CRYSTALLOGRAPHY

UNIT IV

UNIT-IV: SYLLABUS

OPTICAL MINERALOGY : Light: Corpuscular, electromagnetic and quantum theories. Ordinary light and plane polarized light. Refractive index an its determination: Relief method, Becke line, Central illumination, and Oblique illumination methods. Isotropism, isotropic minerals and isotropic ray velocity surface. Behaviour of light in isotropic minerals. Petrological Microscope and its parts-optical accessories and their uses:Quartz wedge, Gypsum plate and Mica plate. Study of Isotropic minerals using the petrological microscope: properties of isotropic minerals under parallel Nicol conditions.

LightCorpuscular

A source of light continuously emits tiny elastic particles called corpuscles. These particles or the corpuscles moves with high velocity as that of light and gets scattered in all directions of light. This theory says that the velocity of light changes with the change in density of the medium in which it is used. This theory could explain three main phenomena of light that is reflection, refraction, and rectilinear propagation of light. This theory also says that the color of light is dependent on the size of the corpuscles.
Some of the

main drawbacks of this theory
are

1) This theory could not explain the phenomena of interference, diffraction, and polarization of light etc.
2) According to this theory the velocity of light in denser medium is greater than the velocity of light in rarer medium but this is proved wrong later
3) This theory assumes that the source of light looses the mass as it emits

corpuscles; but not such determent in mass of the source of light is detected.
4) This theory proposes that velocity of the corpuscles increases as the temperature of the source increases as the temperature increases experiments have proved that the velocity of light is independent of temperature.

Electromagnetic

The electric and magnetic fields in a electro magnetic wave are continuously varying with respect to time and space. At any instant electric and magnetic fields are perpendicular to each other and also perpendicular to the direction of light. The electro magnetic wave is a transverse wave. At every point in the wave at a given instant of time the electric and magnetic field strengths are equal. The velocity of propagation of electro magnetic wave depends on the electric and magnetic properties of the medium.

The main drawback of this theory is it failed to explain the photo electic effect and Compton effect. Electro magnetic theory also failed in explaining the black body radiation

Quantum theories

According to this theory, light energy is released from source discretely in the form of energy packets of specific frequencies called photons or quanta. Photons are propagated as waves and if necessary interact with matter as particles. This phenomena of Compton effect, photoelectric effect and black body radiation. The main drawback of this theory is it could not explain how it is connected with wave nature of light.

Ordinary light

If ordinary light and not polarized light is desired, both prisms may be withdrawn from the axis of the instrument; if the polarizer only is inserted the light transmitted is plane polarized; with both prisms in position the slide is viewed in cross-polarized light, also known as "crossed nicols." A microscopic rock-section in ordinary light, if a suitable magnification (e.g. around 30x) be employed, is seen to consist of grains or crystals varying in color, size, and shape.

Plane polarized light

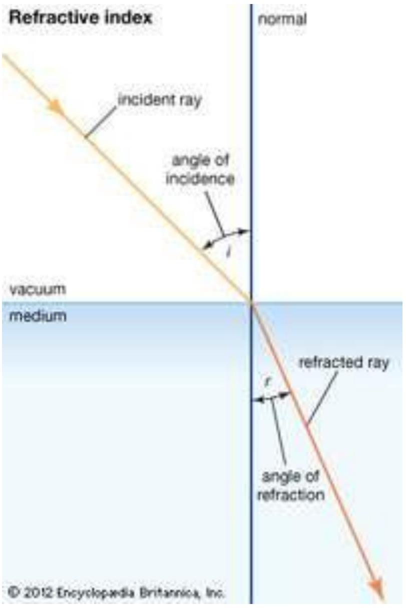
Sunlight and almost every other form of natural and artificial illumination produces light waves whose electric field vectors vibrate in all planes that are perpendicular with respect to the direction of propagation. If the electric field vectors are restricted to a single plane by filtration of the beam with specialized materials, then the light is referred to as **plane** or **linearly polarized** with respect to the direction of propagation, and all waves vibrating in a single plane are termed **plane parallel** or **plane-polarized**.

The human eye lacks the ability to distinguish between randomly oriented and polarized light, and plane-polarized light can only be detected through an intensity or color effect, for example, by reduced glare when wearing polarized sun glasses. In effect, humans cannot differentiate between the high contrast real images observed in a polarized light microscope and identical images of the same specimens captured digitally (or on film), and then projected onto a screen with light that is not polarized. The basic concept of polarized light is illustrated in for a non-polarized beam of light incident on two linear polarizers. Electric field vectors are depicted in the incident light beam as sinusoidal waves vibrating in all directions (360 degrees; although only six waves, spaced at 60-degree intervals, are included in the figure). In reality, the incident light electric field vectors are vibrating perpendicular to the direction of propagation with an equal distribution in all planes before encountering the first polarizer.

The polarizers illustrated in are actually filters containing long-chain polymer molecules that are oriented in a single direction. Only the incident light that is vibrating in the same plane as the oriented polymer molecules is absorbed, while light vibrating at right angles to the polymer plane is passed through the first polarizing filter. The polarizing direction of the first polarizer is oriented vertically to the incident beam so it will pass only the waves having vertical electric field vectors. The wave passing through the first polarizer is subsequently blocked by the second polarizer, because this polarizer is oriented horizontally with respect to the electric field vector in the light wave. The concept of using two polarizers oriented at right angles with respect to each other is commonly termed **crossed polarization** and is fundamental to the concept of polarized light microscopy.

Refractive index and its determination

Refractive index, also called **index of refraction**, measure of the bending of a ray of light when passing from one medium into another. If *i* is the angle of incidence of a ray in vacuum (angle between the incoming ray and the perpendicular to the surface of a medium, called the normal) and *r* is the angle of refraction (angle between the ray in the medium and the normal), the refractive index *n* is defined as the ratio of the sine of the angle of incidence to the sine of the angle of refraction; i.e., $n = \sin i / \sin r$. Refractive index is also equal to the velocity of light c of a given wavelength in empty space divided by its velocity v in a substance, or $n = c/v$.



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Some typical refractive indices for yellow light (wavelength equal to 589 nanometres [10^{-9} metre]) are the following: air, 1.0003; water, 1.333; crown glass, 1.517; dense flint glass, 1.655; and diamond, 2.417. The variation of refractive index with wavelength is the source of chromatic aberration in lenses. The refractive index of X-rays is slightly less than 1.0, which means that an X-ray entering a piece of glass from air will be bent away from the normal, unlike a ray of light, which will be bent toward the normal. The equation $n = c/v$ in this case indicates, correctly, that the velocity of X-rays in glass and in other materials is greater than its velocity in empty space.

Relife method

How does the mineral stand out compared to those surrounding it? Use high, medium, low relief to describe it. NOTE: Try to find a grain that is similar to the circled minerals are at the edge of the slide and in contact with epoxy, which has an index of refraction of 1.54-1.55. You can measure relief against this. Relief is low, moderate, high relative to n=1.54. Positive / negative can only be determined by looking your mineral up (+n>, -n<1.54) or by using the Becke line method

Becke line

The **Becke line test** is a technique in optical mineralogy that helps determine the relative refractive index of two materials. It is done by lowering the stage (increasing the focal distance) of the petrographic microscope and observing which direction the light appears to move. This movement will always go into the material of higher refractive index. This index is determined by comparing two minerals directly, or comparing a mineral to a reference material such as Canada Balsam or an oil of known refractive index (oil immersion).

In microscopy, a method of testing the relative refraction indices. A bright line separates substances of different refractive indices. A faceted, transparent stone is immersed in a liquid of a known refractive index and viewed through the microscope. The faceted edges of the stone travel from light to dark, when focusing down, from the liquid into the gem, hence the refractive index of the stone is higher than that of the liquid, and inverted. Mainly suitable for small fragments. Beck line, Wild method.

n grain > n liquid | *n grain = n liquid* | *n grain < n liquid*

Beck's line in three different grains to same liquid

Open image in new window

This method is standard procedure for mineralogists and petrographers and is designed for use with a petrographic microscope (Figure 4-6)*. A Becke line is a thin bright line at the interface between a transparent fragment and its immersion liquid when the relief is low (Figure 4-7).

If relief is too high, the Becke line is hard to see and may appear as a bright shadow and, if the relief is almost zero, the Becke line may appear as colored dispersion fringes. We can eliminate color fringes and negate the effects of dispersion by using a monochromatic light source, usually sodium vapor light.

Essentially all indices of refraction cited in articles and tables are values for the sodium wavelength ($\lambda = 5890$ Å). Random fragments are almost always thicker in the middle than on their edges and act as crude converging or diverging lenses, so that, by raising the focus of the microscope, the Becke line moves toward the medium of higher refraction index. The bright Becke line moves into the mineral grain if the refractive index of the fragment is greater than the refractive index of its immersion oil, and the Becke line moves away from the fragment if its index is less (Figure 4-7). The Becke line is most visible with high magnification and low light intensity.

Central illumination

In the ***central illumination*** method, at normal magnifications, the intensity of transmitted ***light*** is reduced by closing down the substage diaphragm of the microscope.

Refractive index determinations by the central illumination (or Becke line) method depend upon the diffraction of light by the specimen. The accuracy of the method is therefore influenced by the specimen dimensions and by the degree of defocusing of the microscope. Moreover, the method does not necessarily measure the refractive index of the surface regions of an inhomogeneous specimen.

It is also shown that it is possible to observe Fresnel diffraction bands with a spacing less than the conventional resolution limit. Consequently, such band spacings do not provide a reliable estimate of the resolution limit attainable in either a light or an electron microscope.

Oblique illumination

Oblique illumination is a technique whereby light is projected at the specimen from a sideways, slanting angle to reveal features with higher contrast as compared to when viewed with brightfield illumination. Oblique illumination can be employed on most microscope systems but is most commonly exploited on stereomicroscopes and patch-clamp microscopes.

Specimens that are nearly transparent and colorless may be almost invisible when viewed in the stereomicroscope using traditional transmitted (diascopic) brightfield illumination techniques. This occurs because light diffracted by minute specimen detail is a quarter-wavelength out of phase with direct light passing through the specimen when both are recombined in the intermediate image plane, a classical phenomenon that seriously reduces contrast in brightfield images.

However, if the illumination is directed so that it originates from a single azimuth and strikes the specimen from an oblique angle, details in the specimen may be revealed with much greater contrast and visual clarity than when the light is allowed to pass directly through specimen features along the optical axis of the microscope. Phase and refractive index gradients in the specimen deflect the light rays by diffraction, reflection, and refraction, so that only the zeroth order (undiffracted) and one or two sidebands of diffracted light can recombine at the image plane. This produces a relief-like specimen pattern having regions displaying shadows and highlights, much like that observed with the differential interference contrast (DIC) technique in compound microscopes.

Presented in **Figure 1** is a modern stereomicroscope illumination stand (the Nikon Oblique Coherent Contrast (OCC) diascopic model), which is designed to illuminate specimens through a transitional mechanism ranging from axial brightfield to highly oblique off-axis light rays that render transparent specimens visible in a scheme closely resembling darkfield. The stand contains both a high and low numerical aperture condenser enabling utilization of the entire stereomicroscope objective magnification (generally 0.5x to 2x) and numerical aperture (0.07 to 0.21) range. Oblique illumination is achieved by means of a sliding diaphragm that shields the center of the light beam to produce a partially coherent light source, which is projected obliquely onto the specimen, producing a high contrast image. The diaphragm position is controlled by means of a rotating knob that can be employed to adjust the obliquity of illumination.

Isotropism

Isotropism (isotropy) is a property whereby a substance exhibits an equal or uniform interaction in all directions or along all possible reference axes between it and an internal or external stimulus. Optical isotropism characterizes substances such as unstrained gases, liquids, and isometric (cubic) crystals, which transmit visible light waves of a specified frequency with equal velocity in all directions. Isotropism in volumes larger than single atoms depends on the nature of the stimulus and the volume under consideration, i.e., a crystal optically isotropic to visible radiation is not isotropic in its interaction with X-radiation. Also, a sufficiently large volume of rock consisting of randomly oriented anisotropic crystals (see Anisotropism) may behave isotropically in a stress field. Crystal or fragment accumulations in volumes large enough to behave isotropically in stress fields sometimes are described as being “massive.”

Isotropic minerals

Isotropic minerals are minerals that have the same properties in all directions. This means light passes through them in the same way, with the same velocity, no matter what direction the light is travelling. There are few common isotropic minerals; the most likely ones to see in thin section are garnet and spinel.

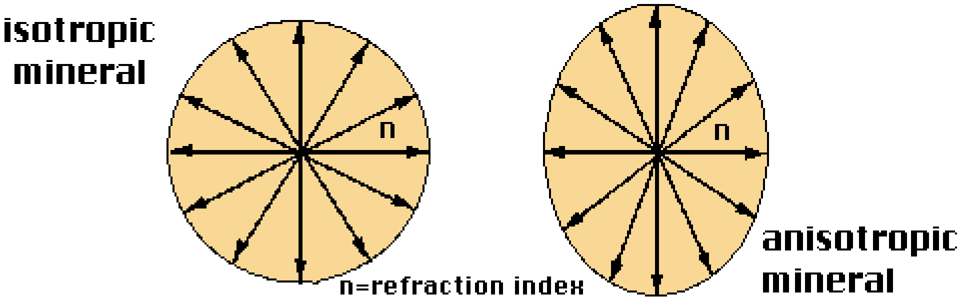
Isotropic ray velocity surface

an isotropic medium with smooth velocity heterogeneities with respect to the wavelength of the signal we want to propagate. Let us attach a Cartesian reference frame (0, x, y, z) to this medium. Consider at a given time, t, a set of particles, at position $x = (x, y, z)$, vibrating in phase on a smooth surface. We call this surface a wave front. Particles on this wave front have the same travel time, $T(x) = T_0$. As time increases, the wave front moves locally at speed $c(x)$ and the gradient $\nabla T(x)$ is orthogonal to the wave front (**Figure 6**). Although the wave front moves in one direction, local properties do not allow us to detect what the direction is, which must be known from the previous position of the wave front. Therefore, we must consider the square of the gradient, which gives us the eikonal equation

Behaviour of light in isotropic minerals

Their behaviour depends on the direction in which the external agent is acting varies. In the case of light, it is translated into a change in the refractive index according to the direction of vibration of the light inside the mineral.

Supposing there were a luminous point in the centre of the mineral, the light would reach the outside of it at the same moment, creating a circumference for an isotropic mineral (equal velocity in any direction) and an ellipse in the case of an anisotropic mineral (different velocity according to direction).



Anisotropy is related to the structure of the mineral, in that if there is no internal organisation (amorphous minerals) or the internal organisation is very regular, the minerals behave like isotropic minerals (1); otherwise they are anisotropic (2).

Amorphous minerals and those which crystallise in the Cubic System (also known as the Regular System) are Isotropic. The ions or atoms in isotropic minerals have an equivalent arrangement along all crystallographic axes.

Those which crystallise in the other systems are Anisotropic. The pattern of atoms varies with direction and thus the elasticity of the mineral also varies in relation to the vibration of the light waves.

Petrological microscope

A **petrographic microscope** is a type of optical microscope used in petrology and optical mineralogy to identify rocks and minerals in thin sections. The microscope is used in optical mineralogy and petrography, a branch of petrology which focuses on detailed descriptions of rocks. The method is called "polarized light microscopy" (PLM).

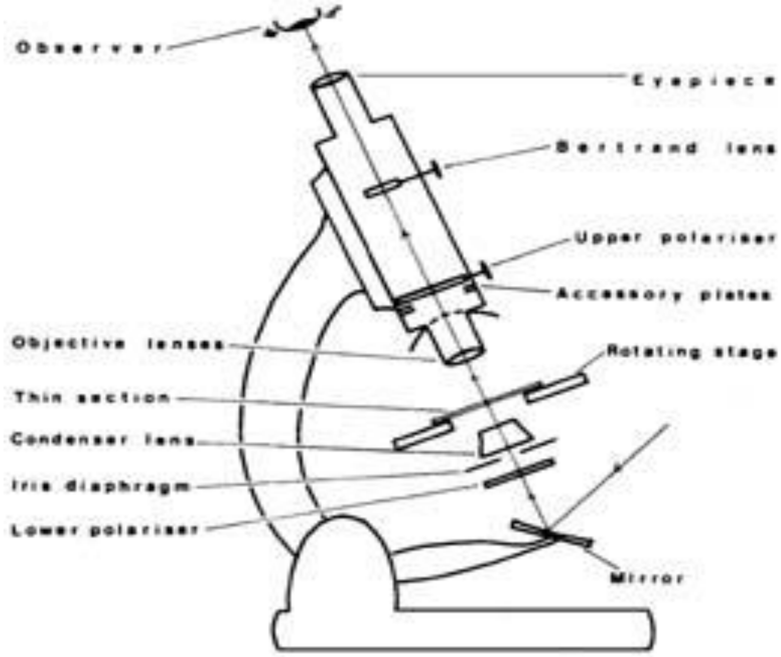
Depending on the grade of observation required, petrological microscopes are derived from conventional brightfield microscopes of similar basic capabilities by:

- Adding a Nicol prism polarizer filter to the light path beneath the sample slide
- Replacing the normal stage with a circular rotating stage (typically graduated with vernier scales for reading orientations to better than 1 degree of arc)
- Adding a second rotatable and removable Nicol prism filter, called the analyzer, to the light path between objective and eyepiece
- Adding a Phase telescope, also known as a Bertrand Lens, which allows the viewer to see conoscopic interference patterns
- Adding a slot for insertion of wave plates

Petrographic microscopes are constructed with optical parts that do not add unwanted polarizing effects due to strained glass, or polarization by reflection in prisms and mirrors. These special parts add to the cost and complexity of the microscope. However, a "simple polarizing" microscope is easily made by adding inexpensive polarizing filters to a standard biological microscope, often with one in a filter holder beneath the condenser, and a second inserted beneath the head or eyepiece. These can be sufficient for many non-quantitative purposes.

The two Nicol prisms (occasionally referred to as *nicols*) of the petrographic microscope have their polarizing planes oriented perpendicular to one another. When only an isotropic material such as air, water, or glass exists between the filters, all light is blocked, but most crystalline materials and minerals change the polarizing light directions, allowing some of the altered light to pass through the analyzer to the viewer. Using one polarizer makes it possible to view the slide in plane polarized light; using two allows for analysis under cross polarized light. A particular light pattern on the upper lens surface of the objectives is created as a conoscopic interference pattern (or interference figure) characteristic of uniaxial and biaxial minerals, and produced with convergent polarized light. To observe the interference figure, true petrographic microscopes usually include an accessory called a Bertrand lens, which focuses and enlarges the figure. It is also possible to remove an eyepiece lens to make a direct observation of the objective lens surface.

In addition to modifications of the microscope's optical system, petrographic microscopes allow for the insertion of specially-cut oriented filters of biaxial minerals (the quartz wedge, quarter-wave mica plate and half-wave mica plate), into the optical train between the polarizers to identify positive and negative birefringence, and in extreme cases, the mineral order when needed.



Pertsand its access

CONDENSER

The condenser consists of two or more lenses that focus the illuminator light onto the sample placed on the stage, and one or more apertures to control illumination (see below). The condenser should be adjusted each time the objective lens is changed to maximize the quality of the image.

LOWER POLARIZER

The first polarizer is located below the condenser and is shown in the interactive video above (**Figure 2.4.5**). Please see the separate section below on polarizers for more information.

LIGHT FILTER

Halogen lights used in microscopes typically give off a yellowish light, so a blue filter is often added to compensate for the yellow color of the light, providing a truer white light to pass through the sample.

DIAPHRAGM OR APERTURE

A diaphragm or aperture cuts down the amount of light that reaches the sample by restricting the area that light can pass through. There are often multiple apertures on a microscope (**Figure 2.4.5**), including an aperture as part of the condenser assembly, as well as a field diaphragm that controls the size of the area which is illuminated on a sample.

THE STAGE

ROTATING STAGE, GONIOMETER, AND VERNIER SCALE

The **stage** is the platform upon which the thin section is placed. The thin section spans a hole in the stage which lets light from the illuminator pass through the sample. One special feature of polarizing light microscopes used for petrography, in contrast to many other types of microscopes, is the **rotating stage**.

.The rotating stage in action, showing how the angle of orientation can be measured using the goniometer and venier. The rotating stage can be locked with the knob on the vernier.

The rotating stage has degrees marked on it: 360 degrees around the circular stage, in units of 1 degree. The angle of rotation can be measured to the nearest tenth of a degree by using the markings on the **vernier scale**. The rotating stage can therefore be used as a **goniometer**, or an instrument that measures rotational angle.

The vernier scale is a clever way of taking an accurate measurement reading between two markings on a linear scale by using mechanical interpolation. **Figure 2.4.9** shows the distance reading recorded as the yellow vernier scale slides alongside the ruler scale. The distance starts at exactly 5.0 mm, when “0” on the vernier exactly aligns with “5” on the ruler. To determine a distance greater than 5.0 mm (but less than 6.0 mm), one identifies the line on the vernier which aligns with one of the lines on the main ruler. For example, when line “1” on the vernier aligns perfectly with one of the lines on the ruler, then the distance is 5.1 mm.

The **mechanical stage** is an accessory which can be attached to the top of the rotating stage. Rather than a rotating motion, it allows motion along the *x*-axis (left-right) and *y*-axis (top-bottom). In **Figure 2.4.10**, the gold knob at the top controls motion in the *x* direction, and the gold knob on the right controls the *y* direction motion. The pincer-like arms (bottom left) wrap around the thin section and hold it in place.

The mechanical stage is not necessary for the optical mineralogy procedures discussed in this chapter. However, it is useful for point counting, in which the petrographer stops at several hundred points along an x-y grid on a thin section and identifies the mineral at each point. This technique is used to determine the modal abundance of minerals in the thin section, and is used to determine the name and composition of rocks.

THE FOCUS

Most polarizing light microscopes have two focusing knobs on each side of the microscope. The **coarse focus** is used to rapidly change the level of the stage and sample, and the **fine focus** knob is used to gently bring a sample into complete focus.

Care is required when using the coarse focus knob! Because it changes the level of the stage rapidly, it may be easier to run the sample into an objective and damage the thin section and possibly the objective also.

THE POLARIZERS

The polarizers in petrographic microscopes are plane (linearly) polarized. See section 2.3 for more information about how polarizers work. There is a polarizer in the substage assembly, and a second polarizer called the **analyzer** between the objectives and the Bertrand lens.

Typically the lower polarizer and analyzer are oriented at 90 degrees to each other, and oriented N-S and E-W relative to the base of the microscope. Polarization directions are marked either on the base of the microscope, or on the polarizers themselves. In some microscopes, the analyzer and the lower polarizer can be rotated (**Figure 2.4.13**) for custom measurements. This is not necessary for standard petrographic analyses.

THE (AMICI-) BERTRAND LENS

The Amici-Bertrand lens (or simply the Bertrand lens) changes the plane of focus so that the viewer can observe interference figures

THE EYEPIECES OR OCULARS

Polarizing light microscopes have **eyepieces** or **oculars** through which the user can observe the sample. Most modern microscopes are **binocular** and have two eyepieces which can be adjusted relative to each other to comfortably fit the user's eyes. Older models may have only one eyepiece (as in **Figure 2.4.1**), but are just as effective in making petrographic observations.

Figure 2.4.15. Eyepieces or oculars removed from two different brands of polarizing light microscope. The magnification (10x) is marked on each ocular.

Most oculars contain magnifying lenses that are typically 10x magnification but can vary from model to model. The magnification should be marked on the eyepiece, and should be included in the total magnification of the microscope. One ocular (typically the right one in a binocular microscope) will include crosshairs with a distance scale. This distance scale can be calibrated for each magnification, to determine the field of view (the diameter of the viewing circle) and the distance represented by each mark on the ocular scale (see **Question 2.4.7** below).

Oculars have a focusing mechanism to adjust the focus to each individual eye. The top portion of the ocular (the part with writing as seen in **Figure 2.4.15**) can be rotated to adjust the focus. If the crosshairs look fuzzy, or one eye seems in focus but the other is not, try adjusting the ocular focus to help you see better,

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THE ACCESSORY PLATES

Figure 2.4.17 shows examples of accessory plates including a **quartz wedge**, a **530 nm plate**, and a **1/4 λ plate**. These can be inserted into the microscope (**Figure 2.4.2**) above the objectives. The accessory plates are used to conduct advanced optical tests such as optical sign determination.

The **quartz wedge** is just that – a slab of quartz polished into a wedge that has a thicker side which grades into a thinner side. The **530 nm plate** can also be called a gypsum plate or a 1λ plate, or be a slightly different wavelength (550 or 537 nm). The **1/4λ plate** can also be called a mica plate, glimmer plate, or 147 nm.

THE CAMERA

Some polarizing light microscopes have digital camera attachments, making it possible to directly photograph the field of view in the microscope. Some microscopes (**Figure 2.4.16.A**) have a camera embedded within the microscope, while for others the camera is attached to the microscope with its own viewing tube (**Figure 2.4.16B**). In microscopes with separate camera viewing tubes, the light must be adjusted to travel partially or completely to the camera. This is accomplished with a pull-out knob (seen to the right of the eyepieces in **Figure 2.4.16B**).

It is possible to obtain images from a microscope by aiming a smart phone camera down the ocular. However, these images will be circular in shape and may be distorted or partially out of focus. If available, the camera attached to the microscope will likely produce better-quality images.

Uses

A **petrographic microscope** is a type of optical **microscope** used in petrology and optical mineralogy to identify rocks and minerals in thin sections.
(Credit: Renee Pillers, USGS. Public domain.)

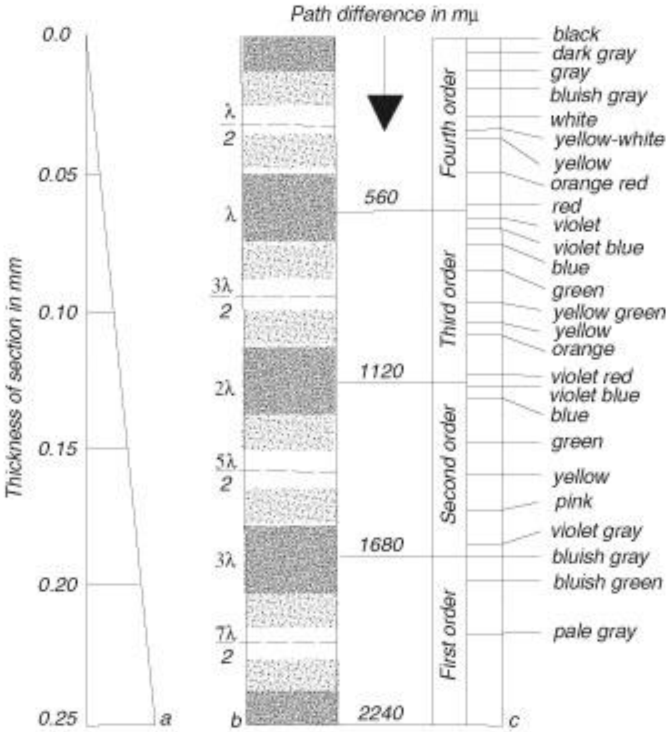
This microscope can be used for optical observations and imaging of samples. There is an attached camera at the top that is connected to a computer that is used to record and save images.

Keyence Optical Microscope used to collect images of samples. It can do 3-dimensional imaging, image stitching, transmitted imaging, reflective imaging, and measurements.

Quartz wedge

The quartz wedge inserted in the microscope substage above the polarizer in order to estimate birefringence and to determine optical sign of uniaxial minerals.

a very thin wedge-shaped piece of quartz cut parallel to an optical axis of a prism of quartz crystal. Used in optical mineralogy and petrography to determine the sign of the birefringence of biaxial minerals. Also used for involving polarized light and its interference figure in convergent light. Also called quartz plate.



a: cross section of quartz wedge, b: monochromatic light, λ = 560 nm and c: colors in four orders of white light

The quartz wedge is a simple, semi-quantitative compensator designed around a crystalline block of quartz cut with an elongated wedge angle so that the optical axis of the quartz is oriented either parallel or perpendicular to the edge of the birefringent crystal. The optical path difference between the orthogonally polarized fast and slow wavefronts traversing the wedge is a continuously variable function of the thickness along the wedge hypotenuse. A typical quartz wedge has an effective range of 4 orders (approximately 500 to 2000 nanometers) and is commonly employed for qualitative retardation measurements of petrographic specimens (rock and mineral thin sections) or other birefringent materials whose retardation value falls within the wedge limits. This interactive tutorial examines optical path differences in a wide range of specimens using the quartz wedge.

Gypsum plate

In polarized-light microscopy, an accessory plate of clear gypsum (replaced by quartz of the appropriate thickness in modern instruments) that gives a first-order red (approx. 1 lambda out of phase for 560 nm) interference color with crossed polars when inserted in the tube with its permitted electric vectors at 45 degrees to those of the polarizer and analyzer. It is used to determine fast and slow directions (electric vectors) of light polarization in crystals under view on the microscope stage by increasing or decreasing retardation of the light. Also called a sensitive-tint plate.

Mica plate

Mica compensating plate with a retardation of 1/4**l**.

This is highly recommended for interference figures with isochromatic curves.

In the quadrants where there is a coincidence of fast-fast and slow-slow (retardation), the effect of this compensator is that the isochromatic curves move towards the centre, (because they receive additive effects from the compensator, the waves do not have to travel so far inside the crystal to produce the same retardation), whilst when subtractive effects (compensation) occur (fast-slow, slow-fast) the isochromatic curves move towards the periphery of the field.

In this section, we explore properties that can be observed for minerals under cross polarized light, when both the lower polarizer and the analyzer (top polarizer) are inserted into the polarizing light microscope.

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