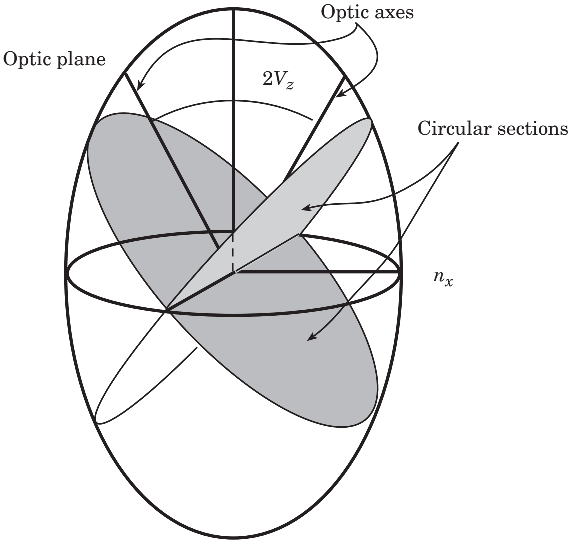
Optics of Biaxial Materials

In this laboratory exercise, we will explore the optical properties of biaxial minerals. The biaxial minerals include members of the orthorhombic, monoclinic, and triclinic crystal systems. Orthorhombic minerals have symmetry elements of three A_2, each aligned along the mutually perpendicular crystallographic axes. (Remember that a mirror plane is equivalent to $\overline{A}_2$.) Examples of orthorhombic minerals are olivine, orthopyroxene, anthophyllite, anhydrite, and andalusite. Monoclinic minerals have a single A_2 (or its improper equivalent mirror plane or both), which by convention is aligned with the b axis. There are many monoclinic minerals: clinopyroxene, tremolite, muscovite, biotite, gypsum, and chlorite and many others. Triclinic minerals have only A_1 or a center of symmetry. The most important members of the triclinic system are the feldspars, but others include kyanite and wollastonite.

Biaxial indicatrix

As in the case of uniaxial minerals, the optical properties of biaxial minerals are characterized by the phenomenon of double refraction. For biaxial minerals, though, there is no ordinary ray; both rays are extraordinary. Instead of two principal indices of refraction, there are three. I label them n_x, n_y, and n_z, in order of increasing value. The resulting indicatrix is a general triaxial ellipsoid. If $n_y - n_x < n_z - n_y$, the ellipsoid is prolate (+); otherwise, it is oblate (−).

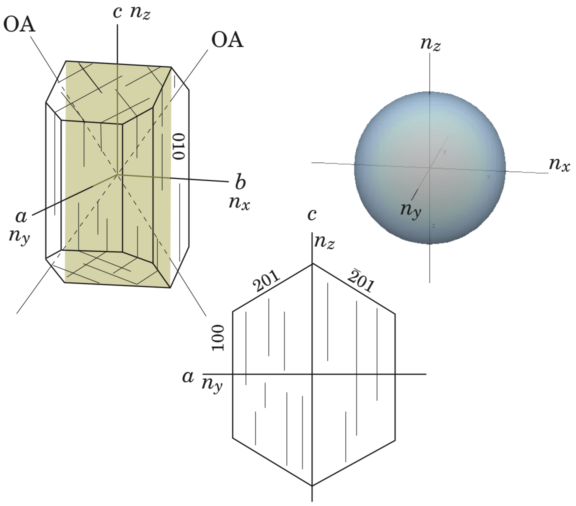


The general ellipsoid has two unique central sections that are circles, with radius n_y and have a dihedral angle bisected by n_z. The normals to these sections are called OPTIC AXES. The angle between the optic axes is called $2V$ (a mineral with a $2V = 0$ is uniaxial).

Orthorhombic minerals. The orientation of the ellipsoid with respect to the crystallographic axes depends on the symmetry. Orthorhombic crystals are required to have n_x, n_y, and n_z parallel to a, b, and c (not necessarily in that order). Monoclinic crystals must have one axis parallel to b. Triclinic symmetry imposes no constraints on the orientation of the indicatrix. The orientation of the indicatrix can be indicated by the extinction angle, ie., the angle between the polarizer or analyzer and a prominent cleavage or crystal face when the crystal is at extinction.

Optic orientation diagrams are used to indicate the orientations of the principal optical axes with respect to the crystallographic directions. An example for hypersthene is shown below.

Orthopyroxene
$(Mg, Fe)_2Si_2O_6$
$a = 18.22–18.43$ Å, $b = 8.81–9.08$ Å, $c = 5.17–5.24$ Å, $Z = 8$
$H = 5–6$
$G = 3.21–3.96$
Biaxial (+ or –)
$n_x = 1.649–1.768$
$n_y = 1.653–1.770$
$n_z = 1.657–1.788$
$\delta = 0.007–0.020$
$2V_x = 50–132°$



Note the indicatrix at the upper right. It is almost, but not quite, a sphere. This is generally the case for anisotropic minerals. It has to be true, though, that the axes of the indicatrix for an orthorhombic mineral must coincide with the crystallographic axes. In thin section, you should be able to identify a crystallographic direction by a straight face or a cleavage trace. You should also be recognize that the mineral has parallel or symmetric extinction. Other physical properties of the mineral also must obey the symmetry. An easily observed phenomenon under the microscope is pleochroism; the principal absorption directions must correspond to the crystallographic axes.

Monoclinic minerals. Monoclinic minerals have only a single 2-fold axis of symmetry or a mirror plane or both. By convention the axis is taken to be the b crystallographic axis. What this means for the optical properties is that only one of the principal indices of refraction, one of the axes of the indicatrix, must coincide with the b axis. The other two lie in the plane perpendicular to b, which is the mirror plane in the classes m and $2/m$. The other two do not coincide with the a or c axes. The result is that (100) and (001) sections have parallel extinction, but (010) sections have inclined extinction. To describe the optical properties of monoclinic minerals, you have to include the extinction angle with the indices, $2V_z$, and the orientation of the OAP. The best way to do this is with an optical orientation diagram. An example for clinopyroxene is given below. There are, of course, two complementary angles; the smaller of the two is taken to be the extinction angle. We can also define positive and negative angles by choosing an angle to be positive if the polarization direction lies in the obtuse angle β. Extinction angles help you orient the optical indicatrix with respect to the crystallographic axes and can be a diagnostic property for identification of minerals under the microscope. For example, clinopyroxene typically has an extinction angle of $\sim 45°$, whereas clinoamphibole has an angle of $\sim 15°$.

Calcic clinopyroxene

Diopside $CaMgSi_2O_6$

a = 9.75 Å, b = 8.90 Å, c = 5.25 Å,
β = 105.6°, Z = 4

Hedenbergite $CaFeSi_2O_6$

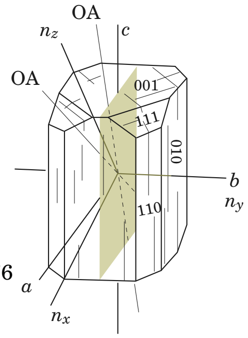
a = 9.85 Å, b = 9.03 Å, c = 5.24 Å,
β = 104.8°, Z = 4

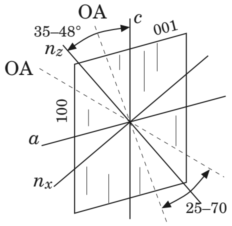
Augite $(Ca, Mg, Fe, Fe^{3+}, Al)_2(Si, Al)_2O_6$

a = ~ 9.7 Å, b = ~ 8.8 Å, c = ~ 5.3 Å,
β = 106.9°, Z = 4

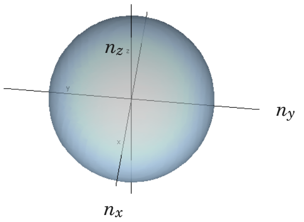
monoclinic $2/m$
H = 5.5–6.0
G = 3.19–3.56

Biaxial (+)
n_x = 1.664–1.745
n_y = 1.672–1.753
n_z = 1.694–1.771
δ = 0.018–0.034
$2V_z$ = 25–70°





(010) section



Triclinic minerals. The symmetry of triclinic minerals imposes no constraint on the orientation of the optical indicatrix with respect to the crystallographic axes. For minerals such as plagioclase feldspar, extinction angles are sensitive to composition. In fact, there are several schemes for determining the composition of feldspar from its extinction angle. We will devote next week's lab to feldspar, pyroxene, and amphibole—common, important, and sometimes confusing minerals. An optic orientation diagram for plagioclase, below, shows the great change in the orientation of the OAP with composition. Remember that the indicatrix is *almost* a sphere, and small changes in n can result in a large change in the shape of the indicatrix.

Plagioclase

$NaAlSi_3O_8$–$CaAl_2Si_2O_8$
triclinic $\bar{1}$

Low Albite

a = 8.137 Å, b = 12.785 Å, c = 7.158 Å,
α = 94.26°, β = 116.60°, γ = 87.71°,
Z = 4

Anorthite

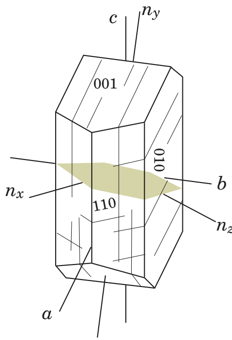
a = 8.177 Å, b = 12.877 Å, c = 14.169 Å,
α = 93.17°, β = 115.85°, γ = 92.22°,
Z = 8

H = 6.0–6.5
G = 2.60 (ab)–2.76 (an)

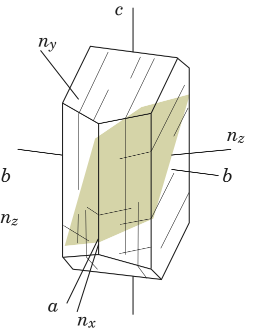
Biaxial (+ or –)
n_x = 1.527–1.577
n_y = 1.531–1.585
n_z = 1.534–1.590

δ = 0.007–0.013

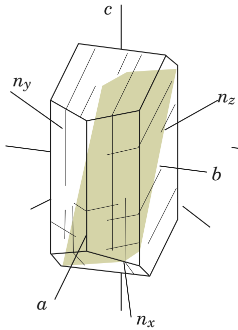
$2V_z$ = 45–102° (high plagioclase)
$2V_z$ = 75–102° (low plagioclase)



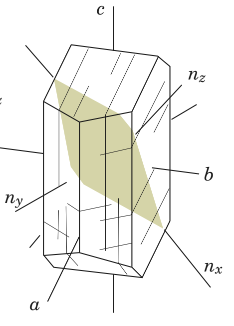
Albite



Andesine



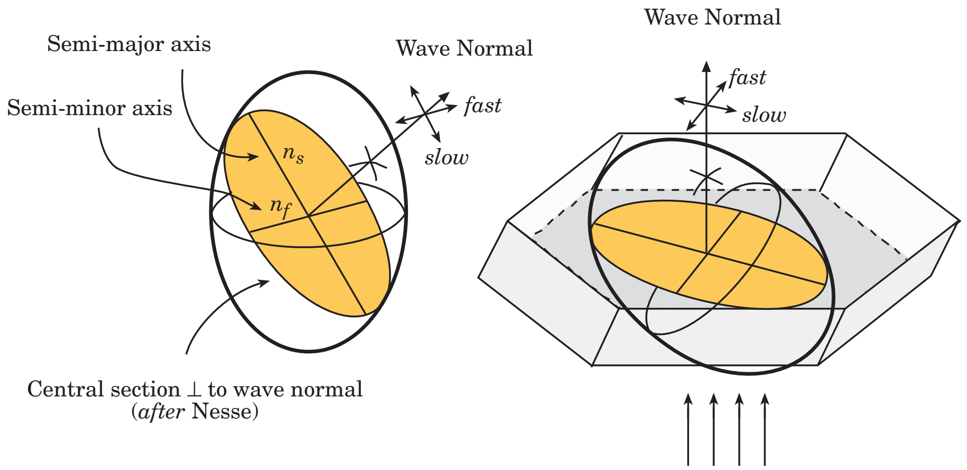
Labradorite



Anorthite

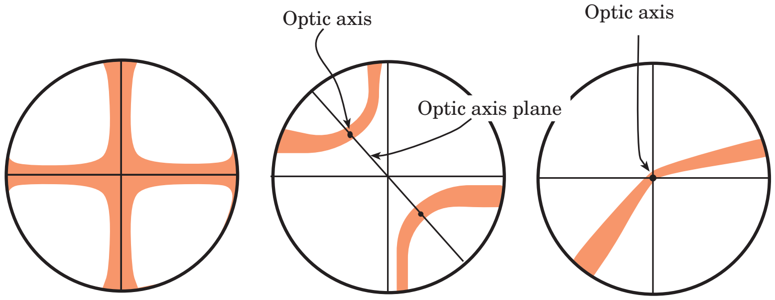
Double refraction. The polarization directions and indices of refraction are given by the central section of the ellipsoid perpendicular to the wave normal, as in uniaxial minerals. An example for incidence in a general orientation is shown below.

Biaxial Indicatrix
Polarization Directions &
Indices of Refraction for Normal Incidence



Conoscopic observation

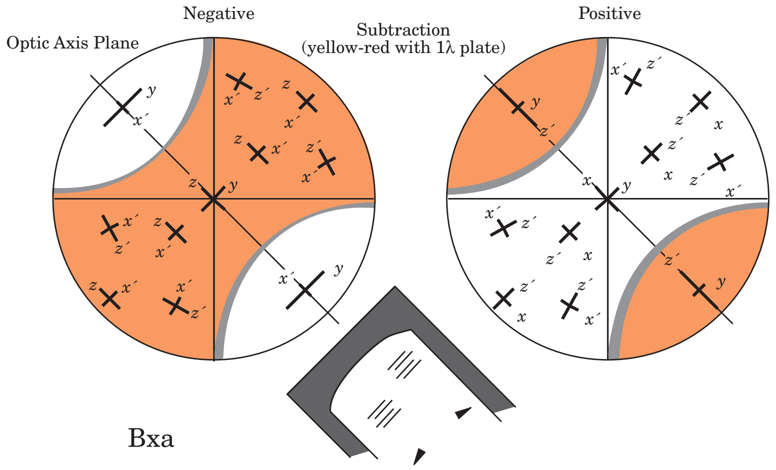
Principal sections of the ellipsoid contain one or two of the principal indices of refraction. These sections are commonly referred to by the interference figure observed. For positive minerals, the section normal to n_z is called ACUTE BISECTRIX (Bxa); the section normal to n_x is the OBTUSE BISECTRIX (Bxo); the section normal to n_y is a FLASH FIGURE; and the section along the optic axis is an OPTIC AXIS FIGURE. Examples of what some of these figures look like are shown below. Look at the oriented mineral sections to learn how to recognize the figures and to see how they change with a change in the magnitude of $2V$.



Extinction Bxa Optic axis figure

The optic sign can be determined from the interference figure with the aid of the 1λ accessory plate, just as for the uniaxial minerals. If the figure is a Bxa or optic axis figure oriented as above, the color of the inside bend is red-orange for positive and blue for negative minerals.

Optic Sign of Biaxial Minerals



Exercises

1. Look at the thin sections of oriented mineral grains from the Krantz collection. Look in both plane-polarized and cross-polarized light. You should be able to recognize pleochroism, if present, and extinction angle. Try to recognize the cleavage in the amphibole, feldspar, and pyroxene samples. You might also be able to recognize growth zoning in the plagioclase sample. Twinning will also be present in the feldspar. Look at sections 57 (bronzite 010), 74 (augite 010), 84 (hornblende 010), 88 (actinolite 010), and 118 (anorthite 010). All are sections parallel to the a–c plane, which is perpendicular to the b axis in the orthorhombic and monoclinic crystals, but not in the triclinic (you should be able to explain why this is so). What is the pleochroism? What is the extinction angle? What cleavage do you see?

2. Pleochroism is a many splendored thing. Look at the section with four minerals mounted on it. Number 1 is tourmaline, 2 is hornblende, 3 is biotite, and 4 is piemontite. Observe (in plane-polarized light, of course) and describe the pleochroism in these minerals. Minerals with combinations of Fe^{3+}, Ti, and Mn^{3+} can show extreme pleochroism and can make looking at thin sections fun!

3. Distinguishing uniaxial and biaxial minerals commonly requires observation in conoscopic light. You have to learn to recognize the uniaxial optic-axis figure, the BXA, the BXO, the biaxial optic axis figure, and the flash figure. Look at the slide with six mounted grains showing the variety of interference figures. Also insert the accessory plate to determine whether the mineral is optically positive or negative. Now go back to the oriented mineral sections from the first exercise and identify the figures you see for each (010) section.

4. The magnitude of $2V_z$ is also a sensitive indication of the mineral. Look at the grain mount with six examples of minerals having different values of $2V_z$. It's a good idea to get the knack of estimating the value of $2V_z$ from an optic-axis or BXA figure. Actually, the value can be measured precisely by knowing the numerical aperture of the objective lens and using a nomogram relating the N.A. and the figure to the $2V_z$. Usually, though, an estimate is all that is required to identify the mineral.

5. Learn to recognize some common biaxial minerals in rock thin sections. Note characteristics of each that will help you identify the mineral quickly. These include color, pleochroism, cleavage, twinning, birefringence, optic sign, $2V$, extinction angle, and mineral association.

5	orthoclase in granite	52	muscovite in gneiss
10	sanidine in trachyte	54	chlorite in schist
13	plagioclase in gneiss	57	chloritoid in schist
27	orthopyroxene in norite	60	olivine in basalt
33	augite in diabase	69	cordierite in hornfels
41	actinolite in schist	82	andalusite in hornfels
47	biotite in gneiss	83	sillimanite in gneiss