Mineralogy and Optical Mineralogy

Lab Manual

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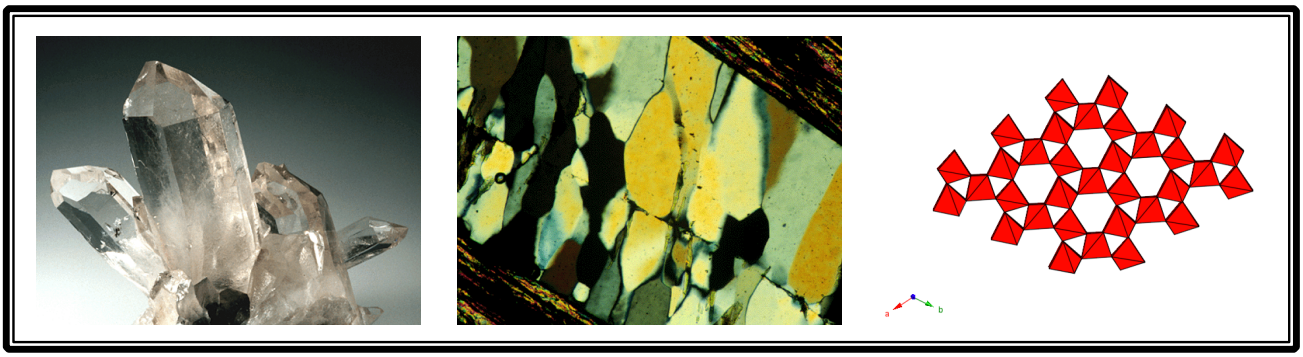

Overview

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to the *Mineralogy and Optical Mineralogy* textbook DVD by M. Darby Dyar and Mickey E. Gunter, illustrated by Dennis Tasa

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Introduction

This lab manual acts as a skeleton to be built upon and instructors are encouraged to add mineral samples, projects, and exercises as they see fit. Throughout this laboratory course, students are walked through the techniques and methods of identifying minerals by their properties. This is achieved by using Dennis Tasa's DVD accompaniment of the textbook *Mineralogy and Optical Mineralogy* by M. Darby Dyar and Mickey E. Gunter (2008) with a variety of tools available, such as the Polarized Light Microscope (PLM). These methods are applied to only a few minerals with an emphasis on Dyar and Gunter's "Big Ten" Minerals (Fig. 1). Instead of overwhelming students with a hundred different mineral species, this lab manual focuses on how to describe and measure the properties of minerals, how to use those observations to identify any mineral, and the unique properties of common mineral groups and species.

Table 1.3. The "Big Ten" Minerals

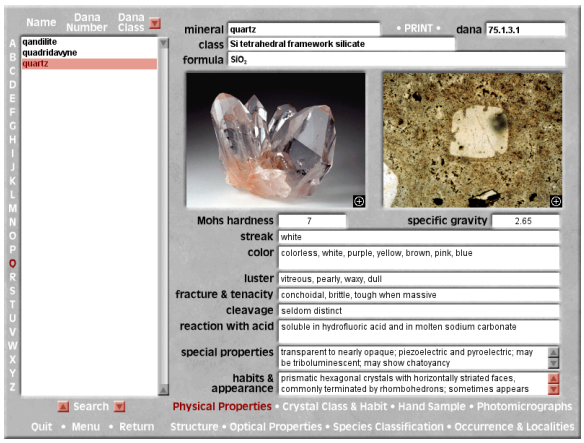
	Mineral group	*Mineral species or series*	*Formula*
1		quartz	SiO_2
2	feldspars	orthoclase	$KAlSi_3O_8$
3		albite	$NaAlSi_3O_8$
4		anorthite	$CaAl_2Si_2O_8$
5	micas	muscovite	$KAl_2(AlSi_3O_{10})(OH)_2$
6		biotite	$K(Mg,Fe)_3(AlSi_3O_{10})(OH)_2$
7	amphiboles		$(Ca,Mg,Fe)_7Si_8O_{22})(OH)_2$
8	pyroxenes		$(Ca,Mg,Fe)_2Si_2O_6$
9	olivines		$(Mg,Fe)_2SiO_4$
10		calcite	$CaCO_3$

Figure 1: The most common minerals in the Earth's crust (Table 1.3, Dyar and Gunter 2008).

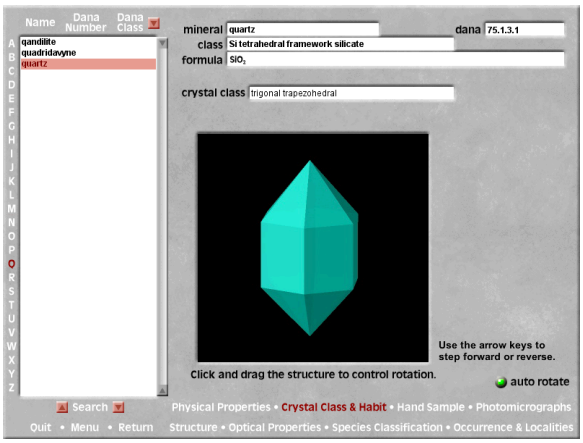
The unique aspect about the textbook Mineralogy and Optical Mineralogy is the DVD complement. The DVD contains all of the book's figures in color and with animation. A searchable mineral database is also included on the DVD (Fig. 2). Each mineral within the database can be printed into a 2-page summary (Fig. 3).

When students are first introduced to the properties of minerals, they will use the properties they have observed and the DVD database search feature to identify their unknown mineral (Fig. 4). They will also use this feature to identify the minerals they found for their mineral collection project at the end of the semester. Throughout the semester, students will refer to the database on the DVD and use the summary sheets as a foundation to create their own mineral database and append their own notes.

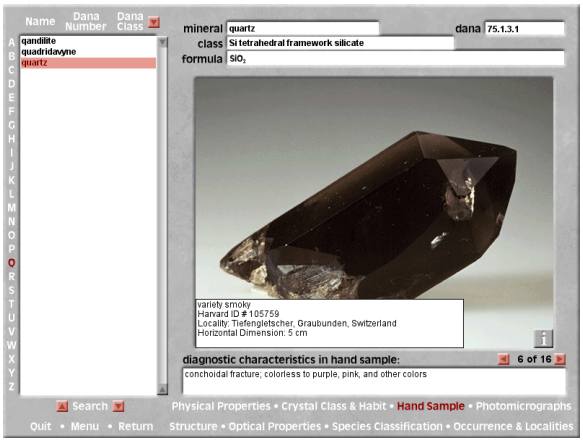
Figure 2: The mineral database and the different screens available for each mineral (Dyar and Gunter 2008).



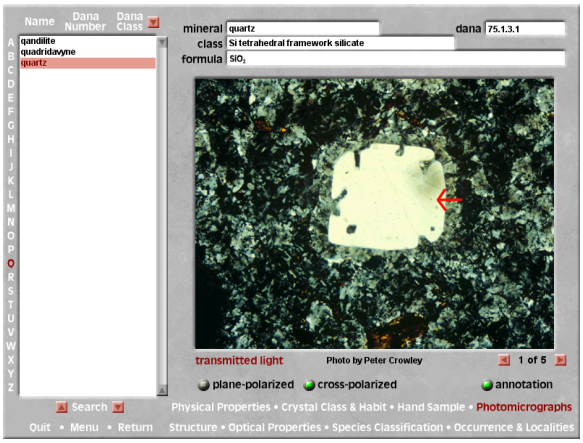
a. Physical properties of the mineral with color photographs of the mineral in hand sample and thin section.



b. The crystal class and habit of the mineral with an interactive 3D model.

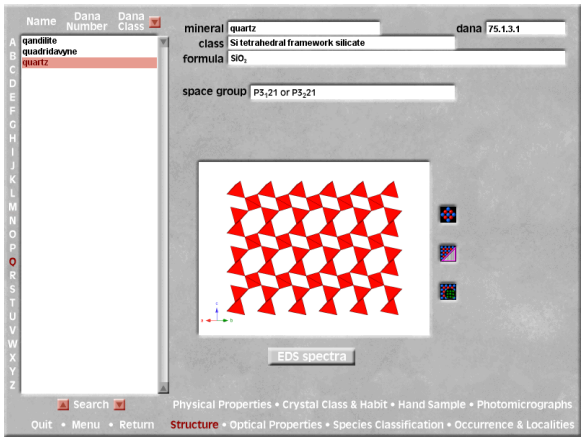


c. Series of photographs of the mineral in hand sample with information about the sample.

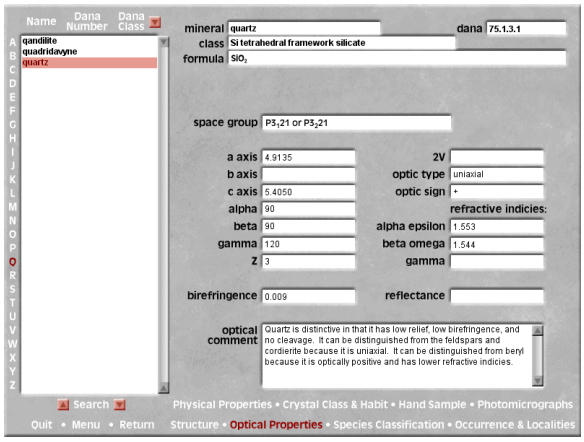


d. Series of photographs of the mineral in thin section view in plane polarized light and crossed polarized light.

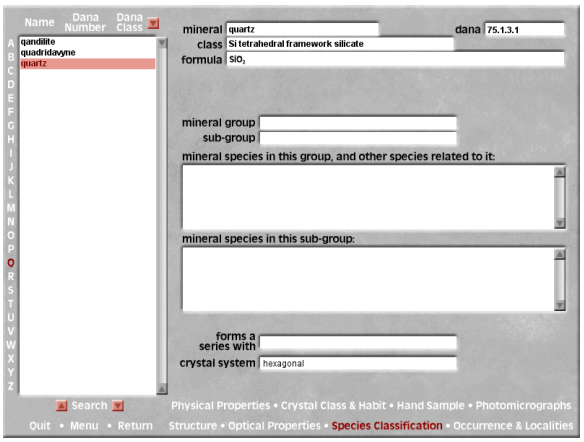
Figure 2 continued



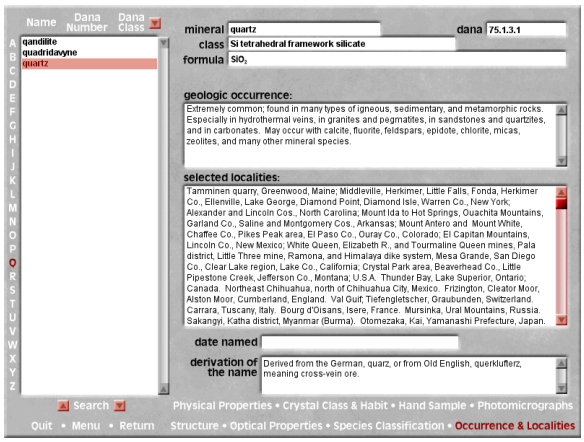
e. An interactive crystal structure of the mineral with buttons on the right which open programs to view the crystal structure, XRD pattern, and electron diffraction pattern (top to bottom, respectively). The button directly below the crystal structure schematic opens a program to show a calculated EDS pattern of the mineral.



f. List of crystallographic and optical properties of the mineral.



g. The mineral's classification and a list of related mineral species.



h. The geological occurrences of the mineral and a list of localities the mineral is found.

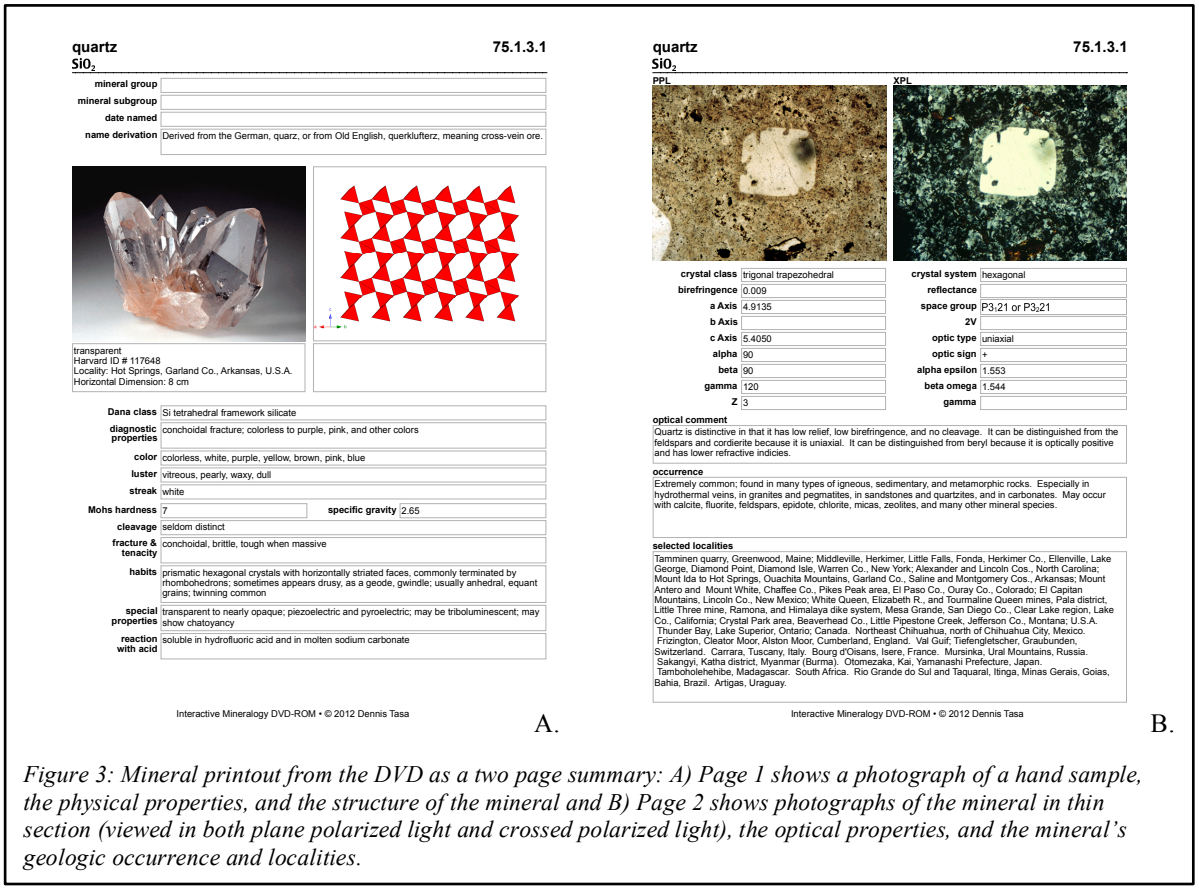


Figure 3: Mineral printout from the DVD as a two page summary: A) Page 1 shows a photograph of a hand sample, the physical properties, and the structure of the mineral and B) Page 2 shows photographs of the mineral in thin section (viewed in both plane polarized light and crossed polarized light), the optical properties, and the mineral's geologic occurrence and localities.

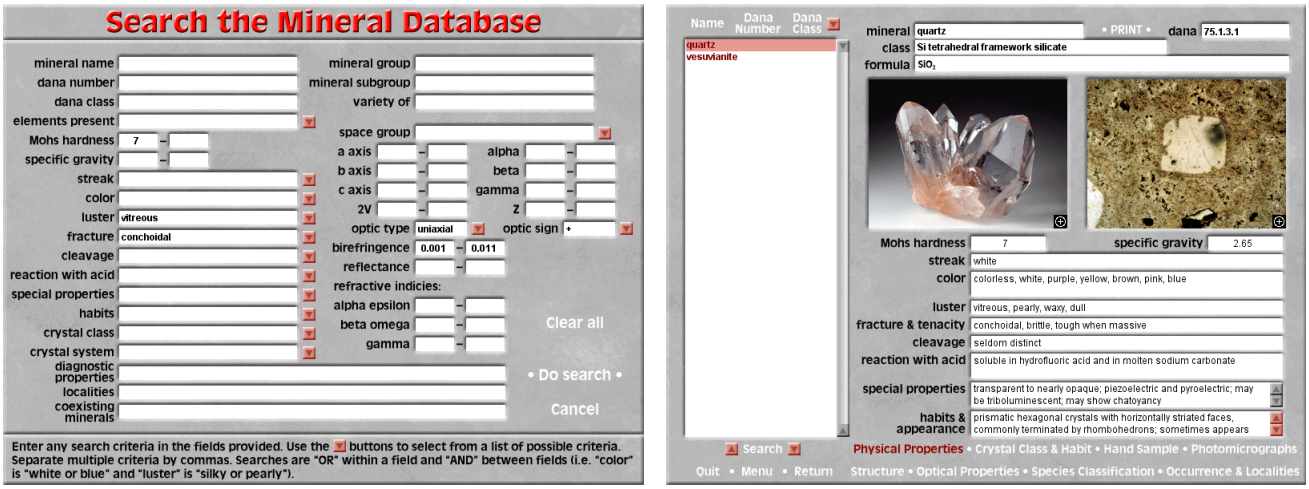


Figure 4: Left) Search window on the DVD mineral database allows users to search for minerals by their physical and optical properties and Right) List of minerals resulting from search.

Analytical Equipment for Identifying Minerals

When identifying minerals, several characteristics need to be taken into account. Minerals are classified and differentiated by chemical composition and structure. You cannot identify a mineral based solely by either its composition or structure. An example is quartz and opal, two minerals with similar chemical composition, but different atomic structures. The following are some examples of the equipment used to determine the composition, structure, and properties of minerals.

1. Scanning Electron Microscope (SEM) / Energy Dispersive Spectrometer (EDS)

    - The SEM uses an electron beam to yield a high-resolution image of the minerals surface and shape.

    - Most SEMs are equipped with an EDS detector which measures characteristic energies of elements to determine composition.

2. X-ray Diffractometer (XRD)

    - Uses geometry of the reflection of X-rays within a material to measure the spacing between atomic planes in the material, which is characteristic of mineral structures.

3. Polarized Light Microscope (PLM)

    - Uses two polarizers to observe unique interactions of light within minerals (in-depth look during the next lab).

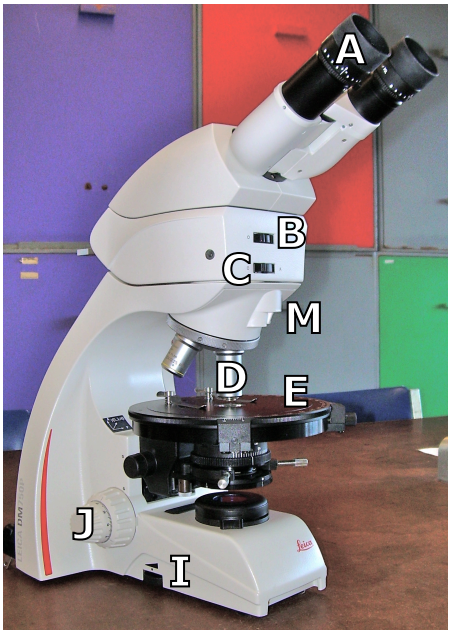
Introduction to the PLM

The Polarized Light Microscope, or PLM, is an analytical tool used by mineralogists and petrographers that uses filtered light and how it interacts with materials to identify minerals. Two types of slides are used with the PLM: thin sections and grain mounts. Thin sections are slices of rocks about 30 μm thick, thin enough for light to pass through the minerals. Grain mounts are mineral grains (think fine grained sand) immersed in an liquid or epoxy. We will be using both with the PLM throughout semester and making our own grain mounts. Figure 5 shows the different parts of the scope and their purpose.

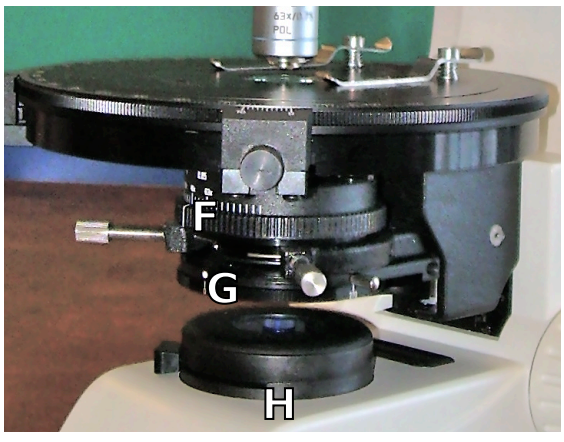
Parts of the microscope and their purpose

A. Eyepiece- viewing apparatus, slightly magnifies sample
B. Bertrand Lens- views interference figures of mineral
C. Upper polarizer- constrains light to vibrate in a N-S direction, can be removed from light path
D. Objective Lenses- interchanging set of lens of varying magnification and numerical aperature
E. Rotating stage- platform under objective lenses to place sample, rotation for viewing of certain optical properties
F. Aperture condenser- changes the angle the light rays interact with the objective lens
G. Lower polarizer- constrains light to vibrate in an E-W direction, typically kept in light path
H. Light source- light bulb within base of scope to illuminate sample
I. Dimmer- controls intensity of light
J. Focusing knobs- enables coarse and fine adjustments to stage height
K. Centering screws- aids in centering of objective lens above sample
L. Accessory plate- quartz plate or quartz wedge placed in notch above objective lens (M)
M. Notch for accessory plate
N. Power cord

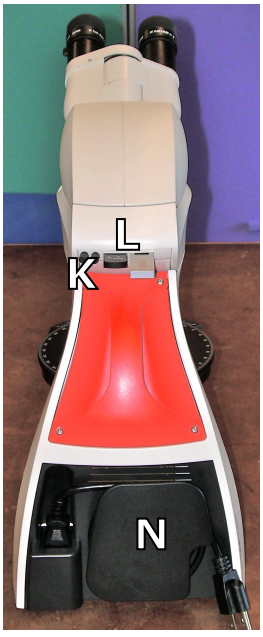
Figure 5: Parts of the Leica DM750P polarized light microscope.



Side View



Substage Assembly



Back View

Exercises: Magnification and Measurements of the Objective Lenses

1. Determine the magnification of the eyepiece: _____X

2. Determine the magnification of each objective lens:

Red= _____X Yellow= _____X Blue= _____X

3. Determine the total magnification for each objective lens by multiplying the magnification of the eyepiece and the magnification of the objective lens.

Total Mag_{red}= _____X Total Mag_{yellow}= _____X Total Mag_{blue}= _____X

4. Measure the field of view for each objective (include units):

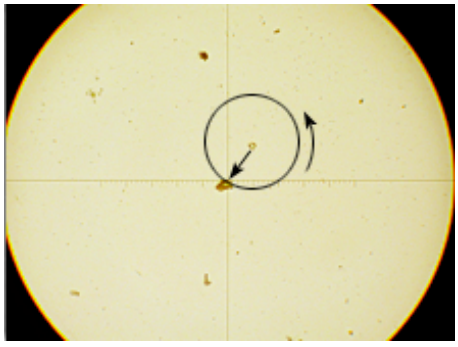
Red= _____ Yellow= _____ Blue= _____

Exercises: Center Object Lenses

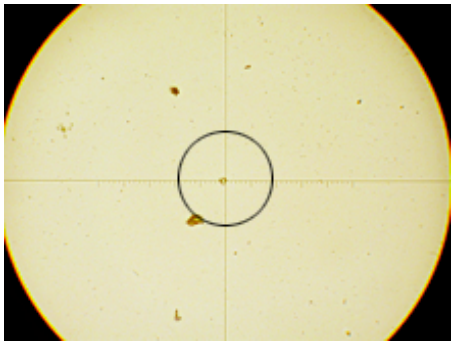
Use the centering screws located on the back of the scope, place them in the holes on either side of the lens desired to be center (Fig. 6), and the turn the screws to center the lens as shown in Figure 7.

Figure 6: Placement of centering screws (Fig. 17.5, Dyar and Gunter 2008)

Figure 7: Centering an objective lens (Fig. 17.6, Dyar and Gunter 2008).



A. When the stage is rotated counterclockwise, the particle that starts out at the center follows a path shown by the circle. To center the stage, the center of the dark circle needs to be moved (translated) so that it corresponds to the center of the crosshairs. This is accomplished by carefully moving the centering screws (Fig. 17.5) to translate the lens in the proper direction.

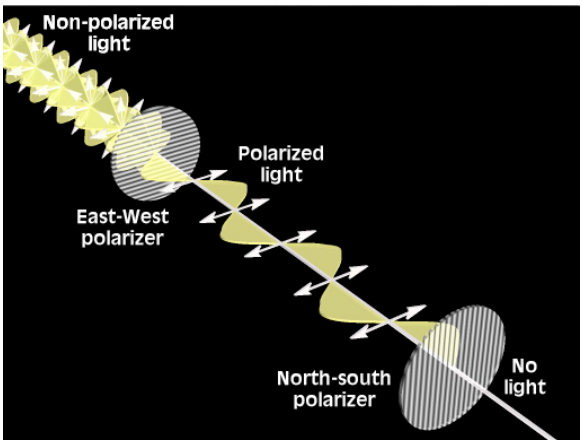


B: After centering, the circle is positioned so that it's center lies directly on the cross-hairs.

Polarization and Vibration Direction of Light

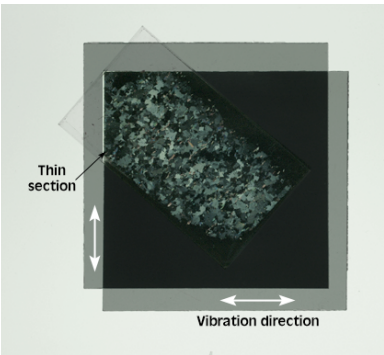
The polarized light microscope, or PLM, uses polarized light and how it interacts with a material for identification. Unpolarized light vibrates in all directions. As light passes though a polarizer it is constrained to vibrate along one plane, shown in Figure 8. Light is polarized by one or two polarizers within the microscope. Figure 9 is a simplistic set-up for a PLM.

Figure 8

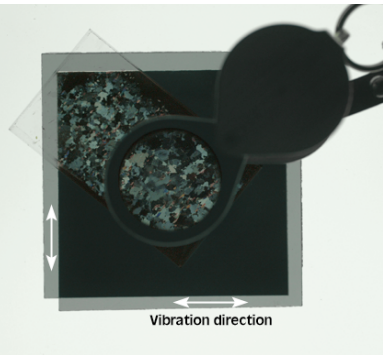


An unpolarized light ray is first plane-polarized in an east-west direction (as is the case for the lower polarizer of a PLM), then travels some distance before reaching a north-south polarizer (i.e., one that is perpendicular to the north-south direction, the case of the upper polarizer in a PLM), and then is completely blocked (Fig. 5.6 Dyar and Gunter 2008).

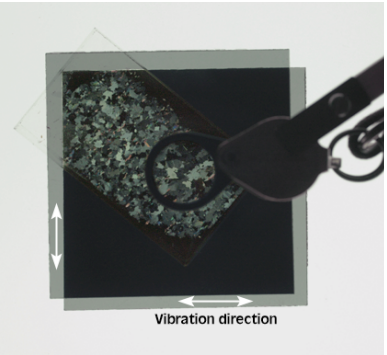
Figure 9: Simplistic set-up of a polarized light microscope (Fig. 5.2 Dyar and Gunter 2008)



A. Thin section of an igneous rock between 2 polarizers. Individual minerals grains in the rock show up as bright and dark specks.



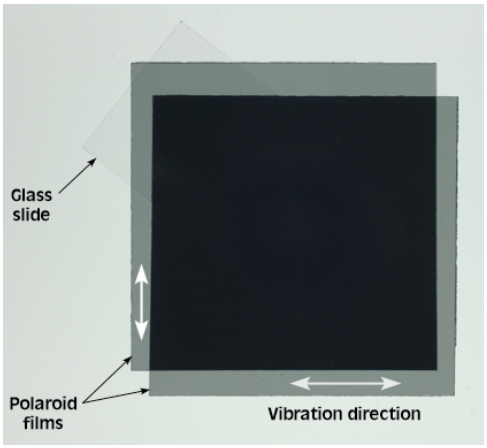
B. The same setup as in Figure 5.2a, except a low-power (73) hand lens is placed over the thin section to simulate the lower power lens on a PLM.



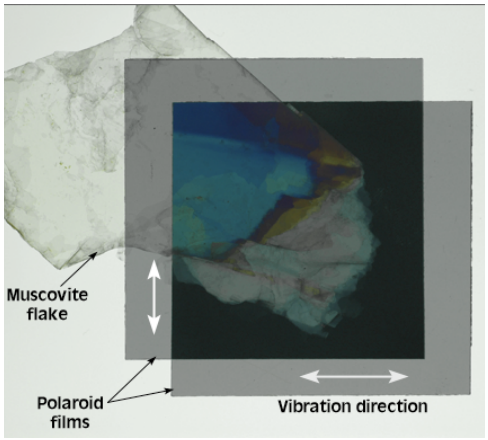
C. The same setup as in Figure 5.2b except a higher power hand lens (143) is placed over the thin section to get a "higher magnification" of the sample. In essence, a PLM is really just two polarizers with some magnification, as simulated in this figure.

There are two different categories of how materials appear between two polarizers of perpendicular vibration directions: isotropic and anisotropic (Fig.10). Isotropic materials have light traveling at the same speed through them equally in all directions, which results in no change of vibration direction as the light exits the material. The mineral appears black when viewed between two crossed polarizers, as shown in Figure 10a. Anisotropic materials have light traveling through them at different speeds, so the light vibrates in a different direction as it exits the material, as shown in Figure 11. The material then shows interference colors, like those seen in Figure 10b.

Figure 10: Isotropic and anisotropic materials between two polarizers (Fig. 5.1, Dyar and Gunter 2008).

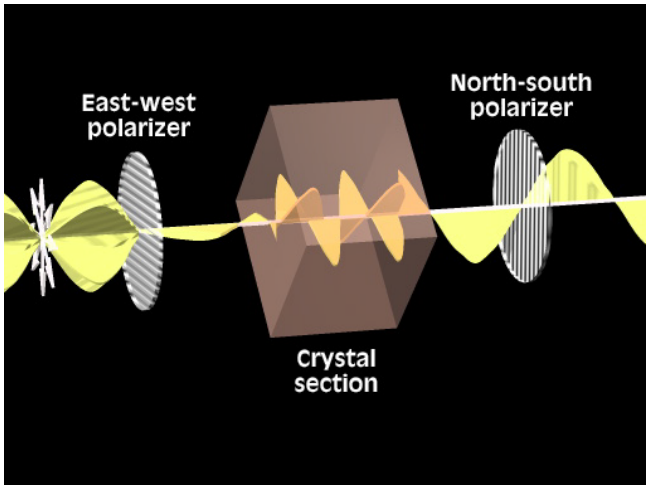


A. Two pieces of 50 x 50 mm sheets of Polaroid film placed on a light table and arranged where their vibration directions are perpendicular to each other to simulate cross-polarized light in a PLM. Where they do not overlap, light is still transmitted, although of less intensity. Also, note the glass slide sticking out from the polarizers in the upper left corner. No light appears from the glass slide as it enters the polarizer sandwich.



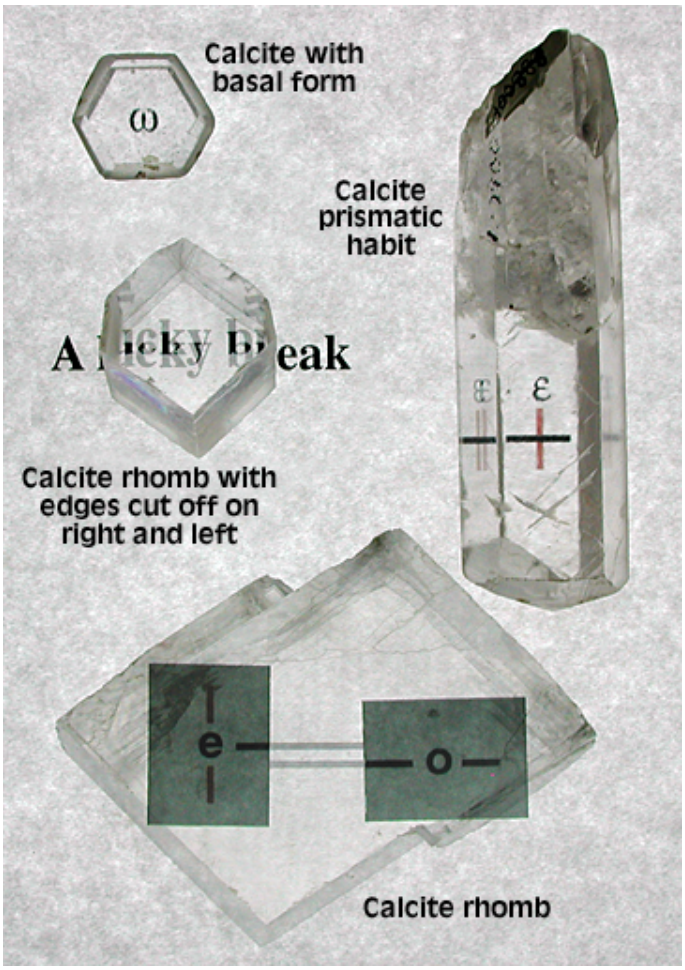
B. The same set up as in Figure 5.1a, except a flake of muscovite (of uneven thickness) replaces the glass slide. In this case, not only is light transmitted, but the light takes on interesting colors based on the thickness of the muscovite flake.

Figure 11



Interaction of polarized light with an anisotropic mineral. Notice how the light wave is split into two different waves when it travels through the crystal, and how a portion of the light is transmitted by the upper polarizer (Fig. 5.16, Dyar and Gunter 2008).

Figure 12



Three morphologies of calcite with light propagating through them. The rhombs show the case of well-known double refraction, where the O-ray (ordinary ray) obeys Snell's law and the E-ray (extraordinary ray) does not. For the basal morphology (top), the view is down the c axis and the light remains unpolarized. For the prism morphology (right), the c axis is parallel to the page, and light passing through the crystal is forced to vibrate along either the **ω** *or* **ε** *vibration direction. Even though the light travels along two separate vibration directions in this orientation, the classic double refraction does not occur and both rays are O-rays by definition. The bottom rhomb is lying on a sheet of paper printed with a horizontal line. It also has sheet of polarizer (the arrow drawn on the sheet is its polarization direction) laid on top to show the polarization direction of the E-ray and O-ray. The double image of the straight line is shown to be a single line after passing through the polarizer. (From Gunter, 2003 with samples were provided by Carl Francis, Harvard Mineralogical Museum and Anthony Kampf, Natural History Museum, Los Angles.)*

Figure 12 shows the double refraction phenomenon in calcite as a function of the mineral's cleavage and orientation. Looking through a calcite rhombohedral (shape resulting of the mineral's cleavage), you are viewing a double image, no matter the face you are viewing through. This is because calcite is an anisotropic mineral and the difference in speed between the two rays traveling through the minerals is so great that it results in two images visually separate, with mutually perpendicular vibration directions. The two rays are described as the ordinary ray (O-ray) and the extraordinary ray (E-ray).

Exercises: Determining the vibration direction of light within materials.

1. Confirm that the vibration direction of your polar is parallel to its long axis. Use the fact that light is partially polarized upon reflection with the vibration direction parallel to the reflected surface. Sketch your polar and its vibration direction.

2. Polarization properties of instruments (use your polarizer)
   a. Is the big laser polarized or unpolarized? In which direction?

   b. Is the small laser polarized or unpolarized? In which direction?

   c. What is the vibration direction of the bottom polarizer of your microscope?

3. Polarization properties of materials (use 2 polarizers)
    a. Is a glass slide isotropic or anisotropic? How do you know?

    b. Is a quartz crystal isotropic or anisotropic? How do you know?

    c. Is a muscovite sheet isotropic or anisotropic? How do you know?

4. Polarization properties of calcite
    a. Make a dot below and place a calcite rhombehedron over it. Sketch the rhomb, the two dots, and label the c-axis of the rhombehedron.
    b. If the calcite is rotated, one dot moves and the other does not. Label the moving dot “E” and the fixed dot “O” on your sketch. Determine the vibration direction and label it on your sketch.

Physical Properties of Minerals

Physical properties of minerals are used to aid in identification of a mineral in hand sample. This method is very subjective and should be approached with an open mind. Physical properties are characterized by a series of adjectives the meanings of which can be arbitrary.

Basic Categories of Physical Properties

A. Color

A highly variable property and is **NOT** diagnostic of a mineral. Several minerals occur in different colors and several minerals share the same color.

B. Streak

The steak of a mineral is the color of the mineral in powdered form. Typically determined by running a sample across a porcelain plate and observing the color of the "streak" left behind. However, a white streak is not diagnostic, because it is unclear as to whether or not the mineral or the plate is what was being powdered. In addition, minerals with a hardness greater than porcelain will scratch the plate and not be powdered.

C. Luster

Luster is the appearance of light as it is reflected off of the mineral's surface and is generally either metallic or non-metallic.

Luster	Description
Metallic	Mineral reflects light brightly
Submetallic	Metallic surface on mineral looks slightly tarnished
Adamantine	Extremely shiny
Splendent	Brightest possible luster
Dull	Does not reflect much light
Earthy	Resembles dirt or clay
Greasy	Resembles a thin coating of oil on the surface of a mineral
Pearly	Resembles the appearance of the surface of a pearl
Resinous	Resemble the surface of a wax candle
Silky	Resembles the shine of a piece of silk
Vitreous/Glassy	Resemble the surface of a piece of broken glass

D. Hardness

A mineral's hardness, or resistance to scratching, is measured on scale of 1 (soft) to 10 (hard) by observing resistance to scratching by materials of known hardness.

Mohs Hardness Scale	**Criteria**
1	rubs off onto skin in tiny flakes, easily scratched by fingernail
2	easily scratched by fingernail
3	scratched by nail, knife, or copper coin and may be scratched by fingernail
4	easily scratched by nail or knife (never by a fingernail)
5	scratched by a nail or knife with pressure applied
6	NOT scratched by a knife but will scratch typical window glass
7	scratches window glass (but not most kitchen ceramics made from glass), can be scratched by topaz, corundum, or diamond (but don't try the latter)
8 – 10	difficult to distinguish except with diamond or corundum for scratch testing (try diamond sandpaper!)

E. Fracture and tenacity

The fracture of a mineral is the description of a broken surface of a mineral. Tenacity describes how difficult it is to break such mineral.

Fracture	**Description**
Brittle/Fragile	Break into pieces or form powders under stress.
Ductile	Can be shaped or drawn into wires.
Malleable	Can be pounded into a sheet with a hammer.
Sectile	Can be cut with a knife.
Flexible	Can be bent but will not return to their former shape.
Elastic	Can be bent but will return to their original shapes afterwards.
Conchodial	Fracture that shows smooth, curving lines like a piece of glass.
Fibrous	Looks like the broken end of a frayed piece of rope.
Hackly	Breakage along a rough, jagged surface.

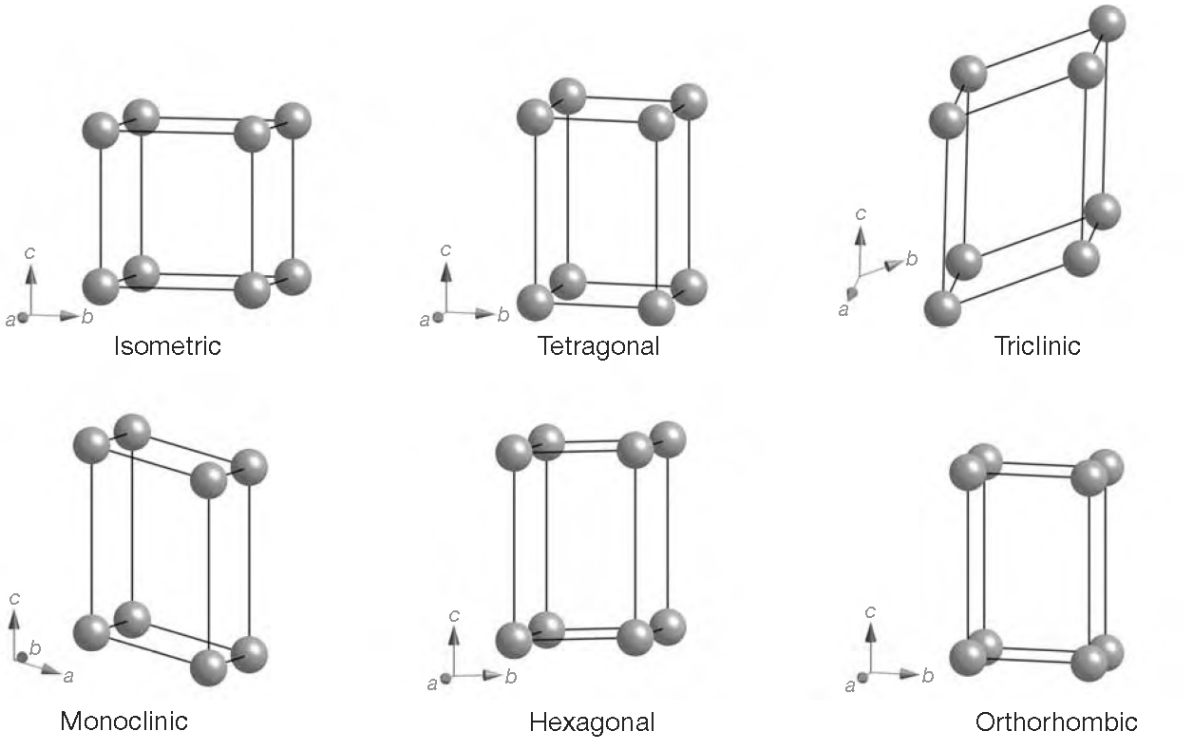
F. Crystal form and system

Crystal form and system describes the external shape of crystal faces that reflect the internal arrangement of atoms. The crystal system of a mineral is defined by the lengths of the axes and the angles between then (Fig. 13).

Figure 13: Table and schematics of the relationships of axes lengths and angels within the different crystal systems (Table 2.5 and Fig. 2.34, Dyar and Gunter 2008).

TABLE 2.5. Crystal Systems

	Relative lengths of axes	*Angles between axes*
isometric	$a = b = c$	all 90°
tetragonal	$a = b \neq c$	all 90°
hexagonal	$a = b \neq c$	$\alpha = \beta = 90°, \gamma = 120°$
orthorhombic	$a \neq b \neq c$	all 90°
monoclinic	$a \neq b \neq c$	$\alpha = \gamma = 90°, \beta \neq 90°$
triclinic	$a \neq b \neq c$	$\alpha \neq \beta \neq \gamma$



G. Crystal shape and habit

A crystal's shape or habit is a description of the shape of the mineral.

TABLE 2.6. Mineral Habits

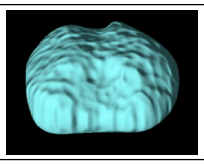
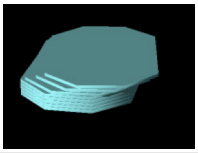
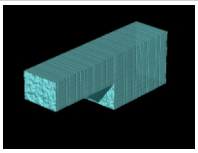
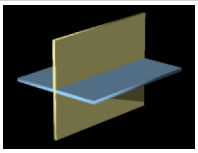
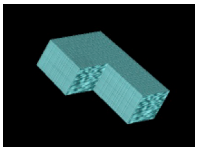
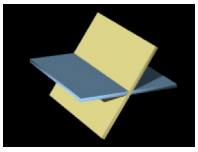
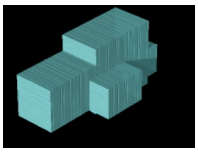
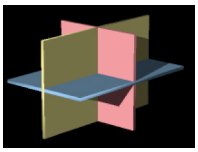
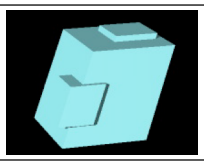
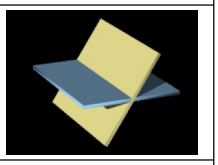
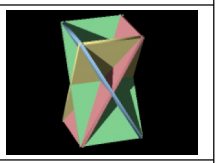
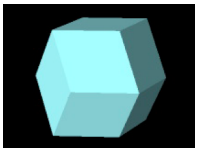
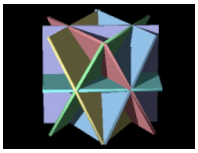
Term	*Description*	*Example*	*Figure Number*
acicular	thin, needle-shaped crystals (capillary)	epidote, natrolite, boulangerite	2.35
arborescent	long, thin branching crystals that form tree-like, three-dimensional growth pattern	ice, silver, copper	2.36
asbestiform	long, thin fibers like asbestos that separate easily	chrysotile, grunerite	2.37
banded	stripes or bands of different color or texture	agate	2.38
bladed	long, flat crystals shaped like the blade of a knife	stibnite, kyanite, scolecite	2.39
blocky	massive, block or brick-shaped	orthoclase	2.40
botryoidal	resembling bunches of grapes	smithsonite, conichalcite, hematite	2.41
capillary	very thin, delicate, hair-like crystals (acicular)	millerite	2.42
colloform	general term for crystals with spherical groups of any size; more specific terms include botryoidal, globular, and reniform habits	hemimorphite, graphite	2.43
columnar	crystal faces with linear intersections between them, resulting in a column or prism shape	beryl, elbaite, dravite, schorl	2.44
concretion	rounded layers around a small center, resulting in an onion-like growth pattern	ironstone	2.45
coralloid	twisted, curved branch-like shapes resembling coral	aragonite	2.46
cryptocrystalline	crystals smaller than can be seen with the human eye	variscite, spodumene, chalcedony	2.47
dendritic	plant-like or moss-like growth patterns, more two-dimensional than arborescent habits	copper, acanthite	2.48
divergent	radiating groups of crystals	mesolite, manganite	2.49
drusy	a coating of small crystals	calcite, stilpnomelane, aurichalcite, quartz	2.50
equant	crystals with equal size in all dimensions	garnet, zircon, anhydrite, cobaltite	2.51
featherlike	overlapping fine scales resembling a feather (plumose)	galena, descloizite, silver	2.52
fibrous	bundles of thin fibers in either parallel or radiating groups	chrysotile, brucite, strontianite	2.53
filiform	thin, thread-like crystals	rutile, hydrozincite	2.54
foliated	general term for crystals forming thin, easily separated sheets or plates; including leaflike, laminar, and micaceous	biotite, lepidolite, micas	2.55
geniculated	knee-like crystals	chalcocite, rutile	2.56
geode	spherical hollow structure lined with small crystals	amethyst	2.57
globular	radiating individuals form small globes or spheres	pyromorphite, smithsonite	2.58
granular	all crystals roughly equal in size, resembling granulated sugar	celestine, monazite, cryolite	2.59
gwindle	growing in a spiral shape	quartz	2.60
helicitic	same as coralloid	aragonite	2.46
lamellar	tabular, flat, platelike crystals stacked on each other and resembling a book shape	gypsum, barite, tilleyite, brucite	2.61
laminated	forming thin cleavable sheets	biotite, clinochlore	2.62

Term	Description	Example	Figure Number
massive	no distinctive shape or other characteristics	purpurite, iron, graphite	2.63
micaceous	very thin sheets that are easily separated	muscovite, biotite	2.64
pisolitic	pea-size spherical aggregates	siderite, bauxite	2.65
platy	forming thin rounded plates	diaspore, lepidocrocite, magnesite	2.66
plumose	same as featherlike	galena, descloizite, silver	2.52
powdery	tiny, powder-like crystals	vivianite	2.67
prismatic	long, slender crystals with parallel faces forming in a column or prism shape	proustite, natrolite, crocoite	2.68
radiated	same as divergent	mesolite, manganite	2.49
radiating spherulitic	slender crystals in rounded masses	wavellite, gibbsite	2.69
reniform	kidney-shaped crystals or groups of crystals	arsenic, sulfur, hematite	2.70
reticulated	net-like lattice pattern of crisscrossing crystals	silver, bismuth, taenite, kamacite	2.71
rosette	shaped like a rose	hematite, barite, gypsum	2.72
scaly	forming thin overlapping plates or scales	aurichalcite, celadonite	2.73
spherulitic	same as radiating spherulitic	wavellite, gibbsite	2.69
spiral	same as gwindle	quartz	2.60
stalactitic	cylinders or cones that grow with the pointed end down, as when forming on a cave ceiling	calcite, arsenic	2.74
stalagmitic	cylinders or cones that grow with the pointed end up, as when growing from a cave floor	calcite	2.75
stellate	radiating star or circle shapes	muscovite, astrophyllite	2.76
striated	crystal faces with fine, parallel lines	pyrite, arsenopyrite, gahnite	2.77
stubby	short, fat prisms	manganotantalite, borax, benitoite	2.78
sugary	same as granular	celestine, monazite	2.59
tabular	shaped like tablets, or flat, rectangles	cerussite, barite, gypsum, albite	2.79
tufted	forming small hair-like tufts	hydromagnesite, rosasite	2.80
wiry	forming thin wires	silver	2.81

H. Cleavage and parting

The cleavage and parting of a mineral describes a mineral's preferred pattern to break (Fig. 14).

Figure 14: Descriptions of the different types of cleavage seen in minerals (Fig. 2.82, Dyar and Gunter 2008).

Number of Cleavage Directions	Description	Sketch	Cleavage Directions
0; no cleavage, only fracture	No cleavage: irregular masses with no flat surfaces		No Cleavage
1	Basal cleavage: "Books" that split apart along flat sheets		
2 at 90°	Prismatic Cleavage: elongated form with rectangular cross sections (prisms) and parts of such forms		
2 not at 90°	Prismatic cleavage: Elongated form with parallelogram cross sections (prisms) and parts of such forms		
3 at 90°	Cubic cleavage: Shapes made of cubes and parts of cubes		
3 not at 90°	Rhombohedra cleavage: Shapes made of rhombohedra and parts of rhombohedra		
4	Octahedra and parts of octahedra		
6	Dodecahedral cleavage: Shapes made of dodecahedra and parts of dodecahedra		

I. Other observable characteristics

Such characteristics include taste, magnetism, reaction with acids, feel, twinning, etc.

Exercises: Physical Properties of Minerals

Using the tools provided and the tables in this lab section, answer the following questions about the provided mineral samples.

quartz

color_____

luster_____

hardness_____

fracture_____

crystal system_____

calcite

color_____

luster_____

hardness_____

cleavage_____

other diagnostic properties_____

_____

What property / properties do quartz and calcite share?

_____

What property / properties differ between quartz and calcite?

_____

Exercises: Using the DVD database

Looking at the given unknown samples, record your observations about their mineral properties in the tables below. Identify the samples using the physical properties of the minerals and the DVD mineral database. Write the mineral name next to sample number.

Unknown A:	
Chemical Formula:	
PHYSICAL PROPERTIES	
Color:	Streak:
Luster:	Hardness:
Fracture/Tenacity:	
Crystal Form/System:	
Shape/Habit:	
Cleavage/Parting:	
Other:	

Unknown B:	
Chemical Formula:	
PHYSICAL PROPERTIES	
Color:	Streak:
Luster:	Hardness:
Fracture/Tenacity:	
Crystal Form/System:	
Shape/Habit:	
Cleavage/Parting:	
Other:	

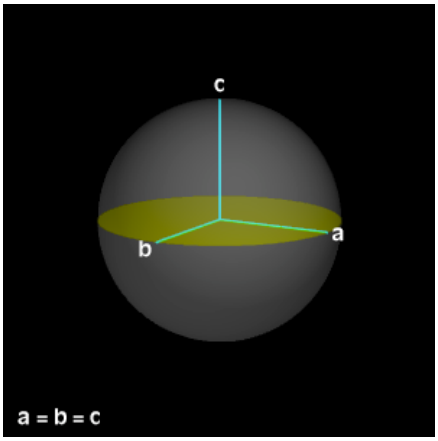
Optical Properties of Minerals

Optical properties of minerals describe the interaction of polarized light rays with the minerals and can be viewed with the PLM. These properties are viewed in either plane-polarized light (using only the lower polarizer) or cross-polarized light (using both polarizers).

As light enters a material it slows down. The speed of light within a material can be described as a ratio between the speed of light in a vacuum and the speed of light in the material. This ratio is the refractive index and is referred to in equations as *n*. Minerals are classified optically by how *n* differs within the mineral.

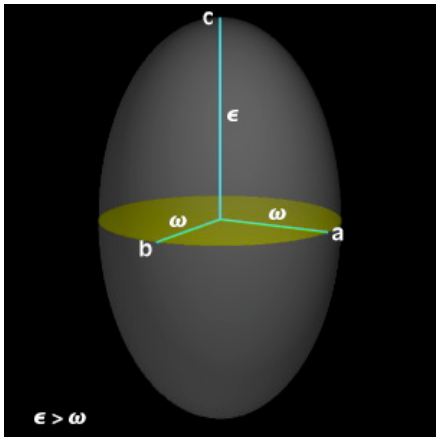
These differences can be represented in an imaginary 3-D model called an optical indicatrix (Fig. 15). The different optical classes of minerals are isotropic (*n* is the same in all directions), uniaxial (there are two different *n* perpendicular to each other), and biaxial (there are three different *n* perpendicular to each other). Uniaxial and biaxial minerals are further classified as being either positive or negative.

Figure 15: The optical indicatrices for the different optical classes of crystals (Fig. 5.14, Dyar and Gunter 2008).

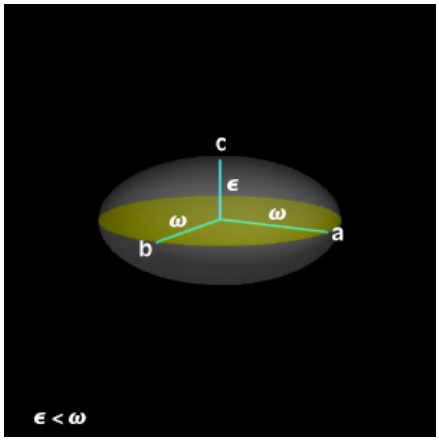


A. In the isotropic indicatrix, the refractive index is the same in all direction.

In uniaxial indicatrices the circular section has a radius of ω *(omega), and the refractive index for light vibrating parallel to the c axis is called* ε *(epsilon). There is one circular section, so there is one optic axis perpendicular to the section.*

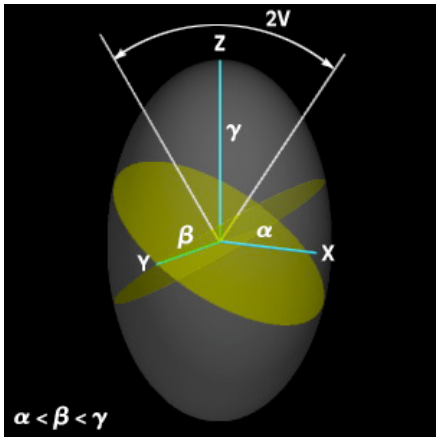


B. The indicatrix is positive if $\varepsilon > \omega$.

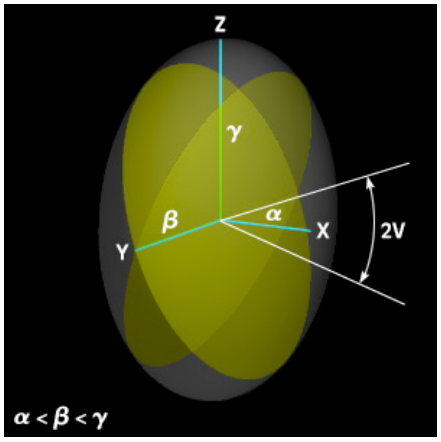


C. The indicatrix is negative if $\varepsilon < \omega$.

In biaxial indicatrices, there are three possible refractive indices (n): $\alpha < \beta < \gamma$. *There are two circular sections (radius of* β*), so there are two optic axes perpendicular to the sections. The acute angle between the optic axes is called 2V.*



D. The indicatrix is positive if β *is closer to* α.

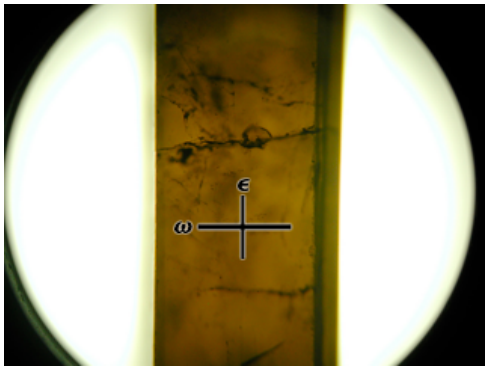


E. The indicatrix is positive if β *is closer to* γ.

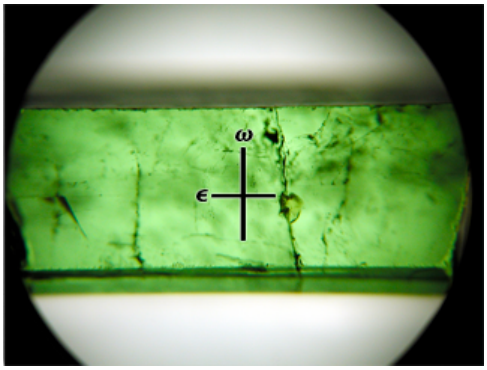
A. Color in Plane Polarized Light (PPL)

Describe general color and pleochroism (color change of grain as stage is rotated) shown in Figure 16.

Figure 16: Tourmaline in the PLM showing pleochroism (Fig. 18.29, Dyar and Gunter 2008).



A. The c axis is vertical, so ω is parallel to the lower polarizer. In this orientation, almost all of the incident light is absorbed and the crystal appears dark brown.



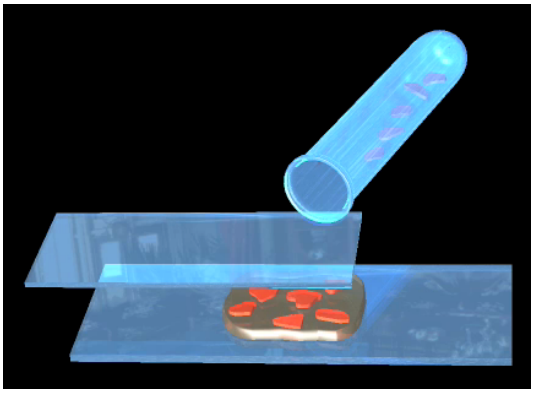
B. The crystal is rotated 90° so the c axis is parallel to the lower polarizer. In this orientation the structure absorbs much less light and appears green. Field of view is 5 mm.

B. Refractive Index and Relief

The speed of light slows down when it enters a material from air. This change is described by the material's refractive index. Relief describes the difference of RI of the mineral of interest to the surrounding material. Relief is best observed in grain mounts (shown in Fig. 17) where grains of a mineral are immersed in an oil of a known refractive index. Relief is observed by noting where Becke lines (light or colored lines outlining mineral grains in PPL) move in relation to the grain of interest as the microscope stage is lowered, as shown in Figure 18. The light Becke line will move into the material with higher RI. When the RI of the mineral grains matches that of the surrounding material, the Becke lines will turn blue and orange.

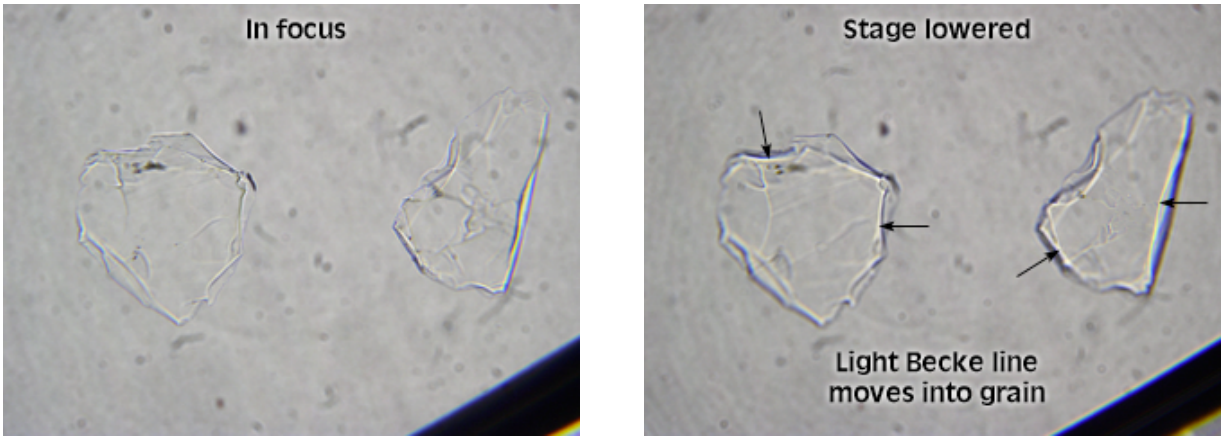
$$n = \frac{speed\ of\ light\ in\ a\ vacuum}{speed\ of\ light\ in\ the\ material}$$

Figure 17

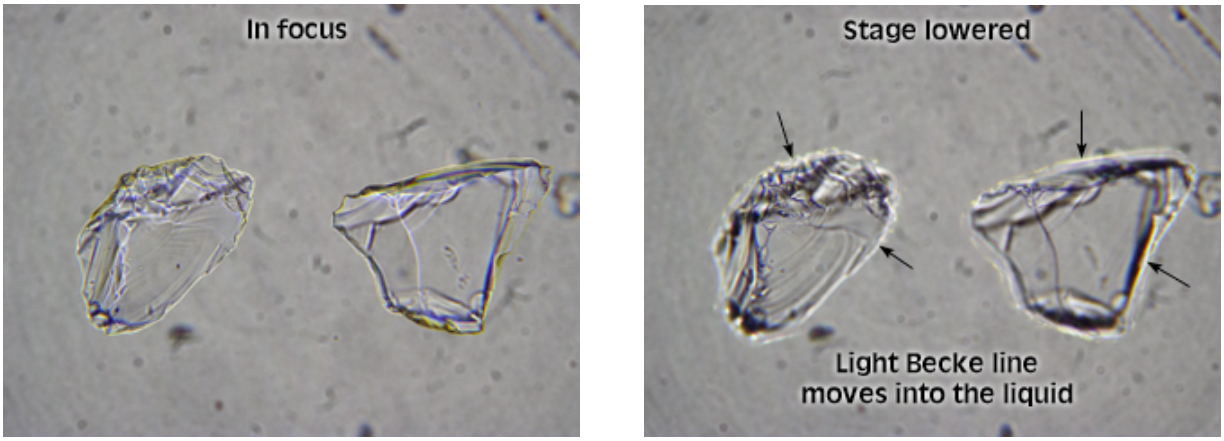


Grain mount preparation:
To make a grain mount, first crush and sieve a sample to a desirable size, about 100μm. Then, drop a couple of drops of a known refractive index liquid onto the slide. Sprinkle the sample grains onto the liquid and cover with a cover slip (Fig. 17.9a, Dyar and Gunter 2008).

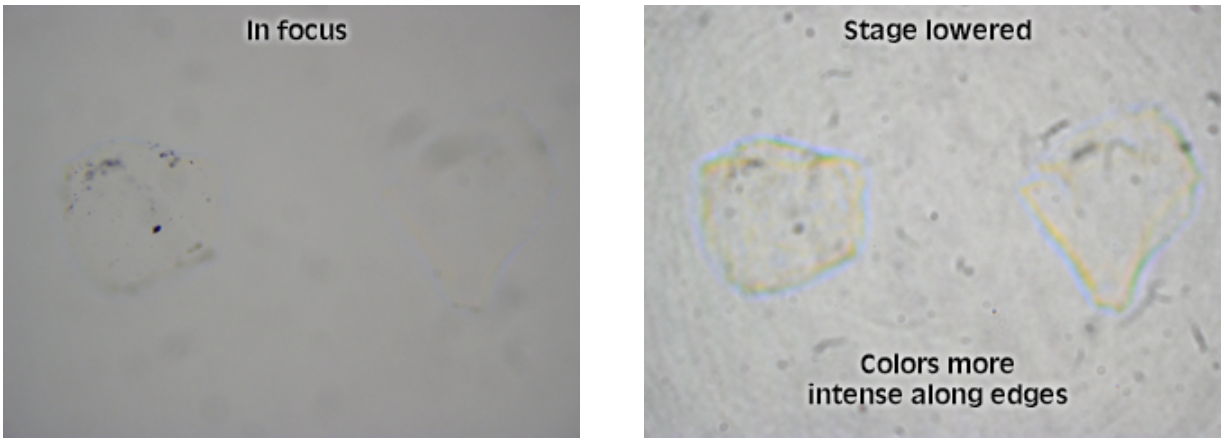
Figure 18: Images of grains of glass immersed in liquids of different refractive indices (Fig. 5.10, Dyar and Gunter 2008).



A. The grain is immersed in a liquid with n = 1.48; when the stage is lowered, the light Becke line moves into the grain. Low relief.



B. The grain is immersed in a liquid with n = 1.55; when the stage is lowered, the Becke line moves into the liquid. High relief.



C. Pieces of glass with n = 1.50 immersed in a liquid of n = 1.50. Notice that some colors around the edge of the grain become more intense as the stage is lowered. Also notice that the closer the liquid and grain are to matching, the harder it is to see the grain. Very low relief.

Exercises: Refractive Index of Minerals

1. Make a grain mount of fluorite grains in RI liquid 1.430, 1.434, and 1.440. Fluorite is isotropic so there is only one *n* to measure. Note the appearance of the grains in each liquid and the movement and color of the Becke lines. Record your observations below.

1.430:

1.434:

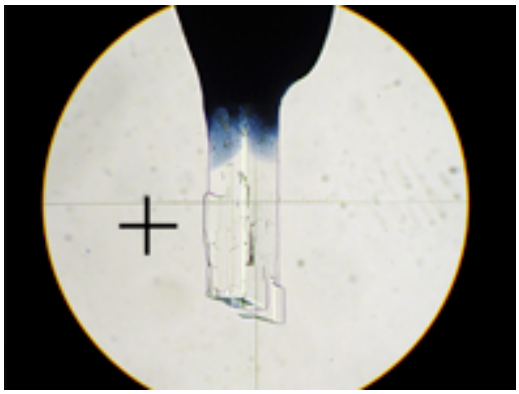
1.440:

2. Make grain mounts of halite and use your observation of the Becke lines to determine the RI of halite.

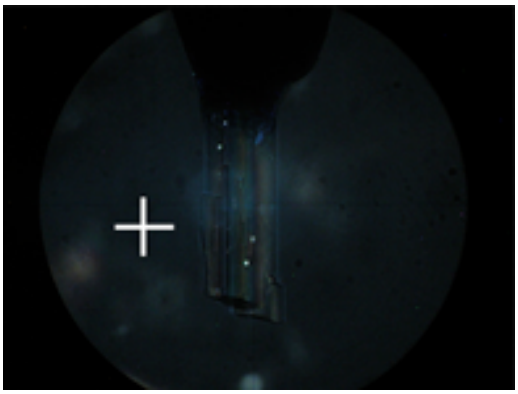
C. Extinction

Extinction is when an anisotropic grain turns completely black under XPL (Fig. 19). Some grains exhibit unique extinction patterns and textures. For example, quartz that has undergone metamorphic pressure can exhibit undulatory extinction, which is a sweeping motion of the extinction across the grain as the stage is rotated. Elongated minerals can have their extinction angles measured (the angle from the cross-hair in the scope will the grain become extinct).

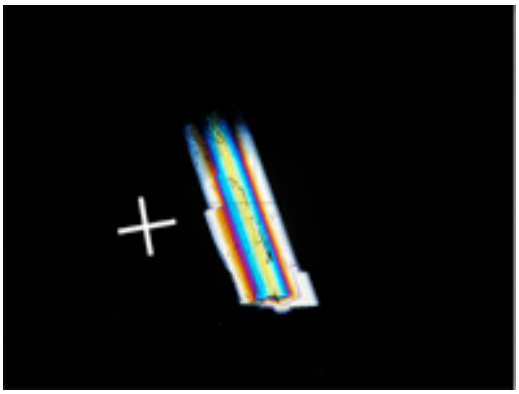
Figure 19: Single crystal in the PLM showing parallel extinction (Fig. 17.63, Dyar and Gunter).



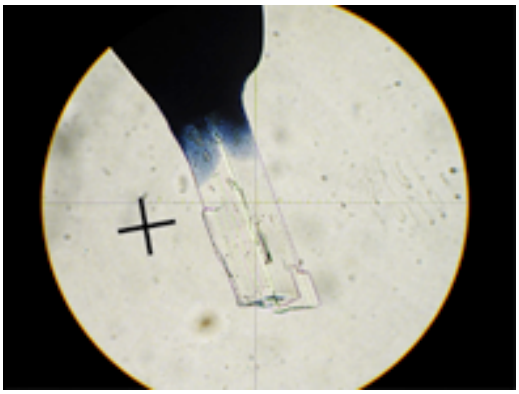
a. Crystal in plane-polarized light.



b. Same orientation as (a.) in cross-polarized light, showing parallel extinction.



c. The crystal has been rotated ~10° counterclockwise so it shows retardation.



d. The same crystal as in (c.) viewed in plane polarized light.

D. Birefringence (δ)

Light travels through a mineral in different ways and at different speeds (*n* and *N*). The variable *n* is the direction with a smaller refractive index (the fast wave) and *N* is the direction with a larger refractive index (the slow wave). Birefringence is the difference in refractive index between *n* and *N*.

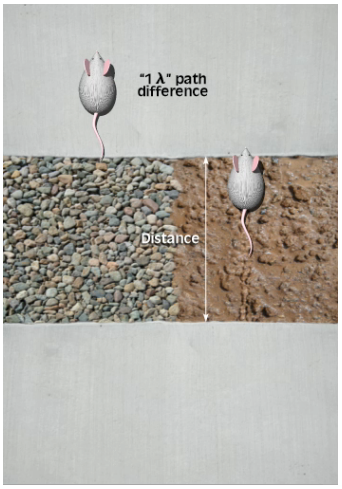
$$\delta = N - n$$

E. Retardation (Δ)

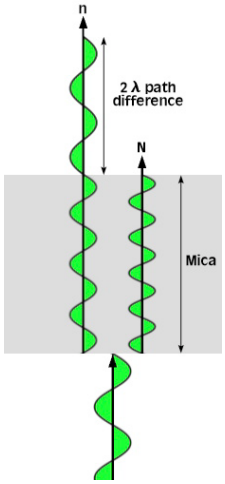
Retardation is the distance by which the slow wave lags behind the fast wave and depends on thickness of the grain (t) and the birefringence of the material (δ) as seen in Figure 20. Retardation is represented by the different interference colors seen in XPL (Fig. 20). The colors are generally divided into First Order (1°), Second Order (2°), Third Order (3°), and Fourth Order (4°).

$$\Delta = t\delta$$

Figure 20: Diagrams relating the wavelengths of light as they travel through an isotropic mineral (Fig. 16.17d and e, Dyar and Gunter 2008).

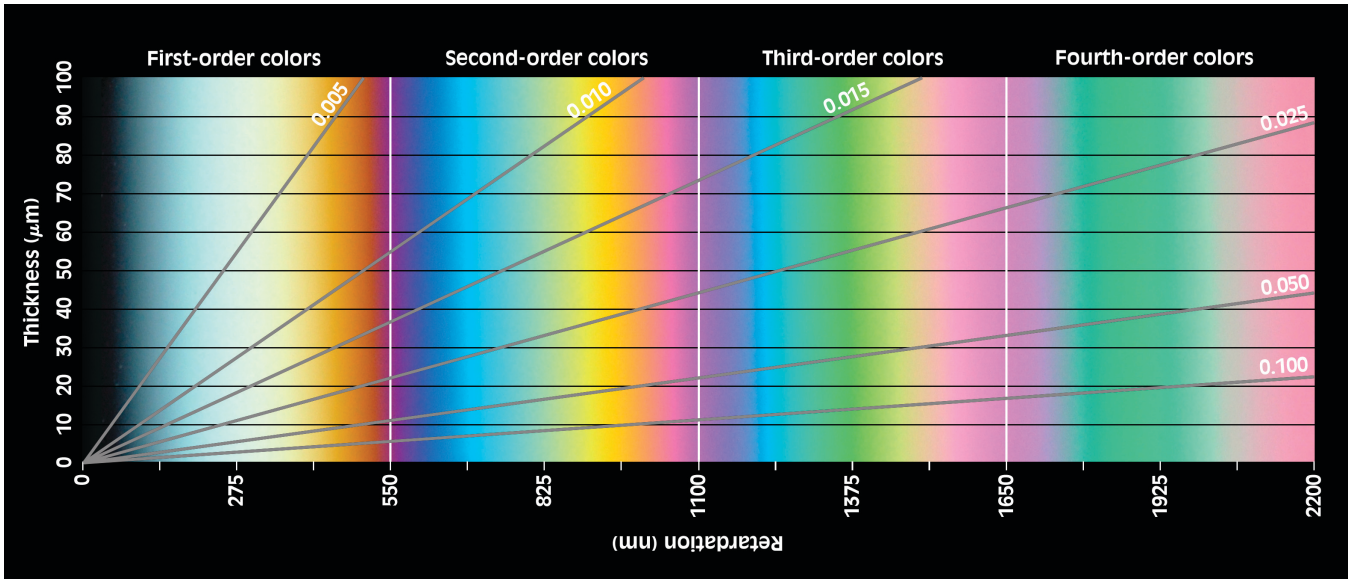


a. When light passes through a crystal, one wave may lag behind the other. To illustrate, two mice are shown here running parallel over a hard surface, then crossing onto different surfaces: gravel on the left, and mud on the right. The mouse running through mud would slow down more than the mouse running on gravel. The progress of the mouse on the right is retarded (slowed), so that the gravel-running mouse will emerge back onto the concrete ahead of his mud-running friend.



b. The behavior of light traveling through behaves much like the mice in Figure 16.17d. As the light wave impinges on the mica grain, it vibrates along two separate directions. The wave on the left (n) is traveling faster than the wave on the right (N), so the left wave will emerge from the crystal first.

Figure 21: Interference colors in relation to retardation (x-axis), thickness of the grain (y-axis) and birefringence (diagonal lines). (Back cover, Dyar and Gunter 2008)



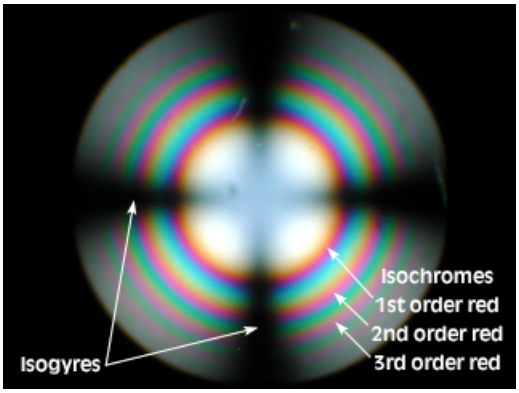
F. Optic Type and Sign

The optic type refers to the relationship between the different refractive indices within a mineral and can be interpreted by an interference figure (Fig. 22 and Fig. 23).
Follow the steps below to obtain an interference figure and determine the optic sign.

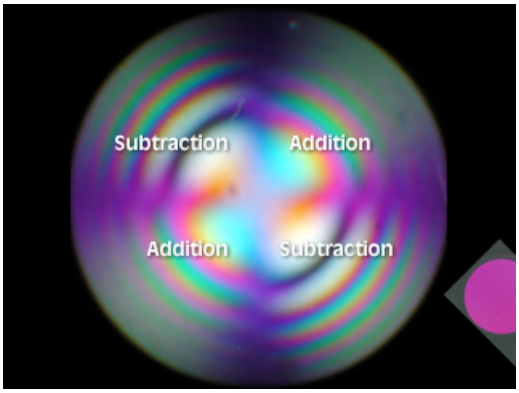
1. Use a low power objective to choose a large grain with the lowest retardation possible, which increases the chance of looking down the optic axis.
2. Switch to the highest power objective and refocus on the grain of interest. Be sure the polars are crossed.
3. To obtain the optic sign, slide in the gypsum wave plate. Look for addition or subtraction of colors in the upper right corner (Fig. 24).

Blue	**Y**ellow
Upper	**U**pper
Right	**R**ight
Positive	**N**egative

Figure 22: Isochromes form in the interference figure, increasing in retardation from the center of the grain outwards. The dark wedges in the interference figure are called isogyres, representing areas where the vibration directions in the crystal correspond to those in the polarizers (Fig. 17.17, Dyar and Gunter 2008).

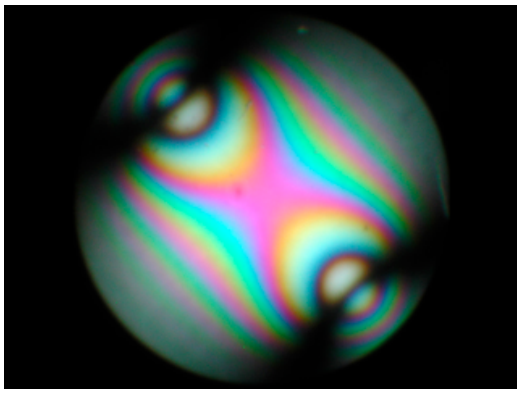


A. An uniaxial interference figure of a centered optic axis of a quartz grain.

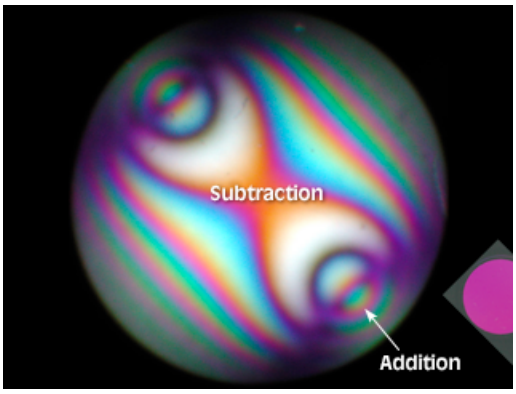


B. The same configuration as in Figure 22a, but a quartz plate has now been inserted to show areas of addition and subtraction.

Figure 23: Isochromes form in the interference figure, increasing in retardation from the center of the grain outwards. The dark wedges in the interference figure are called isogyres, representing areas where the vibration directions in the crystal correspond to those in the polarizers (Fig. 17.19, Dyar and Gunter).

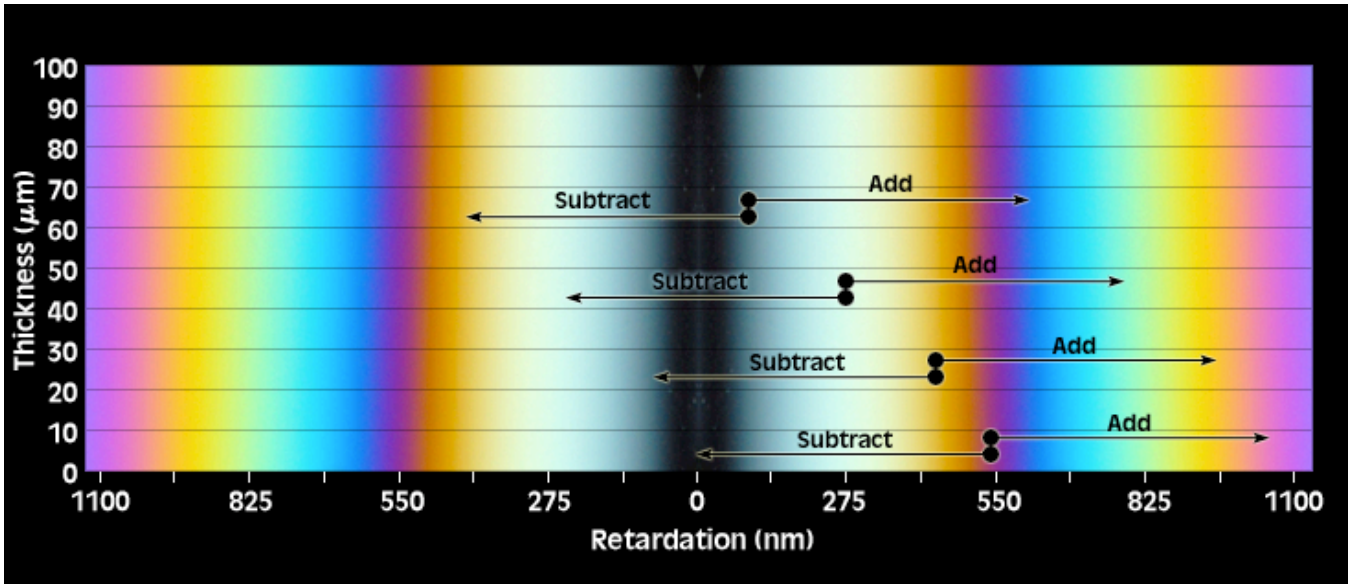


A. A biaxial interference figure of a centered acute bisectrix of a muscovite grain.



B. The same configuration as in Figure 23a, but a quartz plate has now been inserted to show areas of addition and subtraction.

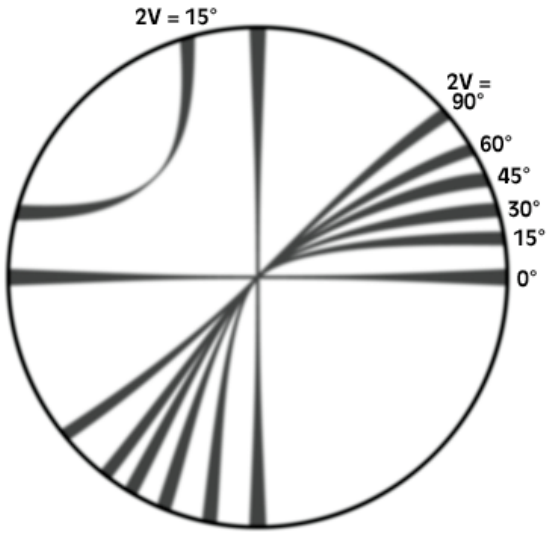
Figure 24: Interference chart "mirrored" to show addition and subtraction of colors (Fig. 17.14, Dyar and Gunter 2008).



G. 2V

The acute angle between the optic axes in biaxial indicatrices and can be estimated by the curvature of the isogyres in centered, or near centered, optic axis figure (Fig. 25).

Figure 25



The curvature of isogyres can be used to estimate 2V in figures centered on an optic axis. When 2V = 0, as is the case for a uniaxial mineral, the isogyres are orthogonal and correspond to the crosshairs. Isogyres that arise from values of 2V varying from 0–90° are shown here. Lower values of 2V are more curved than higher values (modified from Bloss, 1999, Figure 11.15). (Fig. 17.28, Dyar and Gunter 2008)

Exercises: Optical Properties of Minerals

Using the tools and figures provided, write down your observations of the properties of the provided mineral samples.

tourmaline

color (PPL)_____

RI_____

retardation / inference color_____

birefringence_____

Optic Type / Sign_____

other properties_____

biotite

color (PPL)_____

RI_____

retardation / inference color_____

birefringence_____

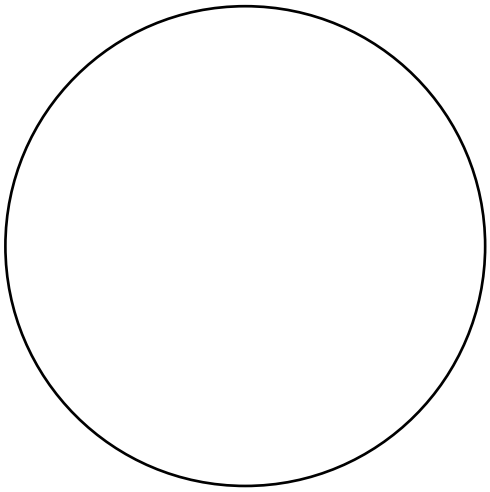
Optic Type / Sign_____

2V_____

other properties_____

Exercises: Using the DVD Database

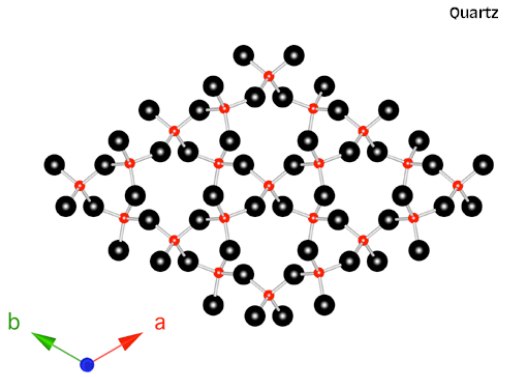
Identify the following mineral samples using the optical properties of the minerals and the DVD mineral database. Write the mineral name next to sample number. Use the space under the sample number to record your observations and make a sketch of the grain as you see it in your microscope.

<table>
<tr><td colspan="2">Unknown A:</td></tr>
<tr><td colspan="2">Chemical Formula:</td></tr>
<tr><td colspan="2">OPTICAL PROPERTIES</td></tr>
<tr><td>Color in PPL:</td><td>RI:</td></tr>
<tr><td>Retardation:</td><td>Birefringence:</td></tr>
<tr><td>Optic Type/ Sign:</td><td>2V:</td></tr>
<tr><td>Other (texture, extinction angle, twinning):</td><td>Sketch and magnification:
  </td></tr>
</table>

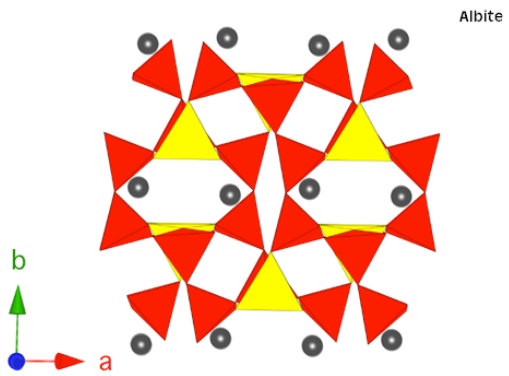
Framework Silicates

The four most common minerals in the earth's crust are framework silicates: quartz and the three end members of the feldspar group. Framework silicates have a Si:O ratio of 1:2. Structurally, all of the tetrahedrons in the structure share corners with other tetrahedra. In the feldspars, Al^{3+} can substitute for Si^{4+} in the tetrahedrons so there is 1 Si or Al for every 2 O (Fig. 26). Due to this framework structure, the optical properties of these minerals are similar in each direction, resulting in low birefringence and 1° interference colors when in thin section.

Figure 26: Examples of framework silicates structures (Fig. 6.1, Dyar and Gunter 2008).



A. atomic structure of quartz. The black dots are oxygen and the red dots are silicon.

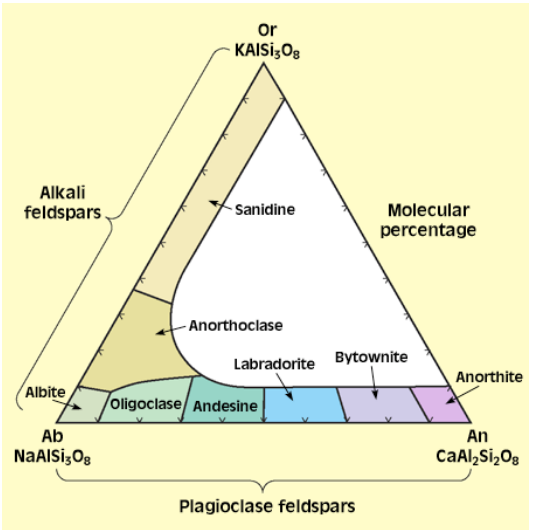


B. Atomic structure of albite (a feldspar). The red tetrahedrons are silica tetrahedrons, while the yellow are Al and O tetrahedrons. Each one represents 1 Si and 4 O.

The feldspar group is chemically represented by the ternary diagram in Figure 27 with K, Na, and Ca end-members. The K end-members include sanidine (found in volcanic rocks with a disordered structure), microcline (found in deep plutonic rocks with a highly ordered structure), and orthoclase (found in intermediate-depth plutons with a structure between sanidine and microcline). Albite is the Na-feldspar end-member and anorthite is the Ca end-member.

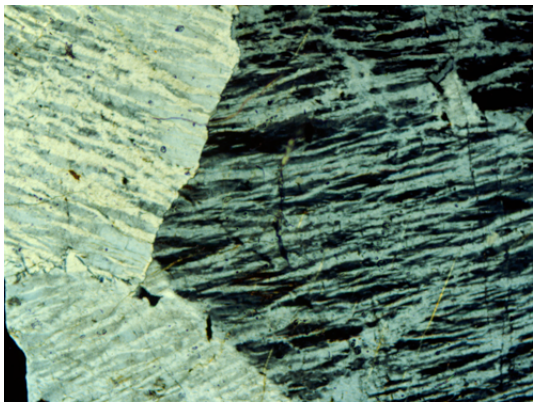
The Na-Ca feldspars make up the plagioclase sub-group and the K-Na feldspars make up the alkali feldspar sub-group. For example, labradorite is a plagioclase feldspar composed of near equal amounts of Na and Ca.

Figure 27: Compositional ternary diagram of the feldspar end-members (Fig. 6.2, Dyar and Gunter 2008).

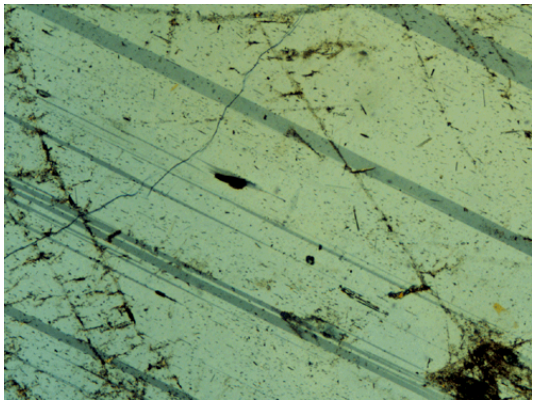


The feldspars can exhibit twinning, which is a symmetrical intergrowth of 2 or more single crystals of the same mineral. Twinning can be observed both in hand sample and optically. The different types of twinning can help identify the species of feldspar, as shown in Figure 28.

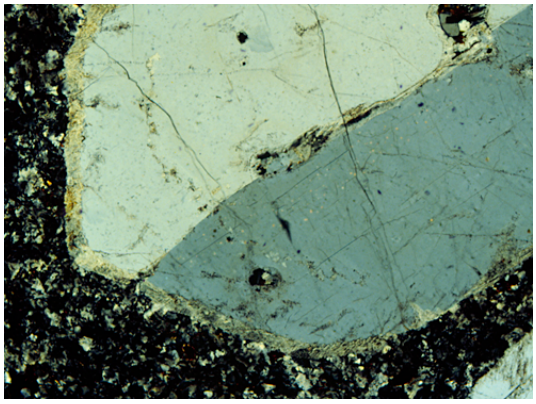
Figure 28: Texture and twinning patterns of feldspars viewing XPL in the PLM (Fig. 22.11 and Fig. 2.90, Dyar and Gunter 2008).



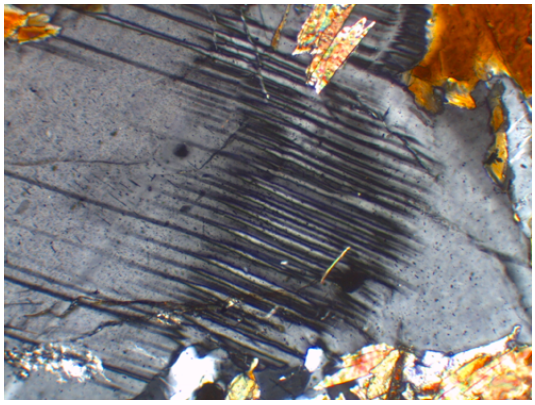
A. Perthite texture: "blebs" or "strings" of Na-rich feldspar within a K-rich feldspar host; can be observed at both macroscopic and microscopic levels.



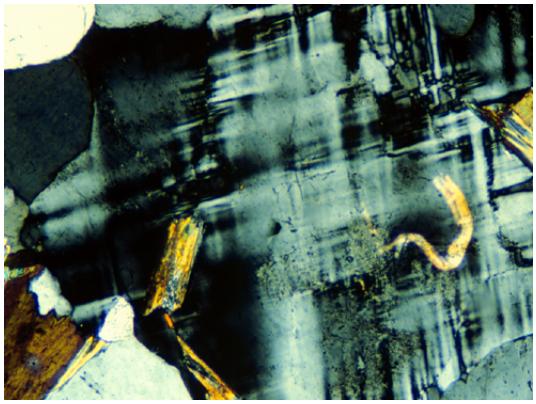
B. Albite twinning: appears as stripes under XPL in thin section; may be observed in hand sample as striations along cleavage planes and crystal faces; common in plagioclase.



C. Carlsbad twinning (simple twinning): two parts of a single crystal which show different extinction angles in XPL; common in orthoclase and occasionally in plagioclase.



D. Pericline twinning: similar to Albite twinning, but the bands pinch out in the crystal; common in alkali feldspar; in combination with albite twinning creates Tartan twinning (E).



E. Tartan twinning, which resembles a plaid pattern; common in microcline.

Exercises: Characterizing Framework Silicates

1. Observe and record the physical and optical properties of each mineral and note unique characteristics. Use the mineral summary sheets from the DVD and append your observations to them. Be sure to look at all of the provided samples.

- quartz
- orthoclase
- albite
- anorthite

2. What are the optical differences between quartz and feldspars?

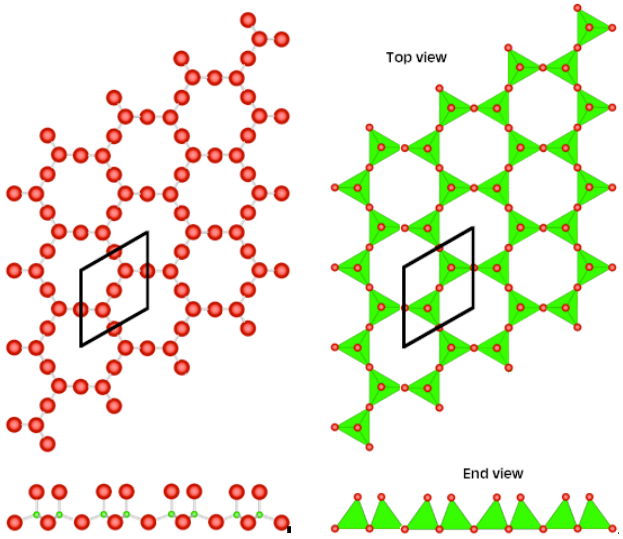
3. What is undulatory extinction in quartz and what does it infer about the environment?

4. What are the differences in the properties between the feldspar end-members?

Sheet Silicates

The next two common minerals in the earth's crust discussed in this lab are the sheet silicates: muscovite and biotite. Sheet silicates have layers (sheets) of tetrahedrons connected to octahedrons and other cations. They have a Si to O ratio of 2:5. There are planes of weakness between each of the layers, so the sheet silicates have basal cleavage (Fig. 29). In thin section, the micas will exhibit "bird's eye" extinction, a mottled or speckled texture that is thought to occur when the thin section is ground down to thickness.

Figure 29: Different representations of the tetrahedral layer of a sheet silicate (Fig. 6.4, Dyar and Gunter 2008).



A. Ball and stick models of a sheet silicate.

B. Polygon model of a sheet silicate.

Exercises: Characterizing Sheet Silicates

1. Observe and record the physical and optical properties of each mineral and note unique characteristics. Use the mineral summary sheets from the DVD and append your observations to them. Be sure to look at all of the provided samples.

- muscovite
- biotite
- chlorite
- talc

2. How do muscovite and biotite differ chemically and how is that related to their color in PPL?

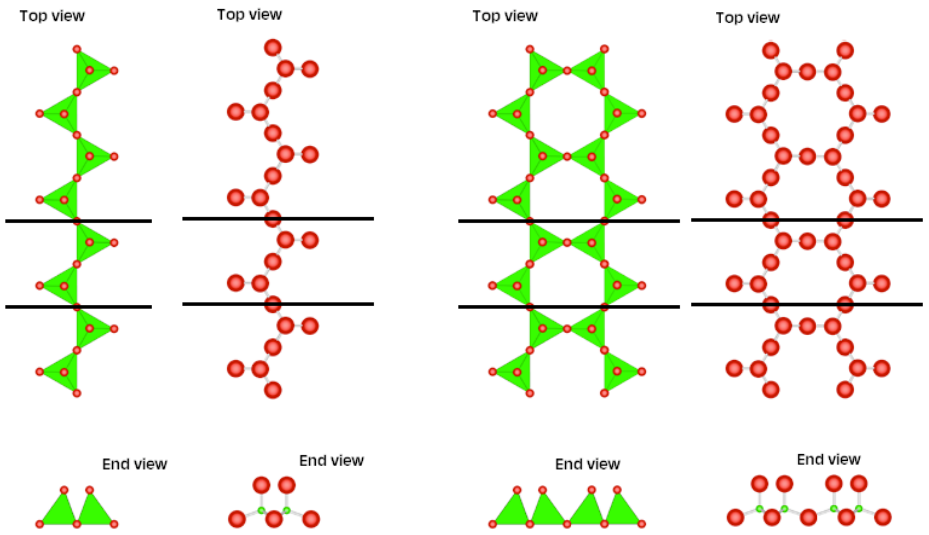
3. The micas show bird's eye extinction. What other sheet silicates show this phenomenon?

Chain Silicates

The 7th and 8th most common mineral groups in the earth's crust are chain silicates. Amphiboles are double chain silicates (Si:O = 4:11) and pyroxenes are single chain silicates (Si:O = 1:3), both tend to be elongated crystals (Fig. 30). Both pyroxene and amphibole are names for mineral groups. There are many species of both pyroxenes and amphiboles, but we will only look at two of each.

Amphiboles tend to be longer and skinnier than pyroxenes, have 2 cleavage planes at 60° and 120°, and stronger pleochroism if the mineral contains Fe. Pyroxenes have two cleavage planes at 90°, weak pleochroism (if any), and have a "grungy" or "dirty" look in PPL. Both groups are further divided into ortho- and clino- subgroups. The subgroups can be distinguished from each other through their extinction angles.

Figure 30: Representations of single and double chain silicates structures (Fig. 6.4, Dyar and Gunter 2008).



A. Polygon model and a ball-and-stick model of a single chain silicate.

B. Polygon model and a ball-and-stick model of a double chain silicate.

Exercises: Characterizing Chain Silicates

1. Observe and record the physical and optical properties of each mineral and note unique characteristics. Use the mineral summary sheets from the DVD and append your observations to them. Be sure to look at all of the provided samples.

- enstatite
- augite
- hornblende
- tremolite

2. What are the three major cations you find in amphiboles and pyroxenes?

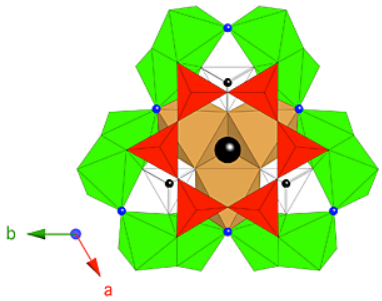
3. What do the terms clinopyroxene (CPX) and orthopyroxene (OPX) refer to in the pyroxenes and how do they differ optically?

4. Explain in words, and / or illustrations, why pyroxenes have 90-degree cleavage and amphiboles have 60 and 120-degree cleavage.

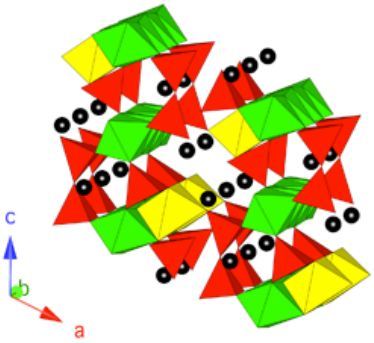
Orthosilicates (also ring silicates and disilicates)

There are several other silicate classes, but there just isn't time to go through them all! So we will look at a few minerals belonging to the ring silicate, disilicate, and orthosilicate classes. Ring silicates have chains of silica tetrahedra shaped into rings (Fig. 31a). Disilicates have pairs of silica tetrahedra (Fig. 32b), sometimes called "bow ties". Orthosilicates have isolated Si tetrahedrons (Si:O = 1:4) in their structure (Fig. 31c) and include minerals such as olivine, the 9th mineral on the ten most common minerals in the

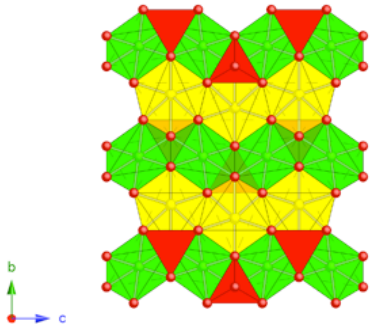
Figure 31: Representations of the crystal structures of tourmaline, epidote, and olivine (Fig. 22.36, Dyar and Gunter 2008).



A. Atomic structure of tourmaline group mineral schorl (ring silicate).



B. Atomic structure of epidote (disilicate).



C. Atomic structure of olivine group mineral fayalite (orthosilicate).

Exercises: Characterizing Orthosilicates

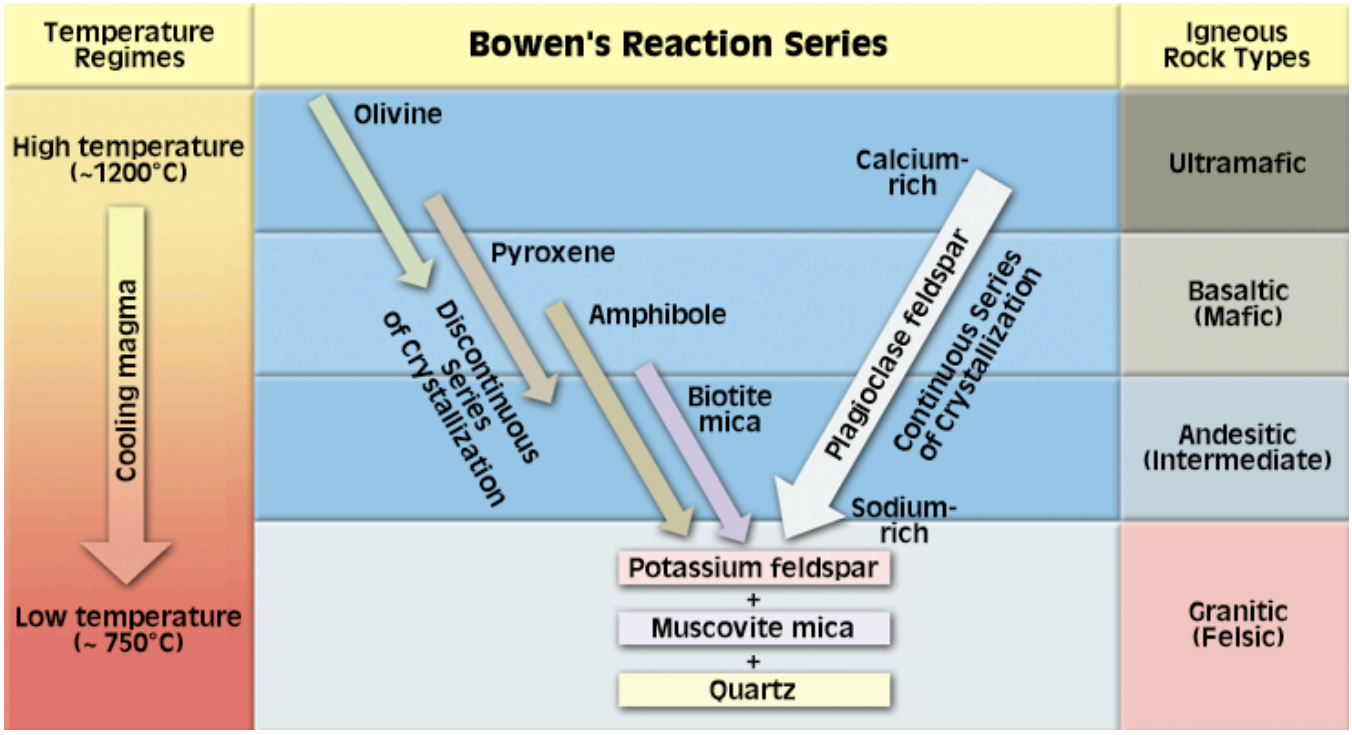
1. Observe and record the physical and optical properties of each mineral and note unique characteristics. Use the mineral summary sheets from the DVD and append your observations to them. Be sure to look at all of the provided samples.

- olivine (group)
- garnet (group)
- alumino-silicates (kyanite, andalusite, and sillimanite)

2. What are the two end members of olivine? Include their chemical formulas.

3. On the diagram of Bowen's reaction series below, draw an arrow on the left side of the diagram pointing in the direction of increasing Si:O. Next to each mineral, write its general mineral class (e.g. albite, framework silicate).

Figure 32: Diagram of Bowen's reaction series (Fig. 20.16, Dyar and Gunter 2008).



Non-Silicates

There is only one mineral on the Top 10 list of most common minerals in the earth's crust that is not a silicate: calcite. Calcite has the distinctive property of fizzing in HCl acid, 3 cleavage planes at ≠90°, and very high birefringence.

Minerals are classified by their main anion or anionic complex. There are several classes of minerals that do not contain Si, but they fall into the general category of non-silicates. Some of the mineral classes are listed in the table below.

Mineral Classes	Anionic Complex	Example
Silicates	Si^{4+} and O^{2-} in 4 coordination	quartz, micas, olivine
Native Elements	"pure" elements (are not bonded to any other elements)	diamond, gold
Sulfides	one or more metal/semi-metal atoms with S^{2-}	cinnabar, galena
Oxides	one or more metal/semimetal atoms with O^{2-}	corundum, hematite
Halides	halogen element (F^{1-}, Cl^{1-}, Br^{1-}, I^{1-}) with metals	halite, sylvite
Carbonates	$C^{1+}O^{2-}_3$ triangle	dolomite, aragontie
Borates	B^{3+} and O^{2-} in 3 or 4 coordination	borax
Sulfates, Chromates, Tungstates	S^{6+}, Cr^{6+}, or W^{6+} with O^{2-} in 4 coordination	barite, gypsum
Phosphates, Arsenates, Vanidates	P^{5+}, As^{5+}, V^{5+} with O^{2-} in 4 coordination	apatite, gunterite

Exercises: Characterizing Non-Silicates

1. Observe and record the physical and optical properties of each mineral and note unique characteristics. Use the mineral summary sheets from the DVD and append your observations to them. Be sure to look at all of the provided samples.

- calcite
- fluorite
- opaque minerals

2. The Si tetrahedron is the anionic complex of silicates. Sketch calcite's anionic complex and label the atoms.

3. Name the mineral classes that calcite and fluorite belong to?

4. Why can you not use the PLM to characterize opaque minerals?

Project: The Spindle Stage and EXCALIBR W

The spindle stage is used as a means to orient single crystals on a polarized light microscope (Dyar and Gunter 2008). This one-axis rotation device enables one to view a single crystal of a mineral from several different orientations and measure their optical properties.

This lab is divided into two sections:

1. Assemble your spindle stage, oil cell, and mount a crystal of olivine onto a straight pin.

2. Use your spindle stage, oil cell, and olivine crystal with the PLM to measure extinction angles of your crystal. Fill out the information on the handout at the end of this section and use with the program EXCALIBR to find the orientation of the ON, OB, or AB axis and measure its refractive index.

Follow the instructions on the following pages for building/assembling your spindle stage and using the EXCALIBR program.

Exercise: How to build a spindle stage

Instructions from the Mineralogy and Optical Mineralogy Chapter 18, pages 510-511, Figures 18.A1-18.A2 (Dyar and Gunter 2008).

Building the base.
Once a material has been selected, the first step is to cut out two 50 x 50 mm pieces. One of these will be the base of the spindle stage (Fig. 33a), and the other will form the protractor scale (Fig. 33b). For the base, scribe lines as shown in Figure 33a to locate its center. Next, take a glass slide and place it as shown in Figure 33b. Use it to mark the sides and top of the base, then cut out this material to form the oil cell.

Building the dial.
Make a 1:1 copy of the circle protractor scale in Figure 33d (either with a copy machine or a scanner). The circle has a diameter of 50 mm. Glue it to a 50 x 50 mm square of the base material (e.g., poster board) as shown in Figure 33e. Trim the edges and cut the circle in half to complete the spindle dial (Figure 33f). If desired, you can glue another circle protractor onto the back of the 50 x 50 mm block before trimming and cutting it; that way you can read the dial from either side. If you mount a scale on the back, be sure to place it so the *S* angles correspond from front to back (see Figure 34b).

Assembling the stage.
Cut a 15 x 50 mm rectangle and trim the edges as shown by the scribe marks (Figure 33g). Glue it vertically in the center of the base (Figures 33h). Then glue the protractor dial to the end of the base. Insert a hollow metal tube, which will serve two functions: one end serves as a sleeve to hold a needle with crystal attached, and the other end is a marker for reading the *S* angle. For example, a 20-gauge 21/2" hypodermic needle can be used to make a hole in the center of the assembled stage, passing through the center of the protractor and the 15 x 50 mm mid-piece. Next, insert a piece of tubing approximately 21/2" long through this hole and allow it to extend a few millimeters into the cavity for the cell. Finally, put a 90° bend in the tubing where it passes through the backside of the protractor scale. If the tube is not long enough on the protractor scale, it can be extended by inserting a straight pin in its hollow end, as shown in Figure 34b. If the pin fits too loosely, place a small bend in the end that is inserted into the tube.

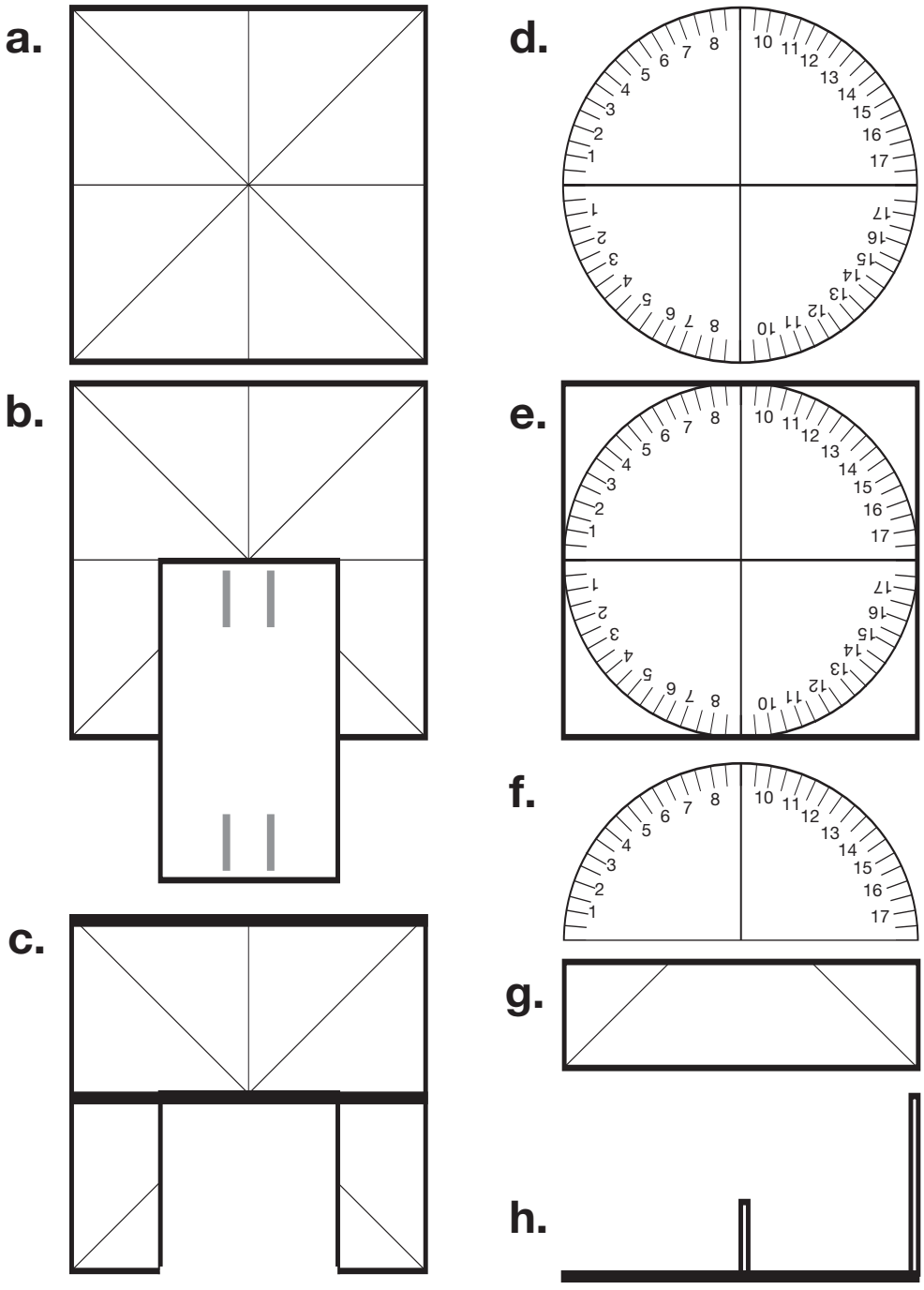
Building the oil cell.
A standard petrographic glass slide (or any glass slide) can be used for the oil cell. Cut two 8–10 mm pieces off the end of a large paper clip. Epoxy them to one end of glass slide (Figures 33b and 34a). Make sure they form a cavity that is centered on the slide with an approximate width of 5–8 mm. Refractive index liquid can be placed between the paper clip pieces and a glass cover slide placed on top. If desired, another oil cell can be added to the other end of the slide.

Mounting the spindle stage on a microscope stage.
Figure 34c shows a completed homemade spindle stage and oil cell mounted on the stage of a polarizing light microscope. In this case, cellophane tape is used, but other more permanent methods could be used. The tape is first placed in front of the protractor dial of the spindle stage. Then the spindle stage, with an affixed crystal, is placed on the microscope stage and the crystal is positioned at the center of the crosshairs. The tape is pushed down to mount the spindle stage to the microscope stage. Other pieces of tape can be placed on the ends of the spindle stage (next to the oil cell) to better secure it. It is also helpful to place the microscope stage to zero (i.e., obtain an *M*r, or reference angle, near 0°), then orient the spindle stage so its axis of rotation is parallel to the E-W cross- hairs and the tip is pointed to the W, as shown in Figure 34c.
The spindle stage in Figure 34c also shows how a straight pin has been bent into the form of a "U" so the *S* angles can be read on the back, as well as the front, of the protractor. If the "U"- shaped needle is removed, translation in the "*x*" direction will be possible, so the crystal can be better centered in the field of view.
The design presented above works well. It is probably the simplest possible design of a spindle stage, and as such might lack some useful features such as a translation in the *Y* direction, or detents for 10° increments of the S setting. We encourage you to experiment with this design and modify it in any way you see fit. Our main goal is to provide a starting point design for something that can easily be made in less than an hour and used to collect extinction data sets.

Exercise: How to build a spindle stage (continued)

Instructions from the Mineralogy and Optical Mineralogy Chapter 18, pages 510-511, Figures 18.A1-18.A2 (Dyar and Gunter 2008).

Figure 33: Diagram of the parts needed to build a spindle stage (Fig. 18.A1, Dyar and Gunter 2008).

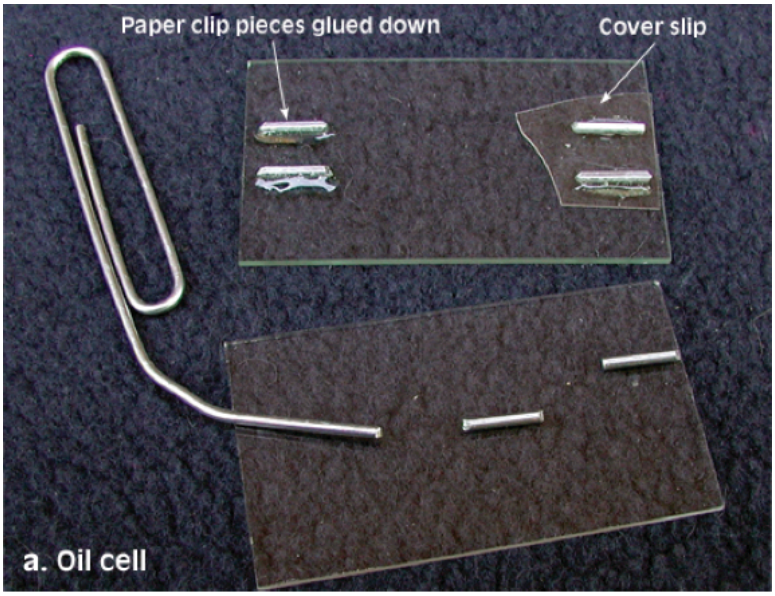


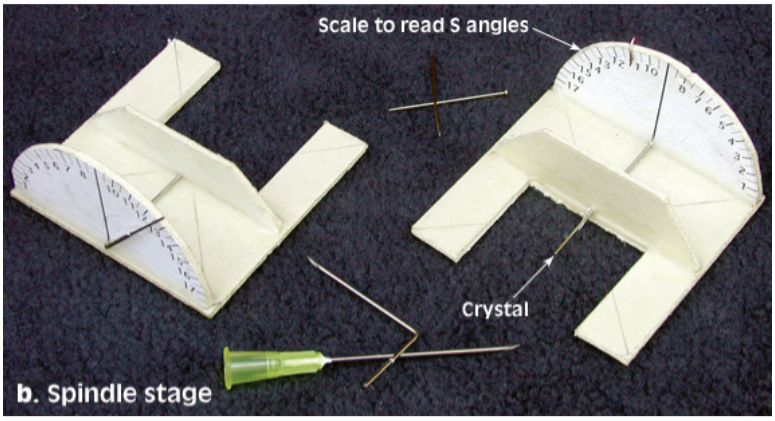
Make a 1:1 copy of this "blueprint" for the parts needed for the spindle stage.

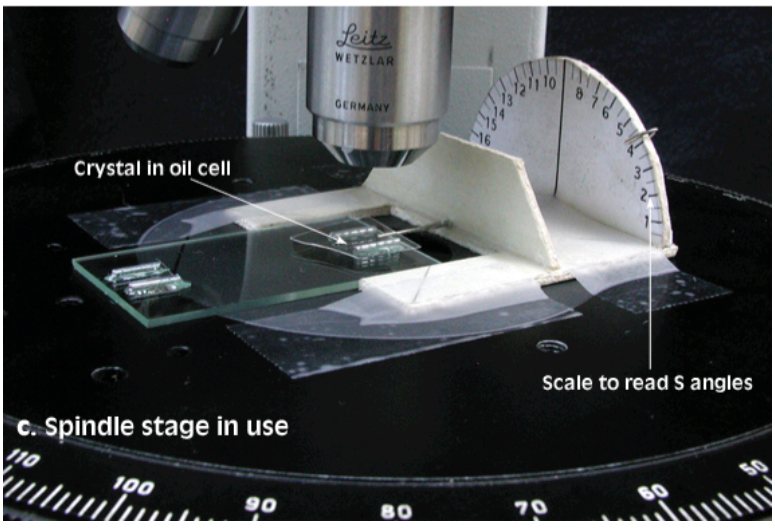
Exercise: How to build a spindle stage (continued)

Instructions from the Mineralogy and Optical Mineralogy Chapter 18, pages 510-511, Figures 18.A1-18.A2 (Dyar and Gunter 2008).

Figure 34: The spindle stage (Fig. 18.A1, Dyar and Gunter 2008).







Exercise: Using EXCALIBR

Instructions from the Mineralogy and Optical Mineralogy Chapter 18, pages 500-501, Figures 18.27-18.28 (Dyar and Gunter 2008).

Using EXCALIBR.

Use of the EXCALIBR software, especially the new Windows-based version, may be the easiest aspect of spindle stage use. You launch it like any application, typically by clicking on its icon. Then select the "File" pull down menu and select "New *.dat." Figure 35 shows the input window (with a data set). There are input fields and radio buttons for the input of data and selection of criteria required by the program. The first field at the top is a title. Next there are radio buttons to select the microscope stage type, followed by a selection of mathematical models for either the uniaxial or biaxial case. Select the biaxial model unless you are sure the crystal is uniaxial. The next fields of the window deal with the light source. Often white light (i.e., polychromatic) is used for routine work. However, up to four wavelengths of monochromatic light can also be entered. When more than one wavelength of light is used, the program determines if movement of the optical directions occurred (i.e., determines the dispersion of the crystal). This may help identify the crystal system of a biaxial crystal. The program will calculate a refined reference azimuth, *M*r, based on the input data, but an approximate reference azimuth should be input. This prevents the program from calculating an *M*r value that may be 90° in error, or some multiple of 90°, as explained above. Finally, enter the *M*s values in the window labeled "Extinction." The *S* values on the window to the left will start at "0" and increment by 10 after each *M*s value is entered. The enter button to the window's right must be clicked to accept the entered *M*s value. The *S* and *M*s pairs will accumulate in the window below. If a mistake is made in entering an *M*s value, double-click on that line in the lower window and edit it in the input window. Once all of the data are input, it is a good idea to click "Save" or "Save As" in the upper portion of the window. When "OK" is selected, the input window vanishes and a stereographic plot of the input data and its graphical solution is shown. To view the numerical results, go to the "Edit" pull-down menu and select "Output." If you then select "Data," the program will return you to the input window.

Numerical and graphical results from EXCALIBR are shown in Figure 36. At the top of the numerical results are the title and refined *M*r value. In this case, the refined *M*r value is –0.89°; this would correspond to a microscope stage setting of 359.11°. The next section gives a value for *R*2, which is an indicator of the overall quality of the fit of the calculated data to the input data. The center portion of the output repeats the input *S* and *M*s values followed by the *E*s value obtained from Equation 18.3in Dyar and Gunter (2008). Because *E*s would be negative (a cw stage was used), 180° is added to the *E*s values (i.e., the program uses the other end of the vector). In the next column are the calculated *E*s values, "CAL(Es)" determined after EXCALIBR solved the extinction data set, and the last column gives the observed *E*s values minus the calculated ones, "*E*s-CAL(*E*s)." Large errors (i.e., greater than 2 to 3°) in this column might indicate a misread extinction position. The bottom portion of the figure provides the useful output. The calculated 2*V* and its estimated standard error (ese) are given along with the S, *E*s, *M*s (for both E-W and N-S lower polarizers) results and their estimated standard errors. The output in this data set shows that all of the optical directions are located to better than 1° and 2*V* is determined to within 0.6°. This type of precision would not be possible with graphical methods. However, the graphical results (Figure 36) do provide a nice way of visualizing the input data (shown as dots) and the output data, which are the calculated extinction curves and the locations of *OA*1, *OA*2, *AB*, *OB*, and *ON*. The graphical output is also useful to see if any *M*s values were misread by observing any departures from the smooth curved pattern of the calculated extinctions curves. Misread extinction values would also be seen in the numerical analysis in the "Es- CAL(Es)" column.

Exercise: Using EXCALIBR (continued)

Instructions from the Mineralogy and Optical Mineralogy Chapter 18, pages 500-501, Figures 18.27-18.28 (Dyar and Gunter 2008).

Figure 35: Screenshot of the EXCALIBR W data entry window (Fig. 18.27, Dyar and Gunter 2008).

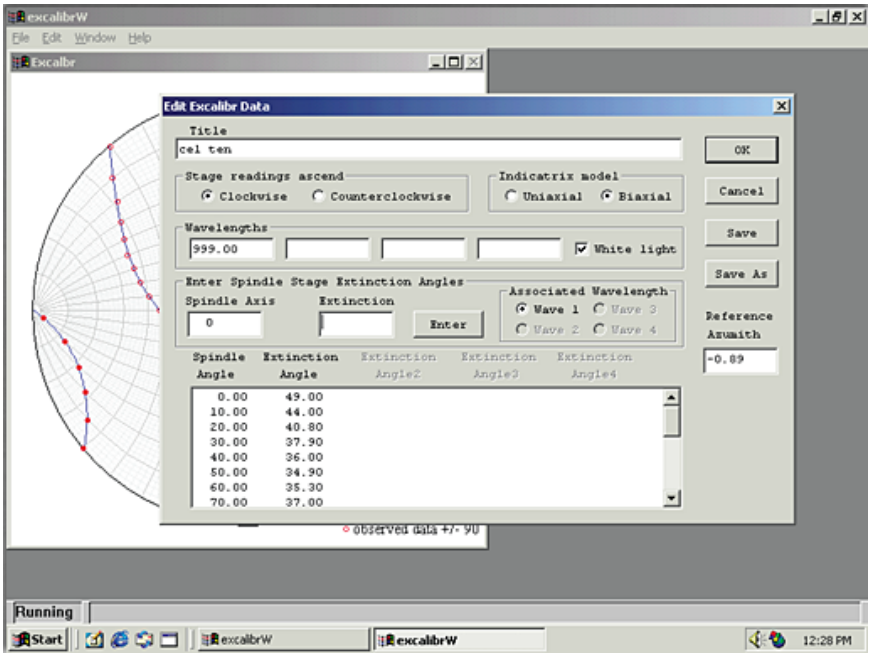
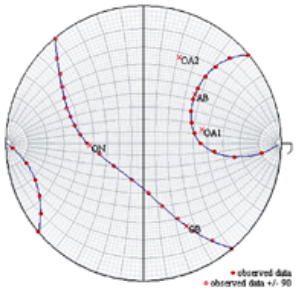


Figure 36: EXCALIBR W data output (Fig. 18.28, Dyar and Gunter 2008)

MEG10
Experimental Treatment ID number = 999.0
Refined Reference Azimuth, Mr = -0.89

Clockwise Stage
Number of iterations(100 max.) = 13
R-squared = 0.99920

S	Ms	Es	CAL(Es)	Es-CAL(Es)
0.00	49.00	130.11	130.19	-0.09
10.00	44.00	135.11	134.92	0.18
20.00	40.80	138.31	138.64	-0.33
30.00	37.90	141.21	141.33	-0.13
40.00	36.00	143.11	143.05	0.05
50.00	34.90	144.21	143.83	0.38
60.00	35.30	143.81	143.62	0.19
70.00	37.00	142.11	142.28	-0.17
80.00	39.80	139.31	139.46	-0.16
90.00	44.50	134.61	134.48	0.13
100.00	53.40	125.71	126.17	-0.47
110.00	65.30	113.81	113.63	0.17
120.00	79.70	99.41	99.01	0.40
130.00	92.80	86.31	86.46	-0.15
140.00	102.00	77.11	76.80	0.31
150.00	110.70	68.41	68.88	-0.47
160.00	117.20	61.91	61.91	0.06
170.00	124.00	55.11	55.46	-0.35
180.00	129.00	50.11	49.81	0.30



Optic Axial Angle, 2V (ese) = 49.359 (0.577)

Spindle Stage Coordinates to measure refractive indices.

	S (ese)	Es (ese)	Ms	
OA1	76.03 (0.45)	44.02 (0.33)		
OA2	23.32 (0.33)	68.94 (0.28)	(e-w pol)	(n-s pol)
AB	45.53 (0.14)	53.60 (0.09)	125.51	215.51
OB	156.13 (0.56)	64.48 (0.51)	114.62	204.62
ON	92.40 (0.77)	132.84 (0.45)	46.27	136.27

Exercise: Measuring Extinction Angles

Fill out the form below. Take 3 separate measurements of your crystal's extinction angles, in case your first dataset does not work with EXCALIBR.

Mineral: _____ Size _____

RI of ON, OB, or AB _____ Interference Colors _____

Color _____ Birefringence (use chart) _____

Grain Shape _____ Optic Class and Sign _____

Cleavage/ Fracture _____ 2V _____

SS Angle	Extinction Angle Dataset 1	Extinction Angle Dataset 2	Extinction Angle Dataset 3
0°			
10°			
20°			
30°			
40°			
50°			
60°			
70°			
80°			
90°			
100°			
110°			
120°			
130°			
140°			
150°			
160°			
170°			
180°			

Project: Mineral Collection

Now that we have looked at the 10 most common minerals and ways to identify them, we can create our own mineral collections. For a final project for this class, we will assemble a collection of minerals, identified by the methods and techniques learned in this laboratory course. Use your mineral observations with the mineral database on the DVD and other mineral and field guides provided by the instructor.

Your collection will contain 20 minerals and will be presented in a box, on a poster, as spindle stage mounts, etc. Be creative. Your minerals tossed into bag is not a collection, it's trash. Each mineral will be accompanied by an identification card (examples below).

Mineral Identification Card

mineral name location found properties mineral was identified by

example:

quartz Mica Mountain, Latah County, ID glassy, clear, conchodial fracture

Grading Rubric

Mineral with ID card	20 minerals…….	2 points each	40 points
Presentation	"tossed" in a bag……..	0 points	
	box/poster/ other creative presentation……	10 points	10 points

TOTAL 50 points