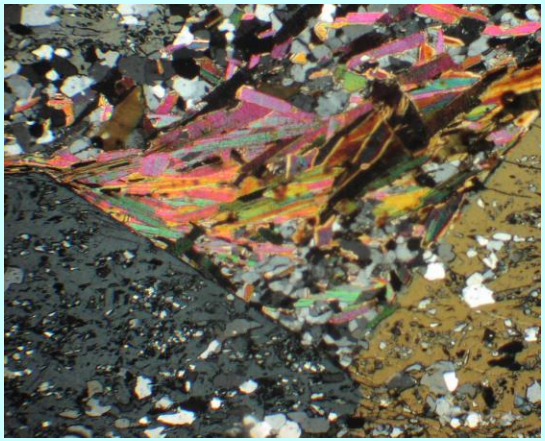
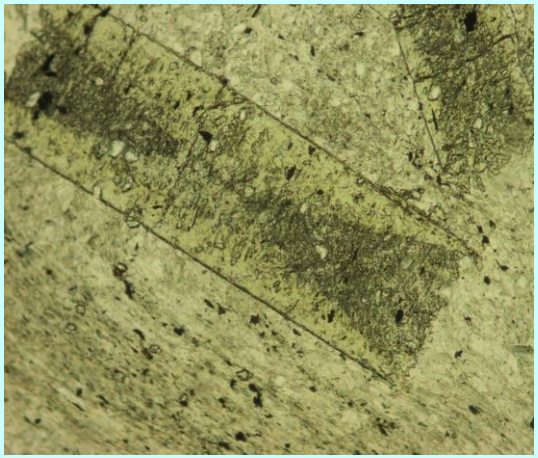
Lecture FOUR
Metamorphic Reactions and Protoliths of Metamorphic Rocks

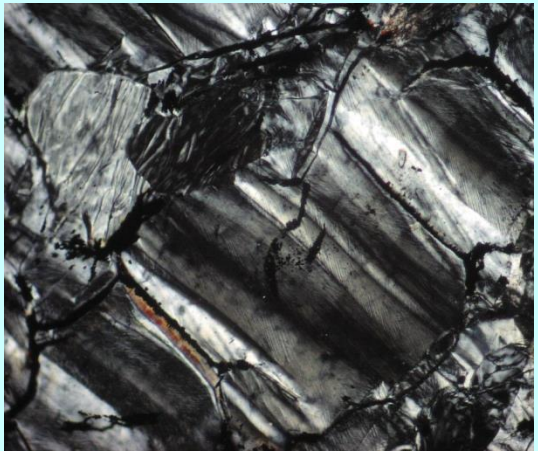
Development of Metamorphic Rocks

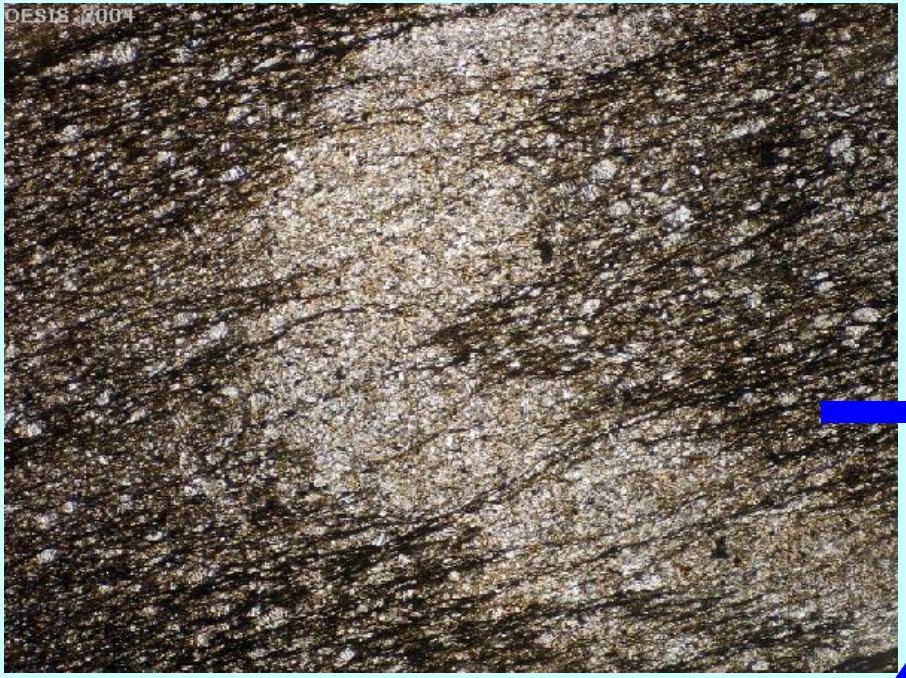
The yielded metamorphic rocks, with specific mineral composition and textures is a function of:

- **Protolith nature i.e: whole rock chemistry** (pelitic (Argillaceous), semipelitic, calcareous (limestone and dolomite), mafic-ultramafic, basic igneous, granitic, Mn-rich sediments, ironstone, laterites... etc.)
- **P-T-X conditions** (the intensity of temperature and the intensity and type of pressure (simple compressed or twisted and broken) influence and the presence or absence of fluids and their chemistry during metamorphism)
- **Time** (how long the rock subjected to HT and HP?. By which the grain size was evolved, and the reactions were proceed)





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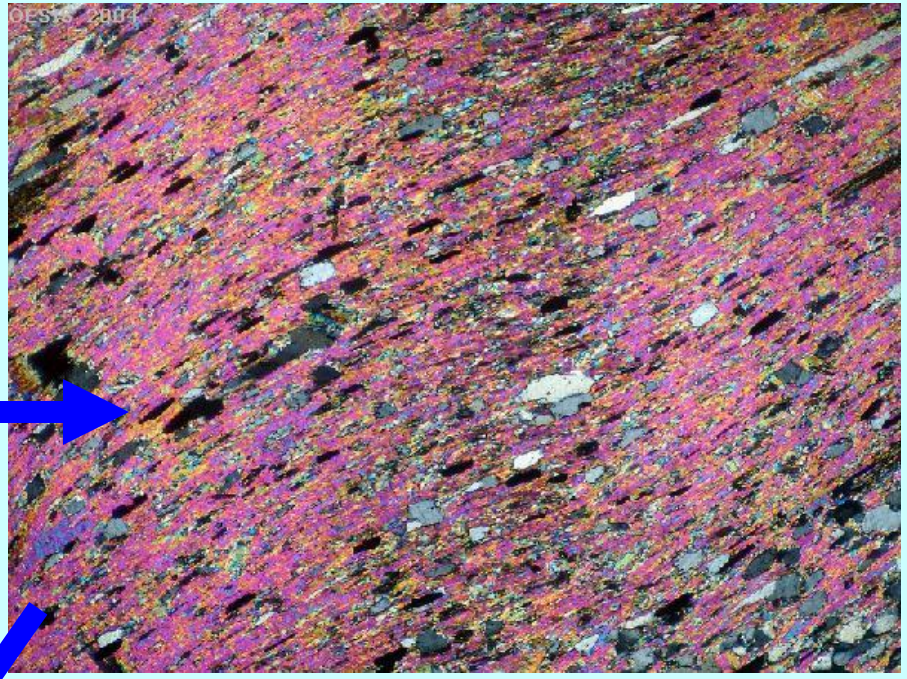
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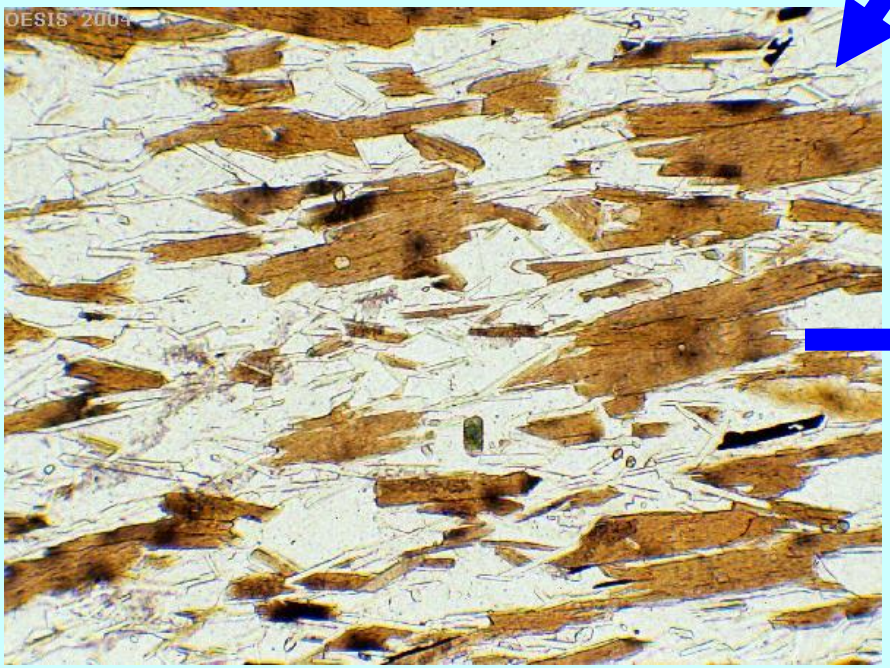
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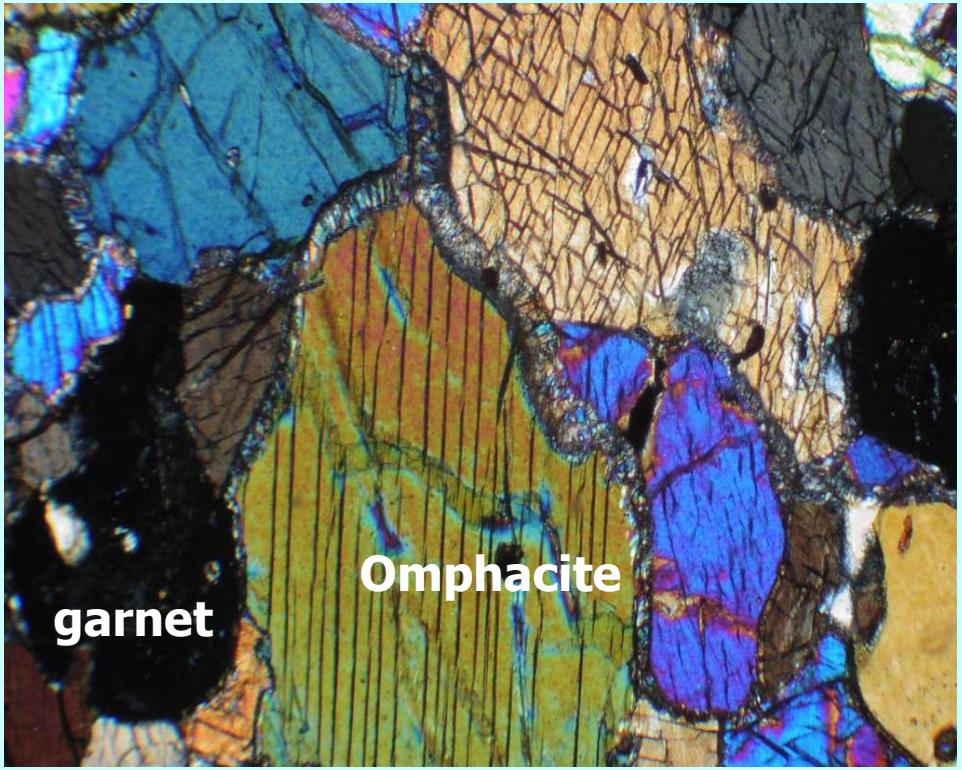
Metamorphic Rocks components and development

A metamorphic rock consists of individual grains of several solid minerals and a network of grain boundaries, which at the time of metamorphism may have held an aqueous fluid, providing pathways for transport through the rock.



Development of Metamorphic minerals

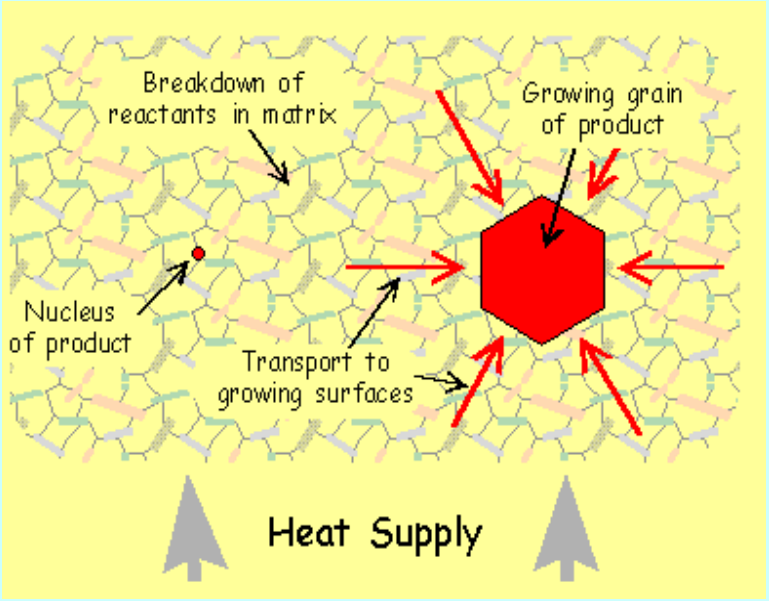
For a new mineral to appear by a chemical reaction, a number of processes have to operate in concern:

➔ ***Nucleation***: nuclei (embryo crystals) of the new mineral appear

➔ ***Interface reactions - dissolution***: reactant minerals break down, their chemical constituents going into solution

➔ ***Interface reactions - growth***: material is added onto the nuclei to build larger crystals

➔ ***Mass transfer***: material is transported through the rock from sites of breakdown to sites of growth



Nucleation, Mineral growth and Grain size

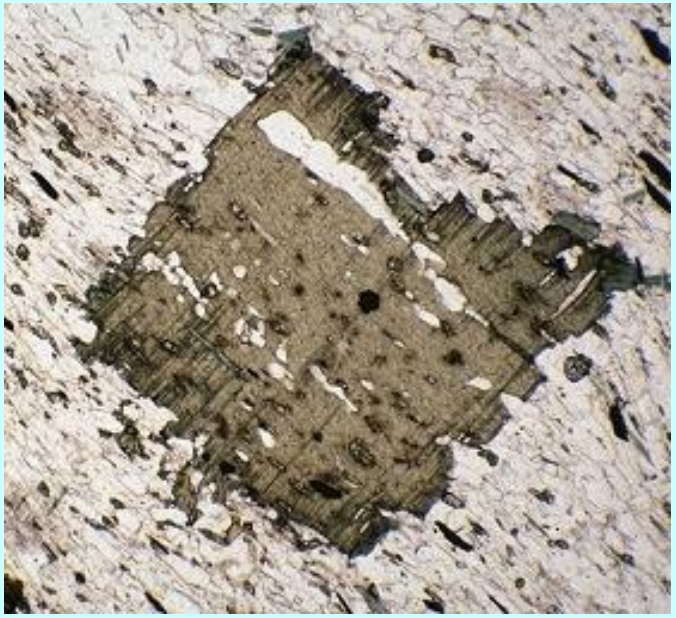
-Completed reaction produces an amount of product (mineral phases). The microstructure, will depend on the relative rates of nucleation and growth of minerals

- Grain size in a metamorphic rocks is a function in:

- Intensity of P-T conditions,
- nuclation rate, and
-Time interval of metamorphism

-Coarse-grained rocks are the product of long sustained metamorphic conditions (possibly over millions of years) at HT and HP (e.g. in high grade regional metamorphic rocks)

-Fine-grained rocks are products of LP, LT, in some cases, short reaction time (e.g. in contact metamorphiic rocks)



Metamorphic Reactions and P-T path

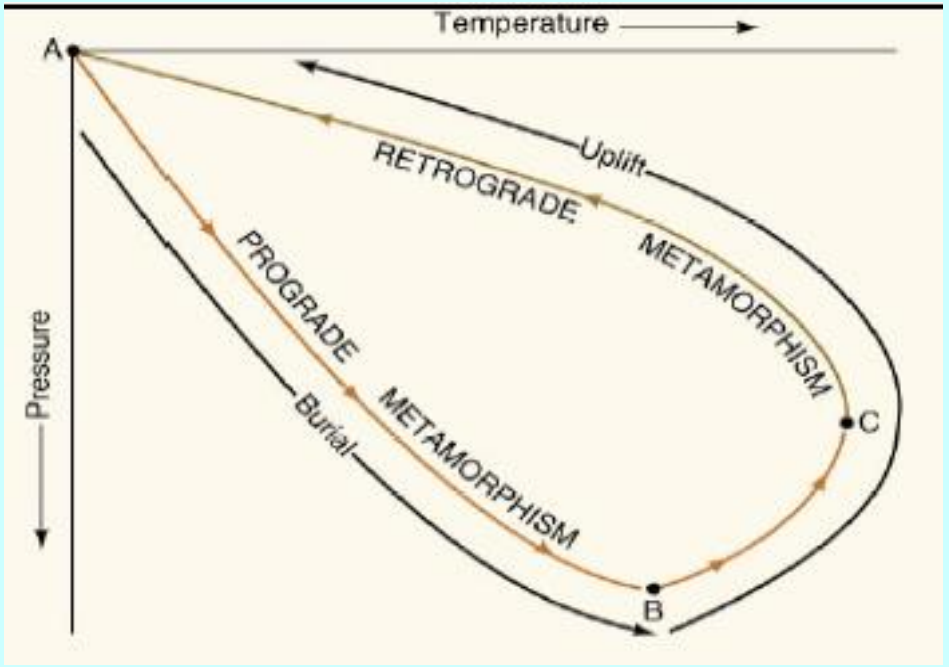
- With increasing P-T conditions, metamorphic reaction toke place (e.g. burial effect) until the maximum pressure and temperature (peak condition), then with decreasing the P-T conditions (e.g. uplift) until cooling of the rock. This is known as *Metamorphic P-T path*

- The P-T path include three segments:

➔ *Prograde segment*: With increasing the P-T conditions (such as burial effect)

➔ *Peak segment*: at maximum P-T conditions (at the summit metamorphic conditions)

➔ *Retrograde segment*: With decreasing P-T conditions (such as uplift)



- The metamorphic P-T can be simple (clockwise or anticlockwise) or complex due to multiphase metamorphism

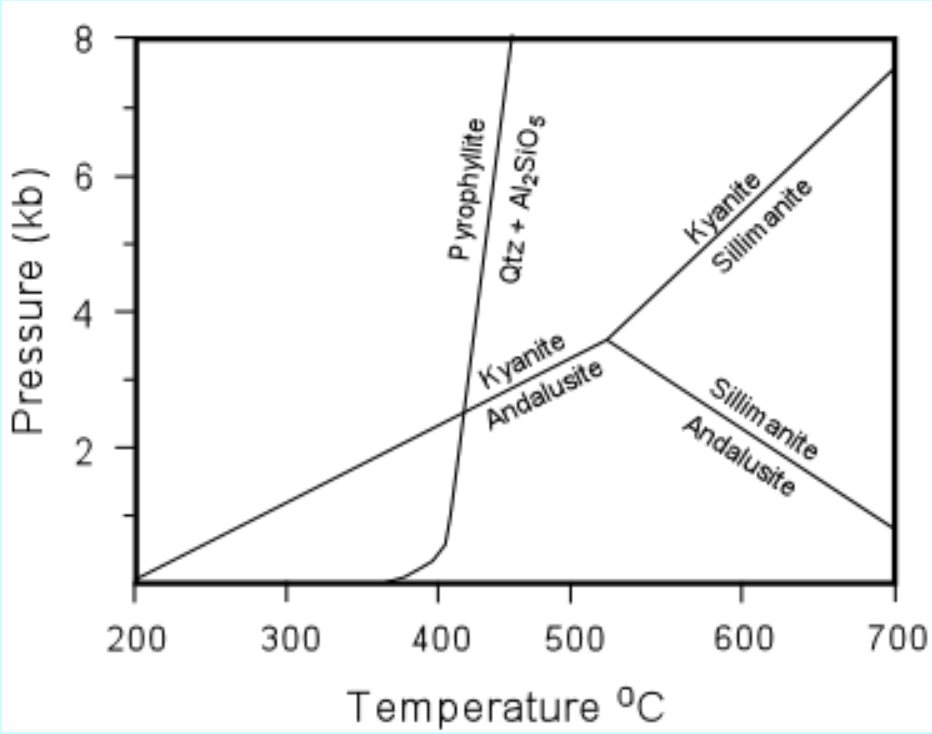
Types of Metamorphic reactions

- With either progressing or retrogressing metamorphism, various types of metamorphic reactions are proceeds e.g.:

1- *Univarient reactions*: reactions that plot as line or curve on the P-T diagram and depend on temperature and pressure only e.g:

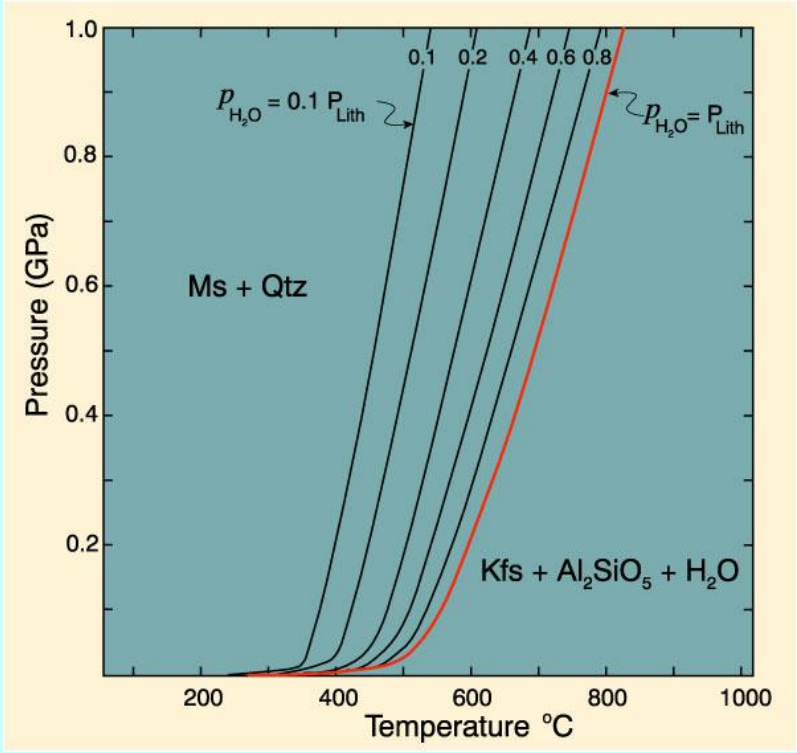
$Al_2Si_4O_{10}(OH)_2 \rightarrow Al_2SiO_5 + 3\ SiO_2 + H_2O$

Pyrophyllite Al-silicate + Qtz + fluid



Cont. Types of Metamorphic reactions

2- *Divarient reactions*: reactions occur over wide range of P-T. This because most minerals involved in the reaction exhibit solid solution (e.g garnet, mica, plagioclase); therefore, the reaction boundaries can changed depend on the composition of solid solution.



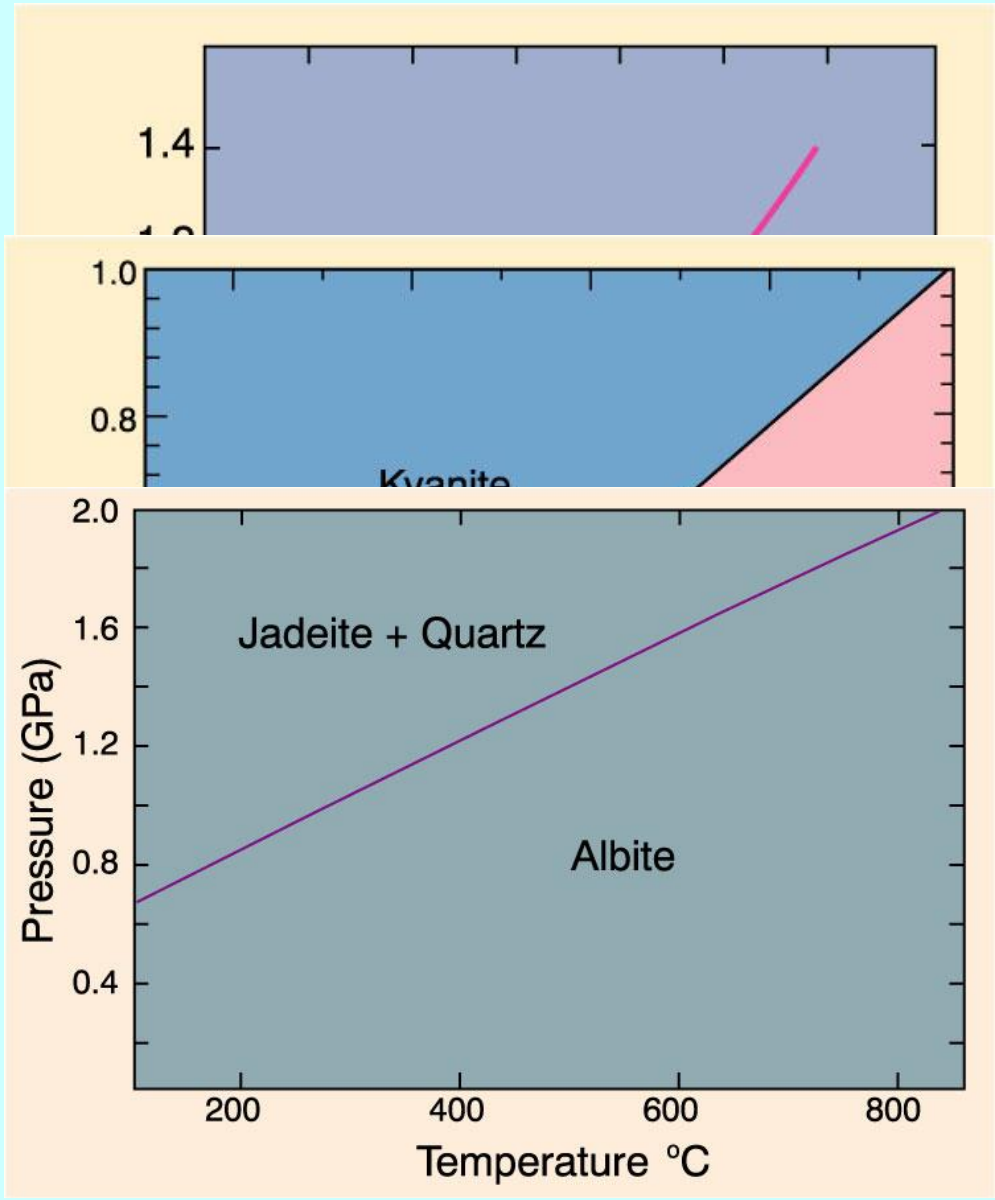
$$KAl_2Si_3AlO_{10}(OH)_2 + SiO_2 = KAlSi_3O_8 + Al_2SiO_5 + H_2O$$

Ms Qtz Kfs Sill W

Cont. Types of Metamorphic reactions

3- *Solid-soild reaction*: only involve the solid-phases for both reactant and products (with no fluid phases). So reactions involves phase transformation e.g.

Calcite ↔ aragonite,
andalusite ↔ sillimanite,
graphite ↔ diamond
Albite ↔ jadite + quartz



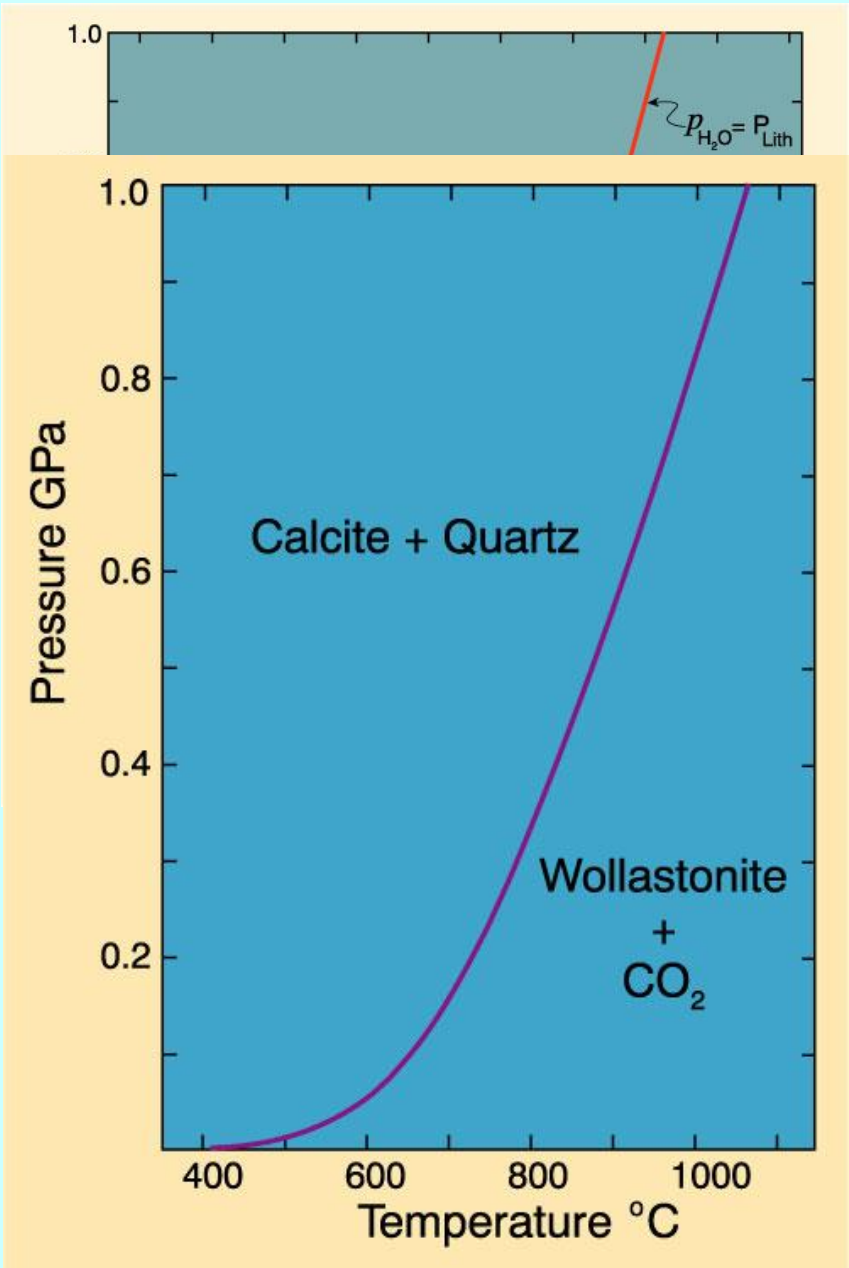
Cont. Types of Metamorphic reactions

***4- Dehydration reactions*: reactions that liberate H_2O. This always occur in the prograde reaction, i.e. with increasing temperature e.g**

chlorite + muscovite →
orthoclase + andalusite + $H_2O\uparrow$

***5- Decabonation reaction* : reactions that liberate CO_2 e.g**

Calcite + quartz → Wallstonite + $CO_2\uparrow$



Cont. Types of Metamorphic reactions

6- Oxidation-reduction reaction: **reactions that involve change the valence state of Fe-Ti oxide phases (Fe^{+2} and Fe^{+3}) e.g: the breakdown of biotite to K-feldspars and magnetite at high P-T cinditions**

$$\text{biotite} + O_2 \rightarrow \text{K-feldspars} + \text{Magnetite} + H_2O$$

7- Cation exchange reaction**: reaction involves ionic substitution of two or more phases in the system e.g:**

$$\text{Fe-garnet} + \text{Mg-biotite} \rightarrow \text{Fe-biotite} + \text{Mg-garnet}$$

Protoliths of metamorphic rocks

⇨As we discuss, The yielded metamorphic rocks is function of:

- **Protolith (original rock) nature ⇨ bulk-rock chemistry**
- **P (pressure)-T (temperature)-X (active fluids) conditions**
- **Time**

At specific P-T-X conditions, reactions in solid state toke place in the rock and new equilibrated mineral assemblage and corresponding textures are arise, which equivalent to the influence metamorphic conditions.

Protoliths of metamorphic rocks

The protoliths of the metamorphic rocks could be:

-Sedimentary rocks

- **-Shales (Pelitic rocks)**
- **-Sandstones (Arenaceous rocks and semipelitic rocks)**
- **-Carbonate (Calcareous rocks)**
- **-marl rocks**

- Igneous rocks

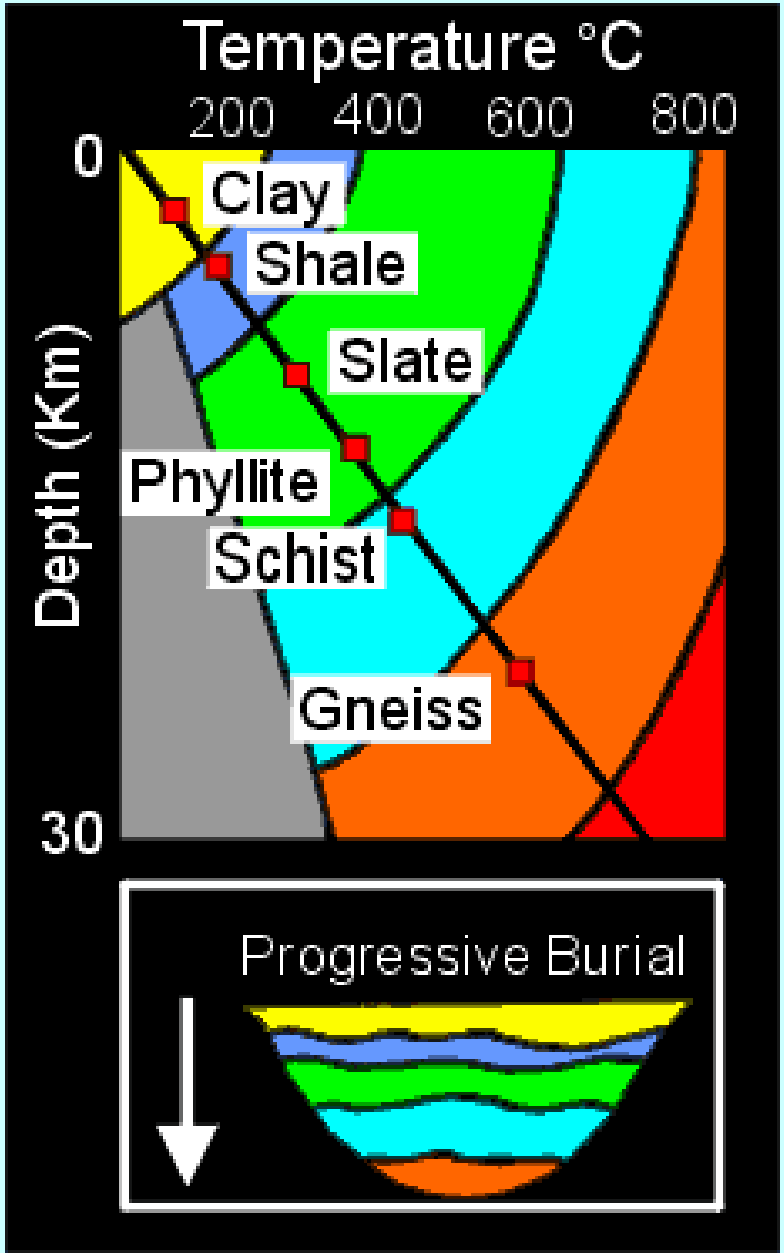
- **- Basic igneous rocks (metabasites)**
- **- Ultramafic rocks**
- **- Intermediate rocks**
- **- Acidic rocks**

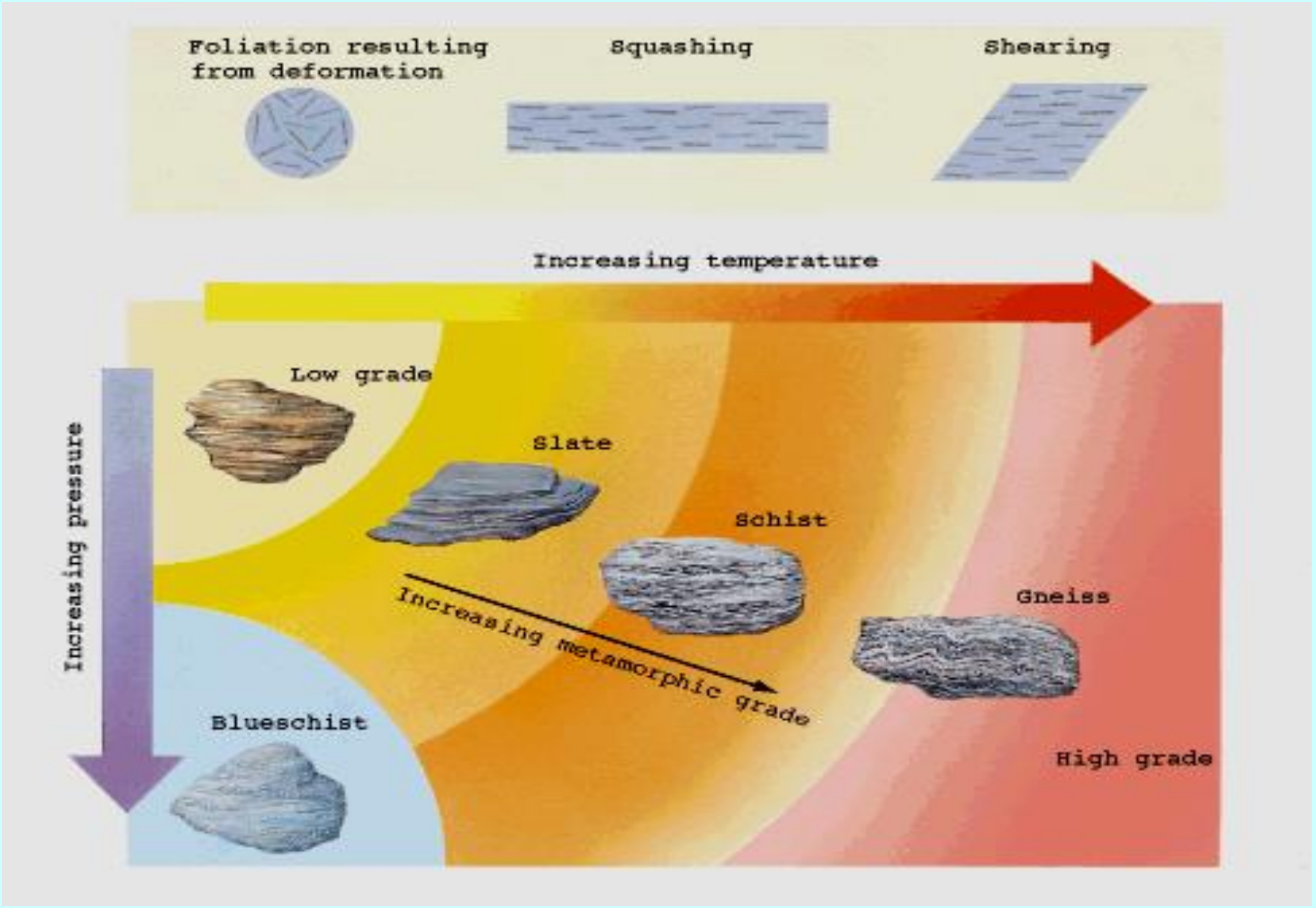
- Prior metamorphic rocks

Metapelites

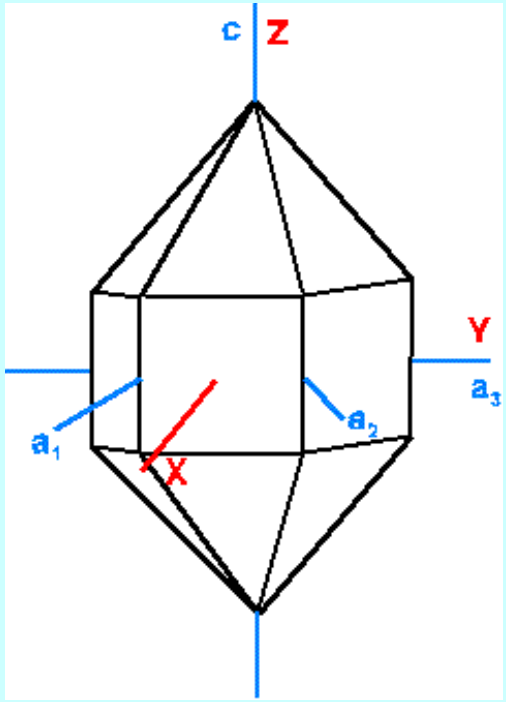
Shales (Pelites): very fine-grained sedimentary rocks, composed of silicate clay minerals rich in the elements (SiO_2, Al_2O_3, FeO, K_2O, Na_2O, H_2O), beside other minor elements.

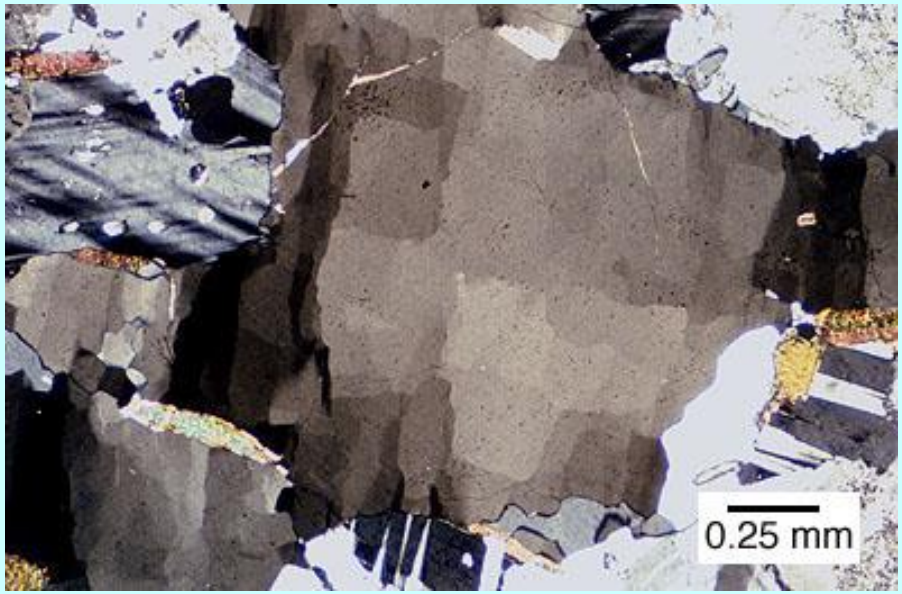
- **Common metamorphic minerals** include
- Quartz
- Feldspars (plagioclase, K-feldspars)
- Mica (sericite, muscovite, biotite, chlorite)
- garnet,
- staurolite,
- cordierite,
- Al-silicate (andalusite, kyanite, silliminite)
- Pyroxene



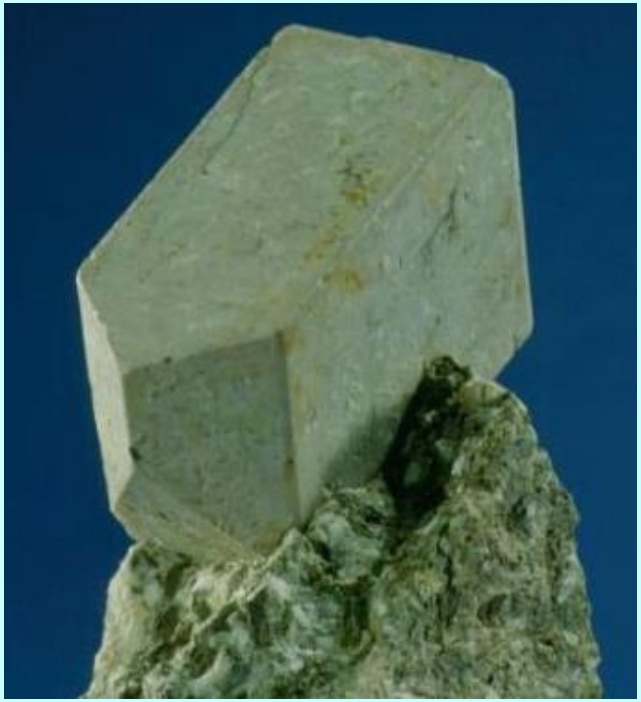

Foliation resulting from deformation
Squashing
Shearing
Increasing temperature
Low grade
Slate
Schist
Gneiss
Increasing pressure
Increasing metamorphic grade
Blueschist
High grade

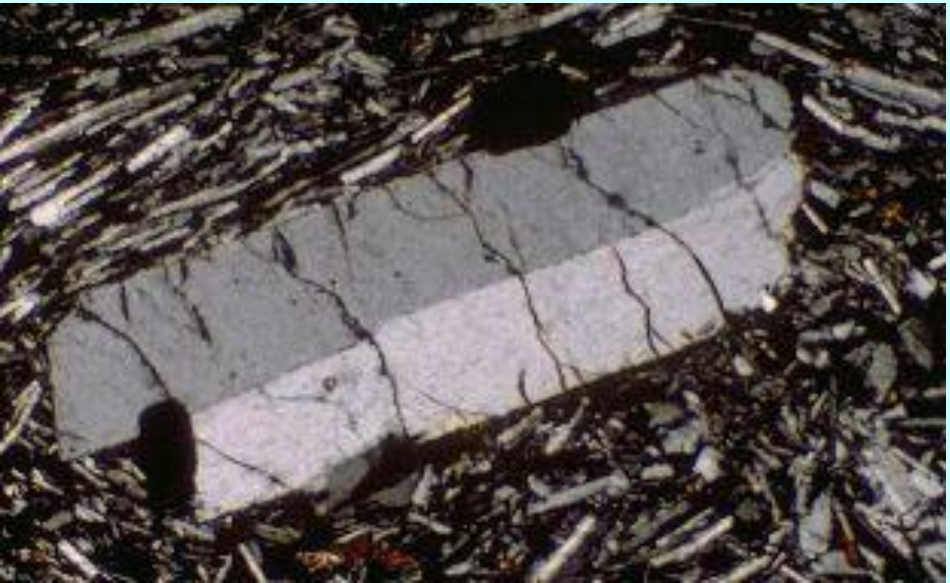
Quartz

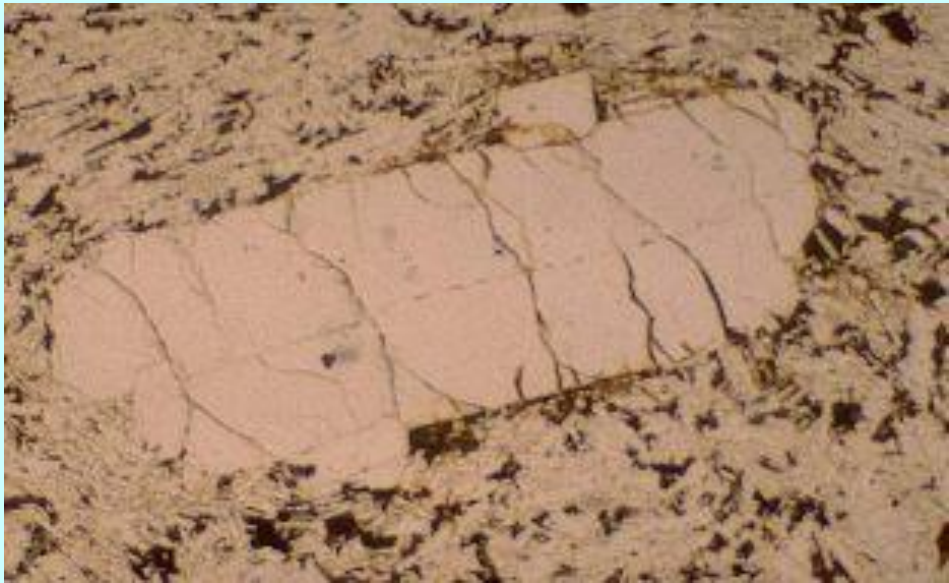




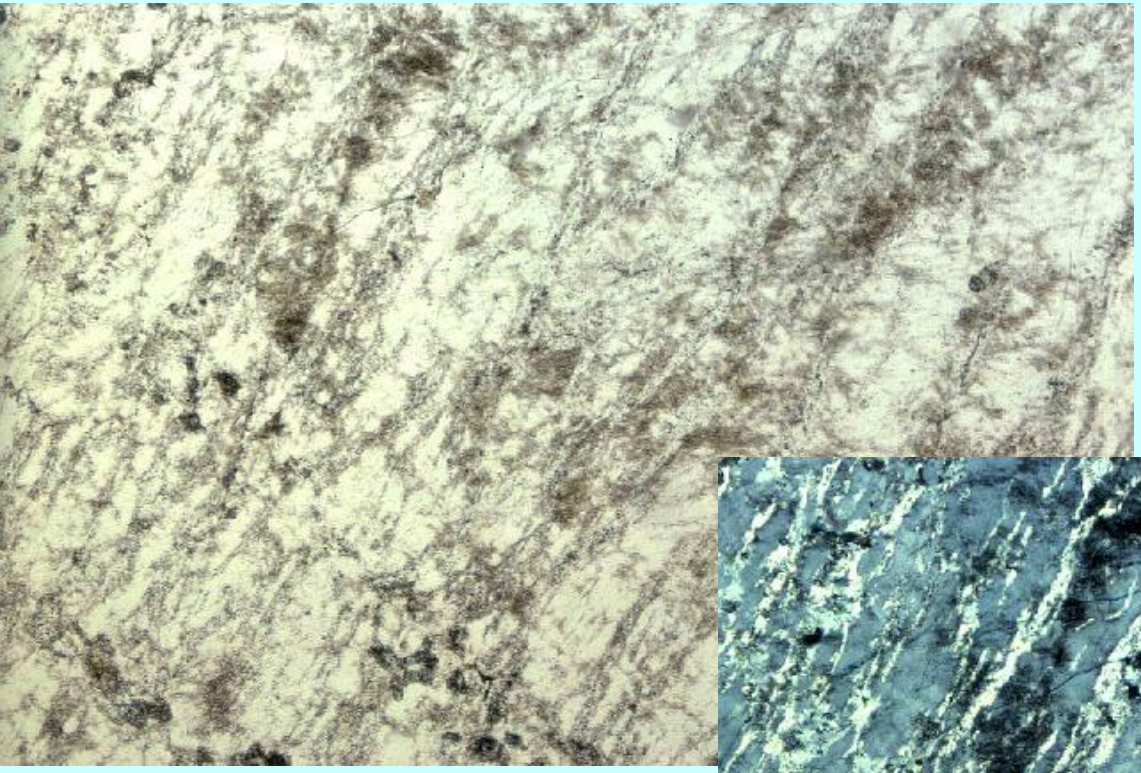
Orthoclase

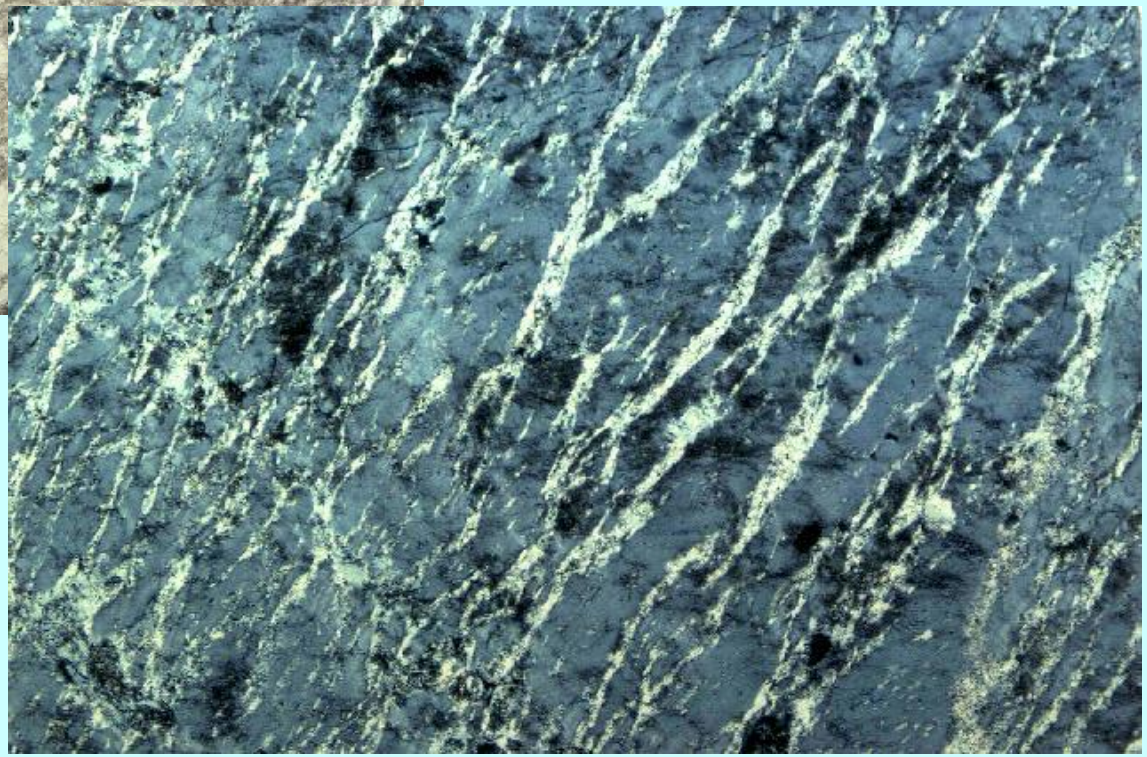




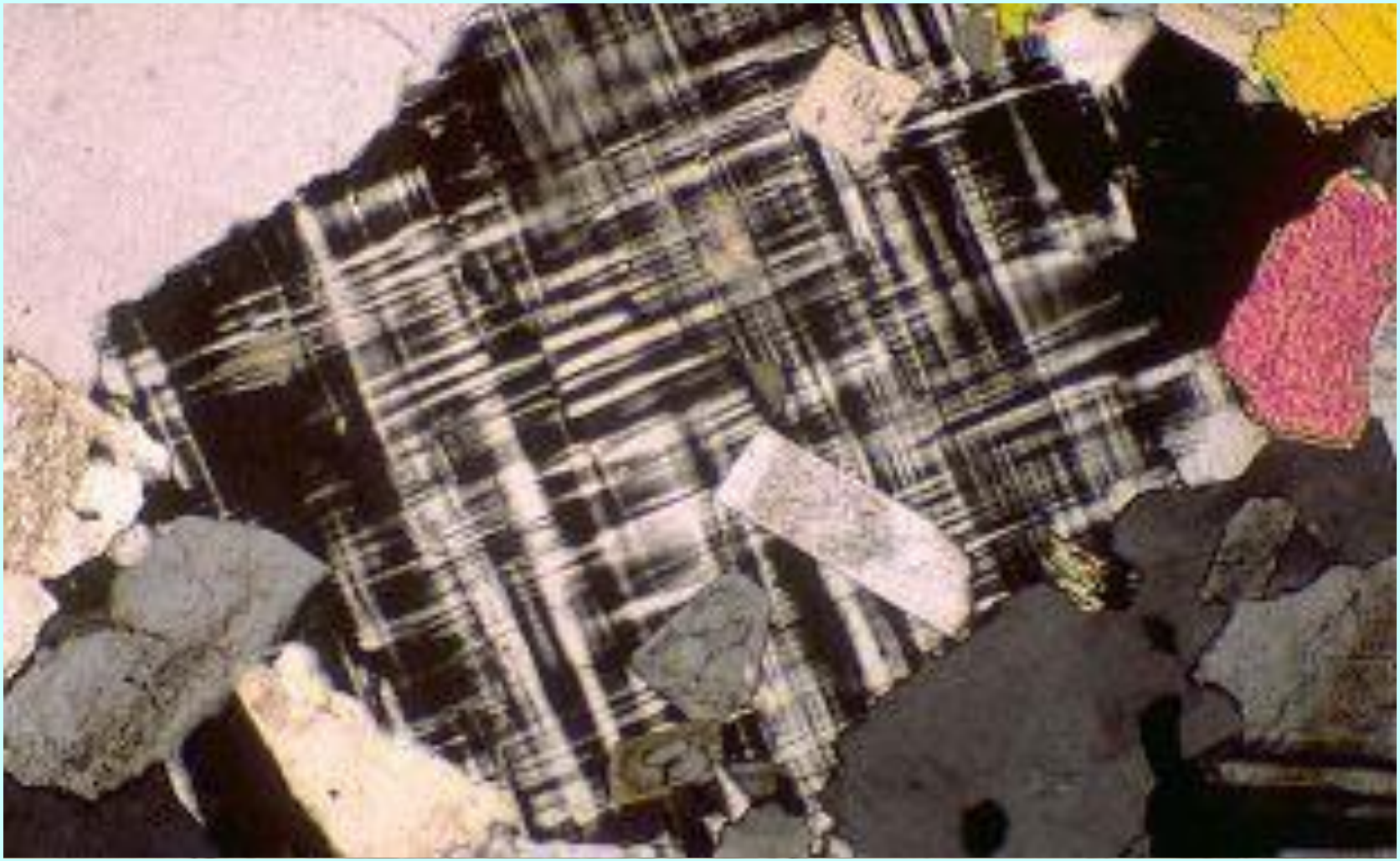


Perthite



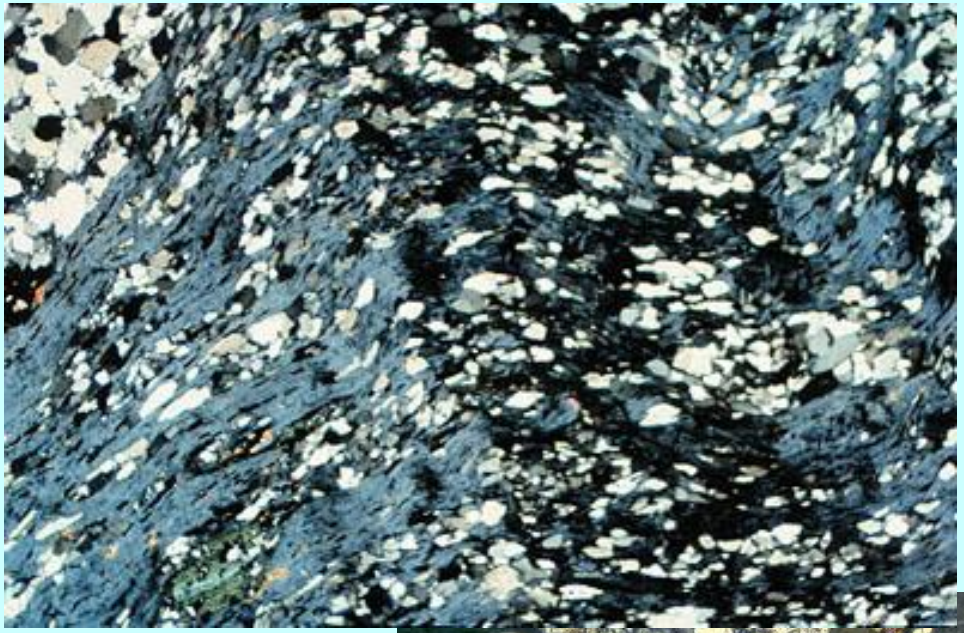


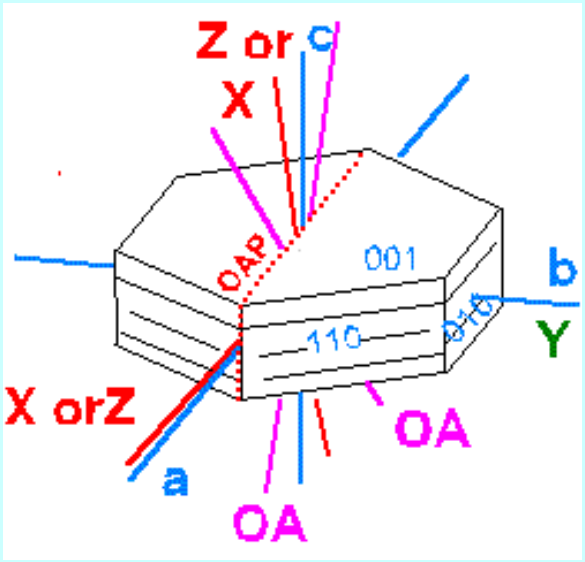
Microcline

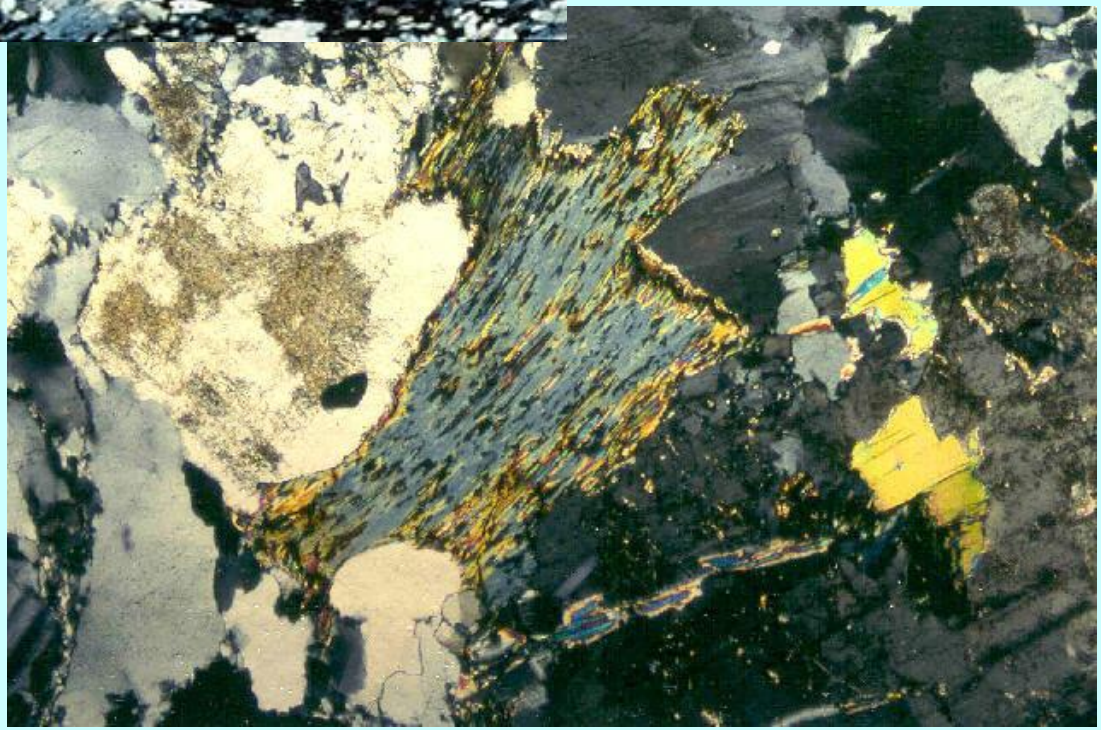


Plagiocalse

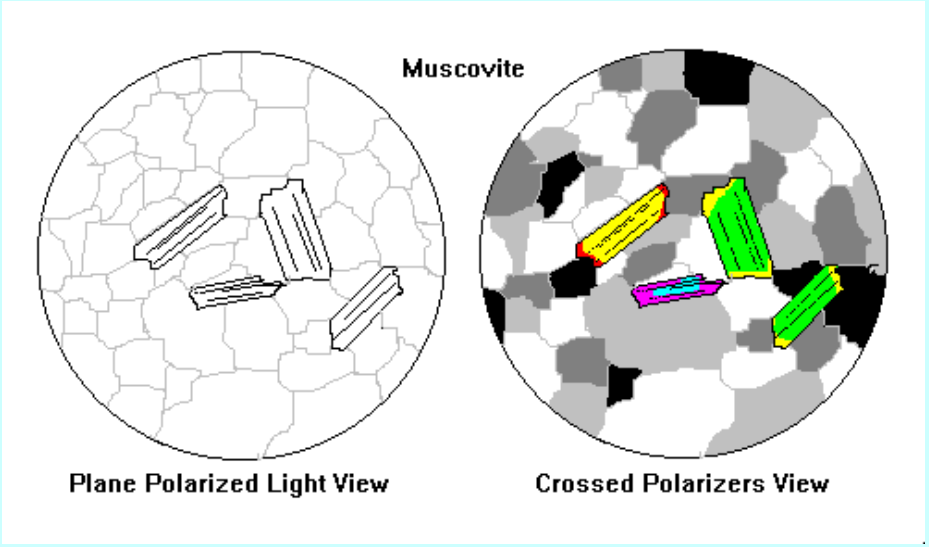
Chlorite

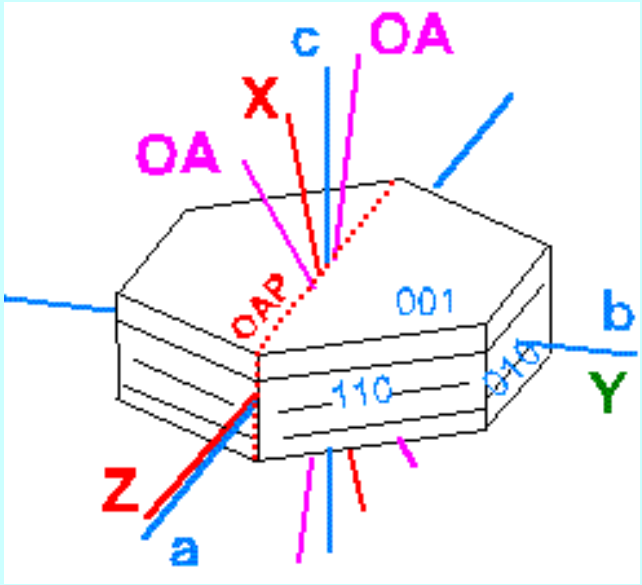






Muscovite


Muscovite
Plane Polarized Light View
Crossed Polarizers View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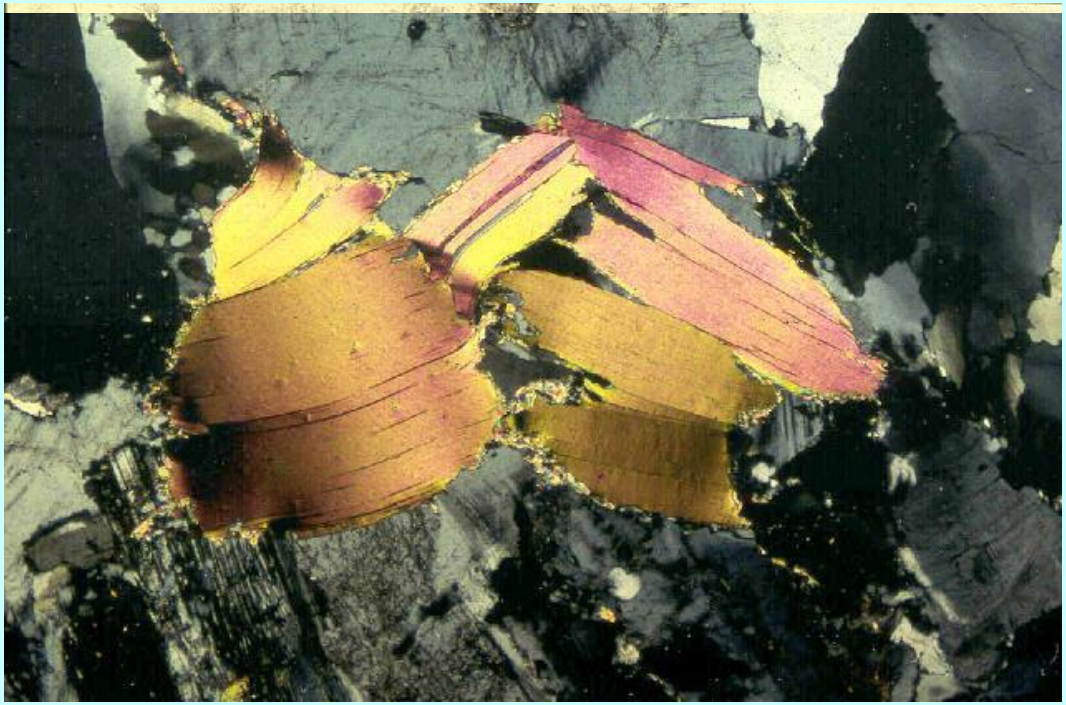
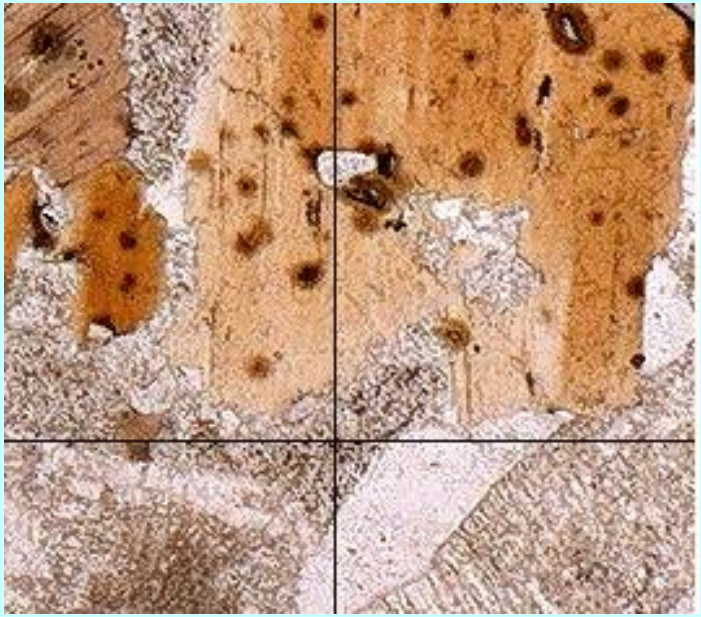
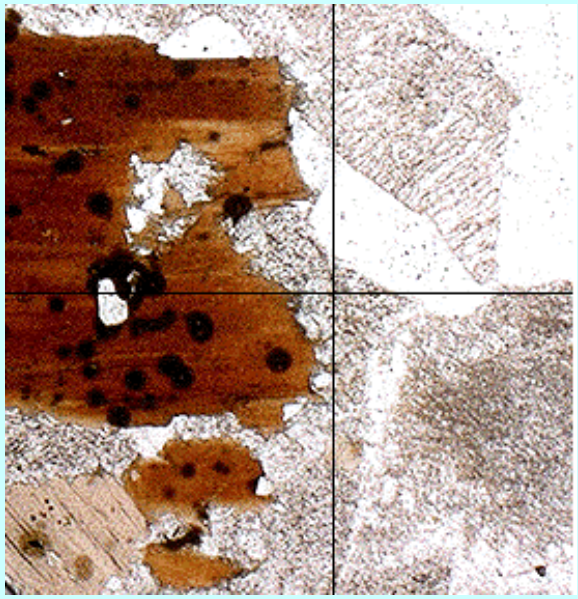
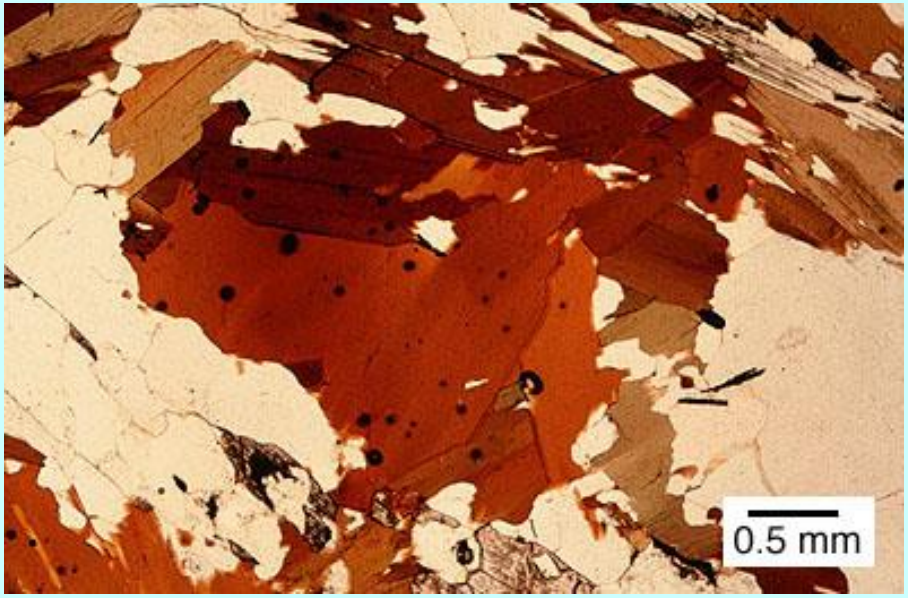
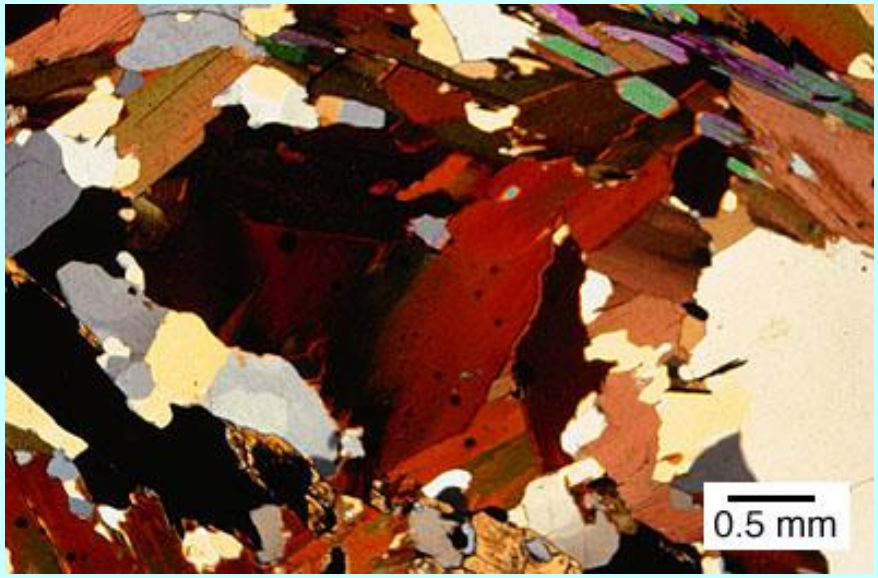


Biotite

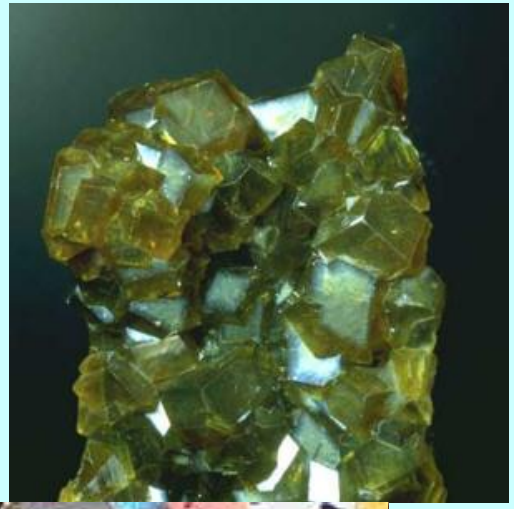


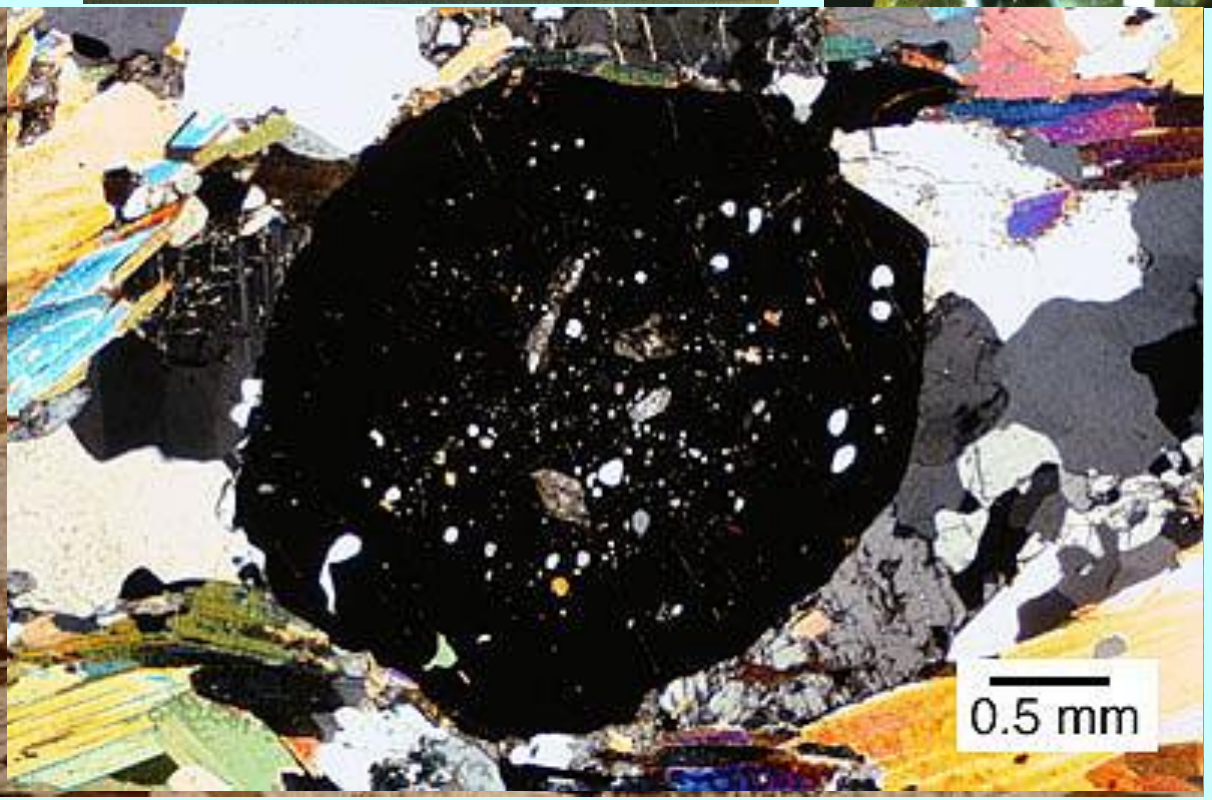




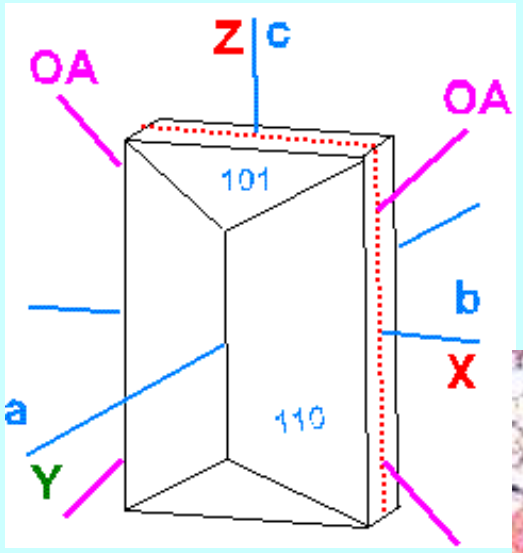


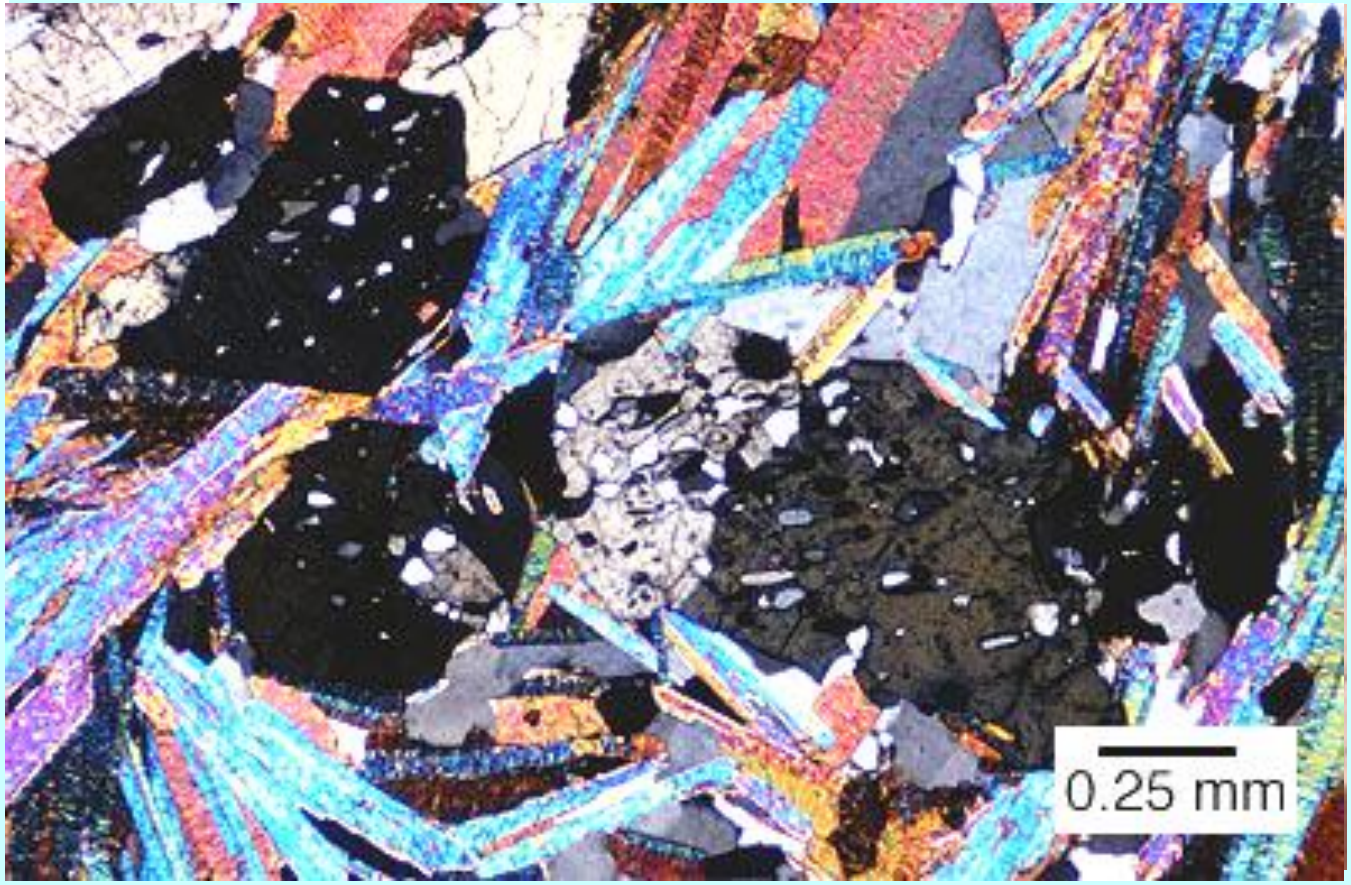
Garnet Group



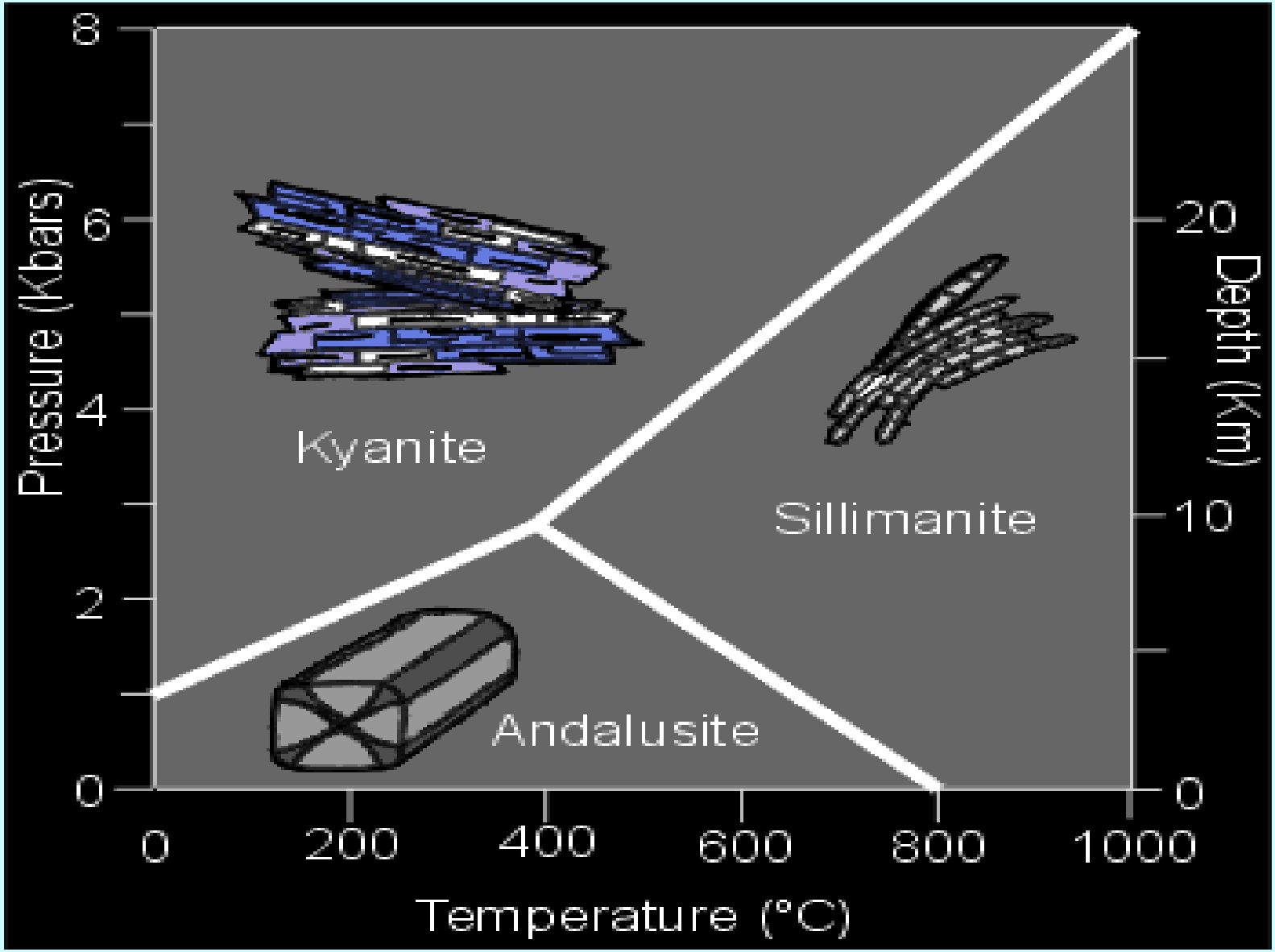


Staurolite

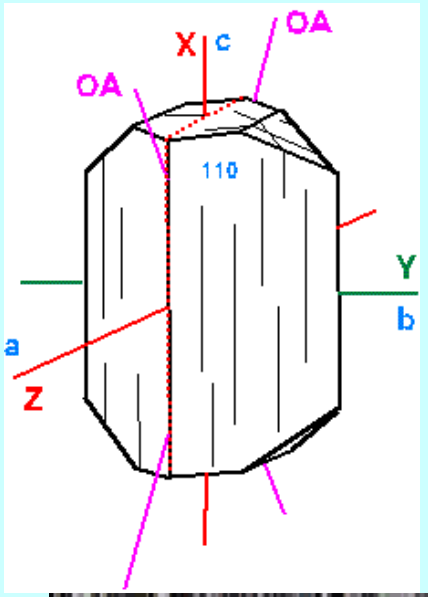


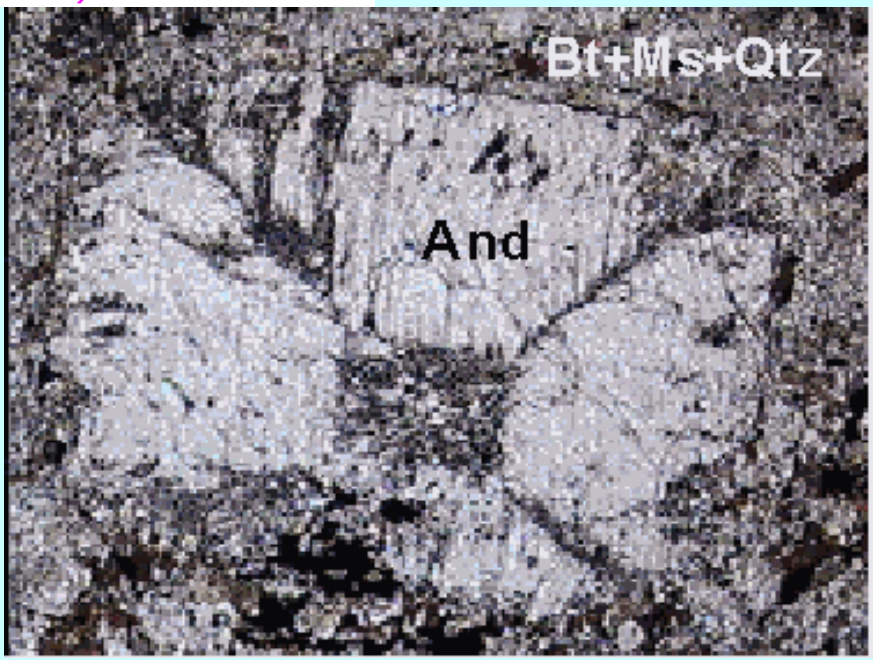


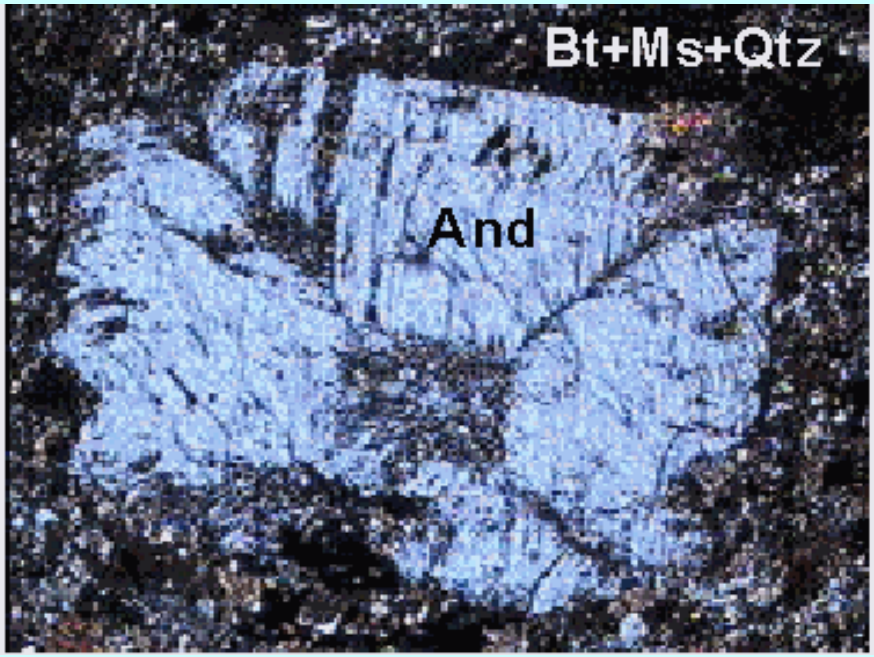
Al-silicates



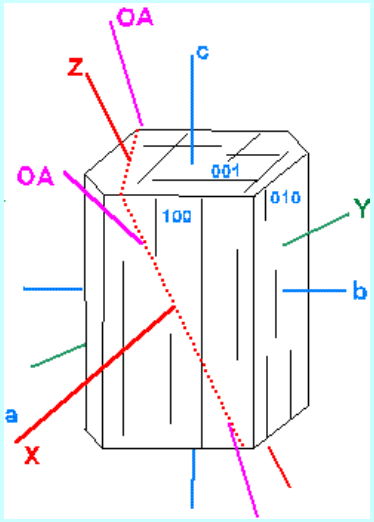
Andalusite

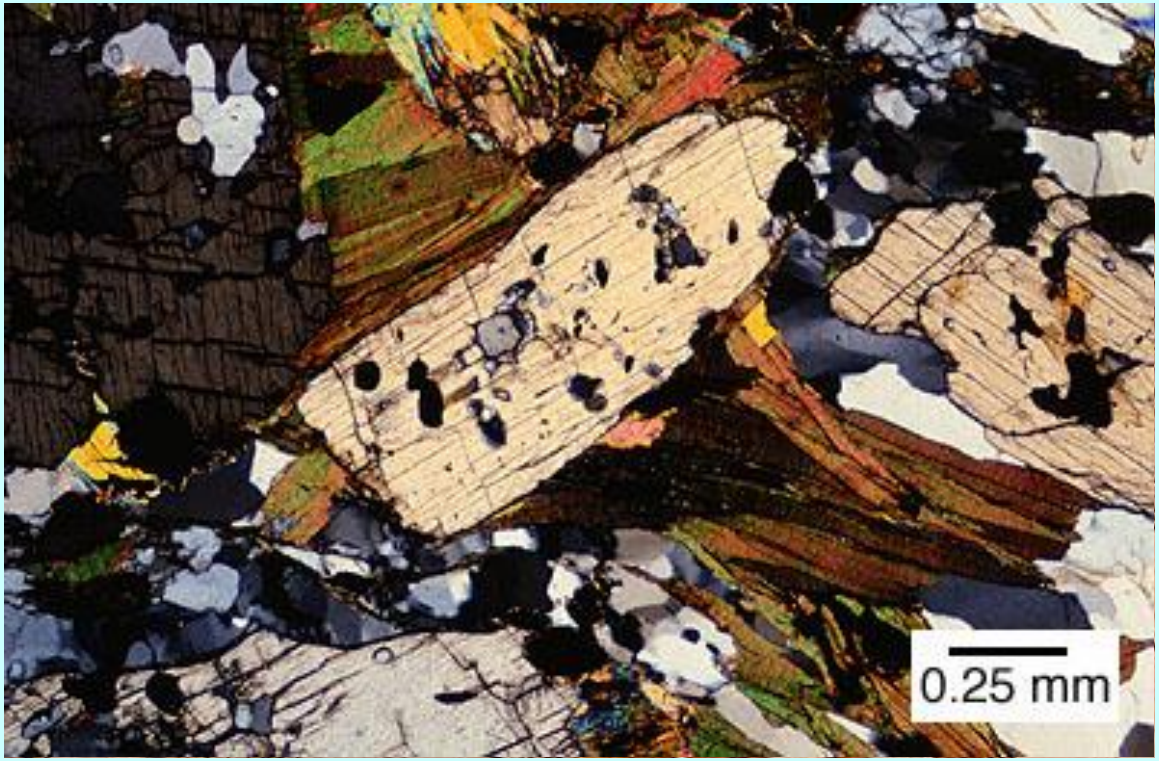




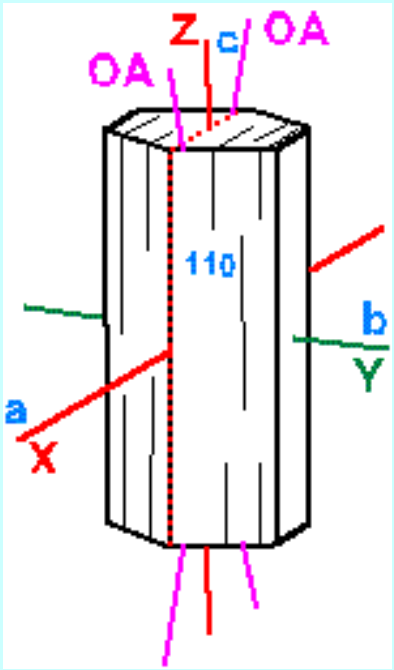


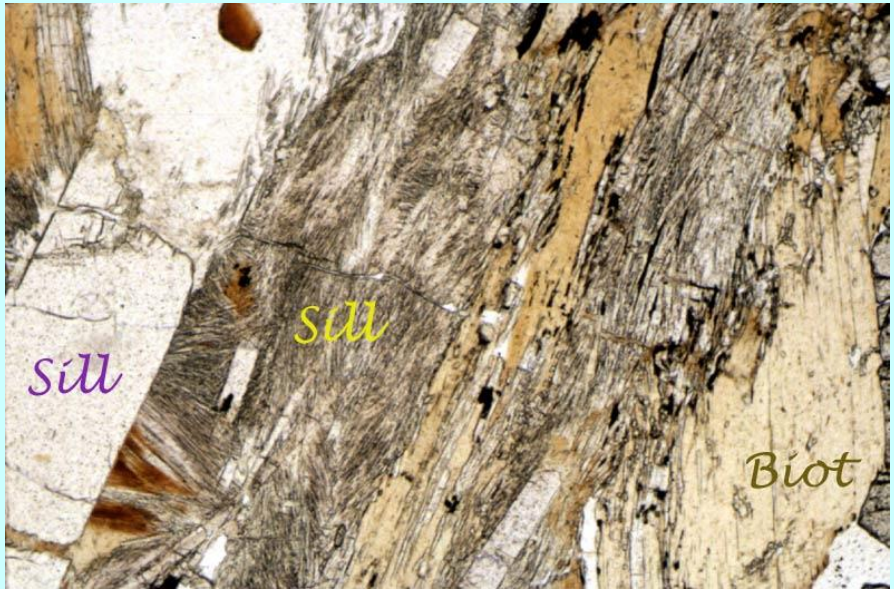
Kyanite

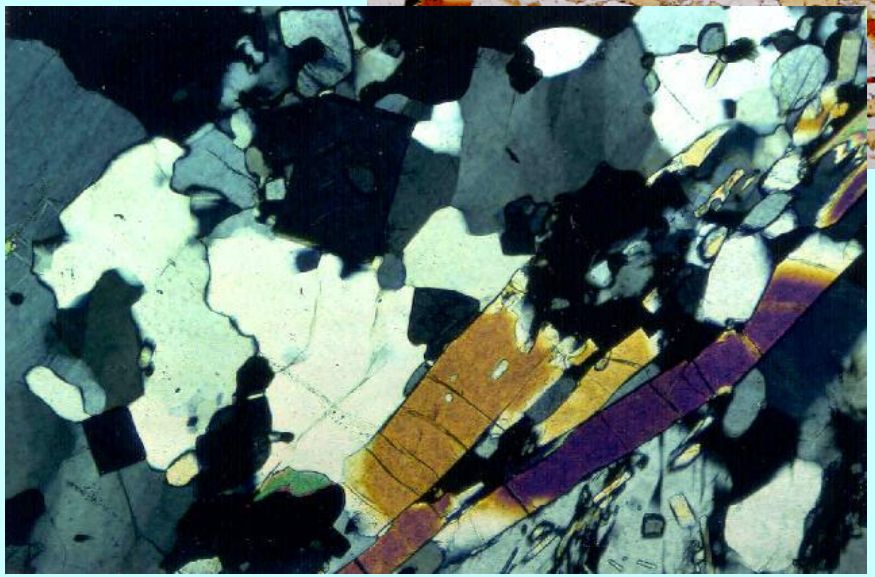




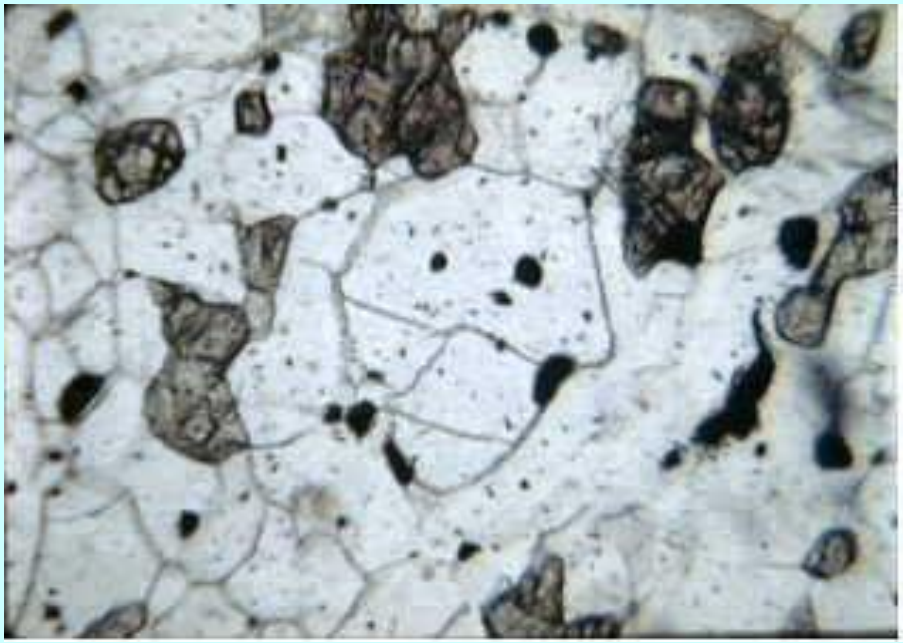
1. Sillimanite (C)

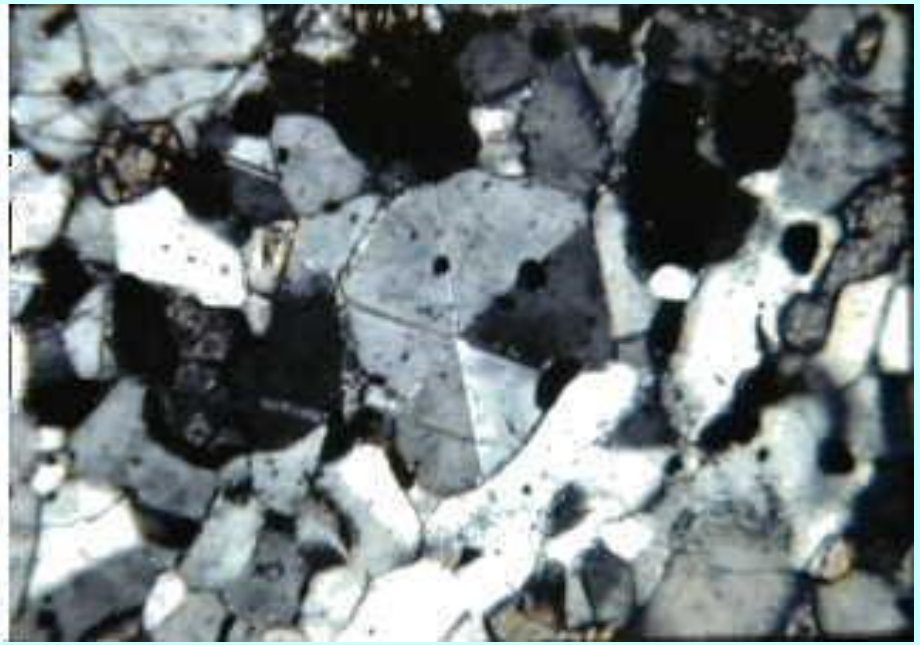




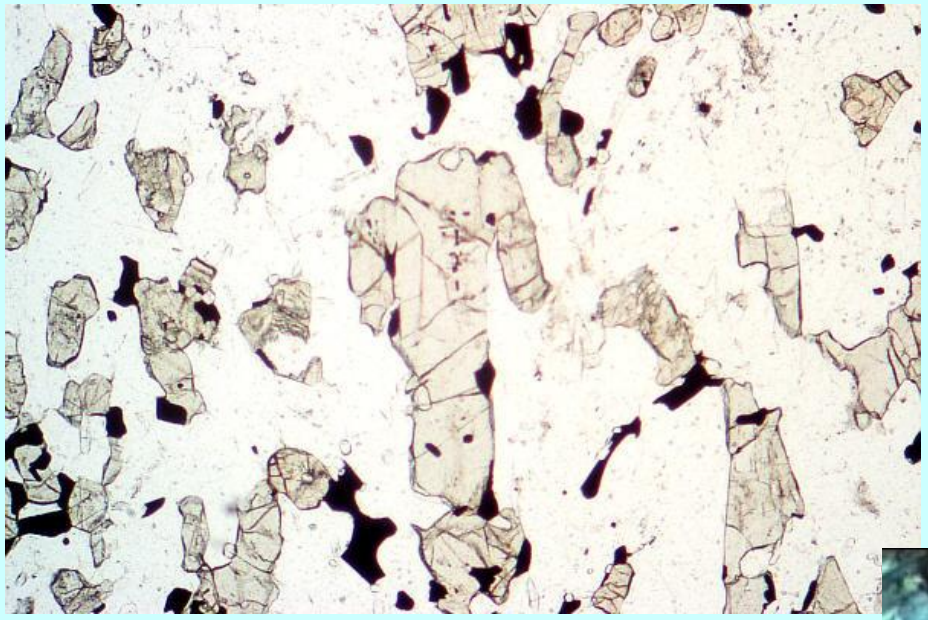


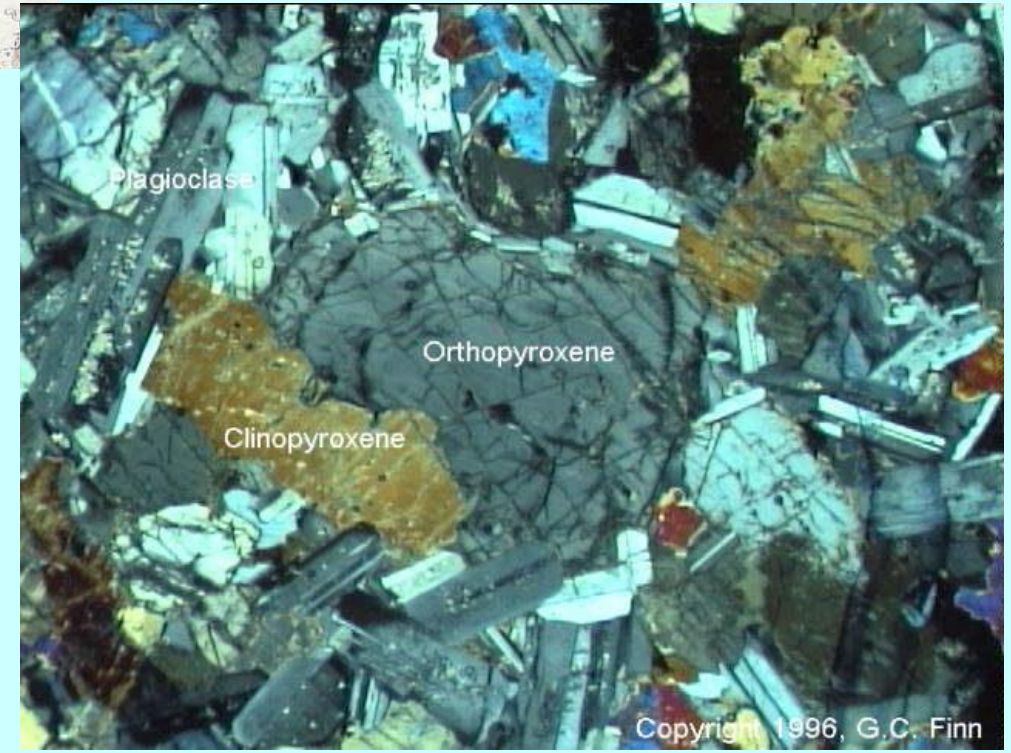
Cordierite





Orthopyroxene





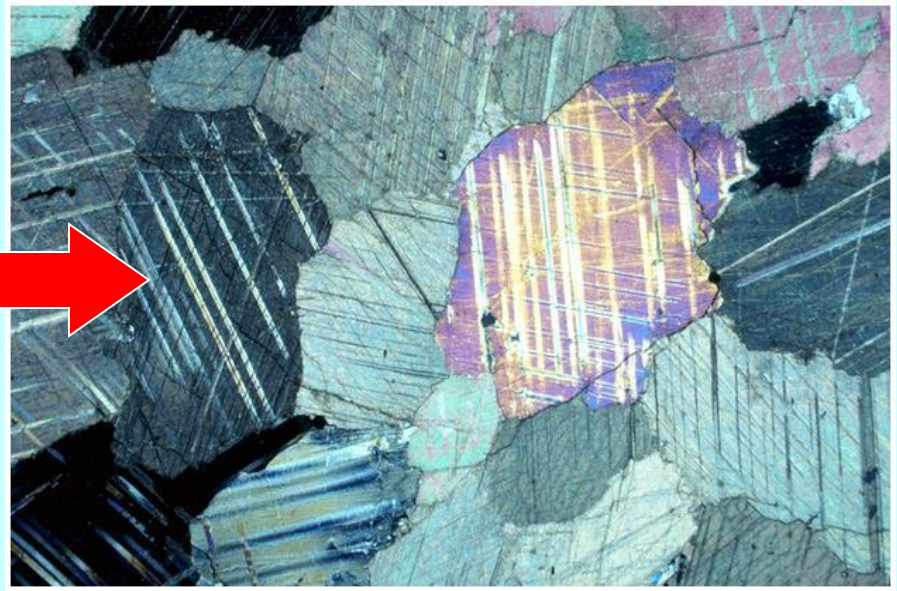
Metacarbonate rocks

<u>Limestone and dolomite (Calcareous rocks)</u>, composed essentially of calcite ($CaCO_3$), doilomite ($CaMg(CO_3)_2$, with minor quartz and clay minerals. If the clay minerals are excess, the rock known as **marl**

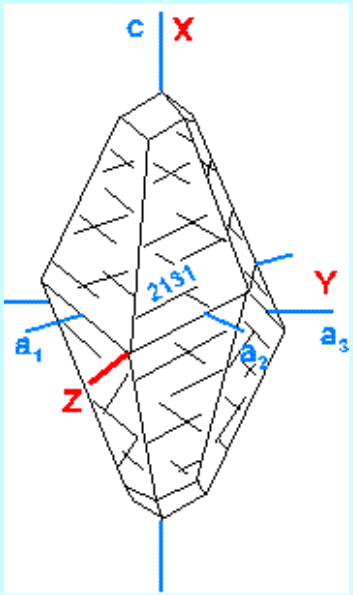
- the yielded rocks is known as **Marble** (mainly calcite) if the calcareous rocks are pure. In case of non-pure calcareous rocks, marble contain silicate minerals such as: wollastonite, grossular-andradite garnet, diopside and tremolite

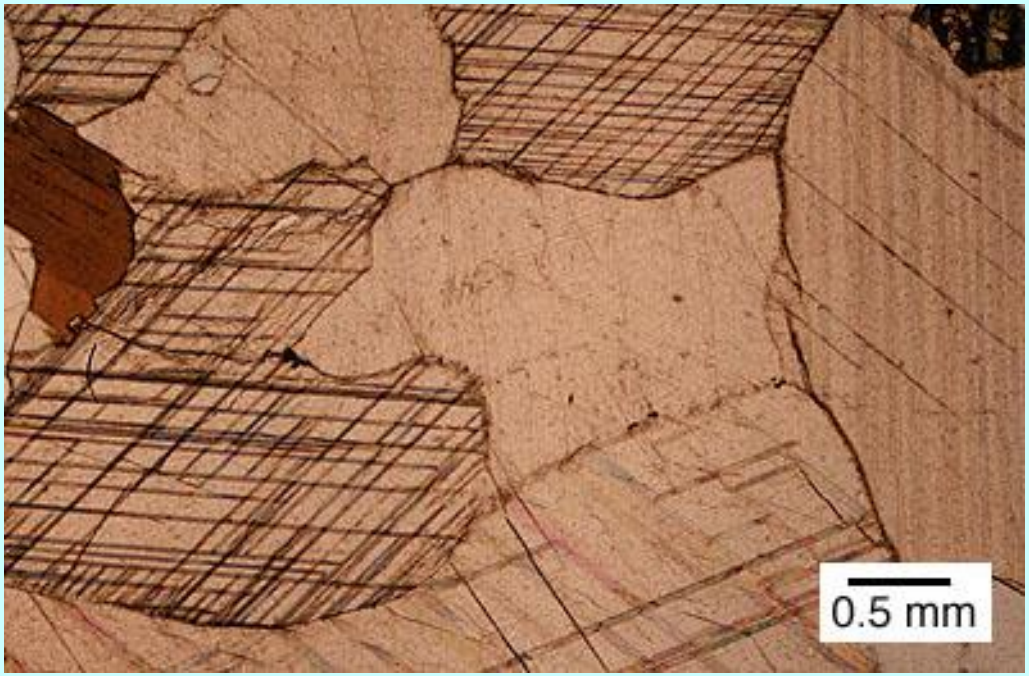
(a) Limestone (fiossiliferous)

(b) Marble

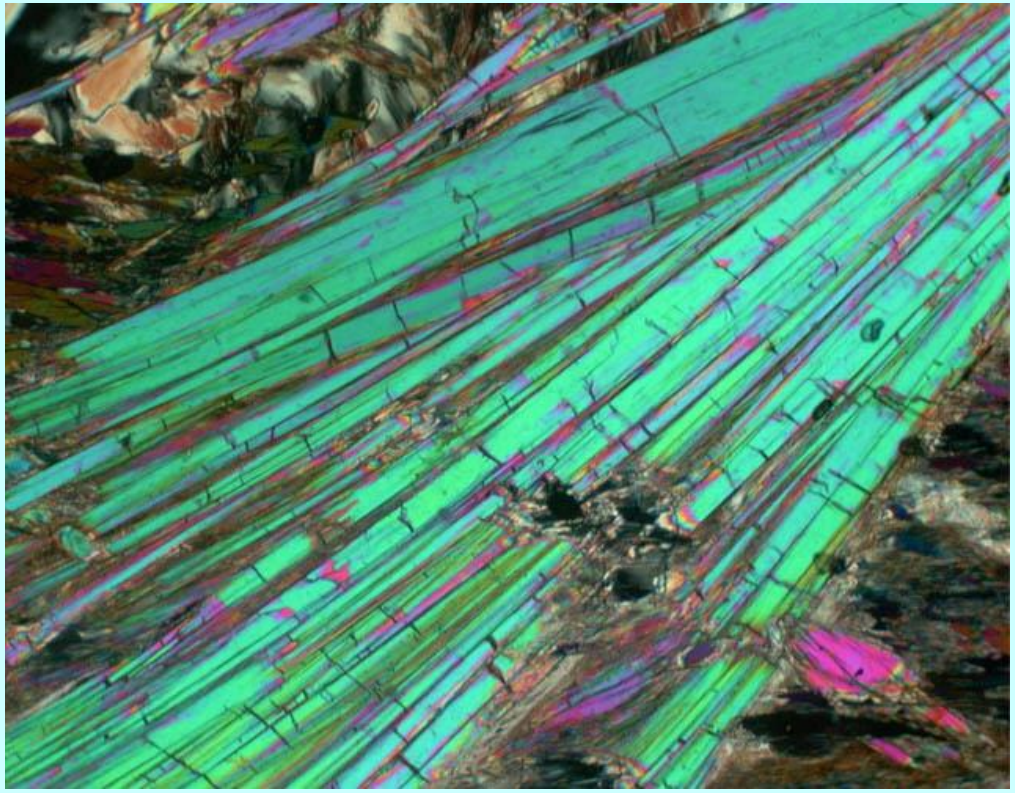


Calcite ($CaCO_3$)





Anthophyllite



Metamorphosed sandstone

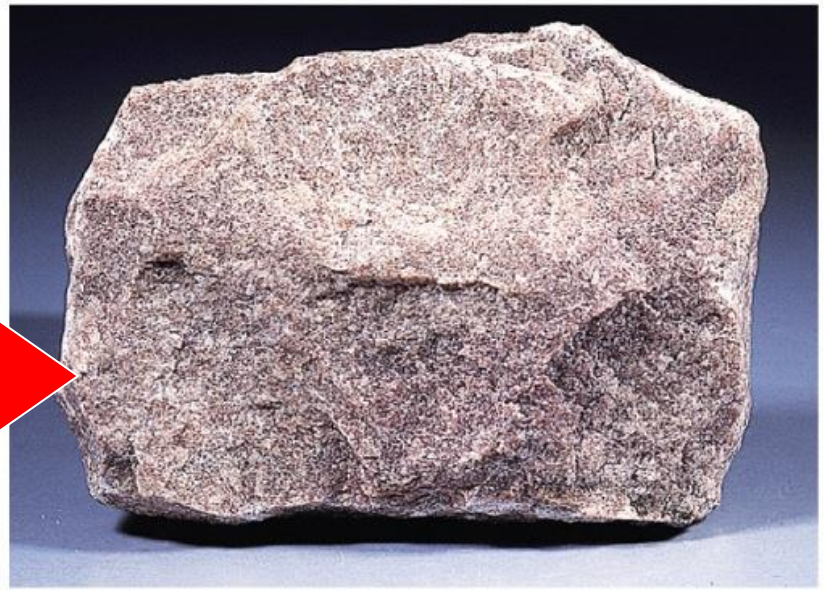
Sandstones (Arenaceous rocks): of variable composition, arenite (wholly quartz), arkose (quartz + feldspars) and graywackes (quartz, lithic fragment and clayey matrix)

-Metamorphism of sandstone yield gneisses (quartz + plagioclase + K-feldspars + biotite + granet + Fe-Ti oxides)

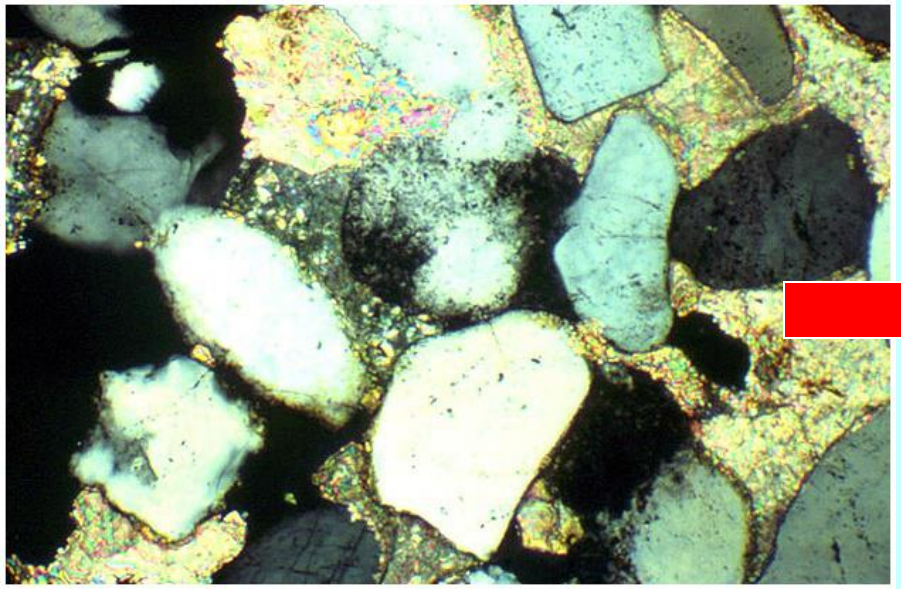
- Metamorphism of graywackes formed a metamorphic rocks intermediate between metapelites and gneisses)

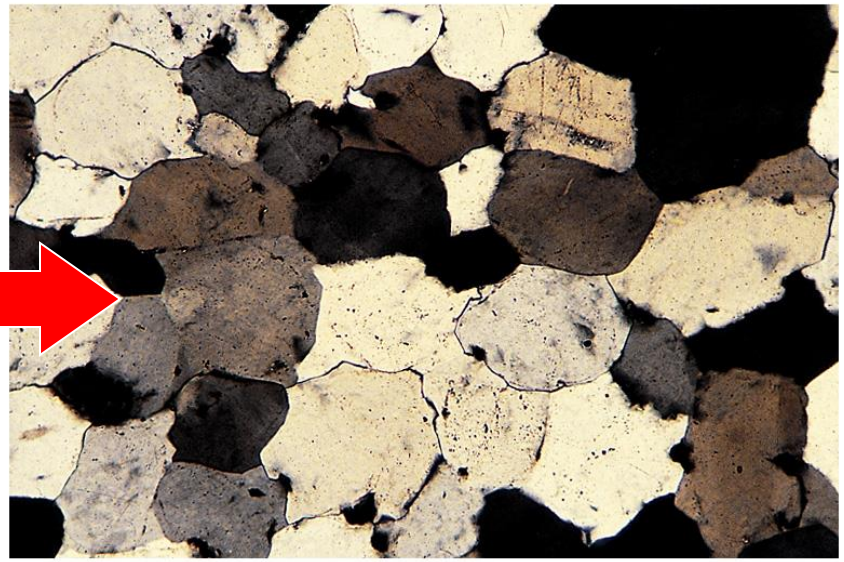
- Arenites yield quartizites

(b)



(a) Quartzite





Craig Johnson.

Metamorphosed basic igneous rocks

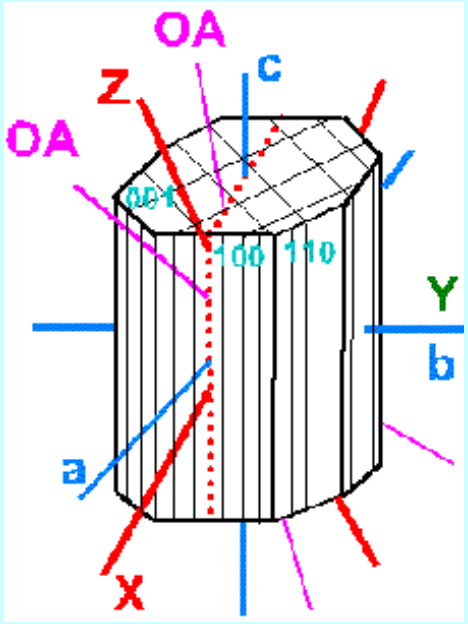
Basic rocks including basalts and gabbros, are low silica igneous rocks that contain plagioclase and pyroxene.

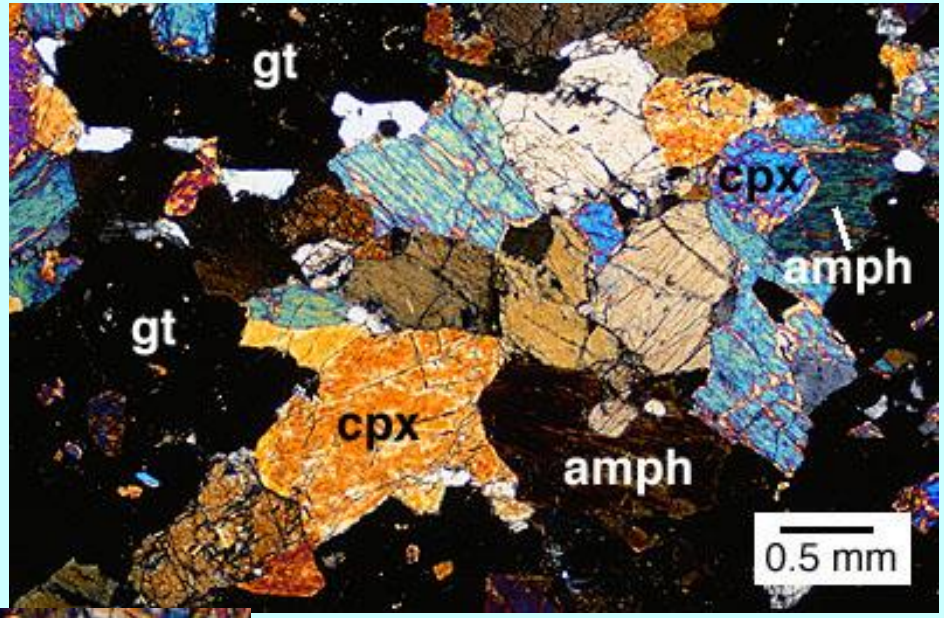
- Metamorphism of basic igneous rocks yielded metabasites (quartz, plagioclase, amphiboles, garnet, epidotes, chlorite)

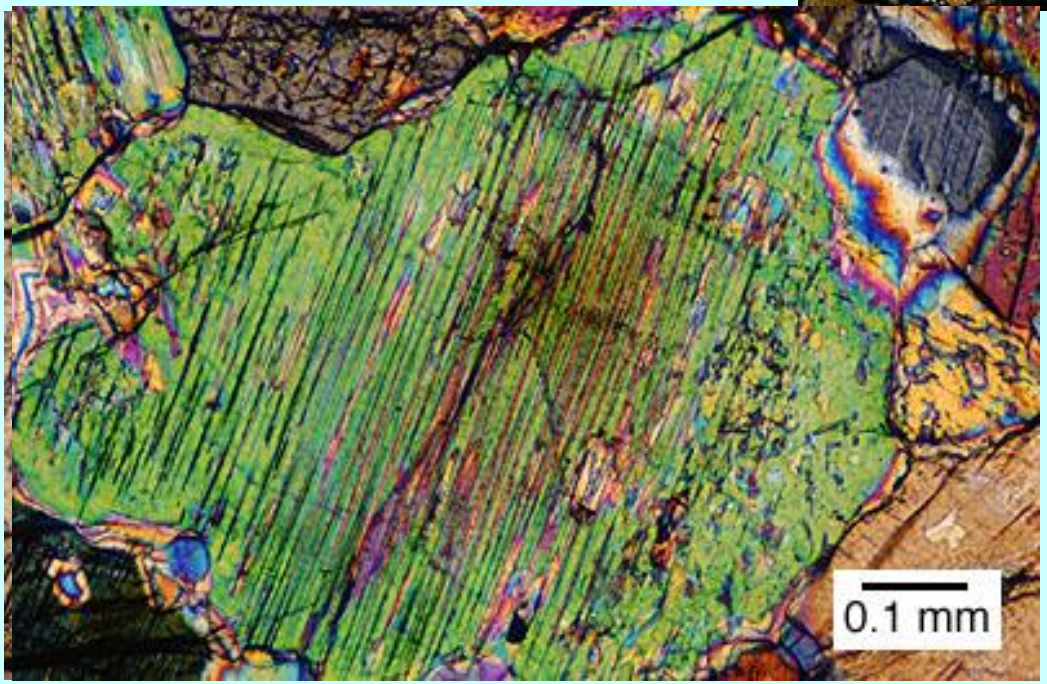
- If the rock is composed of plagioclase and amphibole, amphibolites term are used

- At extreme P-T conditions, Eclogites are formed (garnet + omphacite)

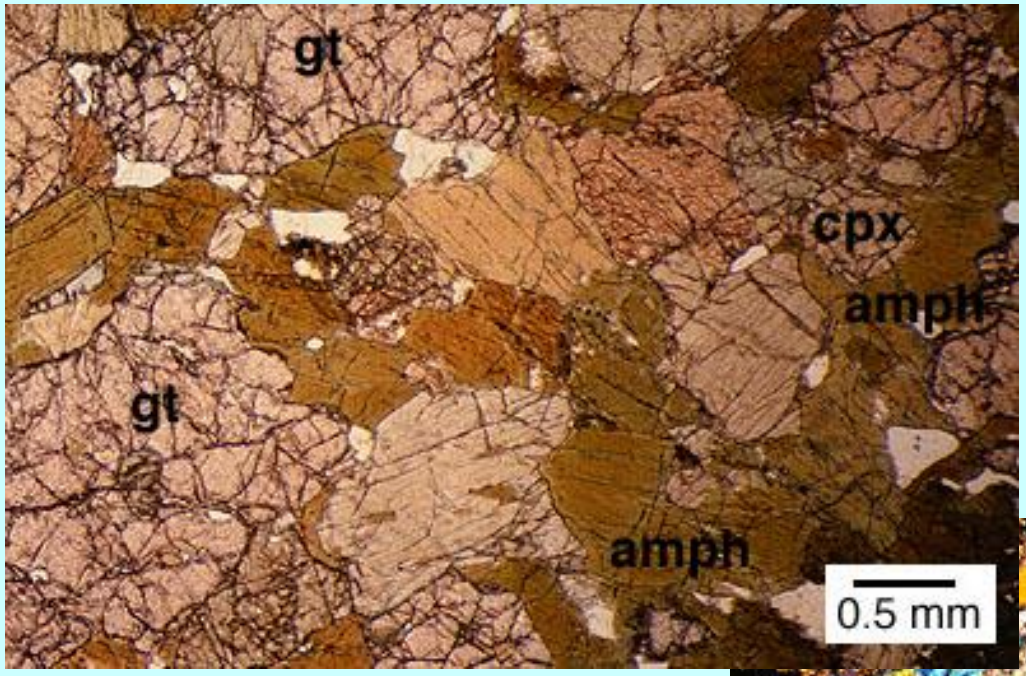
CPX: Diopside - Augite

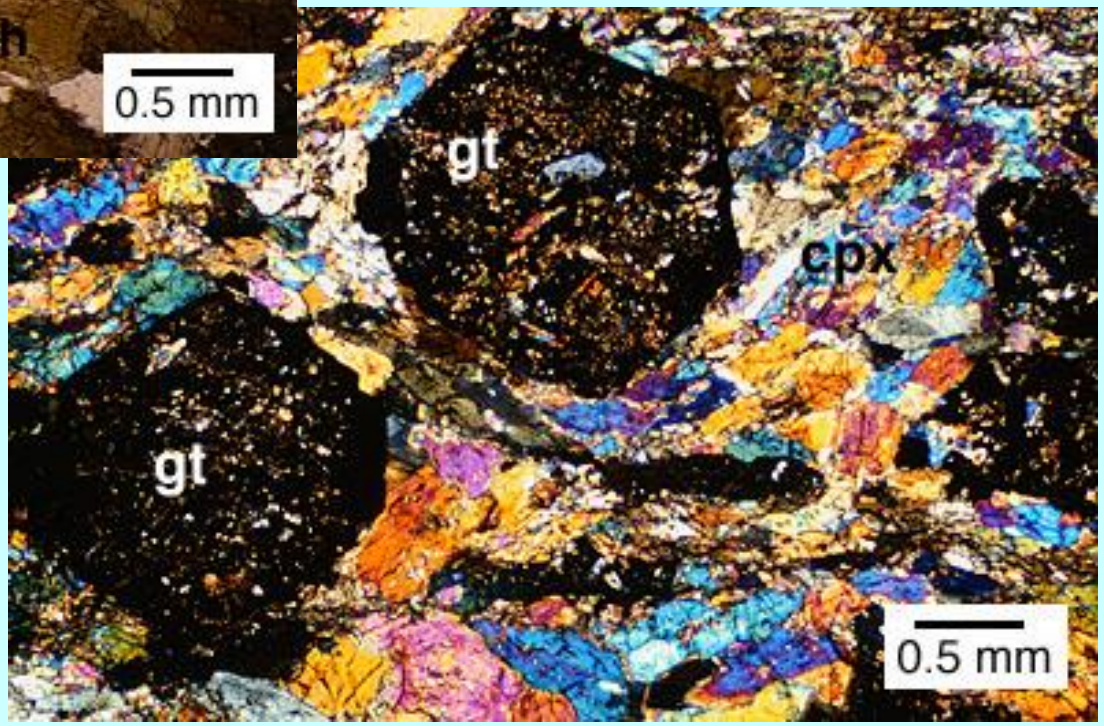




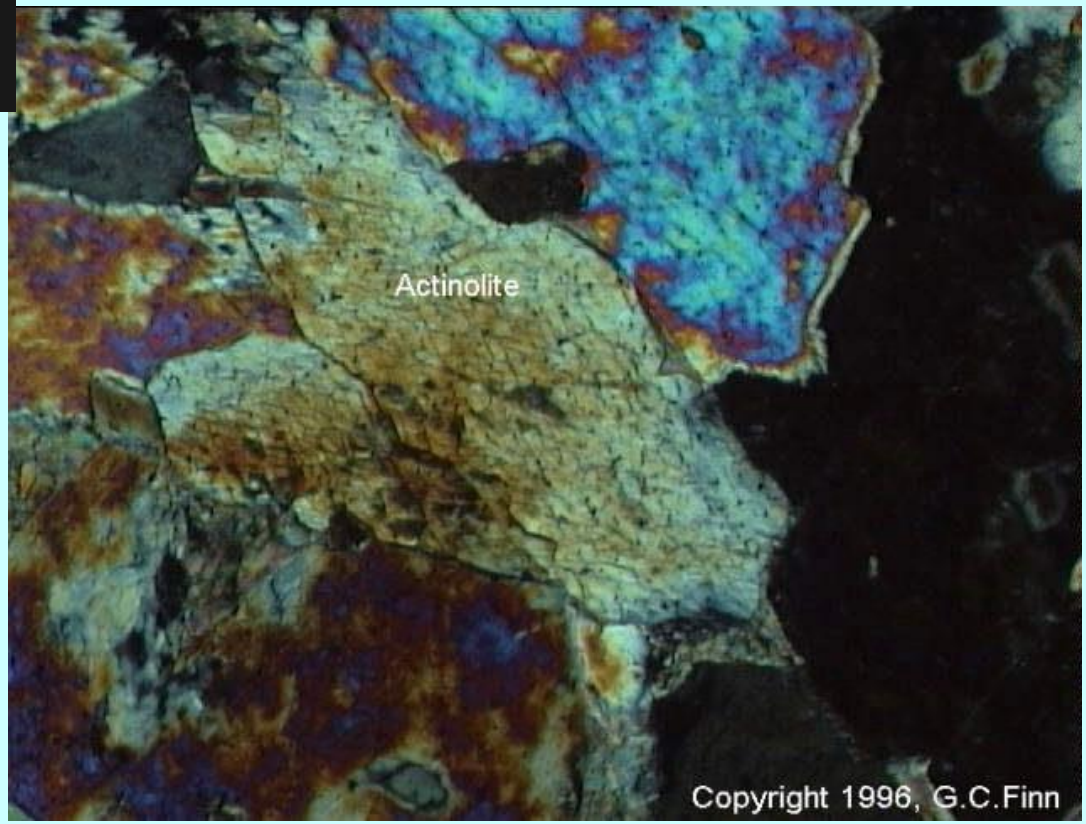


Omphacite

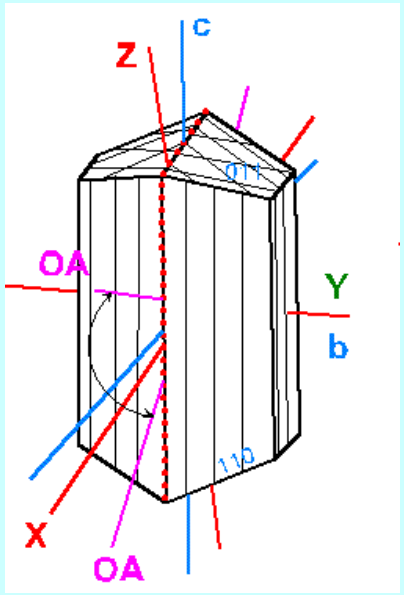




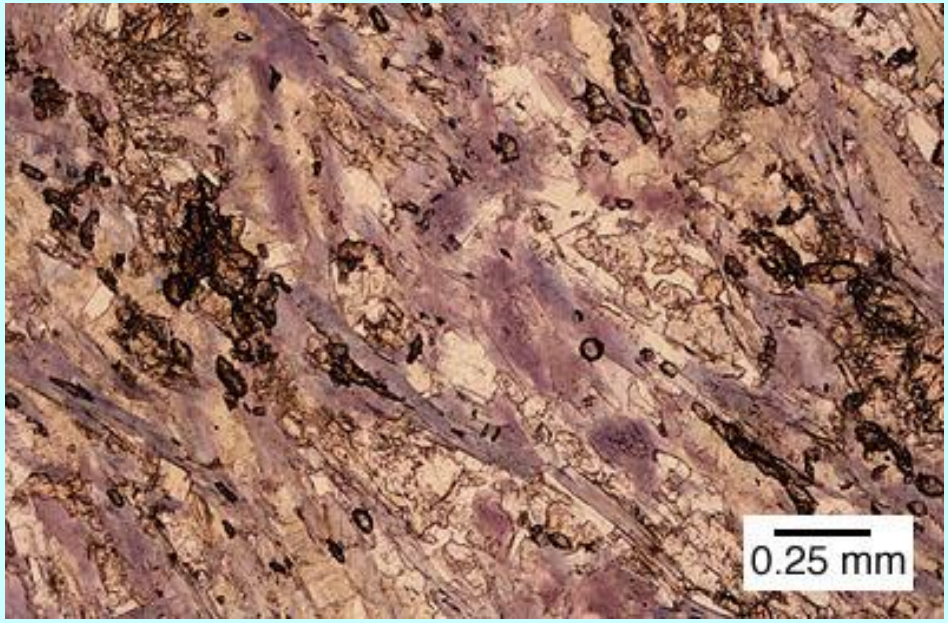
Tremolite-actinolite

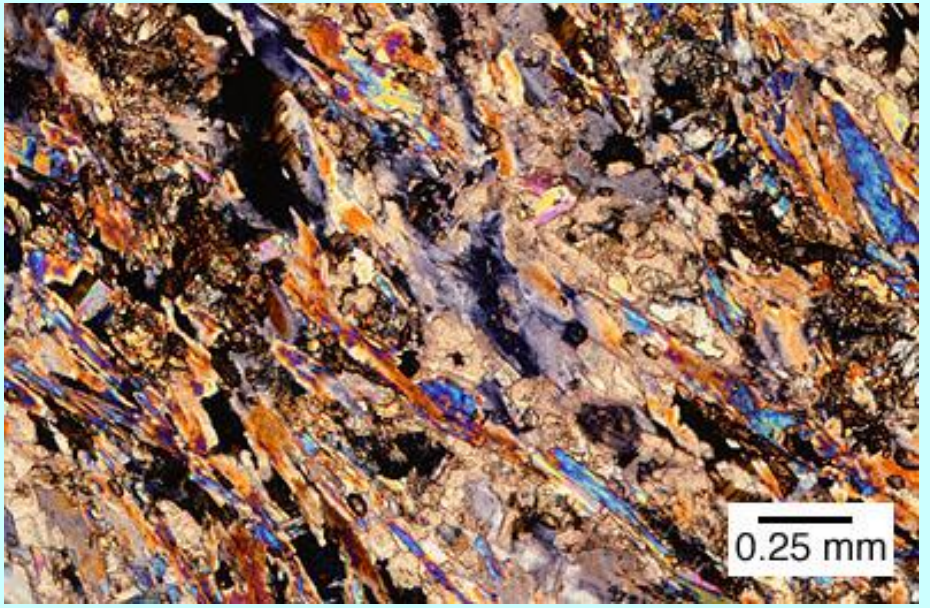


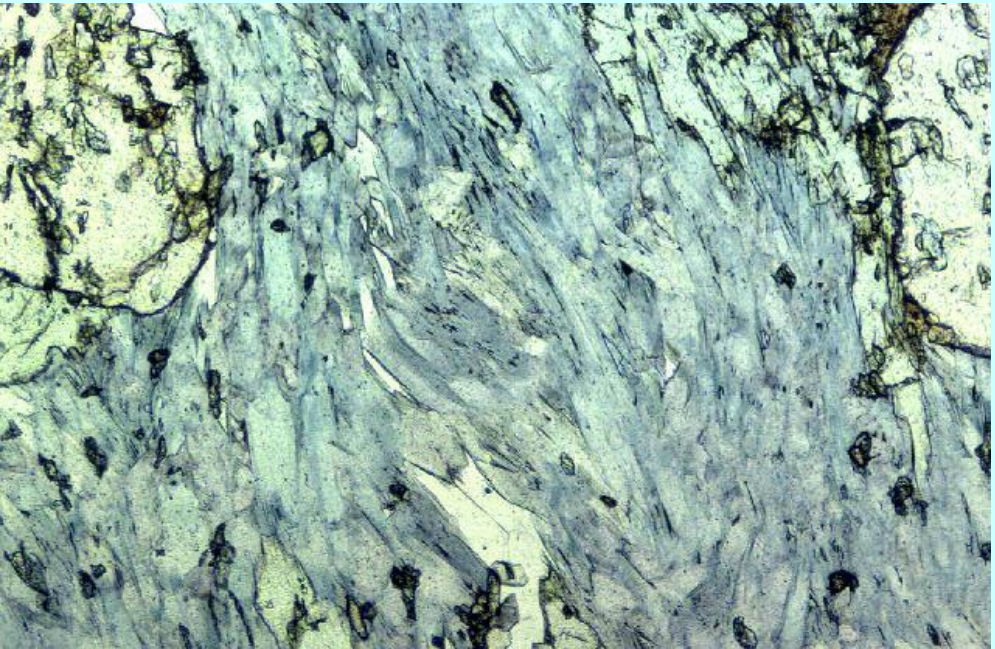
Hornblende

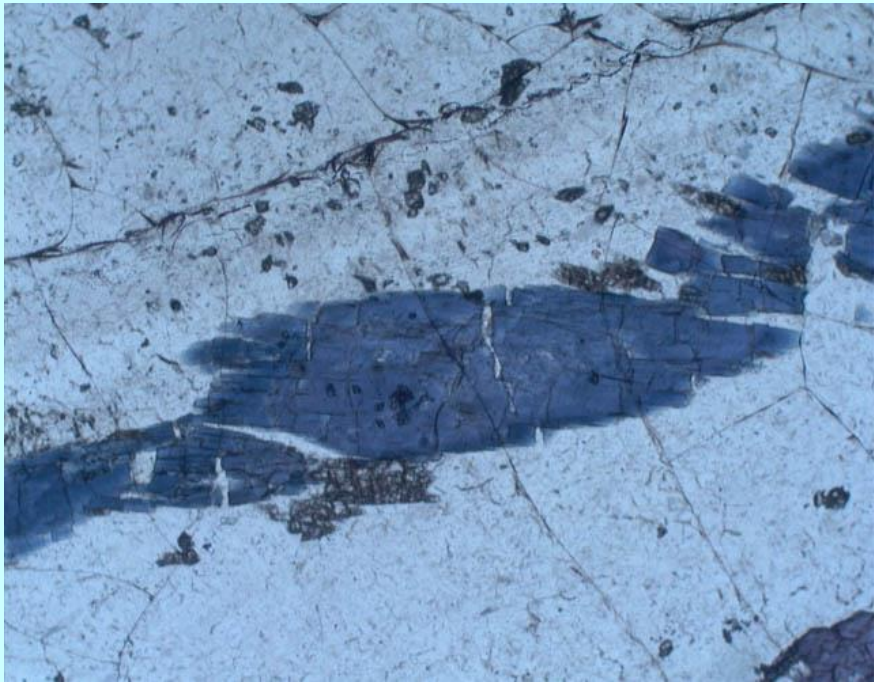


Glucophane







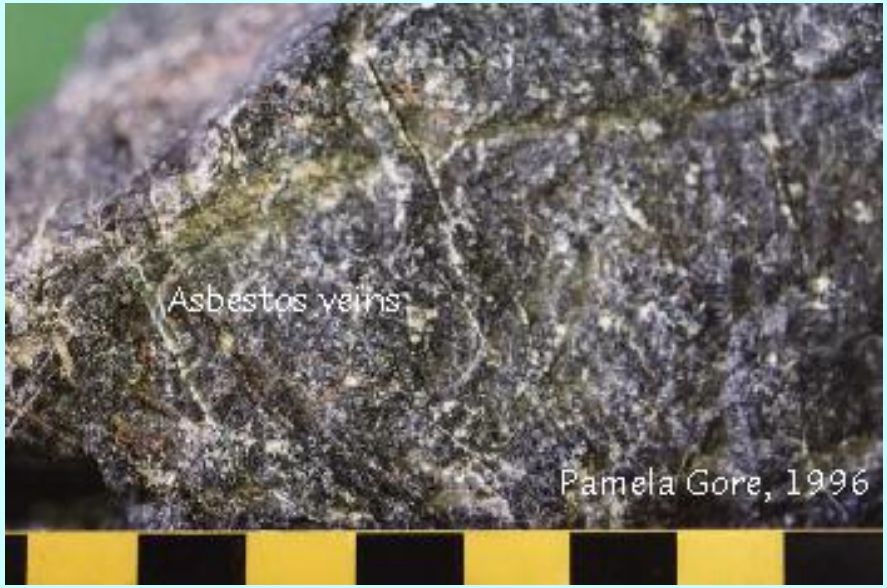


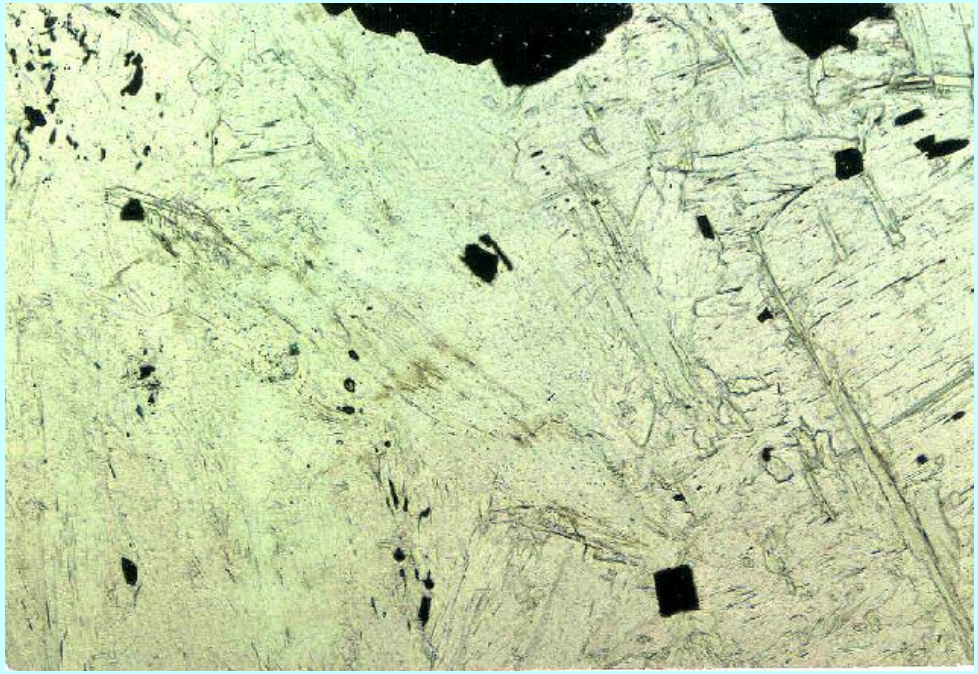
Metamorphosed Ultramafic rocks

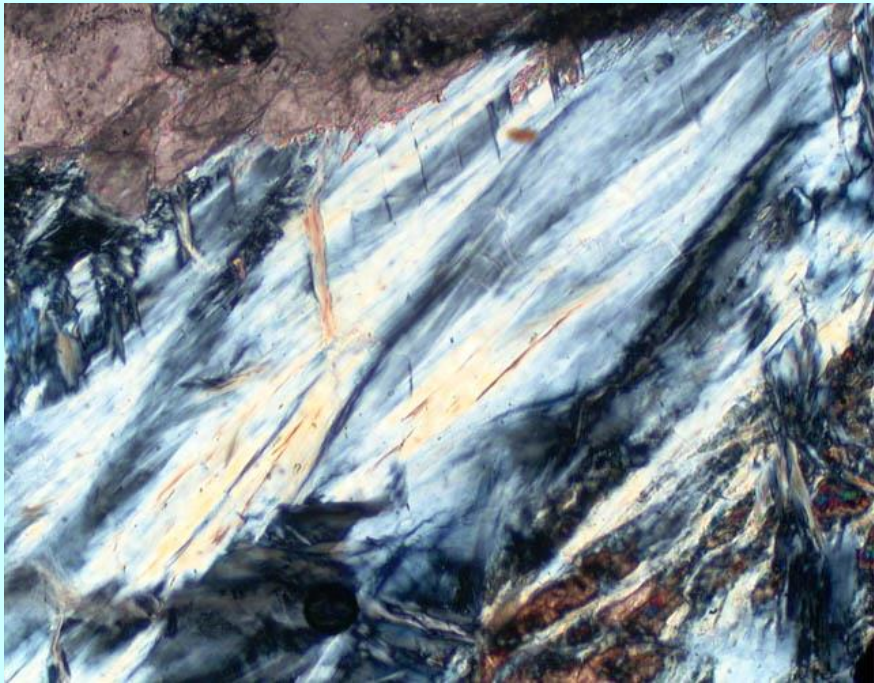
Ultramafic rocks, Mg-Fe rich silicate minerals (Diopside, Olivine)

-When metamorphosed yielded produce serpentinites and talc schists with mineral assemblage include serpentine minerals, talc, enstatite, diopside, anthophyllite, tremolite, hornblende, garnets and chlorite

Serpentine







Talc