Important Optical Mineralogy Terms and Concepts

Part One: Basic Stuff

Light is a propagating wave front that moves fast. The velocity of light in a vacuum is one of the most important constants in science:

\[ V_c = 2.988 \times 10^8 \text{ m/s} \] (this constant is usually designated \( C \))

In any other medium beside a vacuum, the speed of light is less than \( C \). When light travels from one medium to another (vacuum to air, air to water), interesting effects occur. The physics behind this is portrayed in the following sketch:

The Index of Refraction \( (n) \) of a material is a ratio of \( C \) to the speed of light through a material \( (V_x) \).

\[ n_x = \frac{C}{V_x} \]

The index of refraction for some common substances is given in the table below:

<table>
<thead>
<tr>
<th>Material</th>
<th>( n_x )</th>
</tr>
</thead>
<tbody>
<tr>
<td>air</td>
<td>1.000027</td>
</tr>
<tr>
<td>water</td>
<td></td>
</tr>
<tr>
<td>glass</td>
<td>1.50</td>
</tr>
<tr>
<td>minerals</td>
<td>1.40-3.22</td>
</tr>
</tbody>
</table>

The index of refraction of a mineral can be relatively easily measured in a laboratory, but it is important to minimize any dispersion of light that might occur. This is the prism effect that occurs when white light is split up into its component colors:
Light produced from an incandescent source (AKA light bulb) is emitted as waves that have no preferred vibration direction (think of this as the orientation of the waveforms).

In order to do petrography (which is complex enough as it is), you need to restrict the light that passes through your mineral specimens to waves that vibrate in a single direction. This is done with the help of a polarizing lens:

Do not confused polarized light with monochromatic light. The former is white light that vibrates in a single direction. The latter is colored light of a single frequency (e.g. 550 nm is the pure red light you get in a laser pointer).

When it comes to light transmission, most geologists recognize 3 classes of minerals:

1) **Transparent** (minerals that transmit light and images through them) e.g., selenite
2) **Translucent** (minerals that only transmit light) e.g. quartz
3) **Opaque** (minerals that do not transmit light at all) e.g., galena, pyrite.

Transmission light microscopy (AKA thin section microscopy or optical microscopy) studies transparent and translucent minerals. The vast majority of minerals fall within these classes. Even minerals that you might at first think are opaque (pyroxene, biotite) are translucent if they are sliced thinly enough.

The way that light travels through minerals is entirely dependant on the crystalline structure of the minerals. In order to understand this, you need to recall the seven crystallographic systems that caused you so much hell in the crystallography component of this class.
For some minerals (e.g., the cubic system), light is transmitted equally (in velocity or wavelength) in all directions through the crystal. The index of refraction is also uniform in all directions. These minerals are said to be **isotropic**. In the rest of the mineral classes (termed **anisotropic**), the velocity of light is not consistent. There is a preferred orientation where light
travels faster than in other directions. In order demonstrate the different ways that light can travel through minerals and to summarize the optical properties of minerals, microscopists came up with the concept of an **indicatrix**. This is a geometrical figure that is produced around a point using the indices of refraction as radii. Isotropic minerals like the cubic mineral system have spherical indicatris (figure 1 below). Anisotropic minerals come in two major flavors. Minerals in the tetragonal and trigonal/hexagonal classes are termed **Uniaxial** and the indicatrix is defined as a **biaxial ellipsoid** (2 different axes; figure 2). Minerals in the remaining classes (orthorhombic, monoclinic, triclinic) are termed **Biaxial** and the indicatrix is defined as a **triaxial ellipsoid** (3 different axes; figure 3):
All anisotropic minerals do something interesting to light rays that pass through them. They divide the light (including polarized light) into two components which vibrate in mutually perpendicular planes. In the simplest case (that of the uniaxial minerals), one of these rays has a constant velocity regardless of the direction that the light passes through the mineral. This ray is called the **ordinary ray** or **o-ray** for short. The other ray is called the **extraordinary ray** (or **e-ray**) and it’s velocity varies with direction. This splitting of rays is known as **double refraction** (or **birefringence**), and although it is difficult to envision, most geology students have experienced it’s effects in at least one mineral: optical calcite (or Icelandic spar). So pronounced is the double refraction in calcite that it is possible to see a double image when a good crystal is place on top of a piece of paper (think back to GY 111).

In the same way that we can use the indicatrix to portray the various indices of refraction for the mineral classes, it is possible to construct a graphic image summarizing the velocity and vibration direction differences of the o- and e-rays and in so doing, explain while double refraction occurs in anisotropic minerals. The figures below shows the two possible situations that might occur in uniaxial minerals: (1) the o-ray is slower than the e-ray (**uniaxial negative**), (2) the o-ray is faster than the e-ray (**uniaxial positive**). Both figures are from Robinson and Bradbury (1992)

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1 I don’t like to equate double refraction to birefringence. I prefer the more anal interpretation of birefringence which is a measured difference between the indices of refraction of the o- and e- rays
There is only one orientation where the velocity of the o-ray and the e-ray is the same (the places where the circle and the ellipse meet in the figure on the previous page). This orientation is called the **optic axis** and this is the only direction where double refraction does not occur. The orientation of the optic axis frequently follows crystallographic axes (e.g., in quartz, the optic axis is parallel to the c axis), but not always. In calcite, the optic axis is tilted relative to the crystal faces which is one of the reasons why the double refraction is so pronounced.

![Diagram of double refraction in calcite](image)

The phenomenon of double refraction in calcite also allows us to see the effects of polarizers on o-rays and e-rays. Since each of these rays is perpendicular to each other, a sheet of polarized glass placed on top of the calcite crystal as it rotates over a spot will induce predictable changes to the images.

**Part B: Minerals in thin-section**

There are two different ways that thin-sections can be examined with a petrographic microscope. They can be examined with the upper polarizer (analyzer) in or out. Please note that the bottom polarizer is always in and that you are always using polarized light with these microscopes. If the upper polarizer is **out**, then the thin-section is being examined in **plane polarized light**. If the upper polarizer is **in**, then the thin-section is being examined under **crossed polars** or **crossed Nichols**. Under crossed polars, all isotropic materials appear dark (this included the cubic minerals, non-crystalline minerals like opal and non-crystalline materials like glass. In fact, the first thing that you should always do when you first sit down at your microscope is to check that the polars are properly aligned. Before you start looking at thin-sections, first insert the upper polarizer **out**.

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2 By the way, the terms ordinary and extraordinary rays were first used when discussing double refraction in calcite. The first image (the central spot in the diagram on this page) was termed “ordinary” because it stayed stationary as the crystal was rotated over a spot on a piece of paper. The double image projected to the side rotated as the crystal was rotated and it was called the extraordinary image. The e-ray image also appears to be lower in the crystal than the o-ray because of their different speeds through the crystal. Isn’t this a nice story?
polarizer (this is called crossing the polars). The field of view should be as black as possible. If not, see Doug.

Properties of minerals in plane polarized light (PPL)

1) Colour. Most minerals are colourless under PPL, but some minerals intensely coloured. As a general rule, dark coloured minerals in hand specimen (e.g., pyroxene, amphibole, biotite etc.), are coloured in PPL. Light coloured minerals (quartz, fluorite, feldspars, muscovite etc.) are colourless.

2) Pleochroism. This is an interesting phenomenon where anisotropic minerals appear to change colour as they are rotated in PPL. It has to do with variable indices of refraction and is related to the crystal class of the minerals. Isotropic minerals are not pleochroic (light travels at the same velocity regardless of orientation). Tetrahedral, trigonal and hexagonal minerals (uniaxial minerals) are said to be dichroic meaning that they can have up to two distinct colours. The remaining mineral classes are trichoic and may have 3 colours. I say "may" because the orientation of the crystal in the thin-section will determine which (if any) colour changes might occur. Consider the biotite crystal below. It is a biaxial mineral and therefore has 3 possible colours depending upon the orientation of the crystal in the thin section and the orientation of the stage during rotation.

Some common pleochroic colour variations are:

Aegirine: dark green – light green
Hornblende: yellow green - brown
Glauconite: yellow-green

One last thing about Pleochroism. The published colours aren't always the ones you actually see. Biotite, for example, has advertised colours that go from brown to yellow to red. I've seen biotite also go green on rotation. This might just have been a weird mineral (or perhaps I mis-identified a hornblende as biotite). Whatever the reason, like all properties, don't assume that published data is always correct.

3) Cleavage. Same property as seen in hand specimen. Just beware that now, you are more or less looking a 2 dimensional slices so ultimately, the orientation of your grains is important. The only time that you will see more than one cleavage direction is if you are looking down the c axis of the crystal (#3 for the pyroxene and amphibole examples given below). In this orientation, you will see one strong cleavage plane and one that is significantly weaker. Do not confuse cracks with cleavage.
4) **Relief.** The official definition of relief is "the ratio of the index of refraction of a mineral to the index of refraction of the material immediately adjacent to it (usually glass)." A more practical way to regard the relief of a mineral is how sharp and distinct the edge of the mineral looks. The index of refraction of glass is about 1.50. If a mineral is significantly higher or lower than this value, then the edge of the mineral looks very distinct and it is said to have high relief. If the mineral has an index of refraction close to glass, then it has very indistinct edges and it is said to have low relief.

So the relief of a mineral tells you something about the index of refraction of the mineral. It is this property that lets oil emersion testing identify unknown substances. Here's how this works. A
drop of an oil of known \( n \) is added to a slide containing fragments of an unknown substance. If the relief of the mineral is high, you can tell that the index of refraction of the oil is way off what the mineral is. But how do you know if it is way below or way above the mineral? There is a rather nice little procedure called the **Becke Line Test** that can tell you if the index of refraction of a mineral is higher or lower than the oil it is immersed in. The Becke Line is a bright band of light that forms at the edge of crystals due to and edge effect. At the edge of crystals, tapering causes the light rays to bend in toward the mineral if the mineral has a higher index of refraction than the oil it is in, or out toward the oil if the mineral has a lower index of refraction than the oil. If you lower the stage while looking at the mineral in the microscope, the Becke Line will appear to move into the mineral (crystal high) or into the oil (crystal low) as the mineral defocuses. The saying goes; "Becke Line in, crystal high. Becke Line out, crystal low".

The relief of a mineral is also affected by bubbles, inclusions and scratches. Also beware that some minerals (notably calcite and dolomites) have variable relief that like pleochroism, changes upon rotation of the stage.

5) **Crystallinity.** This property is pretty straightforward. A crystal with sharp, geometric edges is said to be **euhedral**. One that has rounded edges (e.g., water abraded) is said to be **anhedral**.

Properties of minerals under crossed-polars/crossed nichols (XN)

Recap: Crossing the polars (inserting the upper polarizer) will result in a dark field of view for any substance that is non-crystalline (e.g., air, glass, non-crystalline materials like opal). Minerals in the cubic class are also isotropic. They include garnet, halite, fluorite, spinel and sphalerite.
Anisotropic minerals will vary from bright to dark during rotation under crossed polars. There is, however, one orientation that will cause anisotropic minerals to appear isotropic. If you look right down the optic axis, you are looking right along the one direction where the e-rays and o-rays travel at the same speed. For all intents and purposes, the minerals is isotropic in this direction. For quartz, the optic axis is the same orientation as the c crystallographic axis. If you see a hexagonal quartz crystal, you are looking pretty much down the c axis and the optic axis. In this orientation, the quartz crystal pretty much stays dark as you rotate the stage.

While we are talking about the optic axis, I should introduce another concept that is used in optical mineralogy. It is possible to see the presence of o- and e-rays if you are looking down the optic axis of a mineral. In order to do this, you must use very high magnification (40X objective lens), have a well centered microscope and insert the Bertrand Lens. This lens defocuses the microscope and produces a cross pattern called an interference figure or an interference cross. The same type of cross can frequently be seen in air bubbles, but for minerals, it tells you a lot about the orientation of the mineral's indicatrix. It also tells you if the mineral is uniaxial or biaxial.
The interference figure for a quartz crystal with a properly aligned optic axis is shown at the bottom of the previous page. The interference figure appears to stay put as the stage is rotated. If the optic axis is a bit off of normal, the interference figure will appear to orbit the center point like the example to the right. Uniaxial minerals (like quartz) are easily identifiable if you can see the interference figure. Biaxial minerals can also be identified if you can get an interference figure that is centered in the eyepiece. As you rotate the stage for a biaxial mineral, you will see the cross separate into two curved components (gyres) that swing away from one another and then recombine again. The distance of separation (actually called the 2V angle) is a diagnostic characteristic of minerals that is useful in their identification.

So if the interference figure is so great, why not just use it for mineral identification? Why do we need to know all this other stuff? Simply put, the only time that you can ever really use the interference figure is when you are looking right down the optic axis. This happens one in 1000 times (if you are lucky). If you are trying to identify minerals in a rock (e.g., a thin section), you will seldom get more than one crystal in the right orientation. So you need other options.

1) Extinction. As you rotate the stage, you will observe that anisotropic minerals vary in brightness/colour. At two points during a complete 360 degree rotation, anisotropic minerals go dark (or nearly so). They are said to go extinct. Extinction occurs when the indicatrix aligns up
with the polars. For some minerals, extinction occurs in a sharp or sudden fashion. In some minerals, it is more like a curtain effect where part of the crystal fades out while other parts do not. Many minerals go extinct when the cleavage directions are parallel to polars. Others do not. The following diagram summarizes the types of extinction patterns that are recognized within minerals:

2) **Birefringence**. This is the most important property of minerals under crossed polars. It is defined as the difference between the index of refraction of the minimum and maximum refractive indices of a mineral. For uniaxial minerals, this is $n_o - n_e$ or $n_e - n_o$. For biaxial crystals, this is
The main thing to note is that the greater the difference, the **higher** the colour that is viewed. Please note that birefringence and extinction are kind of opposite properties. When a mineral goes extinct, it is at a minimum as far as birefringence is concerned. The maximum birefringence occurs when the crystal is orientated exactly half way between extinctions (roughly 45 degrees from each extinction). The amount of birefringence is measured mathematically, but it is best viewed via colour.

Quartz has low birefringence (0.009). Its maximum colour is pale grey with a weak yellowish tinge. In contrast, olivine has high birefringence (0.036) and the maximum colour viewed is blue, green and/or pink. Calcite is said to have extreme birefringence (0.14). The birefringence colours of calcite are so "high" that they are completely washed out and all you really see is white.

The birefringence colours occur in a pattern similar to the colours of a rainbow and like a rainbow, the colours repeat themselves. First order colours go from grey to white to yellow to orange to pink to red to blue. Second order colours are more vivid than first order colours and go from blue\(^3\) to green to yellow to red. Third order colours almost look fluorescent and go from blue to green to yellow to pink. Fourth order colours are so faded that you can't really identify them (but sometimes you catch a faded pink or green tint). Birefringence is very much affected by thickness differences. Quartz has a maximum birefringence of 0.009 only when it is 30 microns thick. If the thin section is 50 microns thick, quartz has orange birefringence. The thickness of most thin sections is regulated at 30 microns to minimize the **retardation**\(^4\) effect.

Reading the birefringence chart that occurs on the next page is a bit tricky at first because it actually summarizes 3 properties: (1) birefringence, (2) thickness variations and (3) minerals. The diagonal lines that radiate from the bottom left corner lead to minerals at the top and right side of

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\(^3\) The transition from first to second order colours occurs at blue. Some people refer to this first blue as first order blue while others call it second order blue. I tend to do the latter.

\(^4\) Retardation is defined as thickness X birefringence
the chart. Quartz, for example, is located at a birefringence of 0.009. If you follow this diagonal line down toward the bottom of the chart, it eventually intersects the 0.003 mm thickness line that runs horizontally across the chart. At this point, the vertical colour band is grey with a light yellow tint. This is the maximum colour that quartz should be in a standard thin section.

Once again, we need to be absolutely clear about the limitations of using birefringence to identify minerals. Orientation is vital. In order to see the maximum birefringence colours, you need to be looking perpendicular to the optic axis of a crystal. This should make sense to you if you recall that looking down the optic axis gives you a maximum (and constant) extinction. It stands to reason that if the birefringence and extinction are opposite properties, the maximum of one should be observed in a direction that is normal to the other.

3) Optical Twinning. This is an interesting phenomenon that results when two or more crystals of a single mineral grow together in a mathematically predictable pattern. This is the same type of thing that happens in a crystallographic fashion and involves twin planes, twin axes etc. From an optical point of view, the effects are quite frequently stunning. Optical twins are slightly out of phase with one another. As you rotate the stage, one section goes extinct before the other does.

Many minerals exhibit optical twins, but the all time leaders in this respect are the feldspars. Plagioclase feldspar exhibits polysynthetic twinning which resembles prison stripes. Microcline feldspar exhibits tartan twinning which resembles the plaid of a Scottish kilt. Orthoclase displays Carlsbad twinning, but it is not as prominent as most of the other feldspars.

By the way, it is possible to determine the composition of the plagioclase feldspars (percentage of Na to Ca) by measuring the extinction angles of the twin sets. I'll show you how to do this in one of the labs. If I fail to do this, Dr. Allison is likely to in GY 343.
4) **Zonation.** Some minerals change their composition as they grow, particularly those that form continuous series through solid solution during igneous processes (e.g., olivine, plagioclase). Because their core may be a different composition than their edges (e.g., plagioclase usually starts off more Ca rich and later becomes more Na rich during crystallization in a magma), the core may go extinct slightly out of phase to the rest of the crystal. Sometimes zonation of crystals is very evident in some rocks (particularly in basalts). Most of the time it is not. Still, when you see it, it really is quite impressive.
The Petrographic Microscope

The **petrographic microscopes** that you will be using in this class are pretty much the best student scopes currently available in the United States. They look much fancier than those usually portrayed in books (or in the figure below), but in many ways, they are no different that the microscopes Bowen used when he was experimenting with igneous petrology about 100 years ago.

**Light Source.** Our scopes use a tungsten light bulb designed to burn at 6000 degrees K (7-9 on your light intensity knob). At this temperature, the emission spectra is yellow so a blue filter is used to soften the light. Do NOT use the intensity knob to lower the brightness of the light. If it is two bright for you, use the aperture or diaphragm

**Condenser assembly.** On our microscopes, this consists of a diaphragm, the bottom polarizer, and a condenser lens. The condenser focuses light into a smaller (but brighter) beam which is necessary when looking at specimens under very high magnifications (25 to 40X objectives). The **stage** on a petrographic microscope is very different that the one that most of you are familiar with
on standard (biological) microscopes. As well as moving up and down via a rack and pinion system for focusing, this one also rotates. The amount of rotation can be measured via a scale on the edge of the circular stage (this is useful for measuring the angle of extinction of a mineral). The stage has a hole through the middle on which, the thin section is placed. A thin section is a complex thing consisting of a glass slide (the base) the rock specimen and a cover slip. Each layer is glued to the others with epoxy resins. The best resins (we use the best ones for our thin sections) are optically isotropic and have indices of refraction close to glass.

The upper assembly of the microscope is the most complex part. It consists of a rotating turret that houses 3, 4 or 5 objective lenses, a fixed barrel that houses the upper polarizer (the analyzer), the Bertrand lens, one or more slots for accessory plates, and the eyepiece(s) (usually 10 X). The eyepieces also contain a cross hair and/or scale for point counting and size measurements (both of these fun jobs will be part of some future labs).