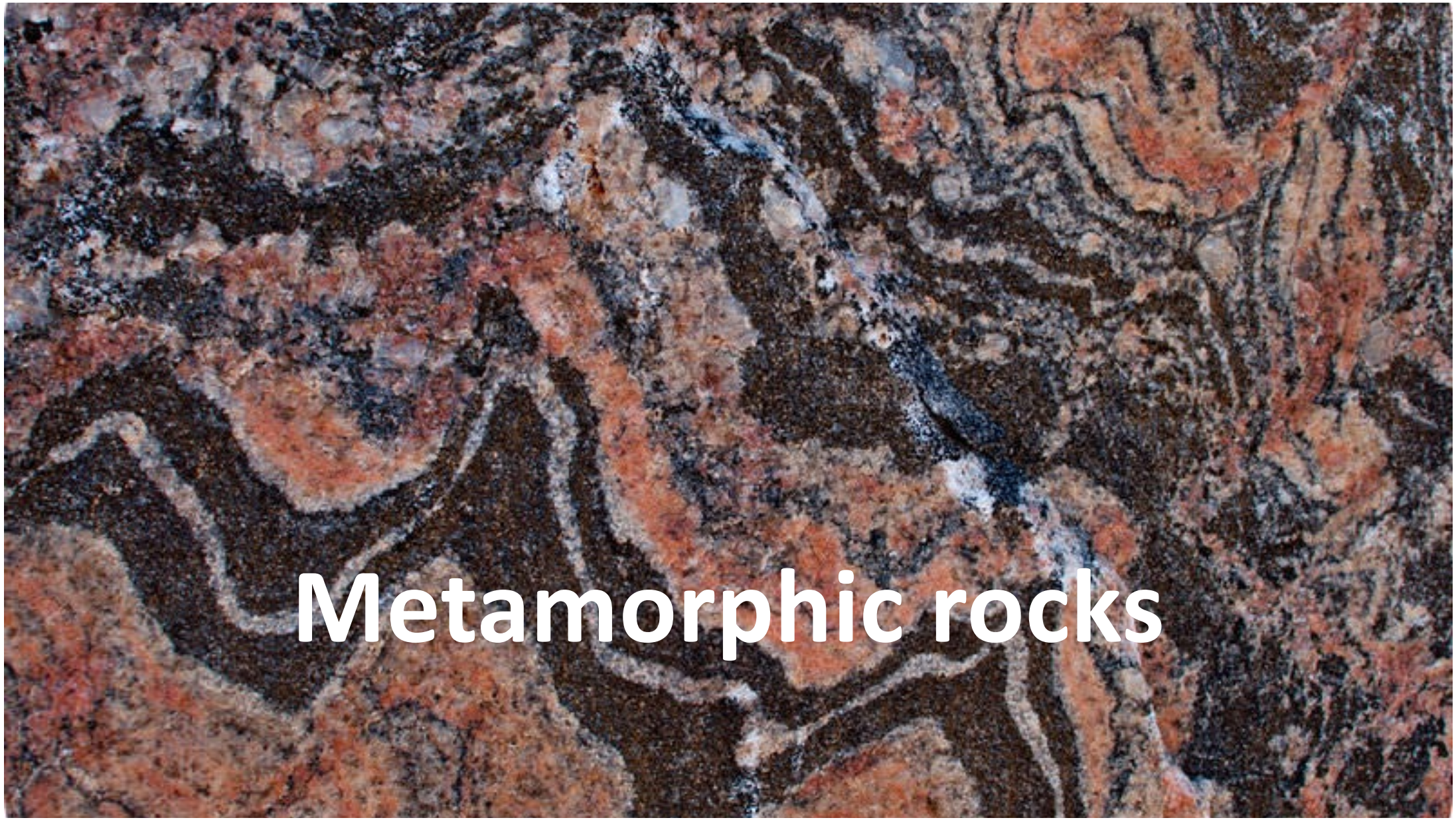
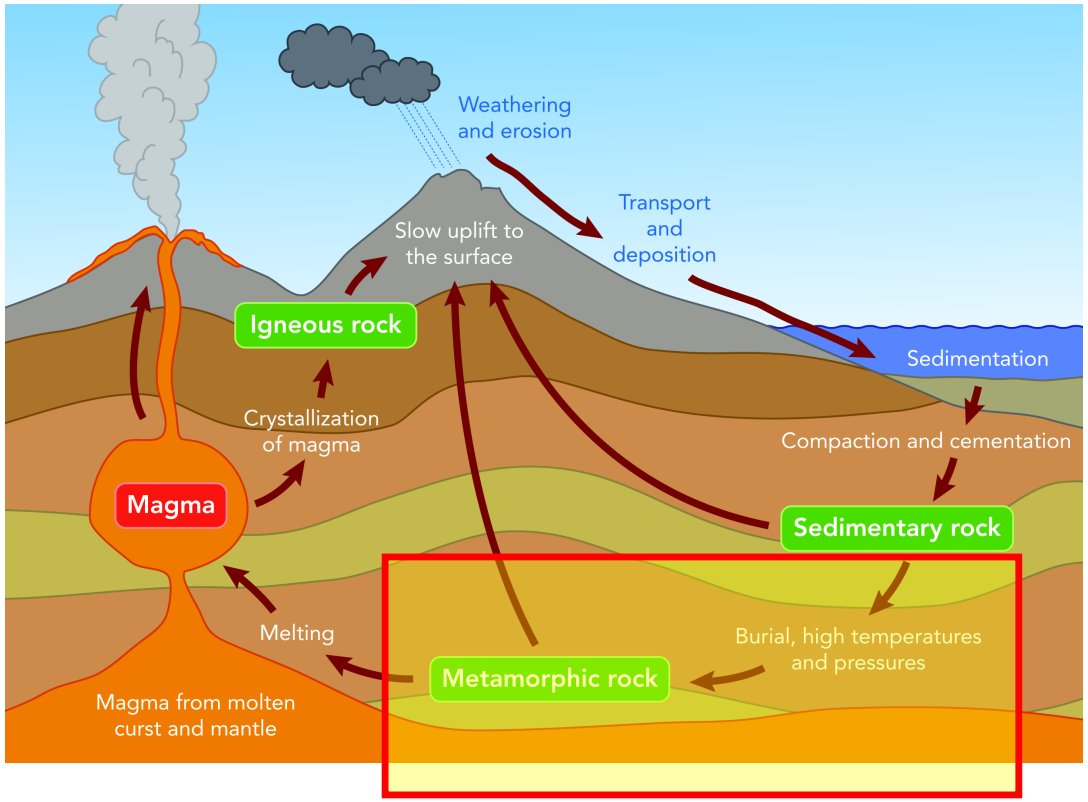

Metamorphic rocks

Metamorphic rocks

Metamorphic rocks form when existing rocks (**protolith**) are undergoing an **increase in temperature and/or pressure.**

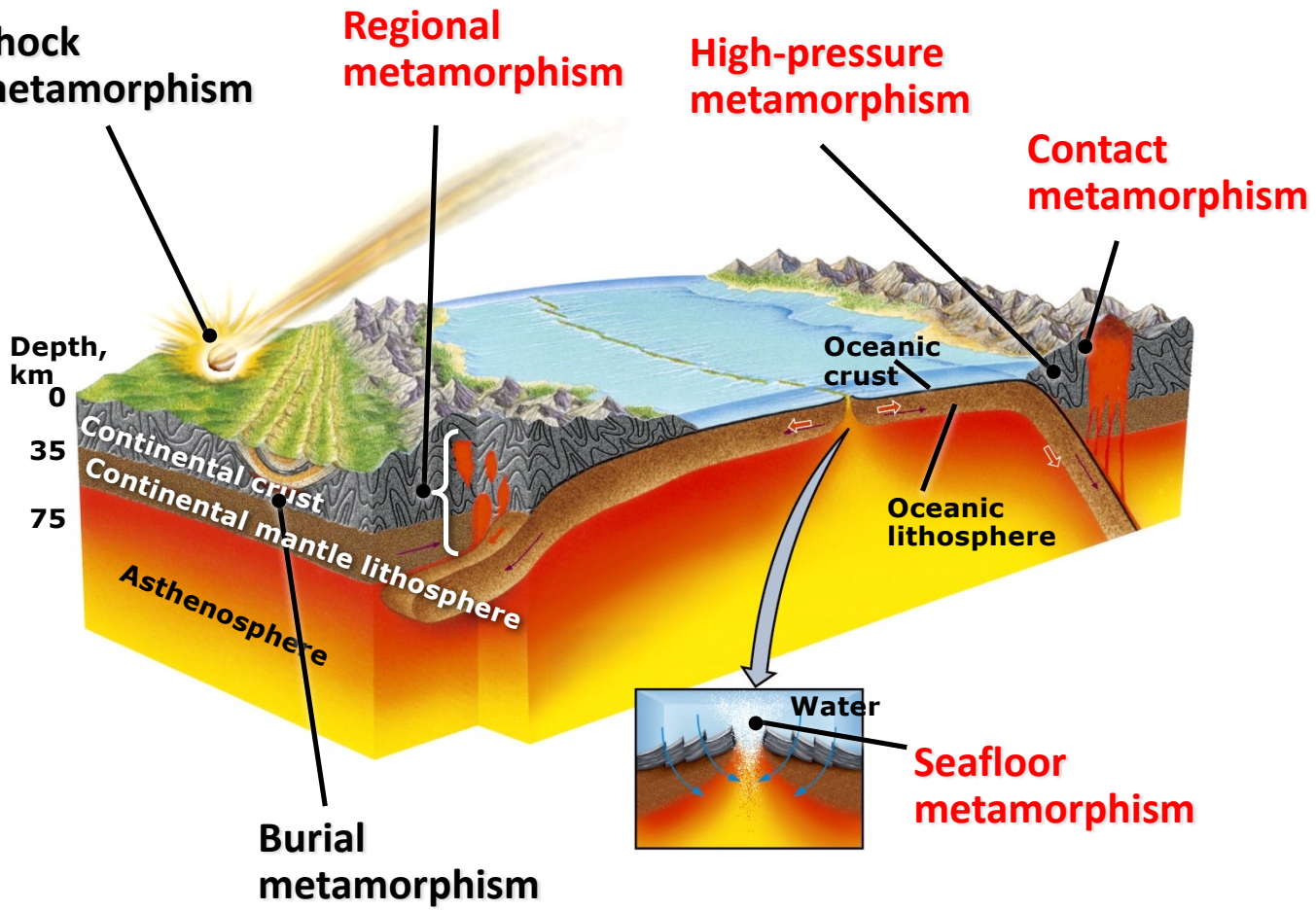
This leads to **recrystallization and new minerals** and in some cases **deformation,** which all happens under solid conditions (no melting).

Metamorphic rocks are classified depending on the **protolith** and the **P-T conditions.**



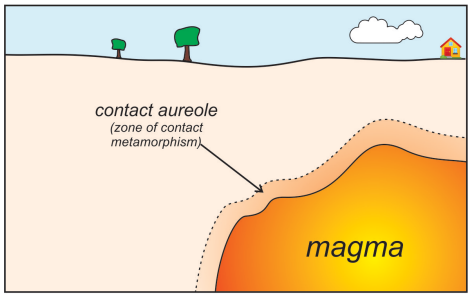
Metamorphic rocks: Geological settings

Geological settings where rocks undergo metamorphism

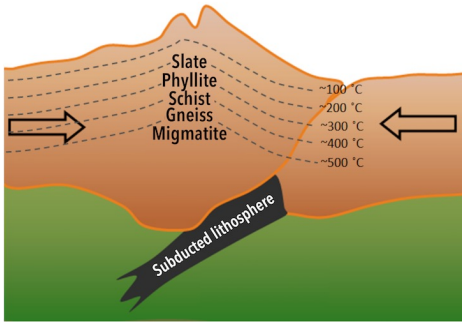


Metamorphic rocks: Geological settings

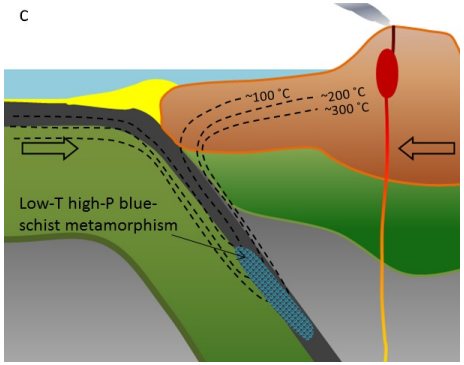
Contact metamorphism: Occurs around magmatic intrusions (high T, low P, relatively local).



Regional metamorphism: Orogens, mountain building, continent collisions (co-temporal increase in P-T, regional).

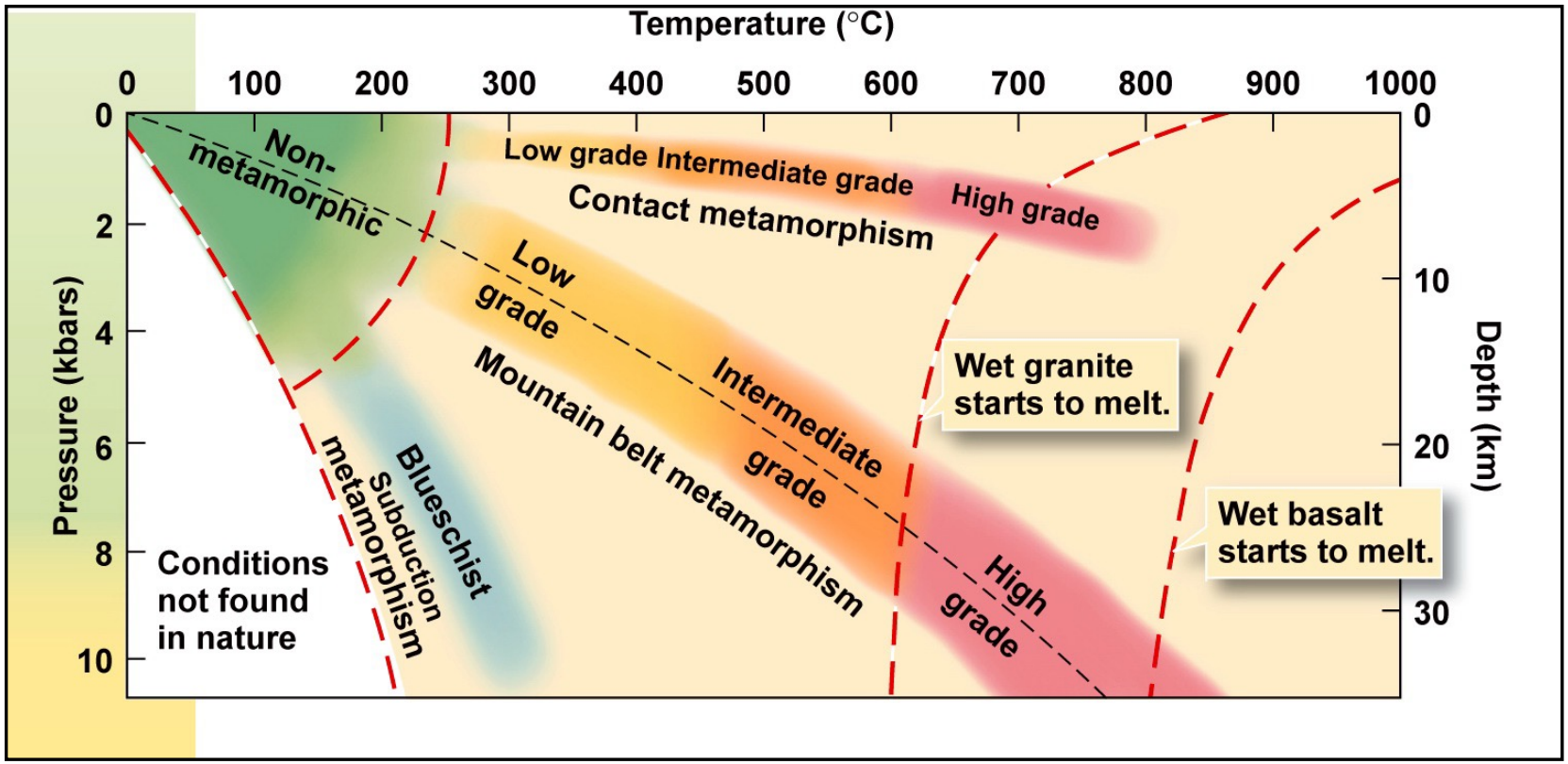


Subduction metamorphism: Down-going slab in subduction zones (high P, but low T).



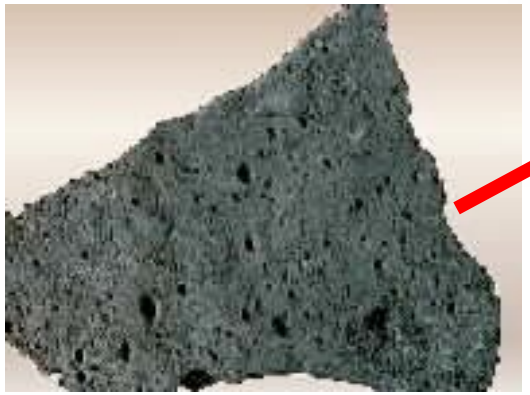
Metamorphic rocks: Geological P-T conditions

The different types of metamorphism can be shown on a pressure-temperature diagram (**P-T diagram**)



Metamorphic rocks: varying P-T: Basalt

20℃, 1bar

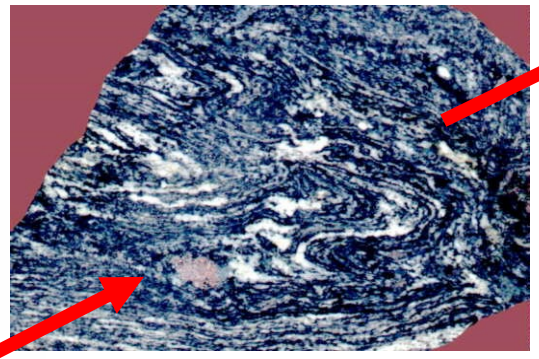


BASALT

300℃, 3kbar

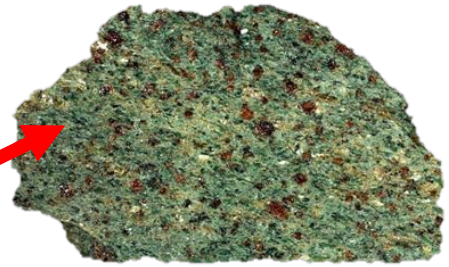
GREENSCHIST

500℃, 6kbar



AMPHIBOLITE

600℃, 14kbar

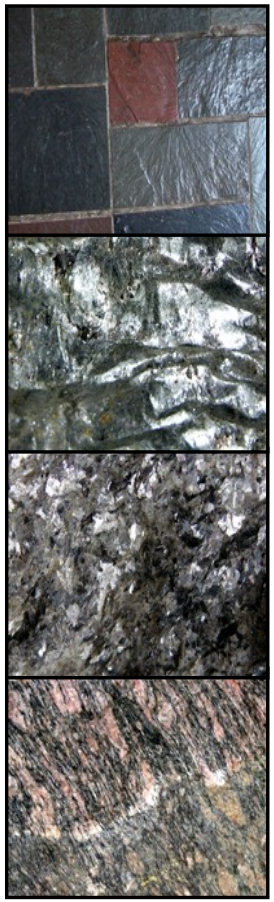


ECLOGITE

The same rock (basalt) exposed to different P-T conditions results in different metamorphic rocks.

Metamorphic rocks: varying P-T: Shale

Metamorphism of shale



slate

↓

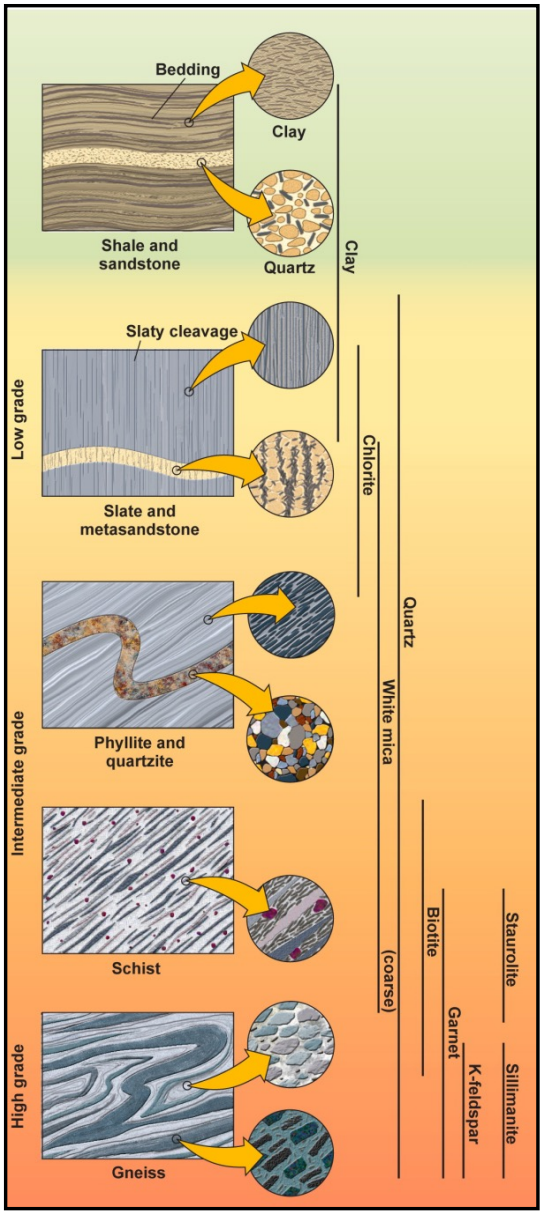
phyllite

↓

schist

↓

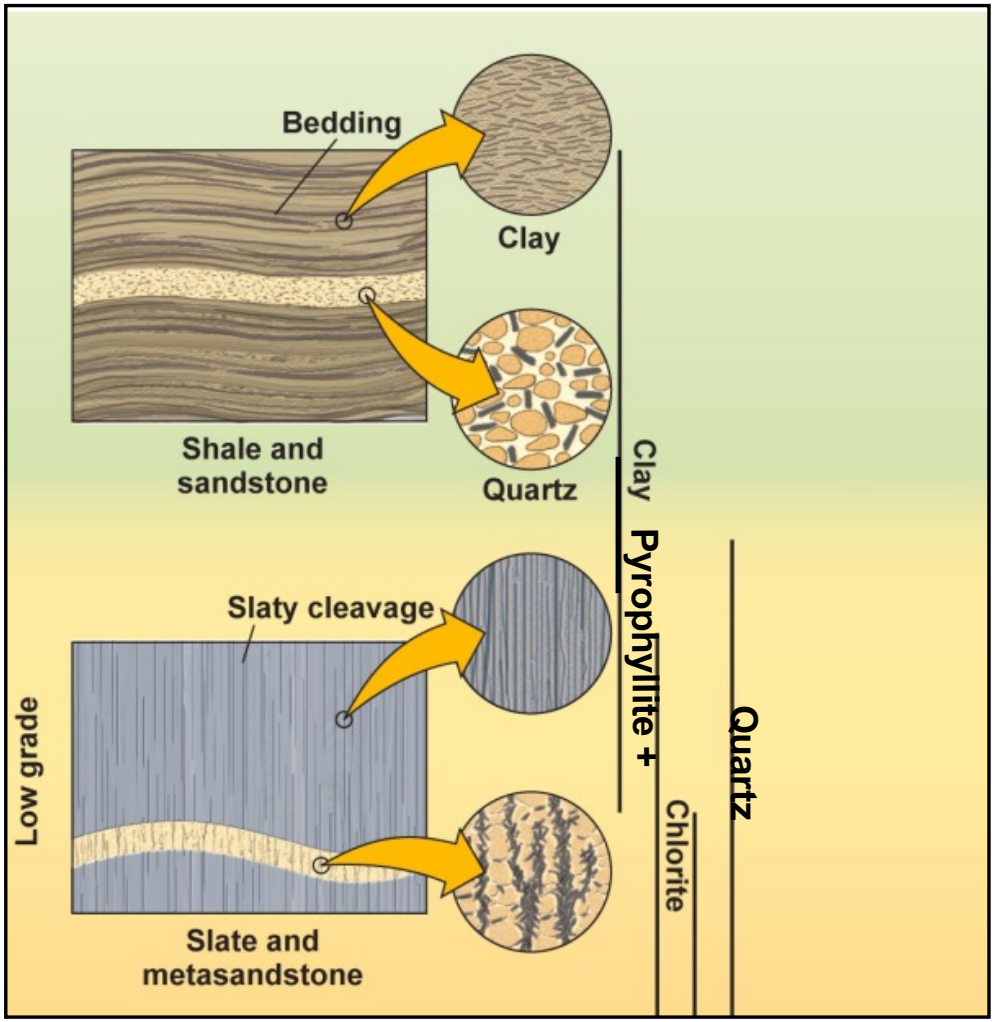
gneiss



Metamorphic rocks: varying P-T: Shale

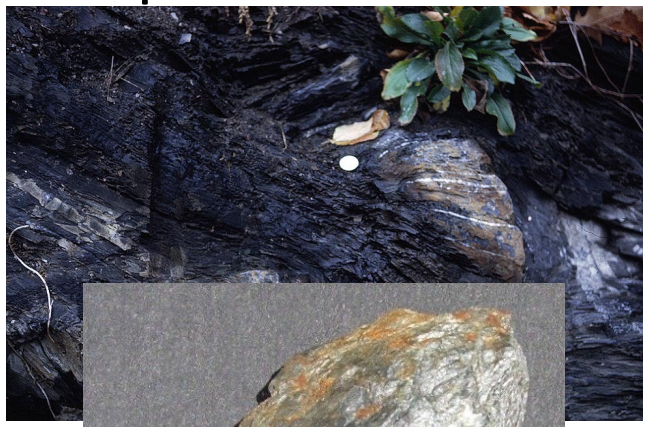
Shale

Slate



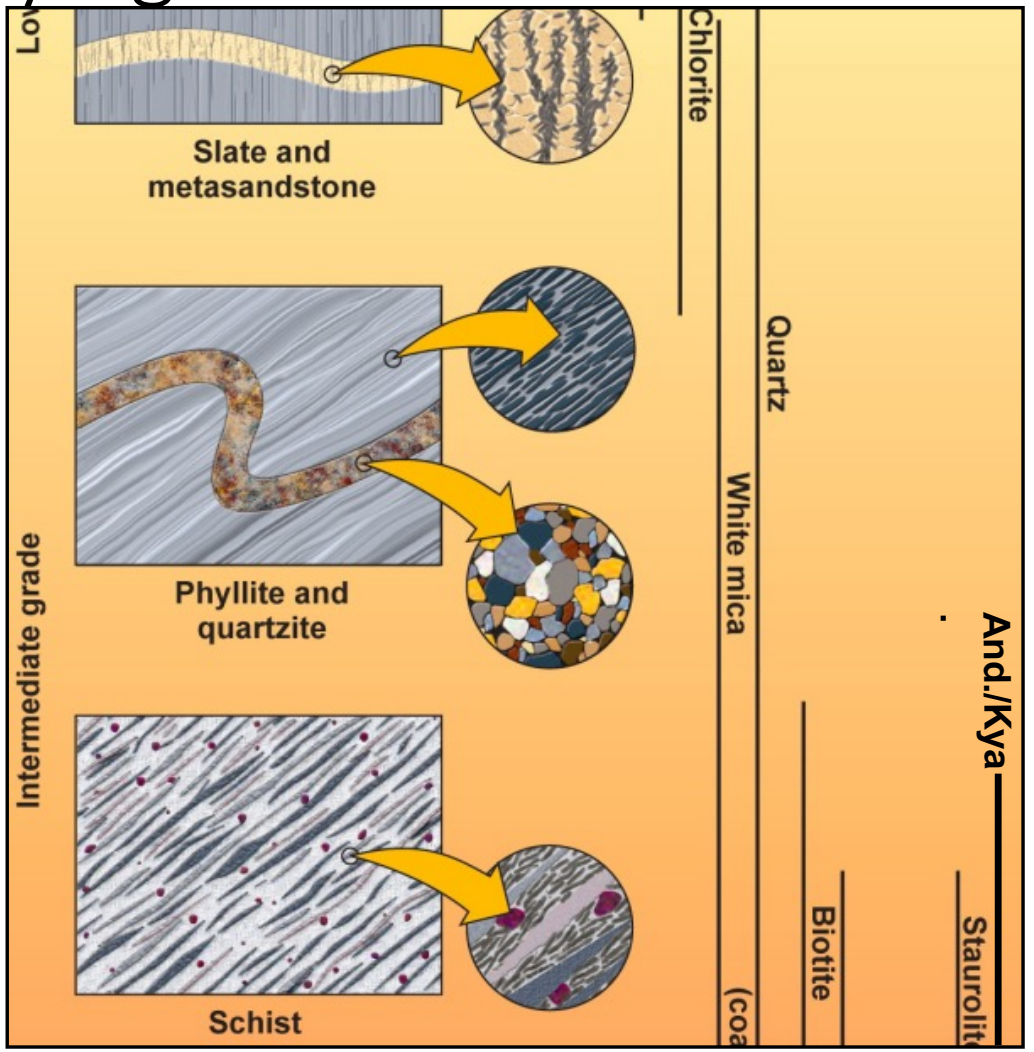
Metamorphic rocks: varying P-T: Shale

Slate



Phyllite

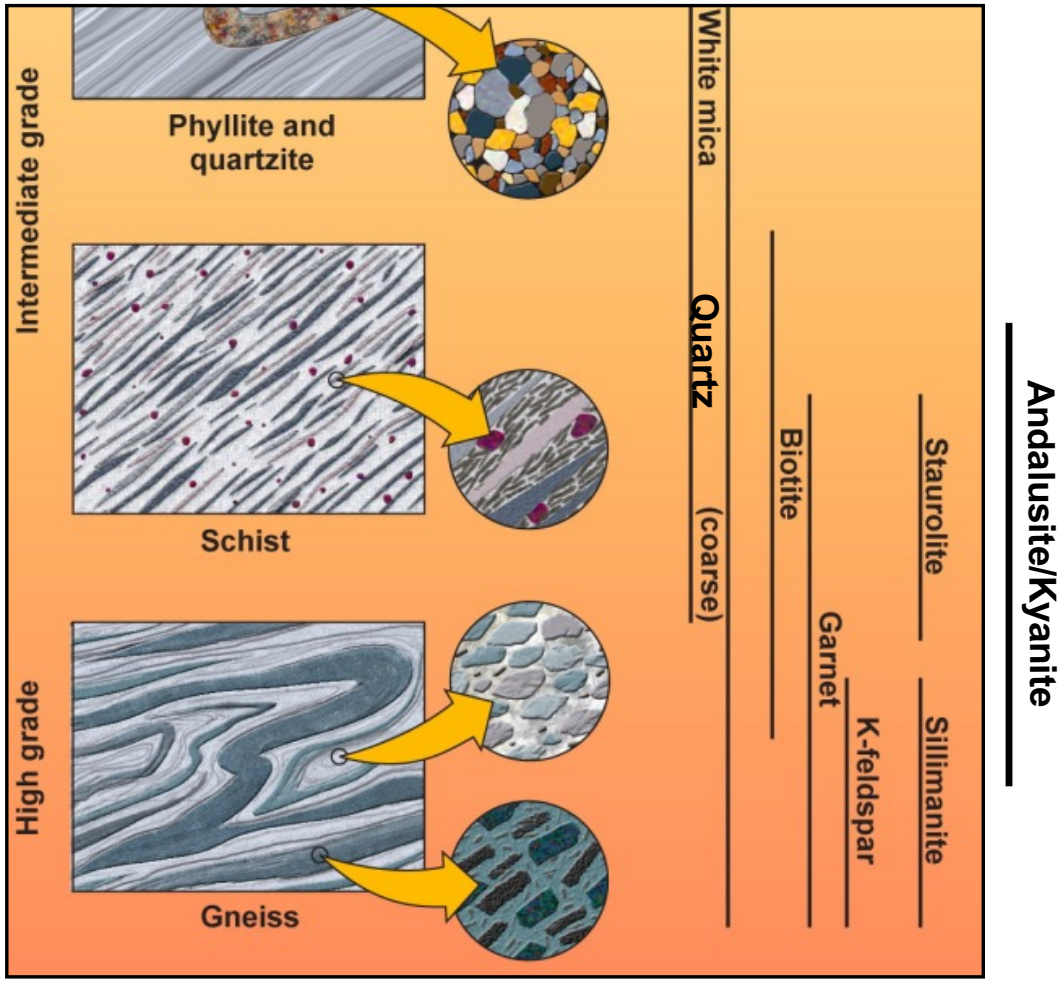
Mica schist



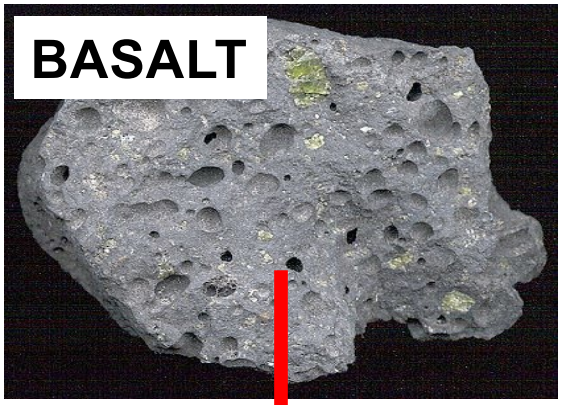
Metamorphic rocks: varying P-T: Shale

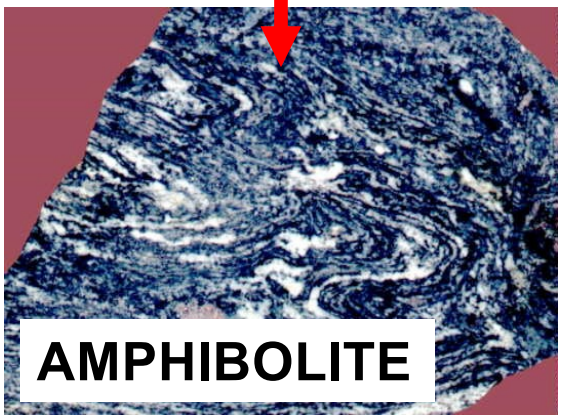
Mica schist

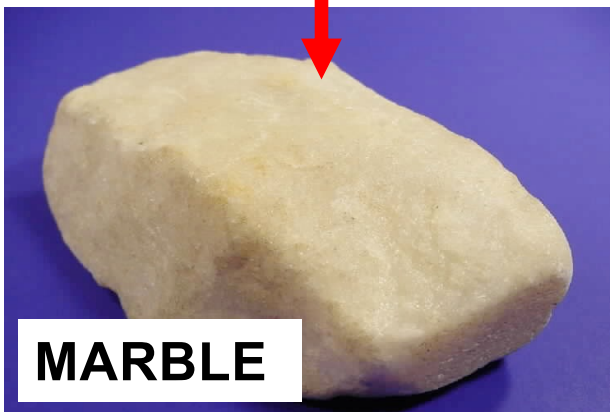
Gneiss



Metamorphic rocks: varying protolith







Here are different rocks (protolith) exposed to the same P-T conditions (450C, 3kbar)

Metamorphic rocks: Protoliths

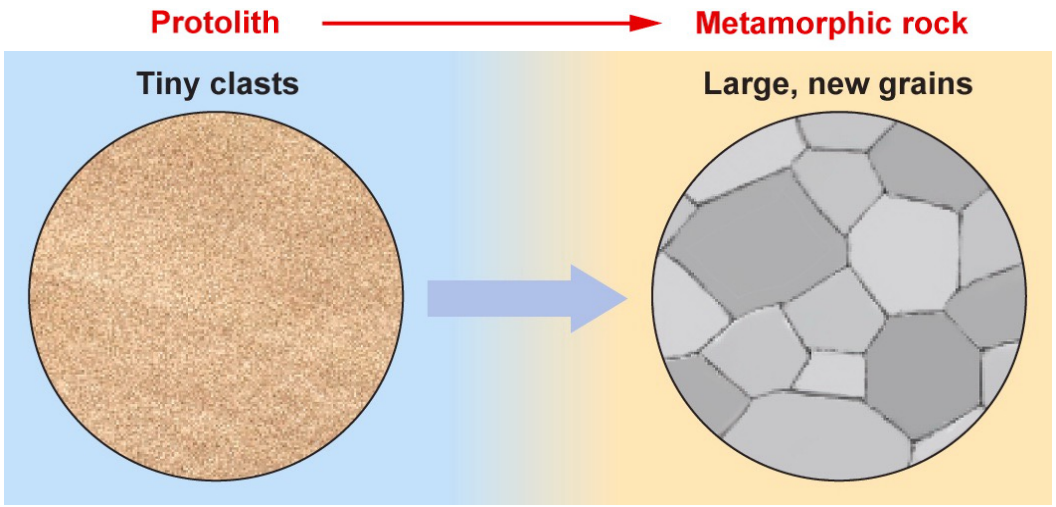
The protolith determines the chemical components that can be part of new metamorphic minerals/rocks

1. Ultramafic - very high Mg, Fe, Ni, Cr
2. Mafic - high Fe, Mg, and Ca
3. Shales (pelitic) - high Al, K, Si
4. Carbonates - high Ca, Mg, CO_2
5. Quartz - nearly pure SiO_2.
6. Quartzo-feldspathic - high Si, Na, K, Al

Metamorphic rocks: Recrystallization

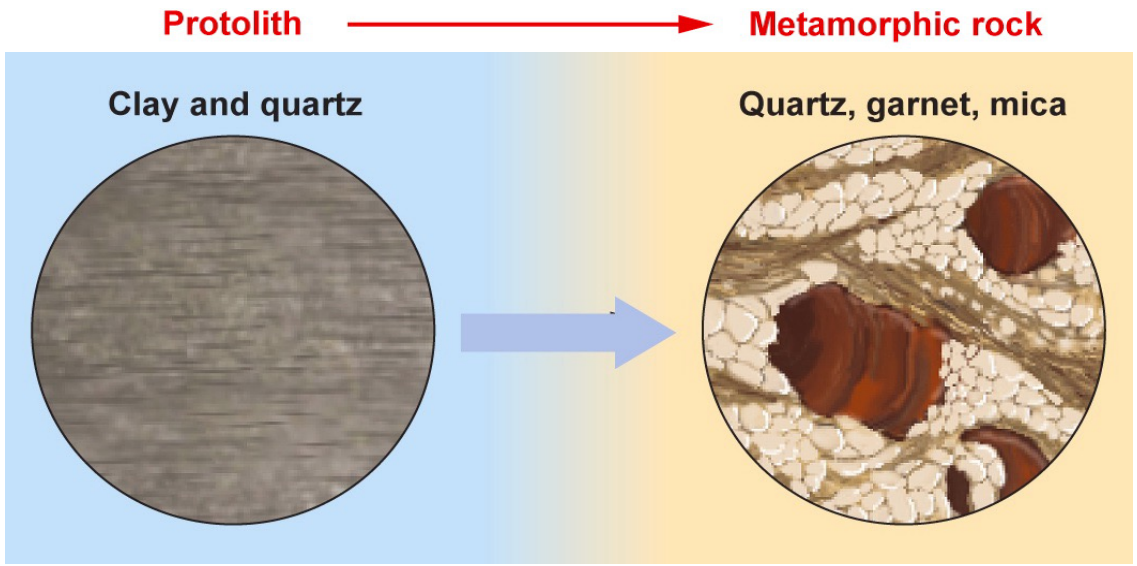
During metamorphism some minerals recrystallize and others are formed newly.

Typically the grain sizes increases during recrystallization. E.g., small calcite grains in a limestone ‘grow together’ and form larger grains in a **marble**.
Equally, hydrous minerals become dehydrated during metamorphism.



Metamorphic rocks: Formation of new minerals

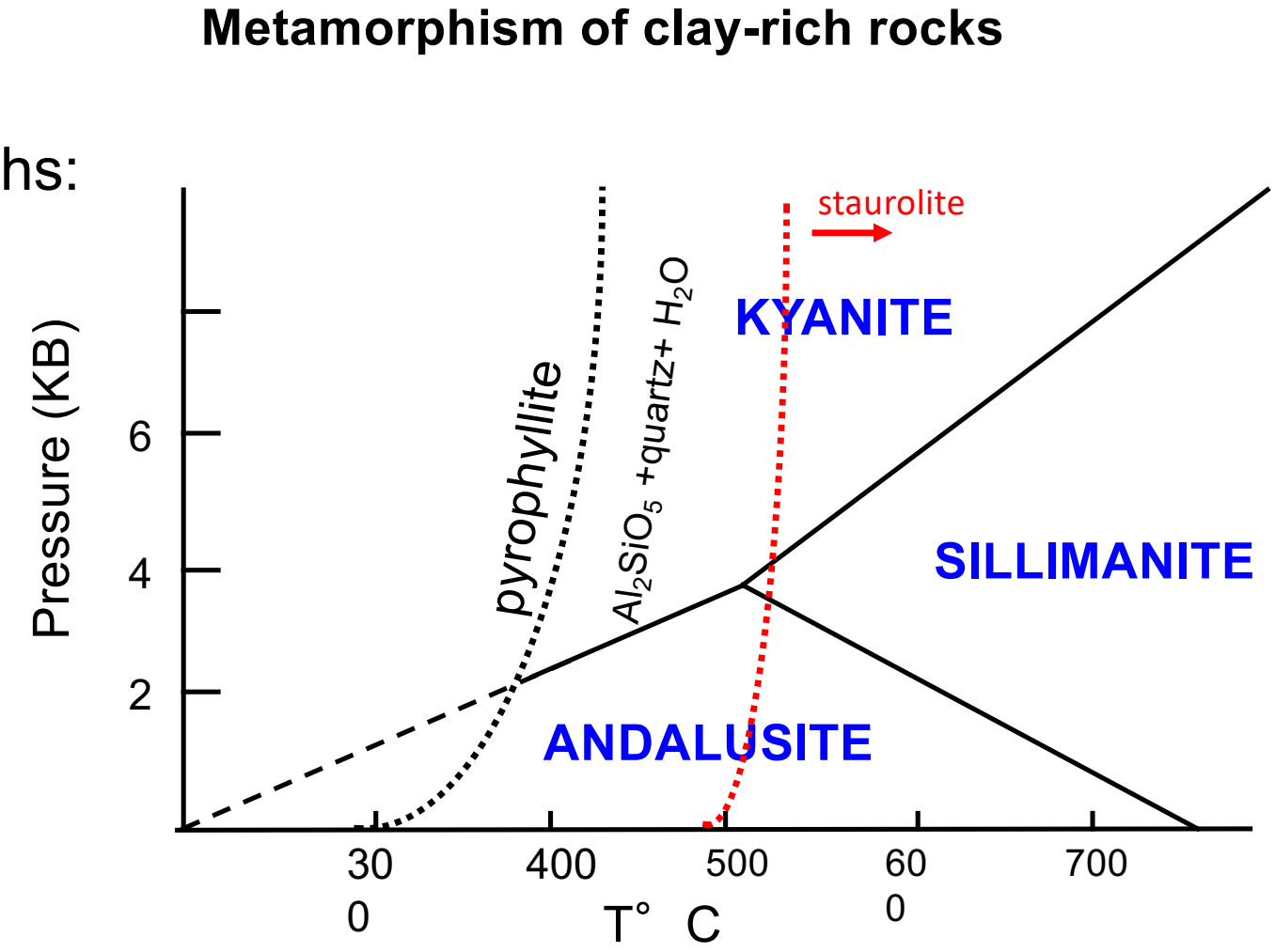
During metamorphism some minerals become unstable and break down. From those chemical components new minerals can form.



Clay minerals become unstable and become garnet and mica

Metamorphic rocks: Geological P-T conditions

Al_2SiO_5 polymorphs:
andalusite,
sillimanite,
kyanite (disthen)



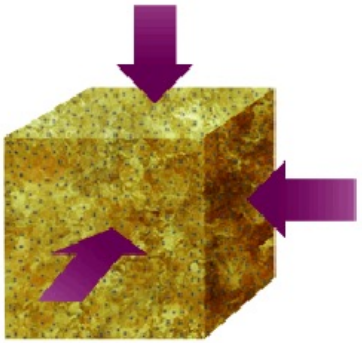
Metamorphic rocks: Rock names

Typically one writes the mineral name of a characteristic metamorphic mineral in front of the metamorphic rock name:

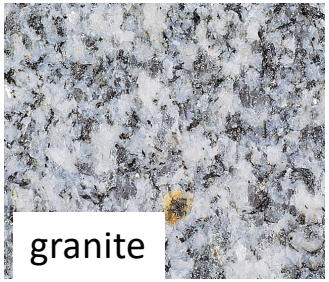
Garnet-mica schist
Garnet amphibolite
Kyanite-staurolite schist
Sillimanite-garnet gneiss
Chlorite phyllite

Metamorphic rocks: Deformation

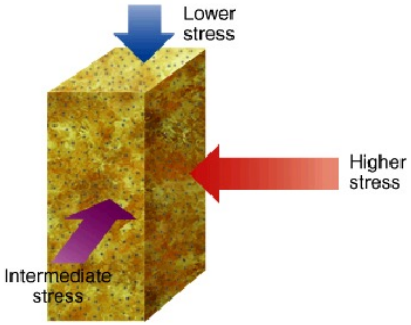
Some types of metamorphism include deformation of rocks under pressure



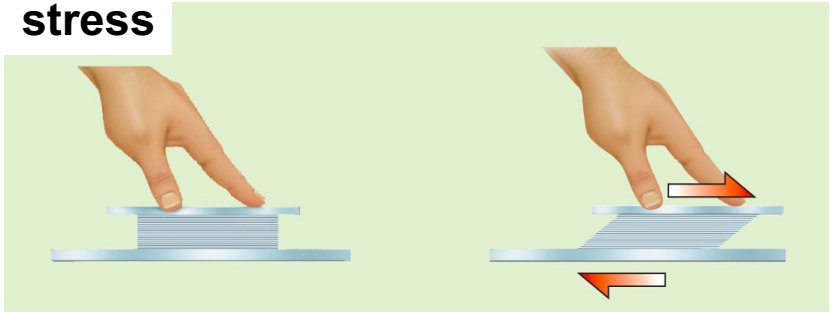
uniform stress



differential stress



shear stress



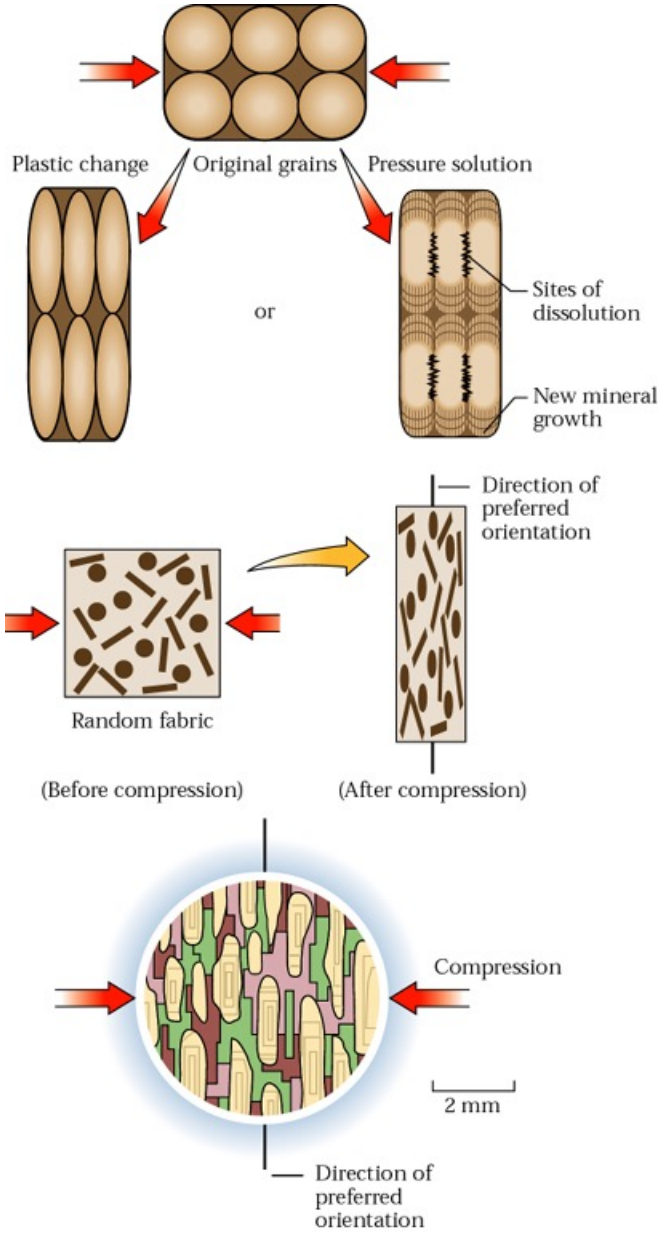
Metamorphic rocks: Deformation

1. **Plastic deformation:** occurs under high temperature when rocks are ductile

2. **Pressure solution:** Minerals get dissolved at points of high pressure and re-precipitate a lower pressure

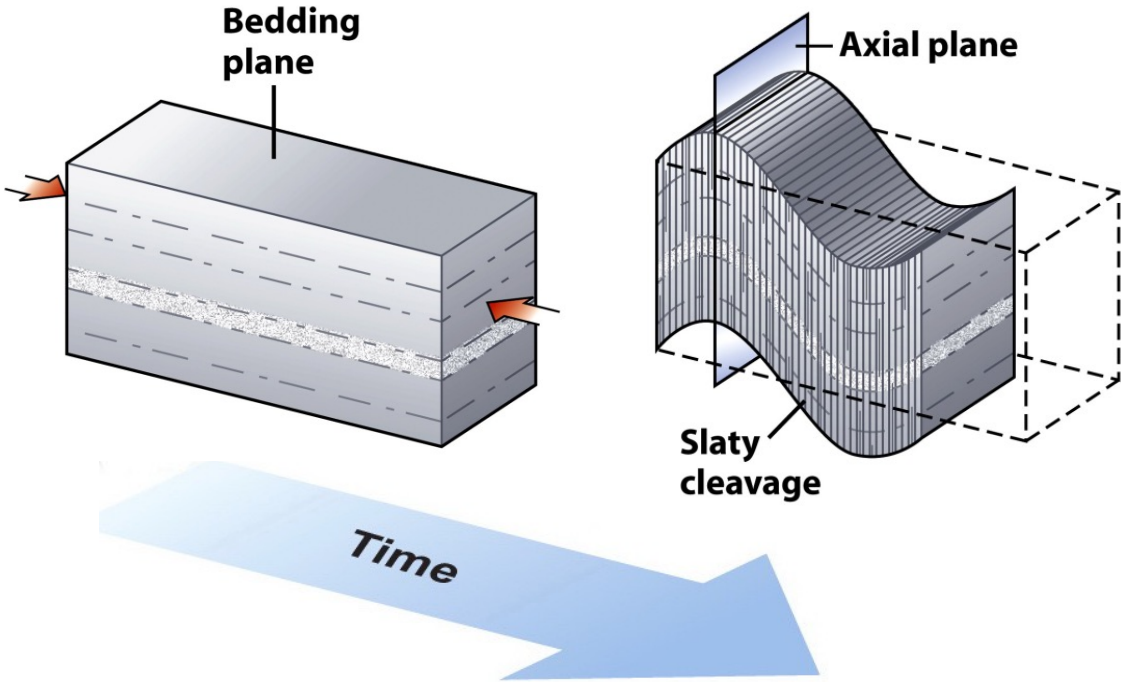
3. **Grain rotation:** Minerals get rotated perpendicular to the max. pressure direction

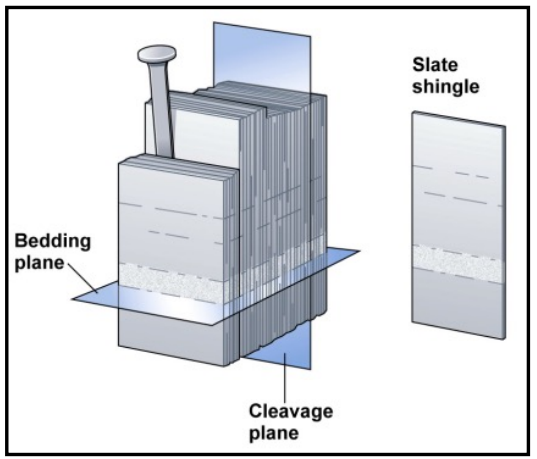
4. **New crystal growth:** new elongated or tabular minerals form perpendicular to the pressure direction

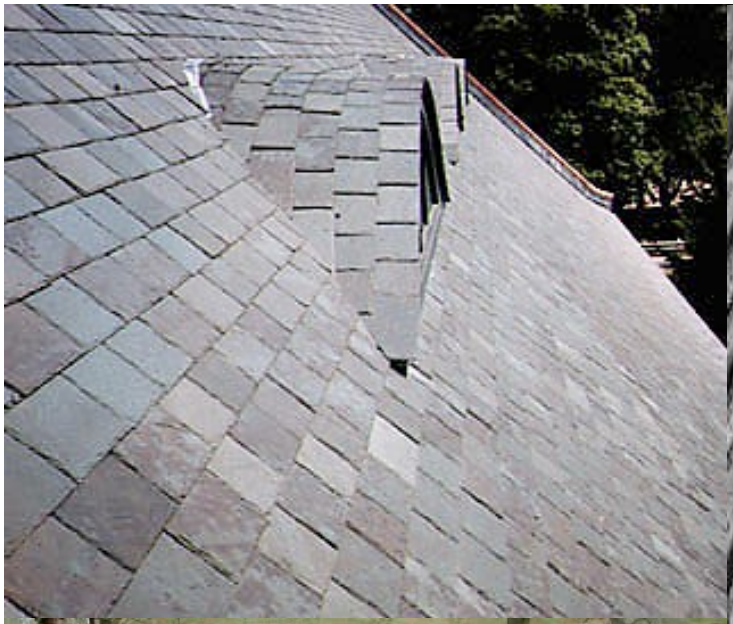


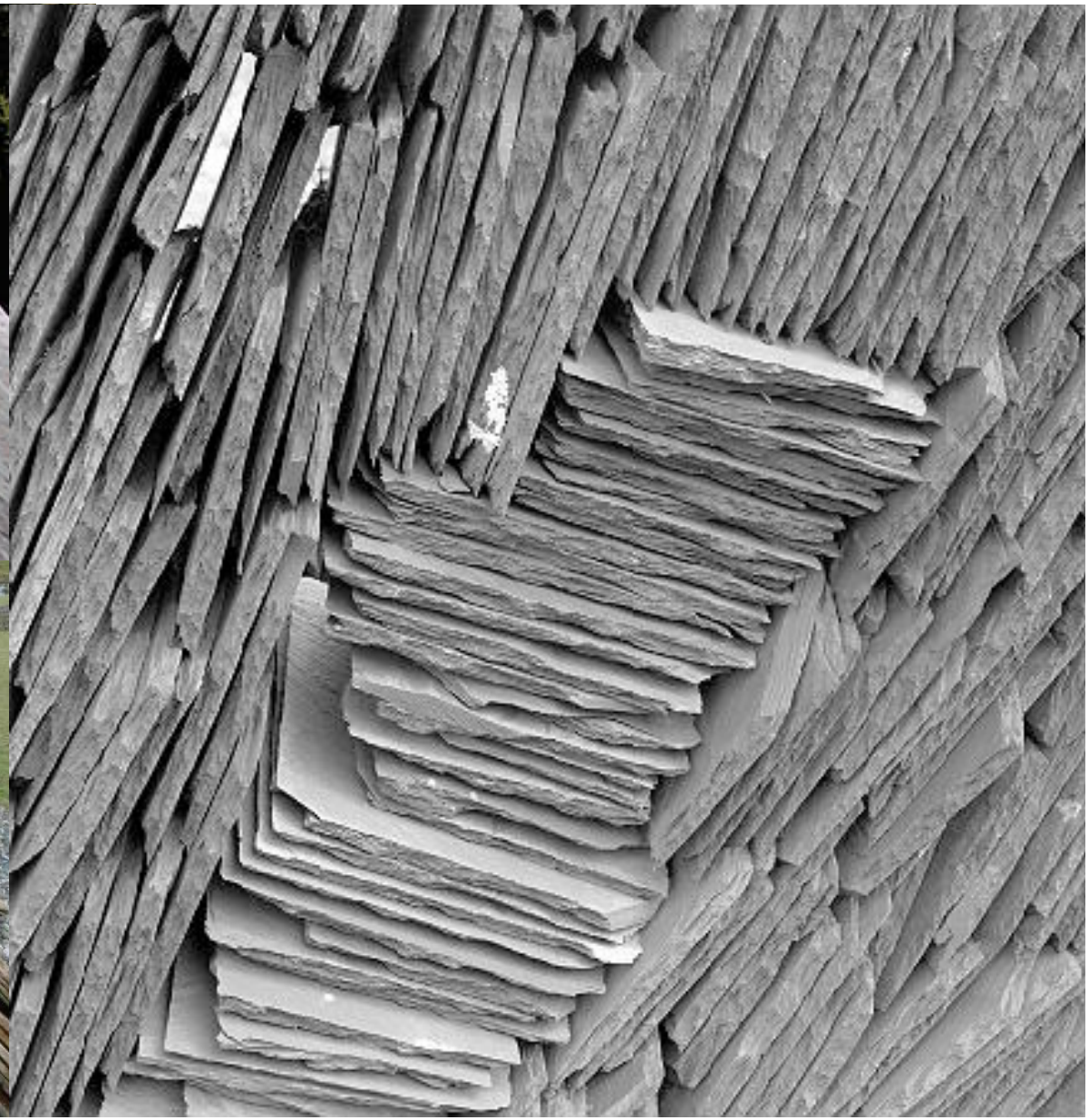
Metamorphic rocks: Deformation: Foliation

Slate as an example: clay minerals are platy and are oriented in one direction (bedding plane). During deformation and temperatures above 200C clay is unstable. New minerals such as chlorite and other mica forms perpendicular to the max pressure and form the foliation/cleavage. At the same time the rock gets folded.



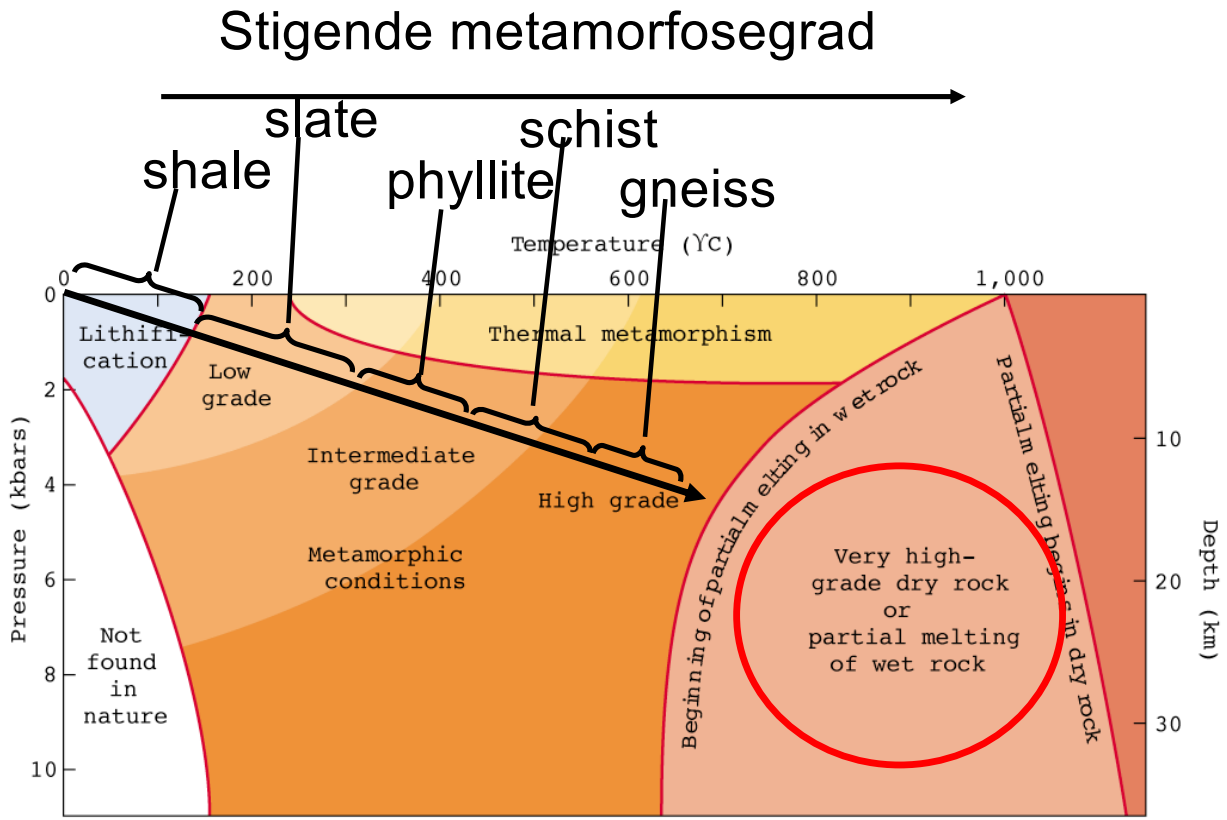






Metamorphic rocks: Migmatite

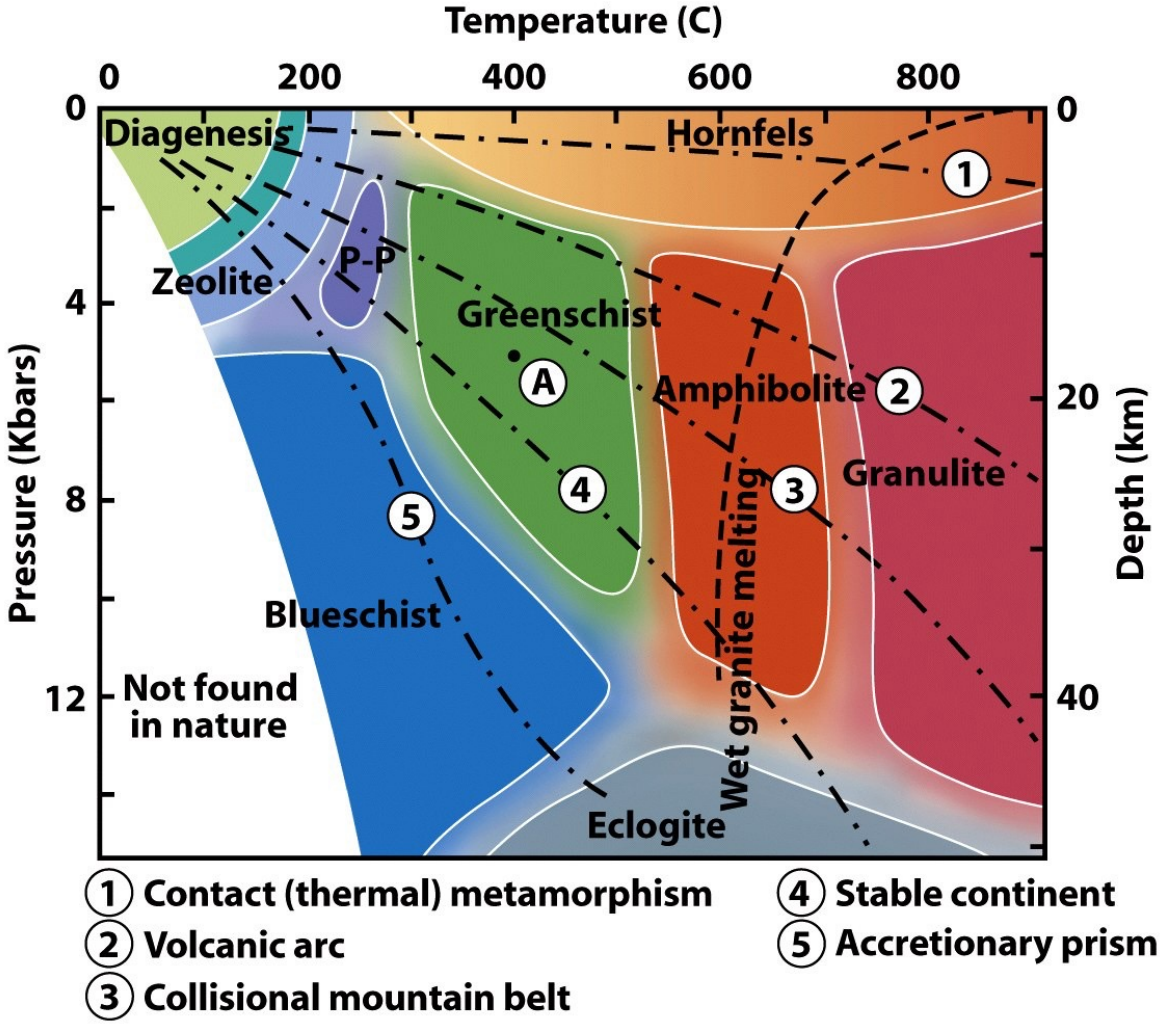
If the temperature is very high, partial melting can occur. A granitic melt forms and separates from the dark (not melted) part. The rock is called a **migmatite.**



Metamorphic rocks: Metamorphic facies

Metamorphic rocks are classified according to their P-T conditions of formation. There can be different types of metamorphic rock in a specific metamorphic facies, depending on the protolith. The facies are based on mafic (basalt) rocks and the color/minerals they have under different P-T conditions.

There are 7 main metamorphic facies that define fields in P-T space.



Metamorphic rocks: Metamorphic facies

The mineralogy of these three rocks is very different, but they are all formed in the same metamorphic facies (same P-T conditions)

Marmor
metamorphosed
limestone

Greenschist
metamorphosed
basalt

Phyllit
metamorphosed
shale

They all belong to the greenschist facies, but note their different names, depending on the protolith.

Metamorphic rocks: Metamorphic facies

ZEOLITE facies: low metamorphic grade (max. 200C)

HORNFELS facies: Thermal metamorphism. Contact metamorphism. Low pressure.

GREENSCHIST facies: Low to medium metamorphic grade.

AMPHIBOLITE facies: Medium to high metamorphic grade.

GRANULITE facies: High to very high metamorphic grade.

BLUESCHIST facies: High pressure, low temperature (subduction).

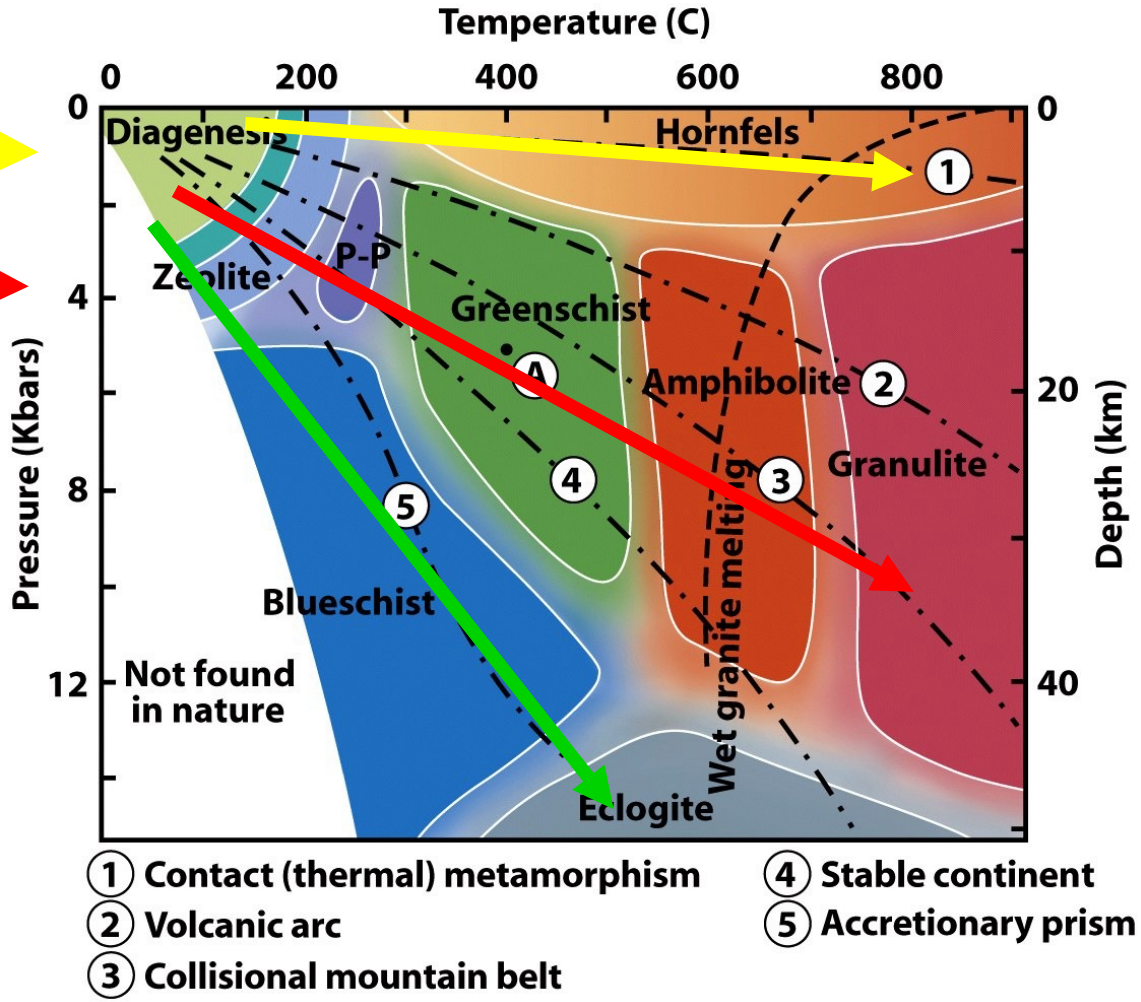
ECLOGITE facies: Very high pressure.

Metamorphic rocks: Metamorphic gradients

Contact metamorphism

Regional metamorphism

Subduction



Metamorphic rocks: Mineral assemblages

	sandstone	*limestone*	*peridotite*	*claystone*	*basalt*	*granite*
protolith	*qtz*	*cal, dol*	*ol, opx, cpx, (pl, sp, grt)*	*clay minerals, qtz, ab, kfs*	*pl, cpx ol, qtz, opx*	*qtz, kfs, pl, bt, wm*
sub-greenschist facies	*qtz quartzite*	*cal, dol marble/ limestone*	*ol, opx, cpx, srp, tlc peridotite/ serpentinite*	*qtz, czo, chl, wm, phyllite*	*pl, cpx, qtz, opx, chl, zeolithe basalt*	*qtz, kfs, pl, wm, bt, chl, ep "Granite"*
greenschist facies	*qtz quartzite*	*cal, dol marble*	*srp, chl, tlc, mag serpentinite*	*qtz, chl, wm, ab, ±bt, ±grt phyllite, mica schist*	*ab, chl, am, (act), ep/czo greenschist*	*qtz, kfs, ab, wm, bt, chl, ep/czo gneis*
amphibolite fazies	*qtz quartzite*	*cal, dol marble*	*srp, ol, cpx, am, chl serpentinite, peridotite*	*qtz, pl, wm, bt, grt, als, st, liq garnet-mica schist*	*pl, am, grt, bt, cpx Amphibolite*	*qtz, kfs, pl, wm, bt, liq gneis*
granulite fazies	*qtz quartzite*	*cal, dol marble*	*ol, opx, cpx, sp, pl peridotite*	*qtz, kfs, pl, bt, opx, sp, liq granulite*	*pl, cpx, grt, opx, am, liq mafic granulite*	*qtz, kfs, pl, cpx, opx, ky, grt, liq granulite*
blueschist facies	*qtz quartzite*	*cal, dol, ar marble*	*srp, ol, cpx, chl serpentinite*	*qtz, wm, grt, czo/zo am (gln), tlc, carpholite garnet-white-mica schist*	*am (gln), chl, tlc, czo/zo, wm, qtz, cpx,... blueschist*	*qtz, tlc, wm, am, ky, czo/zo whiteschist*
eclogite facies	*qtz quartzite*	*cal, dol, ar marble*	*ol, cpx, opx, grt serpentinite, peridotite*	*qtz/coe, wm, grt, ky, omp, (diamond) garnet-white-mica schist/fels*	*omp, grt, am, ky ,czo/zo, qtz/coe eclogite*	*qtz/coe, jd, wm, ky, tlc whiteschist*

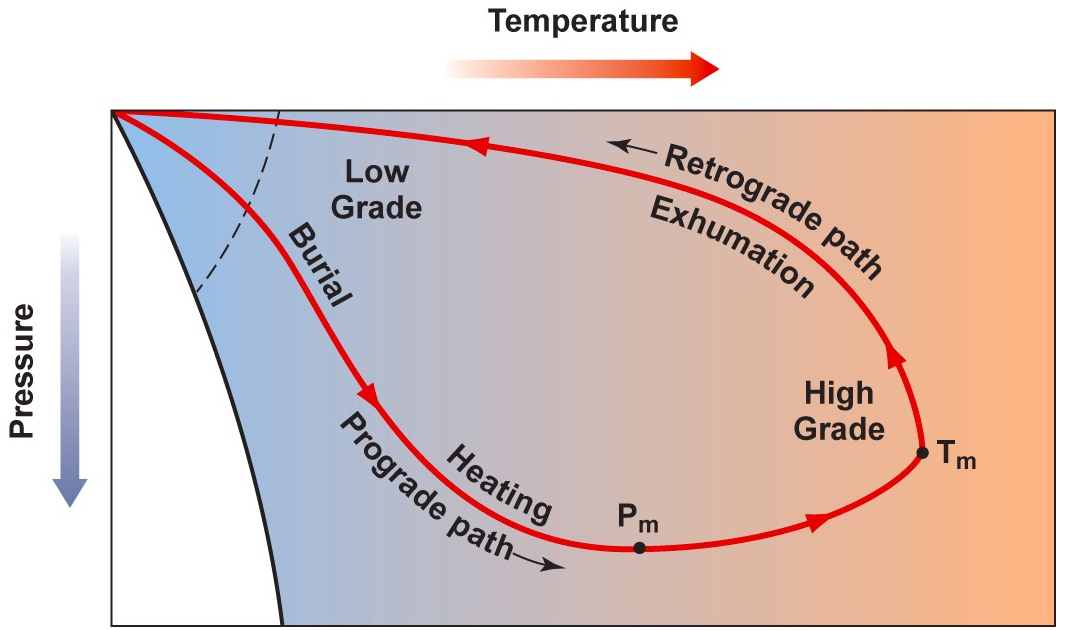
ab: albite, act: actinolite, am: amphibole, als: alumosilicate, ar: aragonite, bt: biotite, cal: calzite, chl: chlorite, coe: Coesite, cpx: clinopyroxene, czo: Clinozoisite, dol: dolomite, ep: epidote, gln: glaukophane, grt: garnet, jd: jadeite, Kfs: K-feldspar, ky: kyanite, liq: melt, mag: magnetite, ol: olivine, omp: omphazite, opx: orthopyroxene, pl: plagioclase, qtz: quartz, sp: spinel, srp: serpentine, st: staurolite, tlc: talc, wm: white mica, zo: zoisite.

Metamorphic rocks: Preservation

Why is a kyanite-garnet schist preserved at the Earth surface despite the mineral stability fields of garnet and kyanite are under higher pressure and temperature?

Many times the ‘peak metamorphic’ mineral assemblage is preserved.

The reactions under prograde metamorphism include dehydration. The peak metamorphic minerals are meta-stable at Earth surface conditions, but will only change very slowly or when water is added.



Prograde vs. retrograde

Metamorphic rocks: Summary

- Metamorphic reactions occur when the P-T conditions are changing.
- The minerals formed in metamorphic rocks depend on the the respective P-T conditions and the protolith composition.
- The mineral formation (re-crystallization) occurs under solid conditions (no melting, except migmatite).
- Distinct P-T fields are defined as metamorphic facies (zeolite, greenschist, amphibolite, granulite, blueschist, eclogite, hornfels).
- Deformation creates folds and cleavage in metamorphic rocks due to the orientation of minerals.
- There are 4 main types of metamorphism: Regional metamorphism, contact metamorphism, subduction metamorphism, sea floor metamorphism

‘Last minute’ paper

Write down what was difficult to understand

Write down what was easy to understand