# ESS 439 Igneous Petrology/Optical Mineralogy

## Lab # 3: Biaxial minerals

In this laboratory session we will introduce the concepts of the **Biaxial Indicatrix, Optic Axes, Vibration Directions and Ray Paths, Biaxial Interference Figures [Bxa figure, Bxo figure, Optic normal figure], 2V, Optic Sign, Extinction, Sign of Elongation, and Pleochroism**.

There is a discussion of biaxial minerals in Chapter 7 of Nesse (p. 133 on). Another very useful source of information is: Bloss, F. D., An Introduction to the Methods of Optical Crystallography, Holt, Winehart, and Winston, 1961.

### Biaxial Minerals (orthorhombic, monoclinic, triclinic)

Biaxial minerals are anisotropic. They are called biaxial minerals because they contain **two optic axes**. Just as in uniaxial minerals the velocity of light traveling through a biaxial crystal is dependent upon the orientation of the **ray path**. Light entering the crystal will be polarized into **two of three** possible vibration directions (**privileged directions**) that are mutually perpendicular. The three vibration directions are referred to as **X, Y, Z**. These vibration directions will coincide with the three crystallographic axes in the orthorhombic system, one of the vibration directions will coincide with the *b* crystallographic axis in the monoclinic system, but in the triclinic system the vibration directions do not correspond to any crystallographic features. The corresponding three indices of refraction are referred to as **$n_\alpha$, $n_\beta$, $n_\gamma$ with $n_\alpha < n_\beta < n_\gamma$**

### Biaxial Indicatrix

The biaxial indicatrix is a **triaxial ellipsoid**, the major axes of which have lengths proportional to $n_\alpha$, $n_\beta$, and $n_\gamma$. There are three **principal planes** defined by **X-Z, X-Y**, and **Y-Z** axes. There are two **circular sections**. The two **optic axes** lie in the X-Z plane and are perpendicular to these circular sections. The X-Z plane is called the **optic plane** and the angle between the two optic axes in this plane is called the **2V** angle. The Y vibration direction is **normal to the optic plane**.

If the acute angle between the optic axes (**Bxa**) is bisected by the **Z** vibration direction and the obtuse angle between the optic axes (**Bxo**) is bisected by the X vibration direction, then the crystal is **Biaxial Positive**. If the acute angle between the optic axes is bisected by the **X** vibration direction and the obtuse angle is bisected by Z, then the crystal is **Biaxial Negative**.

### X-Z Section

Light rays passing through a crystal normal to this plane have the greatest difference in refractive indices ($n_\gamma$ - $n_\alpha$). Therefore an X-Z section yields the maximum **birefringence and the highest interference colors**. In thin sections of uniform thickness, the birefringence may be estimated by looking for the grain with the highest interference color and comparing this color to the interference color chart. This section also contains the optic axes.

### Interference Figures

The type of interference figure observed depends on whether a biaxial crystal is oriented with its acute bisectrix, obtuse bisectrix, optic normal, an optic axis, a principal plane, or none of these, parallel to the microscope stage. The purpose of getting interference figures on crystals is to determine: (1) whether the mineral is biaxial or uniaxial, (2) determine the sign of the mineral, (3) determine the 2V angle. All of these are indicative of the mineral and help you identify it. The 2V angle can also give you compositional information of minerals that show solid solution between two end members.

The two most useful figures you should be able to find are (1) Optic Axis Figure and (2) Bxa Figure. Of these, the optic axis figure is the most easily observed and useful.

### Optic Axis Figure

Just as the uniaxial figures, grains that remain extinct during stage rotation are those that are oriented with their circular indicatrix sections parallel to the stage, i.e., **one of the optic axes is vertical**. In this orientation one of the vibrations directions is **Y** ($n_\beta$) and the other vibration direction corresponds to a refractive index between $n_\alpha$ and $n_\gamma$ that is exactly equal to $n_\beta$. The result is that the crystal acts as in an isotropic fashion and under cross-nicols the grain appears dark. With the substage condenser lens flipped in for conoscopic illumination, the Bertrand lens in, and the high power objective focused on the grain you should be able to obtain an optic axis interference figure. In biaxial minerals this will be a **single straight or curved isogyre**. As the stage is rotated the melatope of the isogyre will rotate around center of the cross hairs. In the north-south and east-west positions it will look like the outer limb of a uniaxial interference figure. As it is rotated it will become curved. In the 45 degree position it will have maximum curvature.

### Estimation of 2V

By comparing the curvature to the diagram shown in Fig. 7.52 the 2V can be estimated. The isogyre must be in the 45 degree position to make this calculation. Use of the compensation plate when the isogyre is in the 45 degree position allows you to determine the optic sign of the mineral.

### Bxa Figure

Bxa figures are harder to find but they will give you the same information as an optic axis figure. Considerable trial and error is often required to locate a grain oriented in such a way that the acute bisectrix is vertical. If the mineral is positive then the Bxa is the Z axis. If the mineral is negative then the Bxa is the X axis. Using the same configuration of the microscope as above, and choosing a grain that is slightly birefringent, you might be able to obtain a Bxa figure. It may take a few tries to find the right grain since there is not a unique orientation that gives low order interference colors.

A Bxa figure contains two curved isogyres which emanate from the melatope where the optic axes emerge. When the optic plane is in the 45 degree position, these two isogyres usually will be just out of the field of view if the 2V angle is greater than 60 degrees. The distance between the melatopes of the two isogyres is proportional to the angle of 2V. **See Figs. 7.41 through 7.49 in textbook.**

### Determination of Sign

The sign can be determined on either a Bxa figure or an optic axis figure. You can think of an optic axis figure as half of a Bxa figure. The configuration of the vibration directions under conoscopic illumination and the method of using the compensation plate to determine optic sign are described in detail in the textbook Even if the interference figure is not perfectly centered it can still be used to determine the optic sign.

### Other Figures

Bxo figure - obtained by looking down Bxo axis

Flash figure - obtained by looking down Y axis.

These figures are described in the textbook and are generally of limited use. However, they can sometimes provide information when determining the orientation of the grain for the pleochroic formula.

### Extinction

Biaxial crystals also show extinction at four stage positions under cross-polars.

### Extinction Angles

Extinction angles in a biaxial mineral can be parallel or symmetrical as in uniaxial minerals. Since the wave vibration direction need not necessarily be parallel to crystallographic features, extinction may also occur at oblique angles to cleavage or crystal faces.

### Sign of Elongation

Like uniaxial minerals, biaxial minerals are often elongated and have signs of elongation. Elongation does not necessarily occur along the c-axis in biaxial minerals.

### Pleochroism

Biaxial minerals may show pleochroism with different transmission colors for the three different vibration directions. Remember that **pleochroism can only be determined in plane polarized light**. The pleochroic formula is the color of a mineral when each of the vibration directions are parallel to the lower polarizer.. For instance the pleochroic formula of a mineral might be X = blue, Y= light blue, Z= green. To determine the pleochroic formula, it is first necessary to determine the optical orientation of the grain or grains.

# Lab Exercises: Biaxial Minerals

**1.** Place a thin cleavage flake of biotite on the microscope stage and obtain an interference figure. What type of figure is this? Draw a sketch of what you see, estimate the magnitude of the 2V angle, and determine the optic sign of biotite. From what you can determine about biotite (look it up in the book if necessary), what can you say about the optical orientation of a cleavage fragment. Describe the pleochroism of biotite in this orientation?

**2.** Place a thin cleavage flake of muscovite on the microscope stage and obtain an interference figure. What type of figure is this? Draw a sketch of what you see, estimate the magnitude of the 2V angle, and determine the optic sign of muscovite. From what you can determine about muscovite (look it up in the book if necessary), what can you say about the optical orientation of a cleavage fragment. Does muscovite show pleochroism?

**3.** Examine the specially prepared section which contains oriented grains of six minerals which show increasing 2V. Each mineral is cut with **Bxa** perpendicular to the stage.

**Mount 1:**

Aragonite (2V = 18°). This grain gives a **centered Bxa** figure that clearly shows the melatopes, isogyres, and isochromes. Does aragonite have high or low birefringence? Determine the optic sign. How many orders of interference color are represented in the isochromes?

**Mount 2:**

A. Quartz (section is perpendicular to c). Determine the optic sign.
B. Epidote **(optic axis figure).** Estimate 2V and determine optic sign.

**4. Mauna Loa basalt (multiple sections).**

This rock contains abundant **olivine** phenocrysts in random orientations.

A. Obtain an **optic axis figure** on olivine. To do this you should locate a grain that shows low interference colors—grain will remain gray on rotation of the stage under crossed polars. Such a grain will be oriented approximately perpendicular to an optic axis. When you have located such a grain, estimate the 2V and determine the sign (if possible). Using Fig. 16.2 (p. 308 in Nesse), determine the approximate composition of the olivine phenocrysts.

B. Note that many of the olivine phenocrysts are euhedral, or subhedral. Explain why.

C. Does olivine have a cleavage?

D. What are the highest order interference colors that you have observed? It helps to look at areas where olivine is wedge-shaped adjacent to epoxy-filled holes in the section. You can then count the number of orders.

E. Assuming that the section is 30 microns thick, determine the maximum birefringence of olivine. Recall that maximum birefringence would be in a section cut parallel to the X-

Z plane. From the information in the book (p. 306) determine the crystallographic orientation of such a section?

F. Describe the extinction. Is it even or undulatory? What do you think causes the kink bands that are present in some olivines?

[Note: In many of these thin sections a fraction of the phenocrysts have been plucked out during the grinding process leaving epoxy-filled holes. In friable rocks like this, it is usually necessary to impregnate such rocks with epoxy prior to grinding to avoid excessive plucking.]

## 5. Lab 101 (multiple sections)

**This is a metamorphic rock which contains biotite, muscovite, corundum, sillimanite, orthoclase/microcline perthite, and plagioclase.**

A. Locate a biotite grain and determine its pleochroic formula (X = , Y= , Z= )

B. Do biotite and muscovite have parallel extinction or inclined extinction? Note the "bird's eye" extinction in biotite and muscovite.

C. What orientation of biotite and muscovite gives a centered Bxa figure?

D. Find a grain of corundum that gives a decent interference figure and determine (1) whether corundum is uniaxial or biaxial, (2) its optic sign, and (3) its birefringence

E. Does corundum have high or low relief?

F. Does corundum show parallel or inclined extinction? What is the sign of elongation?

G. Would you expect to find quartz in this rock?

## 6. Cape Royds, Antarctica (multiple sections)

This volcanic rock contains large phenocrysts of anorthoclase (an alkali feldspar.)

A. Find a grain that gives a good interference figure (either an optic axis figure or a Bxa figure) and determine 2V and sign.

B. What is the birefringence of this alkali feldspar (assume a 30 µm thick section).

C. Describe the twinning in your own words.

D. Do you observe any cleavage in the feldspar?

## 7. Adamello: Pleochroism and pleochroic formula

Pleochroism is one of the most distinctive optical properties of minerals. To describe the pleochroism of biaxial minerals it is necessary to specify three colors, i.e., one color for each of the vibration directions. A typical pleochroic formula might be:

X = yellow
Y = blue-green Absorption: X<Y<Z
Z = blue

There are several ways to identify the different vibration directions. One of the commonest is as follows (see also page 136 of Nesse):

a. Obtain an optic axis interference figure
b. Orient the figure so that the optic normal (Y) is E-W (parallel to lower polar)
c. Return to orthoscopic illumination, remove analyzer, and note the color associated with the Y vibration direction
d. Obtain a grain with maximum interference color, i.e., the X-Z plane
e. Using the gypsum plate, determine which of the vibration directions is fast (X) and which is slow (Z)
f. Orient X (or Z) parallel to the lower polar (east-west)
g. Remove analyzer and determine color of X
h. Rotate the stage 90 degrees and determine the color of Z.

**Adamello contain biotite and hornblende (along with several other minerals). Determine the pleochroic formula and absorption for biotite and hornblende.**

## 8. Extinction and extinction angle (Adamello and 107-M)

The extinction angle is a useful diagnostic property of many biaxial minerals and in the case of feldspars the value of the extinction angle can be used to determine compositions within the plagioclase solid solution series. As discussed previously, the extinction angle is measured relative to a known crystallographic direction that will usually be the **trace of a cleavage, a twin plane, or a crystal face**. As you might imagine, the extinction angle is critically dependent on the orientation of the crystal. Consequently, it is necessary to have the appropriate orientation if the extinction angle is to be used for diagnostic purposes. It is impossible to describe all possible orientations, so some generalizations follow.

For **orthorhombic minerals**, sections cut parallel (or nearly parallel) to the crystallographic axes show parallel or symmetrical extinction. Sections cut in a random direction will show inclined extinction but at a fairly low angle.

**Monoclinic minerals** have lower symmetry and only sections containing the ***b*** axis will show parallel or symmetrical extinction while sections cut perpendicular to ***b*** will show the **maximum** extinction angle. The maximum extinction angle is usually expressed as $\mathbf{Z \wedge c = X^\circ}$ or $\mathbf{X \wedge c = Y^\circ}$. The extinction angle is particularly useful in distinguishing pyroxenes, amphiboles, and different plagioclase feldspars.

For **triclinic minerals**, there are no restrictions on the orientation of the indicatrix relative to the crystallographic axes, so inclined extinction is the norm.

**a. <u>Adamello:</u> Determine the <u>maximum</u> extinction angle for amphibole and biotite.**

**b. <u>107-M</u>: Determine the <u>maximum</u> extinction angle of clinopyroxene**

## c. <u>Determination of plagioclase composition using extinction angles.</u>

### i. a-normal method

The **a-normal** method is the most accurate method of determining plagioclase compositions in thin section because once a suitable grain has been located a single measurement suffices to determine the composition. [Unfortunately, this method is not described in Nesse-he discusses only the Michel-Levy method and the combined Albite-Carlsbad twin method.] In addition, the common twin laws in plagioclase are readily identified in **a-normal** sections. The accuracy of the a-normal method is approximately ± 4% An. As we shall see shortly, it is also important to have some knowledge of the **structural state** of the plagioclase.

Grains cut normal to the **a** axis are also normal to the (001) and (010) cleavage traces which intersect at an angle of 86°. In **a-normal** sections, the cleavages are sharp (may be difficult to see in some grains), and they do not shift laterally when the microscope focus is changed. The composition planes of albite twin lamellae are always parallel to the (010) cleavage, while the composition plane of pericline twin lamellae is normally close to the (001) cleavage.

Extinction angles are measured from the (010) cleavage or albite twin composition plane to the fast vibration direction (X′). It is important to distinguish pericline twins from albite twins since they look similar. The distinction is easy because Ab twins are length fast and pericline twins are length slow. To determine whether the twins are length fast or slow:

(a) Rotate one set of twin lamellae to extinction. In this orientation the vibration directions are parallel to the cross-hairs.
(b) Next rotate the dark set of lamellae to the 45° position.
(c) Insert your gypsum plate and observe subtraction or addition.
Remember that subtraction = Length Fast; Addition = Length Slow

The extinction angle measured between X′ and (010) indicates the plagioclase composition. The sign of the extinction angle is positive if X′ lies in the acute angle between the (001) and (010) cleavage traces and negative if in the obtuse angle. Note that there are two curves, one for high-plagioclase and one for low-plagioclase. In general, volcanic plagioclase will be in a high structural state (disordered) while plutonic plagioclase will be in a low structural state (ordered). In untwinned plagioclase and plagioclase showing simple Carlsbad twins, only one extinction angle is measured. In crystals with albite or pericline twinning, two angles are determined (one for each set of twin lamellae) and averaged.

**ii. Michel-Levy method**

This method is well described on p. 217-219 of Nesse. Most students prefer to use the Michel-Levy method because it does not require one to locate an a-normal section, which can be quite difficult. However, the Michel-Levy method requires the user to measure several extinction angles to find the **<u>maximum</u>** angle.

**iii. Carlsbad-Albite method** (See Nesse p. 219 for details. **)**

**<u>Adamello sections:</u> Find suitably oriented plagioclase grains and determine their composition using <u>one</u> of the methods. Adamello is a plutonic rock—therefore, you can assume that the plagioclase is in the low structural state.**

**<u>84-160 B sections:</u> Find suitably oriented plagioclase grains and determine their composition using one of the methods. 84-160 B is a volcanic rock.**

**<u>Abert Lake (polished thin section):</u> I have marked one plagioclase grain in this section which lies normal to the a axis. Both cleavages [(001) and (010)] are clearly visible and sharp. Orient the grain so that the (010) cleavage is parallel to the N-S crosshair and measure the extinction angles by rotating cw and then ccw. The two extinction angles should be within a degree of each other. Use the diagram on p. 218 in Nesse (high curve because this is a volcanic rock) to determine the composition expressed as An content.**

## <u>9. Zoning</u>

Zoning refers to the variations in composition in a mineral that shows solid solution. It is particularly well exhibited in plagioclase feldspars and some clinopyroxenes. Zoning is optically visible in crossed polars since the different zones in a zoned grain will show different extinction positions and/or different birefringence. In fact, all optical properties are different in different zones but the most obvious one is the extinction position. The origin of zoning and the different types of zoning will be discussed in lecture.

**<u>Adamello sections:</u> Find a zoned grain of plagioclase and draw an accurate sketch of it.**

**<u>M 107 or I-18 sections:</u> Find a zoned grain of clinopyroxene and draw a sketch of it.**

## <u>10. Twinning</u>

Twins occur when two crystals of a given material are intergrown in such a way that all crystallographic directions of the first crystal unit are related to the corresponding directions of the second crystal unit by the operation of either (1) a mirror plane of symmetry, (2) a 2-fold axis of symmetry (much less frequently a 3-, 4-, or 6-fold axis), or (3) a center of symmetry.

We will spend a whole lab on twinning later in the quarter. At this point it will be sufficient to recognize twinning when you see it in the microscope.

### Classification by symmetry

1. Reflection twins, e.g. Albite twins
2. Rotation twins, e.g., Carlsbad twins
3. Centrosymmetric twins

The plane of symmetry relating **reflection twins** is called the **twin plane** and the **axis of symmetry** relating **rotation twins** is called the **twin axis**. In reflection twins the twin plane is always parallel to a possible lattice plane ***(hkl).*** In rotation twins the twin axis is almost always "2-fold" and is called an axis of **hemitropy**—the direction of the axis may usually be specified by designating the zone axis **[*uvw*]** to which it is parallel or by the plane ***(hkl)*** to which it is perpendicular.

### Classification by spatial relationship

If the two twinned individuals are in contact along a well-defined plane they are called **contact twins** and the plane of contact is called the **composition plane**. If the contact between the two twins is irregular they are called **penetration twins**.

### Repetitive twinning

If the twin-producing symmetry operation is repeated numerous times the twinning is called **polysynthetic twinning** (or multiple twinning). If the composition planes are at an angle to each other close to 120º, 90º or 60º, **cyclic twins** are produced.

### Types of rotation-contact twins

1. **Normal twins** [twin axis is normal to the composition plane, e.g., Albite twins]: specified as ⊥ *(hkl)*
2. **Parallel twins and Complex twins** [twin axis is parallel to the composition plane, e.g., Carlsbad twins]. In parallel twins the twin axis is parallel to a [*uvw*] direction (specified as [*uvw*]) while in complex twins the twin axis is perpendicular to a particular [*uvw*] direction specified as ⊥ [*uvw*]/(*hkl*)—read as the direction perpendicular to [*uvw*] within the plane (*hkl*).

### Symmetry-imposed restrictions

**A twin plane or axis can never coincide in direction with any symmetry operation (in the untwinned crystal) for which the twinning operation is identical (or a subgroup).** For example, the (010) plane cannot be a twin plane in the isometric system because it is a mirror plane of symmetry. However, an axis perpendicular to the (111) plane that is also a 3-fold axis in the untwinned crystal can be a twin axis in the isometric system if the twin rotation is 180º. This twinning can also be looked on as reflection across the (111) plane and is known as **Spinel Twinning**.

**General Rule**: **In crystals that have a center of symmetry, twins can be related by a twin plane and by a 2-fold axis normal to this plane and vice versa.**

## Formation of twins

Twins are commonly classified as (a) growth twin, (b) transformation twins or (3) gliding twins. **Growth twins** are primary as the name suggests and occur during the growth of the mineral during crystallization or recrystallization, e.g., most feldspar twins, pyroxene twins and amphibole twins. **Transformation twins** are secondary in that they are produced after the mineral is formed and they usually form during cooling as the structure transforms from a high symmetry state to a lower symmetry state, e.g., high quartz to low quartz transition at 573ºC. **Mechanical twinning** is commonly lamellar (multiple) and is a consequence of mechanical deformation, e.g., twinning in calcite.

## Exercise:

1. **Observe and describe the twinning in plagioclase and amphibole in a thin section of Adamello.**
2. **Observe and describe the twinning of leucite and clinopyroxene in a thin section of Vesuvius I-18.**