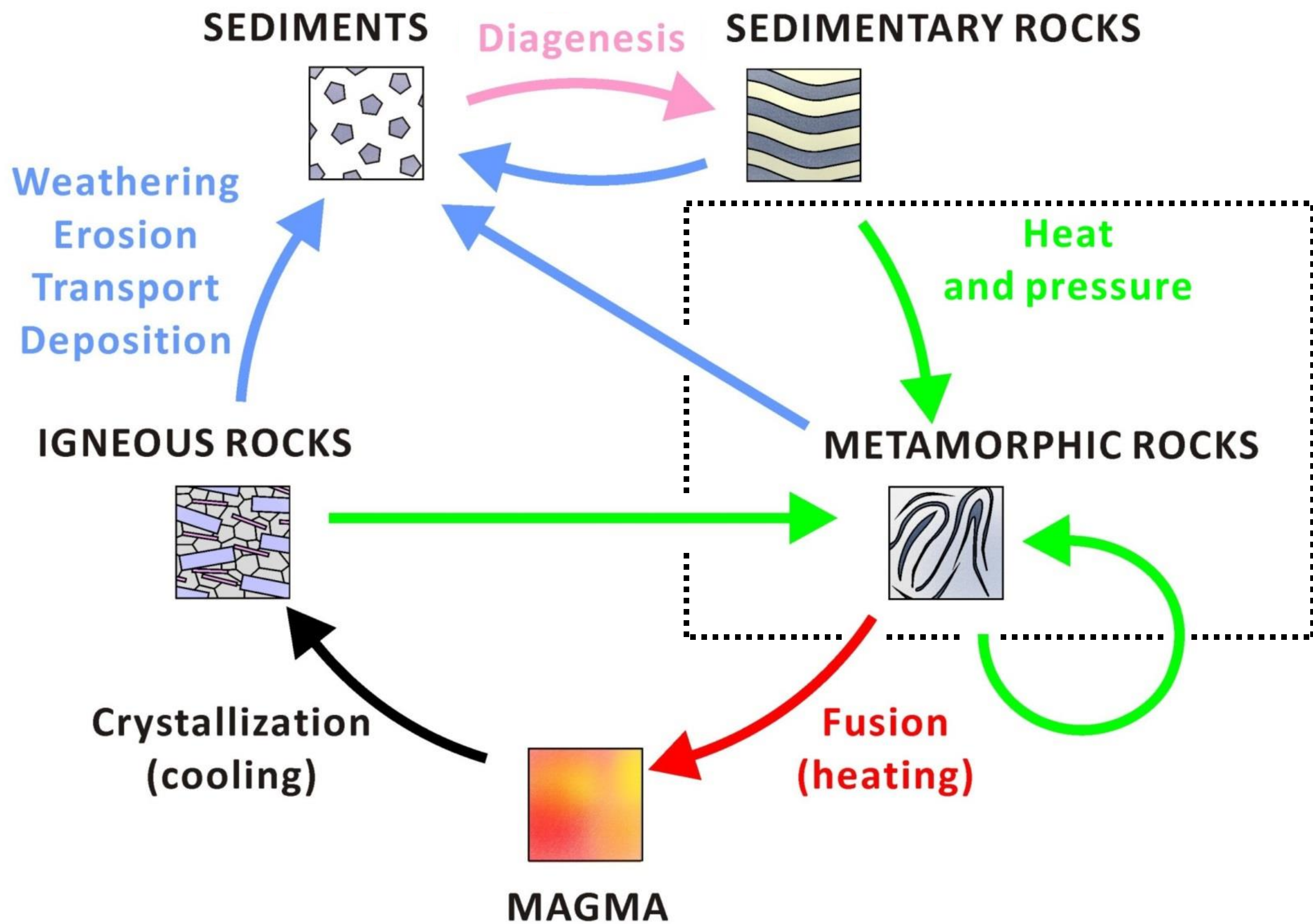
Metamorphic rocks


SEDIMENTS
Diagenesis
SEDIMENTARY ROCKS
Weathering
Erosion
Transport
Deposition
Heat
and pressure
IGNEOUS ROCKS
METAMORPHIC ROCKS
Crystallization
(cooling)
Fusion
(heating)
MAGMA

✶ What is metamorphism?

- Process by which a rock **in a solid state** experiences a transformation of one or a combination of the following characteristics:
  - **Chemical composition**
  - **Mineralogical composition**
  - **Texture**

- 3 factors driving metamorphism:
  - **Temperature**
  - **Pressure**
  - **Hydrothermal fluids**

- Most metamorphic rocks form at depths of **10 to 30 km** (middle to lower half of continental crust)

SHALE

LIMESTONE

SCHIST

MARBLE

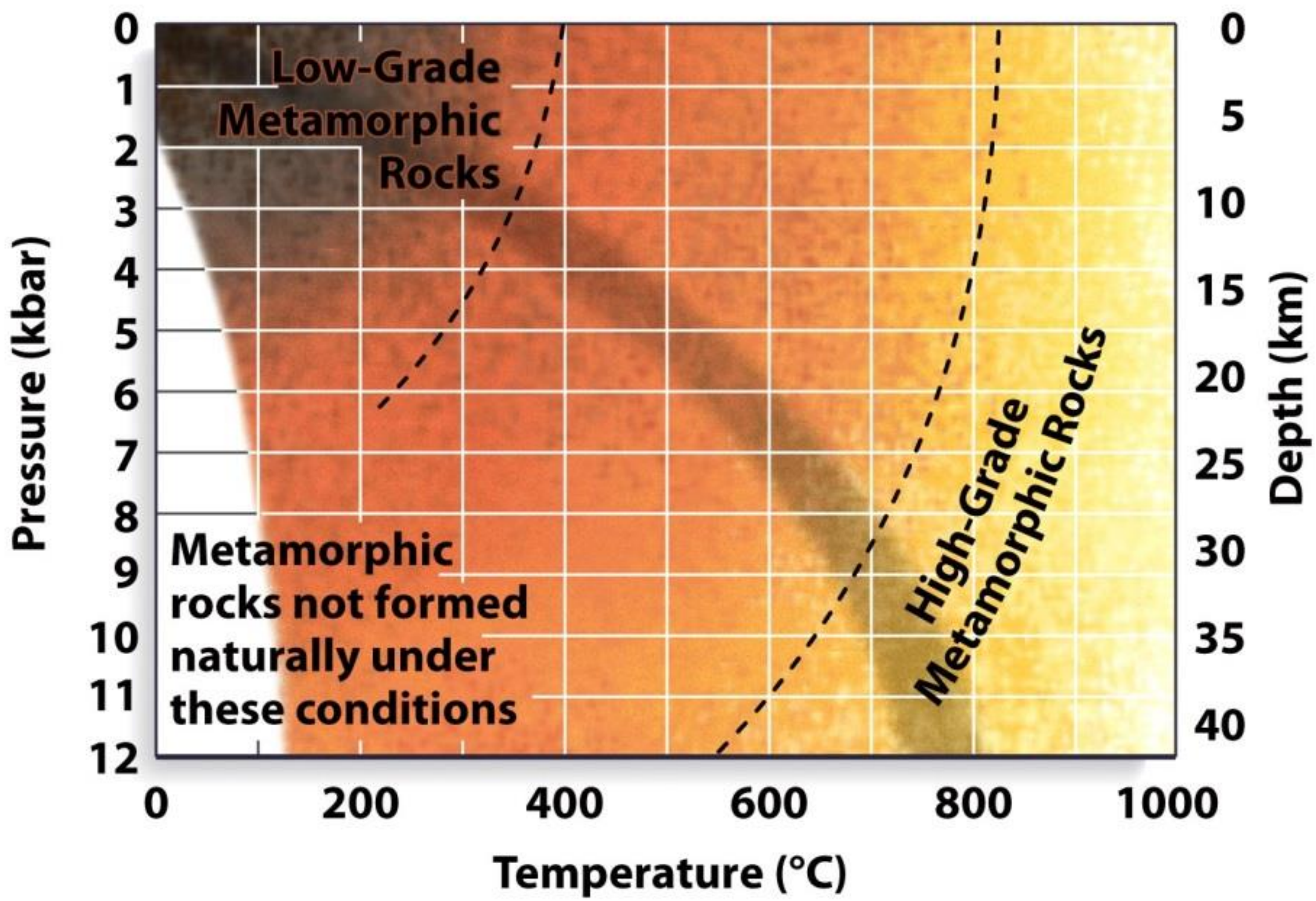
Mineralogy and texture change

Only the texture changes

All pictures from the Geologic Image Archive of the University of Pittsburg

- Metamorphic grade
  - **Low grade**: low P-T (shallow crustal regions)
  - **High grade**: high P-T (at greater depths)

} Associated with different assemblages of minerals

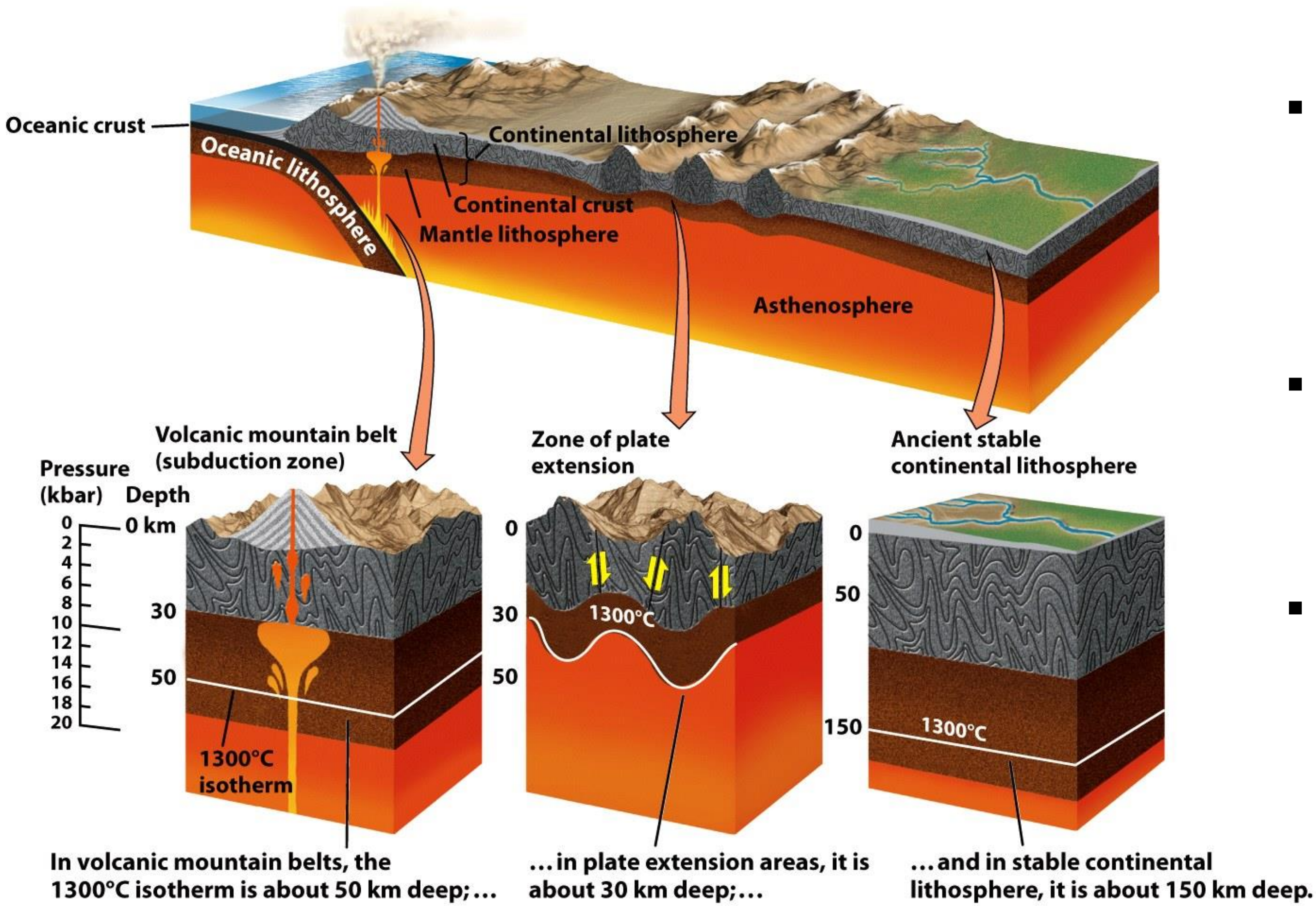


On average: 30ºC/km; 300-400bar/km

Understanding Earth

✶ The role of temperature

- The amount of heat available to metamorphose rocks depends on the **geothermal gradient**, which depends on **the tectonic setting**.



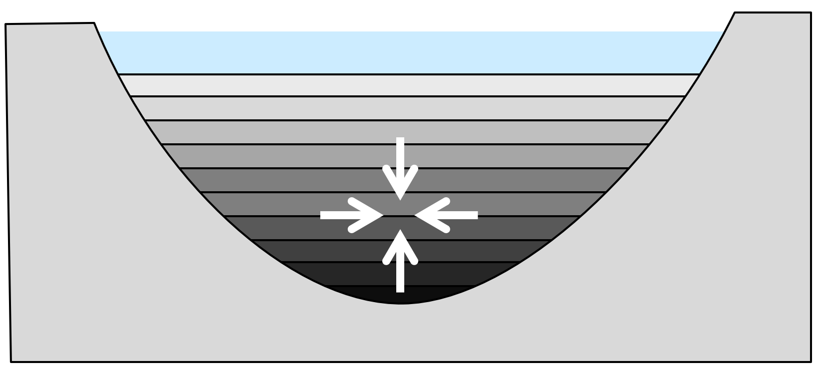
- Average increase in T with increasing depth = **30°C/km**
- Thick, stable continental lithosphere = **20°C/km**
- Thin, stretched continental lithosphere = **50°C/km**

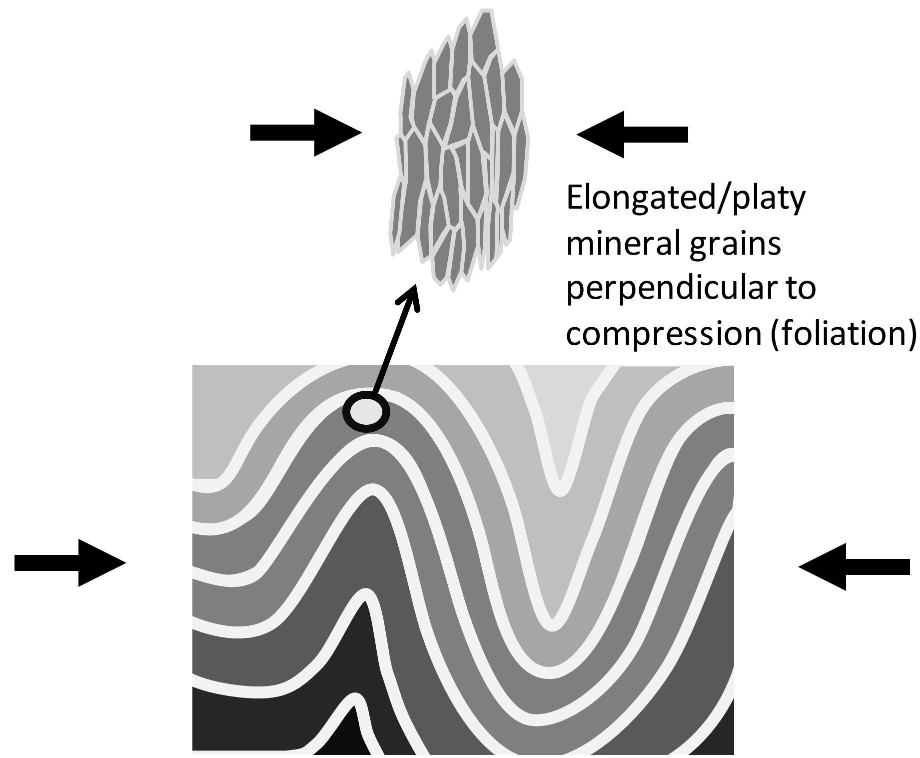
Understanding Earth

✶ The role of pressure

- **CONFINING pressure**
  - same in all directions
  - depends on weight of rock's overlying mass) 0.3-0.4 kbar/km

- **DIRECTED pressure**
  - characteristic of **convergent boundaries**, and guides the **shape and orientation of new crystals** (effect on texture).





Compression

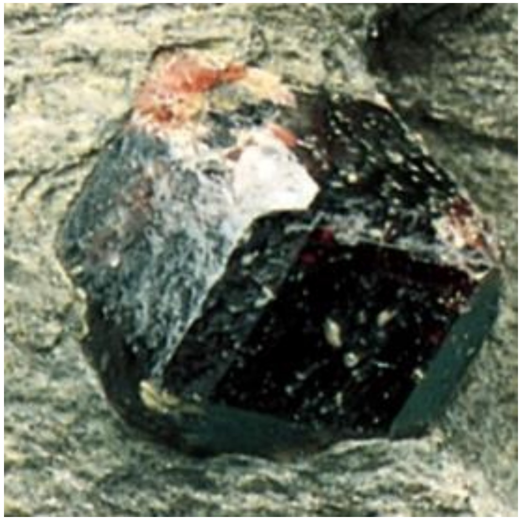
- Mineral assemblages in metamorphic rocks reflect the temperature and pressure at which they were formed. Metamorphic mineral assemblages can be used as natural **geobarothermometers**.

Low grade

Chlorite

→

Intermediate grade



Garnet

✶ The role of fluids

- Heated fluids can affect the chemical and mineral compositions of rocks by introducing or removing soluble chemical components (CO_2, S^{2-}, Fe^{2+}...).

- Water molecules inside clay mineral constitutes a major source of hydro-thermal fluid.

Light grey: limestone ($CaCO_3$)

Metasomatic minerals
- Blue: Lazurite[1]
- Dark grey: pyrite[2]

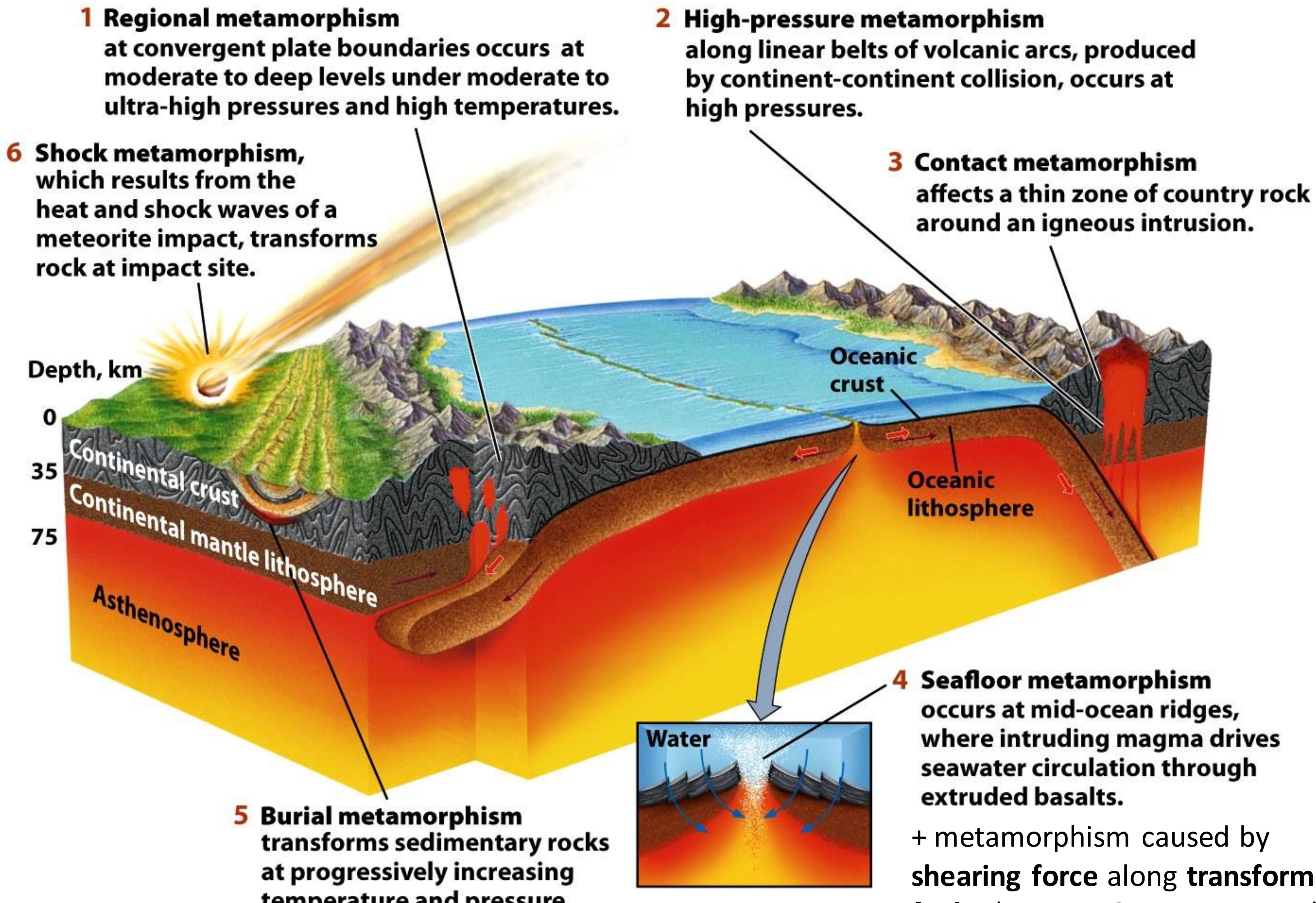
[1] $(Na,Ca)_8[(S,Cl,SO_4,OH)_2|(Al_6Si_6O_{24})]$

[2] FeS_2

www.newark.osu.edu

- The transformation of rock's chemical and mineral compositions due to hydrothermal fluids is called **metasomatism**.

✶ Types of metamorphism

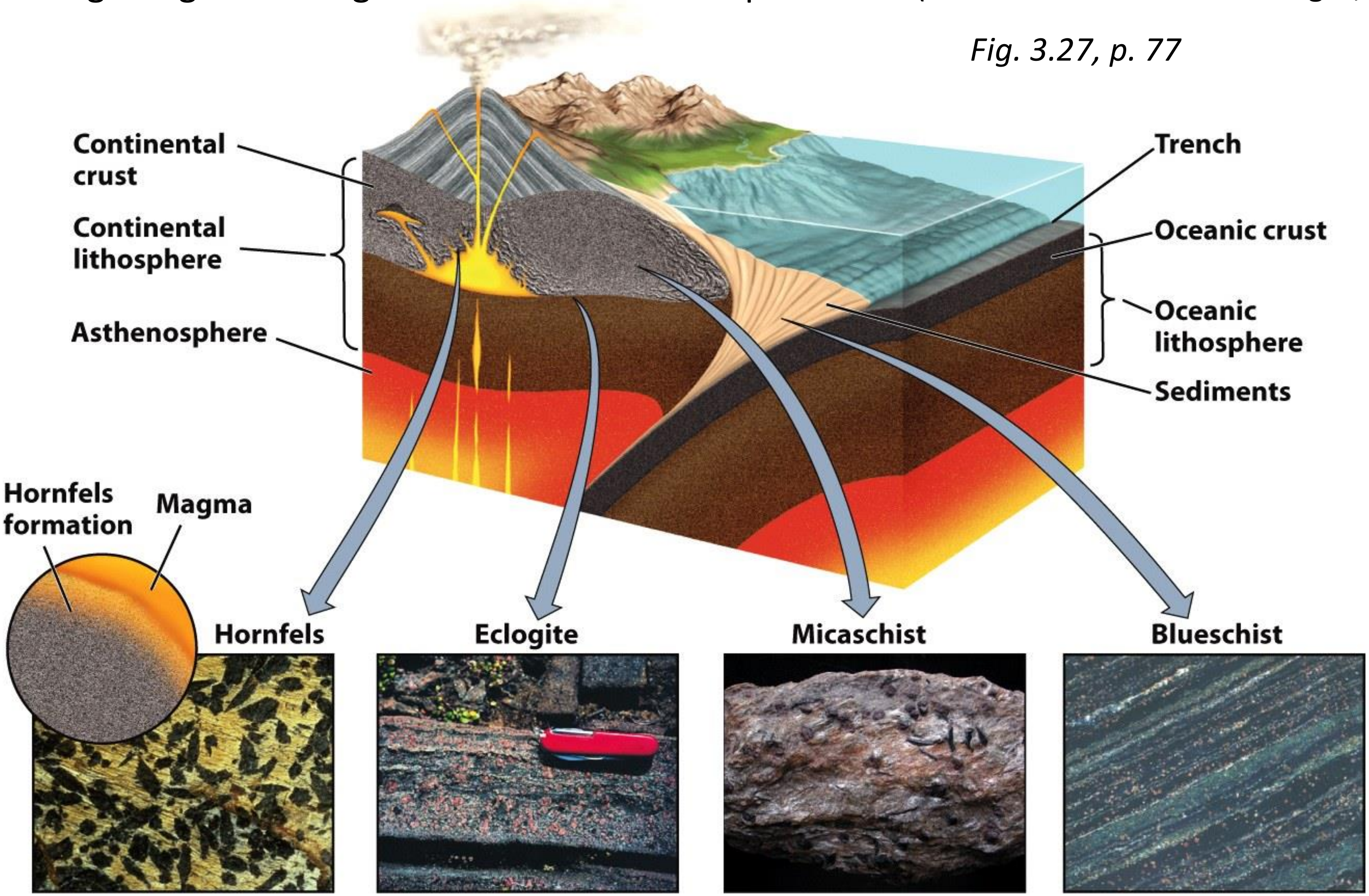


+ metamorphism caused by **shearing force** along **transform faults** (oceanic & cont. settings)

Understanding Earth

Different geological settings → different metamorphic rocks (different mineral assemblages, textures)

Fig. 3.27, p. 77



Contact metamorphism occurs in limited areas where heat from a magmatic intrusion metamorphoses neighboring rock.

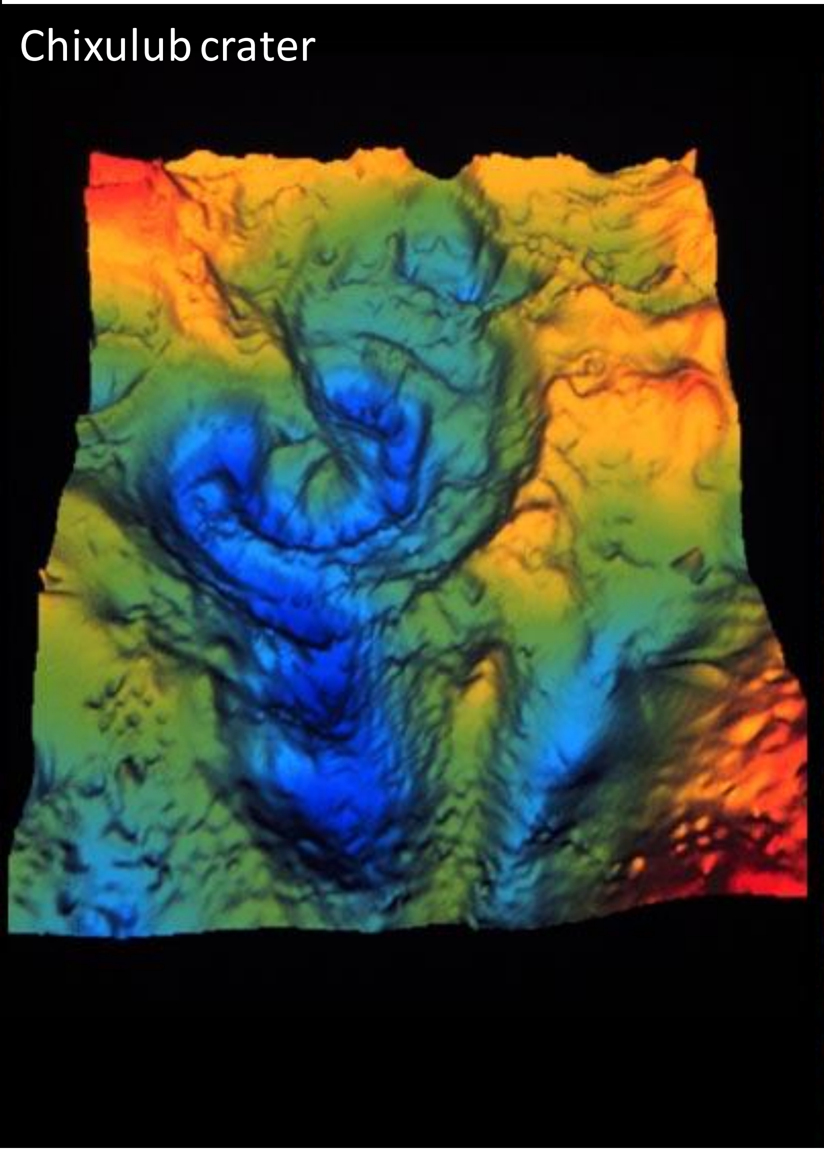
Ultra-high-pressure metamorphism occurs deep in Earth's crust.

Regional metamorphism occurs where high pressures and temperatures extend over large regions.

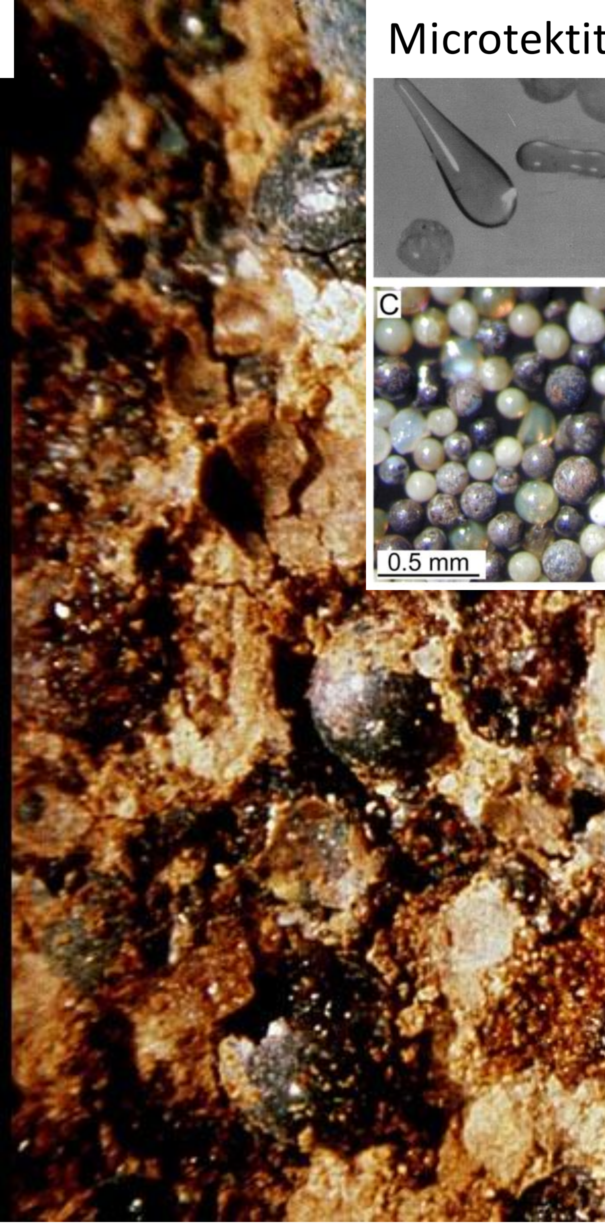
High-pressure, low-temperature metamorphism occurs where oceanic crust is subducted beneath the leading edge of a continental plate.

Understanding Earth

Shock metamorphism

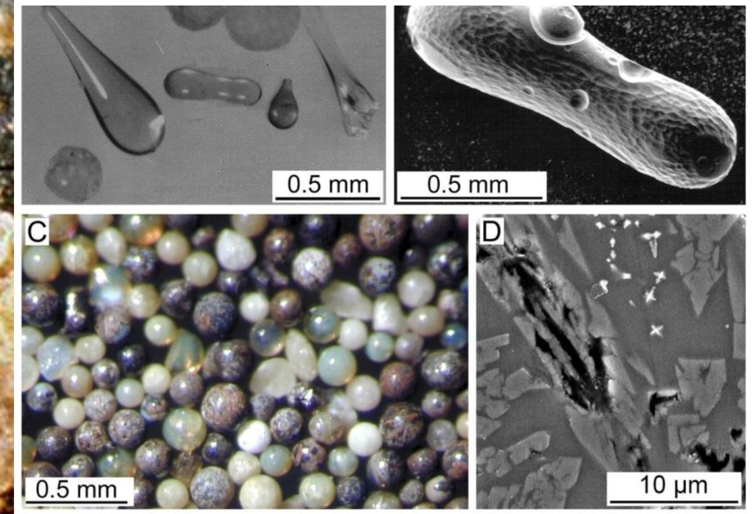


ESRF - European Synchrotron Radiation Facility (2011)

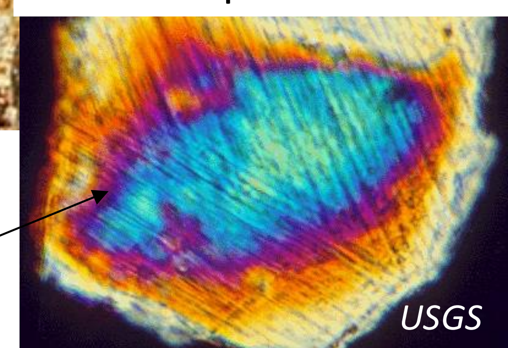


Glass and Simonson (2012)

Microtektites (Chixulub crater)



Shocked quartz



Planar deformation features

Diamonds from the Popigai impact structure, Russia

ABSTRACT

Diamonds were found in impact melt rocks and breccias at the Popigai impact structure in Siberia. The diamonds preserve the crystallographic habit and twinning of graphites in the preimpact target rocks, from which they formed by shock transformation. Secondary and transmission electron microscopy indicate that the samples are polycrystalline and contain abundant very thin lamellae, which could represent stacking faults, with local hexagonal symmetry, or microtwins. Microcrystalline units are ≤1 µm. Infrared spectroscopy indicates the presence of solid CO_2 and water in microinclusions in the diamonds, CO_2 being under a pressure greater than 5 GPa (at room temperature). Trace element and isotopic compositions confirm the derivation from graphite precursors.

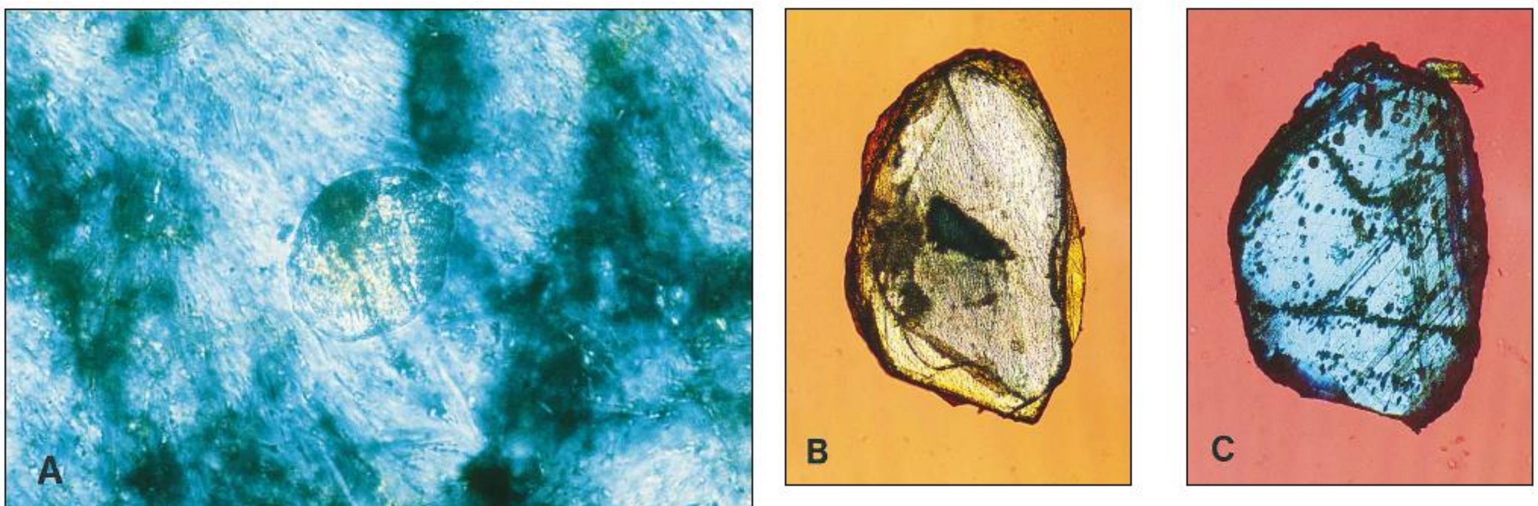


Figure 1. A: Authigenic Popigai impact diamond (diameter about 150 µm) in recrystallized plagioclase within strongly shocked biotite-garnet gneiss, which, in turn, is a clast within massive impact melt; crossed polarizers. B: Popigai diamond (long dimension 560 µm) showing fine lamellar structure due to shock metamorphism, and (dark zone at center) remnant of Wesselowski twin inherited from original graphite; circular polarization. C: Impact diamond (long dimension 570 µm) showing slight etching preferentially along twinning junctions and fissures, and flakes of secondary graphite; circular polarization.

Koeberl et al. (1997), Geology

✶ Metamorphic textures

The metamorphic texture is determined by the **size**, **shape**, and **orientation** of crystals.

1. **Foliated** metamorphic rocks
   - Preferential orientation of new minerals under directed pressure
   - Major causes of foliation:

     (1) formation of minerals with a platy crystal habit (micas, chlorite)

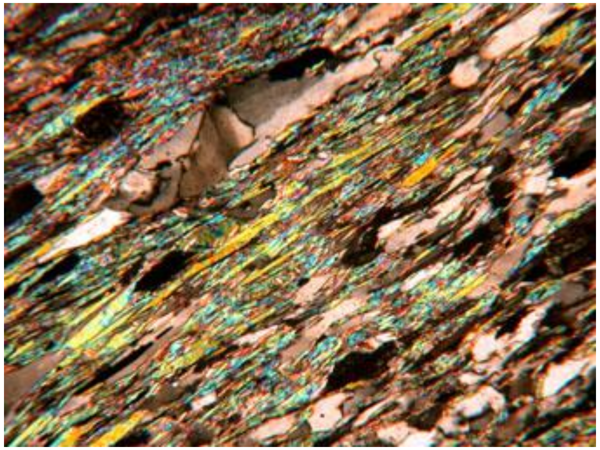
     (2) Reorientation of preexisting minerals

2. **Non-foliated/granoblastic** metamorphic rocks
   - No preferential growth orientation of minerals (absence of directed pressure)
   - Crystals have equidimensional shapes

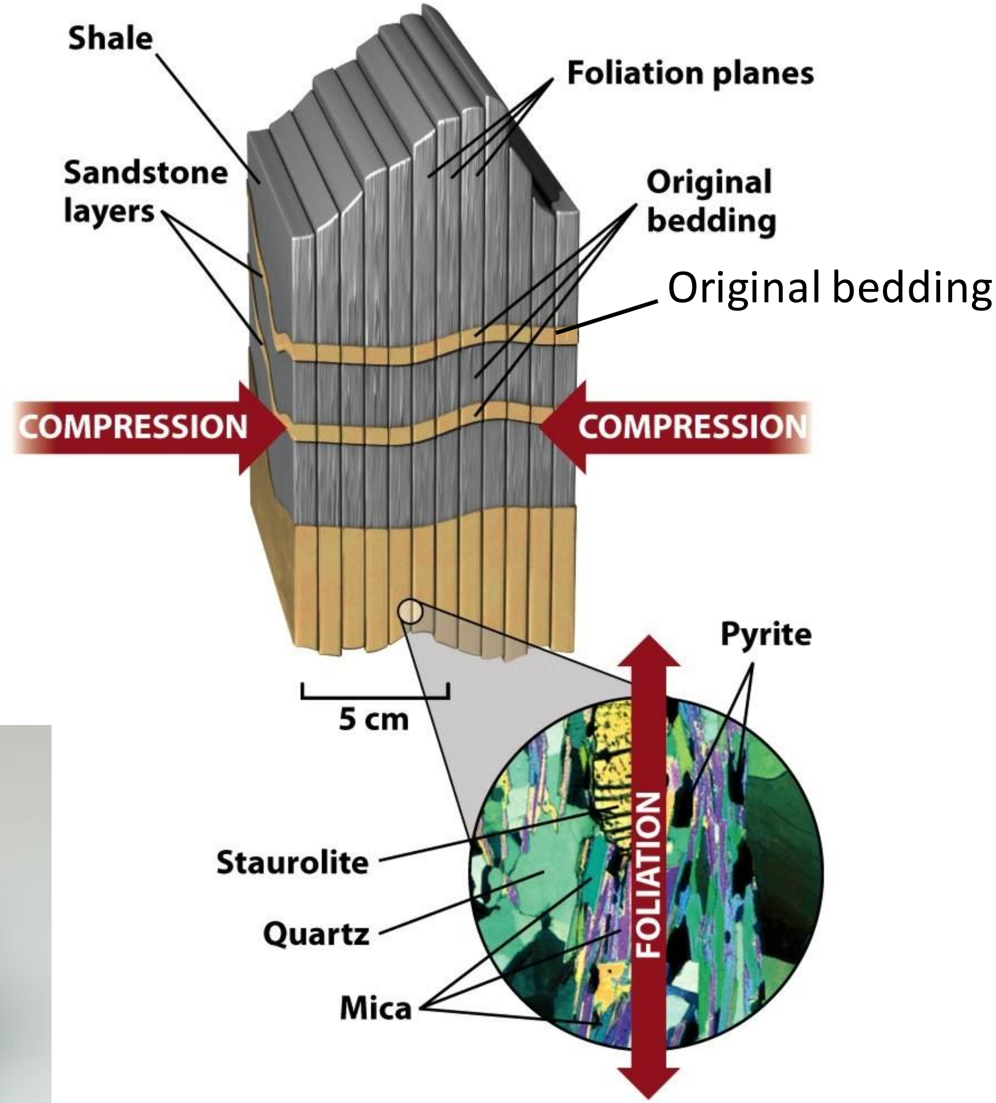
3. **Porphyroblastic** texture
   - Large crystals “floating” in a fine-grained matrix

1. Foliated metamorphic rocks

Schistosity



Ruth Siddall (Univ. College London)



FOLIATION PLANE ≠ BEDDING PLACE

Major types of foliated metamorphic rocks:

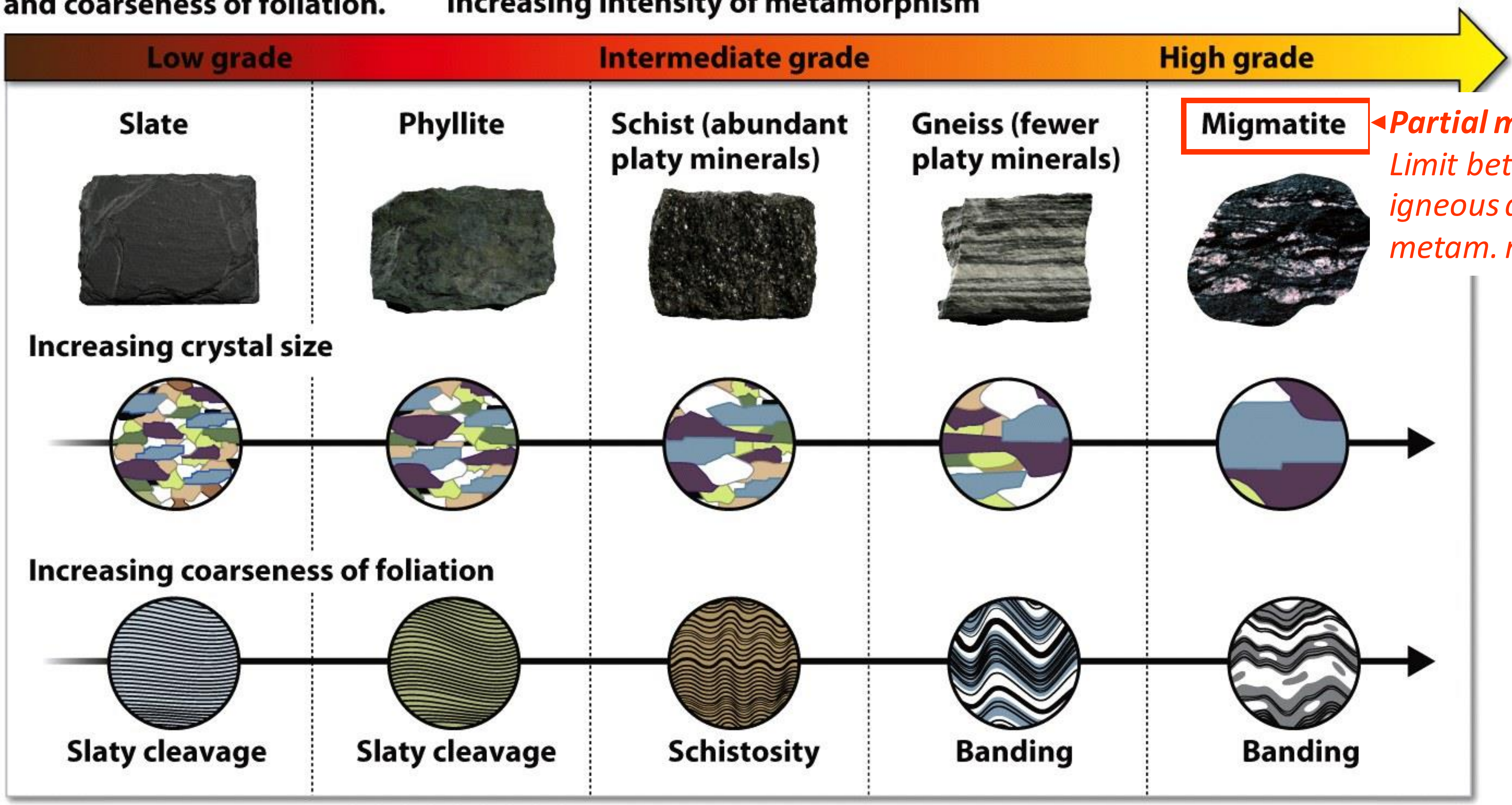
As the temperature and pressure increases, a shale may metamorphose successively into a slate, a phyllite, a schist, a gneiss, and finally a migmatite.

Wikipedia

SHALE

Fine-grained sedimentary rock

As intensity of metamorphism increases, so does crystal size and coarseness of foliation.



Partial melting

Limit between igneous and metam. rock

SLATE (reorientation of preexisting clay minerals perp. to directed pressure)

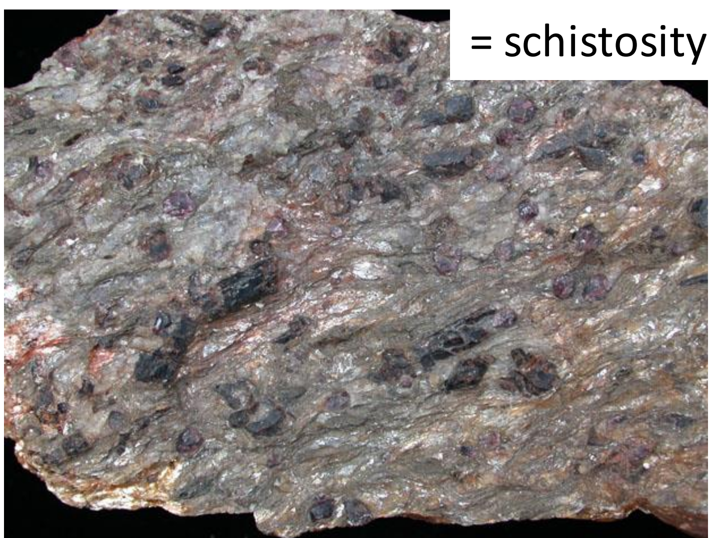
www.pitt.edu

PHYLLITE (formation of new minerals which orientate perp. to directed pressure)

http://itc.gsw.edu

SCHIST (minerals grow larger and foliation becomes more pronounced)

= schistosity



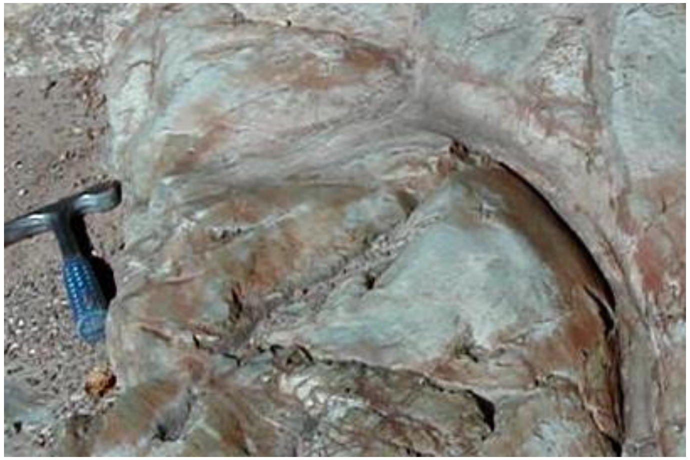
GNEISS (coarse-grained bands of dark mafic and light felsic minerals)

2. Non-foliated / granoblastic metamorphic rocks

Marble

Metamorphosed carbonate rock

Greenstone

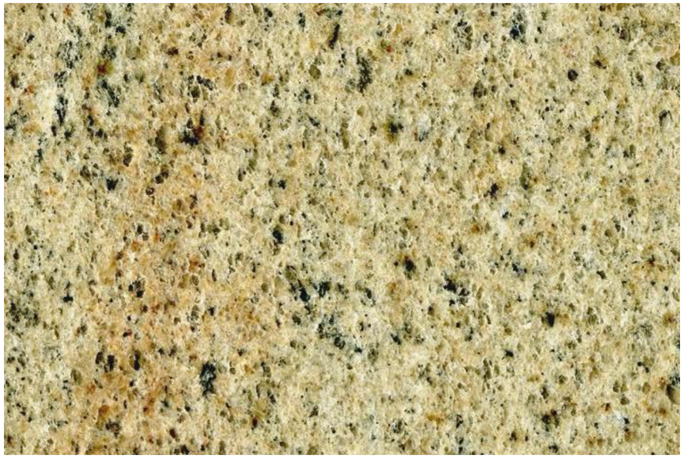


Metamorphosed basalt (low grade)

Quartzite

Metamorphosed quartz-rich sandstone

Granulite



High-grade metamorphism (deep cont. crust)

3. Porphyroblastic texture

- Large crystals in a fine-grained matrix
- Minerals stable in broad range of pressure and temperature grow steadily, whereas minerals of the matrix are constantly being recrystallized as temperature and pressure increase.

Garnet **porphyroblast**

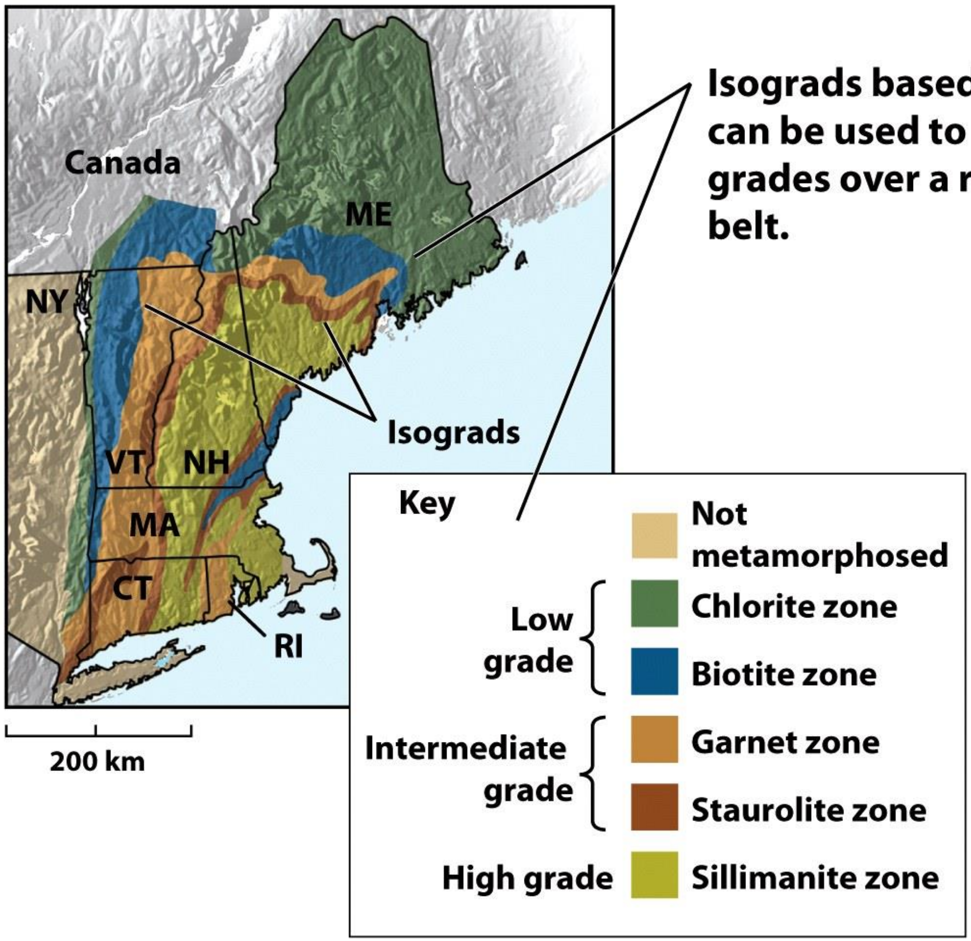
www.geology.about.com

Metamorphosed basalt or shale (moderate grade)

Understanding Earth

✶ Index minerals

Geologists study metamorphic rocks to understand the conditions in which they formed (temperature, pressure, parent-rock composition, and geologic setting).

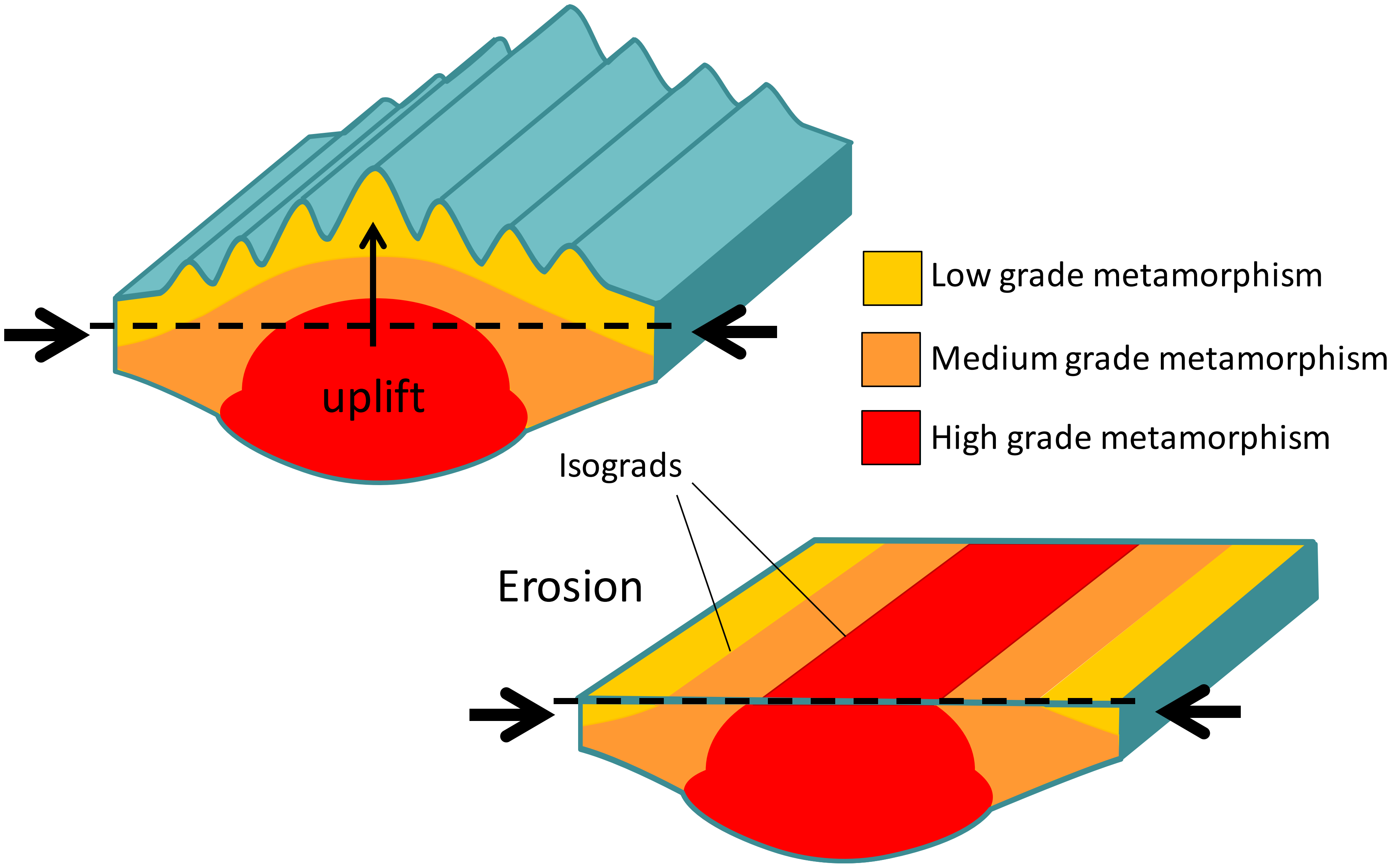


Index minerals are minerals forming in a **limited range of temperatures and pressures** (known by lab experiments).

Based on the occurrence of index minerals, geologists can draw the **boundaries between metamorphic zones characterized by specific metamorphic grades**. These boundaries are called **isograds**.

Understanding Earth

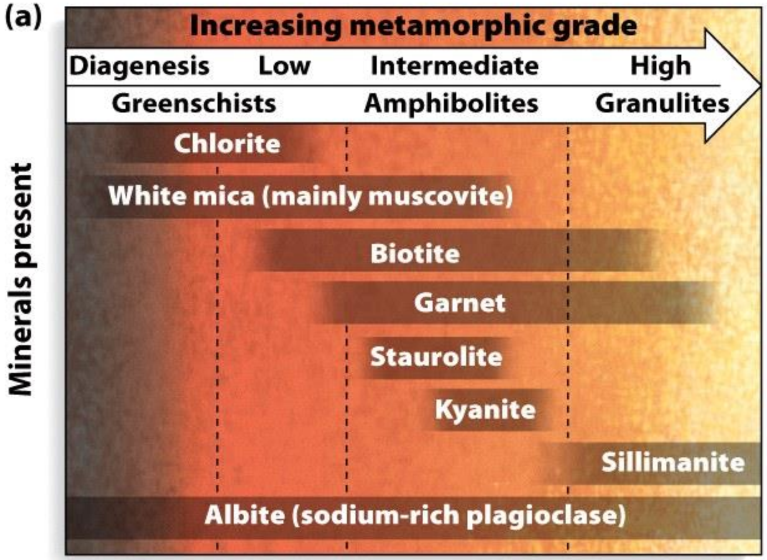
Metamorphic belts



✶ Metamorphic facies

SHALE

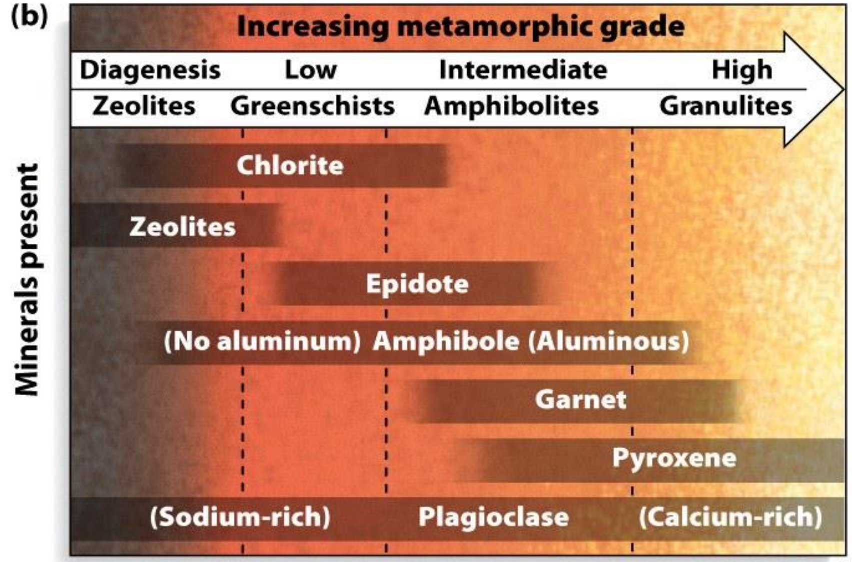
(a)



Changes in the mineral composition of shale during metamorphism

BASALT

(b)



Changes in the mineral composition of mafic rock during metamorphism

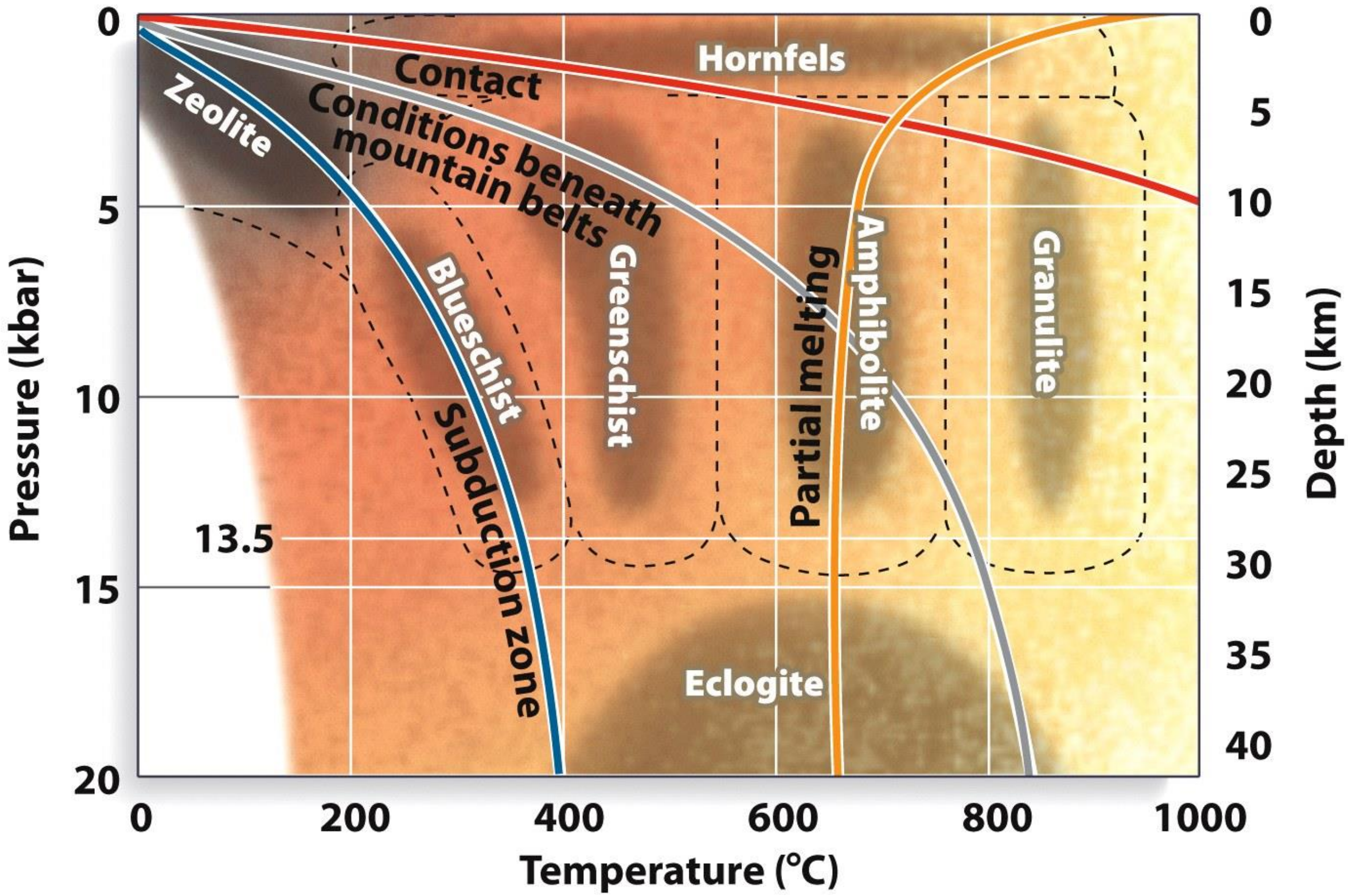
(c)

Metamorphic Facies	Minerals Produced from Shale Parent	Minerals Produced from Basalt Parent
Greenschist	Muscovite, chlorite, quartz, albite	Albite, epidote, chlorite
Amphibolite	Muscovite, biotite, garnet, quartz, albite, staurolite, kyanite, sillimanite	Amphibole, plagioclase feldspar
Granulite	Garnet, sillimanite, albite, orthoclase, quartz, biotite	Calcium-rich pyroxene, calcium-rich plagioclase feldspar
Eclogite	Garnet, sodium-rich pyroxene, quartz/coesite, kyanite	Sodium-rich pyroxene, garnet

Understanding Earth

Metamorphic facies are groupings of various mineral compositions formed under particular conditions of temperature and pressure and derived from various parent rocks.

Once geologists have identified the different metamorphic facies coexisting in a particular region, they can obtain information on the **geologic setting** in which the metamorphic rocks formed.

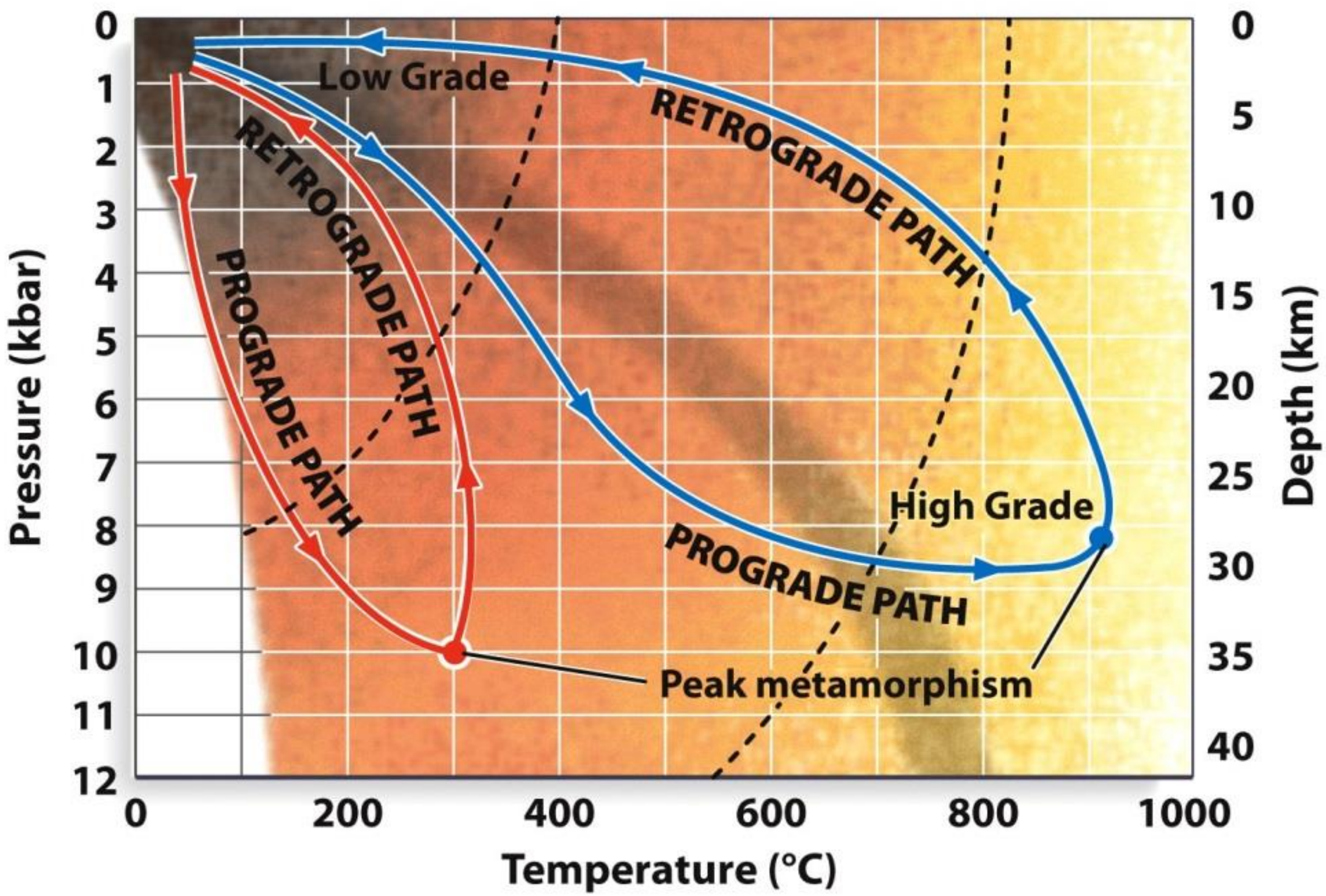


Understanding Earth

✶ Metamorphic T-P paths

Prograde path = increase in T-P as rock reaches greater depths in the crust

Retrograde path = decrease in T-P as rock is progressively exhumed or transported back to Earth's surface



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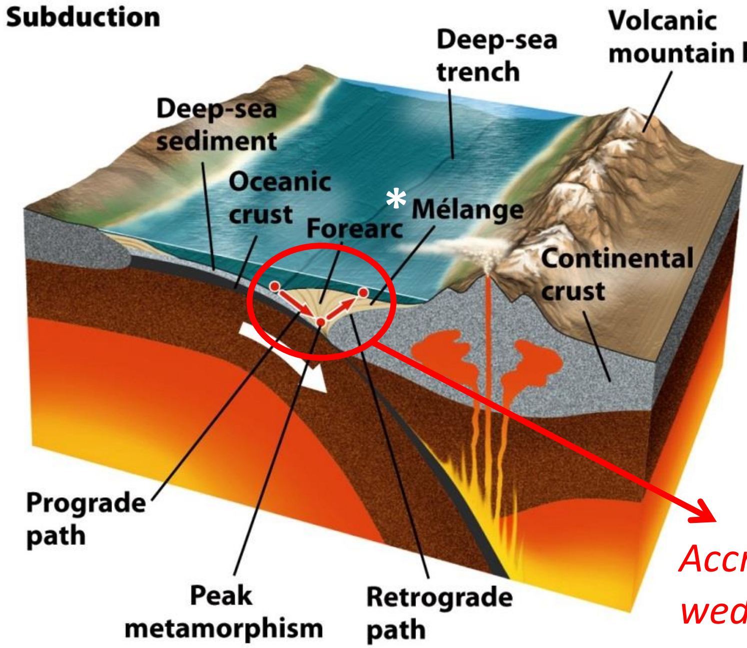
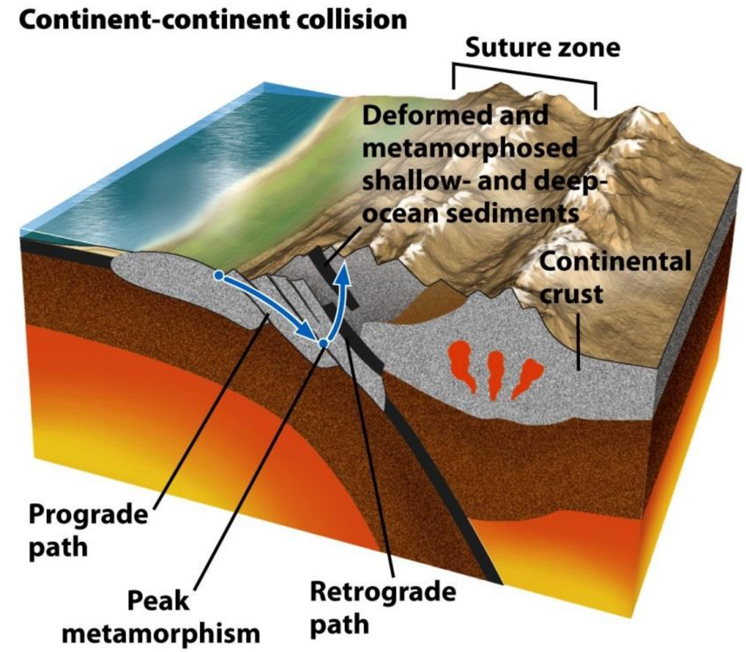
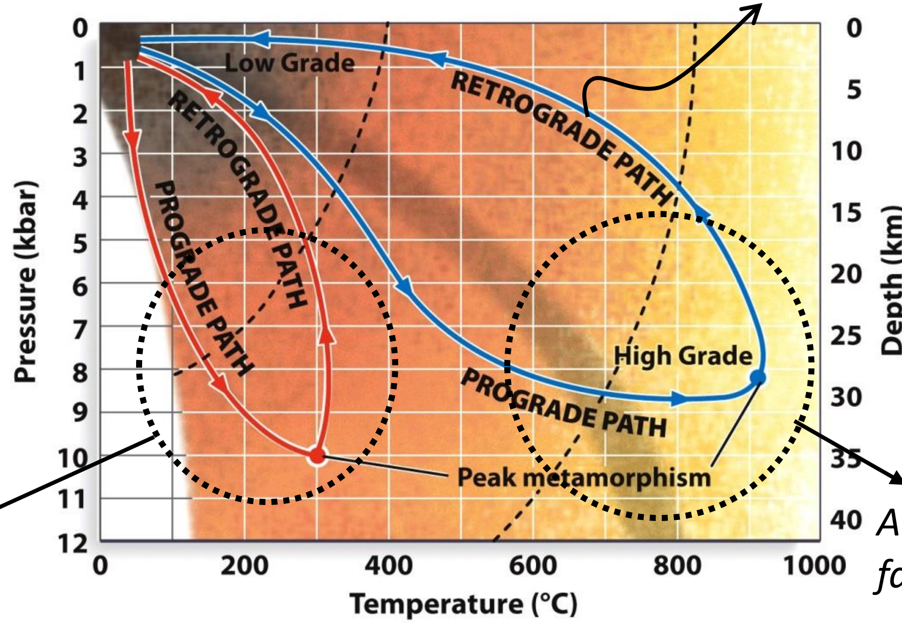


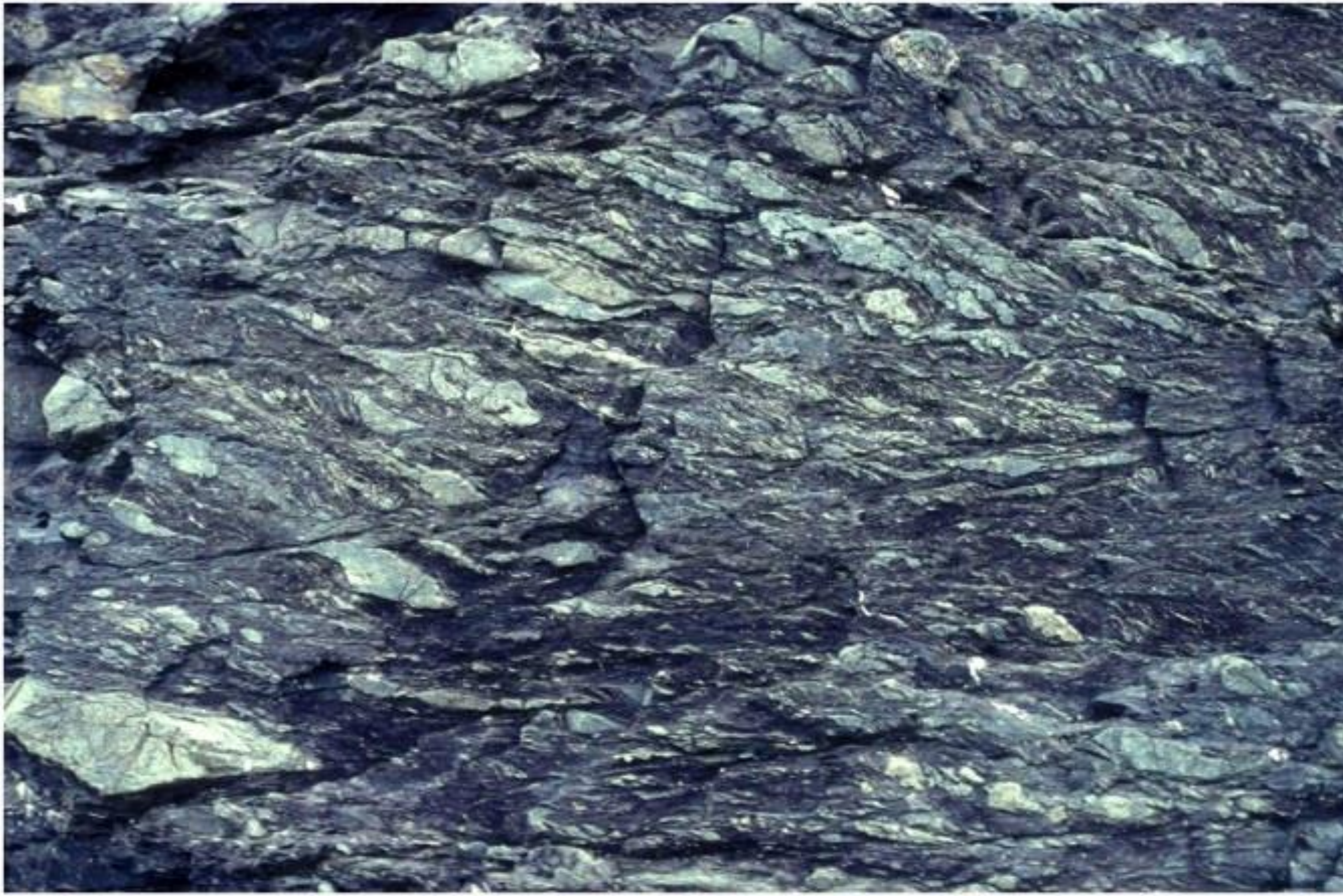


- P-T paths can be associated with particular **geologic settings**.

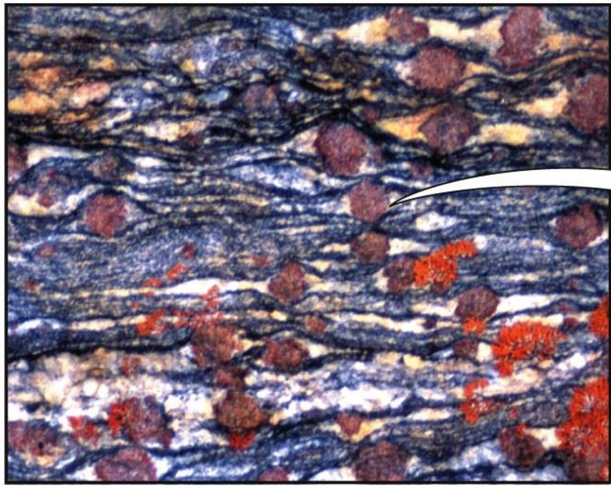


Understanding Earth

*** *Mélange (from French = mixture)***

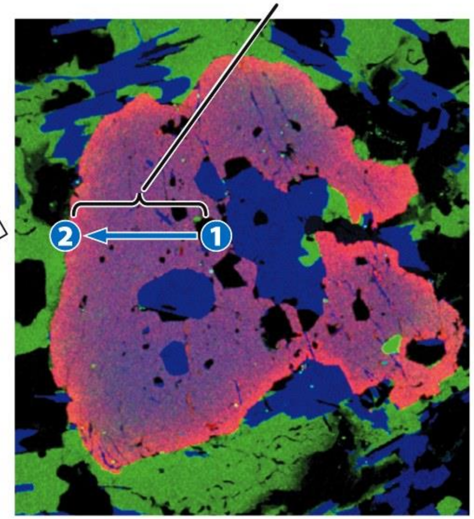


1 During metamorphism, a garnet crystal grows, and the composition of the growing crystal changes as the temperature and pressure around it change.



Thin section of garnet gneiss

2 The composition of the crystal can be plotted on the P-T path as it grows from 1 in its center to 2 at its edge.

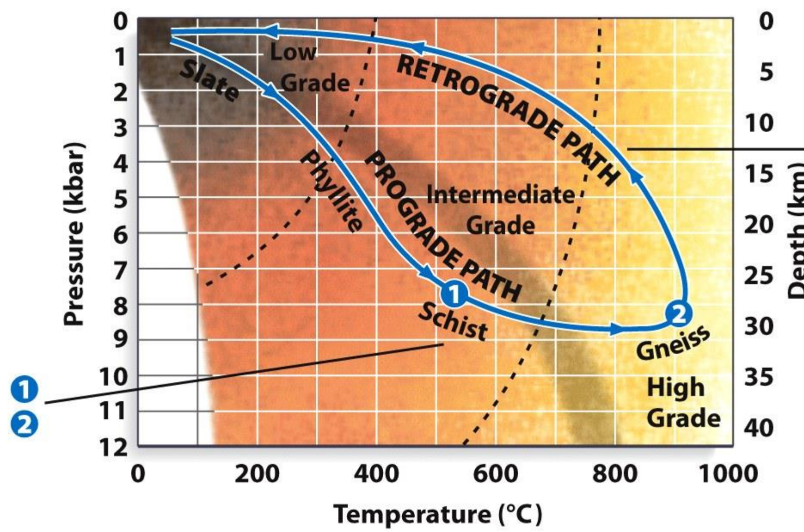


Growth zoning in garnet

- The **chemical composition** of these minerals changes with changing T and P (known through lab experiments). This property can be used to reconstruct the T-P path of metamorphic rocks.

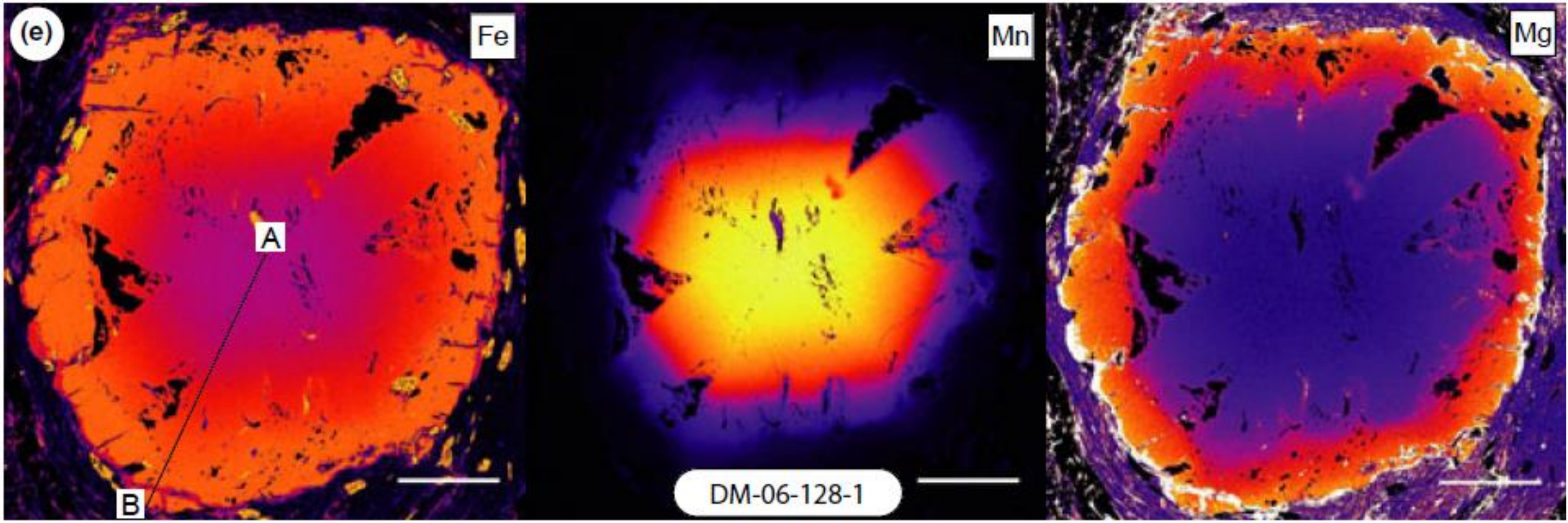
- The best recorders of T and P are minerals which **grow** steadily in a **broad range of T and P** (e.g. garnet).

3 As rock is carried deeper in Earth's crust and is subjected to higher temperatures and pressures (the **prograde** path), the garnet crystal initially grows in a schist but ends up growing in a gneiss as metamorphism progresses.



4 The retrograde path indicates decreasing temperatures and pressures as rock is carried toward Earth's surface.

Understanding Earth



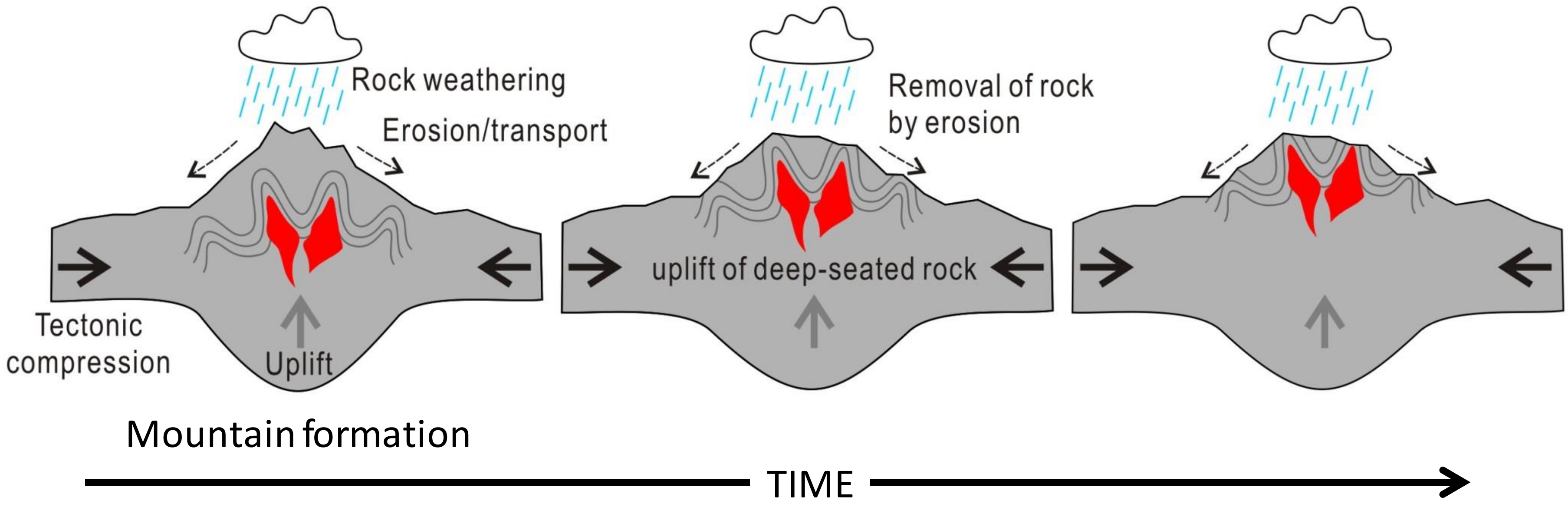
A garnet crystal for which the concentrations of Fe, Mn, and Mg were mapped. Warmer colors indicate higher concentrations (from Moynihan & Pattison, 2013). The technique used here is Electron probe micro-analysis (EPMA*).

* In EPMA, the sample is bombarded by accelerated electrons (same technique as scanning electron microscopy – SEM). The electron beam and sample interact. The products of this interaction (i.e., electrons emitted from the surface of the sample and X-rays) can be used to obtain an image of the sample and analyze its chemical composition.

✶ The retrograde path: exhumation process

- **Exhumation** = "return of once deep-seated metamorphic rocks to Earth's surface" (Ring et al., 1999)

- Interaction between plate tectonics and climate drives the flow of metamorphic rocks to Earth's surface.
  - Continental crust deformation (**rock uplift** controlled by tectonics)
  - **Weathering and erosion** (controlled by climate)



Appalachian mountain chain (USA) – process of mountain building (orogeny) took place in two phases 450-300 Myr ago (leading to formation of Supercontinent Pangaea).


~ 13 km
Image U.S. Geological Survey
Image PA Department of Conservation and Natural Resources-PAMAP/USGS
Google earth