OPTICAL MINERALOGY

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GLOSSARY

anisotropic mineral:	A mineral with more than one principal refractive index.
birefringence:	The mathematical difference between the largest and smallest refractive index for an anisotropic mineral.
biaxial mineral:	A mineral with three principal refractive indices and two optic axes. Its indicatrix is a triaxial ellipsoid.
dispersion:	Change of any optical property with wavelength.
indicatrix:	The three-dimensional surface describing the variation in refractive index with relationship to vibration direction of incident light.
isotropic mineral:	A mineral with the same refractive index regardless of vibration direction. Its indicatrix is a sphere.

optical class:	One of five possible classes (different indicatrices) to which a mineral can belong: isotropic, uniaxial +/-, or biaxial +/-.
optical orientation:	The relationship between a mineral's crystallographic axes and optical indicatrix.
pleochroism:	The property of exhibiting different colors as a function of the vibration direction.
principal refractive index:	For isotropic minerals -n, for uniaxial minerals - and , for biaxial minerals - , , and .
uniaxial mineral:	A mineral with two principal refractive indices and one optic axis. Its indicatrix is a prolate or oblate ellipsoid.

Optical mineralogy - the study of the interaction of light with minerals, most commonly limited to visible light and usually further limited to the non-opaque minerals. Opaque minerals are more commonly studied in reflected light and that study is generally called ore microscopy - alluding to the fact many opaque minerals are also ore minerals. The most general application of optical mineralogy is to aid in the identification of minerals, either in rock thin sections or individual mineral grains. Another application occurs because the optical properties of minerals are related to the crystal chemistry of the mineral -- for example, the mineral's chemical composition, crystal structure, order/disorder. Thus, relationships exist, and correlations are possible between them and some optical property. This often allows a simple optical measurement with the petrographic microscope (a polarizing microscope) that may yield important information about some crystal chemical aspect of the mineral under study.

I. LIGHT

A. *Theory of light*

Light can be thought of both as a wave phenomenon (electromagnetic theory) or a particle phenomenon (quantum theory), depending upon the physical process under study. In optical mineralogy both forms of light are employed to fully explain the interaction of light with minerals. The range and colors of visible light are defined in terms of wavelength: violet (390-446 nm), indigo (446-464 nm), blue (464-500 nm), green (500-578 nm), yellow (578-592 nm), orange (592-620 nm), red (620-770 nm). Visible light commonly is referred to as 400-700 nm. This range is somewhat arbitrary based upon the variation in an individual's eye sensitivity.

The wave theory of light describes light as a longitudinal wave, with the direction of propagation and the direction of energy transfer being perpendicular. In optical mineralogy the direction of propagation is referred to as the ray path and the energy transfer direction as the vibration direction. The geometrical relationships between ray path, vibration direction, and a mineral constitute one major portion of the optical study of minerals, basically a geometrical optical phenomenon. Results from wave theory are used to explain how light is refracted by a mineral. Several techniques for the measurement of optical properties of minerals use observation of light refraction.

The particle theory describes light as composed of photons of different energies with these energies related to the wavelength in the electromagnetic theory. A description of the interaction of photons with the bonding electrons in minerals can be used to explain such phenomena as refractive index, color, and pleochroism, and to interpret most spectroscopic studies.

B. *Polarized light*

The electromagnetic theory of light is used to explain polarization phenomena. There are four types of polarized light: random, plane,

circular, and elliptical. Plane polarized is the most important form for the study of minerals. However, circular and elliptical forms become important in more advanced studies.

Recall that the direction of energy transfer is perpendicular to the propagation for a light ray. In plane polarized light the energy transfer directions (vibration directions) are restricted to a plane parallel to and coincident with the ray path (Figure 1). Plane polarized light is used to study anisotropic crystals because the vibration direction of the light can be made parallel to specific directions within the crystal.

II. POLARIZING LIGHT MICROSCOPE AND GEOLOGICAL SAMPLES

Many different models of polarizing light microscopes (PLMs) exist, ranging in price from a few hundred dollars to several tens of thousands of dollars. However, the basic design of a PLM is fairly simple and has remained unchanged for many years. Figure 2 shows a schematic illustration of a PLM with the minimal number of components for routine optical mineralogical work. A mineral sample is placed on the rotatable stage for observation in plane polarized light. The sample may be rotated so polarized light will vibrate along different directions within the crystal. Another polarizer, at right angles to the lower polarizer, can be inserted and withdrawn from the microscope. When the upper polarizer is inserted, the mineral sample is being viewed between crossed polarizers. With no sample or an isotropic sample present, no light will be visible because the polars are crossed. However, if a randomly oriented anisotropic mineral is inserted, the crystal will appear and will go extinct (dark) every 90° of stage rotation.

Basically, the PLM is nothing more than two pieces of polarizer whose vibration directions are perpendicular with the added ability to magnify the image. Also shown in Figure 2 is an accessory that is made of different types of anisotropic plates that can be inserted into the light train. Observations made before and after insertion of these plates

provide valuable information on the optical characteristics of the mineral under study.

The substage lens system delivers two basic types of light to the sample. For orhtoscopic illumination, the light rays leaving the substage lens system are parallel to the optic axis of the microscope. This is the "normal" viewing condition. In conoscopic illumination, the rays leaving the substage system are no longer parallel but form an inverted cone whose point (focus) is at the sample. Conoscopic illumination is used to observe interference figures of minerals. From these figures the crystal system of the mineral can usually be established; thus, these figures greatly aid in mineral identification.

There are three types of samples commonly studied on the PLM in geology. (1) Powders of minerals in the size range of 0.07 to 0.15 mm for use in the immersion method. (2) Single crystals of minerals approximately 0.03 to 3.0 mm for use on the spindle stage. (3) Rock thin sections, prepared by cutting, grinding, and polishing a slab of rock mounted on a microscope slide to a thickness of 0.03 mm. Thin sections are by far the most common use of optical mineralogy in geology. They are used by petrologists to identify the minerals present, their textural relationships, to classify the rocks, and to locate minerals for microprobe analysis.

III. REFRACTIVE INDEX AND ITS MEASUREMENT

A. *Refractive index*

The refractive index (n) is a physical property of a mineral mathematically defined as:

$$n = \frac{v_v}{v_m}$$

[1]

where,

n = refractive index of mineral

v_v = velocity of light in a vacuum

v_m = velocity of light in the mineral

There are three important points gained from an examination of Equation 1. (1) The refractive index of a vacuum is 1.0. (2) Refractive index is a unitless number. (3) Because the velocity of light cannot exceed that in a vacuum ($3x10^8$ m/s), the refractive index of any material is greater than 1. In routine work the velocity of light in air is substituted for the velocity of light in a vacuum in Equation 1. This only amounts to a small error because the refractive index of air is approximately 1.0003.

Refractive index usually increases when matter changes from a gas to a liquid to a solid. The quantum theory of light is used to explain changes in refractive index. The refractive index is greater than one because as photons enter a mineral they are slowed by interaction with electrons. The more photons are slowed while travelling through a material, the greater the material's refractive index. Generally, any mechanism that increases electron density in a material also increases refractive index. For instance, increasing the density of a material usually increases the refractive index. However, refractive index is also closely related to bonding. In general, ionic compounds having lower values of n than covalent ones. In covalent boning more electrons are being shared by the ions than in ionic bonding; thus, more electrons are distributed through the structure and interact with the incident photons slowing them. Thus, changes in refractive index are related, albeit in a very complicated, as yet not fully understood, manner to the interaction of the incident light's photons and the material's bonding electrons.

B. *Light refraction*

Geometrically, light travels through a crystal with the incident and transmitting rays following Snell's Law, mathematically written:

$$n_i \, \sin(\theta_i) = n_t \, \sin(\theta_t) \qquad\qquad [2]$$

where,

n_i = refractive index of incident media

n_t = refractive index of transmitting media

$_i$ = angle of incidence

$_t$ = angle of transmission or refraction

Much of the science of physical optics and ray tracing is based on this formula. By analyzing Equation 2 the following are noted. (1) Any ray at normal incidence onto a material of different refractive index will be transmitted without any deviation (ray 1, Figure 3). (2) When both the incident and transmitting medias have the same refractive index, the incident and transmitting angles are equal. (3) For the general case, when the angle of incident is not 0° and the refractive indices for the two materials are unequal, the ray is refracted and the angle of refraction can be found from Equation 2 (ray 2, Figure 3). (4) There is some angle at which an incident ray is refracted at 90°; this is termed total refraction and used in refractometery to determine the refractive index of an unknown (ray 3, Figure 3). The angle at which total refraction occurs is called the critical angle.

Every incident ray, before the critical angle is reached, has a reflected as well as a transmitted portion. For the reflected component, the angle of reflection is equal to the angle of incidence. For both rays the intensities and polarization properties can also be calculated (Gunter, 1989). Snell's Law is obeyed by all isotropic materials; however, it is not obeyed for random orientations in anisotropic materials.

C. *Dispersion*

The refractive index of a material depends upon the wavelength of light and can be written mathematically:

$$\mathbf{n} = \mathbf{f}\ (\lambda)$$ [3]

where,

n = refractive index of mineral

= wavelength of light

This change in refractive index is called dispersion and is graphically shown in Figure 4. The bolder curve has a steeper slope and exhibits a greater dispersion than the lighter curve. In general, the dispersion of a liquid is greater than that of a solid. Also, in general, the higher the refractive index of a material the higher the dispersion.

For quantitative optical measurements it is necessary to find a mathematical fit to the data, as in Figure 4. Several relationships, both theoretical and empirical, have been proposed to quantify the relationship in Equation 3. The Cauchy equation (Equation 4) is one such equation.

$$n = C_1 + \frac{C_2}{\lambda^2} + \frac{C_3}{\lambda^4}$$

[4]

where,

n = refractive index

= wavelength of light

C_n = values obtained from a regression

The rainbow, created from drops of rain, or a glass prism are familiar examples of dispersion. The refractive index of water, or glass, decreases with wavelength (like the curves in Figure 4). White light is composed of the different wavelengths of light, and each wavelength possesses a different refractive index. Application of Snell's Law (Equation 2) shows that a different angle of refraction occurs for different colors of light. Thus, because of dispersion and geometrical optics from Snell's Law, the colors of the rainbow are easily understood. Red light, with the lowest refractive index, is refracted the least and occurs on the

outside of the rainbow. Violet light, with the highest refractive index, is refracted the most and occurs on the inside of the rainbow.

D. *Measurement of refractive index*

There are two general methods to measure the refractive index of transparent compounds: (1) a direct measurement of the angle of refraction as found in Snell's Law or (2) a comparison of the unknown material's refractive index to a known. The former method is routinely used to determine the refractive index of liquids and larger solid samples (greater than 1 mm) and was discussed above, with details below, on its application to anisotropic samples. While the latter method is more normally used to determine the refractive indices of smaller samples (less than 1 mm). The comparison method was developed early in this century and has become known as the immersion method. In this method a solid sample of unknown refractive index is placed into a liquid of known refractive index. By microscopic observations, explained later, the liquid is "adjusted" until its refractive index matches that of the solid, thus determining the refractive index of the unknown.

The immersion methods works on the basis of refraction of light rays as defined in Snell's Law. When the refractive index of the liquid (n_l) and solid (n_s) are the same, there is no refraction of the light rays, basically making the samples invisible (the invisible man had the ability to change his refractive index to that of air, thus becoming invisible, but how did he see?). When there is a large difference between the refractive index of the sample and liquid, light is refracted when entering and leaving the solid. The refraction of these waves make the sample visible. The word "relief" is used to semi-quantitatively denote the difference between the refractive index of the solid and that of the liquid. Samples at or near a match are have low relief, while those farther from match have high relief. When $n_l < n_s$ the sample has positive relief; when $n_l > n_s$ the sample has negative relief.

The mineral's relief is observed in thin section mineral identification. The epoxy holding the thin section to the slide has a refractive index of approximately 1.55. Minerals in thin section with a refractive index of within +/- 0.04 will have low positive/negative relief. Minerals with a refractive index within the range of +/- 0.04 to 0.12 will have moderate positive/negative relief, while those with refractive indices above +/- 0.12 will have high positive/negative relief.

The Becke line method is the most commonly used technique to determine a match between n_l and n_s in the immersion method. A crystal is immersed in liquid between a glass slide and a coverslip. After obtaining a focused view of the crystal under the microscope in polychromatic light, the microscope is slightly de-focused by racking the stage down. Two lines, one light and one dark, appear around the grain boundaries. The light Becke line moves into the material which has the larger refractive index. Basically, the grain is functioning as a lens in the liquid. When $n_l < n_s$, the grain acts as a convex lens, refracting the light into the grain's center - the light Becke moving into the grain. When $n_l > n_s$, the grain acts as a diverging lens, sending the bright Becke line into the liquid. Another liquid is selected based upon the findings of the previous observation, and the process of bracketing the solid with the liquid continues until the Becke lines become colored, at which time another strategy is used.

The Becke lines become colored when the dispersion curves for the liquid and solid intersect in the visible. The intersection point marking the precise wavelength of match were the refractive index of the liquid and solid are equal. The microscopist usually attempts to determine the refractive index at 589.3 nm, the spectra line produced by a sodium gas discharge bulb. This match is found when the Becke line that enters the grain becomes sky blue and the other orange-yellow line enters the grain. An entire progression of colors occur, depending upon the point of intersection of the two curves.

The double-variation method is a refinement on the above technique. With it, and careful observations, refractive indices can be obtained with an accuracy and precision of +/- 0.0001. The "double" originates from the microscopist's control over both wavelength of light and temperature of the liquid. As shown in Figure 4, refractive index decreases with wavelength. In this method a monochrometer is used and the precise wavelength at which a Becke line disappears can be found. Also, refractive index decreases with increasing temperature. For a material this change is mathematically written as dn/dt. The dn/dt for liquids is several orders of magnitude greater than that of solids. By raising the temperature of the liquid a few degrees centigrade, a large change occurs in its refractive index, while the crystal's refractive index does not significantly change. By making several wavelength matches at different temperature, the precision of the refractive index determination is increased. This is the chosen method, coupled with use of the spindle stage (discussed below), to obtain accurate and precise optical data on single crystals.

IV. OPTICAL CLASSES - INDICATRIX THEORY
A. *Optical classes: isotropic vs anisotropic minerals*
Minerals are divided into one of six crystallographic systems based upon their symmetry: cubic, hexagonal, tetragonal, orthorhombic, monoclinic, or triclinic. (See Bloss (1971) for an excellent presentation of crystal symmetry.) Minerals are also divided into classes based upon their optical behavior. There are two broad optical classes: isotropic and anisotropic. Anisotropic minerals are further subdivided into uniaxial and biaxial classes. Unpolarized light remains unpolarized after passage through an isotropic sample but will be linearly polarized into two mutually perpendicular planes after passing through an anisotropic mineral.

There is a direct relationship between the crystallographic and the optical class (i.e., there is a relationship between crystal structure and

light interaction). Isotropic materials belong to the cubic crystal system (some isotropic materials are amorphous). Uniaxial minerals belong to either the hexagonal or tetragonal crystal systems. Biaxial minerals belong to either the orthorhombic, monoclinic, or triclinic systems.

In isotropic minerals, the refractive index is the same in all directions, and Snell's Law always applies. For certain orientations in anisotropic minerals Snell's Law does not apply. In these orientation two separate ray paths occur, because the refractive index differs has a function of orientation. Also, in anisotropic minerals the ray path is no longer perpendicular to the vibration direction (Figure 1). These complexities make it very difficult to construct ray paths in anisotropic samples. The interested reader is referred to Bloss (1961) for a detailed discussion.

The refractive index a mineral exhibits is more directly to the vibration direction than to the ray path. The observable refractive index is parallel to the vibration direction for special directions in anisotropic and all directions in isotropic crystals it is perpendicular to the ray path. To understand how light interacts with minerals, especially anisotropic minerals, it is necessary to think in terms of how the vibration direction of linearly polarized light moves through the crystal with regard to the crystal's structure.

The optical indicatrix is a geometrical solid relating the refractive index of a mineral to the mineral's structure. The surface of the indicatrix represents the different refractive indices in the crystal. These different refractive indices are related to the different vibration directions that linearly polarized light can vibrates parallel to while in the mineral.

B. *Isotropic indicatrix*

Isotropic minerals belong to the cubic crystal system and possess only one refractive index, usually labelled as n. The isotropic indicatrix is a sphere with radius proportional to the n of the mineral (Figure 5). Each vector drawn in Figure 5 can be thought of as a vibration direction. Light

vibrating parallel to that vector would exhibit the refractive n of the mineral. For isotropic minerals all the vectors are the same length, so the refractive index does not vary with differing vibration directions.

C. *Uniaxial indicatrix*

Uniaxial minerals belong to either the hexagonal or tetragonal crystal systems and possess two mutually perpendicular refractive indices,   and   , which are called the principal refractive indices. Intermediate values occur and are called ', a non-principal refractive index. The uniaxial indicatrix is an ellipsoid, either prolate (>), termed positive, or oblate (<), termed negative (Figure 6). In either case, coincides to the single optic axis of the crystal, yielding the name "uniaxial." The optic axis also coincides with the axis of highest symmetry of the crystal, either the 4-fold for tetragonal minerals or the 3- or 6-fold of the hexagonal class.

Because of the symmetry imposed by the 3-, 4-, or 6-fold axis, the indicatrix contains a circle of radius   perpendicular to   (perpendicular to the optic axis). Light vibrating parallel to any of the vectors labelled in Figure 6 would exhibit the refractive   . Light vibrating parallel to the optic axis would exhibit . Light that does not vibrate parallel to one of these special directions within the uniaxial indicatrix would exhibit a refractive index intermediate to   and   and is termed '. Values of ' can be found based upon the angle the light vibrates to the optic axis by the formula:

$$\varepsilon' = \frac{\omega\,\varepsilon}{\sqrt{\omega^2\cos^2\theta + \varepsilon^2\cos^2\theta}} \qquad [5]$$

where,

' = non-principal refractive index

,   = principal refractive indices for uniaxial mineral

= angle between optic axis and ' direction

As previously stated, the ray path and vibration direction for isotropic minerals are perpendicular. This is not always the case in anisotropic minerals. For the case when linearly polarized light is vibrating parallel to either of the principal refractive indices the ray path and vibration direction will be perpendicular. Thus, in Figure 6 light whose ray path is parallel to the optic axis would be vibrating in the   direction and exhibit the   . Likewise, any light whose ray path was perpendicular to the optic axis, that is travelling within the circular section, would have its vibration direction parallel to the optic axis and exhibit   . For light not travelling along one of these two special directions, the ray path and vibration direction would not be perpendicular and   ' would be exhibited.

The indicatrix provides the framework for understanding optical measurements on crystals. To determine the principal refractive indices for uniaxial minerals, linearly polarized light must be forced to vibrate parallel to them. This can be accomplished with the aid of the PLM (Figure 2). A crystal can be oriented on the microscope stage so that, for instance, the optic axis is parallel to the microscope stage. Then a rotation of the microscope stage is made so the E-W lower polarizer is made parallel to the optic axis. This done,   can be determined as later discussed.

D. *Biaxial indicatrix*

Biaxial minerals belong to either the orthorhombic, monoclinic, or triclinic crystal systems and possess three mutually perpendicular refractive indices,   ,   , and   , which are the principal refractive indices. Intermediate values also occur and are labelled   ' and   '. The relationship between these values are   <   ' <   <   ' <   . The three principal refractive indices coincide with three mutually perpendicular directions, X, Y, and Z, which form the framework for the biaxial indicatrix (Figure 7). The point group symmetry of the biaxial indicatrix is 2/m 2/m 2/m. In orthorhombic minerals the X, Y, Z axes coincide with either the 2-

fold axes or normals to mirror planes. In monoclinic minerals, either X, Y, or Z coincide with the single symmetry element. In triclinic minerals, no symmetry elements necessarily coincide with the axes of the indicatrix.

Also shown in Figure 7 are the two optical axis, labelled OA1 and OA2, which is how this class derives its name. The optic axes are perpendicular to circular sections, having radii , that can be inscribed inside the indicatrix. The optic axes lie in the XZ plane of the biaxial indicatrix. The acute angle between the optic axes is defined as 2V, sometimes labelled has $2V_z$ or $2V_x$. $2V_z$ and $2V_x$ are supplementary angles. When $2V_z$ is acute the mineral is termed biaxial positive, and when $2V_x$ is acute the mineral is biaxial negative. The following mathematically relates   , , , and $2V_z$ for biaxial minerals:

$$\mathbf{cos\ V_z} = \frac{\alpha}{\beta} \sqrt{ \frac{(\gamma + \alpha)\ (\gamma - \beta)}{(\gamma + \alpha)\ (\gamma - \alpha)} }$$

[6]

where,

V_z = the angle between Z and an optic axis, or 1/2 $2V_z$

, ,   = the three principal refractive indices

For light vibrating parallel to either X, Y, or Z, the principal refractive indices   , , or , respectively results. Also, for these three directions, the ray path would be perpendicular to the vibration direction. For any other vibration direction within the crystal an   ' or a   ' non-principal refractive index would result and the ray path and vibration direction would not be perpendicular.

The three optical indicatrices progress from high - isotropic to lower symmetry - uniaxial and then biaxial as the crystal structure of the minerals decrease in symmetry from cubic to hexagonal or tetragonal and finally to orthorhombic, monoclinic, or triclinic. The biaxial indicatrix will become uniaxial when, for instance,   and   become equal. Also, when this happens the two circular sections in the biaxial indicatrix would rotate into coincidence with each other and become the single circular

section, with radius   of the uniaxial indicatrix. The two optic axes would rotate into coincidence and become the single optic axis of the uniaxial indicatrix. In the previous example a positive biaxial mineral would become a positive uniaxial mineral. If   and   were to become equal, a negative biaxial mineral would become a negative uniaxial mineral.

Because the optical indicatrix is related to the crystal system, optics play an important role in crystal structure determination. Certain minerals, for instance some garnets, appear anisotropic while they are supposed to belong to the cubic crystal system, and most structure determinations place them there. However, optics is more sensitive to slight structural changes than x-ray diffraction and when used in combination with it can help avoid incorrect crystal system assignments.

E. *Retardation and birefringence*

Anisotropic minerals possess different values of refractive index depending upon the vibration direction. The mathematical difference between two vibration directions is termed the crystal's birefringence. For example, the birefringence of a uniaxial positive crystal would be   -   . If the precise vibration directions are not known in the crystal, another nomenclature is used: N (referred to as "big N") is used to signify the larger refractive index and n (referred to as "little n") is used to signify the smaller refractive index.

In microscopy the birefringence is not directly observable, but a property termed the retardation is. Retardation is related to birefringence by:

$$\Delta = \delta \; t \qquad\qquad\qquad [7]$$
where,

   = retardation
   = birefringence = (N - n)
   N = largest refractive index
   n = smallest refractive index

t = mineral's thickness

A crystal's birefringence is found by determining its retardation (explained in the next section) and its thickness. The birefringence, or retardation, is very useful in identifying unknown minerals in thin section.

F. *Interference*

Light can interact with itself to produce many different colors. Interference of light occurs when two light rays travelling in the same direction, but having different intensities or wavelengths, interact with one another to form a single light ray. This is the phenomenon that produces color in such things as oil slicks and hummingbird feathers. The interaction of light in a crystal produces interference which is a function of the wavelength of light used and the optical characteristics of the crystal, namely the birefringence.

For instance, if a uniaxial mineral is illuminated with unpolarized light whose ray path is normal to the optic axis, the crystal will constrain the light to vibrate parallel to   and   . Because, by definition, the light travels at different velocities along these two vibration directions, it will not be in phase upon exit from the crystal. However, after exit the two rays will combine - interfere - with each other and produce a single beam of light. This interference results in two distinct differences for the final ray: (1) it will, in general, be linearly polarized with its plane of polarization not parallel to the upper or lower polar and (2) the crystal will appear colored when viewed between crossed-polars - the resulting color is termed as an interference color.

Interference colors of minerals are directly correlated to the mineral's retardation. In thin sections the thickness is known, so the birefringence is easily calculated. The birefringence, along with determination of the optical class and approximate refractive index, is usually all that is required to identify most minerals in thin section.

Reference books on mineral identification (Nesse, 1986; Fleischer, et al. 1984) commonly list these optical properties.

The accessory shown in Figure 2 of the PLM is a retardation plate. Retardation plates are used to determine optic sign of minerals by determining the orientation of N and n of the crystal. They are also used to determine retardation, both qualitatively and quantitatively. These plates have a metal holder with an anisotropic crystal that can be inserted into the optic path of the microscope. Retardation plates are manufactured based upon two criteria. First, the crystal's orientation must be known and marked on the plate (usually the N direction will be labeled). Second, the thickness of the crystal must be controlled so the amount of retardation it produces is known.

There are three types of retardations. Plates cut to a single thickness that produce 1 or 1/4 retardation, plates cut into the form of a wedge that produce a range of retardations, say from 0 - 4 , and tilting compensators, in which a flat plate rotates, thus changing its thickness and retardation value. The tilting compensators are used for precise measurement of retardation.

G. *Interference figures*

Interference figures from anisotropic minerals have two main uses. (1) They aid in mineral identification by revealing the optical class of a mineral and (2) they allow the microscopist to determine the mineral's orientation, which is required for refractive index measurements and, in conjunction with x-ray crystallography, to determine a mineral's optical orientation. Interference figures are viewed by converting the PLM into conoscopic illumination. This is done by using the high numerical aperture lens (usually the highest power), crossing the polars, inserting a substage condensing lens, and inserting the Bertrad lens or removing the ocular.

There is a relationship between conoscopic and orthoscopic illumination. Whatever is occurring at the center of the field (the cross-

hair intersection) in conoscopic illumination will occur over the entire field in orthoscopic illumination. The crystal will be at extinction when switched to an orthoscopic view if the center of the field was dark in conoscopic illumination.

1. Uniaxial:

There are two limiting types of interference uniaxial figures: the flash figure (when the optic axis is parallel to the microscope stage) and the optic axis figure (when the optic axis is perpendicular to the microscope stage). There is an infinite number of off-centered optic axis figures in which the optic axis is not parallel or perpendicular to the microscope stage.

Figure 8 is a view of a centered optic axis figure. The figure shows isogyres, which are areas of extinction, and isochromes, which are lines of equal retardation. Stage rotation has no effect on a perfectly centered optic axis figure. The retardation increases moving outward from the outcrop of the optic axis, the melotope, which is in the center of the field of view. To determine the optic sign, a retardation plate is inserted with its N (slow) direction known and areas of the figure exhibiting subtraction and addition are observed. Recall that uniaxial minerals are positive when > and negative when < . The   vibration direction always occurs tangent to the isochromes, and   or ' are always perpendicular to . If subtraction occurs when N of the plate is parallel to , then   is n of the crystal and the crystal is positive. Conversely, as shown in Figure 8, if N of the plate is parallel to   and addition occurs, the mineral is negative. Only the   index can be measured when the optic axis is perpendicular to the stage.

The characteristic of a flash figure is the entire field of view is dark at extinction, except for some small areas at the edge of the field of view. After a slight stage rotation of only a few degrees, the interference figure "breaks-up" and leaves the field of view. When the figure "breaks-up" it does so into two diffuse dark hyperbolas that leave the field of view into

the quadrants into which the optic axis is being rotated. Once this type of figure has been located, both the   and   principal refractive indices can be measured. To locate crystals that may exhibit these interference figures from the many small crystals that may be present on the slide, look for the largest grain with the lowest retardation for a centered optic axis figure and the smallest grain with the greatest retardation to obtain a flash figure.

2. Biaxial:

There are four limiting types of biaxial interference figures. Three occur when either X, Y, or Z is perpendicular to the stage and the fourth occurs when an optic axis is perpendicular to the stage. The four figures are called optic axis (OA), acute bisectrix (AB), obtuse bisectrix (OB), and optic normal (ON). The Y direction always coincides with the ON. The AB and OB figures correspond with X and Z when the mineral is negative, or with Z and X when the mineral is positive.

The centered AB is the most useful biaxial figure. From it the microscopist can determine the mineral's optic sign and approximate 2V. 2V is found by the separation of the melatopes (OA1 and OA2, Figure 9). The optic sign is found by determining whether X or Z is the AB. Figure 9 is an example of a positive mineral because we are looking down Z. Note, that at the crosshair intersection true   and   outcrop, which coincide with Z and Y. Addition occurs with insertion of an accessory plate when N of the crystal is parallel to N of the plate -- for instance, at the crosshair intersection. If the crystal were negative,   would be replaced by   at the crosshair intersection and subtraction would occur at that point.

There is no clear set of rules for locating the different types of interference figures for biaxial minerals, except for the OA figure, which is the same as in the uniaxial case - find a large crystal with small retardation. Depending upon 2V and the mineral's birefringence, different grains will exhibit different interference figures.

Uniaxial vs biaxial character can often be determined without centered figures. An isogyre that passes through the center of the crosshairs and is not parallel to a crosshair indicates a biaxial mineral.

H. *Optical Orientation*

The optical orientation of a mineral relates the orientation of the optical indicatrix to the crystallographic axes (Figure 10). The optical orientation is required to relate the optical properties to the crystal structure and is determined by using optical techniques to locate the crystal's indicatrix. Next, the crystal is x-rayed to determine the orientation of its crystallographic axes. This information is then combined and the relationship between crystallographic axes and indicatrix determined. One major use of optical orientation is the measurement, with associated correlations, of chemistry with extinction angles on various cleavage traces.

The spindle stage greatly aids in determination of optical orientation. The indicatrix orientation can be rapidly and precisely found with it. Next, the crystal used on the spindle stage can be transferred to an x-ray diffractometer and the crystallographic axes located.

The optical orientation of an isotropic mineral is trivial because the indicatrix is a sphere and can be oriented in any direction. Likewise, the optical orientation is simple for uniaxial minerals. The vibration direction is always parallel to the c-crystallographic, by definition. However, for biaxial minerals a more complex, and useful, situation exists. For the biaxial minerals it is necessary to consider each crystal system individually.

For orthorhombic minerals the three mutually perpendicular crystallographic axes, a, b, c, are parallel to the three mutually perpendicular optical directions, X, Y, Z. There are six possible relationships between these directions: (1) a=X, b=Y, c=Z (2) a=X, b=Z, C=Y (3) a=Z, b=X, c=Y (4) a=Y, b=X, c=Z (5) a=Y, b=Z, c=X and (6) a=Z,

b=Y, c=X. An example of case #6 is shown for the orthorhombic mineral andalusite in Figure 10.

In the monoclinic crystals one of the optical directions X, Y, or Z is parallel to b, the single symmetry axis. For the monoclinic mineral scolecite (Figure 10) b=Z. Because of the monoclinic symmetry, the other two directions, in this example X and Y, lie in the plane containing the other two crystallographic axes. To complete the optical orientation for a monoclinic mineral, the angle between c and the optical direction nearest to it is usually given.

For triclinic minerals none of the optical directions coincide with any of the crystallographic axes. To relate the two, sets of axes angles must be determined between them and reported, or shown schematically in an optical orientation diagram.

Dispersion of the optical orientation can occur for monoclinic and triclinic crystals. In these systems the indicatrix actually moves as a function of wavelength. Dispersion of the optical orientation is not possible in the other crystal systems because of symmetry constraints placed upon the indicatrix by the crystal system.

The morphological correlation between the refractive indices and the crystal is an important property for mineral identification. When the smallest refractive index value is parallel to the longest dimension of a crystal, it is termed length fast (andalusite, Figure 10). When the largest refractive index is parallel to the longest dimension of the crystal, it is termed length slow. A third possibility exists for biaxial minerals when is parallel to the long axis of the crystal. In this case the crystal is termed length intermediate.

I. *Plecochroism, absorption, and color*

Plecochroism, absorption, and color are helpful aids in mineral identification and useful in fully understanding the crystal structure of a mineral. These three phenomena are closely related. Pleochroism is the change in color of an anisotropic sample as a function of the vibration

direction. Absorption occurs when light is absorbed in the crystal, which results in a decrease in light transmission. Pleochroism and absorption manifest themselves on the PLM in plane polarizer light by a change in color and light transmission upon stage rotation.

Many minerals are colored, and many colored minerals exhibit both pleochroism and absorption. The causes of these phenomena are well beyond the scope of this article. The interested reader should consult Nassau (1978) for an excellent discussion of color in minerals.

V. RELATIONSHIP OF OPTICAL PROPERTIES TO CRYSTAL CHEMISTRY

A. *General relationships*

In general, the refractive index is related to the electron density of the mineral. Anything causing the electron density to increase throughout the structure (such as substituting elements of higher Z, changing bond type from covalent to ionic, increasing the pressure, lowering the temperature, etc.) will cause the refractive index to increase. Diamond has an approximate refractive index of 2.4, while fluorite has an approximate refractive index of 1.4 - diamond has nearly 100% covalent bonding while fluorite has predominantly ionic bonding. For any solid solution series, except one in which bonding type varies considerably, the refractive index increases when higher Z cations replace lower Z cations. For example, in the olivine series the mean refractive index goes from approximately 1.65 in forsterite to 1.86 in fayalite as Fe replaces Mg.

Many simple interpretations of the structural basis for optical properties exist, and an understanding of them greatly enhances one's appreciation of optical mineralogy. The hexagonal carbonates, calcite, dolomite, etc. all have planer CO_3 groups oriented in a plane normal to their c crystallographic axis. Thus, the electron density of the structure is very large in the direction normal to c, and low parallel to c. For this

reason, this group of minerals has low   values and high   values (about 1.5 vs 1.7) and is uniaxial negative.

The silicates provide several good examples. The chain silicates tend to be optically positive because the electron density is the greatest parallel to the chains. In the sheet silicates the electron density is the greatest in the sheets, causing them to be optically negative. Also, the two directions in the sheet are nearly equal, so the micas possess very small 2Vs. In the framework silicates the structure is very homogeneous; thus, this class has very small birefringence because the electron density is nearly equal in all directions.

B. *Andalusite*

Andalusite, $(Al, Fe, Mn)^{VI} Al^V SiO_5$ is an orthosilicate whose structure is composed of edge sharing chains of octahedron parallel to the c crystallographic axis. Al, Fe, and Mn can occupy these octahedral sites. Pure andalusite (Al_2SiO_5) is length fast as shown in Figure 10. With substitution of Mn and Fe for Al it changes to length slow. The refractive index parallel to the c crystallographic axis actually changes from   in pure andalusite to   in the Fe, Mn rich variety. Plots of the three refractive indices vs Mn+Fe in the early literature showed all three refractive indices increasing at the same rate, when indeed they increased at different rates and intersected at about 6 mole % Fe+Mn. When the values intersect, this causes the mineral appears isotropic.

C. *Feldspar*

Feldspars are the most important mineral group simply because of their abundance, and, accordingly they have been the basis for many optical studies. One of the more recent studies (Su et al., 1986) showed how the structural state (i.e., order/disorder) could be determined by measuring 2V and the chemical composition, thus providing a rapid method for petrologists to determine possible cooling histories of feldspar crystals.

D. *Cordierite*

Cordierites are framework Mg-alumino-silicates which have channels running parallel to their c crystallographic axis. Several ionic complexes can enter these channels. Armbruster and Bloss (1982) studied cordierites with differing amounts of CO_2 and H_2O. Their studies showed that positive cordierites contained CO_2 while negative cordierites contained H_2O. Also, they determined the orientation of these molecules within the channels by observing rates of refractive index change along the different crystallographic axes - the fastest changing directions would have the molecules more nearly oriented to coincide with them.

E. *Zeolites*

The zeolites are all alumino-silicate framework structures and thus have very low birefringence. The refractive indices are very sensitive to small changes in the crystal structure. They are typified by channels, several angstroms in diameter, running through the framework. Many different cations and ionic complexes, along with H_2O, reside in these channels.

Preliminary work on the natrolite group zeolites, natrolite (Na rich), mesolite (intermediate Ca, Na variety), and scolecite (Ca rich) shows an opposite trend as in the andalusites. Natrolite is length slow, mesolite is length intermediate, and scolecite is length fast (Figure 10).   This trend is easily explained: similar to the sheet structures, the refractive index increases at a greater rate in the plane perpendicular to the c crystallographic axis as Ca and H_2O replaces Na, so the two principal refractive indices in the ab plane increase at approximately the same rate, which is much greater than the increase parallel to c. This simple observation explains why the optical orientation for these three minerals is so different.

The zeolites provide an excellent example of how poorly the optical properties of minerals are understood. The optical properties are usually reported but not crystal chemically and structurally interpreted. However, these interpretations are usually fairly straightforward and aid in our total knowledge of the relationships between the crystal chemistry and physical properties of minerals. Also, a major research project will be studying the effects of channel occupants on the optical properties as was done in the cordierites.

A brief review article (Gunter and Bloss, 1988) gives more references to recent optical studies.

VI. ADVANCED METHODS IN OPTICAL MINERALOGY
A. *Spindle stage*

The spindle stage is a one-axis rotation device that mounts onto the stage of a PLM. With it, any privileged vibration direction of an anisotropic crystal can be rotated into the plane of the microscope stage and brought parallel to the incident plane polarizer light, thus allowing for direct measurement of any refractive index without appreciable error due to misorientation.

Figure 11 shows a schematic diagram of a spindle stage mounted onto a microscope stage, with a mineral on its tip. When the crystal is immersed in an oil cell (not shown) the mineral's refractive index can be checked against the oil's as described in the immersion method above. The main advantages of the spindle stage are: (1) all the measurements can be made on the same crystal, (2) the oil cell is changed and the crystal retained, thus not requiring multiple slide mounts as in the routine immersion method, and (3) the microscopist has complete control over the mineral's orientation.

The orientation of the biaxial indicatrix can be determined in one of two ways with the spindle stage: (1) the interference figures can be observed while the crystal is rotated about the spindle axis, or (2) extinction data can be collected and solved to determine directly the

spindle stage setting (S) and the microscope stage setting (M_s) that orients AB, OB, and ON into the plane of the microscope and parallel to the lower polarizer. The latter method has the advantage of determining 2V for the mineral to within a few tenths of a degree. See Bloss (1981) for a thorough treatment of the spindle stage method.

B. *Refractometry*

Refractometers are normally used to determine the single refractive index for a liquid or an isotropic solid. However, refractometers can be used to determine all the principal refractive indices for anisotropic samples. Further, all that is required is a single polished random section through the mineral. In fact, these techniques were developed and refined in the late 1800's, long before the immersion method. However, they have fallen so far out of use that most current books and research papers are filled with mistakes and lack of references to the original works.

Figure 12 shows a schematic view of the hemicylinder of a refractometer. Light is incident from the back and is reflected from the mineral / hemicylinder interface. Analysis of this reflected light and application of Snell's Law (Equation 2) is required to determine the refractive index of the mineral. For anisotropic minerals the orientation of the plane polarized light must be controlled. Figure 12 shows the intersection of the measurement plane (X-Y plane) of the refractometer with an anisotropic indicatrix. When the incident polarized light is made to vibrate parallel to N, its value can be found; likewise, when the light is parallel to n, its value can be found. By rotation of the sample about X and collection of N and n values, the size and shape of the optical indicatrix can be found.

The following similarity exists between the spindle stage and the refractometer: with the refractometer any vibration direction brought into the X-Y plane can be determined, and with the spindle stage the vibration direction must be brought into the plane of the microscope

stage. For either case, once the vibration direction is in the "measurement" plane, the next step is to orient the plane polarized light parallel to it.

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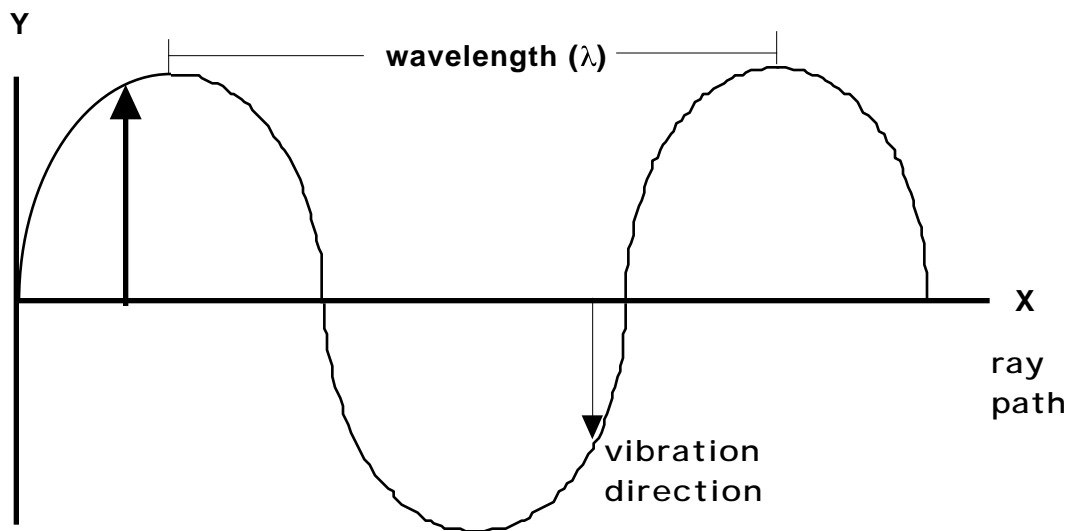
Figure 1. Plane polarized light, showing wavelength, ray path, moving in
the x direction, and vibration direction perpendicular to X in the Y
direction. The light is plane polarized in the XY plane. The vibration
direction is perpendicular to the ray path in isotropic and certain
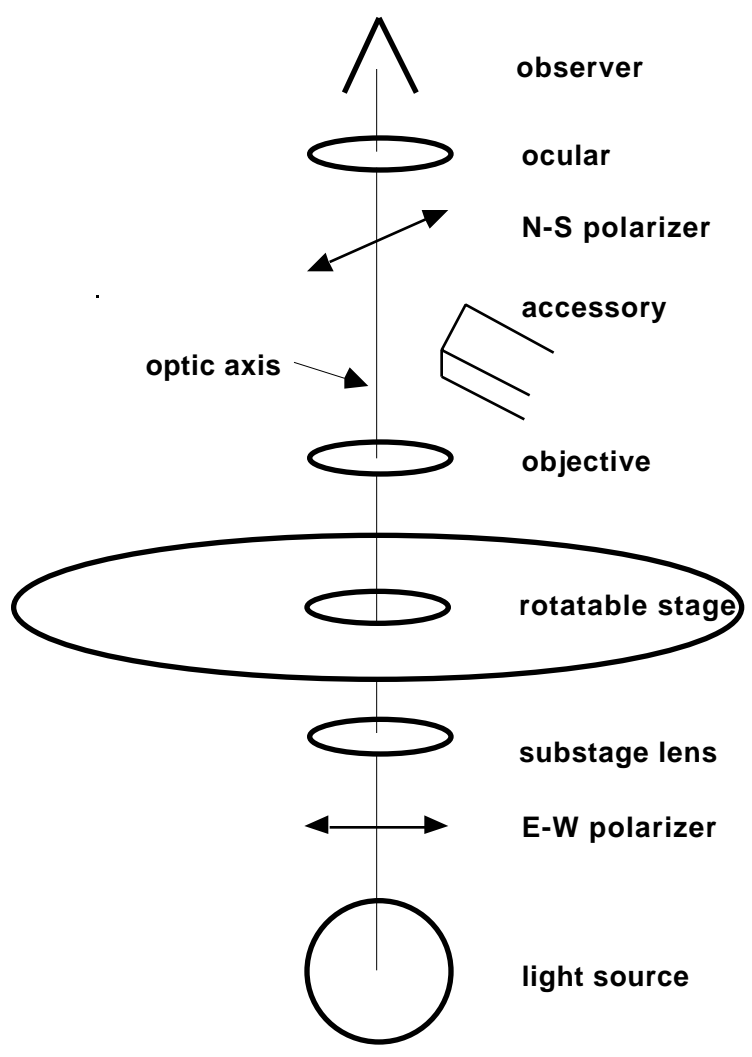directions in anisotropic crystals.

Figure 2. Schematic view of a polarizing light microscope (PLM). Light
travels along the optic axis from the light source into the substage
lens system, in which either orthoscopic or conoscopic light rays exit
onto the sample placed on the rotatable stage. There is an E-W
polarizer below the stage and a removable N-S polarizer above.
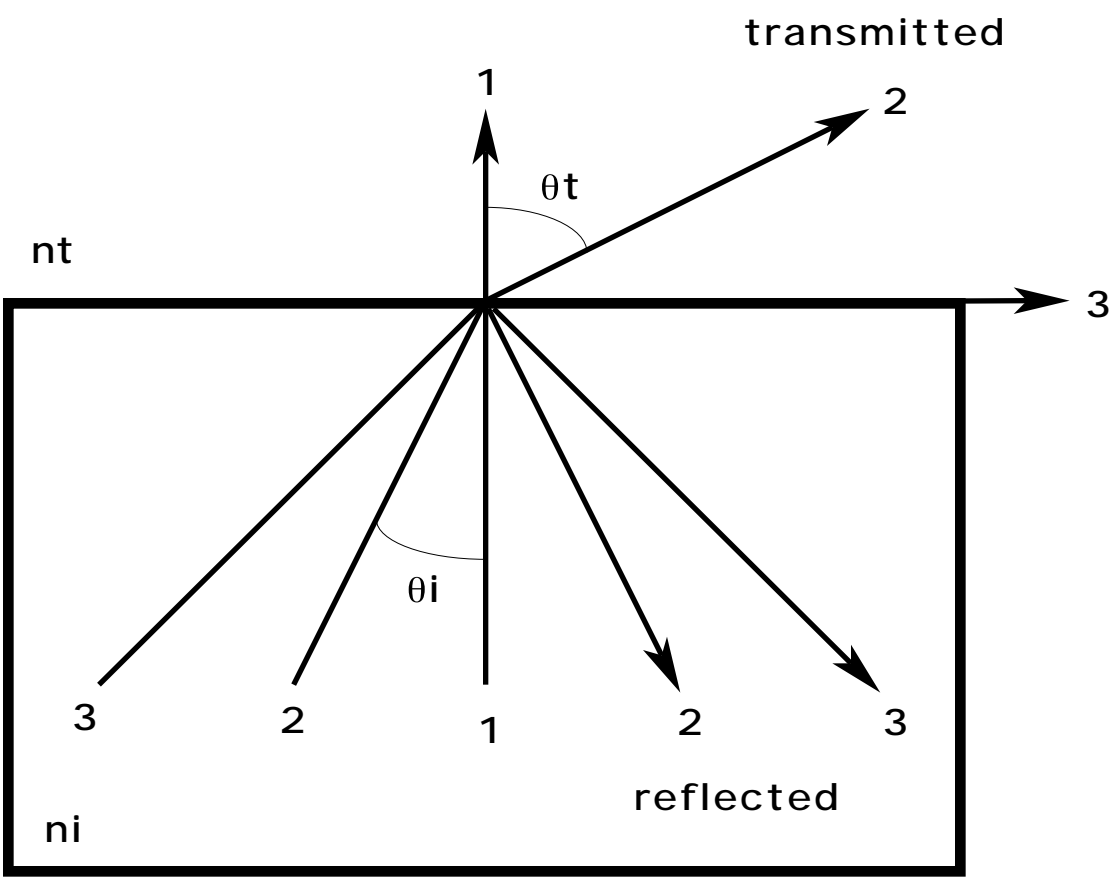
Figure 3. Ray paths illustrating reflection and refraction. Rays 1, 2, 3 are incident from the lower left and each ray has a reflected and refracted portion. The angle of reflection is equal to the angle of incidence (θ_i). The angle of refraction, or transmittance (θ_t), can be found by application of Snell's Law. Ray 3 shows the case of total internal reflection when $\theta_t = 90°$.
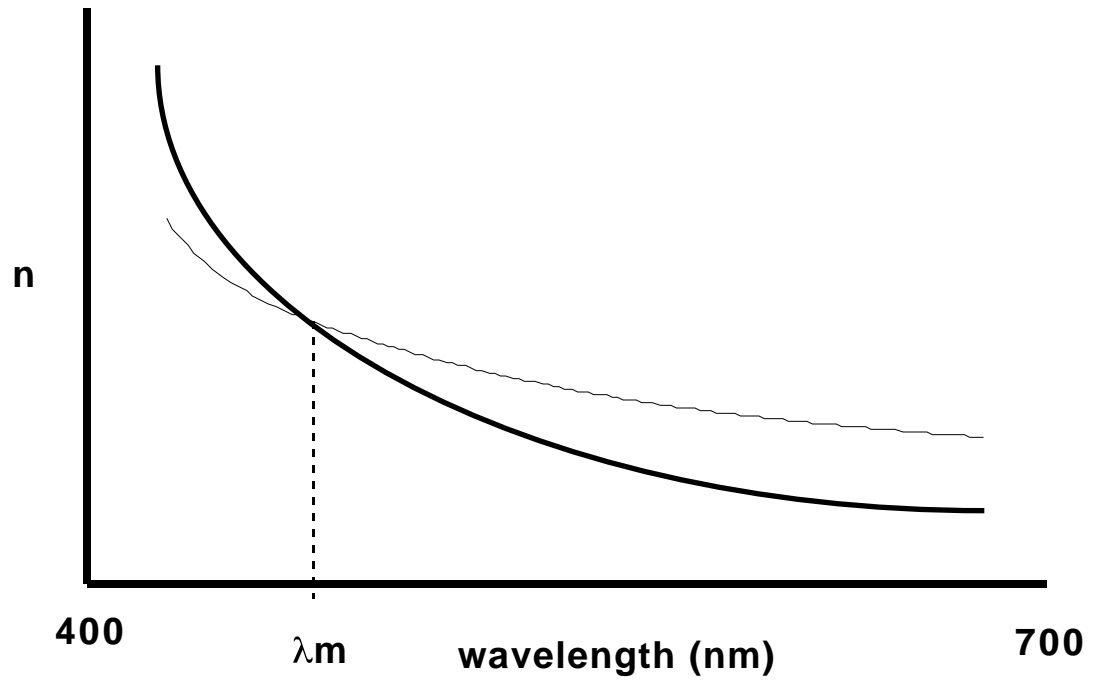
Figure 4. Dispersion curves for two materials. Dispersion curves in the
  visible have this distinctive concave upward shape. The bolder curve
  has a higher dispersion than the lighter curve. The refractive index of
  the two materials are equal at $_m$, the wavelength of match.
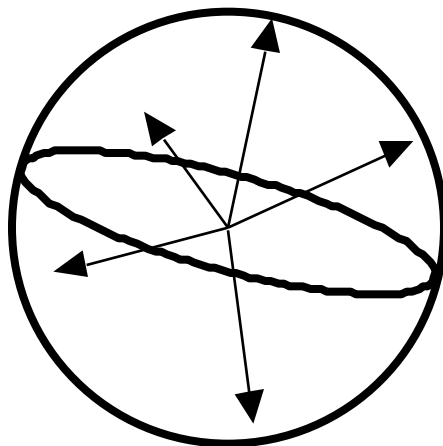
Figure 5. Optical indicatrix for isotropic minerals. A series of vectors, whose length is proportional to n, is constructed from a common origin. The surface the tips of these vectors describe, in this case a sphere, is the optical indicatrix.

optic axis

ε

ω

ε

ω

-

+
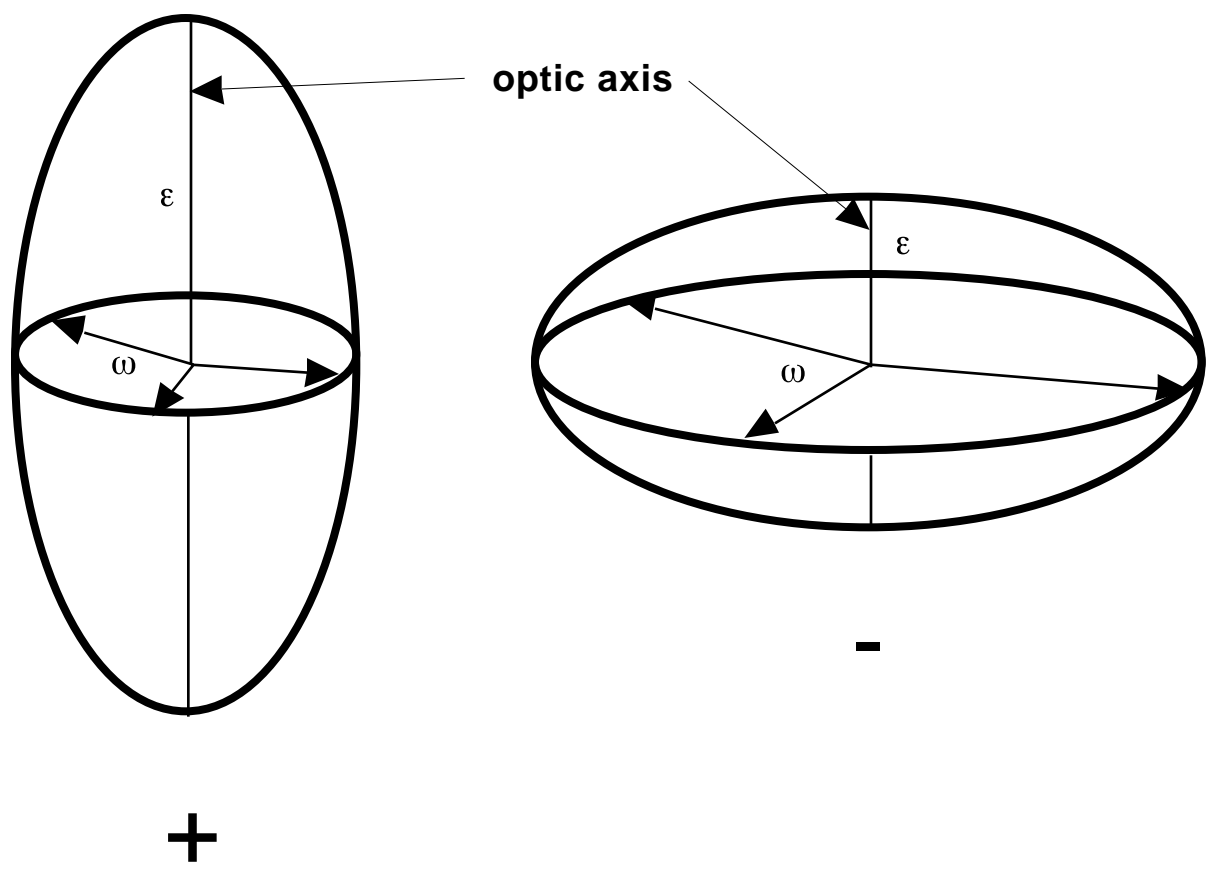
Figure 6. Optical indicatrix for uniaxial minerals. When   >   the mineral
is positive; when   <   it is negative. These indicatrices were formed
in a similar manner to the isotopic indicatrix. However, because the
refractive indices differ, depending upon the vibration direction, they
are no longer spheres.
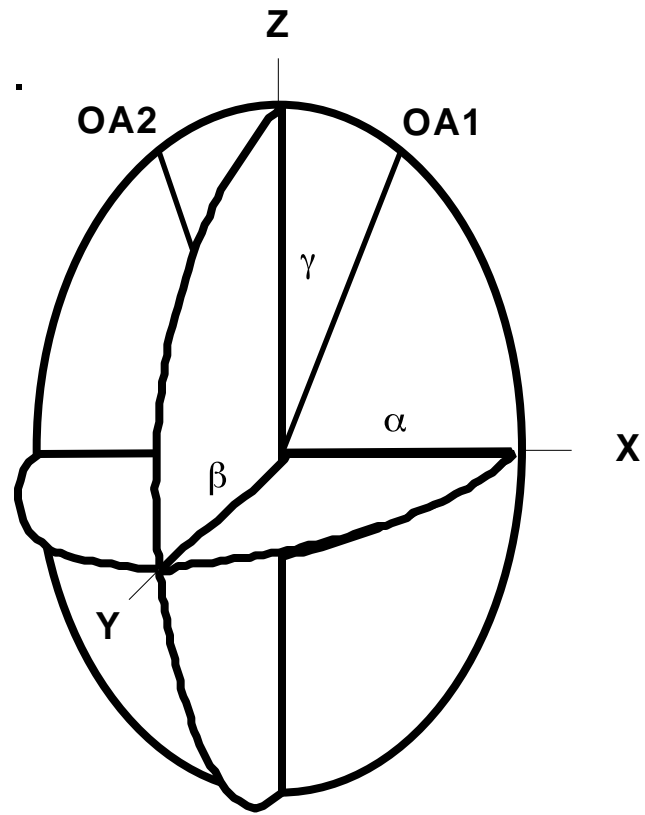
Figure 7. Optical indicatrix for biaxial minerals. This indicatrix is built on
   the three mutually perpendicular directions X, Y, and Z. The , , and
      refractive indices correspond to these directions. Both optic axes
   are shown (OA1 and OA2) -- they occur in the optic plane (XZ). This
   indicatrix shows a positive mineral because Z is the acute bisector of
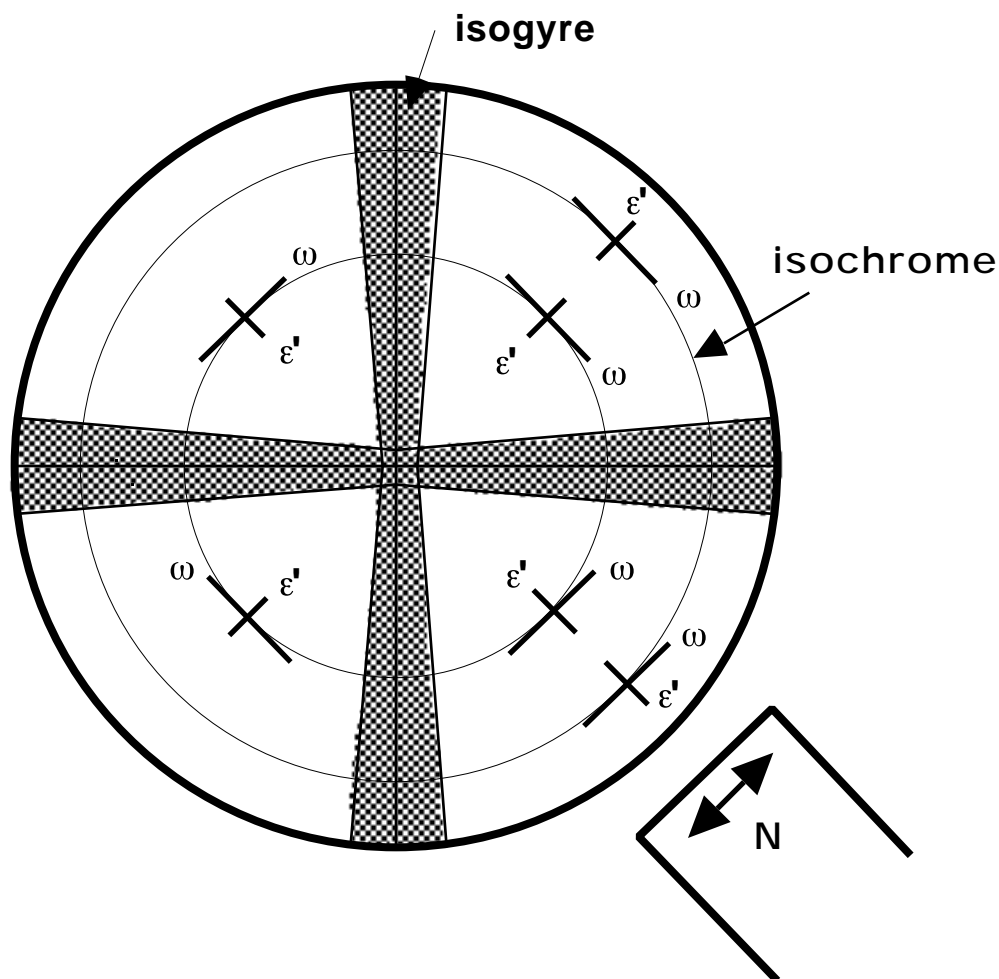   the optic axial angle.

Figure 8: Centered uniaxial optic axis interference figure. All interference figures are viewed with conoscopic light. Areas that appear dark - at extinction - are called isogyres, and cones of equal retardation are isochromes. The outcrop of the optic axis is at the center of the field of view. The vibration directions are shown in this uniaxial negative mineral. The sign is determined by insertion of an accessory plate and observation of addition and subtraction within the figure.
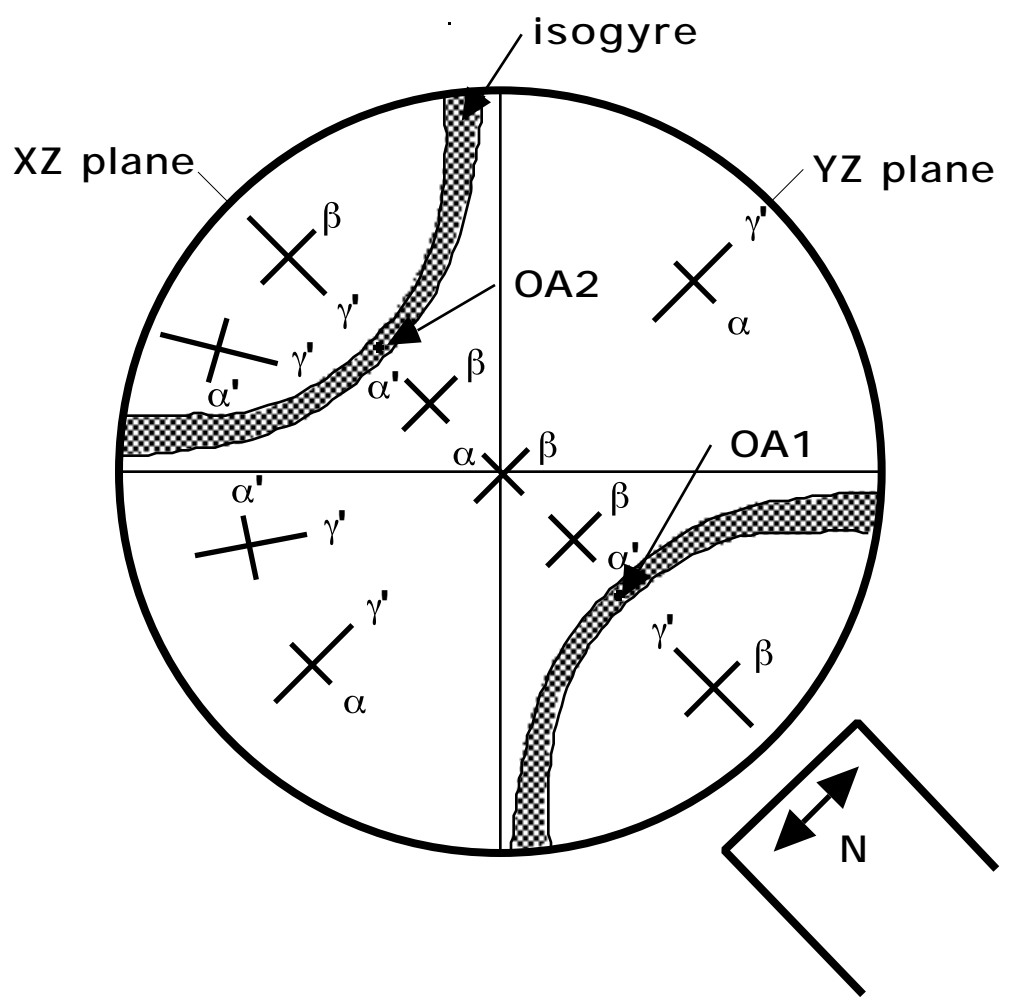
Figure 9: Centered acute biaxial interference figure. All the vibration directions are labelled for this positive mineral and the isogyres shown. 2V is the distance between OA1 and OA2; several methods exist to measure, or estimate, that distance (Bloss, 1961).
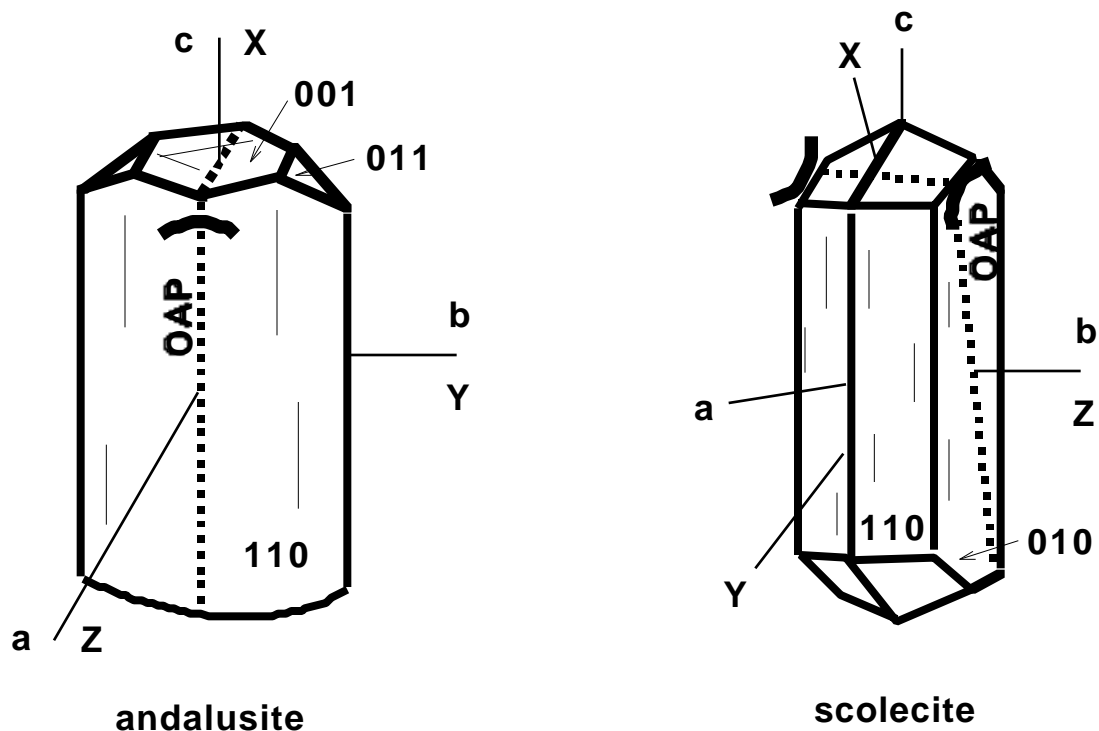
andalusite

scolecite

Figure 10: Optical orientation diagrams for an orthorhombic mineral,
andalusite, and a monoclinic mineral, scolecite. Andalusite shows
the crystallographic axes a, b, c parallel to the indicatrix axes Z, Y, X,
thus defining its optical orientation. Scolecite shows b=Z and the
approximate angle between c and X defines its optical orientation.
Both minerals also show the relationships to cleavage, the location of
the optic axial plane (OAP), and the location of the two optic axes
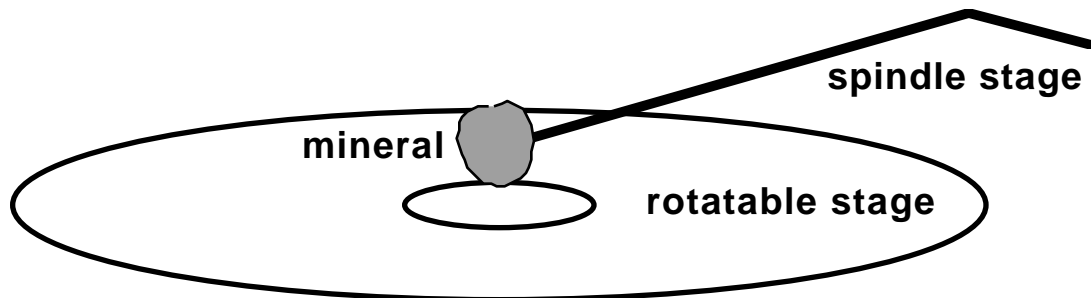marked by the short, heavy arcs.

Figure 11. Schematic representation of a mineral mounted on a spindle
stage which is in turn mounted on a rotatable stage of a polarizing
microscope. The crystal is immersed in an immersion media cell (not
shown) and the crystal can be oriented to bring any vibration direction
into the plane of the stage by rotation on the spindle axis and parallel
to the lower polar by rotation on the microscope stage. This done, the
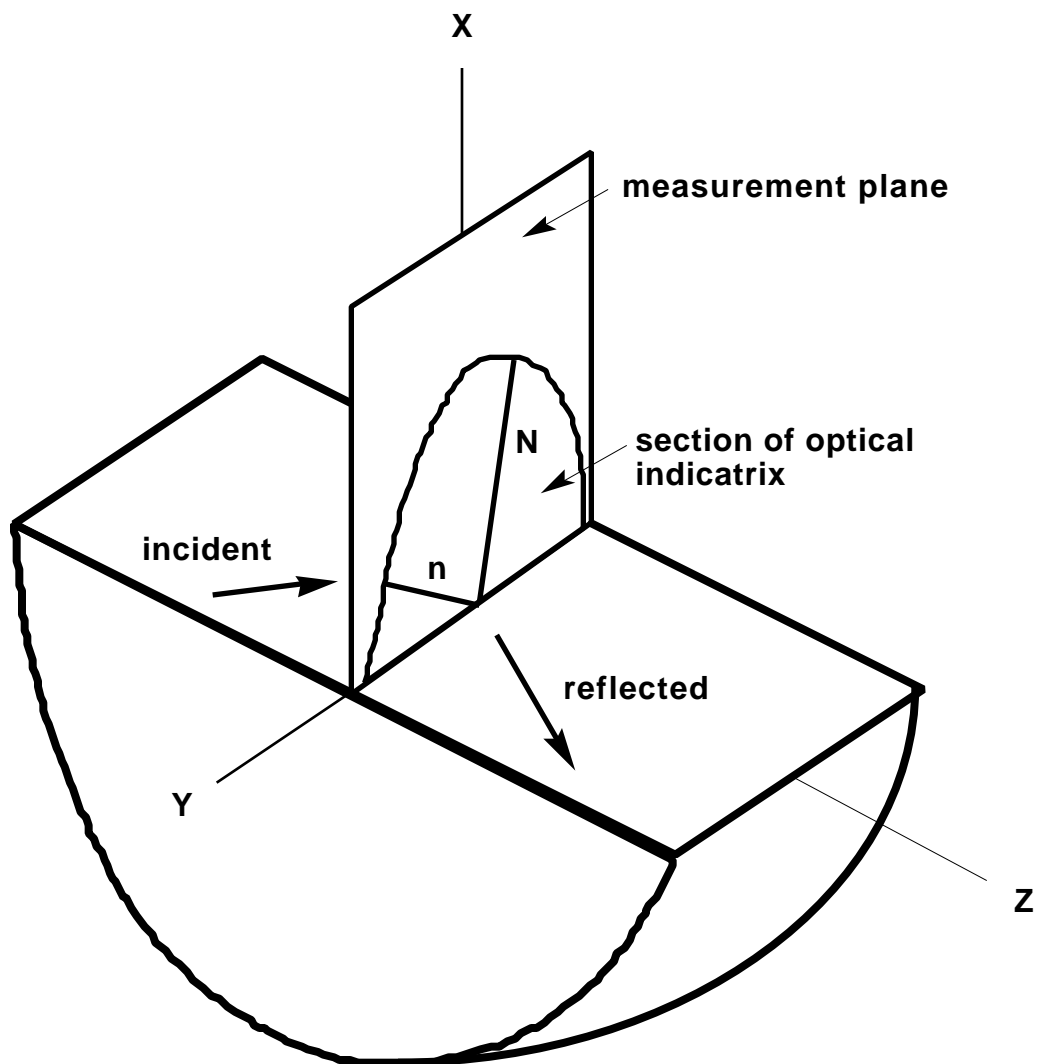refractive index can be determined by the immersion method.

Figure 12. Schematic representation of refractometer with a sketch of a
plane through the optical indicatrix. Light is incident from the rear of
hemicylinder and reflected toward its front. The critical angle for any
vibration direction brought into the the XY plane can be measured by
aligning the vibration direction of the incident light parallel to it. A
series of measurements can then be made while rotating the sample
about X and varying the plane of polarization of light. This data can
then be analyzed to give the shape and orientation of the optical
indicatrix.