Optical Properties of Minerals

UNIT -4

Optical Mineralogy (Microscopic Study of Minerals)

- **Study optical properties under the microscope to identify minerals. Mineral identification is needed in petrology studies.**

  - **Crystal Lattice** (symmetry) + **Chemistry** = **A unique mineral phase**

  - **The mineral crystal lattice is reflected in the external crystal shape** and in the **optical properties of mineral.**

  - **Microscopic study is the most cheap and fastest method for identifying minerals.**

- **What are limitations to optical methods for identifying minerals?**
- **Very fine grain size (sub-microscopic) of minerals and/or complex solid solutions are poorly identified.**

What is the importance of optical mineralogy?

- **Microscopic study is required for:**
  - **Textural (natural arrangements of minerals) analysis**
  - **Rock type identification and crystallization sequence**
  - **Deformation history or observing frozen-in reactions**
  - **Constraining pressure-temperature history**
  - **noting weathering/alteration**, etc.

* To study the optical properties of minerals we need to understand:

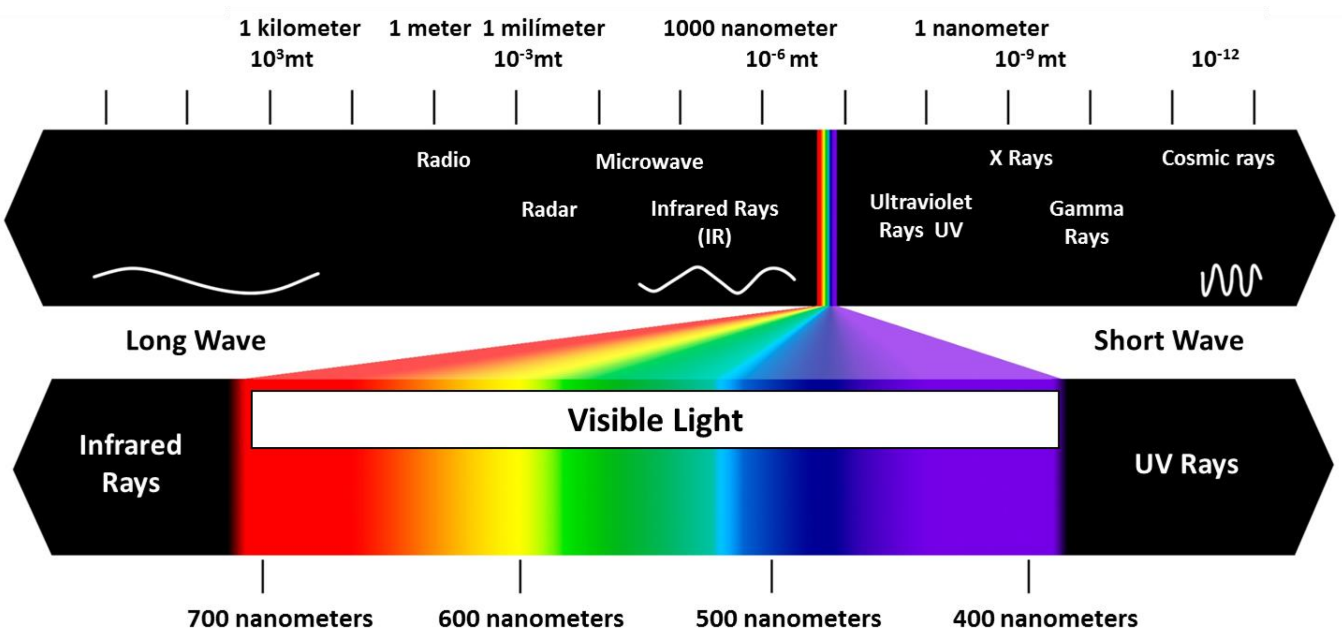
1. What light is and especially polarized light?
2. The difference between isotropic and anisotropic media
3. The petrographic microscope
4. The use of specific charts of physical properties in order to identify unknown minerals.
5. Few specific optical properties that can help in quick identification of the common rock-forming minerals.

* What is light?

* **Light is part of the electromagnetic spectrum, which ranges from radio waves to gamma rays.**

* Electromagnetic radiation waves, as their names suggest are fluctuations of electric and magnetic fields, which can transport energy from one location to another.

* **Visible light** (also known as polychromatic light) is not different from the other parts of the electromagnetic spectrum with the exception that **the human eye can only detect visible waves**.

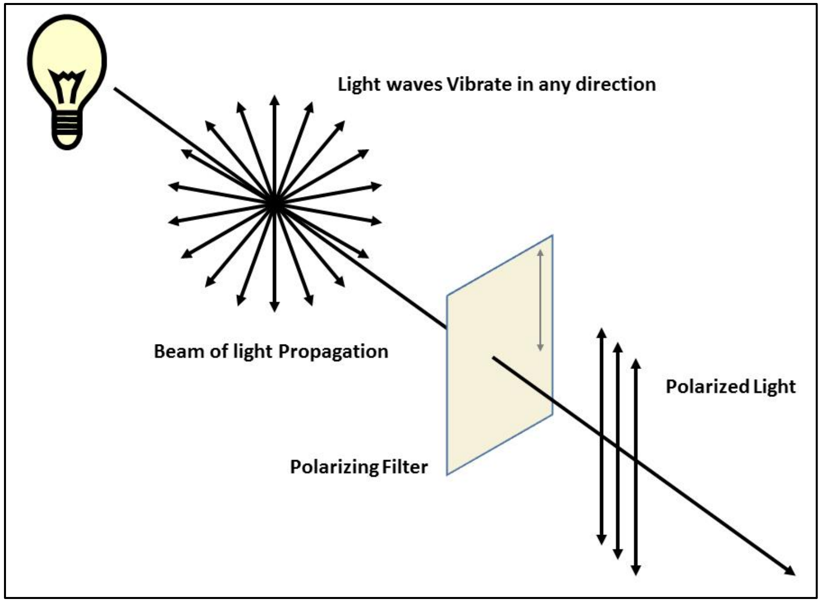


Plane polarized light

* **Natural light vibrates in all the directions** perpendicular to the direction of propagation .

* Therefore we can say that there is infinity of planes of vibrations (all possible planes that intersects/contain the direction of propagation.

* **Plane polarized light (PPL) has one single plane of vibration**, in which the direction of vibration is always perpendicular to the direction of propagation.



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Plane polarized light

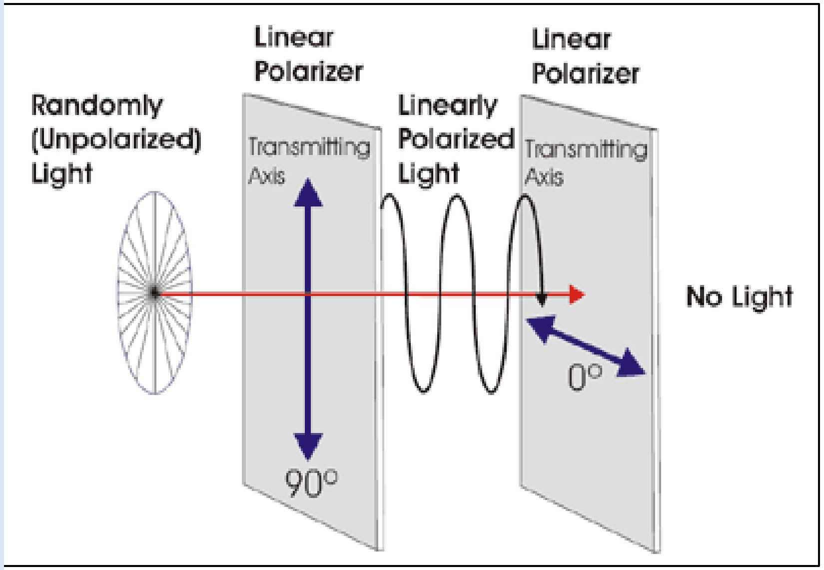
* We can use this plane of vibration as a geometrical reference for the optical properties of mineral.

* Keeping this plane fixed and rotating (changing the orientation of) the mineral, all of the mineral optical properties can be measured or related to such a plane.

* Note that **we can polarize light with a special designed material, called a <u>nicol</u> or polarizer**.

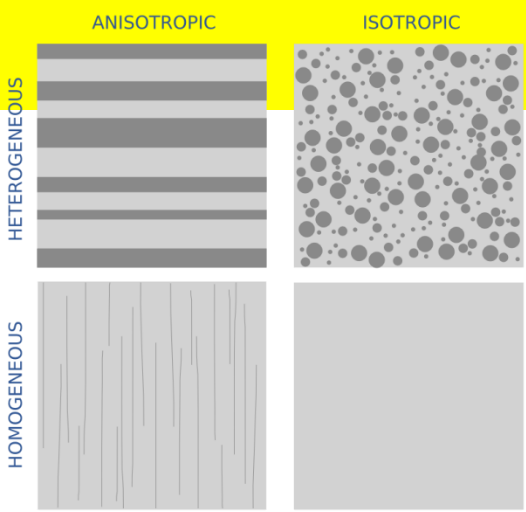
- **The name "nicol" comes from Nicol (Nicol prism), a French scientist who first built a kind of prism of calcite**, made of two halves of the same calcite crystal, adjusting the angles of the prism to a convenient value in order to eliminate all other planes of vibration but one.

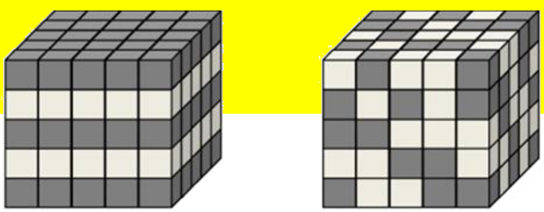
- **Nowadays, materials called <u>polaroids</u> are used for manufacturing polarizers** (microscopic oriented crystals of iodoquinine sulphate embedded in a nytrocelulose polymer film).



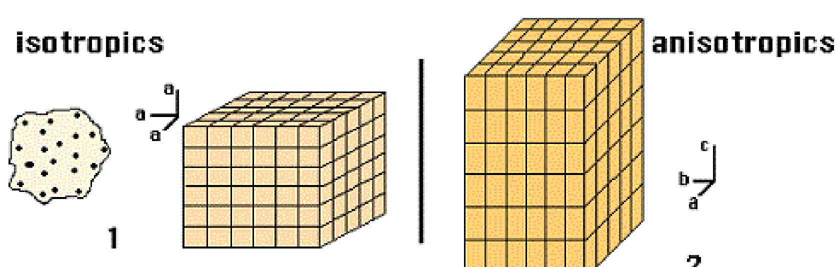
ISOTROPIC AND ANISOTROPIC MATERIALS

- **Isotropic mineral = similar physical properties at any point.**
- **Isotropic mineral crystallizes in the cubic symmetry.**
- **Isotropic mineral has the same refractive index and the same absorption of light at any point and for any direction in the mineral.**
- **Non-crystalline materials such as glass, liquids, and gasses are isotropic.**
- **Refractive index of a mineral:** نسبة سرعة الضوء في الفراغ إلى سرعته في المعدن





(a). Anisotropic layered structure (b). Isotropic uniform structure



* **Anisotropic mineral = physical properties are different at all points or directions.**

* **Anisotropic mineral = different absorption of light, different refractive indexes, etc.**

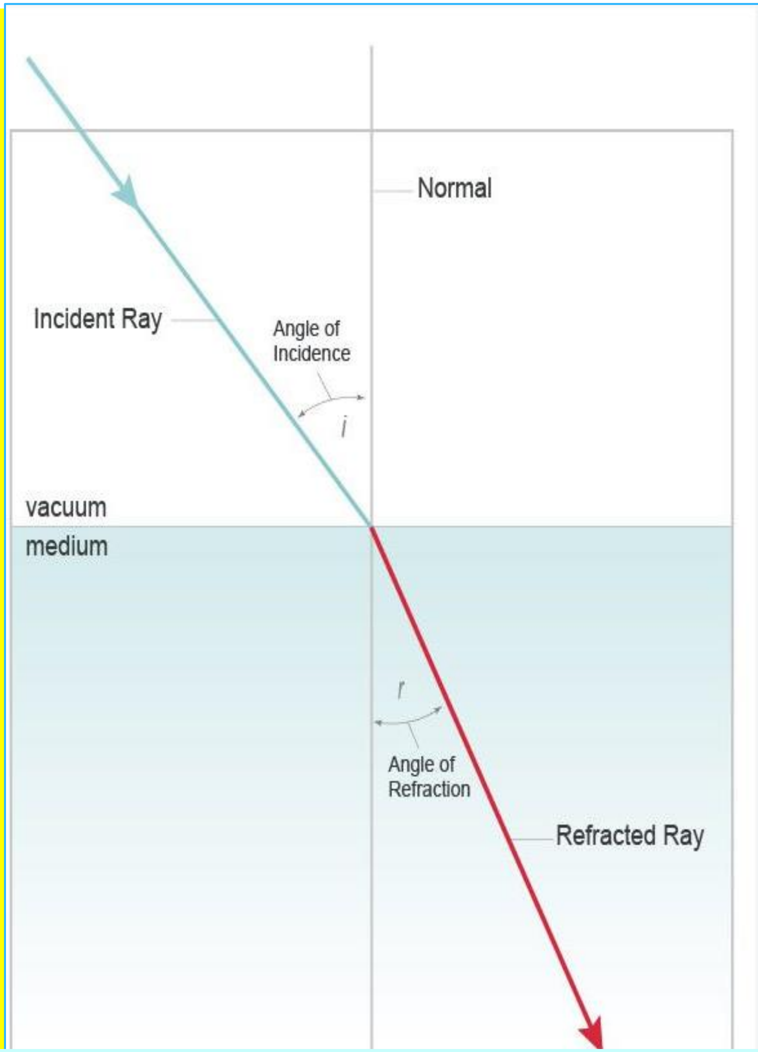
* **Anisotropic mineral crystallizes in all crystal systems except the cubic system.**

* **Some minerals are “more anisotropic” than others.**

* **The isotropy-anisotropy is related to the symmetry of crystals.**

* Anisotropic mineral crystals have variable refractive indices. WHY?
* Because light passing through the crystals will travel at different speeds, depending on the direction of travel (the orientation of the crystal to the incident light).
* In optics the refractive index or index of refraction **n** of an optical medium is a dimensionless number that describes how light, or any other radiation, propagates through that medium.
* **Refractive index (n) = the speed of light in vacuum or air (c) / the speed of light in a transparent material (v).**

$$n = c/v$$

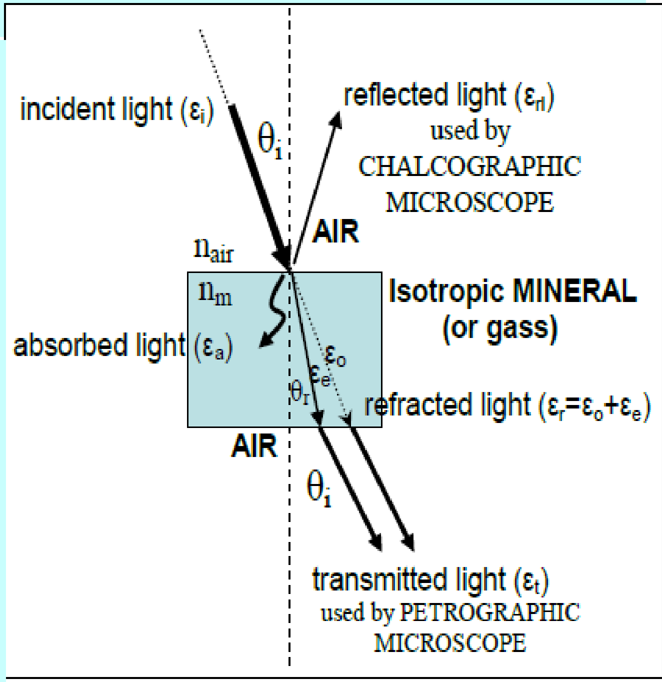


- For example, the refractive index of water is 1.33, meaning that light travels 1.33 times faster in a vacuum than it does in water.

Interaction between light and mineral

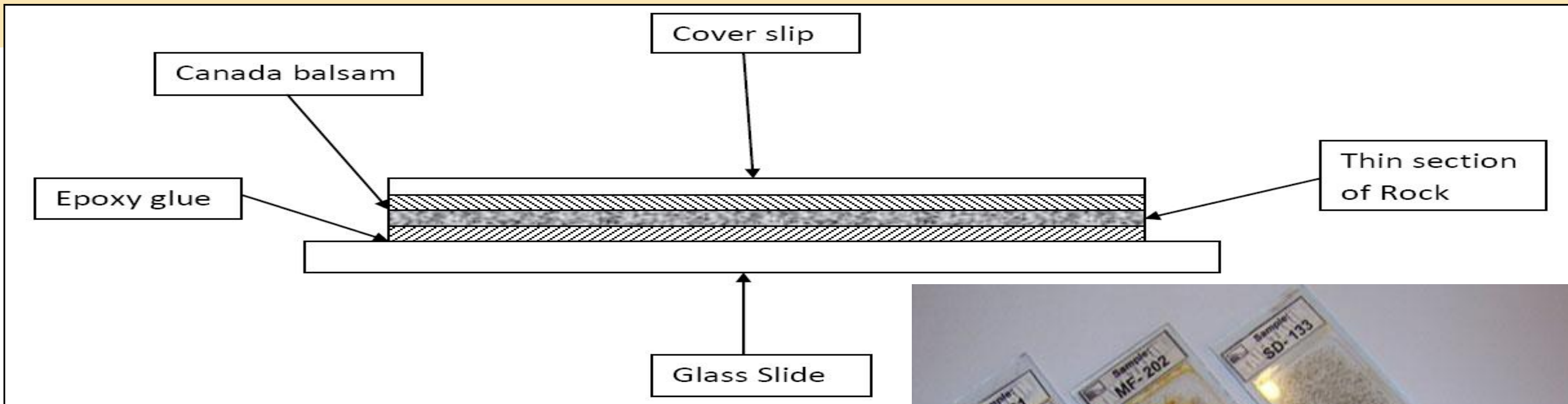
* **As light intersects isotropic material (glass or isotropic mineral), the light suffers several optical phenomena and is decomposed into several components.**

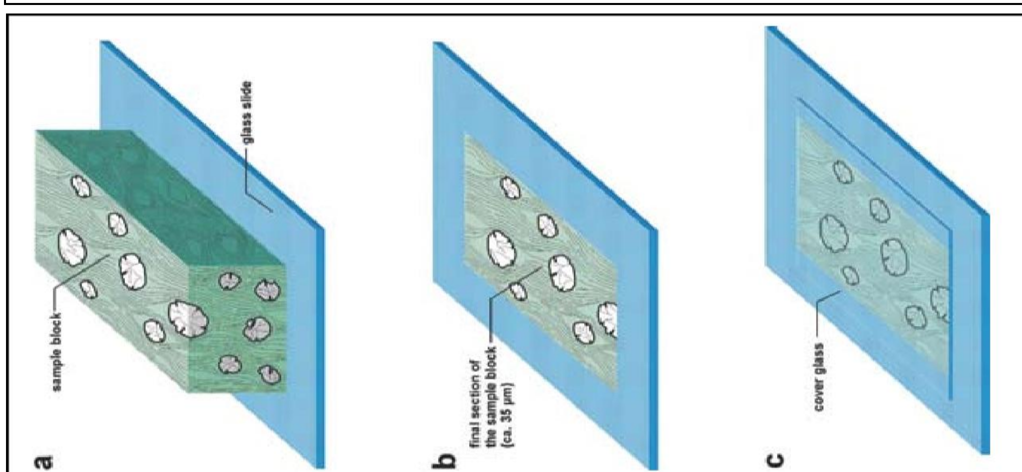
- Some fraction of the incident light is **reflected** by the surface of the mineral.
- Another component of light entering the mineral is **refracted**.
- A variable component of the light that enters the mineral is **absorbed**.
- The remaining light (intensity), if any, succeeds in escaping from/through the mineral grain. This light is called **transmitted light**.
- **The mineral optical properties are determined from this transmitted light.**



Thin sections for optical studies in transmitted light

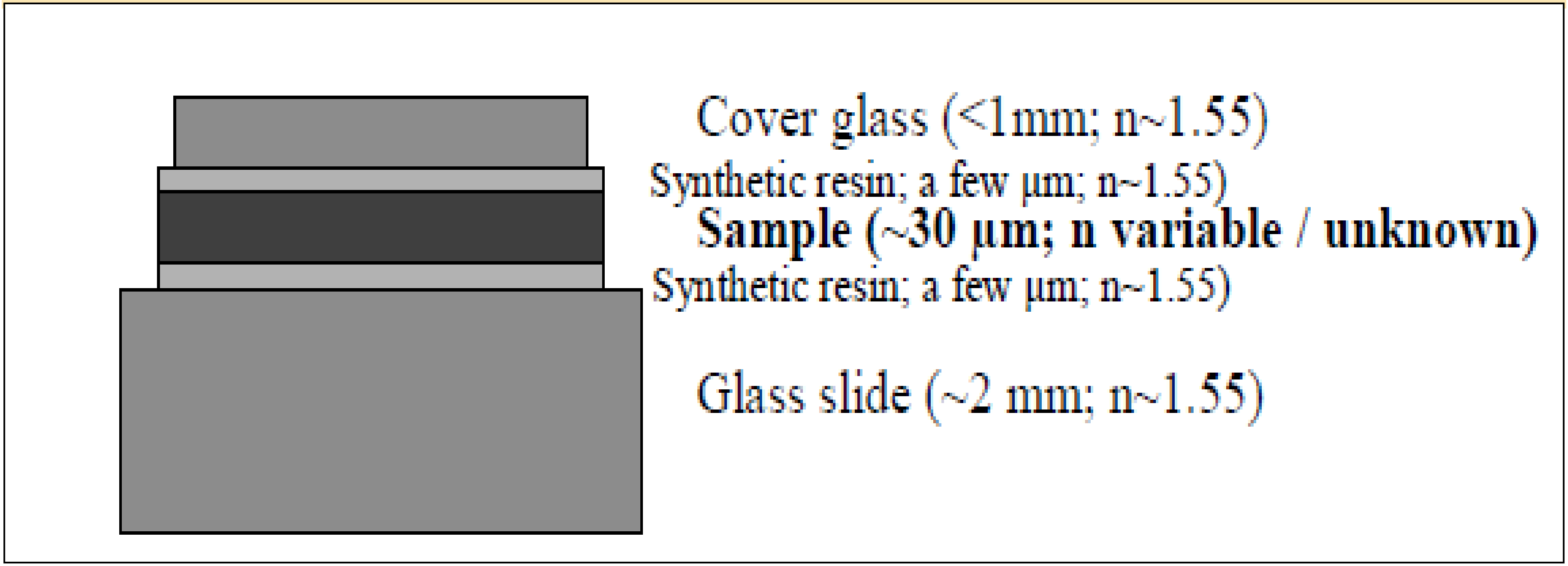
* For optical mineralogy we need to cut a slice of the rock, grind and polish a flat surface of it down to 30 microns (0.03 mm) thick, and glue it, using a polymerized resin, onto a glass slide.





* The refractive index of the resin must be known, in order to estimate correctly the (unknown) refractive indexes of minerals in thin sections **(usually resin is 1.542; if the resin is Canada Balsam)**.

* **A cover glass slip is usually glued on top of the thin section (with the same resin) in order to protect the sample from weathering but also to have the same (known) refractive index below and above the sample.**

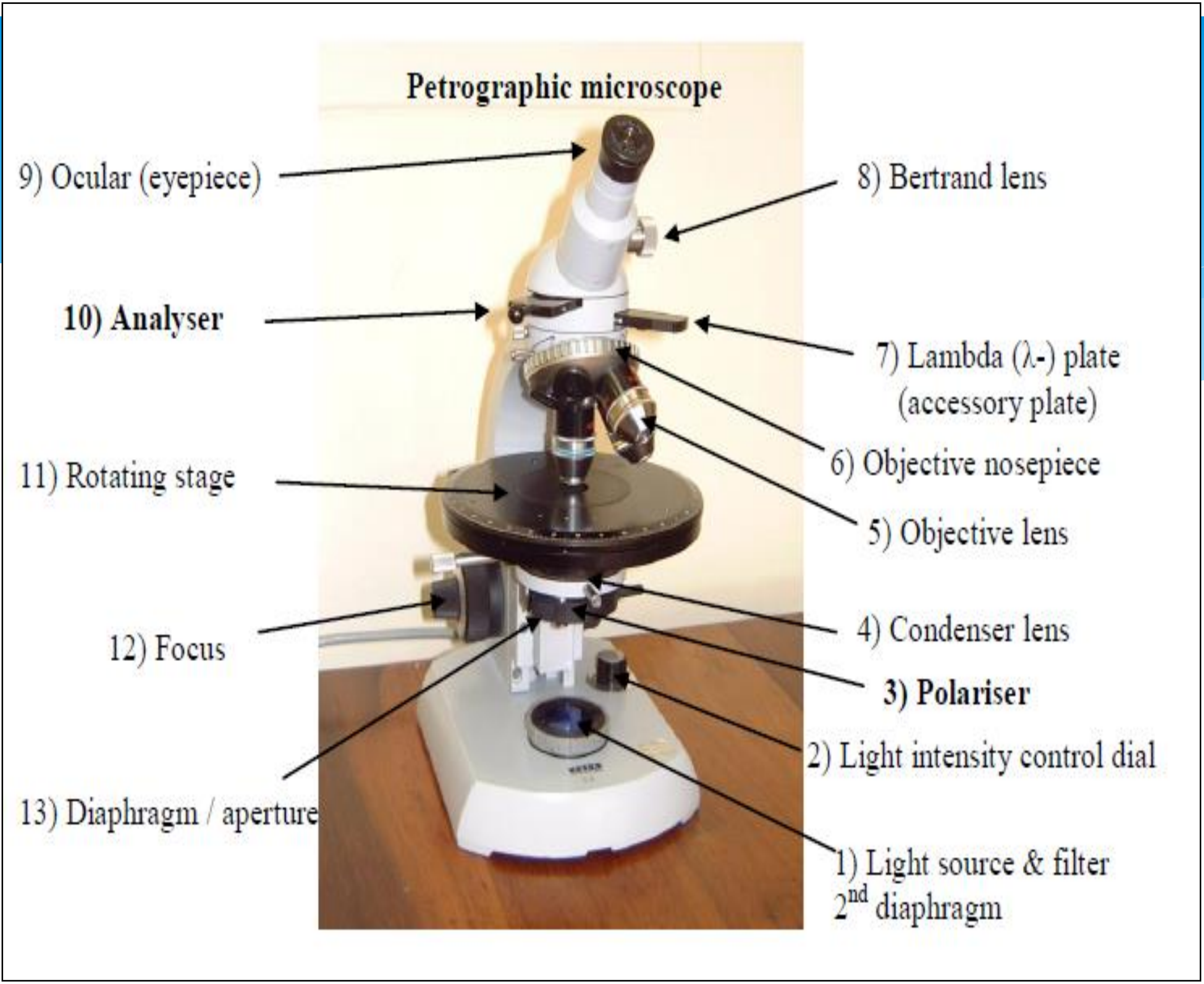


Petrographic Microscope

* The optical methods used light to provide information about the optical behavior of minerals.

* The microscopes using transmitted light are called petrographic microscopes and they are used for studying the transparent minerals.

* The petrographic microscope is used to analyze the properties of the transparent minerals.



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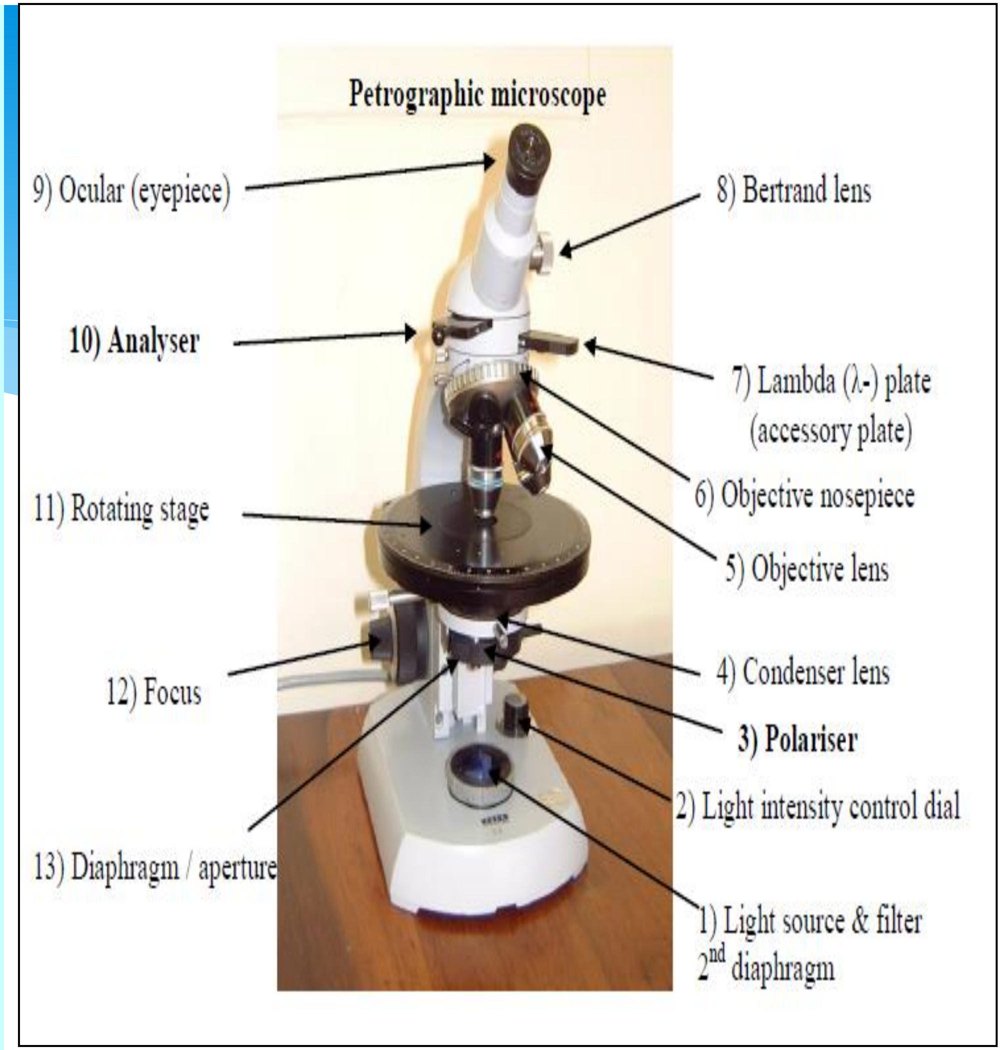
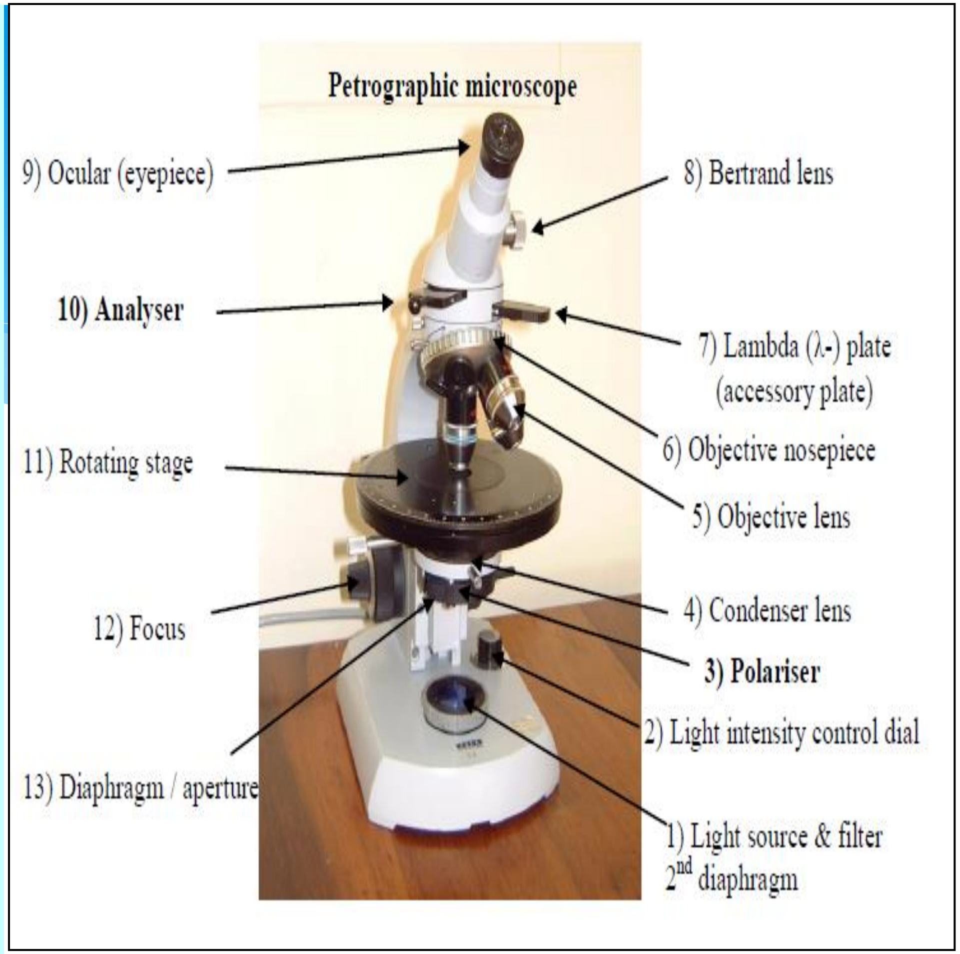
* The light source (1) is on the bottom of the microscope, under the blue filter.
* The blue filter is needed for absorbing the strong yellow-orange component of the light emitted by the electric bulb, in order to produce normal-looking white-colored light .
* The 2nd diaphragm is used for reducing the intensity of light (useful sometimes, for evaluating properties such as relief and chagrin).
* Similar effects can also be obtained by using the light intensity control dial (2).
* The white light coming up from the blue filter passes through a group of other diaphragms and apertures (13) also used for adjusting the light intensity and homogeneity.
* On its way up, the light passes through the polarizer (3), which is mounted so that the polarization plane is East-West in the image we see through the eye-piece, or ocular.



* Above the polarizer is mounted a mobile lens (convergent lens, 4).
* Above the convergent lens there is a rotating plate (11), which is the stage, and is graduated (360°) so that angular measurements can be made.
* In the middle of the plate there is a round hole where the polarized light goes through. Here we put the thin section (sample), so that the light from below can pass up through the sample.
* The polarized light will interact with the sample and the resulted light will continue upwards.
* To magnify the light transmitted through the sample, an objective (or a set of objectives) is normally used (5), having different powers of magnification (usually 2.5x, 6.3x, and 10x, 20x, 40x or more).
* Up to 4 objectives are mounted on a typical nosepiece (6).

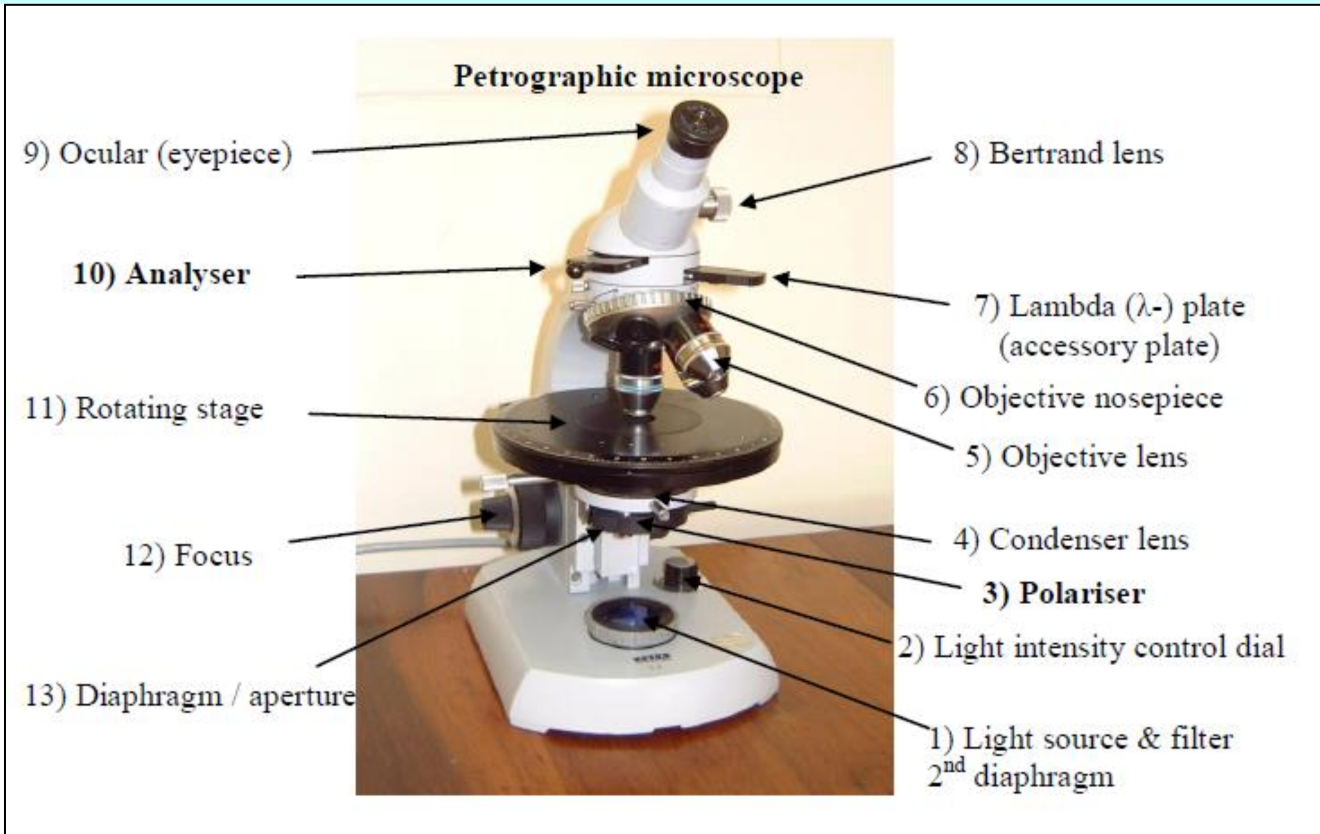


* Above the objective, the analyzer (10) is mounted.

* It also polarizes light, and is mounted so that its plane of polarization is perpendicular to the polarization plane of the polarizer (i.e., the analyzer has the polarization plane mounted N-S).

* The analyzer is mobile, so it can be pushed in (or pulled out) so that observations can be made either with or without the analyzer.

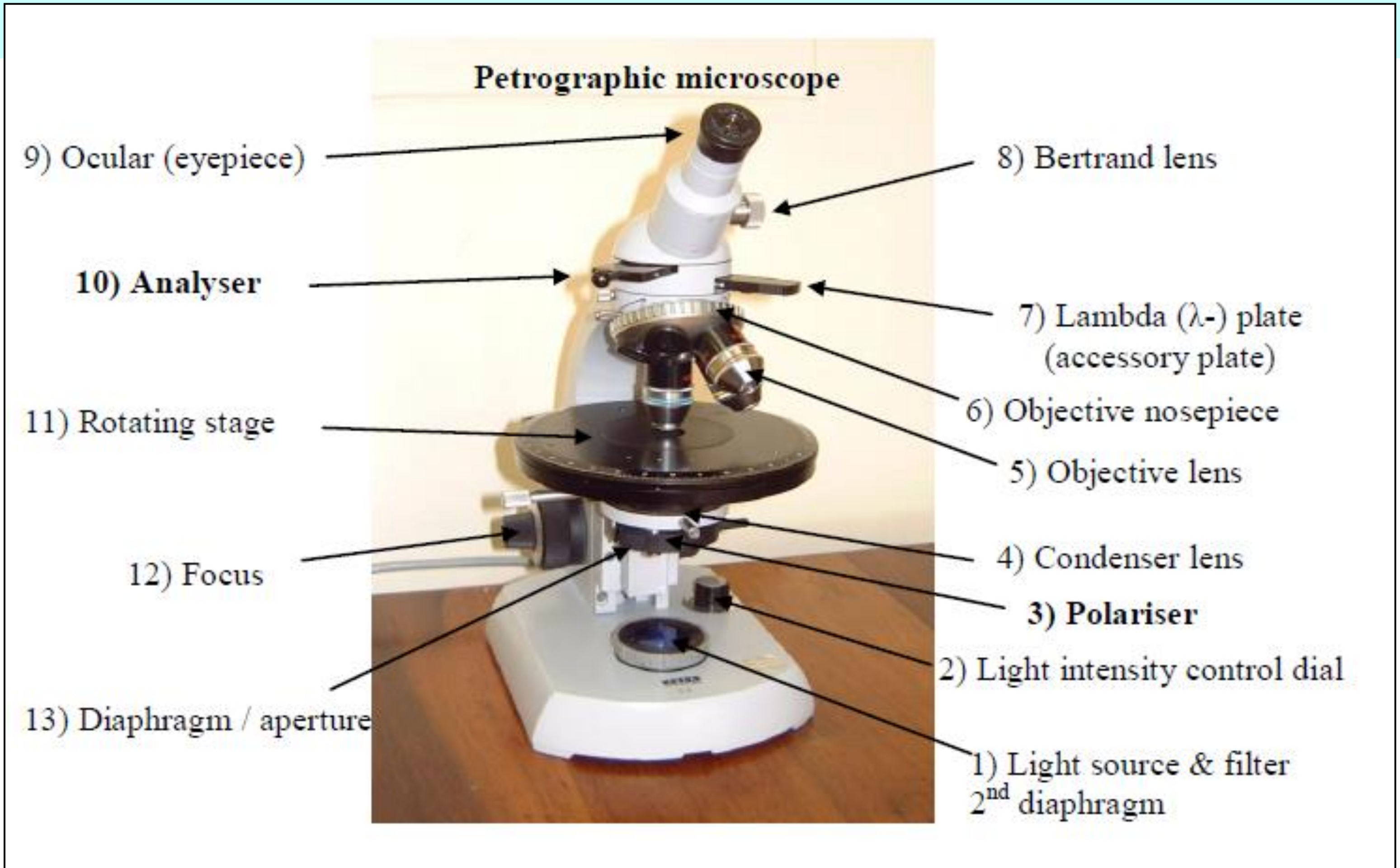
- The final magnification of the image is provided by the ocular (9), which typically provides 10x additional magnification.



* The total power of magnification of the microscope is equal to the power of magnification of the objective in use multiplied by the power of magnification of the ocular; these values are written on both the objective and the ocular.

* For some specific determinations, the lamda plate (λ-plate = gypsum plate, or λ/4-plate = muscovite plate; 7) and the Bertrand lens (8) can be used.

* The focused image through the microscope is achieved by using the focus knobs (12) (one large, for coarse focusing, and one smaller, for fine focus).

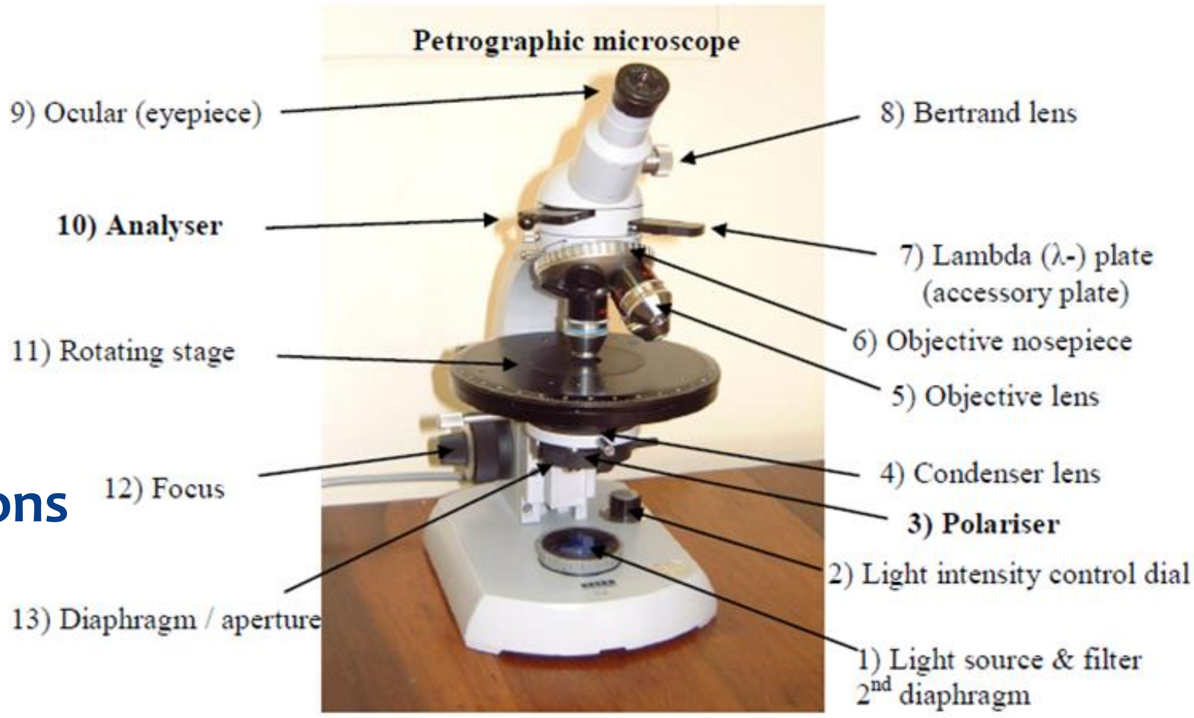


MINERAL IDENTIFICATION USING THE PETROGRAPHIC MICROSCOPE

Observations using plane polarized light (PPL) mode (Analyzer is out)

* The observations typically made in PPL are

1. Transparency
2. Shape/habit/size
3. Color
4. Pleochroism
5. Cleavage
6. Relief
7. Inclusions/alterations



Transparency

* **Opaque mineral: appears totally black** (stays black regardless of the rotation of the stage) = No light pass through mineral.
* **For an opaque mineral we can observe shape, habit, and transparent inclusions, where present.**

* **To study opaque minerals we use the reflected light petrographic microscope.**

* Usually the **opaque minerals are** either **sulphides** (e.g. pyrite, chalcopyrite, etc.), **oxides** (e.g. magnetite, hematite, or ilmenite), or **graphite**.

* If the mineral appears anything other than totally black (no matter what other colour is observed!) it means that the **light passes through the mineral, so the mineral is transparent**.

SHAPE, HABIT & SIZE

- **Shape:** **Euhedral** (or, if metamorphic, we call it **idiomorphic**), **subhedral** (**hypidiomorphic**) or **anhedral** (**xenomorphic**).

- **Habit:** **isometric, prismatic, tabular, sheeted, etc.**

- **Size:** **estimated in mm, based on the field of view determined from the magnification by the objective and ocular lenses.**

* Looking at the mineral boundaries, we can see the shape of the analyzed grain.

* In order to estimate the habit, several grains of the same mineral should be examined.

* If the **grain boundaries are well developed with predictable interfacial angles, the grain is called euhedral (idiomorphic).**

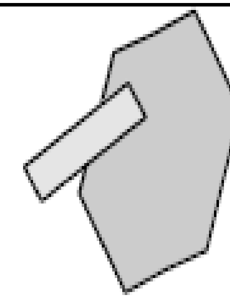
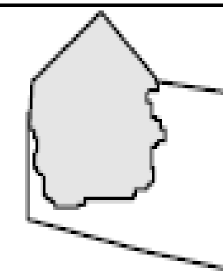
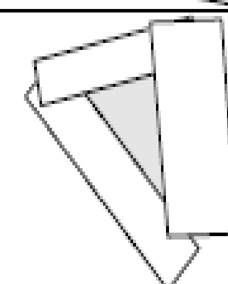
* If the **grain shows irregular boundaries only, the grain is anhedral (xenomorphic).**

* If the grain has **both regular and irregular boundaries, it is subhedral (hypidiomorphic).**

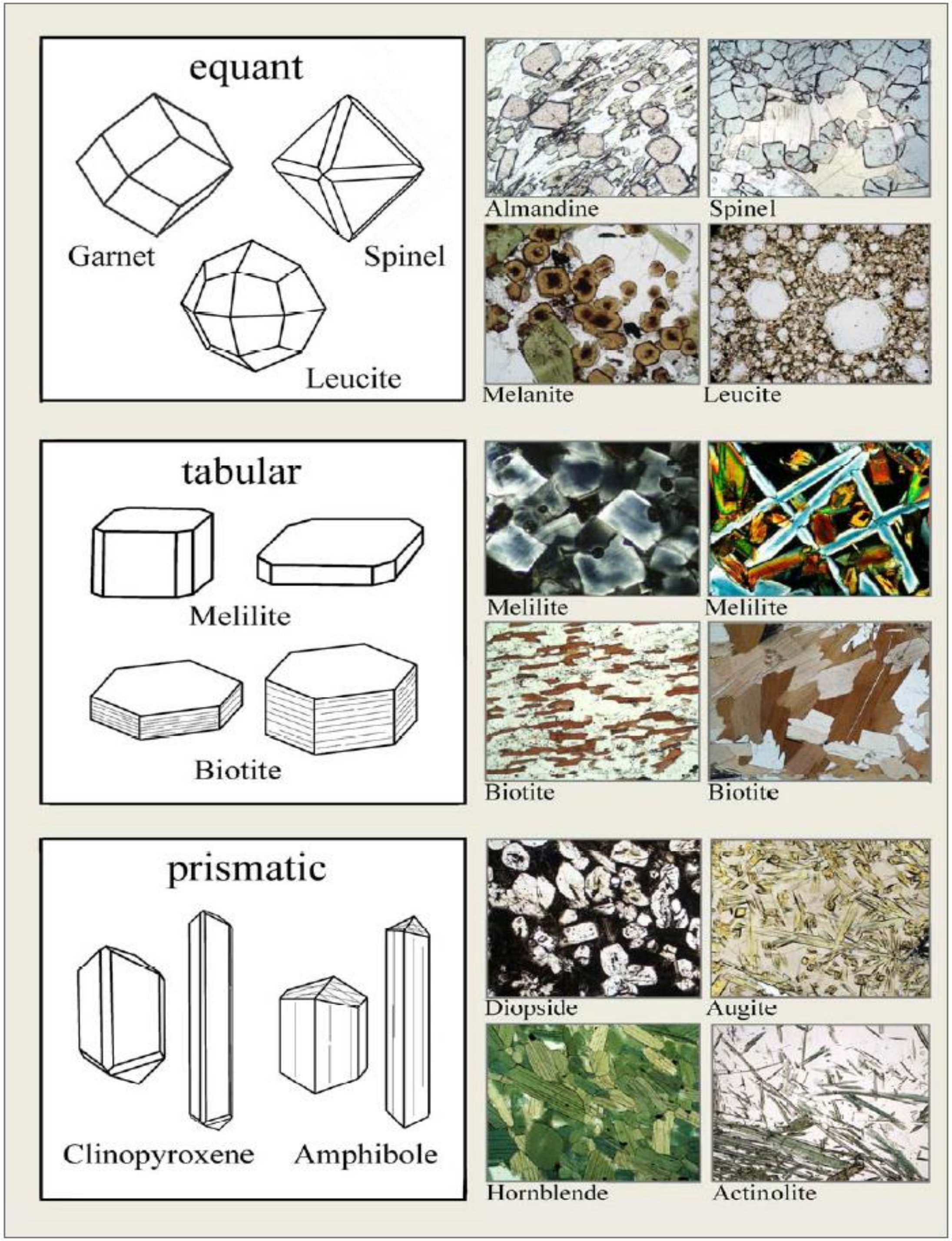
* The shape and size of the grains are related to the conditions of growth (crystallization).

* When crystals grow, depending on how favourable the conditions are, they may develop all of their crystal faces, or none of them at all (no preferred faces, so crystal grows as a shapeless blob = anhedral growth), or anything in between.

CRYSTAL SHAPE

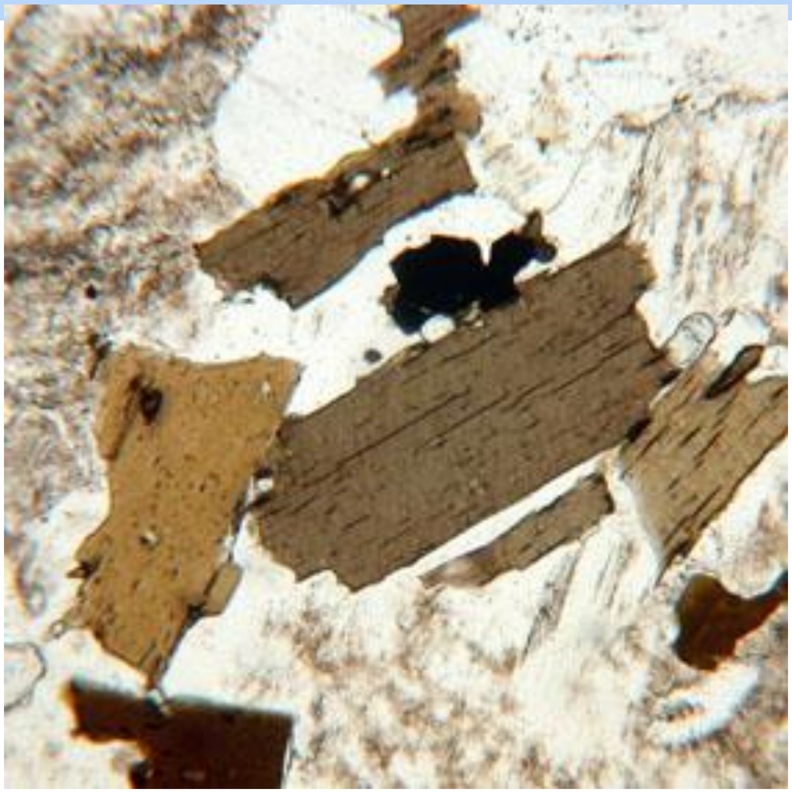
Degree of crystal development	Igneous minerals (crystallised from a liquid)	Metamorphic minerals (crystallised by solid state diffusion)	shaded grains as examples
grain has most/all well-developed crystal faces (i.e., linear grain boundaries whose orientations are controlled by the crystallography of the particular mineral)	**euhedral** (idiomorphic)	**idioblastic**	
grain has some well-developed crystal faces	**subhedral** (subidiomorphic)	**subidioblastic** (hypidioblastic)	
grain has no well-developed crystal faces (its boundaries are defined by the shapes of the adjacent crystals)	**anhedral** (allotriomorphic)	**xenoblastic**	

CRYSTAL HABIT

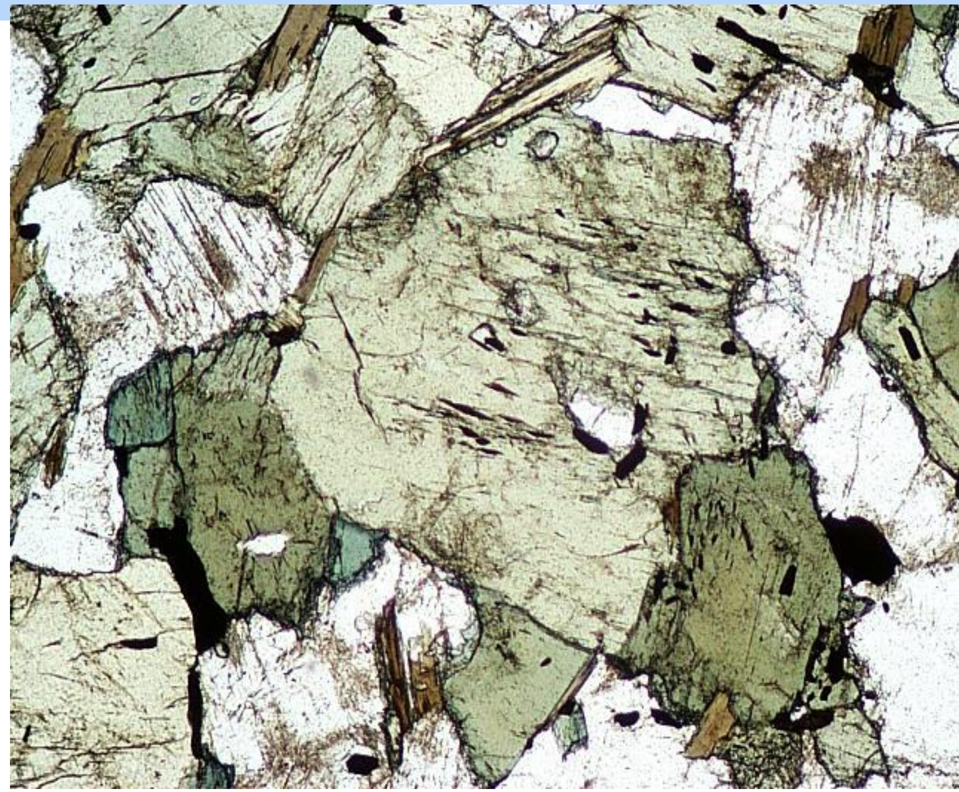


COLOR (ABSORPTION COLOR)

- The mineral is colorless, weakly colored or strongly colored (e.g. pale yellowish brown, bluish light grey, etc.).
- The observed color is the absorbed color spectrum.



Biotite crystals in PPL



Hornblende crystals in PPL

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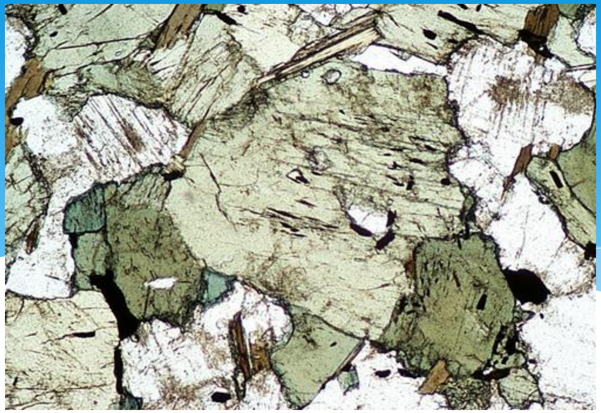
PLEOCHROISM

* **Change of the mineral absorption color when the stage is rotated. A property of anisotropic minerals.**

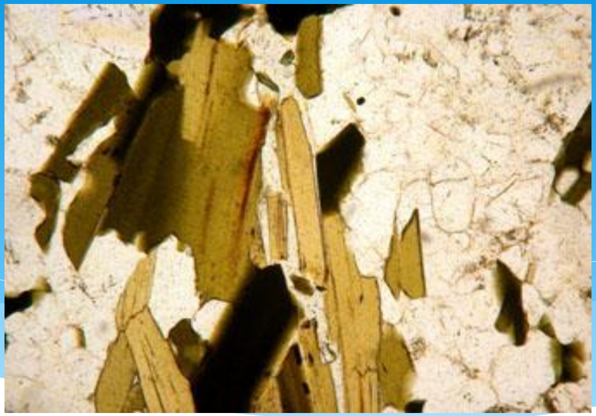
* **Pleochroism means that the absorption of specific light wavelengths depends on the crystal orientation.**

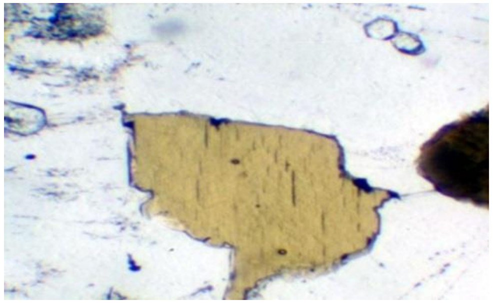
* **Based on intensity, pleochroism ranging from strong to weak (e.g., biotite, amphibole).**
* E.g. pleochroism from light yellowish green to dark bluish green).

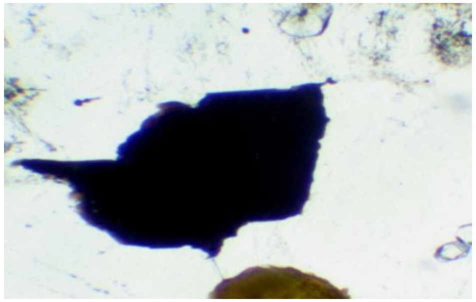


Hornblende

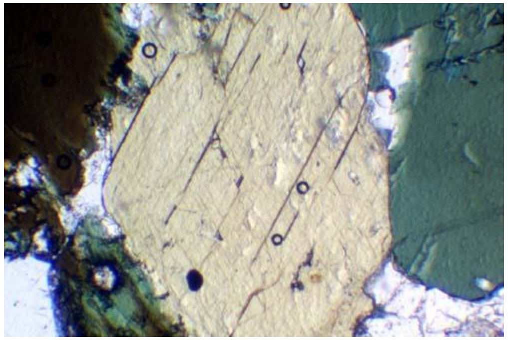
Biotite

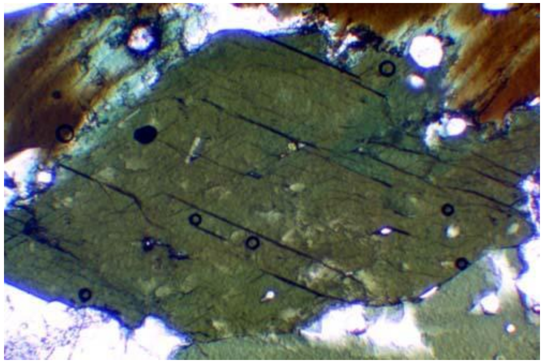






Pleochroism in Biotite when the stage is rotated 90°

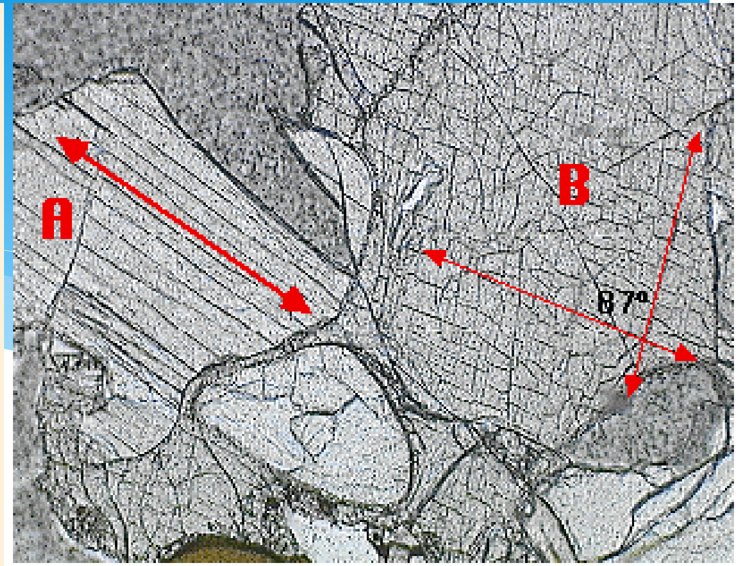


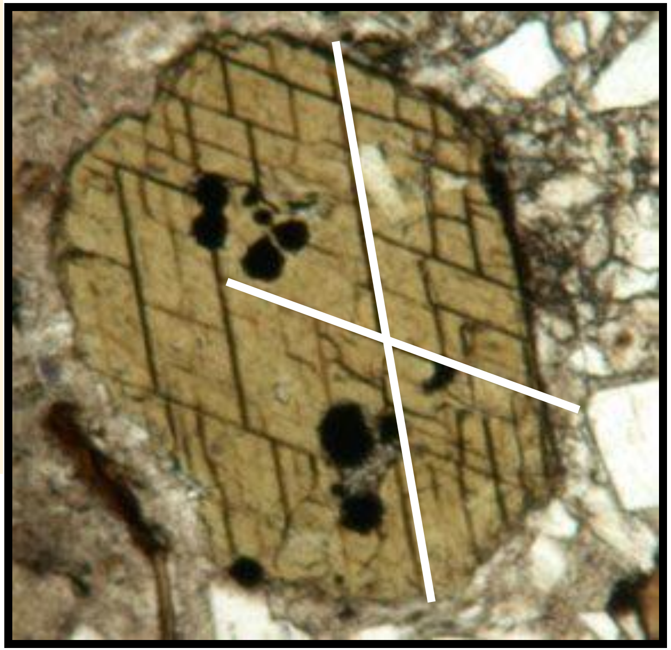


Pleochroism in Hornblende when the stage is rotated 90°

CLEAVAGE

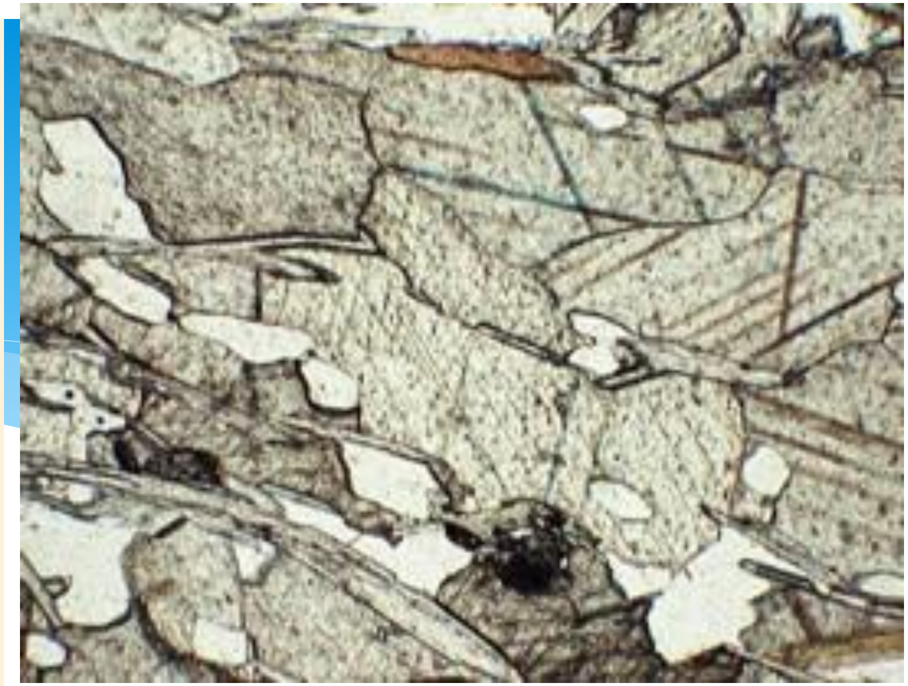
- Cleavages are planar surfaces of low cohesion produced by weaker atom bonds across them.
- They are visible when the cleavage is more or less vertical in the thin section.
- Cleavages seen in thin sections are linear expressions of the intersection of particular planes of crystal faces with the cut surface of the thin section.
- Some minerals may have three "good" cleavages (e.g., calcite), some have a "perfect" cleavage (e.g., micas).
- Some may have no cleavages at all (e.g., olivine, which therefore has no "preferred" planes of splitting, and gets fractured, instead).
- The same mineral will always have the same cleavage.



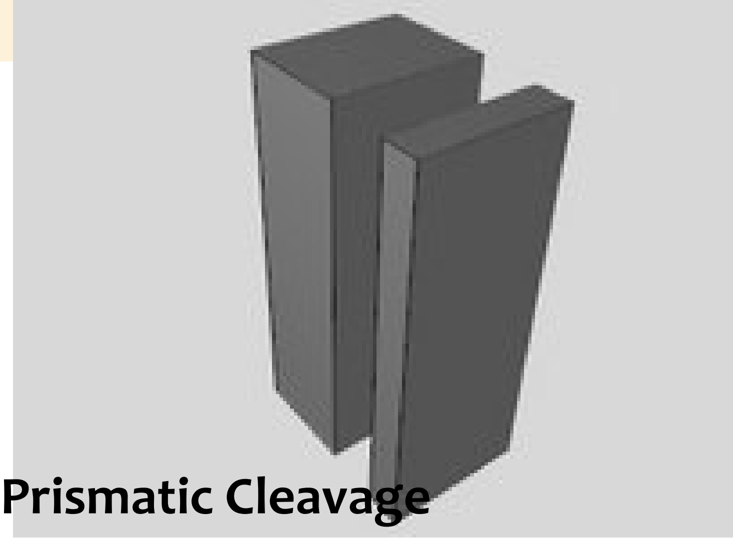


* Cleavage is said to be basal when it occurs perpendicular to the "c" axis of the mineral, and prismatic when it occurs parallel to the "c" axis.

* Multiple cleavages that produce geometric polygons are referred to using the name of the geometric polygon, such as octahedral cleavage in the mineral fluorite, cubic cleavage in the mineral halite, or rhombohedral cleavage in calcite.

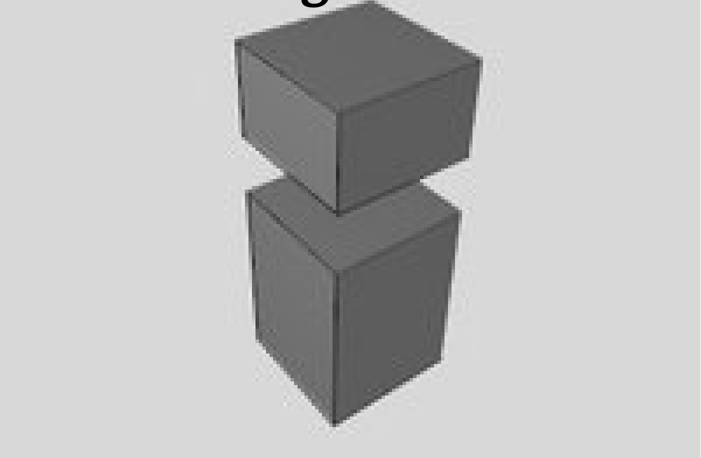


Cleavage in Calcite



Prismatic Cleavage

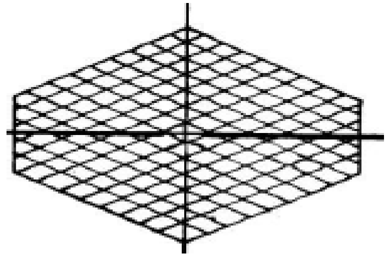
Basal Cleavage



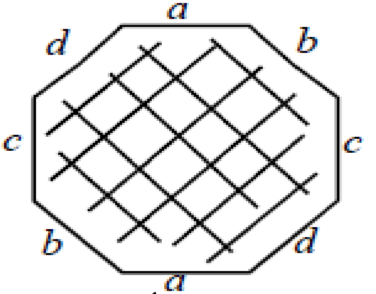
* The cleavage (quality and number of different cleavage planes) is diagnostic of some mineral species.

* From the shape of the observed grain in thin section and the quality and orientation of the cleavage(s), we can have an idea of the orientation of the section cut through the 3-D grain morphology.

* In the figure we can see basal sections of amphibole (left) and pyroxene (right), displaying two characteristic sets of cleavages.



Amphibole (2 cleavage at 120 and 60°)



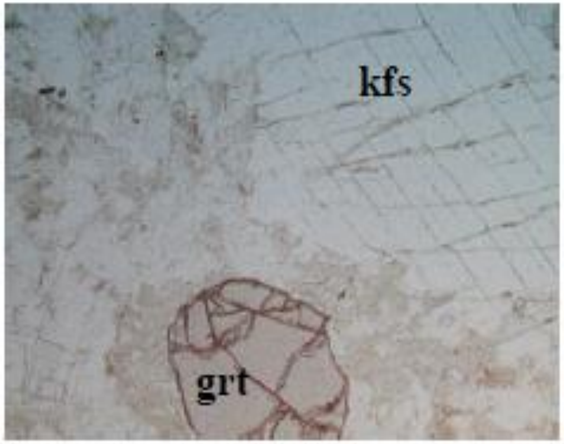
Pyroxene (2 cleavage at 90°)

* **The quality of the cleavage is estimated observing the density, continuity and width of the cleavage lines (which are always parallel lines) in thin section.**

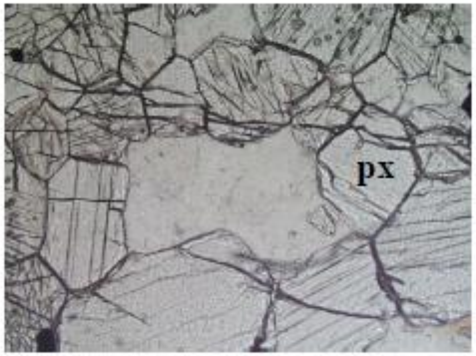
* The quality of cleavage is described as **perfect, imperfect, good, distinct, indistinct, poor, or absent.**

* The quality decreases from perfect (dense, almost continue and thin lines of cleavage) to weak cleavage (few, disperse segments of thicker lines) to absent (no cleavage, different curved and/or broken thick lines).

* For example:
  * **Perfect cleavage: micas, all phyllosilicates;**
  * **Good cleavage: feldspars, pyroxenes, amphiboles**
  * **Weak cleavage: apatite, sodalite, olivine;**
  * **Absent: quartz**



One good cleavage in feldspar (kfs and no cleavage in garnet)



One good cleavage in Pyroxene (px)

RELIEF

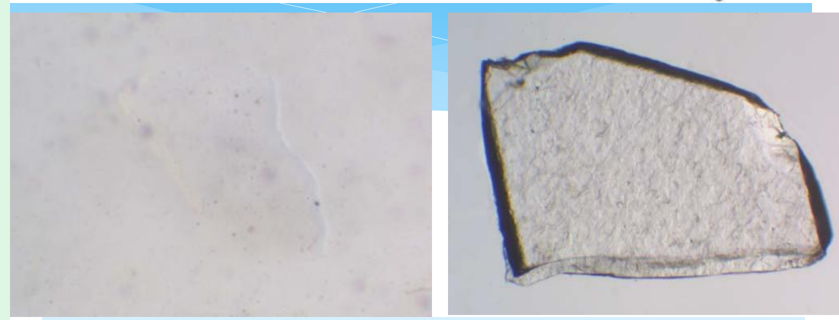
- Relief refers to the relative difference in Refractive Index (RI or n) between neighboring crystals.

- The higher the RI, the slower the light propagation in the mineral.

- Although relief is most useful as a comparative term (some minerals show higher relief than others), the relief can be positive or negative compared to a reference material of fixed and known RI.

- This reference standard is the resin, which has a known refractive index (n = 1.54-1.55).

- All minerals with relief higher than the resin have positive relief and all minerals with lower relief than the resin, have negative relief.



Left: low relief of quartz (it can hardly be distinguished from the resin because the refractive indexes of quartz and resin are very similar). Right: High relief of garnet comparing to the resin. It boundary appears extremely distinct and thick

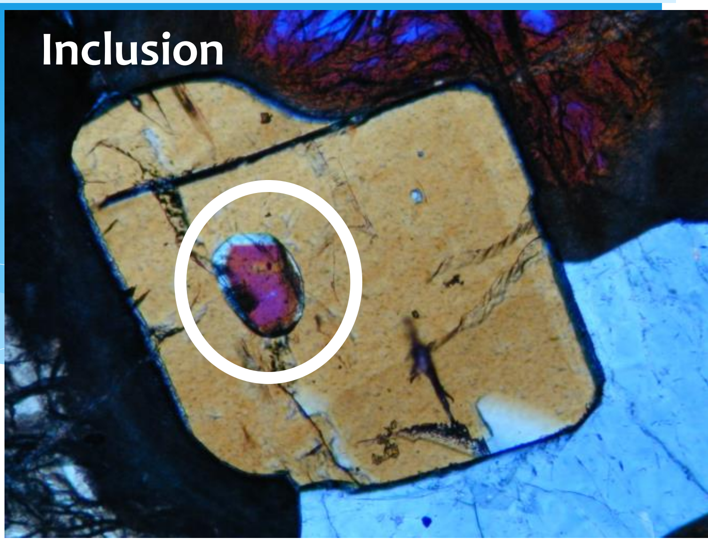
Inclusions & Alterations

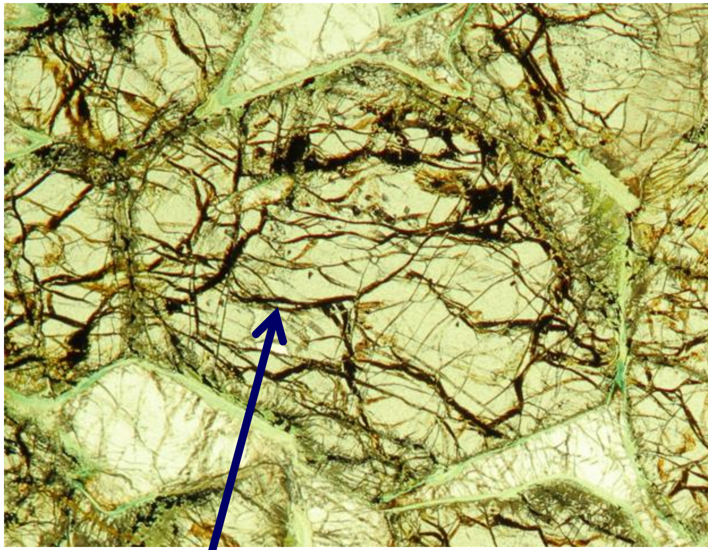
* **Minerals can have inclusions, which can be solid (other finer-grained minerals) or fluid (liquid and/or gas) inclusions.**

* Choose a higher magnification objective and describe the inclusions, if present (transparent or opaque, colorless or colored, relief, etc.).

* **If altered, other minerals (alteration minerals) can appear at the margin of the analyzed mineral, or along its cleavages or cracks.**

* Describe the alteration mineral separately using a **higher magnification objective**.





Alteration

Observations using crossed polarized light (XPL) mode (Analyzer is in)

* The observations typically made in crossed niclos (XPL) are

1. Isotropy/Anisotropy
2. Extinction angle
3. Birefringence color
4. Twinning/Zoning
5. Specific textures (Exsolution)

ISOTROPY/ANISOTROPY

* **A transparent isotropic mineral: black in crossed nicols, and the color doesn't change during rotation of the stage.**

* NOTE: do not confuse **isotropic mineral** (or isotropic section through anisotropic mineral) with an **opaque mineral**!

* **An opaque mineral is totally black whether the analyser is in or out, while the transparent, isotropic mineral is not opaque!**

* **If the mineral is anisotropic, it shows 4 positions of extinction and 4 positions of maximum interference when rotating the stage 360°.**

EXTINCTION ANGLE

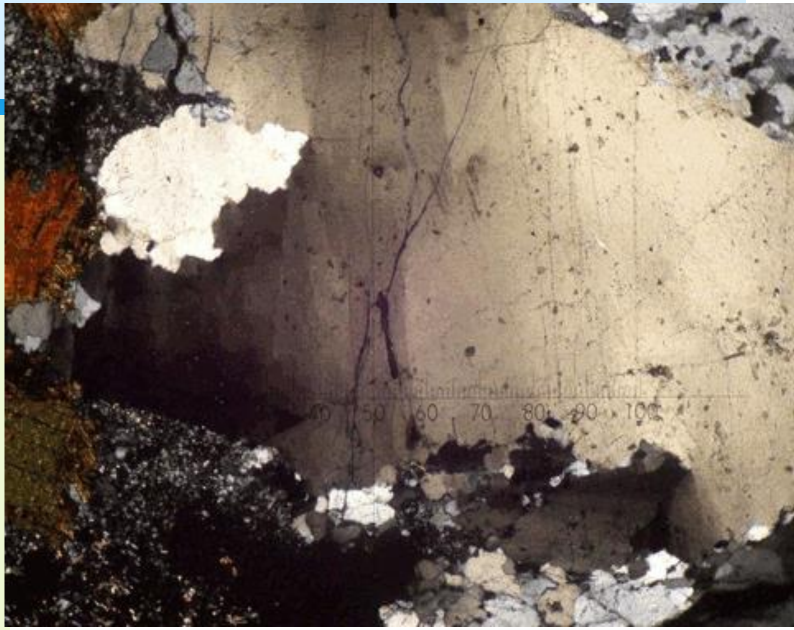
* **Mineral in extinction = mineral dark orientation during rotation of the stage. (must be anisotropic mineral)**

* **The extinction angle (0 to 89) = the angle between the maximum illumination and the maximum extinction of mineral (XPL).**

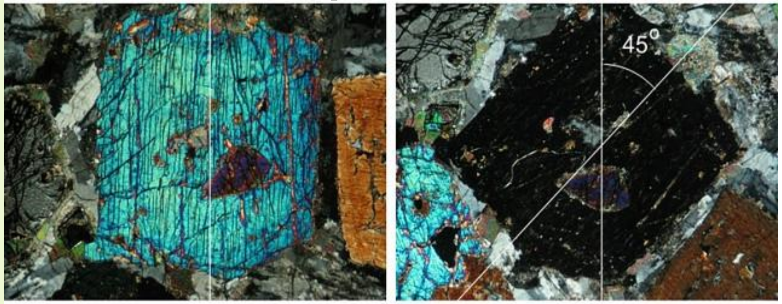
* **Extinction angles can only be measured relative to planar crystal boundaries or cleavage planes**. The extinction angle is the measure between the cleavage direction or habit of a mineral and the extinction.

* To find this, simply line up the cleavage lines/long direction with one of the crosshairs in the microscope, and turn the mineral until the extinction occurs.

* The number of degrees the stage was rotated is the extinction angle, between 0-89 degrees.

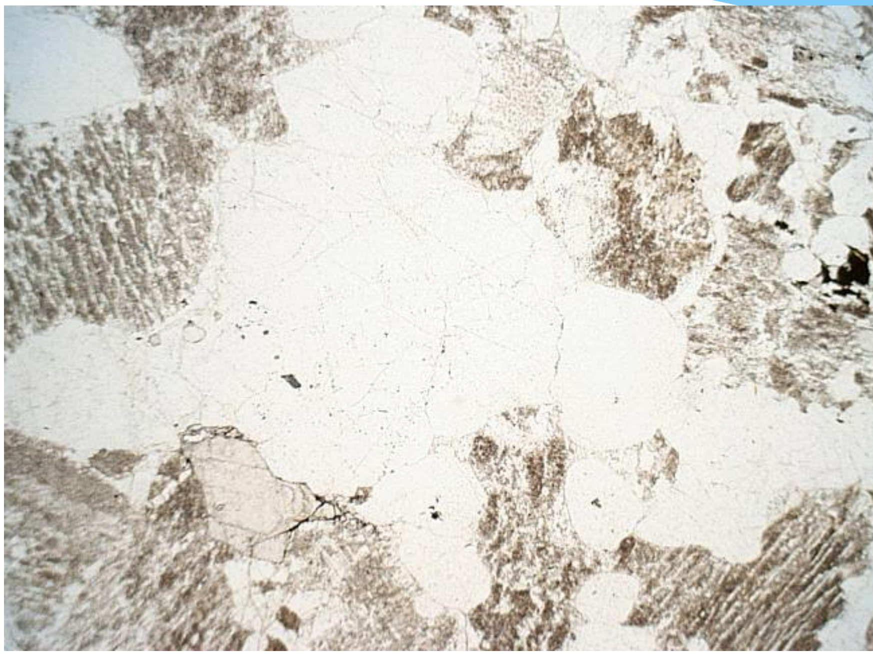


Clinopyroxene

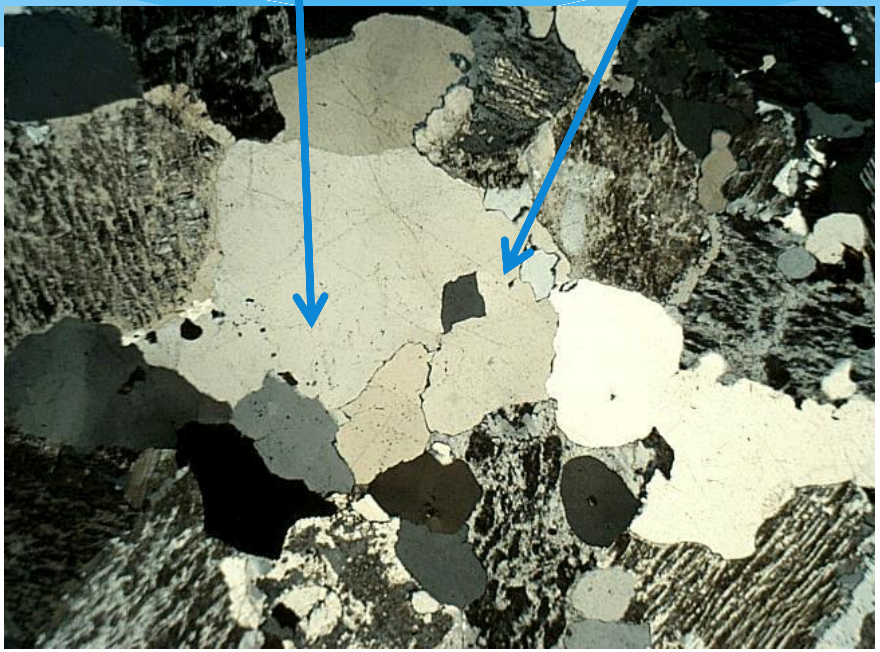


The extinction can be parallel, symmetric or oblique.

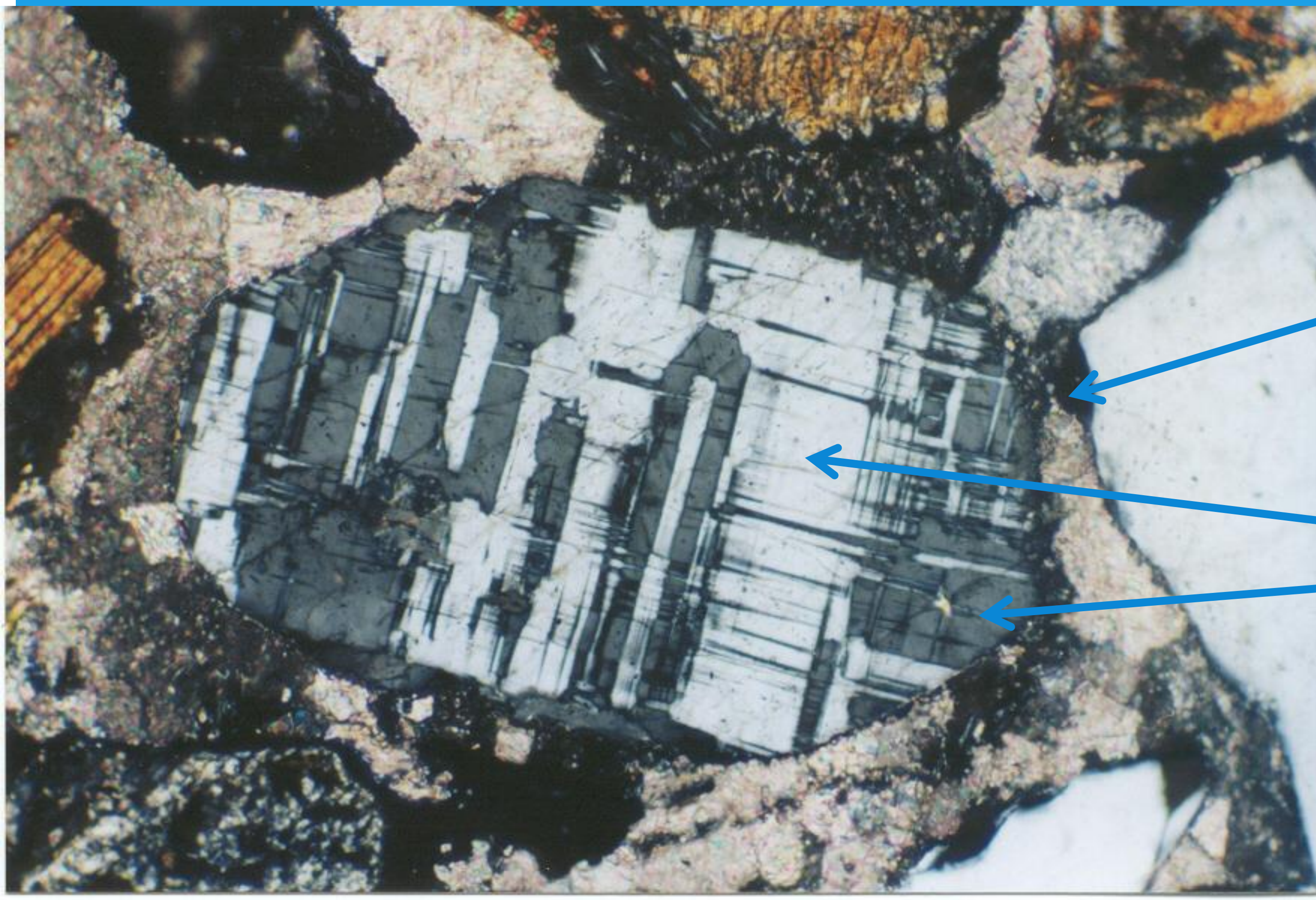
- **Extinction direction provides important information on the crystal system of minerals, since orthorhombic, tetragonal and hexagonal crystals have an extinction angle of zero, that is they have parallel extinction, whilst monoclinic and triclinic minerals have a finite extinction angle, that is they have inclined extinction. Some minerals have characteristic ranges of extinction angles.**



Quartz crystals in plane polarized light



Same quartz crystals with analyzer inserted (XPL)



One grain

Individual crystals

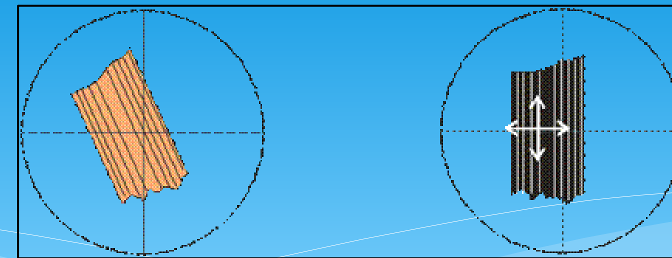
https://youtu.be/JM0fqEEcMMQ

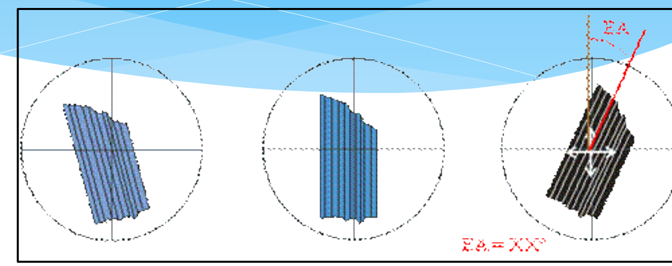
Type of Extinction

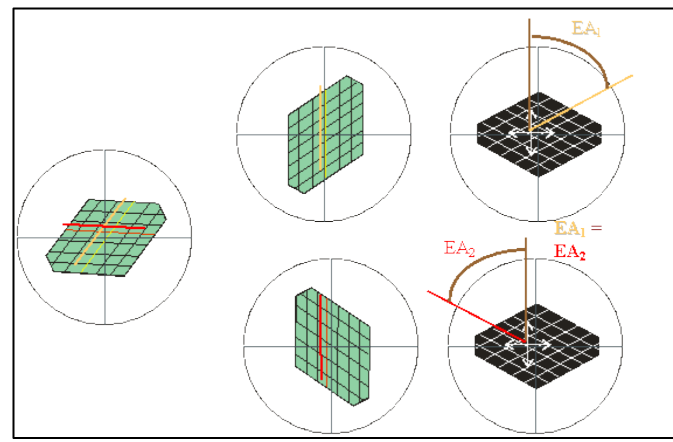
- **Parallel Extinction:** The mineral is extinct parallel to the cleavage and the length is aligned with one of the crosshairs.
- The extinction angle (EA) = 0° **Example Orthopyroxene, Biotite**
- **Inclined Extinction:** The mineral is extinct when the cleavage is at an angle to the crosshairs.
- **EA** > 0° **Example: Clinopyroxene, Hornblende**
- **Symmetrical Extinction:** The mineral grain displays two cleavages or two distinct crystal faces.
- It is possible to measure two extinction angles between each cleavage or face and the vibration directions. If the two angles are equal then Symmetrical extinction exists.
- Example: **Amphibole, Calcite**

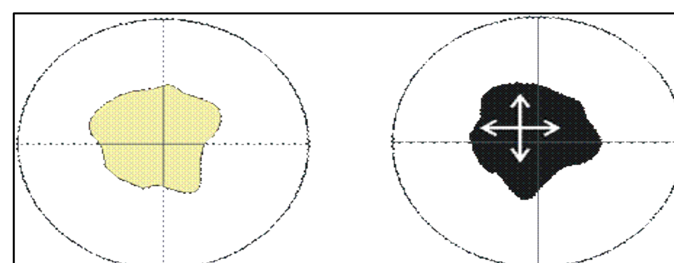
- Minerals which are not elongated or do not exhibit a prominent cleavage will still go extinct every 90° of rotation, but there is no cleavage or elongation direction from which to measure the extinction angle.
- Example : **Quartz, Olivine**

- **Wavy extinction in quartz or deformed/stressed minerals.**







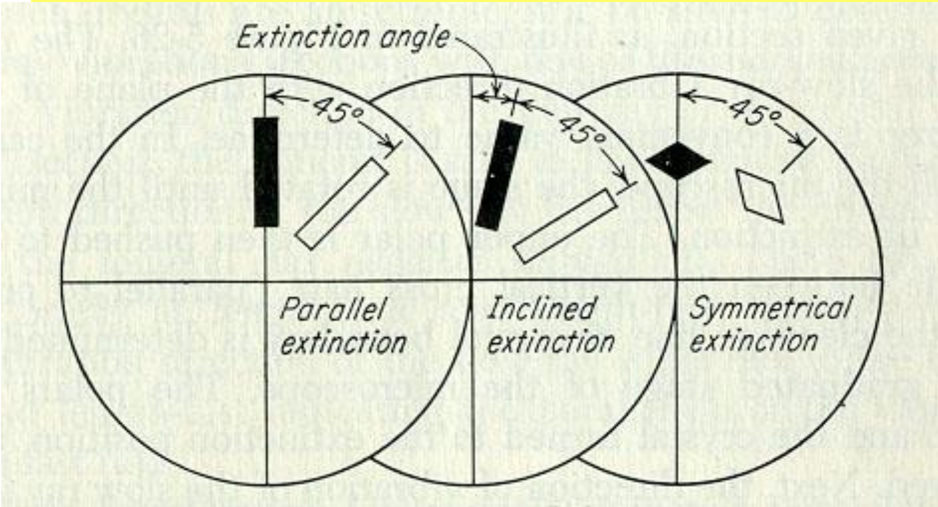


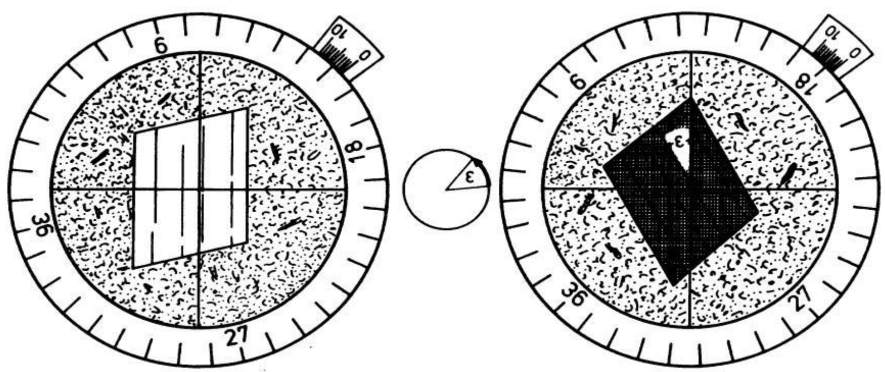
How to measure a mineral extinction angle?

- Move the stage so that the crystallographic reference (e.g. the crystal face, cleavage, etc.) is aligned N-S.
- Record the angle position of the stage.

- Then rotate the stage (in the sense where the crystal arrives faster in the extinction position) until the crystal has its maximum extinction (remember that there are four positions of extinction at each 90°).

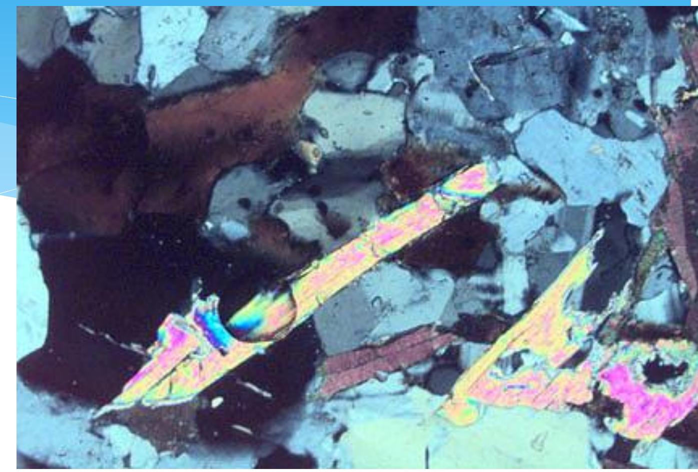
- In this second position, when the crystal is extinct, record the stage angle position again.
- **The difference between the two readings is the extinction angle.**





Birefringence/interference color

- Birefringence is a value that can be used to determine interference color of a mineral section in cross polarized light.
- **Interference color is the mineral color under cross polarized light.**
- **The birefringence is the difference between the largest and smallest refractive index of a mineral section.**
- **The birefringence of isotropic minerals is zero in any direction.**
- The birefringence of uniaxial and biaxial minerals (aniosotropic minerals) is only zero where the light ray is incident parallel to the optic axes.



Muscovite showing 2nd and 3rd order interference colors

- **Common minerals with low order interference colours: Quartz, Plagioclase, K-Feldspar, Chlorite**
- **Common minerals with moderate order interference colours: Amphiboles, Pyroxenes**
- **Common minerals with moderate-high order interference colours: Muscovite, Biotite, Olivine**
- **Common minerals with very high order interference colours: Calcite**

- The interference color is produced by interference between the two rays produced as light passes through an anisotropic mineral, the fast ray and the slow ray.

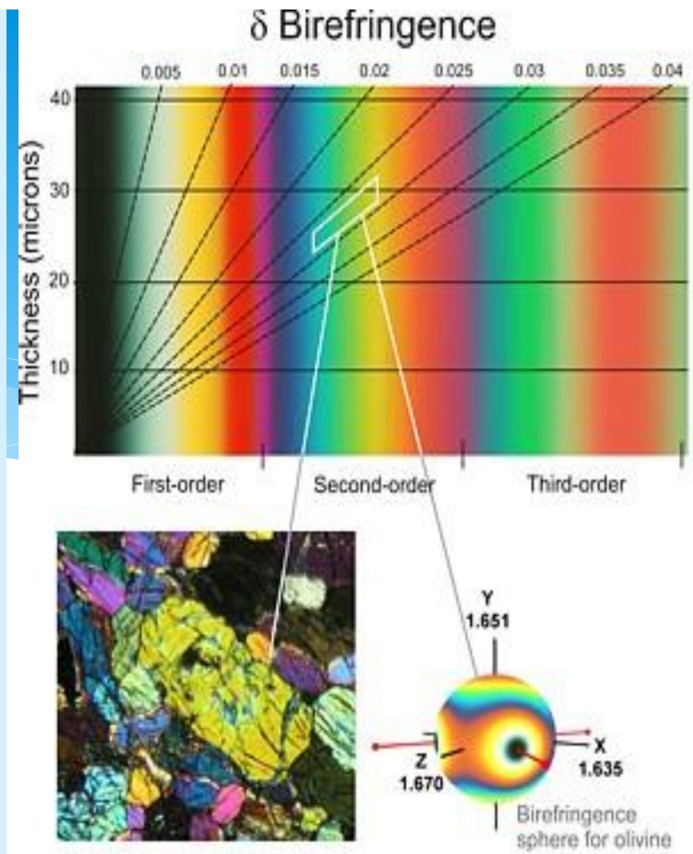
- Interference color can be interpreted using color charts. A relationship between interference color and retardation can be graphically illustrated in the classical **Michel-Levy interference color chart.**

- **If the thickness of a section is known then the birefringence can be determined from the interference color.**

- **Maximum birefringence can be diagnostic of a mineral when used with other properties.**

- If the thin section contains a known mineral, with a restricted range of birefringence, then the interference colour can be used to determine the thickness of the section.

- **Standard thin sections are 30 microns thick. Thin sections thicker than 30 microns will produce higher order interference colours.**



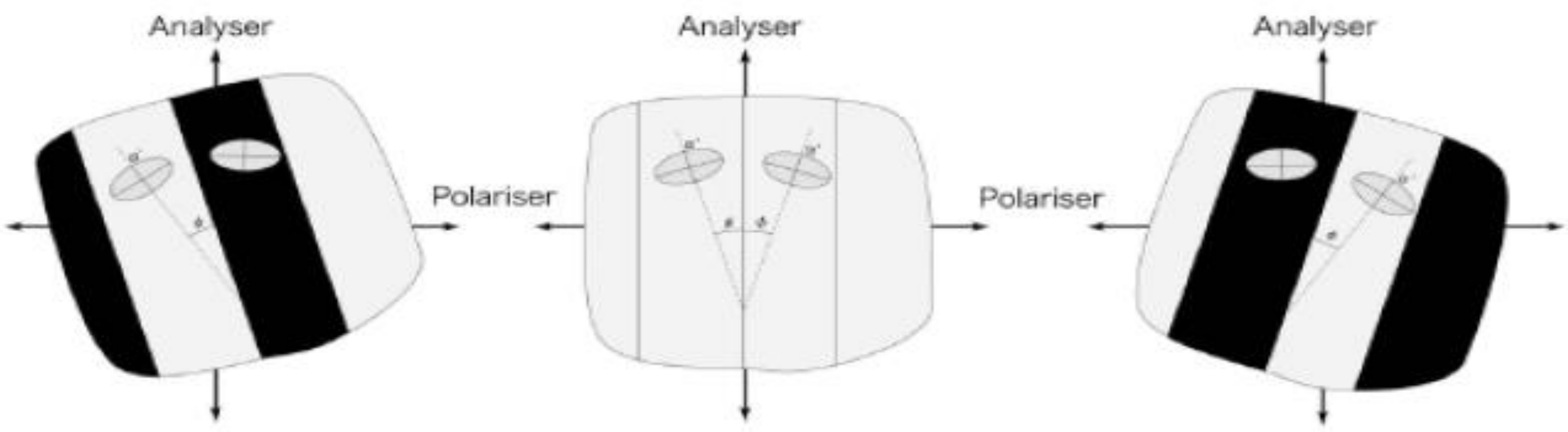
Olivine in a dunite, the yellow green crystal has a second order colour with a birefringe of 0.028. The thickness of the section decreases to 25 microns in places showing a second order blue.

Twinning & Zoning

* Twinning is observed under cross polarized light (XPL).
* A twin is a symmetrical growth of two or more crystals of the same mineral.
* The common plane of the twinned crystals (which is called the twinning plane) is a symmetry plane, seen in thin section as a straight line separating two identical crystals which have a symmetrical optical orientation to the twinning plane.

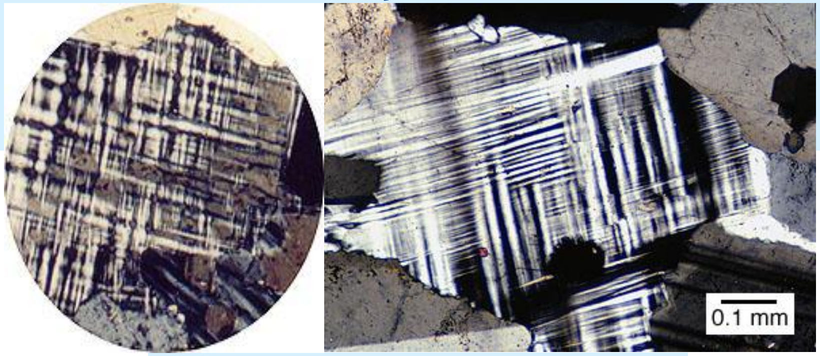
* This is observable by rotating the stage when crystal (1) is in extinction, its twin crystal (2) shows interference colours.

* Continuing the rotation of the stage, crystal 1 shows interference colors and crystal (2) will enter into a position of extinction.



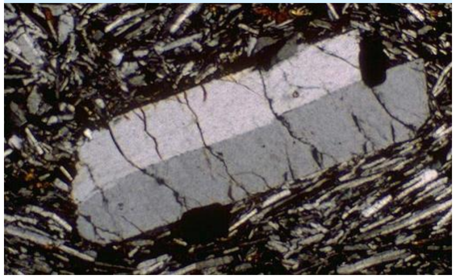
- **Polysynthetic** (**lamellar twinning**) more than two crystals are twinned, having parallel twinning planes.
- **Plagioclase commonly shows lamellar twinning**. Such twinning is one of the most diagnostic features of plagioclase.
- Twinning may take a variety of different forms and is particularly common and distinctive in the feldspars (plagioclase and K-Feldspar).
- Several laws of twinning are possible and they can be recognized using the microscope (e.g. Polysynthetic twins after the "albite" and "pericline" laws in plagioclase, **Carlsbad twins in plagioclase or orthoclase**, cyclic twins in leucite, etc.).

Polysynthetic albite-type twins in plagioclase



Tartan = cross hatching = percline twinning, microcline – K-feldspar

Carlsbad (simple) twinning, in orthoclase

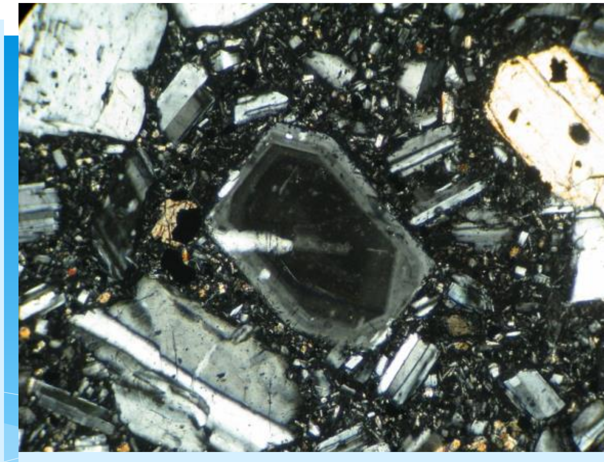


* Chemical zoning = different crystal growth zones that have different compositions = **Zoned Crystals**.

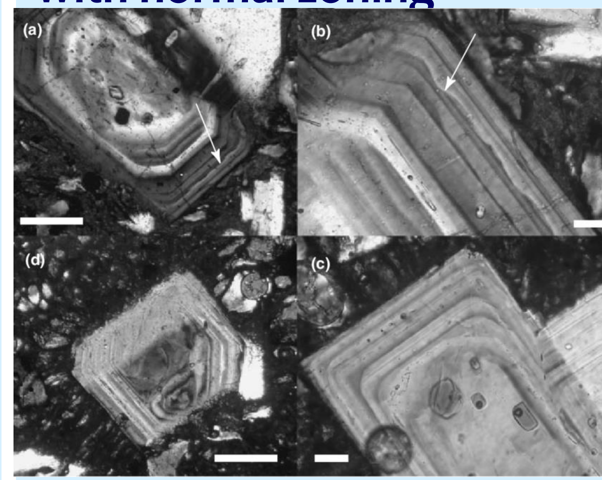
* Chemical zoning occurs only in minerals that belong to **solid solution series** that crystallize with different compositions at different temperatures and/or pressures.

* **Types of zoning**: (1) normal zoning, (2) reverse zoning, (3) oscillatory zoning, (4) sector zoning, (5) convolute zoning, (6) continuous zoning, and (7) discontinuous zoning.

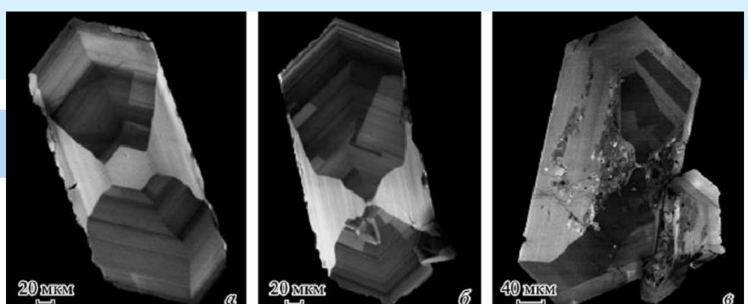
* **Crystals that have chemical zoning exhibit growth zones with different interference colors in thin section, they may also have different colors in plane polarized light.**



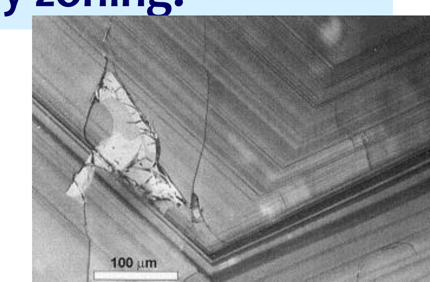
Euhedral plagioclase crystal with normal zoning



Euhedral plagioclase with oscillatory zoning.

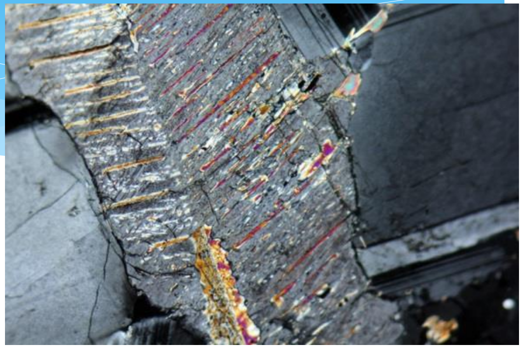


Sector zoning in zircon

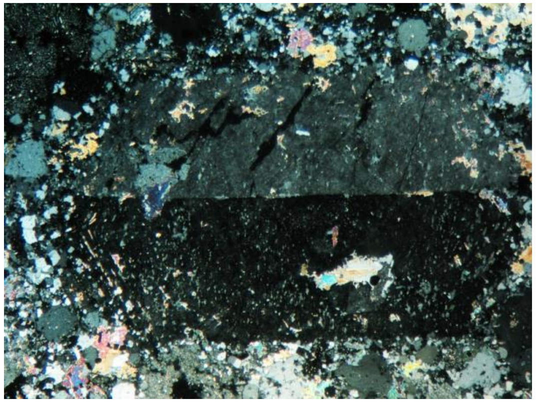


SPECIFIC TEXTURES (EXSOLUTION)

- **At high temperature, some minerals may incorporate a range of different elements in their crystal lattice (homogeneous mixtures).**
- **on cooling** the lattice may become more stable if a **physical separation into two mineral phases** occurs.
- The host mineral may exsolve small crystals of the other mineral and a distinctive exsolution texture resulted.
- **Such exsolution textures are observed in cross polars as host and exsolved minerals often have rather similar optical properties and so may have similar relief.**
- Common minerals that show **exsolution textures: Feldspars (plagioclase and K-feldspar), Pyroxene (clinopyroxene and orthopyroxene).**



Pigeonite exolution lamellae in Augite



A twinned orthoclase crystal with cryptoperthite (exsolution of albite)