More Practice, More Perfect

Lectures in Ore Microscopy

Edit.,

Dr. Mahmoud Sabry Abdel-Hakeem

Preface

Ore minerals are considered the main storage of various metal commodities (e.g. magnetite "Fe-commodity", chalcopyrite "Cu-commodity" and Sphalerite "Zn-commodity") and the principle feed materials for different metallurgical industries. These minerals are formed in a similar way to the rock-forming minerals including magmatic, hydrothermal, and sedimentary processes. But, the ore minerals differ from the rock-forming counterparts in their metal-enrichment, making them unable to transmit the visible light throughout the mineral crystal. So, the traditional petrographic microscope is not a good choice to study such mineral type, but instead, the reflected light optical microscope is needed here. The study of optical properties along with the different intergrowths of ore minerals using the reflected light microscope is called ***Ore Microscopy***. The current work is suitable for the undergraduate students, taking them in an excited journey through the reflected light from the polished mineral sections and allowing them to know the different optical properties of ore minerals with/without analyzer (*e.g. color, plaeochrosim, isotropism, and internal reflection*). After that, hold your breath; be ready for a long-time staring through the eyepieces; try to interpret the different intergrowth types between ore minerals and join your notes to the relevant geological environment; and make time-based order for all minerals that you perceived.

My best regards,

Authors


NO GAIN WITHOUT PAIN

Contents

Lecture#1: Definition of Ore Minerals and their Classification

1. Ore Mineral Definition

Ore minerals are a specific mineral category from which one or more metals can be extracted at profit (e.g. Galena "Pb", Bauxite "Al", Gold "Au", Chalcopyrite "Cu", and Hematite "Fe"). As being minerals, ore minerals are inorganic, naturally occurring, solid materials. Ore minerals are valuable commodities commonly associated with unwanted minerals called gangues (e.g. quartz, olivine, calcite, and barite).Two factors determine whether a given mineral is suitable to be an ore mineral:

- The first is the ease with which a mineral can be separated from the gangue and concentrated for smelting. Concentrating processes, which are based on the physical properties of the mineral, include magnetic separation, gravity separation, and flotation.
- The second factor is smelting—that is, releasing the metal from the other elements to which it is chemically bonded in the mineral. Smelting processes are of primary importance in this consideration regarding the amount of energy needed to break the chemical bonds and release the metal. In general, less energy is needed to smelt sulfide, oxide, or hydroxide minerals than is required to smelt a silicate mineral. For this reason, few silicate minerals are ore minerals.

Note: not all ore minerals have a metallic lustre, this is dependent on the geological environment in which the ore mineral formed. For example, hematite resulting the chemical weathering of pre-existing minerals (e.g. chemical weathering of glauconite) possesses earthy non-metallic lustre, while hematite hydrothermally formed has a metallic lustre.

The other types of minerals, in particular silicates, excluded from the above definition are considered industrial minerals can be exploited for different fields of industry and agriculture. For instance, feldspars ($KAlSi_3O_8$ & $CaAl_2Si_2O_8$) and kaolinite [$(Al_2Si_2O_5(OH)_4$] contain considerable concentrations of aluminium (19%-37% Al_2O_3), however, they are employed for cement and ceramic industry rather than aluminium metallurgy.

2. Classification of Ore Minerals:

► Firstly, the chemical classification of ore minerals:

The ore minerals are classified depending on the attached anion group rather than cations. This is attributed to two reasons:

1. Firstly, the similarities in properties of minerals with identical anionic groups are generally more pronounced than those with the same dominant cation. For example, carbonates have stronger resemblance to one another than do copper minerals.
2. Secondly, minerals that have identical dominant anions are likely to be found in the same or similar geologic environments. Therefore, sulfides tend to occur together in vein or replacement deposits.

Depending on the anion groups, ore minerals are classified into four classes:

3.1. Sulphide Class:

This important class includes most of the ore minerals in which one or more metals are attached to sulfur. When sulfur is partly replaced by arsenic, this is called sulfarsenides group, the most common sulfarsenides mineral is arsenopyrite ($FeAsS$) resulting from the partial replacement of sulfur in the crystal structure of marcasite (FeS_2) by arsenic As. Sulfides are generally opaque and exhibit distinguishing colours and streaks (e.g. pyrite is brass-yellow in color and has black streak), with an exception for the non-opaque variety (e.g. cinnabar HgS). Ionic and covalent bonding is found in many sulfides (covellite, chalcosite, bornite), while metallic bonding is apparent in others as evidenced by their metal properties (e.g. pyrite, chalcopyrite, and galena).

3.2. Oxides and Hydroxides Class:

These classes consist of oxygen-bearing minerals; the oxides combine oxygen with one or more metals, while the hydroxides are characterized by hydroxyl $(OH)^-$ groups. **The oxides are further divided into two main types**: simple and multiple. Simple oxides contain a single metal combined with oxygen in one of several possible metal: oxygen ratios (X:O): XO, X_2O, X_2O_3, etc. Multiple oxides consist of two metals attached to oxygen atoms (e.g. Ilmenite $TiFeO_3$). Oxide minerals generally display strong ionic bonding. They are relatively hard, dense, and refractory. Oxides and hydroxides are a large and diverse group of ore minerals. The major ore minerals of the geochemically abundant metals aluminum, iron, manganese, and titanium are oxides or hydroxides, while the oxide-forming scarce metals are chromium, tin, tungsten, tantalum, niobium, and uranium. Vanadium is found mainly by atomic substitution in magnetite, a major oxide ore mineral of iron.

The $(OH)^-$ group of the hydroxides generally results in structures with lower bond strengths than in the oxide minerals. The hydroxide minerals tend to be less dense than the oxides and also are not as hard. *All hydroxides form at low temperatures and are found predominantly as weathering products*, as, for example, from alteration in hydrothermal veins. Some common hydroxides are brucite [Mg(OH)2], manganite [MnO · OH], diaspore [α-AlO · OH], and goethite [α-FeO · OH]. The ore of aluminum, bauxite, consists of a mixture of diaspore, boehmite (γ-AlO ·OH—a polymorph of diaspore), and gibbsite [Al(OH)3], plus iron oxides. Goethite is a common alteration product of iron-rich occurrences and is an iron ore in some localities.

3.3. Carbonate Class:

The carbonate minerals contain the anionic complex $(CO_3)^{2-}$, which is triangular in its coordination—i.e., with a carbon atom at the centre and an oxygen atom at each of the corners of an equilateral triangle. These anionic groups are strongly bonded, individual units and do not share oxygen atoms with one another. The triangular carbonate groups are the basic building units of all carbonate minerals and are largely responsible for the properties particular to the class. The carbonate ore minerals include siderite, rhodochrosite, and malachite.

3.4. Native Class:

A native element is a chemical element that may occur in nature uncombined with other elements. The group of native elements does not include those that occur as atmospheric gasses, however. These native elements are commonly divided into three groups—namely, metals (platinum, iridium, osmium, iron, zinc, tin, gold, silver, copper, mercury, lead, chromium); semimetals (bismuth, antimony, arsenic, tellurium, selenium); and nonmetals (sulfur, carbon).

► Secondly, the genetic classification of ore minerals:

Ore minerals can be classified according to the geological processes by which the valuable minerals formed. Three main types of ore minerals are recognized here as follows:

1-Magmatic ore minerals that resulting from the direct crystallization of magma either during the early stages of magmatic differentiation (e.g. ilmenite and chromite deposits) or during the pegmatitic stage (e.g. uranium mineralization associated with pegmatite feldspar).

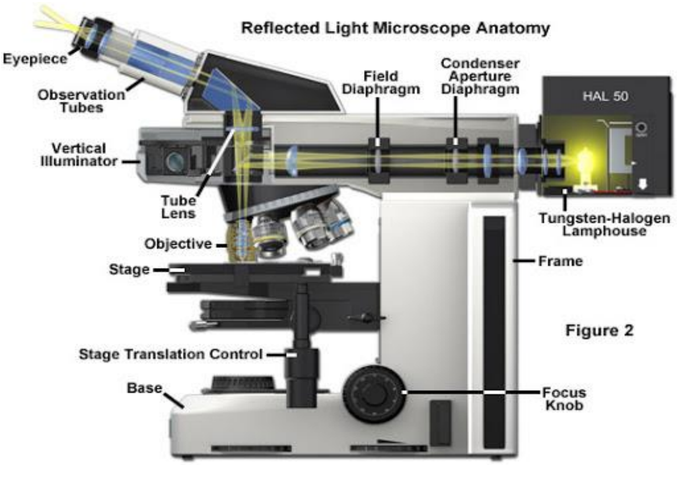
2-Hydrothermal ore minerals that crystallize from the ascending hydrothermal solution, which that in turn leach and concentrate various metal types (e.g. pyrite, chalcopyrite, galena……etc).

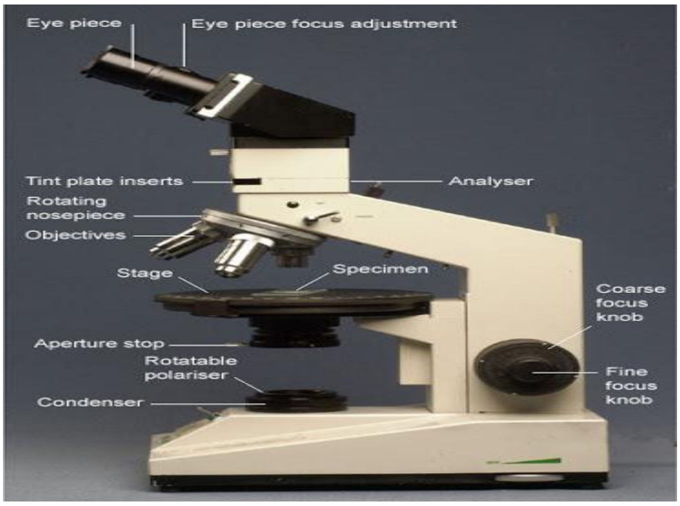
3-Sedimentary ore minerals that are created by chemical weathering processes of the pre-existing minerals (e.g. bauxite, malachite, some iron ores…..etc).

Lecture#2: Ore Microscope

4. Ore Microscope:

The ore microscope is used for the study of ore minerals depending on the optical properties of ore minerals in the same way as a petrological microscope. The main difference here is that the ore microscope uses the visible light reflected from the polished mineral surface *due to the opaque nature of ore minerals that makes the majority of ore mineral unable to transmit the visible light through its crystal structure.* The petrographic microscope is used to investigate the non-ore minerals that permit the transmission of light through its crystal structure (e.g. the common rock-forming minerals like feldspars, mica, olivine, calcite, siliminite). So, we will see pyrite and iron oxides in the basalt thin sections as dark-colored grains.



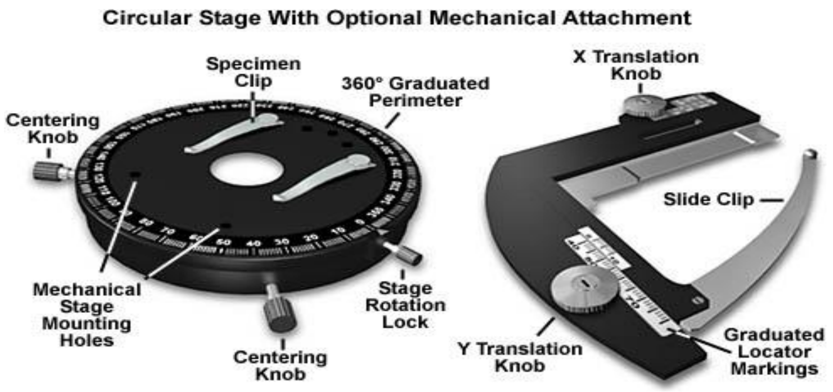


3.1. Components of Ore Microscope:

Six main components are needed for the reflected polarized light microscope:

1. **Rotatable stage.**

The stage must be perpendicular to the light path and centered relative to the objectives. Most microscopes accept a mechanical stage equipped with X and Y movement for systematic examination or point counting of grains in specimens.

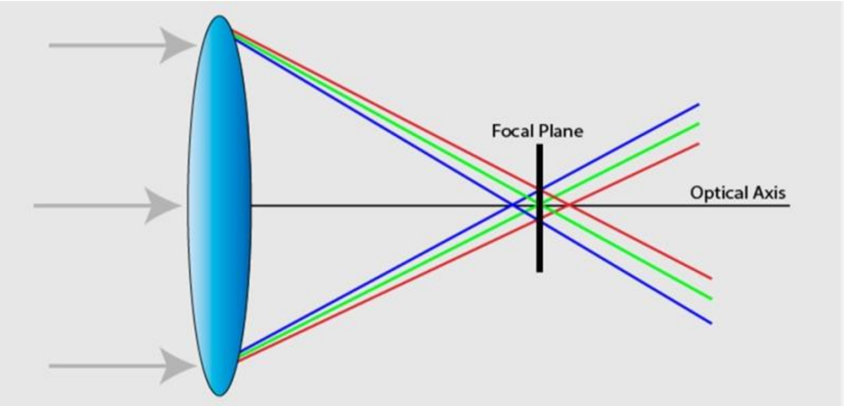


2. Objective lenses.

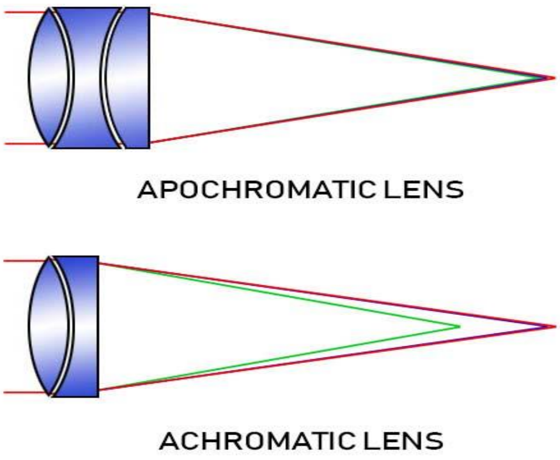
The objective lenses are essential for the primary image formation. The magnification of objective lenses varies between 2x and 125x. These lenses may be classified as: **achromatic**, **fluorite or semi-apochromatic** and **apochromatic**.

- ✓ ***Achromatic lenses*** are the most common and the cheapest. They are designed to bring two wavelengths (red & blue colors) to the same focus point and corrected for spherical aberration for the green color. This lens type is useful for the black-white imaging due to its ability to focus only two basic components of the visible wave lengths. The achromatic lenses are manufactured to limit the effect of what so-called ***chromatic aberration***, which means many images form at different focal points from the lens center, resulting in image distortion.
- ✓ ***Fluorite or Semi-apochromatic lenses*** can focus the principle color components (red "R", blue "B" and green "G") at the same focal plane. It is much better for the colored images.
- ✓ ***Apochromatic lenses*** are chromatically adjusted for four colors (deep blue, blue, red, and green).

Chromatic Aberration



Lenses without chromatic aberration



Most lenses of a low to medium magnification ***are dry lenses***, and as such are designed to be used when air is the medium between the sample and the objective lens and/or when the specimen is covered with a glass. Though they are frequently used in transmitted light studies, in reflected light microscopy they may give distorted images. ***Immersion objective lenses***, which are manufactured to give all possibly required magnifications, should be the most commonly used type in reflected light studies and especially so when high resolution and magnification are demanded. Such lenses require a drop of immersion oil between the sample and the objective; some objectives are designed for use with water instead of oil. The presence of the immersion medium (oil or water) reduces the reflectance of the minerals but enhances color differences, reduces diffuse light scattering, and generally permits the observation of weak anisotropism and bireflectance

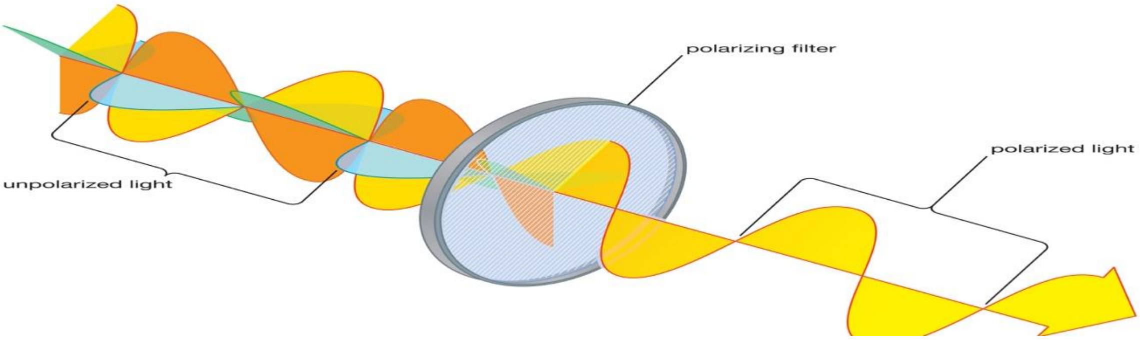
3. An ocular lens (eyepiece).

Monocular and binocular eyepieces are available for most microscopes. If possible, to alleviate eye strain, binocular eyepieces should be used and the position of the two eyepieces adjusted so that a single perfectly circular field of view is observed. The oculars are normally of X5 and X10 magnification, with or without a perpendicular crosshair.

4. Polarizer and analyzer.

Polarizer:

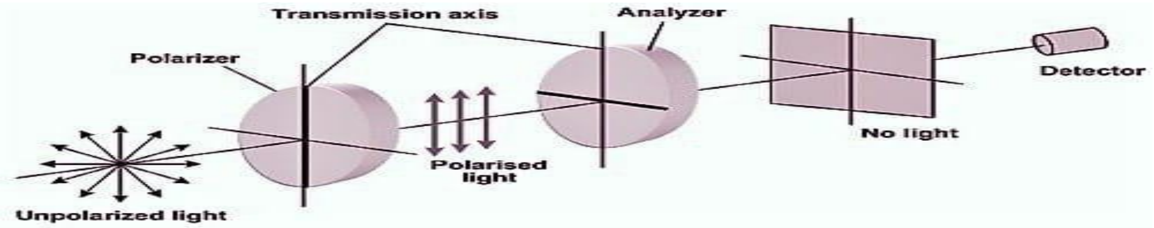
The white light consists of electromagnetic vibrations. These vibrations move outwards in every direction from the illumination source of the microscope. The polarizer in a standard ore microscope is usually positioned within the illuminating system between the lamp and the collector lens but may be located between the diaphragms. It is either a calcite prism or, more commonly, a polaroid plate that *permits only the passage of light that is plane (or "linearly) polarized*, usually in a E-W orientation.

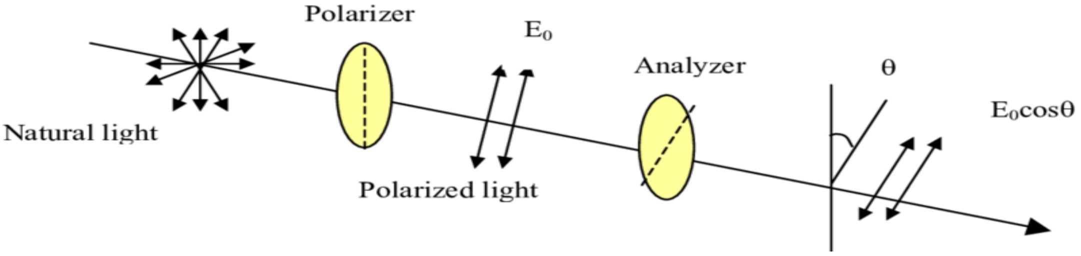


Analyzer:

The analyzer is similar to the polarizer; it is also made of polarizing film but oriented in a N-S direction, i.e. at right angles to the polarizer. When the analyzer is inserted into the optical train, it receives light vibrating in an N-S direction from the polarizer and cannot transmit this; thus the field of view is dark and the microscope is said to have crossed polars

In standard transmitted-light thin-section or grain mount petrography, the polarizer and analyzer are perpendicular to one another. However, many ore microscopists find that polarization effects are more readily observed if the polars are a few degrees from the true 90° position. This is especially true of very weakly anisotropic minerals and even some moderately anisotropic grains if they occur in a matrix of more strongly anisotropic minerals.





Polarized Light Microscope Configuration

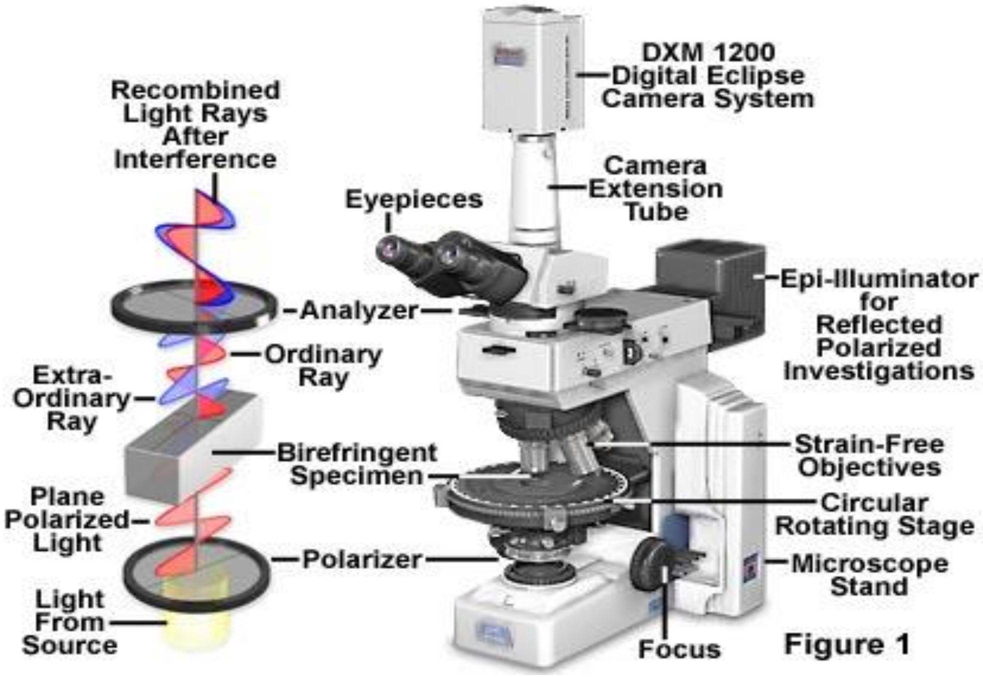
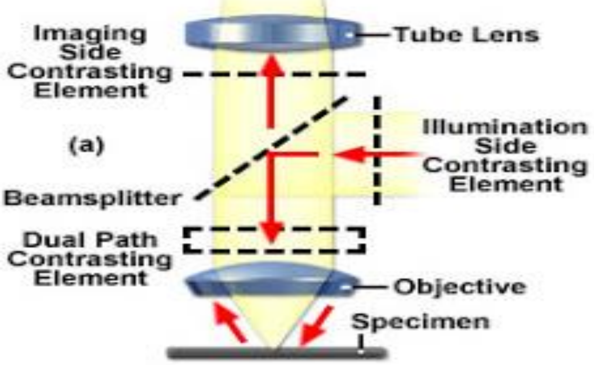


Figure 1

5. Reflector.

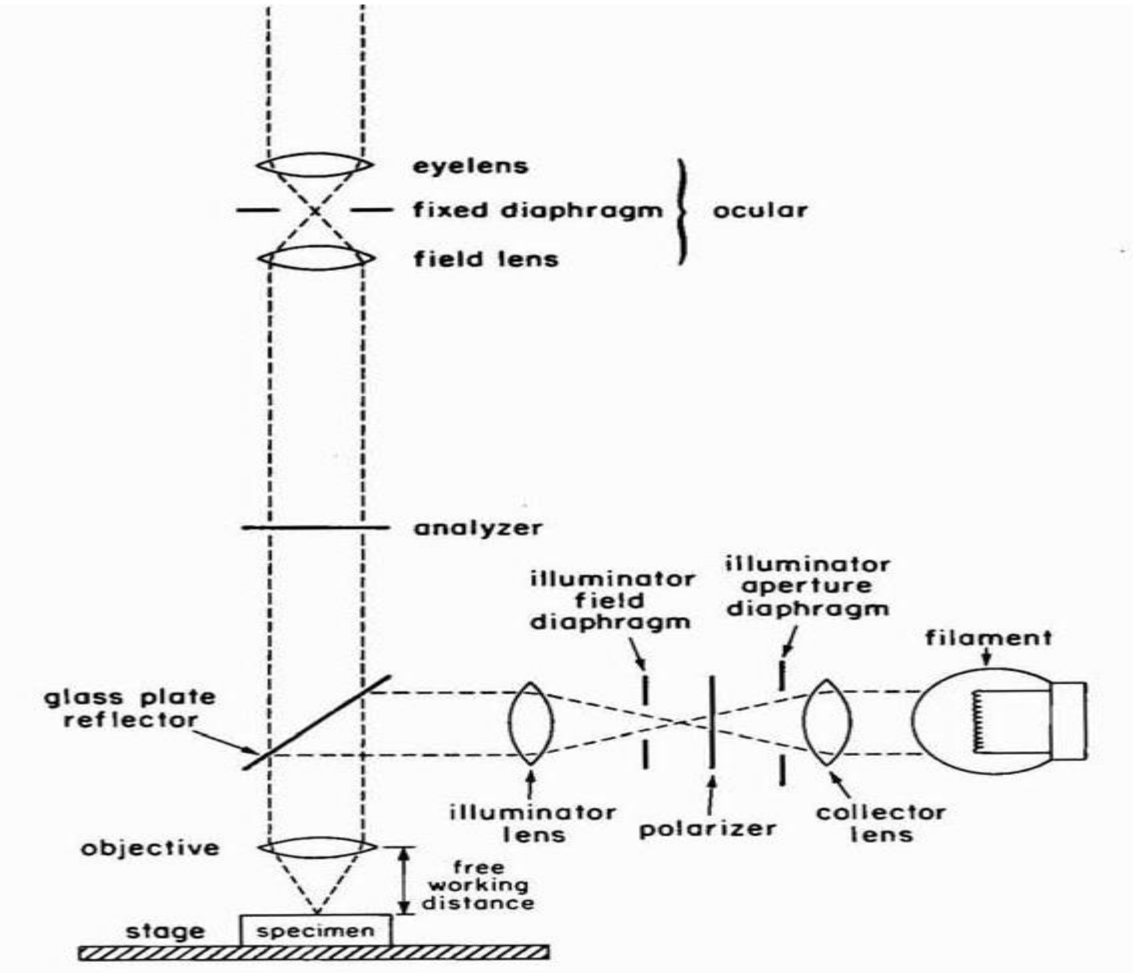
The reflector is a critical component of the ore microscope, being the means by which light is brought vertically onto the polished specimen surface. The function of Reflectors is that part of the light from the illuminator is reflected (25-50% reflectance) downward through the objective onto the sample and part of the light passes through the reflector and is lost. The light that passes downward is then reflected back up through the objective until it reaches the reflector again.

Reflected Brightfield Configuration



6. Illumination source.

Two main types of lamp are commonly used in ore microscopes: the tungsten filament lamp and the gas discharge lamp.



Schematic cross-section of the ore microscope.

3.2. Preparation procedures of the polished sections:

Ideally, A sample suitable for examination should be *a plane polished surface as free as possible of pits, scratches, fractures, pores, and relief*. This requirement is rarely attained on ore samples due to the hardness differentiation between the ore minerals, resulting in scratching, polishing pits.

- **Cutting ore samples:**

Normally a sample is cut with a water-lubricated, thin-bladed diamond saw. The lubricating fluid prevents, or aims to prevent, heating of the specimen while it is being cut. If the specimen is fractured, porous or friable or even consists of grains or powder, it will be necessary ***to impregnate*** it initially. Vacuum impregnation of epoxy into the sample is the standard technique. Most samples are cast in circular or rectangular moulds which may have an enclosing permanent plastic ring. The ring gives near uniformity to the overall thickness and permits ease of storage, labelling and handling.

Grinding and Polishing of ore samples

Grinding removes surface irregularities and adhering resin, reduces the overall thickness and removes any surface deformations which may have resulted from cutting, and it prepares the smooth surface for subsequent polishing. ***Polishing*** is a continuation of grinding but with the progressive use of finer and finer abrasives. The final removal of the surface layer of deformation and a resultant scratch-free surface are the aims. Regarding the loose mineral grains resulting from crushing and sieving processes can also be examined as polished **grain mountings**. This can be done by casting them in an epoxy resin mould and cutting and polishing the sample as described previously.


Cutting ore samples


Impregnation using epoxy

Grinding and Polishing


Final Polished sections

Lecture#3: Optical Properties of Ore Minerals

4. Optical Properties of Ore Minerals

For the identification of ore minerals under the reflected light microscope, it is necessary to investigate the optical properties of each mineral that can be observed without analyzer and under the crossed polars.

1. ***Without the analyzer***, i.e. using only the polarizer (which is generally left permanently inserted). This is said to be viewing the sample using linear or plane polarized light’ , and is the mode used for observations of:

- ✓ **Colour**
- ✓ **Reflectance**
- ✓ **Bireflectance and Reflectance pleochroism**

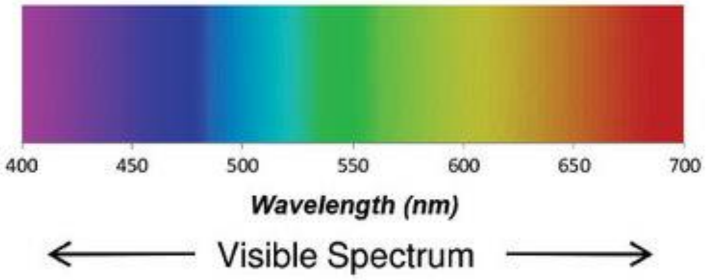
2. ***With the analyzer inserted***. This is said to be examining the sample using crossed polars and is the mode used for observation of:

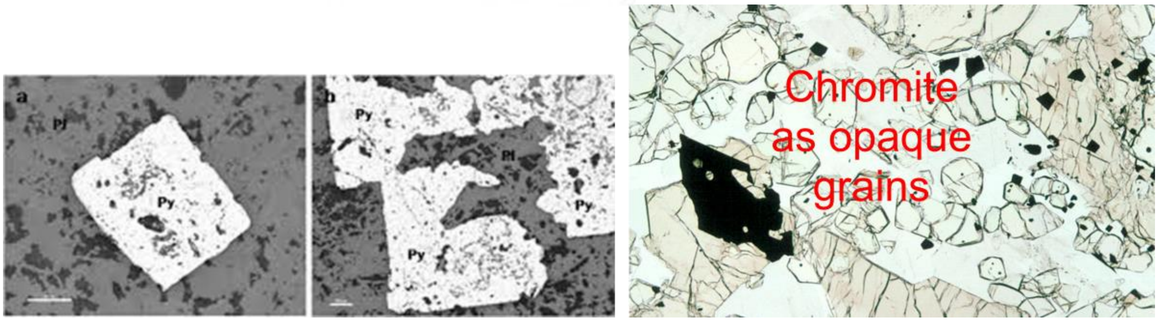
- ✓ **Isotropism v. Anisotropism**
- ✓ **Polarization colours (Rotation properties)**
- ✓ **Internal reflections**

4.1. Optical Properties of ore minerals without analyzer:

A) - Color of ore minerals:

Color is related to the wavelength of visible light, which ranges from violet (wavelength ≥390 nm) to red (≥ 760 nm). White light consists of all the wavelengths between these two extremes. The incident light on a mineral surface is subjected to absorption, transmission, and reflection by the mineral grain. The color of a mineral is represented either by the absorbed and reflected wavelengths, in the case of ore minerals, or by the transmitted wavelengths, in case of silicate, carbonate, halides, sulfates. So, under the reflected microscope the silicate minerals appear as dark grains while the ore minerals appear as lighter grains. On the opposite side, the ore minerals occur as dark grains while the silicates appear as light colored minerals under the transmitted light microscope. The color of an ore mineral is a function of: (a) the index of refraction of the medium between the lens and the sample (normally air); and (b) the transparency of the mineral. Most ores are opaque, whereas most gangue minerals are transparent to translucent. These appear darker when polished as they do not reflect light as well as opaque minerals.





Pyrite appears as light-colored euhedral grain under the reflected light "the left side", while chromite occurs as opaque grains on the transmitted light "the right side"

B) – Pleochroism and Reflectance:

When a mineral is viewed in plane polarized light and is rotated, a change in the colour of the mineral may occur, which is called ***pleochroism*** (e.g. the color of covellite changes from light blue to dark blue with stage rotation). Another property refers to the percent of incident light that is reflected from the polished surface, ***the mineral reflectance***. The reflectance of a given mineral depends mainly on:

- The refractive index of the ore mineral "n" and the immersion medium "N" between the polished surface and objectives.
- The absorption coefficient of the mineral "k".

For a specific wavelength "λ", the mineral reflectance%=

$$R_\lambda\% = \frac{(n_\lambda - N_\lambda)^2 + k_\lambda^2}{(n_\lambda + N_\lambda)^2 + k_\lambda^2} \times \frac{100}{1}$$

Example, a polished section of hematite "n= 3.15& k= 0.42" is investigated in air-medium between the mineral surface and the objective lens "N= 1", the reflectance of hematite will be = 27.58%.

Note: the refraction index of air= 1 and of oil = 1.52

5.2. Optical Properties of ore minerals under the crossed-polars:

A) – Isotropism:

Under the crossed-polars, the ability of mineral to give color shades on stage rotation is called ***isotropism***. So, the ore minerals can be divided into:

(a) Isotropic mineral: all grains remain dark on rotation of the stage, e.g. magnetite & pyrite. *This division is mostly restricted to minerals crystallizing in the cubic system, but also the other anisotropic minerals of hexagonal, tetragonal, trigonal class can be isotropic if the polished section is cut perpendicular to c-axis.*

(b) Weakly anisotropic mineral: slight change on rotation, only seen on careful examination using slightly uncrossed polars, e.g. ilmenite.

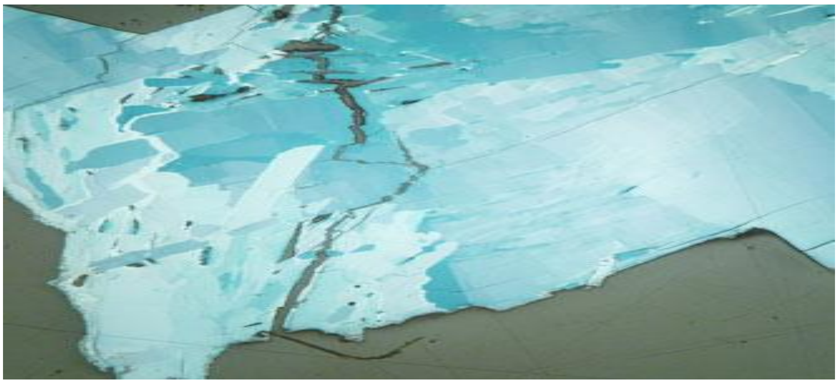
(c) Strongly anisotropic mineral: pronounced change in brightness and possible colour seen on rotating the stage when using exactly crossed polars, e.g. hematite & covellite& goethite.

B) – Polarization colors:

Regarding polarization colors, incident linearly polarized monochromatic light, vibrating E-W, is resolved into two components, on the surface of the section. On reflection, recombination of the components results in reflected linearly polarized light vibrating in a direction closer to the principal vibration direction of analyzer.

The reflected light is now no longer vibrating normal to the analyzer and some of the light will be able to pass through the analyzer. The vibration velocity of the reflected wavelengths varies on stage rotation, resulting in color changes.

Note: The changes in mineral color on stage rotation under the crossed-polars are called polarization colors.

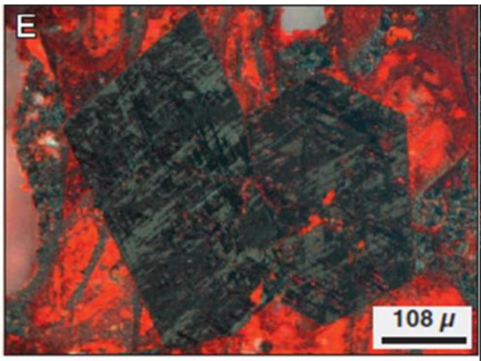


Covellite appears as a pleochroitic grains with color changes from light-to-dark blue.

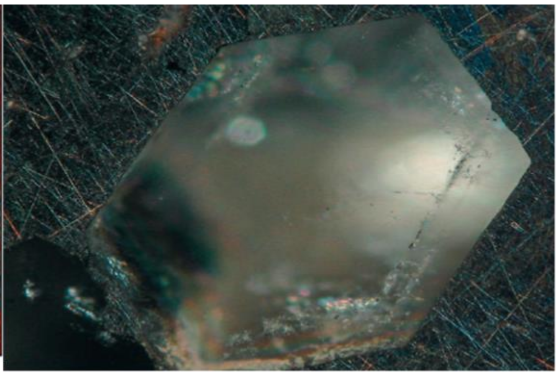
B) – Internal Reflection:

Internal reflections are due to light passing through the surface of the mineral and being reflected back from *natural or artificial cracks or flaws within it or from a crystal face*. Samples which have been collected in a mine or open pit exhibit more abundant reflections as they have probably been shot-blasted. Internal reflections can only therefore be detected in minerals which have a degree of transparency and fortunately only a few opaque minerals show this feature. Most of the non-opaque minerals, i.e. the carbonates, sulphates etc., may show abundant internal reflections. The internal reflection of a given mineral appears as a characteristic color unchanged with stage rotation.

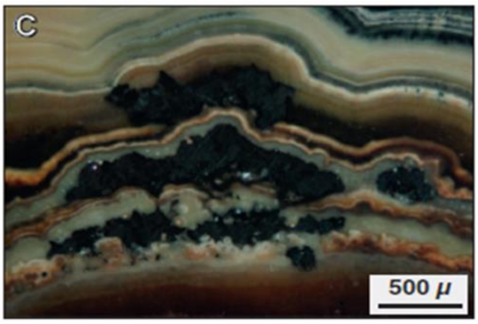
Note: The difference between the polarization colors and the internal reflection colors is that the former changes on stage rotation, while the latter isn't.



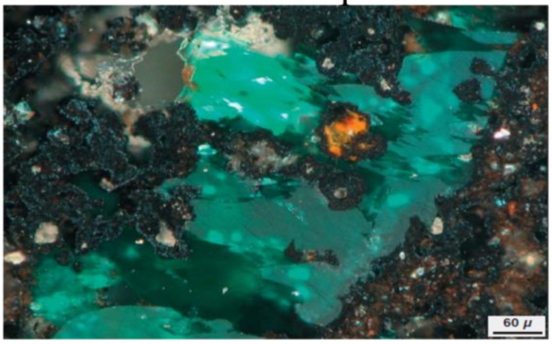
Red internal reflection of hematite



Multi-colored internal reflection of quartz



Brown shades internal reflection of Sphalerite



Green internal reflection of malachite

Internal reflection of some ore minerals

Predominant internal colour	*Mineral*
Yellow	Sphalerite, cassiterite, goethite, rutile
Brown	Sphalerite, cassiterite, rutile, chromite (often red-brown and more distinct in oil), uraninite (rarely seen), wolframite (deep brown; more distinct in oil)
Red	Cuprite, proustite, pyrargyrite, goethite, sphalerite, tennantite, manganite, boulangerite, stibnite (rarely seen), rutile, hematite (more distinct in oil), sphalerite (rare), cinnabar (blood-red)
Colourless	Sphalerite, cassiterite, scheelite, rutile and most of the gangue minerals

Lecture#4: Physical Properties of Ore Minerals

5. Physical Properties of Ore Minerals

Physical properties of ore minerals include cleavage, grain shape, and hardness. These properties are useful for the qualitative identification of ore minerals under the polarized ore microscope.

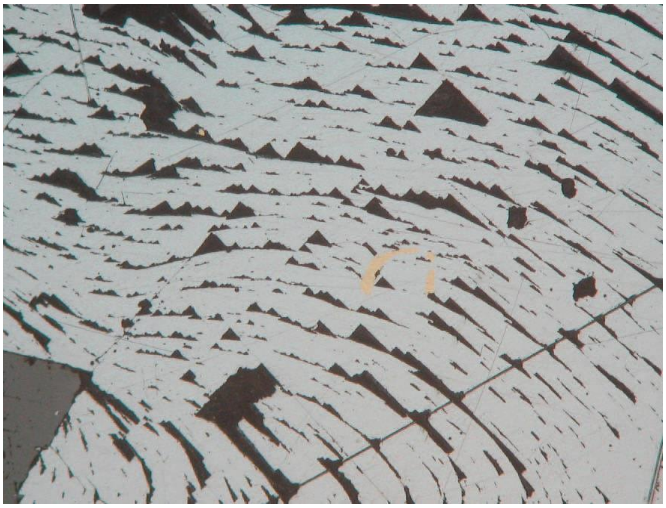
5.1. Cleavage

In general, the mineral cleavage refers to the ability of a given mineral to split, under stress conditions, in a certain crystallographic directions that are weaker than the other directions. The cleavage of a specific mineral can be described by identifying the number of cleavage planes present through the mineral crystal. For example, polished sections **of bismuthnite** exhibit one set cleavage planes, while **galena** is characterized by three sets. Cleavage can be seen with or without analyzer.

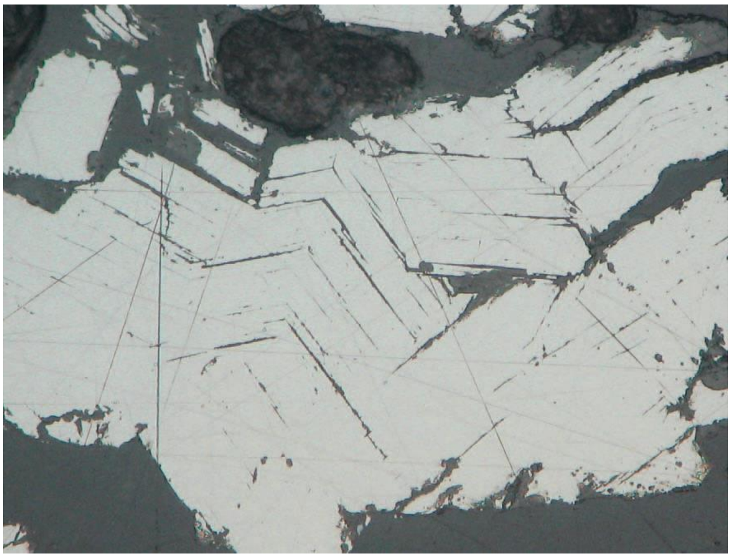
Note: the three sets of cleavage planes of galena intersect with each other and appear as a triangular shape. The intersection area is weak, leading to form polishing pits during the preparation of polished sections.

What is the difference between cleavage and scratch lines???

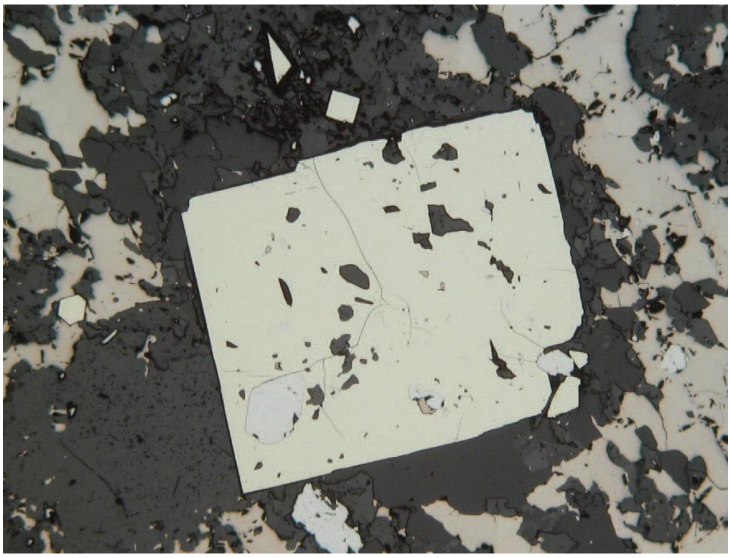
Anyone with little experience can be confused between scratch lines and cleavage planes, especially in case of the one set of cleavage. Scratch lines are randomly distributed lines through the whole surface of mineral grain and result from the polishing process. Cleavage, on the other hand, is deeply incised, oriented planar features cutting through the whole mineral grain.



Cleavage in galena appears as three sets intersecting with each other in the form of triangular polishing pits (black in color).



Bended one set of cleavage in arsenic mineral (light grey). Note the difference between the oriented cleavage planes and the surficial scratch lines.

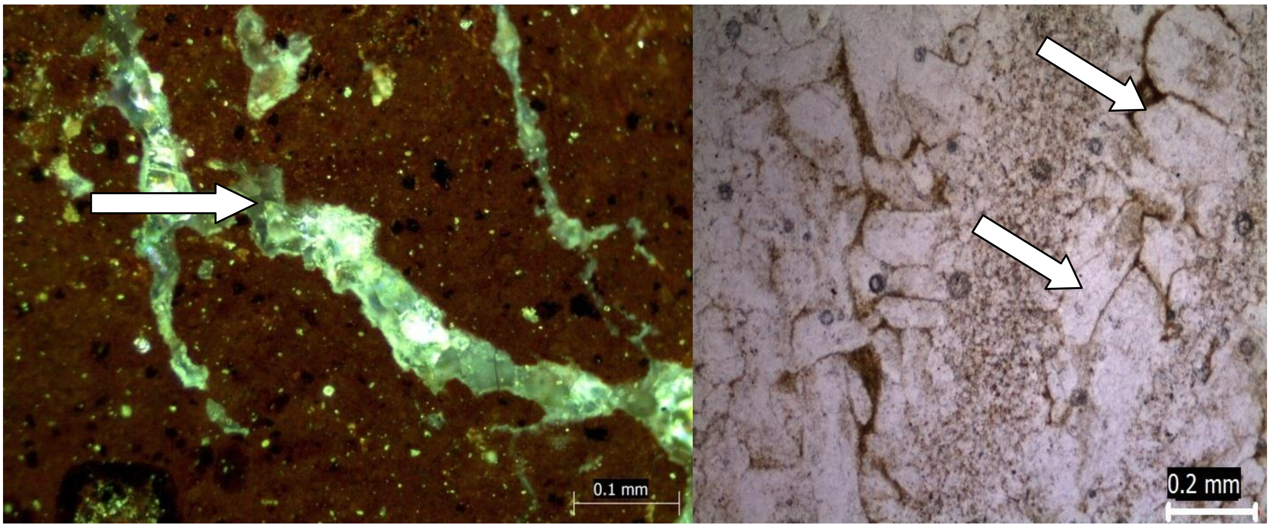


Pyrite cube without noticeable cleavage.

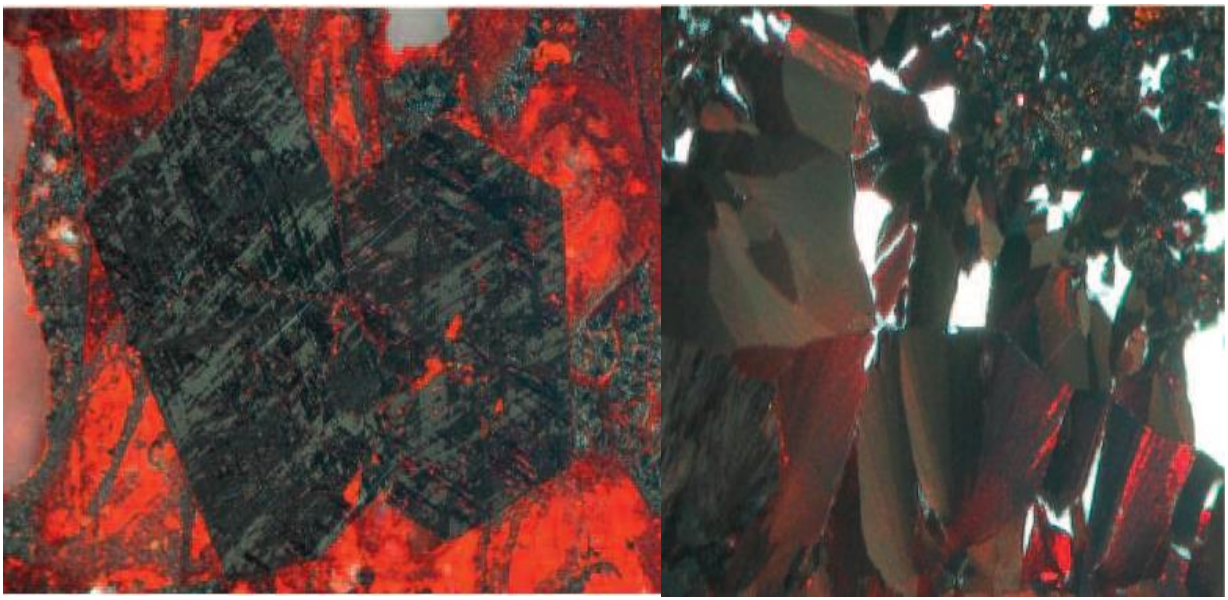
5.2. Grain Shape

Grain shape of ore minerals depends on several factors among which:

*-**The formation conditions***, like the occurrence of barite as well-developed crystals if they grow in open spaces, while it can occur as cement material connecting between the other mineral grains. Another example include the occurrence of hematite as well-developed prismatic grains or as colloform clusters.



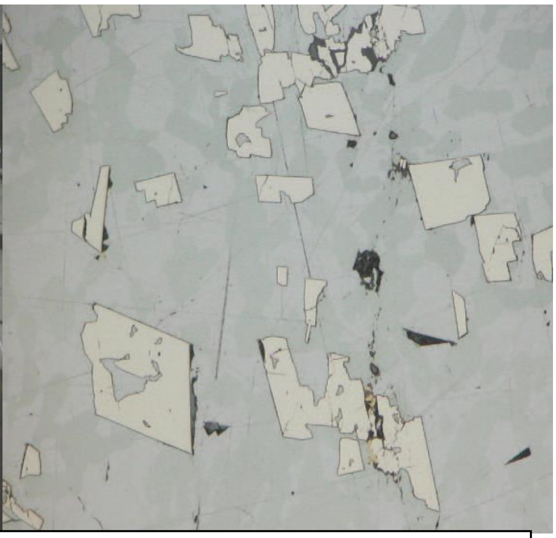
Occurrence of barite as cement between hematite grains (left side, light in color, look at arrow) and as well-developed crystals due to the growth in an open-space filling (right side, light in color, look at arrow).



Occurrence of hematite as well-developed prismatic grains (on left side) and as colloform clusters (on right side).

-The post-depositional deformation, like the brecciation of pre-existing mineral grains that causes irregular granular aggregates, deformation-driven bending, and replacement and corrosion.

Bended and spindle-shaped molybdenite.



Rhombohedral and skeletal arsenopyrite floated in and corroded by galena.

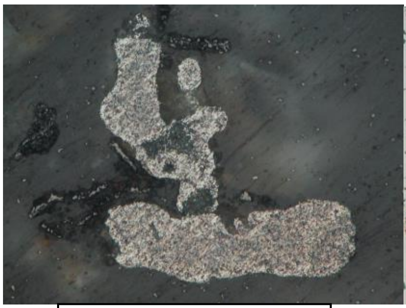
So, there are many descriptive terms for the grain shape of ore minerals, as follows:

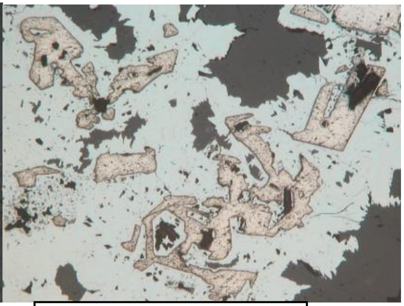
1. **Euhedral** (crystal faces are all developed)**, subhedral** (some crystal faces are developed), **and anhedral** (mineral grains without crystal faces)**.**
2. **Myrmekitic shape**, crystals are in worm-like shape.
3. **Wood-shape grains.**
4. ***Granular***, an intergrowth of mineral grains of approximately the same size.
5. ***Lamellar***, flat, plate-like individuals arranged in layers.
6. ***Bladed***, elongated crystals flattened like a knife blade.
7. ***Fibrous***, an aggregate of slender fibres, parallel or radiating.
8. ***Acicular***, slender, needle-like crystals.
9. ***Radiating***, individuals forming starlike or circular groups.
10. ***Dendritic***, in slender divergent branches, somewhat plantl-ike.
11. ***Botryoidal***, globular forms resembling a bunch of grapes.
12. ***Colloform***, spherical forms composed of radiating individuals without regard to size (this includes botryoidal, reniform, and mammillary forms).

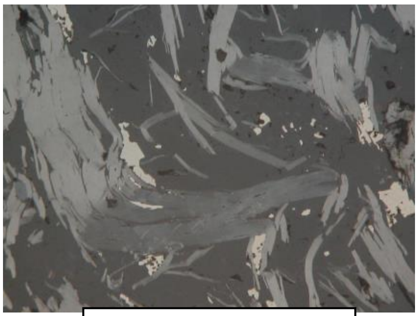
13. ***Concentric***, roughly spherical layers arranged about a common centre, as in agate and in geodes.

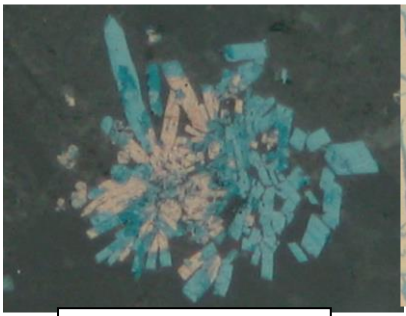
14. ***Oolitic***, an assemblage consisting of small spheres resemble fish roe.

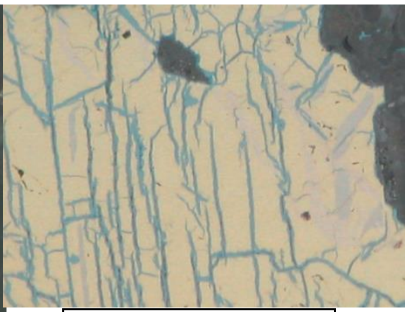

Myrmekitic

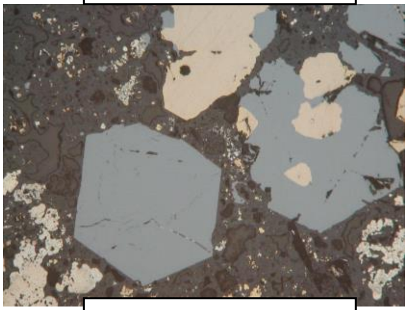

Anhedral

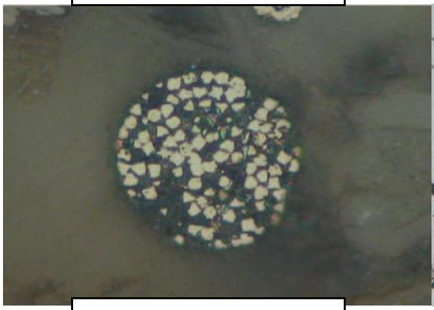

Skeletal

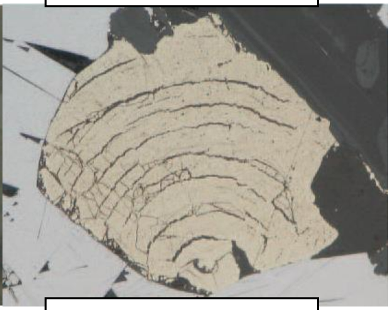

Fibrous

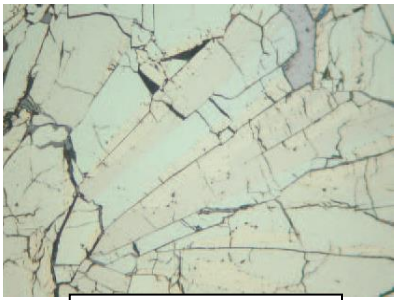

Bladed

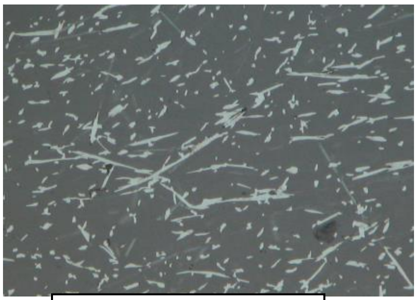

Lamellar

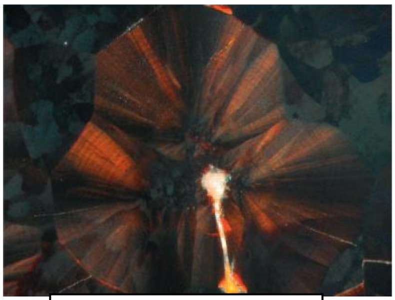

Euhedral


Farmboidal


Colloform


Radial


Acicular


Botryoidal

5.3. Hardness

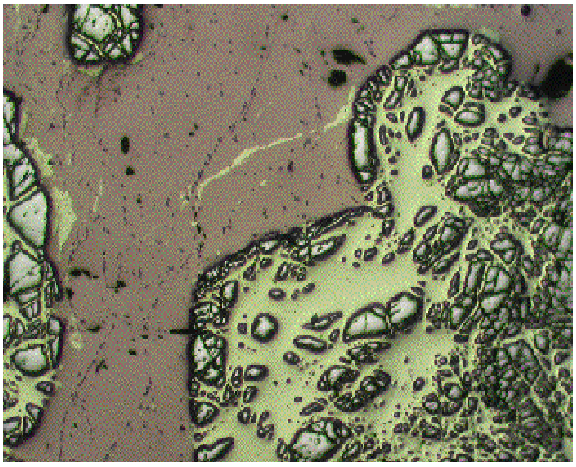
Hardness of ore minerals indicates to the resistance of mineral to abrasion. Hardness measurement is a qualitative procedure to discriminate between the softer and harder minerals. There are two types of hardness:

1-Scratch hardness:

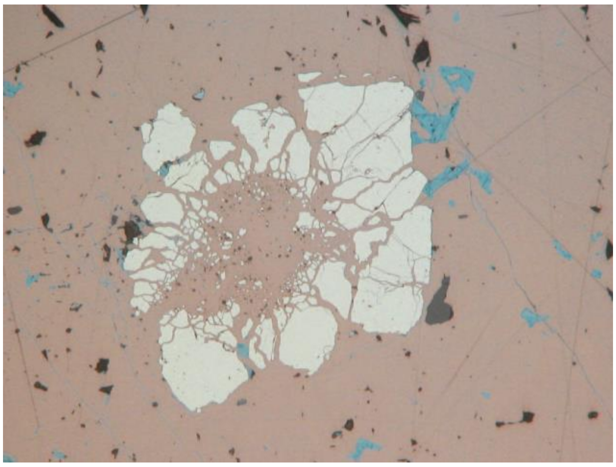
Scratch hardness means the resistance of a particular mineral to be scratched during the polishing process. During polishing process, the surface of mineral grains contains randomly distributed scratch lines, which are deeply incised in softer minerals comparing with the harder ones.

2-Polishing hardness:

Polishing hardness is defined as the resistance of a particular mineral to be worn away during the polishing process. The fact that hard minerals are worn away more slowly than soft minerals means that they may stand slightly above the surface of softer grains giving rise to an effect called *"polishing relief".* Polishing hardness can be examined under a standard ore microscope by comparing the relative hardness (i.e. relief) of adjacent phases and can be very helpful in mineral identification.



Pyrite (light in color) stands as high-relief blocks against softer chalcopyrite.



Bornite is more scratched than pyrite (light fractured grains).

The determination involves a simple test using the Kalb light line, as follows:

The procedure is as follows:

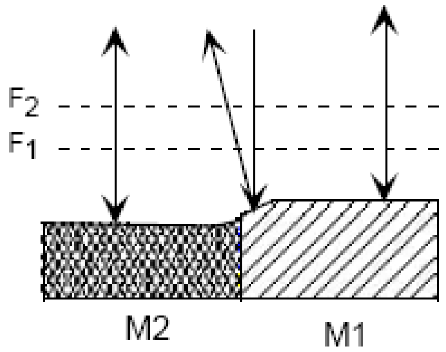
a) Polarizer is inserted and analyzer is withdrawn.

b) Focus on a clear boundary between two mineral grains.

c) Close the aperture diaphragm partly.

d) Raise the microscope tube slowly (or lower the stage in microscopes where focusing is dome by moving the stage) so that the sample begins to go out of focus as the distance between the sample and objective is increased.

e) Observe the "line" of light which will move from the boundary towards the softer mineral, provided there is appreciable relief.



Focus initially at F1; Lower mineral specimen so that the focus is now at F2 and observe th Kalb line.

Formationof the Kalb Line at the junction of a hard mineral (M1) and a soft mineral (M1).

Lecture#5: Textures of Ore Minerals-Primary Magmatic Textures

6. Textures of Ore Minerals:

Textures of minerals indicate the geometric relationship between the different mineral associations (e.g. grain size, grain morphology, and the nature of mineral intergrowths). These geometric relationships form either during the mineral formation from magma/hydrothermal solutions "***Primary textures***" or after crystallization due to replacement or deformation processes "***Secondary textures***". Textural identification and interpretation for ore deposits and associated gangue minerals are tools necessary for:

- *Understanding the processes involved in the genesis of these deposits.*
- *Understanding the timing of formation of the ore minerals relative to the host rocks and their structures.*
- *Provide valuable information for the subsequent ore dressing processes (e.g. comminution & concentration of valuable minerals).*

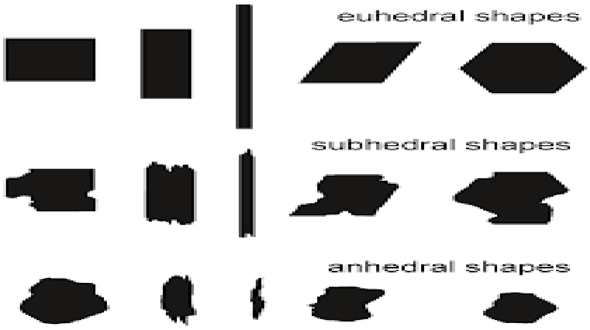
6.1. Primary Magmatic Textures

Magmatic deposits are unique among ore deposits in being direct crystallizations from magmas, usually deep-seated (plutonic), rarely volcanic. Most magmatic ores are differentiation products from basic magmas, and, as these are characteristically poor in volatile components, we should expect that pneumatolytic and hydrothermal processes would be lacking or rare in association with such deposits. *The mineral composition of the ore usually aids in diagnosis*, for worldwide observation has shown that most magmatic ores are valuable mainly as sources of iron, nickel, copper, chromium, titanium, and the platinum group.

- **Xenomorphic / Hypidiomorphic granular texture:**

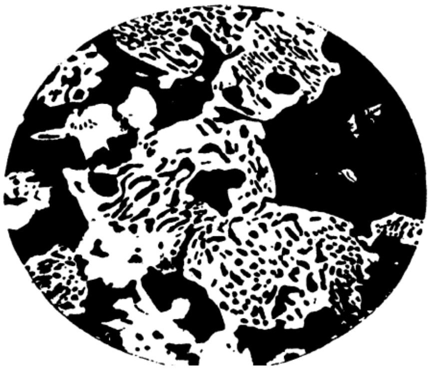
The presence of sufficient free space for crystal growth is a critical factor, which determine whether the grown crystal will have crystal faces or not. The mineral crystal begins to grow until it comes in contact with neighboring crystal.

Crystal grains can occur with well-developed faces "allotriomorphic", without facets "xenomorphic" or with some crystal faces and tend to be fairly uniform in size "hypidiomorphic". For example, when chromite crystals occur as rounded-semi rounded grains associated with olivine.



- **<u>Graphic/Micro-Graphic texture:</u>**

The mineral growth occurs between two minerals as same as the ancient cuneiform writing. The minerals of such intergrowths are usually regarded as contemporaneous (e.g. the micrographic intergrowth between olivine "gangue" and titanomagnetite"ore mineral").



Micrographic texture between olivine "light" and titanomagnetite "dark".

Banded texture:

This texture type results from the mineral differentiation from flowing magma. As example, the chromite bands alternating with olivine bands form due to the continuous settling of chromite crystals during the flowing motion of dunite magma. *Banded texture here resembles that of the sedimentary banded iron formation consisting of bands of magnetite/hematite alternating with jasper.*

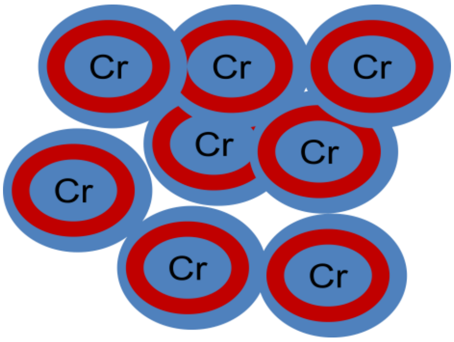
Banded Chromite deposits "dark color" alternating with olivine-rich layer "light color"

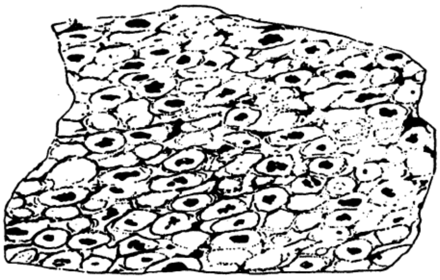
Banded iron formations "reddish brown color of iron minerals" alternating with silica-rich layer "light red color"

- **Orbicular and Nodular textures:**

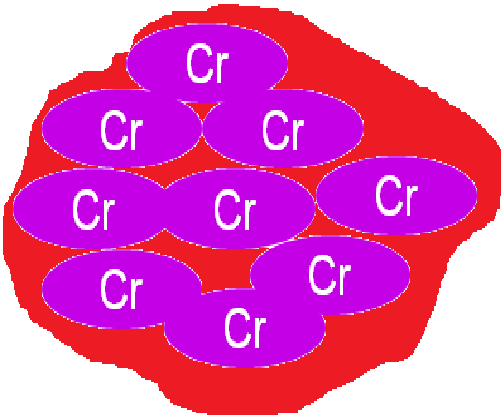
The orbicular texture is made up of many spheroidal units, each of which consists of a nucleus of chromite surrounded by a shell composed, in the main, of partially serpentinized olivine. Each nucleus is composed of a number of chromite crystals. Each sheath of olivine is surrounded by a thin outer sheath of chromite and commonly contains several concentric layers of chromite.

The nodular texture consists of spheriodal grains, e.g. of chromite, without concentric structure. The interstices are usually filled with olivine/or serpentinized olivine.





Orbicular texture consisting of chromite nuclei "dark" surrounded by sheath of olivine "light".

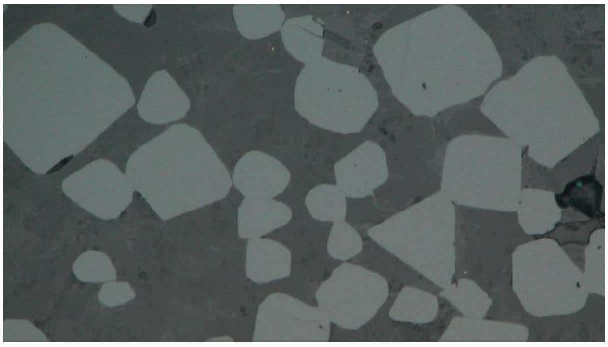


Nodular chromite grains

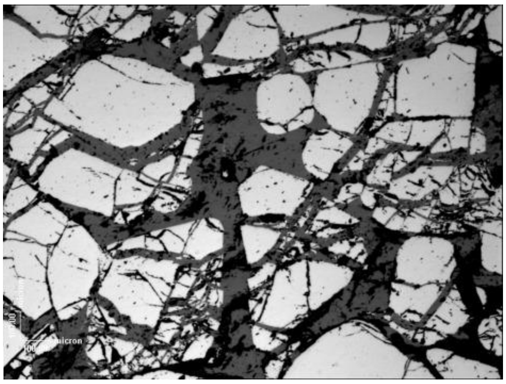
"dark" surrounded by serpentinized olivine"light"

Cumulus texture:

It is a descriptive term for the geometric arrangement of specific ore minerals, which are separated from the surrounding melt by the gravitational settling to the base of magma chamber, resulting in euhedral-subhedral crystals set in silicate-rich ground mass (e.g. euhedral-subhedral chromite crystals cemented and corroded by olivine).



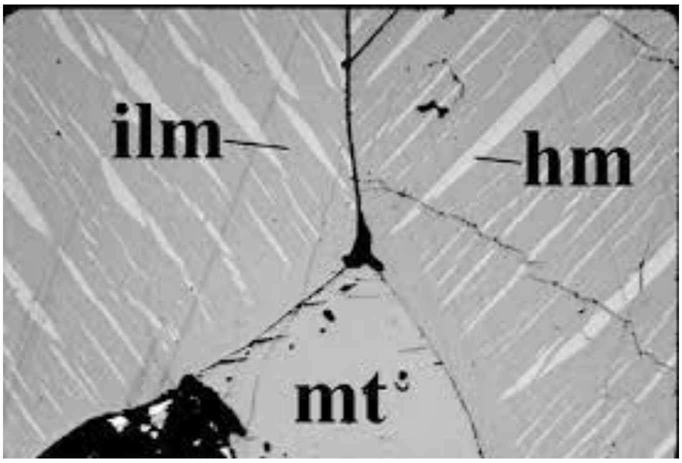
Cumulus texture consisting of euhedral, subhedral, and anhedral chromite crystals engulfed by olivine-rich matrix



Cumulus texture consisting of euhedral, subhedral, and anhedral chromite crystals engulfed by fractured olivine-rich matrix

Ex-solution texture:

Exsolution textures are caused by changes in the mineral equilibrium after the magmatic stage. After the complete crystallization of magma there may still be changes in equilibrium due mainly to the continued cooling of the rock. In magmatic ores, nearly all of which are plutonic rocks, cooling is usually slow, and minor textural modifications may take place in the solid state with the formation of new minerals. More clarifications are represented by *the break-down of solid solution occurring between two different mineral phases*.

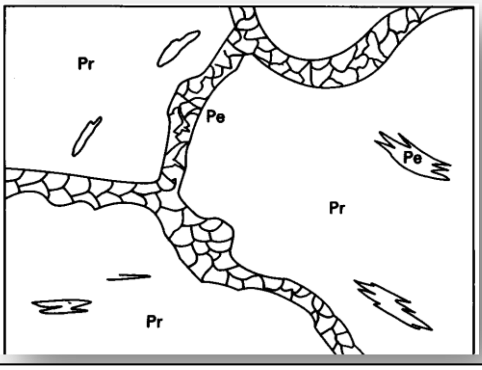


- ***The term solid solution*** refers to semi-crystalline structure in which two elements "A" & "B" freely replace each other under high temperature condition where the components of the two mineral phases are well-homogenized.
- ***On cooling,*** the homogenous solid solution is separated into two phases, one rich in element "A" and another rich in "B".
- ***This breakdown*** of a homogeneous solid solution is known as ***Ex-solution***. The extraneous materials which are forced out of the mineral structure upon cooling tend to accumulate along cleavage surfaces in the form of lamellae or blades.
- ***The ex-olution texture*** consists of host crystal "the high percentage phase" and exsolved lamella "the lower percentage phase".
- ***Some Ex-solutions*** are chemically ***'closed'***, that is, the previously simple solid solution is chemically equivalent to the composition of the disintegration products. An example is perthite of 70 percent orthoclase and 30 percent albite lamellae that was earlier ahomogeneous high temperature feldspar with 70 percent Orthoclase and 30 percent Albite composition. An ore example is hematite-ilmenite.
- ***Other Ex-solution*** are ***chemically 'open'*** in that a change in the stoichiometric relationships is observed. For example, if a feldspar exsolves to yield orthoclase and small hematite plates, then either the solid solution could not have been expressible by the feldspar formula or some elements were added or removed. Another example is the ilmenite-magnetite pair. No solid solution exists between the end-members, but blebs of magnetite are found in ilmenite and vice versa - - a phenomenon attributed to the expulsion of iron from ilmenite and titanium from magnetite.

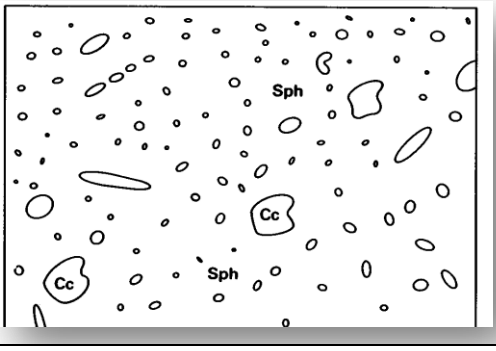
Criteria for the recognition of ex-solution textures:

1. *Interpretation of the textures must be based on the visible relationships of the minerals concerned.*
2. *Minute inclusions distributed generally in the crystallographic directions of the host mineral (solvent) so that the orientation of the intergrowth varies with the orientation of the crystal (with the exception of emulsion ex-solutions).*
3. *The inclusions (lamellar, blade, plate rod-like emulsions, rounded blebs) have sharp smooth boundaries and are generally single crystals.*
4. *The inclusions show an even or seriate distribution through the host.*
5. *If the solute mineral occurs outside the host (solvent) mineral it must occur as more or less interstitial grains.*
6. *Where the ex-solution bodies form a connected lattice work they show no widening at the contact with one another.*
7. *The composition and crystal structures of the two minerals involved must be such that a solid solution between them is feasible at high temperatures.*
8. *There must be a general absence of textures indicating replacements between them.*
9. *Ex-solutions do not occur in vein form.*

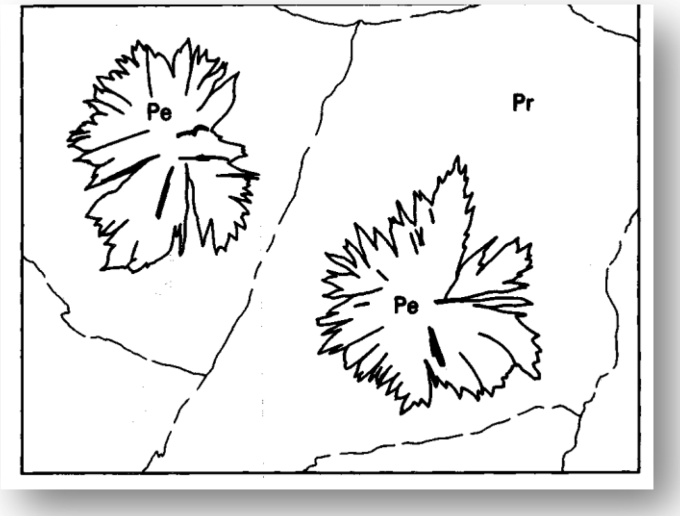
Exsolution intergrowths types:



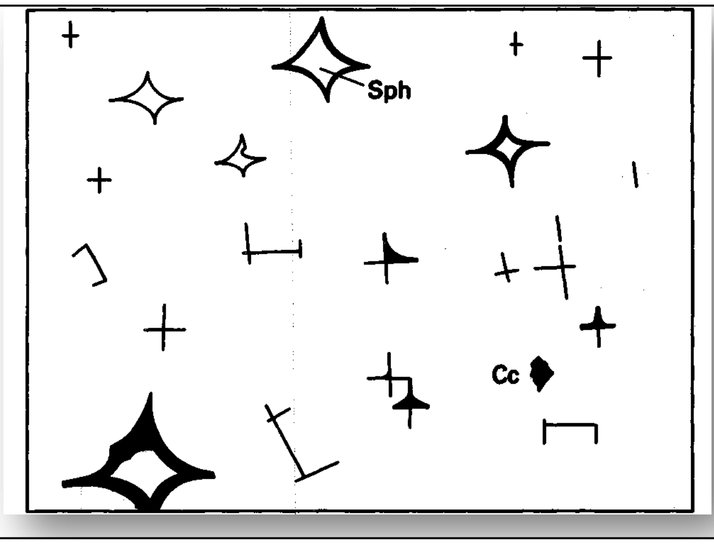
Net-like shape intergrowth in which the exsolved phase"pentalendite Pe" is concentrated at edges of the host mineral"pyrrhotite Pr"



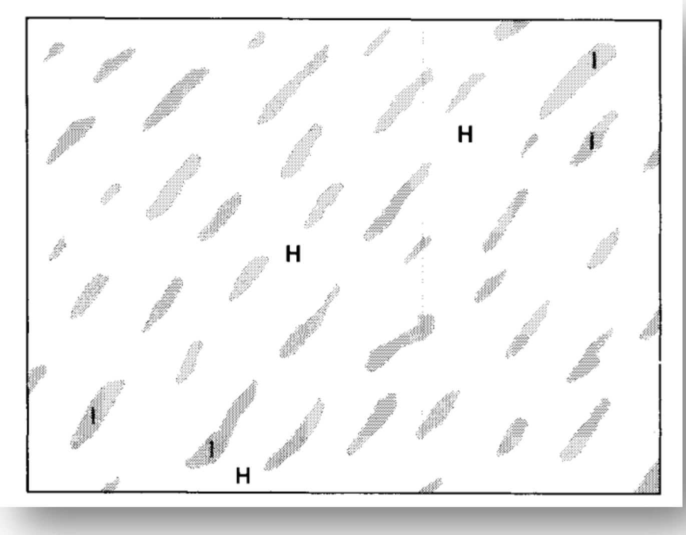
Emolusion intergrowth in which Rounded globules of the exsolved mineral (guest or daughter) normally occur at random in the host or parent. It may appear similar to spherical replacement texture, but in this case the guest would be noted at grain boundaries and as discrete grains (e.g. Chalcopyrite Cc-Sphalerite Sph).



Flame-like shape intergrowth" The name fully describes this exsolution texture which may form flames of the daughter totally in the parent" Pentalendite Pe-Pyrrhotite Pe.



Star-like shape intergrowth" More or less perfect star-shaped exsolution bodies of the daughter in the parent are observed. (Normally very high magnification is required in order to confirm that they are star-shaped). They are invariably crystallographically, not randomly, orientated. Sphalerite-Chalcopyrite.



Seriate intergrowth" This texture is seen as blebs or blades of the exsolved body in the parent grain. Ilmenite "I" in Hematite "H".

Favorable Factors for the Solid Solutions and Ex-solution intergrowths:

If we assume that the solute is present in the solvent as a result of crystallization from melts or a precipitation from solutions, the attainment of the state of solid solution would depend on the following factors, provided sufficiently high temperatures prevailed:

(i) The relative size of the metal atom;

(ii) The valency of the two metals;

(iii) Their crystal structure.

Therefore, the most favorable conditions for the formation of a wide range of solid solutions are that the solvent and the solute are of nearly the same size, do not form intermediate compounds and have the same valency.

In contradistinction to the factors favouring solid solutions the following favour diffusion (ex-solution):

- Low solubility of the solute;
- Larger difference of melting points between solute and solvent;
- Large difference of atomic radii of solute and solvent;
- Increasing separation of solute and solvent in the periodic table (a most constant factor) which actually is the valency difference.

Comparing the factors favoring ex-solution with the factors favoring solid solution it can be seen that whereas large differences in atomic radii of solute and solvent encourage diffusion, solid solution in contrast is favored when solute and solvent atoms are of nearly the same size. Also, separation of the solute and the solvent in the periodic table is a factor favoring diffusion whereas solid solution is aided when solute and solvent have the same valency. It appears that these contradictions complicate further the problem of solid solutions - ex-solutions.

Another interpretation concerning the problem is that the crystal structure is in a disordered state at high temperatures and thus can accommodate the solute atoms. As cooling takes place and the crystal structure passes from the disordered to the ordered state the solute atoms ex-solve or diffuse out. The unmixing of solid solutions takes place by the diffusion of the solute atoms or ions through the lattice of the solvent substance. Regarding the cooling rate, as such example, solid solutions of bornite and chalcopyrite cooled from 600° C to room temperature in 5 minutes, unmix to some degree in this tune interval. Also another feature of unmixing, revealed by experimental studies, is the speed with which ex-solution bodies will segregate to the grain boundaries of the host mineral if the specimens are annealed or cooled slowly.

Lecture#6: Textures of Ore Minerals-Primary Hydrothermal Textures

6.2. Primary Hydrothermal Textures

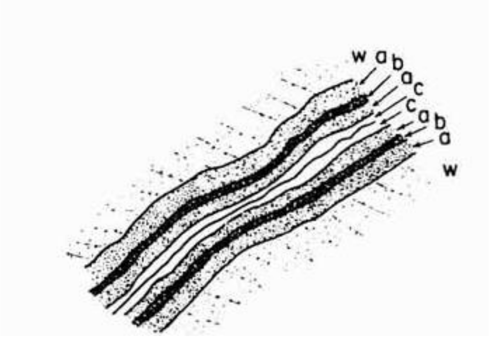
Primary hydrothermal textures refers to the geometric shapes and structures resulting from the direct crystallization of ore minerals from hydrothermal solutions, without any evidence or indication for the corrosion of a given mineral by another "replacement". The crystallization from hydrothermal solutions occurs within different types of openings in the host rock; this is called ***hydrothermal open-space filling***. There are different kinds of these openings that are considered the preferential paths for the invaded solutions:

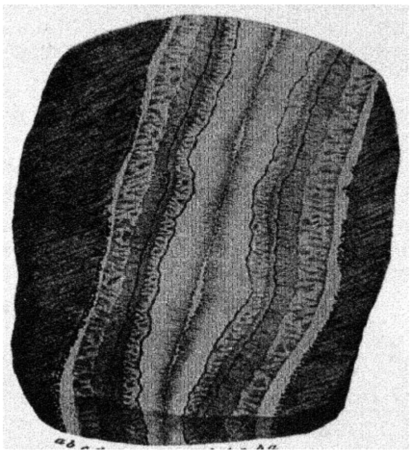
(1) Pores (in sediments and pyroclastics mainly)--- (2) Vesicles.
(3) Miarolitic cavities-----(4) Solution cavities----(5) Fissures----(6) Faults--(7) Joints
(8) Bedding-plane fractures---(9) Tension fractures in folds---(10) vein fractures----
(11) Brecciation of rocks or mineralized veins.

Note: As a general rule minerals deposited in open spaces are younger than those forming the walls of such spaces. The open-space fillings are characterized by well-developed crystals and matching of the wall fracture.

6.2.1. Crustification texture:

Crustification is the deposition of mineral matter in successive layers or crusts upon the walls of openings in rocks. There may be many such layers. In fissures the bands are symmetrical in kind on opposite walls but not necessarily symmetrical in width. The youngest bands may meet in the center of the fissure. So, the Crustification is a significant indication for the time sequence of mineral deposition.

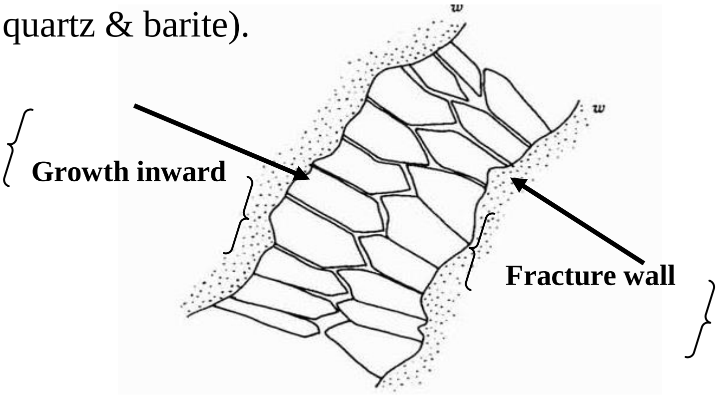




Crustified vein indicating successive pulses of hydrothermal solutions

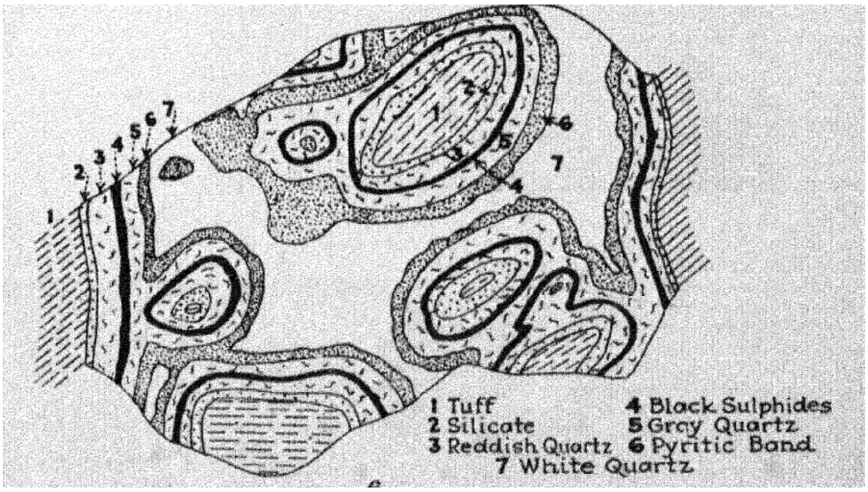
6.2.2. Comb-like structure:

This term refers to an open-space filling from the two opposite sides of a fissure, where there is a gradual increase in the crystal growth inward from the fracture wall. This structure type is common for minerals that tend to crystallize in elongate forms are arranged with their long axes (e.g. quartz & barite).



6.2.3. Cockade/or ring structure:

This structure is a variant of crustification. Where a fissure becomes partly filled with a rubble of fragments torn or dropped from the walls these may become crusted with successive layers of mineral matter.

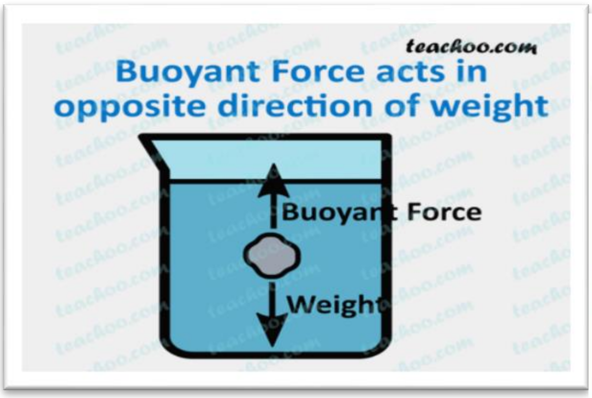


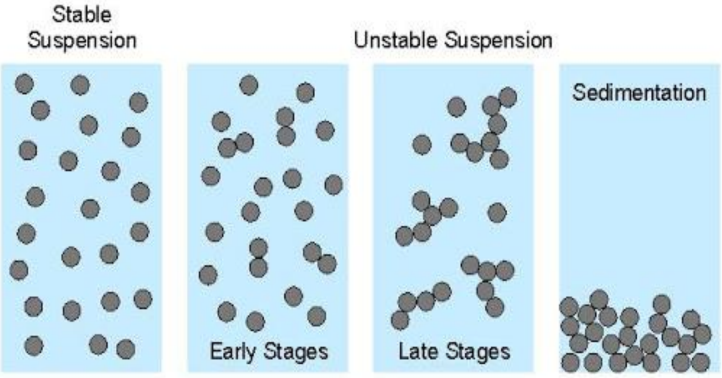
6.2.4. Colloidal/ or Colloform textures:

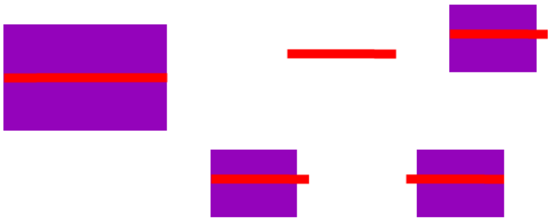
These textural patterns are generated from what so-called colloidal solutions. To understand the nature of colloidal solutions, consider a cube of sphalerite is crushed and milled up to *the colloidal size"1μm-1nm"*, thus, the exposed surface area will be increased and the sphalerite fine particles will not readily deposited in the surrounding dispersion medium due to its suspension/or colloidal state. Such systems are called colloidal dispersion/ or sol. The colloidal dispersions are characterized by:

- **Buoyancy:**

This character is due to the increased surface area in relative to the mass of a substance. For instance, as the particles in most colloidal dispersions in water are much heavier than water we may inquire why they do not rapidly settle. If a cube of unit diameter is divided into cubes of a fourth that diameter each of these has one sixty fourth the mass of the original cube but has one sixteenth as much surface. Thus as materials become progressively finer-grained the ratio of surface to mass increases, and buoyancy tends more and more to delay settling.







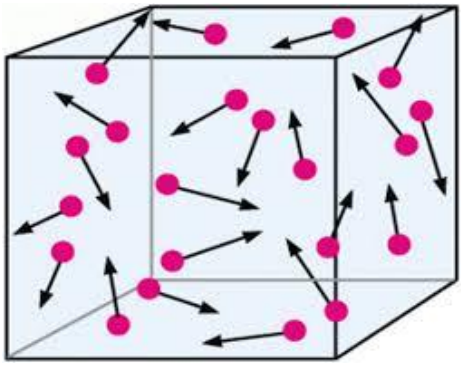
D= 1/4

A= 1/4*1/4= 1/16

V= 1/4*1/4 *1/4= 1/64

- **Brownian motion:**

This is a random movement of the colloidal particles due to the successive bombardments of the dispersion medium molecules. In very fine particles the magnitude of the random motion may be many times the motion due to gravitation. So, Brownian motion along with buoyancy keeps the colloidal particles in a suspension state and delays their deposition for a long time.

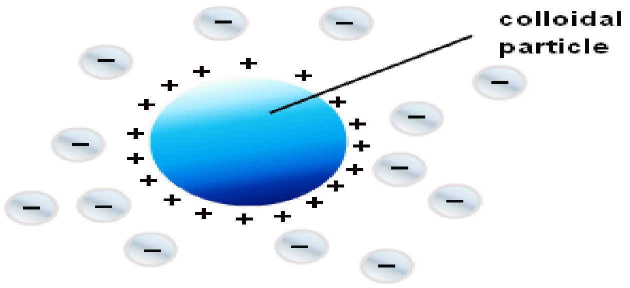


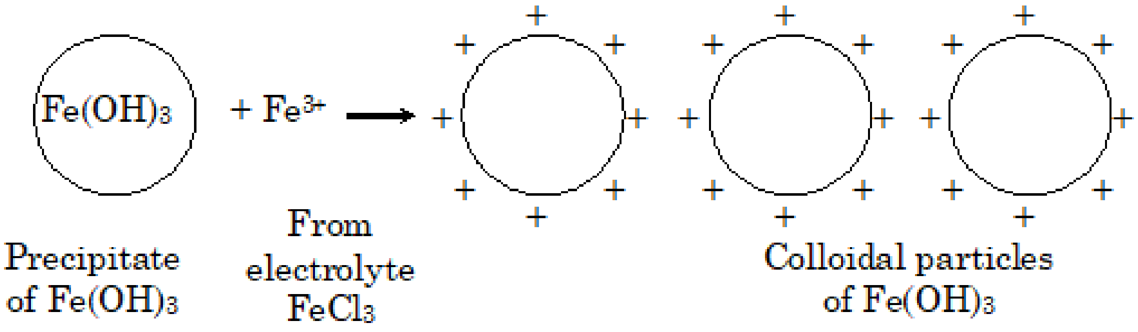
- **Adsorption:**

Adsorption is the capability of solid particles to attract ions and molecules from the ambient medium on their surface. The adsorption capacity of colloidal particles is of high magnitudes due to the proportional relationship between the attraction force and the surface area.

- **Electrical charges of colloidal particles:**

Not only do fine particles dispersed through liquids adsorb molecules of the liquid, but they may adsorb ions as well, and as these ions carry electrical charges the solid particles also become electrically charged. Some substances adsorb positive ions more readily than negative ions, and vice versa. In dispersions of a single substance in a liquid the particles become similarly charged and tend to repel each other. This is an important factor in keeping colloidal particles in suspension because flocculation takes place readily when the charges are neutralized. An important consequence of the electric charges on the particles of colloidal dispersions is that when such dispersions are brought in contact with other colloidal dispersions whose particles are oppositely charged neutralization of both charges may occur and flocculation begins.

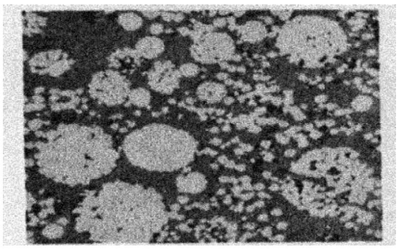




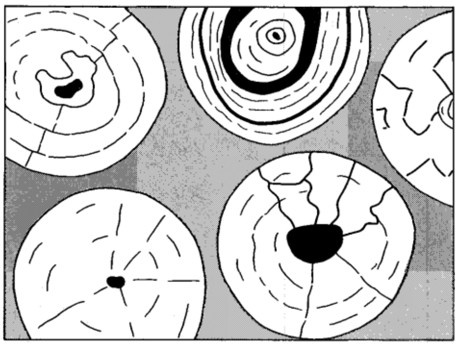
Preparation of colloidal sol by peptisation

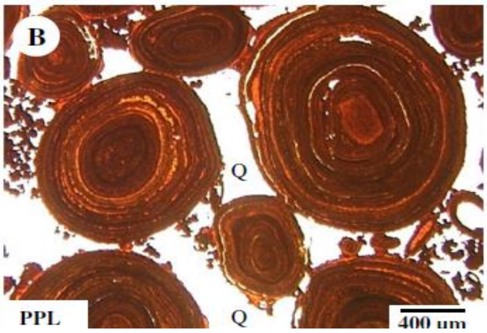
The colloform deposition of the extremely fine ore particles results in several morphological patterns:

- ***Farmboidal texture*** *consists of clusters of round-shaped mineral grains like grape cluster*.

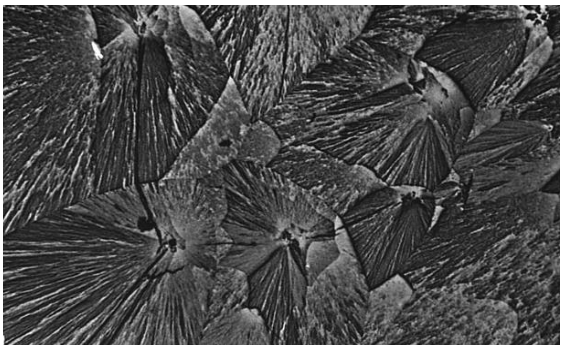


- ***Pelletal textures*** *"homogenous/or show concentric structures*.



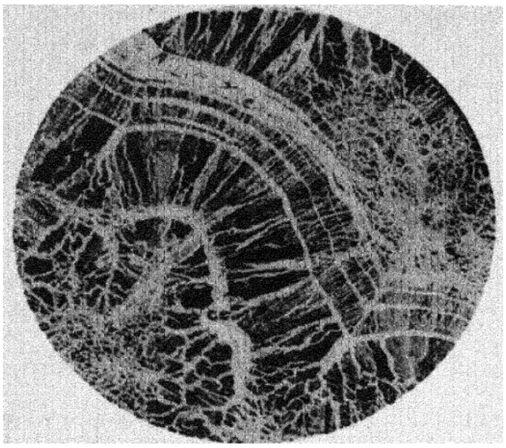


- ***Botryoidal shapes*** *"spherules each one consists of radial fine-grained crystals"***.**



- ***Concentric colored-rings& colored-bands*** *due to the ability of colloids to adsorb different ions from their surroundings***.**

- ***Shrinkage cracks*** *due to water loss***.**



6.2.5. Brecciation textures:

First of all, the term breccia refers to angular fragments of rock or mineral debris cemented by a specific mineral material. The Brecciation process occurs as a response to the imposed chemical weathering and erosion conditions, shearing of different rock types along shear zones, or to the hydrofracturing of rocks by highly pressured hydrothermal fluids. The hydrothermal breccia or brecciated veins are formed when the angular rock/or mineral fragments are in contact with the invaded hydrothermal solutions.

Hydrothermal Breccia

Criteria of Open-Space Filling:

1-Well-develped crystals.

2-Matching walls of the mineralized veins.

3-Com-like texture.

4-Cockade texture.

5-Colloform texture.

Lecture#7: Textures of Ore Minerals-Secondary Replacement & Deformation Textures

6.3. Secondary Textures Resulting from Replacement:

Replacement is the dissolving of one mineral or group of minerals and the immediate deposition of another mineral or group of minerals in the place thus vacated. Replacement may occur due to 1) dissolution and subsequent reprecipitation (e.g. fossilized wood); 2) oxidation (e.g. oxidation of pyrite to goethite).

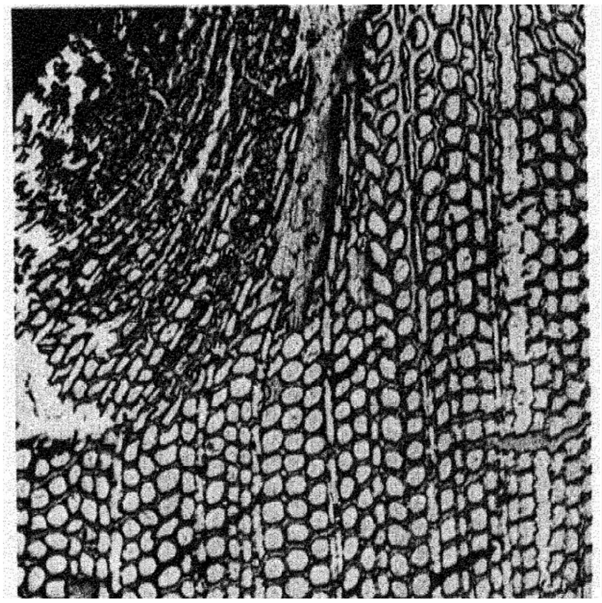
Note: minerals can be dissolved by one solution, and after an interval, during which open spaces exist, new minerals are deposited in these spaces by solutions of a different composition. This is not replacement.

There are two types of replacement:

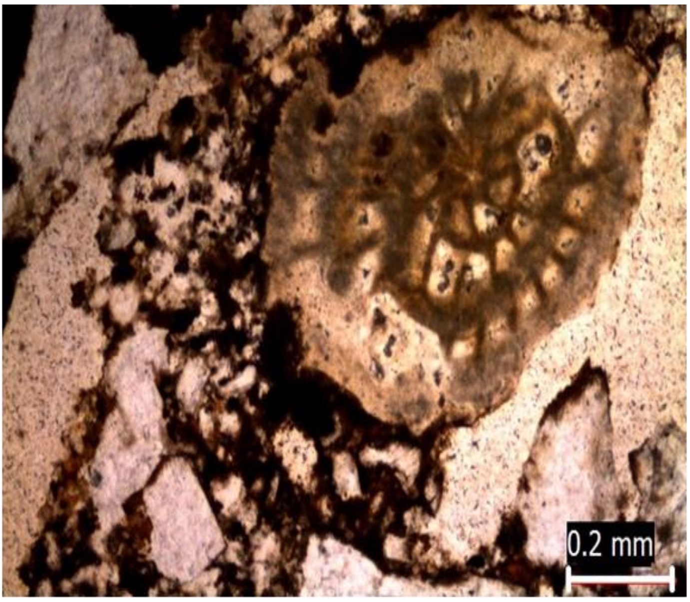
- **Pseudomorphic replacement :**
  - ✓ Pseudomorphism is the presence, in a mineral or mineral aggregate, of forms, textures, or structures not characteristic of itself but characteristic instead of other minerals, or mineral aggregates, or even of organisms. Pseudomorphism results from the dissolving of one mineral or group of minerals and the depositing of another mineral or group of minerals in its place.
  - ✓ Usually the processes of solution and deposition go on concurrently through the medium of the same solution and without the development of open spaces that is, by the process known as ***replacement or metasomatism.***
  - ✓ Probably the most easily recognized pseudomorphic replacement textures are those in which organic materials, such as wood fragments or fossil shells have been pseudomorphed by metal sulfides (commonly pyrite,

marcasite, chalcocite) or oxides (commonly hematite, goethite, "limonite," uranium minerals).

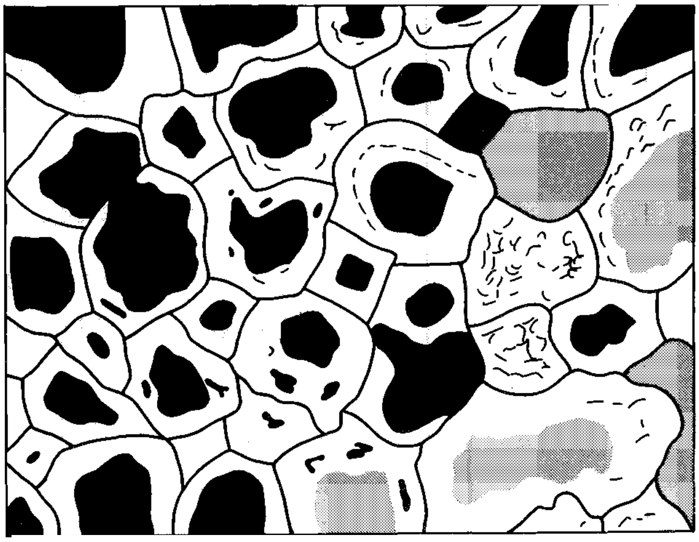
- Pseudomorphism is considered an important criterion for the mineral replacement due to the preserved parts of the original phase (*e.g. organic structure of fossils and wood, crystal shapes and cleavage planes*).



Pseudomorphic replacement of plant cell by pyrite, with keeping the original plant structure.



Pseudomorphic replacement of foraminiferal test by barite, with keeping the original fossil structure



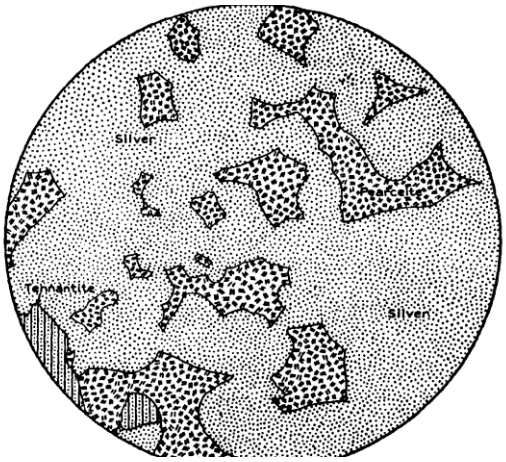
The dark-colored mineral replaces the light one with keeping the crystal outline of the replaced phase.

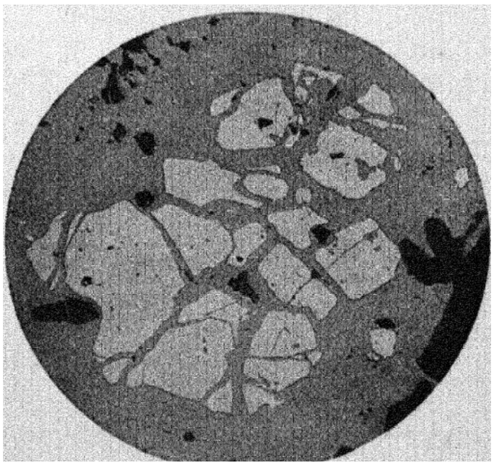
- **Penetrative replacement:**
  - Unlike pseudomorphic replacement, the penetrative replacement results in partial/or complete corrosion of the original phase, without maintaining the

original crystal form or even cleavage planes. During the advanced stage, it is difficult to determine the time order for two minerals due to a complete removal of the original phase.

- The penetrative replacement occurs along the weakness places of the mineral grains such as:

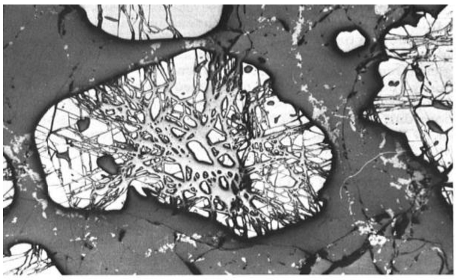
  A. The penetrative replacement can occur **<u>along the grain boundaries</u>** between minerals, and hence, **<u>there will be irregular widening along the grain boundary by the replacing phase.</u>**

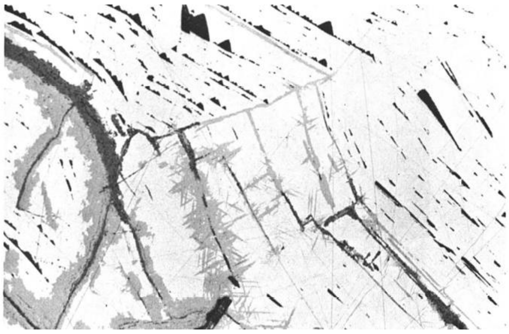




B. The mineral may be corroded **<u>along fractures through its grain</u>**. Irregular widening of fractures occurs. In this case, we have irregular-shaped remains of the original phase floated through the replacing phase, as illustrated by the attached figure in which pyrite grain is corroded by chalcosite along grain fractures.

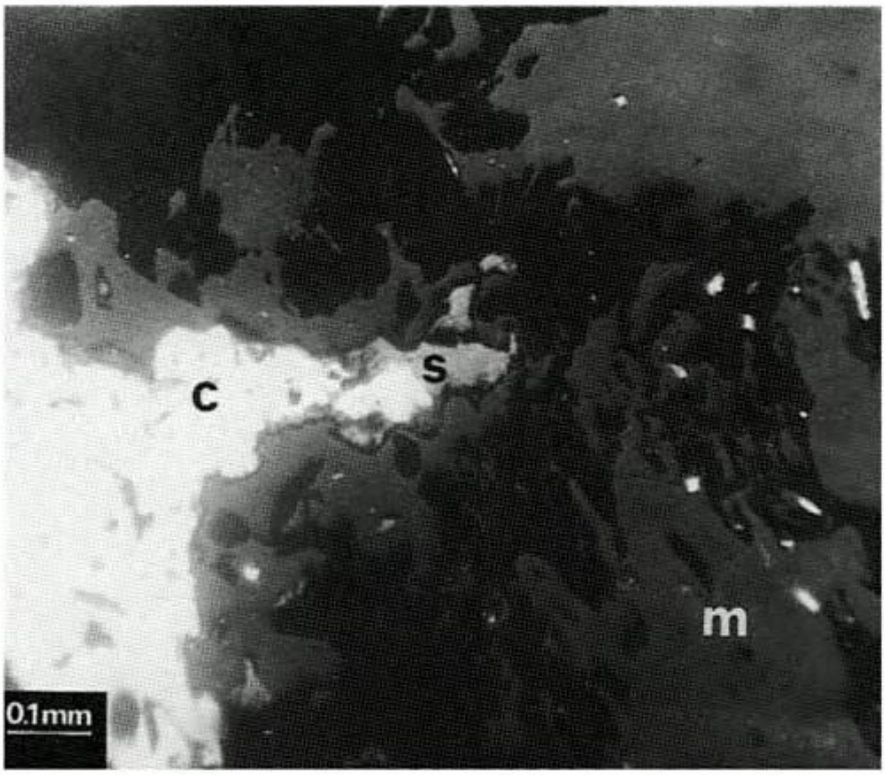
C. The replacement can also take place along the cleavage planes, e.g. replacement of galena "PbS" by cerussite "$PbCO_3$".



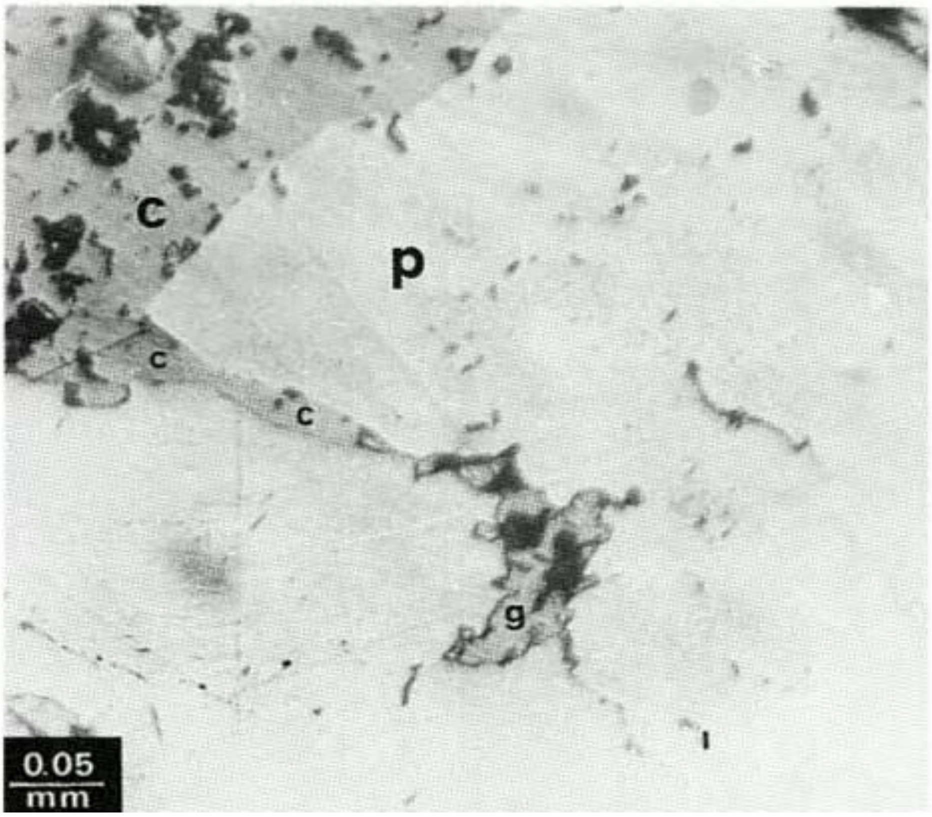


- **Successive replacement:**

Successive replacement is a penetrative remobilization of elements through successive stages. Taking also into consideration that not all the elements comprising an ore deposit are mobilized at one time and simultaneously, successive mobilization processes in the sense of successive replacements are most important. Also, the supply of material forming an ore body might be due to successive supplies of solutions. For examples, in the below figures, magnetite is successively replaced by sphalerite and chalcopyrite. Considering the formulae of the minerals involved, magnetite ($Fe3O4$) is replaced by Sphalerite (ZnS). This replacement involves dissolution of magnetite and precipitation from subsequent solutions of sphalerite. In turn chalcopyrite ($CuFe2S$) replaces both magnetite and sphalerite; also in this case, dissolution of both magnetite and sphalerite and precipitation of chalcopyrite took place. Another example, the successive replacement patterns of pyrite ($FeS2$) where it is successively replaced by galena (PbS) and chalcopyrite ($CuFeS2$). Also in this case, the intergrowth is due to dissolution or perhaps successive dissolution of pyrite and of galena as well and the precipitation from solution in the first instance of galena in the voids (dissolved) of pyrite and chalcopyrite in the voids of pyrite and galena, respectively.

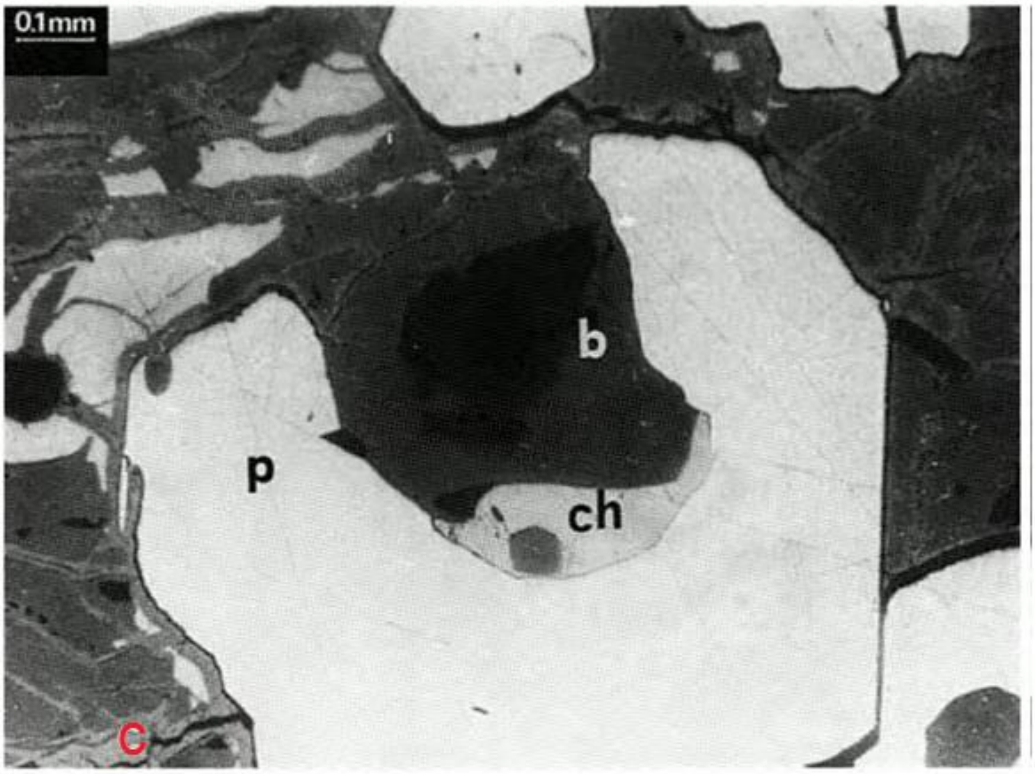


Successive replacement of magnetite "m" by Sphalerite "s" and chalcopyrite "c"

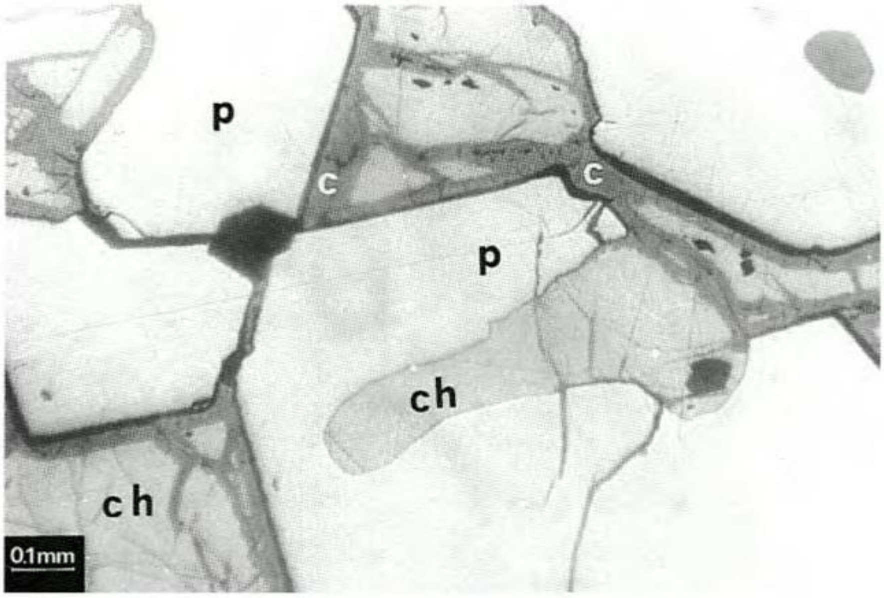


Successive replacement of pyrite "p" by galena "g" and chalcopyrite "c"

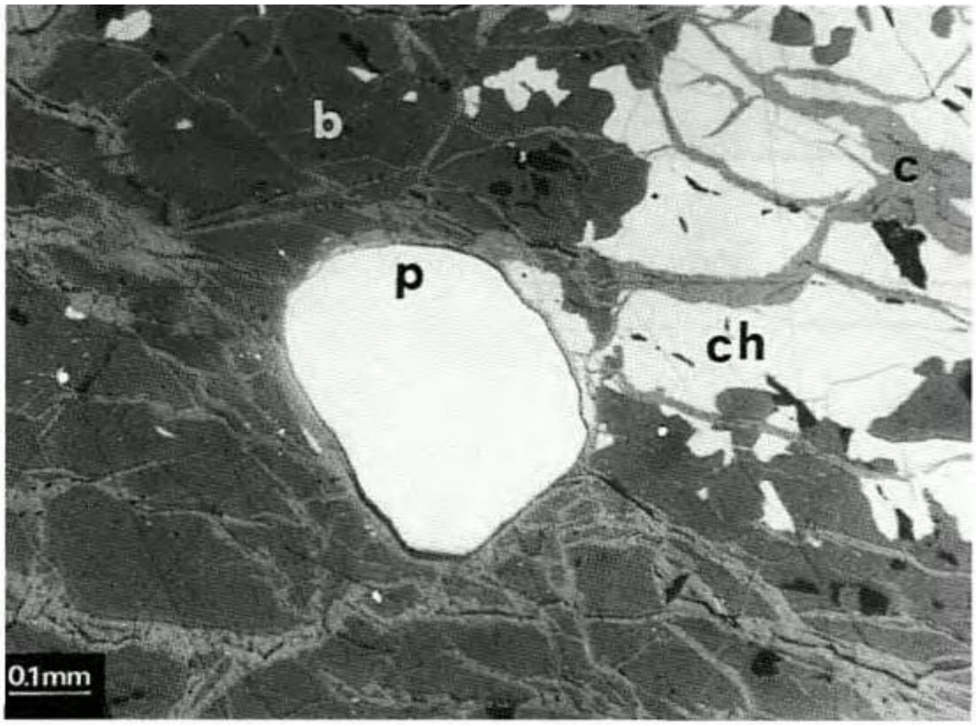
In addition the dissolution mechanism, the successive replacement can occur due to the element migration/or mobilization. For example, Progressive enrichment in Cu of the successive replacement of substitute copper minerals is endorsed by the patterns shown in the following figures where pyrite is replaced by chalcopyrite and where chalcopyrite replaced pre-existing bornite. Both the bornite and the chalcopyrite are replaced by chalcocite. These patterns show atoll-type replacement of pyrite by chalcopyrite. Considering the chemical composition of the minerals, it is more likely that pyrite was dissolved prior to the precipitation from solutions of chalcopyrite. In contradistinction, the replacement of bornite by chalcopyrite could be interpreted as either the result of dissolution of the bornite and precipitation of chalcopyrite by solutions or as due to the migration of elements, meaning that there was a relative increase in copper and, of course, the necessary volume re-adjustment and lattice reorganization took place. The formation of chalcocite veinlets transecting both the bornite and the chalcopyrite could be interpreted as the result of leaching out of Fe and as mobilization of Cu enriched solutions.



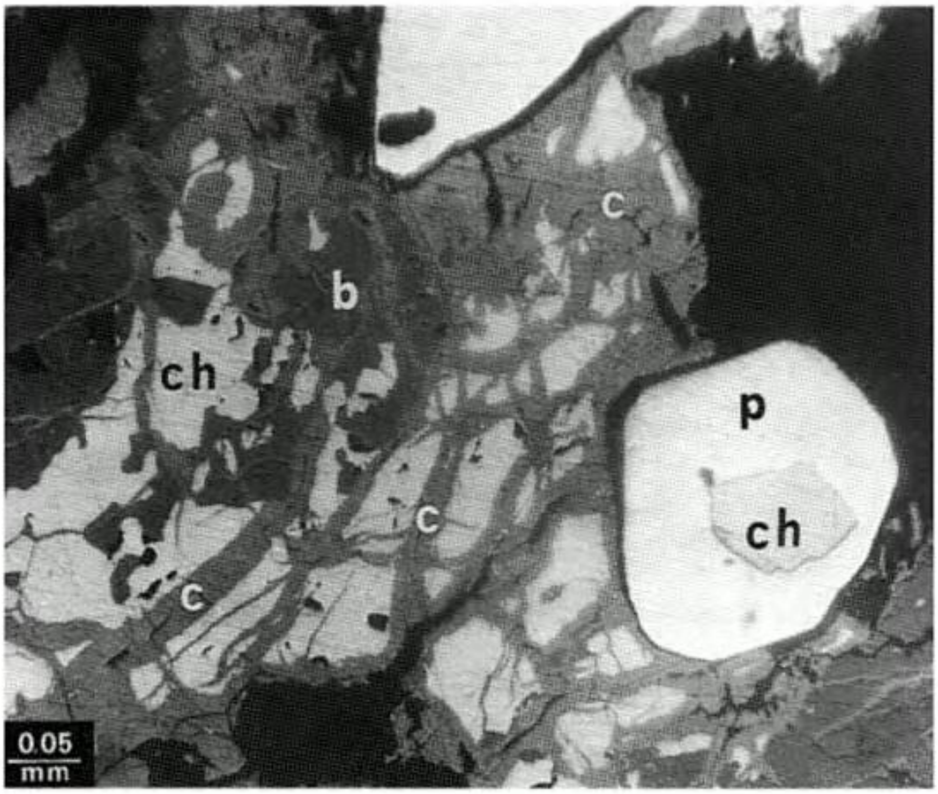
Atoll-shape successive replacement of pyrite "p" by chalcopyrite "c", bornite "b", and chalcocite



Atoll-shape successive replacement of pyrite "p" by chalcopyrite "c", bornite "b



Chalcopyrite "ch" is successively replaced by bornite "b" and chalcocite "c". pyrite "p" does not exhibit noticeable dissolution.



Pyrite"p" is replaced by chalcopyrite "ch", bornite "b" is replaced by chalcopyrite and the two minerals are replaced by veinlets of chalcocite "c"

Depending upon whether the mineralizing solution (the source of the replacing phase) is located near the ground surface "percolating super-gene" or deep-seated "ascending hypogene", replacement can be divided into:

Super-gene replacement:

- It occurs near the ground surface in the oxidation zone by descending solutions.
- Certain minerals occurring under the near-surface conditions of the oxidizing zone are criteria for such replacement type. For instance, the development of anglesite and cerussite along galena cleavages, also replacements by limonite and malachite are also supergene
- The replacement of the host mineral cannot take place simultaneously by two minerals. For example, galena is first replaced by argentite and later by native silver.

Hypogene-replacement:

- It occurs at deep-seated places by ascending solutions.
- Certain minerals formed under hypogene conditions are indicators. As such example, the replacement of limestone by wallstonite, garnet, and epidote is an indication for the hypogene replacement at the contact metamorphism where hydrothermal solutions of metamorphic origin occur.
- In hypogene mineralization apparently simultaneous replacement of one or more host minerals by an aggregate of many guest minerals is common.

Criteria for identifying replacement:

1. Pseudomorphs like mineralized wood/ fossils.

2.Irregular widening of fractures along the mineral grain, the surrounding groundmass.

3.Irregular widening of grain boundaries.

4.Non-matching walls of fractures.

5.Concave-convex grain boundaries.

6.Island relicts of the original phase surrounded by the new mineral.

7.Topotaxy replacement: is a process where the replacing mineral overgrows the replaced one along certain crystallographic directions controlled by the structure of the replaced mineral (e.g. replacement of galena by cerussite along cleavage planes).

6.4. Secondary Textures Resulting from Deformation:

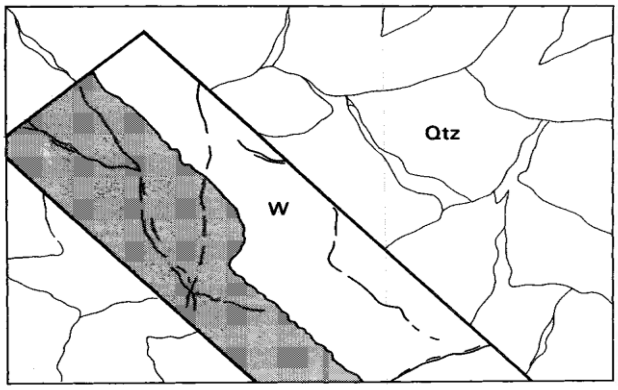
The deformation of ore minerals may result from tectonic forces (e.g. faulting, folding, and shear stress of the mineralized veins). Many ores contain textural evidence of deformation. The evidence ranges from minor pressure-induced twinning to complete cataclasis. The degree to which individual mineral grains both respond to and preserve deformational effects depends on:

- **The mineral hardness** (native minerals are deformed readily in relative to oxides and Cu-Fe sulfides).
- **The rate of strain** (some minerals respond for deformation in the form of fissures through mineral grains, e.g. ilmenite, while the others occur as fractured and curved grains, e.g. molybdenite& bismuthnite.
- **The mineral association** (The softer minerals deform most readily, but they also recrystallize most readily, so that the deformational effects are obliterated before those in more refractory minerals).
- **The post-deformational history** (the deformed mineral can be completely replaced by another mineral, so the deformation evidence is completely obliterated).

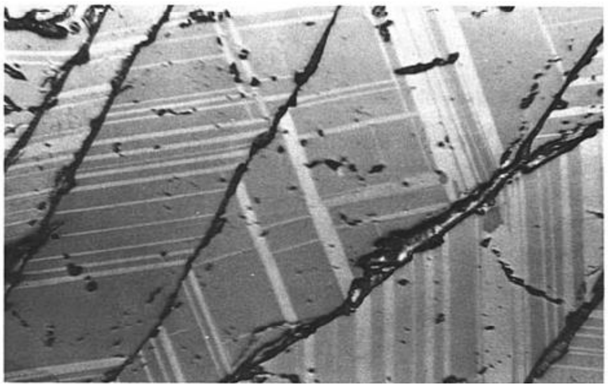
There are specific deformational features indicate for such textural type:

1. **Deformation twinning:**

Deformation twinning is as a result of bending and cataclasis and as lamellae of uniform width. On controversy, **the growth twinning** is of irregular width generating during the crystal growth.



Growth twinning of irregular thickness



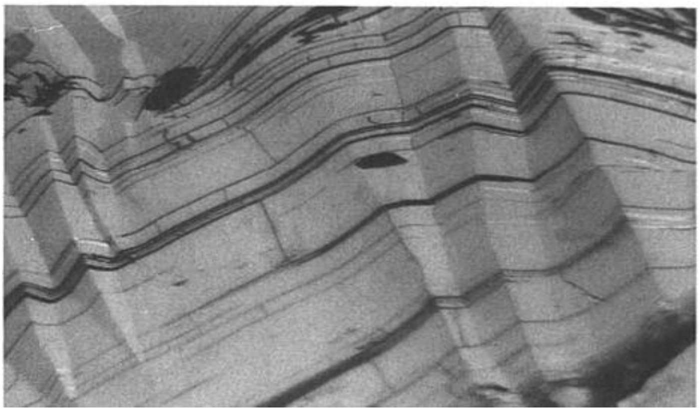
Pressure twinning or uniform thickness

2. Pressure lamellae:

Pressure lamellae are spindle-shaped lamellae of undulose extinction. Examples include stibnite and bismuthnite.

3. Kinkbanding:

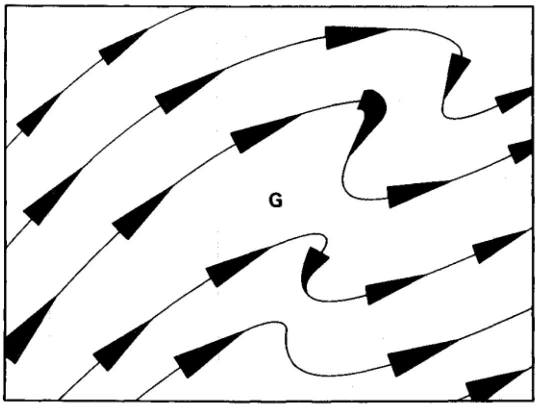
If a mineral has subjected to deformation, it may be kinked. This means that sub-parallel bent lamellae form and each of which may show undulose extinction. The kinkbanding is more pronounced in minerals contains colored bands or cleavage (e.g. kinkbands of bismuthnite).



Kinkbanding in bismuthnite

4. Curvature:

Deformation of ores is often evidenced by the curvature or offset of normally linear or planar features, such as crystal faces, cleavages, fractures, twins, exsolution lamellae, and primary mineral layering or veining.



5. Brecciation or Cataclasis

Often the more brittle components of an ore mineral assemblage (e.g. pyrite, chromite and magnetite) are more fractured and/or brecciated relative to the softer ore and gangue minerals. The ultimate stage of brecciation is achieved when pulverization of all the ore and gangues are expressed *as ball-shaped texture*.

Lecture#8: Paragenesis of Ore Minerals

8. Paragenesis of Ore Minerals:

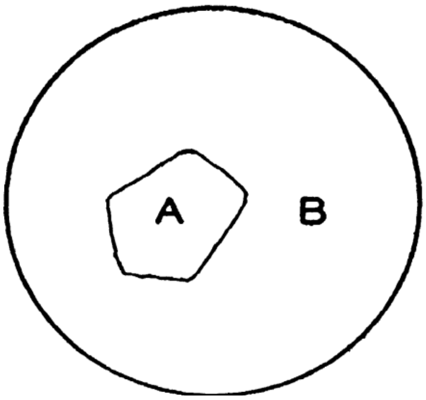
The paragenetic sequence of an ore deposit is the time succession of the minerals formation (e.g. oldest to youngest minerals) and of events which gave rise to and affected that deposit. In addition to the ore minerals, the paragenetic sequence should note the time at which the gangue minerals started to be deposited and the duration of their deposition. For example, if we have exsolution texture of sphalerite "guest" and chalcopyrite "host" along with irregular width veinlets of bornite cutting through chalcopyrite. Thus, the paragenetic sequence is that the first crystallization of chalcopyrite followed by exsolving sphalerite as exsolution texture, and then post-depositional replacement of chalcopyrite by bornite.

8.1. Criteria for determining the paragenetic sequence:

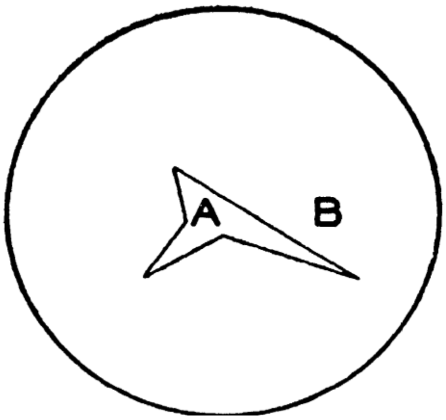
1) Crystal shape "automorphic outlines"

In general, euhedral (idiomorphic) crystals have grown early in an unobstructed medium or an open space (e.g. magma chamber, vein, vug or cavity). Certain minerals are commonly found to crystallize in idiomorphic form which is often related to their specific depositional environment or position in a general paragenetic sequence; such minerals include: pyrite, galena, sphalerite, quartz, cassiterite and covellite. For example, if we have mineral associations of pyrite "cubes", chalcopyrite "anhedral or matrix" and quartz "hexagonal outlines", the paragenetic sequence in the absence of replacement criteria will be pyrite---quartz----chalcopyrite.

The shape of the individual faces may also help, for convex faced crystals have often been interpreted as being formed before crystals with concave faces. In the below attached figure#1, mineral A may not show certainly identifiable outlines but its general outlines are convex or protruding outward, and its crystal faces join to enclose an isolated grain of A in B. Very probably the crystal faces are those of mineral A rather than B and therefore mineral A antedates B. On the other hand, figure#2 shows crystal boundaries of A are in general concave outward, and probably these are crystal faces of mineral B rather than A.



Figure#1:Convex crystal faces of mineral A, the oldest mineral.



Figure#2:Cocave crystal faces of mineral A, the younger mineral.

2) Partial automorphism in two intergrown minerals:

Even in the same field of the microscope mineral A may in places show its own characteristic crystal outlines against mineral B and a short distance away the relations may be reversed. In most such ores there is evidence of only one generation of A or of B. Such cases usually indicate simultaneous crystallization of A and B. Such an interpretation is often supported by chemical evidence, as for example in the case of certain intercrystallizations of cuprite and native copper formed by the oxidation of chalcocite according to some such reaction as:

$3Cu_2S + 4O_2$--- $Cu + 2Cu_2O + 3SO_2$.

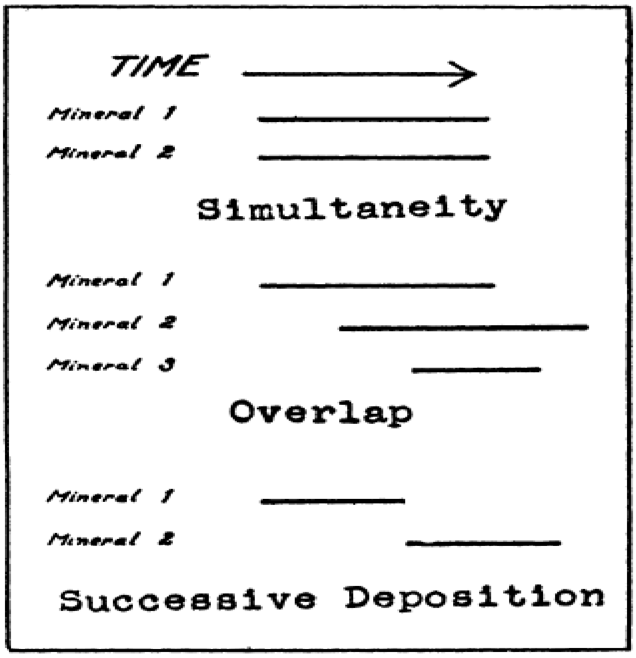
3) Mineral deposition in open-space fillings:

There are three types of mineral deposition in the open-spaces:

i. Simultaneous deposition (in which two or more minerals are formed from the beginning to the end of the process) e.g., galena-sphalerite.

ii. Overlapping deposition (in which two or more minerals have formation periods that overlap in part) e.g., sphalerite-pyrite.

iii. Successive deposition (in which the formation periods of two or more minerals succeed each other with practically no overlap) e.g., sulfide-carbonates.



4) Replacement:

As the mineral which is being replaced must have formed before the secondary mineral which is replacing it, the paragenetic sequence is obvious. In some cases, remnants of the original phase may be present, showing an island texture consisting of residual fragments of the first mineral in a matrix of the later phase.

5) Exsolution:

Exsolution intergrowths provide the best evidence that simultaneous deposition has taken place.

- If cooling has been very slow, it may have allowed the complete unmixing and segregation of the precipitated minerals. This may take place if the concentration of the exsolved mineral was low, when small amounts of the exsolved mineral can occur as thin films in the grain boundaries of the host as well as at the contact of the host with transparent gangue minerals. Such textures indicate simultaneous deposition.

- In the case of ilmenite-hematite, the deposition of host and guest minerals is partially simultaneous. The solid solution was enriched in ilmenite with considerable concentrations of iron, and hence, the host first builds up its own crystal outlines and then hematite is exsolved along certain crystallographic directions. The formation of hematite does not occur after the separation and solidifying ilmenite, so, this kind of deposition is not a successive deposition.

6) Deformational twinning:

Deformational twinning may occur at any stage and can indicate that varying deformational processes were active during the crystallization history of the deposit. It may indicate an early deformation, if present in one or more primary mineral phases, or if located in minerals of all stages it shows that deformation post-dates mineral deposition.

7) Cross-Cutting relationships:

This is possibly one of the most important aspects in erecting a paragenetic sequence, and can be one of the easiest to observe. If one feature cuts another, then it must be younger than that which it cuts. The feature may be a vein, veinlet, fault (infilled or not) or a sedimentary structure, all of which frequently occur in syngenetic ores.

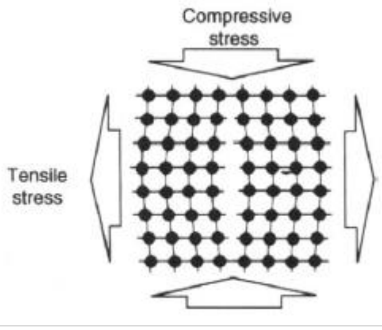
Lecture#9: Applied Ore Microscopy in Ore Dressing

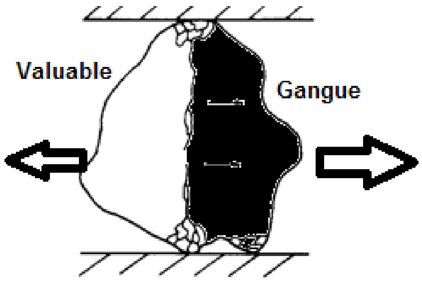
9. Applied Ore Microscopy in Ore Dressing

Ore minerals are valuable commodities (e.g. Fe, Zn, Pb, Au, W….etc) having a wide range of industrial applications. The concentration of a specific precious metal in an ore mineral "ore mineral grade" is greatly affected by the associated percentages of gangue minerals, which in turn convert the ore minerals from a high-grade commodity to a low-grade commodity. For example, titanium ore "ilmenite" in the low-grade case contain 36wt% TiO_2 along with 28wt% Fe_2O_3. Such ore grade in unsuitable for the extraction of titanium and need further purification to remove the iron impurities. So, the mined ore minerals may require specific processes, by which the valuable minerals are separated from the associated gangues. Here we can define the term ***ore dressing*** as all physical and chemical processes by which ore mineral are concentrated and separated from gangue minerals. *The ore dressing is subdivided into three main stages:*

i. Mineral comminution and size reduction:

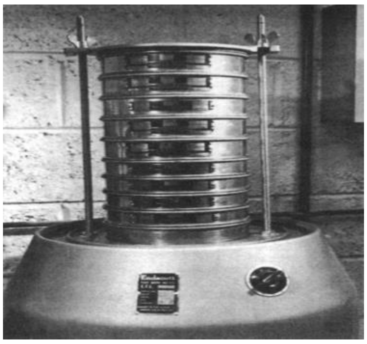
Before concentration, the interlocking between valuable minerals and gangues must be broken to obtain liberated valuable grains suitable for the subsequent beneficiation processes. This can be done by comminution, the size reduction of an ore deposits through crushing "up to -1mm" and milling "up to 74µm). The mechanism of comminution involves break down the crystal lattice of a given mineral by two applied stresses: *compressive stress and tensile stress.*





ii. Particle Size Analysis:

Particle size analysis is of great importance in determining the quality of grinding and in establishing the degree of liberation of the values from the gangue at various particle sizes. In the separation stage, size analysis of the products is used to determine the optimum size of the feed to the process for maximum efficiency methods.



(1) Sieve size range (µm)	(2) Sieve fractions wt (g)	(3) wt %	(4) Nominal aperture size (µm)	(5) Cumulative % undersize	(6) oversize
+250	0.02	0.1	250	99.9	0.1
−250 to +180	1.32	2.9	180	97.0	3.0
−180 to +125	4.23	9.5	125	87.5	12.5
−125 to +90	9.44	21.2	90	66.3	33.7
−90 to +63	13.10	29.4	63	36.9	63.1
−63 to +45	11.56	26.0	45	10.9	89.1
−45	4.87	10.9			

iii. Mineral Separation and Concentration:

The separation of valuable minerals from the associated gangues usually results in:

- ***Concentrate*** *"rich in the liberated valuable grains"*
- ***Middlings*** *"mainly locked particles of valuable and gangues".*
- ***Tailings****" rich in the liberated gangue minerals".*

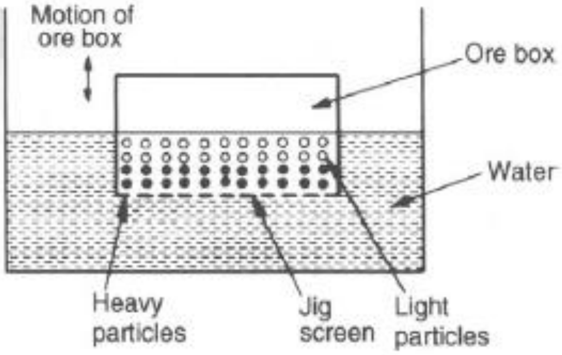
The separation processes can be classified into physical and chemical operations depending on certain physical and chemical properties of the minerals.

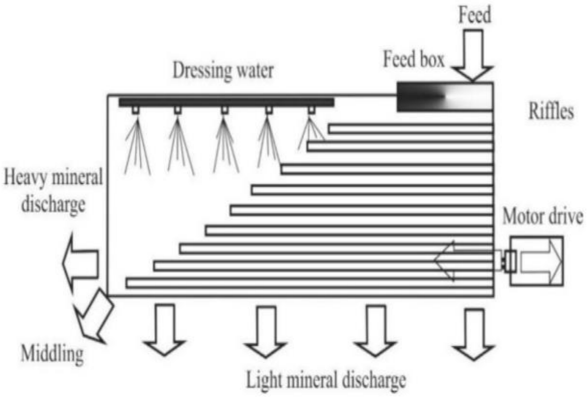
- **The physical beneficiation methods:**
  - ✓ **Hand sorting:** Separation based on optical and physical properties "e.g. hand picking of Abu-Ghalaga ilmenite and Ghorabi barite minerals".
  - ✓ **Gravity separation:** Separation based on differences in density/or specific gravity between the minerals. The gravity separation is controlled by what so-called gravity criterion "must be equal 2.5 or more for efficient separation":

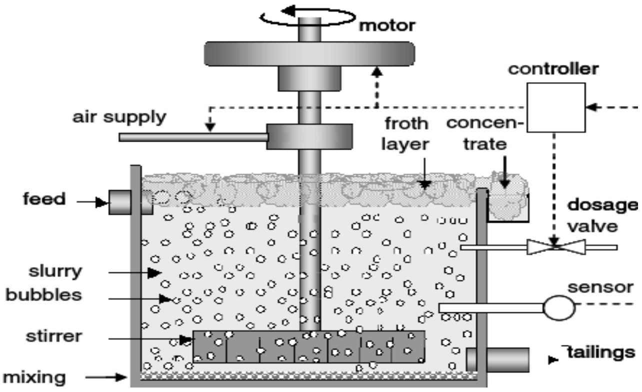
$$\frac{D_h - D_f}{D_l - D_f}$$

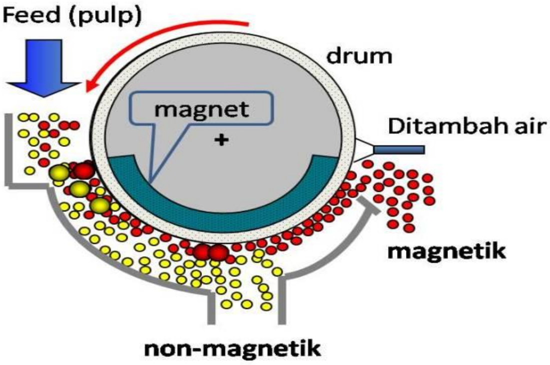
Dh=specific gravity of the heavy mineral **Dl**= specific gravity of the light mineral, **Df**= specific gravity of the surrounding medium

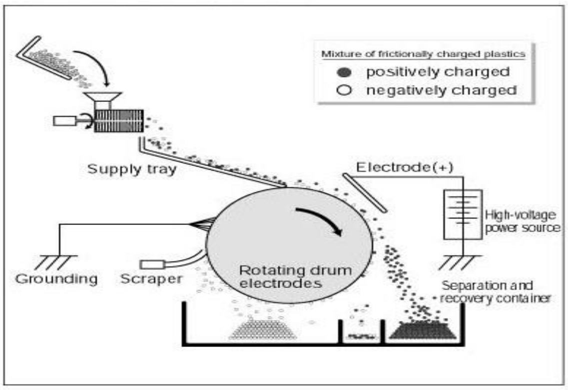
- ✓ **Froth floatation**: Separation depends on the surface properties of mineral grains "hydrophobic and hydrophilic minerals". The hydrophilic minerals can be wetted by water, while the hydrophobic cannot. So, the hydrophobic grains can be separated by attaching to air-bubbles flowing through the floatation cell and arising upward.
- ✓ **Magnetic separation**: The separation of valuable from gangues relies on their magnetic properties, and hence, minerals in general are separated into magnetic fraction and non-magnetic fraction.
- ✓ **High-tension separation**: It uses the difference in the electrical conductivity of minerals to yield conductive minerals and non-conductive minerals.











- **The Chemical Beneficiation Methods:**

This beneficiation type mainly depends on the chemical properties of minerals "e.g. the reaction with acids and bases". For example, the intergrowth of hematite and barite can be separated into iron fraction and barite fraction using 4M HCl solution in which hematite dissolves, leaving the inner barite behind. Also, the silica content of a siliceous iron ore can be reduced using concentrating solutions of NaOH, with which silica reacts to form soluble sodium silicate.

The application of ore microscopy in ore dressing is an essential step to gather information related to:

- ✓ *Identify the mineral species of both valuable and gangue minerals and their quantities*.

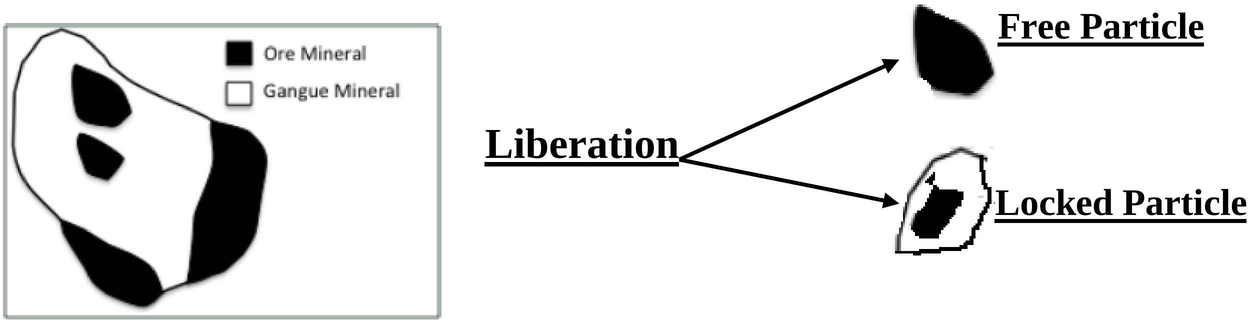
For example, if the microscopic investigation of a given ore reveals that the main mineral composition consisting of iron minerals "hematite &limonite" along with barite as a gangue mineral, the beneficiation method can be suggested as high-intensity magnetic separation due to the quite difference of the magnetic susceptibility of iron and barite minerals. Also, if the contained iron minerals are represented by magnetite "not hematite", the wet low-intensity magnetic separation is preferred here. Also, the microscopic investigation determine the quantity of each mineral "e.g. by counting", and hence it is easy to know the dominant target mineral and the gangue mineral. For more instances, if the amount of barite is 70% and that of hematite is 30%, the hematite will be regarded as gangue mineral, not as valuable, and vice versa.

- ✓ *The nature of the mineral interlocking between valuables and gangue.*

The study of the intergrowths and interlocking types between valuable minerals and gangues contributes greatly to estimate the extent to which the liberation occurs. ***The term liberation*** refers to the separation degree of valuable grains from gangues during comminution and concentration processes. After liberation, we have two main products:

Free particles: consisting only of valuable or gangue mineral.

Locked particle: consisting of both valuable and gangue minerals.



The liberation degree of mineral particles= No. free particles/No. total*100.

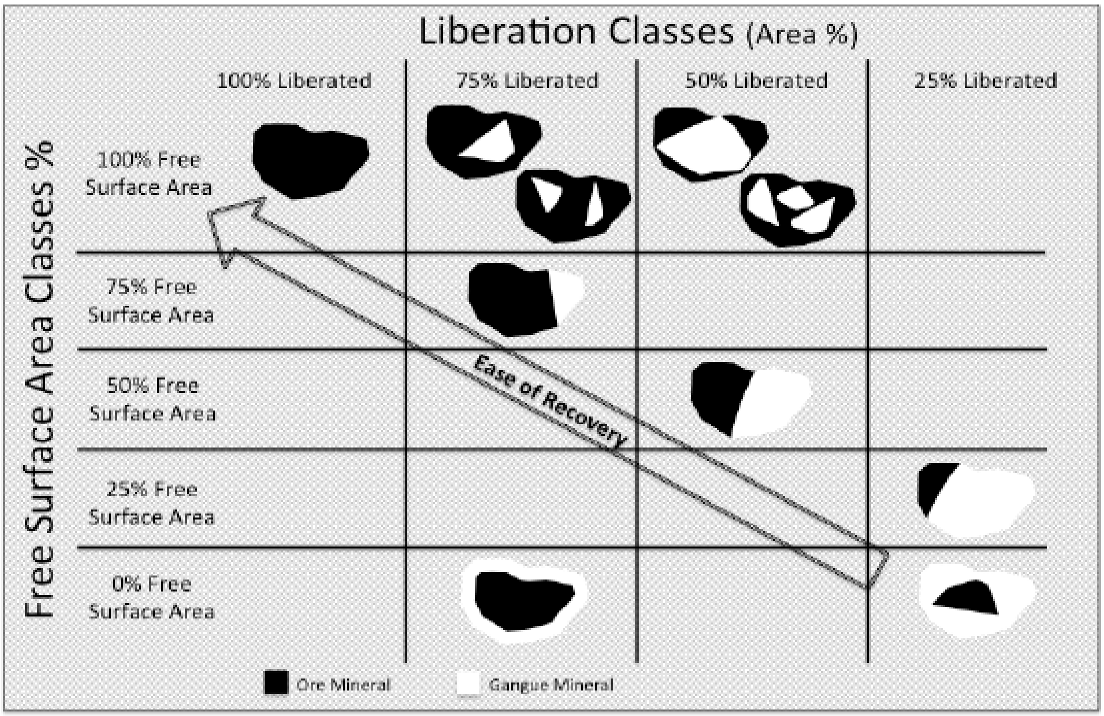
Example:

The microscopic investigation of sandy glauconite deposits revealed that the glauconite pellets occur as oval to sub-oval grains and interlock with quartz through curved and rectilinear grain boundaries. The comminution process of glauconite deposit by jaw crusher is monitored through a set of standard sieves as showing in the following table: **Estimate the liberation degree of glauconite grains.**

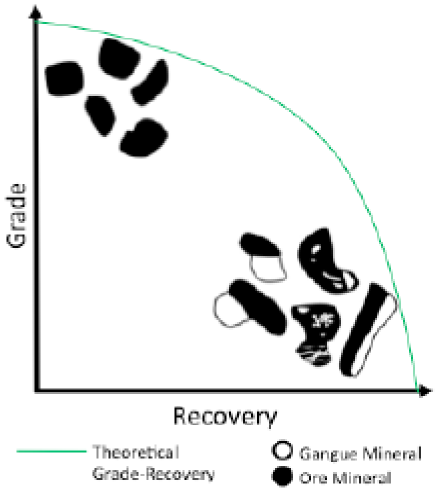
Sieve fraction "µm"	Wt "gm"	Glauconite	Locked particles
-1+500	20	250	175
-500+250	35	340	230
-250+125	60	380	176
-125+75	45	195	230
-75	15	85	190

From another perspective, the crushed ore particles can be classified depending on the free surface area "the outer periphery of a mineral particle" into:

- *100% free surface area.*
- *75% free surface area.*
- *50% free surface area.*
- *25% free surface area.*
- *0% free surface area.*



- The free surface area of a mineral particle is accessible for magnetic field or bubbles in the floatation cell.
- The increased free surface area does not mean high liberation degree.
- With increasing the free surface area, high mineral recovery can be achieved.
- With increasing the mineral recovery, the mineral grade decrease.
- The efficient recovery can be reached with increasing both the liberation degree and the free surface area.

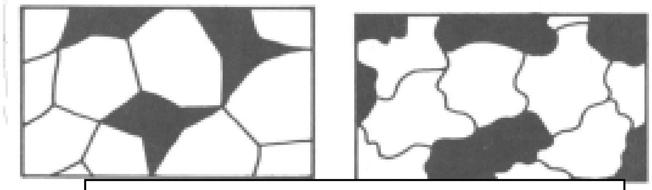


Calculation the metal recovery

Suppose the feed material, assaying $f\%$ metal, separates into a concentrate assaying $c\%$ metal, and a tailing assaying $t\%$ metal, and that C is the fraction of the total feed weight that reports to the concentrate, then:

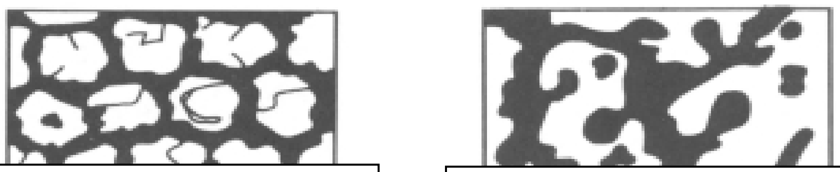
$$Rm = \frac{100Cc}{f} \tag{1.2}$$

Several intergrowths may occur between the investigated ore and gangue minerals and between different ore minerals that may eventually require separation.



Rectilinear, straight, and curved margins

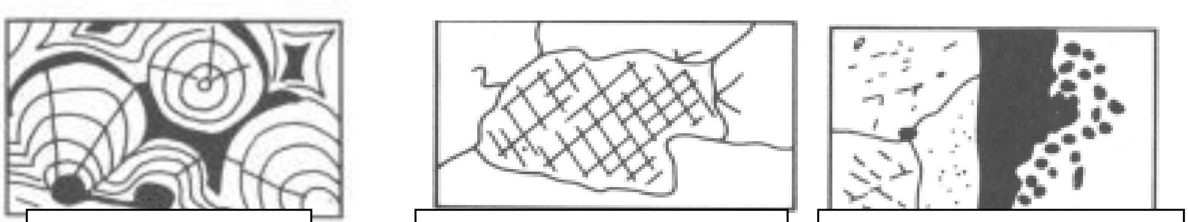
Fig.1: Complete liberation is fairly easy



Cement and coating interlocking

Replacement along numerous veinlets

Fig.2: Complete liberation is fairly difficult



Concentric locking

Reticulate "net-like locking

Dissemination interlocking

Fig.3: Complete liberation is impossible

- ✓ *Estimating the particle size of both valuables and gangues for liberation.*

The estimation of particle size using microscope can be performed in the case of the granular ore minerals/ or industrial minerals. This is useful to determine the size fraction at which the valuable grains are mostly concentrated. For example, if we have chromite grains (1mm-800µm in diameter) intergrown with olivine (500-250µm in diameter) and Ca-feldspar (300-150µm in diameter), the chromite grains are expected to be concentrated at the coarse size fraction and the gangues at finer fractions after adequate crushing. Some industrial minerals are not necessary to be crushed for achieving liberation. For example, glauconite deposits are mostly cemented by clay matrix, and hence, wet sieving can be sufficient to concentrate the glauconite grains at specific size fraction.

✓ *The extent to which sieving is effective in ore up-grading.*

The microscopic investigation of the crushed and sieved ores can indicate the percentage of both free particles and locked particles for each size fraction. This is followed by chemical analysis for each size fraction to monitor the effect of sieving on the up-grading of valuable minerals.

✓ *Choice the suitable beneficiation method.*

Depending on the mineralogical and textural investigations, it is possible to suggest the suitable beneficiation method. For example, if we have ilmenite deposit contains hematite in the form of exsolution texture, reduction-roasting of hematite to magnetite followed by wet low-intensity magnetic separation is suggested. However, the exsolution interlocking between ilmenite and hematite makes the liberation on crushing and grinding difficult, consequently the percentage of locked particles will be high to give sufficient recovery of ilmenite. So, the chemical beneficiation of such ore using HCl for removing iron impurities is preferred here.

Questions to be answered

Choose the Correct Answer for Each Sentence

1. Pentalendite commonly occurs as a…………mineral.

(A) magmatic. (B) hydrothermal . (C) metamorphic . (D) sedimentary.

2. Among factors that determine whether a given mineral is considered an ore mineral is………

(A) the type of separation (B) the separation efficiency (C) the metal concentration (D) the mineral type.

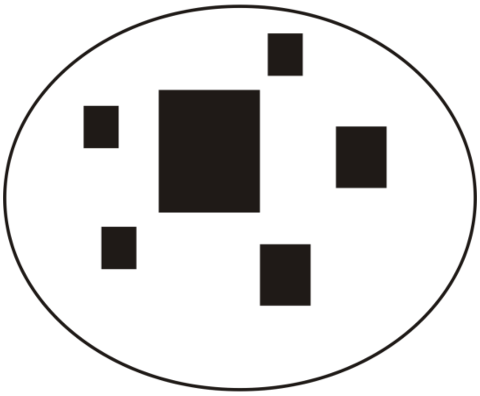
3. The ore microscope can be used to study……………...

(A) sulfides & oxides. (B) silicates. (C) carbonates . (D) all the mentioned groups.

4. Once the visible wavelengths are brought to the reflector they are subjected to………..

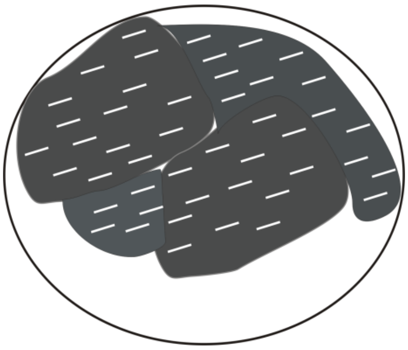
(A) reflection (B) transmission (C) refraction . (D) reflection & transmission

5. The acquired image of pyrite cubes is taken here by……………



(A) hand lenses. (B) petrographic microscope. (C) scanning electron microscope . (D) ore microscope.

6. The attached figure shows exsolved lamellae of ilmenite enclosed within hematite grains. So, the parent solid solution was……………

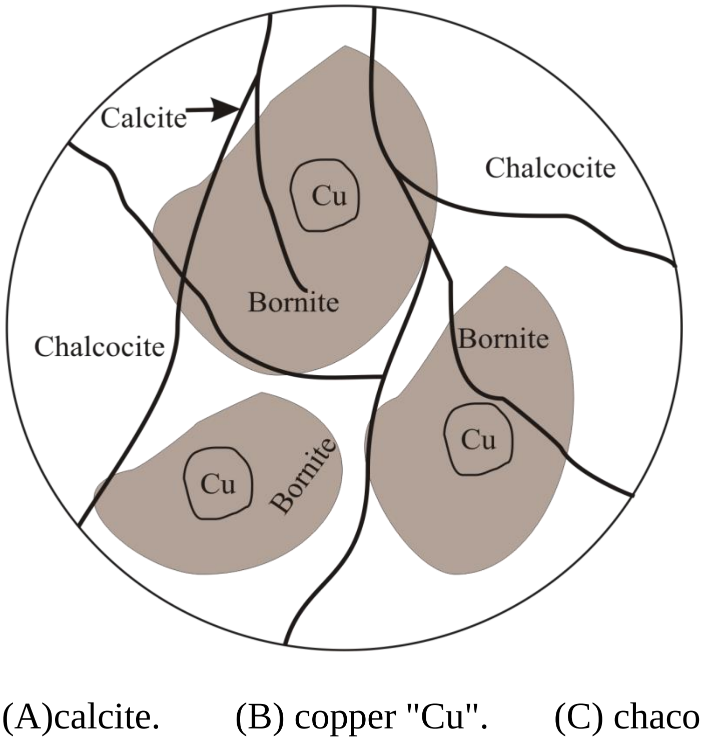


(A) chemically opened rich in Fe. (B) chemically closed rich in Ti. (C) chemically closed rich in Fe. (D) chemically opened rich in Ti.

7. Pyritization of plant cells occurs through what so-called……………

(A) metamorphism (B) metasomatism. (C) open-space filling. (D) etching.

8. The attached figure illustrates mineral associations of chalcocite, bornite, and copper "Cu" cut by calcite veinlets. The early-formed mineral will be…………



(A)calcite. (B) copper "Cu". (C) chacocite. (D)bornite.

9. The replacement of pyrite under chemical weathering leads to form………

(A) hematite. (B) goethite. (C) martite. (D) magnetite.

10.Comb-like structure occurs in minerals like…………

(A) pyrite. (B) galena. (C) quartz. (D) olivine.

11.The overlapping deposition of an ore mineral occurs………. the deposition of another one

(A) during. (B) after. (C) before. (D) simultaneously.

Part Two:

Determine the true and false statement of the following

1. Feldspars are considered to be ore minerals for Al commodity.
2. Hematite is exploited as an ore mineral of Fe commodity and always characterized by metallic lustre.
3. Ore minerals can be divided depending on the bonded, negatively charged groups.
4. Achromatic microscopic lenses are cheap and used to eliminate the chromatic aberration in the colored imaging.
5. Both polarizer and analyzer have the same task for the incident and reflected light.
6. Both plaeochroism and isotropism refer to color changes with stage rotation.
7. The internal reflection is observed in ore minerals and rock-forming minerals.
8. The cumulus and nodular textures of chromite are created by the same mechanism.
9. Exsolution textures are an indication for a simultaneous deposition.
10. The colloidal dispersion is due to the high surface area/mass ratios.
11. To say a mineral replacement, the dissolution and precipitation processes must simultaneously take place.