

ESS 439 Igneous Petrology - Optical Mineralogy

Laboratory 2b: Uniaxial minerals (Tetragonal and Hexagonal systems)

Discussion Topics: Ordinary (ω) and Extraordinary (ϵ) rays, Interference Colors, Indicatrix, Interference Figures, Extinction, Sign of Elongation, Absorption, Pleochroism, Relief.

[**Note:** A more detailed descriptions of the optical properties of uniaxial minerals appears in: Bloss, F D, An Introduction to the Methods of Optical Crystallography, Holt, Winehart, and Winston, 1961. Nesse (Chapter 7) also has a good discussion that you should read carefully.]

Uniaxial Minerals (hexagonal and tetragonal)

Uniaxial minerals are **anisotropic**. The velocity of light traveling through a uniaxial crystal is dependent upon the orientation of the **ray path**. Light entering the crystal will also be polarized into two rays with vibration directions (**privileged directions**) that are mutually perpendicular. These two rays are called the **Ordinary Ray (ω)** and the **Extraordinary Ray (ϵ)**. **The extraordinary ray vibrates in a plane containing the c-axis and the ray path, and the ordinary ray vibrates at right angles to the plane containing the ray path and the c-axis.** The refractive indices (velocities) of these two rays are n_{ω} (ordinary ray) and n_{ϵ} (extraordinary ray). The ordinary ray obeys Snell's Law, while the extraordinary ray appears to violate Snell's Law. However, the **wave normals** of both rays do obey Snell's Law, i.e., **Snell's Law should be applied only to wave normals.**

Uniaxial Indicatrix

Like the Isotropic Indicatrix, the Uniaxial Indicatrix is a three dimensional representation of the refractive indices of light vibrating in a particular direction within a crystal. **The Uniaxial Indicatrix is an ellipsoid.** This indicatrix will help you visualize how plane polarized light behaves as it passes through a uniaxial mineral. **Read Chapter 7 in the textbook.**

Optic Axis - Always coincides with c-axis in uniaxial minerals. Light travelling along the optic axis is reduced in velocity but is otherwise unaffected by the mineral and the mineral acts like an isotropic material.

Circular Section- a section cut **normal** to the optic axis - light passing perpendicular to this plane is unaffected and the refractive index equals n_{ω} .

Principal Section - an elliptical section cut parallel to the optic axis whose semiaxis are n_{ω} and n_{ϵ} . Light passing through this plane of the crystal will be resolved into a fast and a slow ray. Light passing through a crystal perpendicular to the principal section will show the **maximum birefringence** possible.

Random Section - elliptical sections whose semiaxis are n_{ω} and $n_{\epsilon'}$. Light passing through this plane is resolved into a fast and slow ray. Note: $n_{\epsilon'}$ is intermediate between n_{ω} and n_{ϵ} . Crystal will show intermediate birefringence.

Optic Sign - The optic sign of a mineral is said to be **positive** if $n_{\omega} < n_{\epsilon}$ and **negative** if $n_{\omega} > n_{\epsilon}$.

Interference Colors

Interference colors result from the interference between extraordinary ray and the ordinary ray as they are resolved in the analyzer. Since for all ray paths except those passing along the optic axis one ray is **retarded** with respect to the other ray, they are out of phase when they emerge from the crystal. Depending on the difference in refractive indices of the two rays (**birefringence**) and the thickness of the crystal, certain wavelengths will pass through the analyzer and others will be excluded. If the retardation is some multiple of the wavelength then the two rays will be resolved into a single ray vibrating at right angles to the privileged direction of the analyses and the resultant ray will be totally absorbed by the analyzer. If the retardation is some multiple of half the wavelength, the two rays will be resolved into a single ray vibrating parallel to the privileged direction of the analyzer and it will produce an interference color which is a function of the retardation.

The **retardation** (Δ) is a function of the **birefringence** ($\delta = |n_{\omega} - n_{\epsilon}|$) and the thickness of the section (t) and is equal to $\Delta = (t \times \delta)$. Interference colors are observed under **crossed polars** and for any given mineral the colors depend on the optical orientation. Interference colors are illustrated on the color chart in the pocket at the back of the textbook. A grain has a **maximum interference color** when examined perpendicular to the principal section. The circular section will be dark (like isotropic minerals) and random sections will have **lower order colors** than the perpendicular section. Thicker grains exhibit higher interference colors, other factors being equal.

Extinction

The effect of rotation of the stage is that a uniaxial mineral grain will become extinct (become black) at four positions. These positions correspond to the orientations when the vibration directions of the extraordinary and ordinary rays are parallel to the polarizer and analyzer. The **intensity** of the light viewed becomes greater as the crystal is moved away from extinction and reaches a **maximum at 45 degrees from extinction**. Interference colors are not affected by rotation of the grain.

Extinction Angles

An extinction angle is the angle between any planar crystallographic feature (cleavage plane, twin plane, crystal face, etc.) and the privileged directions of the microscope polarizer and analyzer. [Planar features appear as lines in thin sections.] In uniaxial crystals, there are two types of extinction angles: parallel and symmetrical. Parallel extinction occurs when extinction occurs with the crystallographic planes parallel to the cross hairs. Symmetrical

extinction occurs when extinction occurs at equal angles from two crystallographic planes to the cross hairs.

Sign of Elongation

Frequently uniaxial minerals will be elongated parallel to the c axis. If such an orientation is known you can determine the sign of elongation. Rotate the mineral to the 45° position, i.e., 45° from extinction position and insert the accessory plate. When inserting the gypsum plate with the slow direction parallel to the E vibration direction of the crystal, the interference colors are increased when the elongation is positive and decreased when the elongation is negative. Alternatively, the phenomenon is referred to as the mineral being **length fast** or **length slow**, which is easier to remember. **The accessory plate either enhances the retardation or cancels some of the retardation in the mineral.**

Accessory Plates (Compensation Plates)

Accessory plates are anisotropic crystals that have been cut in such a way as to have a known retardation. They are constructed so that the fast ray (labeled X) vibrates parallel to the long dimension of the plate holder and the slow ray (labeled Z) vibrates transverse to the long dimension. The accessory plate can be slid into position through the accessory slot which is oriented at 45 degrees from polarizer and the analyzer vibration directions. There are three important accessory plates: gypsum plate (cut in such a way to have a retardation of exactly 550 nm), mica plate (1/4 wave length), and the quartz wedge which increases in thickness (and retardation) from its leading edge. These accessory plates will **increase or decrease** the birefringence depending on the orientation of the crystal relative to the plate.

Absorption and Pleochroism

Uniaxial minerals may show selective absorption (they appear colored) under **plane polarized light**. As with refractive index, absorption may differ according to vibration direction. A change in color as a crystal is rotated around the stage is called **pleochroism**. A pleochroic formula might be indicated by: ω =blue, ϵ =red. When the ω vibration direction is parallel to the polarizer all wave lengths of light but blue are absorbed and when the ϵ vibration direction is parallel to the polarizer all wavelengths but red are absorbed.

Relief

Relief is a relative concept and it refers to the degree to which a mineral “stands out” relative to neighboring grains. Relief may be positive or negative and, if positive, it may be high, moderate or low.

Interference Figures

Interference figures can be used to determine whether a grain is uniaxial, the orientation of a grain, and the optic sign. Interference figures result when a uniaxial mineral is viewed under **high** power in **conoscopic** light (with the substage condensing lens flipped into position) through **crossed polars** with the **Bertrand lens** in position. The effect of the condensing lens is to produce a cone of light which is refracted by the crystal. Ray paths of this strongly convergence light therefore pass normal to different sections of the indicatrix depending on the angle of incidence.

Optic Axis Interference Figure

For grains that are viewed down the optic axis (such grains will be at extinction at all stage rotations) the ϵ rays will vibrate in radial directions while the ω rays will vibrate tangential to the cone of light. Along the east-west and north-south vibration directions these rays are vibrating parallel to the analyzer and polarizer which results in a dark cross. The center of this cross is called the **melatope**. The limbs radiating out from the melatope are called the **isogyres**. Light travelling through the outer part of the crystal has a longer ray path which results in increasing order of interference colors. These circular lines of equal retardation are called **isochromes**. If an optic axis figure is perfectly centered then the position of the figure does not change with rotation of the stage. If the grain is viewed at an angle to the optic axis then the melatope will be displaced from the center and will move in a circle when the stage is rotated.

Using the Optic Axis Figure to determine optic sign of mineral

When an accessory plate is moved into the light path interference colors can be observed in the four quadrants defined by a centered interference figure. If the ω ray is faster than the ϵ ray (positive) then the slow direction of the accessory plate will further retard the E ray in the NE quadrant and higher order interference colors (Blue) will be observed in the NE and SW quadrants immediately adjacent to where the isogyres cross (the melatope). Lower order interference colors (Yellow) will be observed in the NW and SE quadrants. If the ϵ ray is faster than the ω ray (negative) yellow will be observed in the NE and SW quadrants and blue in the NW and SE quadrants.

If a quartz wedge (increasing retardation) is inserted into the accessory slot the isochromes will move towards melatope in the NE quadrant if the mineral is positive and the isochromes will move away from melatope if the mineral is negative. As a general rule, the best results will be obtained as follows:

Low Birefringent Minerals (use gypsum plate)

Positive Mineral - Blue in NE quadrant (Yellow in the NW quadrant)

Negative Mineral - Yellow in NE quadrant (Blue in the NW quadrant)

High Birefringent Minerals (use quartz wedge)

Positive Mineral - Isochromes move towards melatope in NE

Negative Mineral - Isochromes move away from melatope in NE

Abnormal Interference Colors

An abnormal interference color is one that does not match any of the normal interference colors on an Interference Color Chart. Usually this is the result of selective absorption of a particular color or a large variation in the value of **differences in refractive indices** for different wavelengths of light, i.e., variable retardation.

1. Examine one of the **quartzite** thin sections under your microscope. This is a metamorphosed quartz arenite and it contains >90% quartz with the rest being microcline, plagioclase, muscovite and chert.

- a. Look for a grain with the highest birefringence, i.e., one in which the principal section (c-axis) is parallel to the stage. This would be first order gray/white with a tinge of yellow. Assuming that this is a properly made thin section it should be 30 microns thick. Determine the **birefringence** of quartz by using the interference color chart.
- b. Does quartz show **pleochroism**? Does quartz show **cleavage**?
- c. Locate a quartz--microcline contact (I'll help) and using the Becke line test determine which mineral has the highest **refractive index**.
- d. What optical effect would you use to locate a grain that is cut \perp c-axis? Locate such a grain (or as close as you can get). You are now looking down the optic axis, i.e., the **c** axis, with the circular section of the indicatrix parallel to the stage. Focus the grain with the high powered objective under crossed polars—make sure the lens is centered. Flip in the condensing lens and the Bertrand lens. Adjust condensing lens so that the small circle of light is maximized in size. If you did it correctly, you will see an **optic axis interference figure**. **Make a sketch of what you see and compare with Figs. 6.13 or 6.18 in the textbook.**
- e. Use the accessory plate (gypsum plate) to determine the **optical sign** of the quartz (positive or negative). [The interference figure does not have to be perfectly centered to determine the sign as long as you can recognize which quadrant you are in.] Sketch the optic axis interference figure indicating the colors in the four quadrants: Find another grain with high birefringence. Using the same set-up as above, find a “flash figure” and draw it.
- f. Determine the range of grain sizes and the average grain size from your calibration of the crosshairs.
- g. Do you have any explanation of why the extinction in quartz is not sharp? This phenomenon is commonly referred to as “**undulatory extinction**.”

2. Examine one of the marble thin sections (V20 or AB89-6.6). The most abundant mineral in these thin sections is calcite—it forms the interstitial matrix. [Other minerals include olivine, phlogopite and diopside—ignore these]. Carbonates are usually quite easy to identify in thin section because of their extreme birefringence, rhombohedral ($10\bar{1}1$) cleavage and lamellar twinning: twin plane is ($01\bar{1}2$). However, it is difficult to distinguish calcite from dolomite from magnesite (staining techniques are commonly used).

- a. Find an optic axis figure (you may need help on finding a section cut \perp c-axis). **Sketch** what you see including the **isochromes**. Determine optic sign; you may have to use a quartz wedge (instead of the gypsum accessory plate) to do this since the birefringence of calcite is so high.

b. Estimate the **birefringence** of calcite? Because calcite has very high birefringence (fifth or sixth order) this is difficult but you can get an idea by counting the number of colored orders (isochromes) in a centered optical axial figure of calcite. You can also try using the quartz wedge to do this but the interference colors of calcite are a milky white and it is difficult to see changes.

3. Tourmaline. Examine one of the five tourmaline grain mounts (mounted in epoxy). Note the varied colors in polarized light.

- a. Since tourmaline is trigonal, it is uniaxial. Tourmaline grains also show deep colors in ppl.
- b. Try to locate a grain that is approximately perpendicular to an optic axis and obtain a centered (or near-centered) optic axial figure. Recall that a grain \perp OA will show only the ω vibration directions. If you can locate such a grain, determine the color associated with ω (ppl). How many isochrome do you see? Do a becke line test on this grain and compare n_{ω} with the refractive index of epoxy (1.54). Becke lines are clearly visible in tourmaline.
- c. Determine the pleochroic formula of tourmaline. Since you have determined the color associated with ω it will be necessary to find a grain that shows the color associated with ϵ .

4. Zircon. (Two mediocre grain mounts). These are poor grain mounts but hunt around and try to find an elongated zircon grain (there are a few).

- a. Determine the type of extinction shown by zircon (parallel or inclined)
- b. Determine if the zircon is length fast or length slow.
- c. Do you think zircon has high birefringence. Why?

5. Magnet Cove, Arkansas

Thin sections of this rock contain three uniaxial minerals and two isotropic minerals. [The rock also contain green clinopyroxene and brown biotite which you should ignore for now]. Two of the uniaxial minerals (**apatite** and **calcite**) are accessory minerals (present in minor amounts) while the third one (**nepheline**) makes up ~60% of the rock. Try to locate the three uniaxial minerals and determine the optic sign for the nepheline. The brown isotropic mineral is a rare form of **garnet called melanite** that occurs in some alkalic igneous rocks. The other isotropic mineral is **pyrite** but, because it is opaque, it cannot be easily indentified in transmitted light. It is easily identified in reflected light, however.

6. In the sections containing **quartz and epidote**, locate a grain of quartz that gives a centered optic axis figure and determine the optic sign—there are excellent large quartz grains cut normal to the c axis. Be careful to not to mistake holes in the section for c-axis section of

quartz. Holes are filled with epoxy and can usually be identified easily. Obtain an interference figure and determine the sign of quartz.

[The other mineral in this section is epidote—it's biaxial so not the subject of this lab. However, note the third order (maximum) interference colors in epidote. Note also the anomalous interference colors in many grains—this is very typical of minerals in the epidote group. Note also the pleochroism of epidote.]

Common Uniaxial Minerals

Positive: Quartz, Ice, Brucite, Stishovite, Zircon, Rutile, Cinnabar

Negative: Melilite, Nepheline, Beryl, Apatite, Calcite, Dolomite, Magnesite, Ankerite, Corundum, Ilmenite, Hematite, Tourmaline

Double refraction experiment (ϵ ray and ω ray)

- Select a clear calcite rhomb.
- Draw a black dot (1-2 mm diameter) on a sheet of paper.
- Place the calcite rhomb above the dot (obtuse angle of rhomb towards you, i.e., the c-axis is oriented N-S and points down at a steep angle).
- You will observe two dots produced by the two refracted rays (**ϵ ray and ω ray**)
- Move your head from side to side to convince yourself that one dot appears shallower than the other—**the image produced by the ω ray is shallower than that produced by the ϵ ray**. What does this tell you about the relative refractive indices of the two rays?
- Rotate rhomb and observe that one of the dots describes a circle around the other one (which remains stationary). The stationary one is the **ω ray**.
- Place a piece of Polaroid film on the rhomb with the privileged direction (short dimension) of the film oriented N-S. One dot will disappear. Which of the two rays is being cut out by the Polaroid plate and why?
- Rotate the film 90 degree and repeat. The other dot will disappear. Why?

With the aid of a vibration direction diagram, explain what is happening—the textbook might be helpful. Remember that the c-axis of calcite bisects the obtuse angle of the rhomb and passes into the rhomb at a fairly steep angle.