Lecture 11: Optics I

The Optical Microscope

The optical microscope is a more powerful tool for identifying minerals than the naked eye. With an optical microscope, a geologist uses not only the physical properties that help identify a mineral in a hand sample, but also properties that result from the interaction of the light with the mineral's electronic structure.

Physical Properties

An optical microscope provides a close up look at physical properties that help identify a mineral, such as cleavage, habit, and color.

Optical Properties

An optical microscope uses polarized, visible light with wavelengths between about 4000Å and 7000Å to illuminate a thin section of minerals. The way in which this light interacts with the minerals' electronic structures leads to properties such as relief that are helpful for identification. Other properties like birefringence and the optic sign can be observed when a piece of film polarized in the opposite direction of the incident light is inserted above the objective lens. This piece of film is called the analyzer.

Refractive Index and Relief

Relief is an easily observed property that helps identify a mineral by giving a sense of its relative density. It is related in a straightforward way to a mineral's refractive index.

Defining the Refractive Index

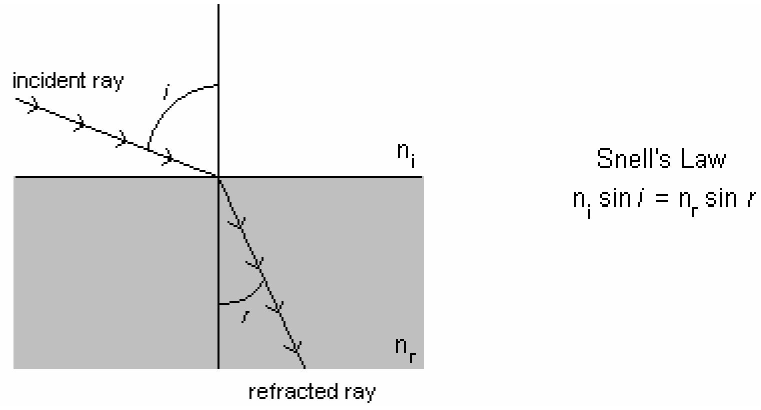
Light that travels from one material into another changes velocity because of the different atomic structure of the new material. This change in velocity is expressed as a ratio. When this ratio is standardized by using the speed of light, it is called the refractive index (n).

$$\text{n or RI} = \frac{\text{wave velocity of light in a vacuum}}{\text{wave velocity of light in the material}} = \frac{c}{v}$$

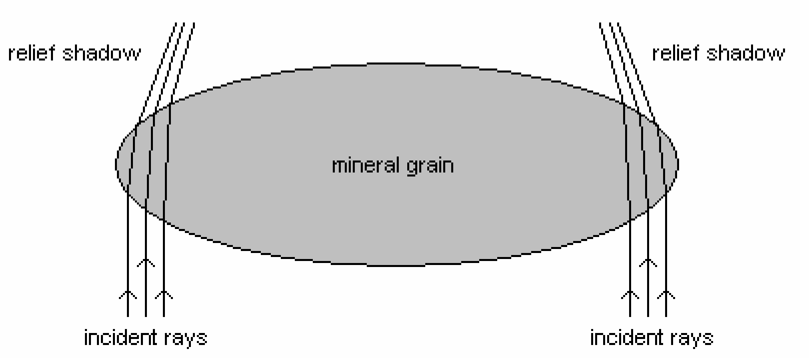
Since v is always less than c, a mineral's refractive index is always greater than one. In general, light travels more slowly through dense materials, so high-density minerals have higher refractive indices.

Relief and Snell's Law

When light travels from one material into another, its direction of propagation changes in addition to its velocity. This change is related to the refractive indices of the two materials and is expressed in Snell's Law.



Since dense materials have higher refractive indices, light bends toward the perpendicular when traveling from low-density to high-density minerals. This phenomenon creates shadows around the edges of grains that are referred to as relief.



Picture of how relief forms when light rays are bent toward the center of a mineral grain.

When the difference between the refractive indices of a mineral and its surroundings is large, the mineral shows high relief. When the difference is small, the mineral shows low relief.

Isotropic vs Anisotropic Minerals

Isotropic minerals have the same chemical bonding in every direction, and consequently have the same refractive index in every direction. Light travels through them with a single velocity regardless of the direction of propagation and vibrates in all directions at right angles to the direction of propagation. Isotropic minerals belong to the isometric system.

All minerals that do not belong to the isometric system are anisotropic. Anisotropic minerals have different chemical bonds in different directions and consequently have different refractive indices in different directions. Light that is incident on anisotropic minerals breaks into two polarized rays that vibrate in mutually perpendicular planes and travel with different velocities, according to the refractive indices associated with the direction of propagation. Anisotropic minerals will be discussed later in more detail.

Identifying Isotropic Minerals

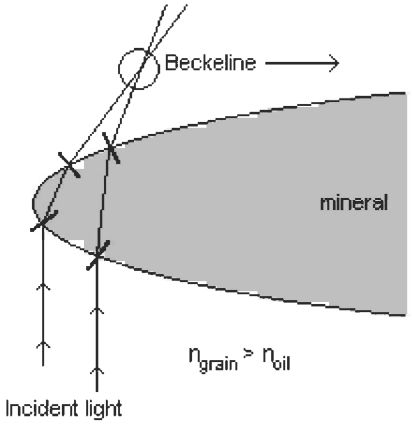
The fact that an isotropic mineral has a single refractive index is very useful. Because it does not change the polarization of incident light, it will appear black when the analyzer is inserted unlike anisotropic minerals.

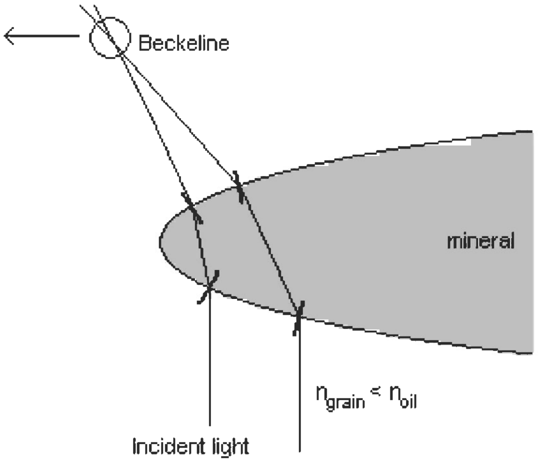
Beckeline Method

The single refractive index of an isotropic mineral is a powerful tool to help identify it. The refractive index can be determined using the Beckeline Method. This method is based on observing the movement of a halo of light in a mineral when it is submersed in oils whose refractive indices are known.

Procedure

1. Put oil with known *n* onto a slide and load mineral grains.
2. Lower the stage to focus above the plane of the slide.
3. The Beckeline moves into the medium with higher refractive index.
4. Repeat procedure with oils of higher or lower *n* until the Beckeline disappears.



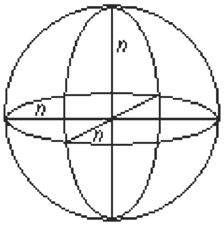


Identifying Anisotropic Minerals

Since anisotropic minerals do not have a single refractive index, the Beckeline Method is not very useful. Instead, birefringence and interference figures are used to identify them. Understanding these phenomena requires a more in depth look at how the refractive index of anisotropic minerals changes with direction.

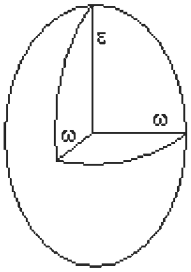
Optical Indicatrix

The optical indicatrix is a geometric figure that shows the relationship between the index of refraction and the direction light propagates through a mineral. It is an ellipsoid in which the length of radial lines is proportional to the refractive index of light vibrating parallel to the lines. Since the refractive index is the same in all directions for an isotropic mineral, its indicatrix is a spheroid.

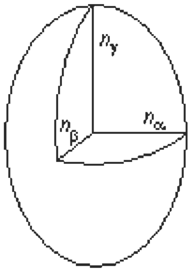


Indicatrix of an isotropic mineral.

Since an anisotropic material has more than one refractive index, its indicatrix is an ellipsoid. An optical indicatrix for both types of anisotropic minerals—uniaxial and biaxial—is shown below.



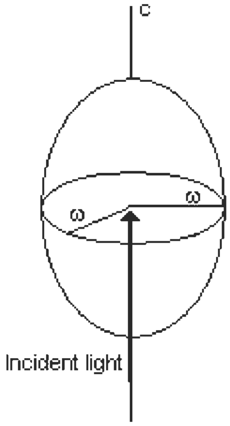
Uniaxial Indicatrix



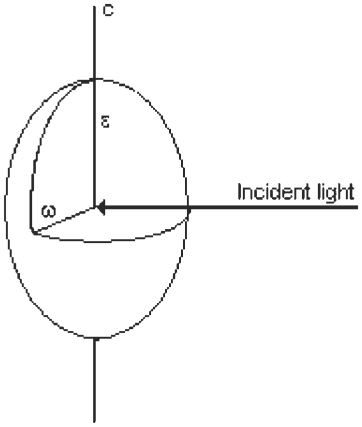
Biaxial Indicatrix

Uniaxial Minerals

Uniaxial minerals belong to the tetragonal and hexagonal systems. They take their name from the fact that they have a single optic axis—the c axis—along which light behaves as if it were traveling through an isotropic mineral. The refractive index associated with the optic axis is called ω.

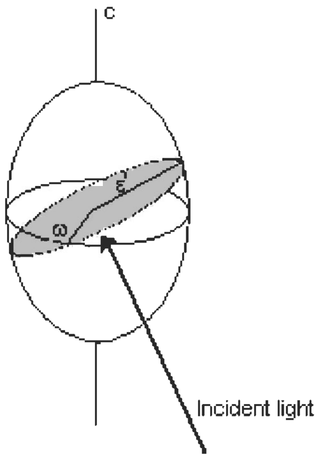


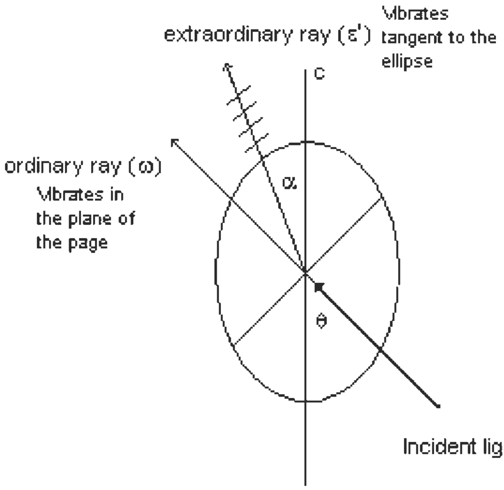
Light traveling perpendicular to the optic axis encounters two refractive indices, ω and ε.



This light is broken into two rays called the ordinary ray and the extraordinary ray. The ordinary ray vibrates in the basal plane and travels at the speed $v = c / \omega$. The extraordinary ray vibrates in a plane that includes the c axis and travels at the speed $v = c / \varepsilon$.

Light traveling at an oblique angle to the c-axis also encounters two refractive indices, ω and ε'. As shown in the figures below, the ray associated with ε' does not propagate parallel to the direction of incident light like the ordinary ray, but travels at an angle (α) to c-axis that is related to the angle of incidence (θ). The vibration direction of the extraordinary ray is also not parallel to the vibration direction of incident light, but is tangent to the surface of the indicatrix where the ray emerges.





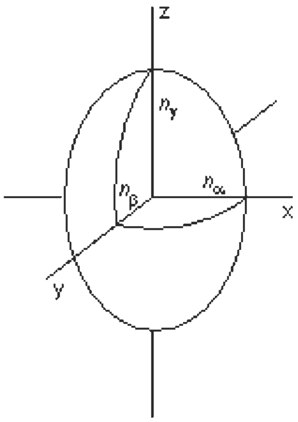
The value of ε' is given by the rearranging the equation of an ellipse in polar coordinates:

$$\varepsilon' = \frac{\omega}{\left[1 + \left(\frac{\omega^2}{\varepsilon^2} - 1\right)\sin^2\theta\right]^{1/2}}$$

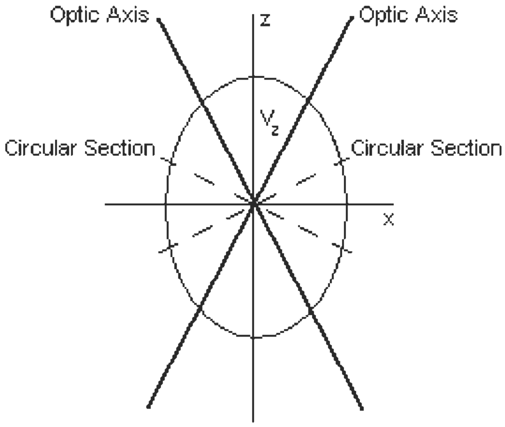
Biaxial Indicatrix

Biaxial minerals are less symmetric than uniaxial minerals and belong to the orthorhombic, monoclinic, and triclinic systems. They take their name from the fact that they have two optic axes, which are contained in the optic plane. Just as in uniaxial minerals, light traveling along these axes behaves as though it were travelling through an isotropic material. Another similarity to uniaxial minerals is that light traveling obliquely to these axes separates into two rays that vibrate in mutually perpendicular planes.

The major difference between biaxial minerals and uniaxial minerals is that biaxial minerals require three indices of refraction to describe their optical properties. The nomenclature of these indices varies; this discussion will refer to them as n_α, n_β, n_γ. A second difference is that the optic axes are inclined to the z-axis.



Biaxial Indicatrix



Cross-section through a biaxial indicatrix showing the optic axes

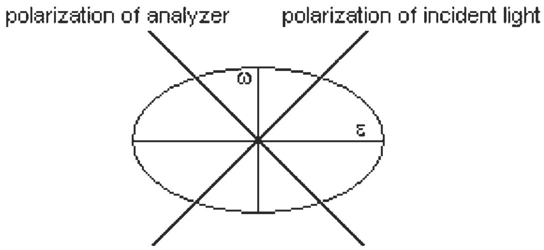
Note that any cross-section though a biaxial indicatrix can be described by only two indices of refraction. If the cross-section is oblique to every axis, the values of its indices can be found from the equation of a triaxial ellipsoid.

Interference Colors

If an anisotropic mineral on a slide is cut perpendicular to its optic axis, it will appear dark when the analyzer is inserted just like an isotropic mineral. If it is cut at any other angle, though, it will appear dark only when the stage is rotated every 90° and one of the mineral's vibration directions is parallel to the polarization of incident light. Turning the stage away from this orientation produces interference colors from the mineral. These colors form when the two plane-polarized rays that emerge from an anisotropic mineral are resolved at the analyzer.

Incidence of Monochromatic Light

To understand how interference figures are formed, first consider illuminating an anisotropic mineral with light of only a single wavelength. Take the vibration directions of the mineral to be at 45° to the polarization of incident light and the analyzer.



When light enters an anisotropic mineral, it breaks into a fast wave and a slow wave that are polarized in the mutually perpendicular vibration directions of the mineral. Because these waves travel at different velocities, they are usually out of phase when they emerge from the mineral. If they are out of phase by an integral number of wavelengths, vector addition of the two waves at the analyzer results in a single wave with the same polarization as the incident light. No light will pass though the analyzer and the mineral will appear dark. If they are out of phase by a half number of wavelengths, the emergent light will have the opposite polarization as the incident light. All of the incident light will pass though the analyzer. If the rays are out of phase by neither an integral nor half number of wavelengths, the incident light will pass though the analyzer at a reduced intensity.

Incidence of Polychromatic Light

The white light used by optical microscopes contains a spectrum of wavelengths. As a result, the waves that make up the white light will be out of phase by slightly different amounts after passing through an anisotropic mineral. While some waves will pass though the analyzer, others will not. The combination of waves with different wavelengths that do pass though creates the interference colors.

Using Interference Colors for Identification

Interference colors reflect the exact distance by which the slow wave lags behind the fast wave. This distance is called the retardation (Δ) and is proportional to the difference between a mineral's refractive indices. This difference is called the birefringence and its maximum value is a characteristic of each mineral. Since birefringence affects the interference color of a mineral, it can be estimated with an optical microscope and used for identification.

Derivation of Birefringence

The distance by which the slow wave lags the fast wave is given by the retardation (Δ).

$$\text{distance} = \text{velocity} \times \text{time}$$

$$\Delta = c\,(t_{slow} - t_{fast})$$

where t is the time it takes the rays to travel the thickness of the mineral d.
Since

$$t_{slow} = \frac{d}{V_{slow}} \qquad t_{fast} = \frac{d}{V_{fast}}$$

The equation can be rearranged to give

$$\Delta = d\,c\,\left(\frac{1}{V_{slow}} - \frac{1}{V_{fast}}\right)$$

and the retardation becomes equal to the product of the mineral's thickness and birefringence.

$$\Delta = d\,(n_{slow} - n_{fast})$$