

Study of Ore Minerals in Reflected Light

The Ore Microscope

The basic instrument for petrographic examination of 'ore' minerals or 'opaque' minerals is the ore microscope, which is similar to a conventional petrographic microscope in the system of lenses, polarizer, analyzer and various diaphragms. An ore microscope however, differs from a petrographic one in that it has an incident light source rather than a substage transmitting one, which allows examination of polished surfaces of opaque minerals under reflected light.

Components of the Ore Microscope: Though there are numerous models of ore microscopes, there are certain basic elements common to all. These are:

1. The frame or stand which carries the other components.
2. A circular stage, graduated in degrees, that can be rotated through 360°, attached to the frame. This is usually equipped with a rack-and-pinion movement permitting it to be moved up and down for focusing the specimen, and sometimes a mechanical stage equipped with X and Y movement for systematic examination and point counting of grains in the specimen.
3. Objective lenses which are interchangeable and may be classed in terms of type (achromat, apochromat or fluorite). Their magnification, numerical aperture, and whether they are for oil immersion or air usage is indicated.
4. The ocular serves to enlarge the primary image formed by the objective and render it visible to the eye. Oculars commonly contain cross hairs, a micrometer or a grid with a fixed rectangular pattern used for measuring particle sizes.
5. The standard illuminating system consists of two lenses, two or three diaphragms, a polarizer and an incandescent lamp of 6-12 V and 15-100 W, or an LED. The illuminator aperture diaphragm restricts the field of view and stray scattered light. The illuminator field diaphragm controls the angle of the cone of light incident on the specimen and should be set to just enclose the field of view (this restricts the light to the most parallel rays, minimizes elliptical polarization and maximizes contrast). In many microscopes a third diaphragm helps sharpen the image.
6. The reflector is a means by which light is brought vertically onto the polished surface. Reflectors are of two types: the glass plate reflector (a partial mirror) and the half-field prism (see figure 1). Both types have their advantages and disadvantages. Many microscopes have both types mounted on a horizontal slide so that either may be used.
7. The polarizer is usually positioned within the illuminating system between the lamp and the collector lens but may also be located between the diaphragms. It is usually a calcite prism or a polaroid plate that renders light linearly polarized in a N-S orientation. The analyzer is a device similar to a polarizer but is positioned between the objective and ocular with its vibration directions perpendicular to those of the polarizer.

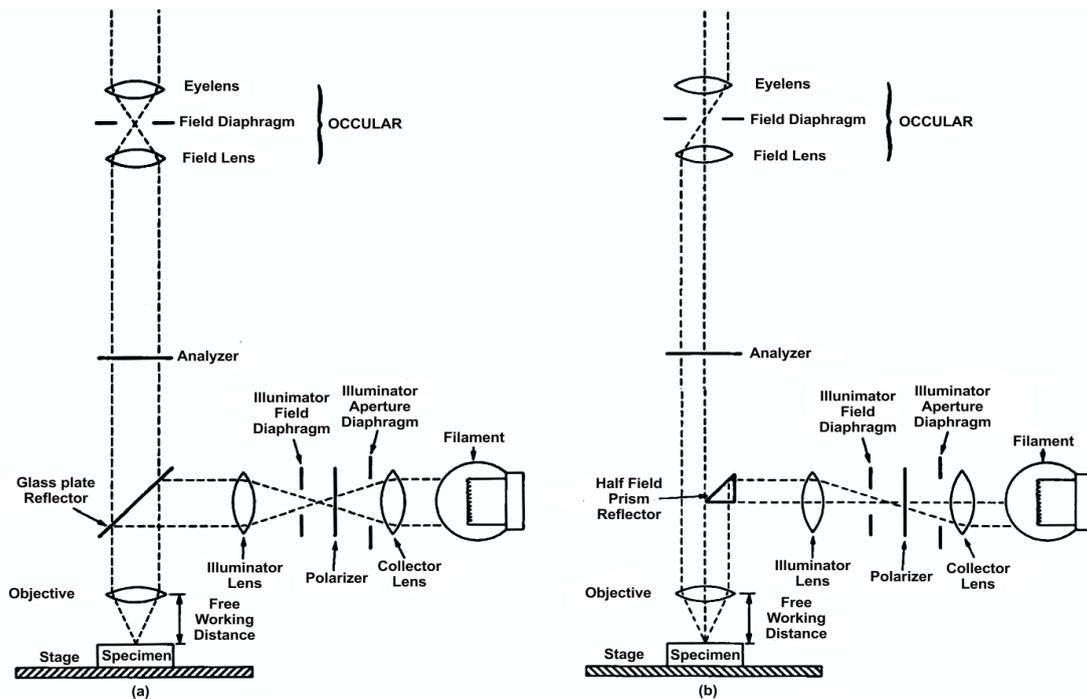


Figure 1: Schematic diagram through an ore microscope illustrating essential components and the path of light through the system involving (a) the whole field glass-plate reflector and (b) the half-prism reflector.

Accessories of the Ore Microscope:

Monochromators: The visible range of light lies between 400 to 700 nm, whereas the operable range of most microscopes extends several hundred nm above and below this range. Since the optical properties of minerals vary as a function of wavelength, it is sometimes necessary to provide light of a particular wavelength. This is commonly achieved by the use of:

- a) Fixed monochromatic interference filters which consist of a glass plate on which alternating layers of low reflecting transparent dielectric substances and higher reflecting semitransparent metal films or dielectrics of high R.I. are deposited. Light passing through these filters is not truly monochromatic but lies within a narrow band, usually less than 15 nm.
- b) Continuous-spectrum monochromators are interference filters for which the wavelength of transmitted light varies continuously along the filter. A window, the width of which may be varied to control the passband width, may be slid along the monochromator to whatever wavelength is desired, thus providing monochromatic light over the entire visible range and even beyond.

Photometers: These are used to measure the reflectance of minerals. Most of them consist of a photomultiplier tube that has a high sensitivity throughout the visible spectrum. Photometers must be used in conjunction with stabilized light sources, high quality monochromators, and reflectance standards.

Adjustment of the Microscope

For accurate observation of optical properties, a proper adjustment of various elements of the microscope is extremely important. Although most adjustments are done at the factory, certain others must be made by the ore microscopist.

1. Place a polished section on the stage and centre the objective / stage properly.
2. Replace the ocular with a pinhole eyepiece and close down the aperture diaphragm until its image is a small circle of light. Rotate the reflector until the image of the aperture diaphragm is at the centre of the field.
3. Rotate the stage. If the image does not move, the polished section is level. If the image moves, the section should be leveled before proceeding.
4. Centre the light source. Attach a low power objective to the microscope, throw out the analyzer and remove the ocular. The field of view should be evenly and brilliantly illuminated. If peripheral shadows appear, the light source is off centre and must be adjusted by means of the centring screws.
5. Check the orientation of the axis of the reflecting device. Focus with a low power objective on a leveled polished surface. Close down the iris diaphragm until brilliant illumination of the field is restricted to the smallest possible bright spot. Now rotate the reflector on its axis. The bright spot should move across the field in a path precisely parallel to the N-S cross-hair of the ocular. If the path is at an angle, the axis of the reflector is not horizontal and needs correction.

Optical Properties of Ore Minerals in Polished Sections

The optical properties of ore minerals determinable under the microscope fall under two categories:

1. Properties observed in plane polarized light (without analyzer): These include color, reflectivity, bireflectance (= absorption, pleochroism or reflection pleochroism).
2. Properties observed between crossed nicols: These include isotropism vs. anisotropism, polarization colors and internal reflections. Besides these, other rotation properties viz., polarization figures and phase differences may be determined.

Color: Most ore minerals have colors ranging from pure white to gray, and only a few have definite tints of the spectral colors. The human eye has a poor memory for colors but at the same time it has a marvelous sensitivity to very slight differences in hue or brightness of adjacent objects. The apparent color of a mineral as seen under the microscope depends upon a number of factors, and as such is of limited diagnostic value by itself. Factors affecting the apparent color of a mineral are:

- a) Perceptions.
- b) Color of surrounding minerals.
- c) Type of illumination.
- d) Tarnishing and incorrect polishing.
- e) Index of refraction of the immersion medium.

TO OBSERVE COLOR

- IFD (Illuminator Field Diaphragm) and IAD (Illuminator Aperture Diaphragm) opened wide
- Low power objective
- High voltage for light of good intensity
- Polarizer inserted, Analyzer withdrawn

Reflectivity: is the ratio of the intensity of light reflected by a mineral to the intensity of light incident upon it, expressed in per cent (R or R%). Reflectance of minerals varies as a function of the following:

- a) Crystallographic orientation of the polished surface relative to the vibration directions of linearly polarized incident light.
- b) Wavelength of light.
- c) Angle of incidence.
- d) Degree of polish.

Quantitative reflectance measurements are done with various types of photometers, but rough visual estimates may be made and minerals in a section may be arranged in an order of increasing or decreasing reflectance. Eg. Quartz (5%), magnetite (20%), galena (43%), pyrite (55%).

Bireflectance: Most minerals of the non isometric groups show changes in reflectance or color (or tint) or both, when sections of certain orientations are rotated under plane polarized light. These properties are collectively termed bireflectance. In some literature, bireflectance refers only to change in reflectivity and reflection pleochroism is the term used to describe a change in color. All sections of the cubic minerals and basal sections of the hexagonal and tetragonal crystals do not exhibit these properties. In addition to noting this property it is

usual to note the intensity (e.g. very strong, strong, moderate, weak, very weak) with which these properties are exhibited. The following are some examples of bireflecting minerals:

Strong - graphite, molybdenite, covellite, stibnite, valleriite.

Moderate - marcasite, hematite, niccolite, cubanite, pyrrhotite.

Weak - ilmenite, enargite, arsenopyrite.

Weak or very weak bireflectance in minerals may be identified by closely observing adjacent grains.

TO OBSERVE BIREFLECTANCE

- IFD and IAD opened wide
- Polarizer inserted, analyzer withdrawn
- Low power objective
- High voltage

Anisotropism: Polished sections of non-isotropic minerals, when rotated through 360° under 'crossed' nicols, will show either a) complete darkness, or b) faint illumination with no change in intensity or color of illumination. Such minerals are termed isotropic. Minerals crystallizing in the non-isometric systems will show a change in the intensity of illumination or color of illumination (or both) in white light. Such minerals are termed anisotropic. Sections of certain special orientations of anisotropic minerals (e.g. the basal sections of hexagonal and tetragonal crystals) may be isotropic. As with pleochroism, the anisotropy can range from a maximum to zero depending upon the orientation of the section, and therefore the terms very weak, weak, moderate, strong and very strong are used to describe it. Anisotropy is best observed under intense illumination using a plane glass reflector and a low power ocular. In cases of weak anisotropy, the effects may be detectable only when a number of adjacent grains of a mineral are minutely examined while rotating the stage. Observation of anisotropy may be more easily accomplished by either a) throwing the analyzer slightly off from the precise crossed position, or b) leaving the stage stationary and slowly rotating the analyzer $5-10^\circ$ back and forth through its crossed position.

NOTE: Fine parallel scratches of improper polishing or careless buffing can produce effects similar to pleochroism and anisotropy

Polarization colors: The change in color of a mineral during rotation under crossed nicols produces a beautiful effect. These are the polarization colors. The polarization colors of certain minerals are highly characteristic and extremely useful in identification. However they are used less than they deserve to be for several reasons:

- a) The colors are constant only if the nicols are precisely crossed, which is rarely the case.
- b) Polarization colors appear different to different observers, hence the difficulty in applying precise color terms.
- c) The intensity and hue of polarization colors varies from microscope to microscope.
- d) Constant illumination is necessary for consistent results.

TO OBSERVE ANISOTROPY/POLARIZATION COLORS

- Polarizer and analyzer inserted
- Intense illumination
- Low power objective (10X)
- IFS may be closed down to cut out periphery of field

Internal Reflections: Translucent minerals, when observed under reflected light, allow light to penetrate beneath the surface and be reflected back to the observer from cracks, crystal boundaries, cleavages and other flaws within the crystal. Such light will appear as diffuse areas or patches known as internal reflections. Although visible in plane polarized light, internal reflections are best seen under crossed nicols and intense illumination using oil immersion and high power magnification. They are best seen at the edges of grains or in fine grains. It is important to note that many grains of a mineral that could show internal reflections may not exhibit them. Both the occurrence and colors of internal reflections are of diagnostic value. The following are some examples:

Sphalerite	Yellow to brown (sometimes red to green)
Cinnabar	Blood red
Proustite-pyrargyrite	Ruby red
Rutile	Clear yellow to deep red-brown
Anatase	Blue
Azurite	Blue
Malachite	Green
Cassiterite	Yellow brown to yellow
Hematite	Blood red
Wolframite	Deep brown
Chromite	Very deep brown

TO OBSERVE INTERNAL REFLECTIONS

- IAD opened
- IFD opened or closed down
- Nicols crossed 40X or 10X objective
- Cedar oil immersion (R.I. = 1.515) strongly recommended for use with 100X objective
- Large grains generally show internal reflections best

Physical Properties of Ore Minerals in Polished Sections

The physical properties of ore minerals observed in polished sections are of great assistance in mineral identification, and hence their study is routine in ore microscopy. The most useful and easily observable physical properties are crystal form and habit, cleavage and parting, twinning, zoning, inclusions and intergrowths and hardness.

Crystal Form and Habit: Some ore minerals, particularly the harder ones viz., pyrite, hematite, wolframite, arsenopyrite, cobaltite and magnetite have a remarkable power of crystallization and develop well formed crystals even under adverse conditions. The softer minerals, e.g. chalcopyrite, galena, tetrahedrite and pyrargyrite have somewhat lower powers of crystallization and form crystals only in open spaces. Since a polished surface shows two dimensional sections rather than whole crystals, the shape as seen in a polished section depends upon the manner the crystal is intersected by the polished surface. Thus cubes appear rectangular or triangular of various shapes; hexagonal prisms appear hexagonal or rectangular, etc., so that the crystal form must be mentally reconstructed from observations of a number of crystals of a particular mineral.

Terms used in mineralogy e.g. cubic, octahedral, acicular, radiating, columnar, bladed, tabular, foliate, micaceous, concentric, colloform, prismatic, fibrous, etc. are appropriate for describing crystal form and habit as seen in polished sections.

Zoning: Many ore minerals exhibit zonal growth in the form of concentrically shelled structure indicating deposition in successive layers around a nucleus. The shells may be few or many and thin or thick. Zoning is sometimes visible in ordinary light due to color contrasts, physical discontinuities or zonally arranged inclusions. In other cases zoning is visible only in crossed nicols or after etching with an appropriate chemical. Zoning in minerals is due to either of the following reasons:

- a) Pauses in deposition
- b) changes in the rate of growth
- c) Simultaneous crystallization of more than one mineral at certain stage / stages.
- d) Variation in the composition of successively deposited layers.

Galena, sphalerite, pyrite, stibnite, cobaltite, safflorite and arsenopyrite are some of the many minerals that show zonal structure.

Cleavage and Parting: In polished surfaces the cleavages of minerals are not as well developed as in thin sections. Cleavage or parting is evident in the form of one or more sets of parallel, distinct or indistinct cracks. Minerals may exhibit one to three sets of cleavages depending upon the number of sets present and the orientation of the polished surface with respect to these. The presence of three or more sets of cleavages may give rise to triangular pits usually arranged in rows parallel to one set. Such pits are characteristic of galena, and may also be present in magnetite, pentlandite, gersdorffite, etc. A prismatic cleavage gives rise to diamond-shaped, triangular or rectangular patterns; a pinacoidal cleavage gives rise to a set of parallel cracks.

Cleavage of a mineral may not be evident in a well polished surface, or in minerals occurring in fine grained aggregates. It is likely to be more evident in slightly weathered ores, during the earlier stages of polishing, at the margins of grains, or after etching.

Twinning: Three major types of twinning may be observed in ore minerals seen in polished sections - growth, inversion and deformation. Twinning is best seen in anisotropic minerals

under crossed polars. In isotropic minerals it is generally not visible unless the surface is etched. It is sometimes evident from abrupt changes in the orientation of cleavages or of rows of inclusions. The crystallographic planes involved in twinning are usually not determinable in polished sections.

Nevertheless, the twin patterns in some minerals are quite characteristic e.g. “arrowhead” twins (growth) in marcasite, lamellar twins (deformation) in hematite and chalcopyrite and “oleander leaf” twins (inversion) in chalcopyrite, stannite and acanthite.

Inclusions and Intergrowths: Inclusions of one or more minerals in another is a very common feature of ores. The characteristics of inclusions depends to some extent on the mode of formation of the guest and the host. They may have either of the following modes of formation:

- a) Grains of a mineral accidentally included during growth of the host.
- b) Remnants of a pre-existing mineral that was replaced by the host.
- c) Result from simultaneous deposition of a mineral with the host.
- d) Products of breakdown (exsolution) of a solid solution into two components.

In so far as the mode of occurrence is concerned, inclusions may:

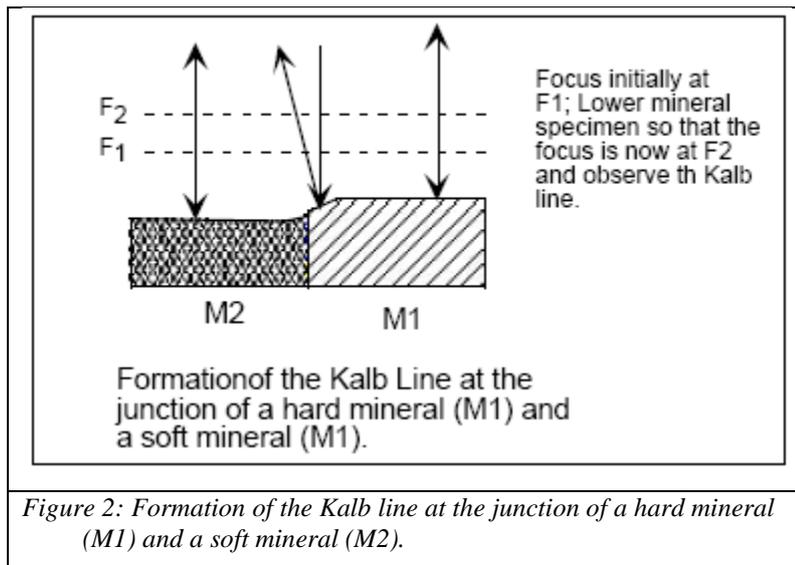
- a) Occur singly or in groups
- b) Be regular (signifying a control of crystallographic planes of the host over the guest) or highly irregular in shape.
- c) Be large or very minute (submicroscopic).
- d) Be evenly distributed through the host (signifying control of crystallographic planes of guest on the growth of host) or unevenly distributed.
- e) Being abundant in certain bands, signifying a zonal growth structure of the host.

Intergrowths refer to simultaneous deposition of one mineral with another. The term also covers graphic and subgraphic arrangements of two minerals, or exsolutions in which the two minerals are intimately associated and neither can be said to be the host. A knowledge of inclusions is useful in deciphering the paragenetic sequence while that of intergrowths in identification since the number of mineral combinations which may occur as intergrowths is limited. This is particularly true of exsolution intergrowths.

Hardness: The term hardness as used in ore microscopy refers to a number of phenomenon. Three types of hardnesses are particularly important – polishing, scratch and microindentation. It is important to note that these three forms are not entirely equivalent, being the response to different kinds of deformation or abrasion. Only the polishing hardness shall be discussed here.

Polishing hardness is the resistance of a particular mineral to abrasion 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. The determination involves a simple test using the Kalb light line, a phenomenon analogous to the Becke line used in transmitted light (see figure 2).



The procedure is as follows:

- Focus on a clear boundary between two mineral grains.
- Close the aperture diaphragm partly.
- Raise the microscope tube slowly (or lower the stage in microscopes where focusing is done by moving the stage) so that the sample begins to go out of focus as the distance between the sample and objective is increased.
- Observe the “line” of light which will move from the boundary towards the softer mineral, provided there is appreciable relief.

Usually the polishing hardness of an unknown mineral is compared to one or several known minerals. This permits the mineral to be arranged in a sequence of increasing or decreasing polishing hardness with other known minerals, and can be of great assistance in mineral identification.

TO OBSERVE THE KALB LINE

- Moderate illumination
- IFD opened wide IAD closed
- 10 X or 40 X objective used
- Polarizer inserted, analyzer withdrawn