Introduction to Optical Mineralogy

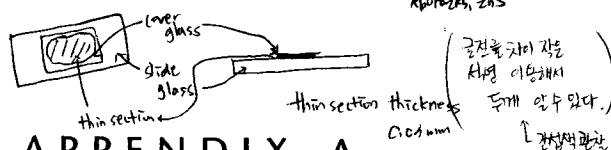THIRD EDITION *(2004)*

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APPENDIX A

Sample Preparation

Grain Mount

A grain mount (Figure 2.2*a*) consists of a number of small grains of an unknown mineral placed on a glass microscope slide, immersed in a liquid, and covered with a cover slip. The basic steps involved in preparing a grain mount are as follows:

1. Crush a sample of an unknown mineral in a mortar and pestle or other apparatus.
2. Sieve the sample and retain for examination the fraction that passes a 140-mesh sieve and does not pass a 200-mesh sieve. These grains will be between 0.105 and 0.074 mm. The finer material may be saved for X-ray examination and the coarser material recrushed if needed. Less than a gram of sample is all that is needed in most cases. If needed, wash fine materials from the grains by gently rinsing with distilled water or acetone, decanting the liquid, and allowing the samples to dry.
3. Sprinkle a few dozen grains of the unknown mineral on a microscope slide and cover with a piece of cover slip. One cover slip may be broken into enough pieces to prepare a half a dozen or more grain mounts. Avoid getting fingerprints on the cover slip or glass slide.
4. With a dropper, place a small amount of immersion oil next to the cover slip so that capillary action draws it under and immerses the grains. The usual error at this point is to use too much oil or to get oil on top of the cover slip.
5. Place the sample on the microscope stage and examine. Do not get immersion oils on the lenses or other parts of the microscope.

Other, more sophisticated techniques that involve mounting the grains in various resins or gels also are available. Consult Hutchison (1974) for details of these procedures. A permanent grain mount may be prepared by placing a drop or two of cement (epoxy, UV-curing adhesive, etc.) on the microscope slide, sprinkling a selection of grains into the adhesive, covering both with a cover slip, and allowing the adhesive to cure.
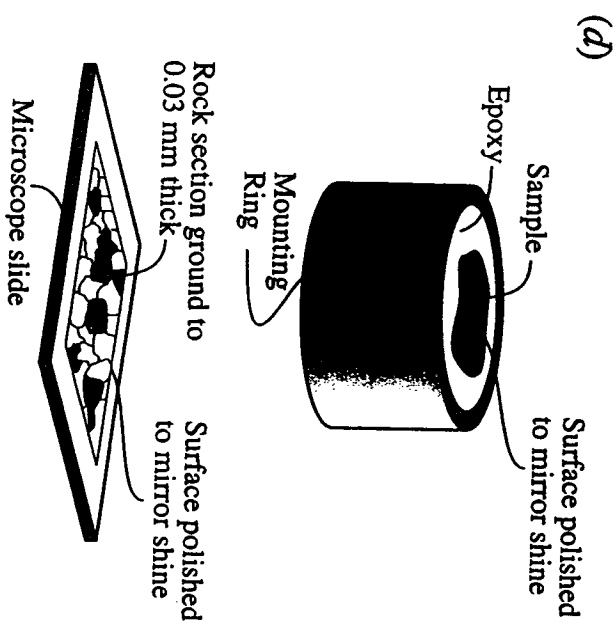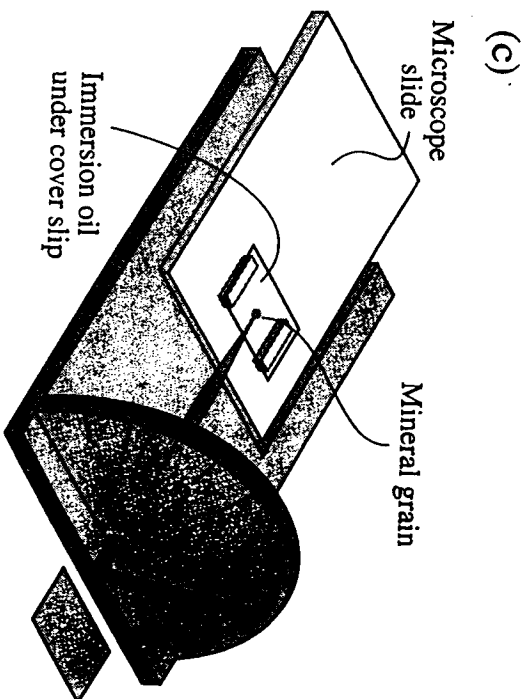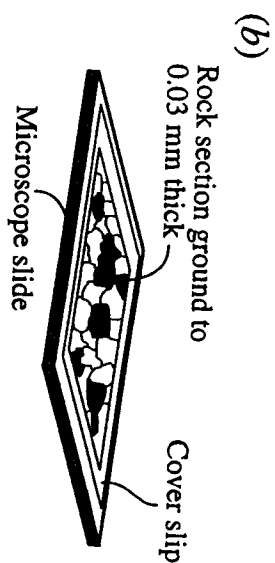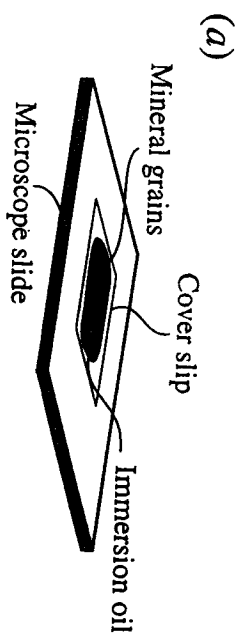
Thin Section transmitted light 이용해서 투명,반투명 광물 관찰

Rock-forming mineral

A thin section (Figure 2.2*b*) is a slice of rock about 0.03 mm thick that is mounted on a microscope slide. ZnS
Standard petrographic microscope slides are 27 × Sphale
46 mm. A wide variety of machinery is available to speed various steps in the process and improve accuracy and consistency. Consult Humphries (1992) for more details. The basic process is as follows.

1. A chip of rock is cut out of a hand sample with a diamond saw. The chip should be cut so that it is no larger than a microscope slide.
2. The side of the rock chip that will be glued to the slide is ground flat on a lap wheel and then polished using progressively finer and finer abrasive. The usual procedure is to start with 120-grit and then move progressively to 240-, 320-, 400-, and 600-grit abrasive. Finer abrasive may be used to produce a higher-quality polish, but this is not generally necessary for routine work. It is important at this point to ensure that the polished surface is as flat as possible. If it is not flat, the usual culprits are the uneven application of pressure while grinding, or lap wheels that are not flat.
3. The rock chip is then glued to a clean microscope slide. The details of the procedure depend on which type of cement is used. Canada balsam is the traditional cement, but a number of epoxies and ultraviolet-light curing cements with superior qualities are now used for most work. The glue line

316

(a)

Mineral grains   Cover slip

Microscope slide

Immersion oil

(b)

Rock section ground to
0.03 mm thick

Microscope slide

Cover slip

(c)

Microscope
slide

Mineral grain

Immersion oil
under cover slip

(d)

Epoxy

Sample

Mounting
Ring

Surface polished
to mirror shine

Rock section ground to
0.03 mm thick

Surface polished
to mirror shine

Microscope slide

Figure 2.2 Samples used with the petrographic microscope. (*a*) Grain mount. (*b*) Thin section. (*c*) Spindle stage. The geometry shown here utilizes a standard microscope slide on which an immersion oil well is fabricated from small pieces of microscope slide and a piece of cover slip. (*d*) Polished sections. (*Top*) Sample mounted in an epoxy plug. (*Bottom*) Thin section whose top surface has been polished.

needs to be thin and uniform, so be sure the slide and rock chip are free of grit and dust, and use the least possible cement. One or two drops are generally more than adequate for a conventional thin section. Bubbles trapped in the cement are a persistent problem. One technique for avoiding them is to place the cement in the middle of the rock chip and then place the slide on the cement. As the cement spreads outward it will, with luck, expel the air between slide and rock chip. If bubbles are trapped, they can sometimes be worked out by judicious poking and prodding on the slide with the eraser end of a pencil.

4. Once the cement is cured, the surplus rock is cut off with a diamond trim saw.
5. The rock chip is now ground down to its final thickness of about 0.03 mm. A wide range of equipment is available to do this grinding. The simplest is just a glass plate on which water and abrasive are sprinkled. Lap wheels and other, more sophisticated equipment also can be used. Usually, the final grinding to just the right thickness must be done by hand with fine (600 grit) abrasive on a glass plate. The thickness of the thin section can be determined by examining the interference color of quartz, feldspar, or other minerals whose birefringence is known (see Chapter 5).
6. If desired, the thin section can be stained for K-feldspar, plagioclase, carbonate minerals, and others. Hutchison (1974) describes a variety of staining techniques and additional techniques are mentioned in the chapters in which minerals are described.
7. The cover slip is now cemented in place. In most cases, the cover slip is 0.17 mm thick. Because there are many places to make errors, the novice thin section maker can anticipate that a frustratingly high percentage of his or her initial attempts will wind up in the trash.

Spindle Stage

The spindle stage (Figure 2.2c) consists of a fine wire on which a single mineral grain is cemented. The spindle is mounted on a base plate so that it can pivot about a horizontal axis while holding the grain in immersion oil between a glass window and a cover slip. The spindle stage is attached to the microscope stage with stage clips or a mechanical stage.

A mineral grain is mounted on the spindle stage as follows:

1. Select a fragment of the mineral to be examined that is about 0.2 mm in diameter. Larger or smaller grains may be used if needed.
2. Place a very small amount of adhesive on the tip of the spindle by gently touching it to a drop of adhesive. A wide variety of adhesives can be used including model airplane glue, yellow or white carpenter's glue, Duco brand cement, and so forth.
3. While the adhesive is still wet, touch the spindle to the grain and align the grain so that it is centered as closely as possible on the tip of the spindle. Allow the adhesive to cure.
4. Insert the spindle into the spindle stage and slide an immersion oil well over the spindle and mineral grain. Introduce a drop or two of immersion oil into the well.

Consult Bloss (1981) for a more detailed discussion of the spindle stage.

Polished Section

A polished section (Figure 2.2d) is a piece of rock/mineral whose surface is brought to a high polish so that it can be examined with the reflected light microscope. A common technique is to polish the surface of a thin section so that it can be examined both with transmitted and reflected light; no cover slip is required. Use of a polished thin section allows both transparent and opaque minerals to be identified. Blocks or fragments of rock or mineral may also be mounted in epoxy plugs or glued to a conventional microscope slide so that the top surface can be polished. Friable or porous samples must be impregnated with epoxy. Once the sample is mounted, the procedure for polishing the surface is as follows:

1. If the sample is a thin section, proceed as described above to prepare the thin section, including the final grinding to the desired thickness. Complete the grinding with 1000-grit abrasive.
2. For other samples, trim so that the top surface that will be polished is parallel to the surface that rests on the microscope stage. The surface to be polished is ground using silicon carbide abrasive until the surface is smooth and uniform. Initial grinding can

begin with 120-grit abrasive, and then progress through finer abrasives, ending with 1000 grit.

3. Polishing is usually a two- or three-step process that uses lap wheels or other machinery on which a disk of fabric or paper is mounted to hold the abrasive.

   a. Initial polishing uses 6-μm diamond paste and an oil-based lubricant. The sample is polished until all of the irregularities left by the grinding are removed. This polishing stage is the longest and most important, so don't try to rush it.

   b. After thorough cleaning, the sample is polished with 1-μm diamond paste until all the scratches produced by the coarser polishing are removed. For some purposes this produces an acceptable surface.

   c. If needed, final polishing is accomplished with 0.25-μm diamond paste and 0.05-μm alumina.

Producing good-quality polished sections requires that the samples be carefully cleaned between steps, and that the work environment be kept clean. It also requires patience. The objective is to produce a mirror-like surface that has a minimum of topographic relief. However, well-prepared polished sections always retain some scratches and other imperfections, and even imperfectly prepared sections can provide a wealth of textural and mineralogical information.

Consult Material Safety Data Sheets concerning the safe handling, storage, and disposal of the adhesives and other chemicals used in preparation of samples.

◆ REFERENCES

Bloss, F. D.. 1981, *The spindle stage: principles and practice*: Cambridge University Press, New York, 340 pp.

Humphries, D. W., 1992, *Preparation of thin sections of rocks, minerals, and ceramics*: Oxford University Press, Oxford, 83 pp.

Hutchison, C. S., 1974, *Laboratory handbook of petrographic techniques*: Wiley, New York, 527 pp.

A Colour Atlas of

Rocks and Minerals in Thin Section

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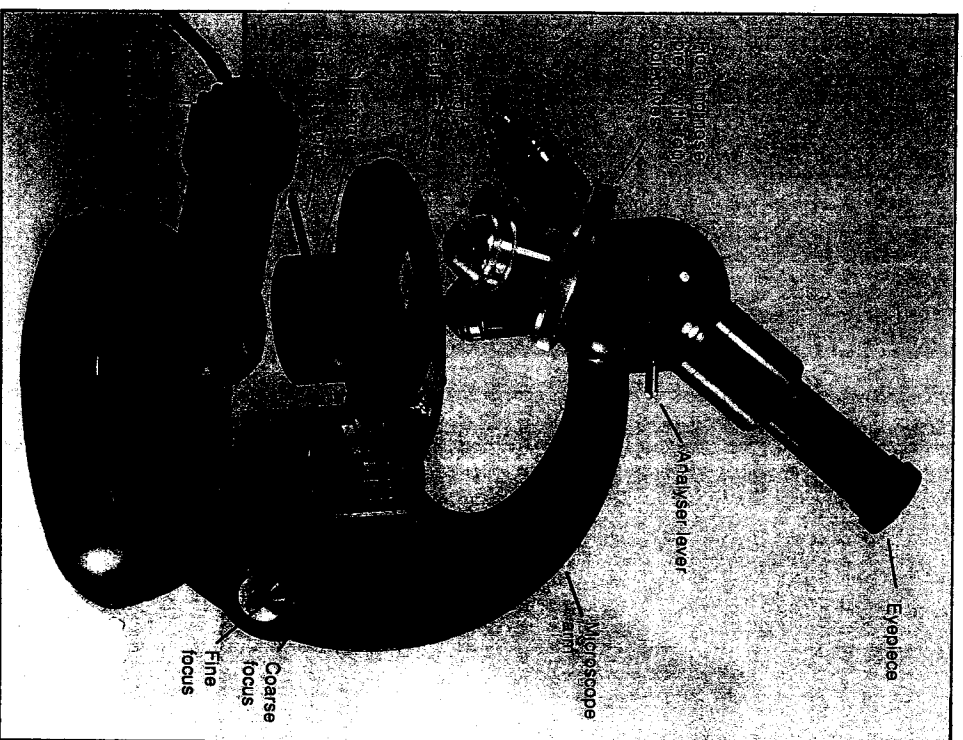
A student-model petrographic microscope.

The polarizing microscope

The polarizing or petrographic microscope is distinguished from the more usual biological microscope in that it is equipped with a rotating stage and two polarizing filters, one below the stage and the other above it. Ordinary light may be considered to consist of waves vibrating in all directions whereas polarized light consists of vibrations in one plane only—the plane of polarization. The polarization filters are made from material known as polaroid. Polaroid is used in some makes of sun glasses and photographic filters to cut out glare from reflecting surfaces. The polarizing filters in the microscope are normally set so that their polarization directions are at right angles to one another and parallel to the cross-wires in the eyepiece of the microscope. The polarizing filter below the stage is known as the polarizer, that above the stage is the analyser. The analyser is mounted in such a way that it can be removed from the light path so that the rock section can be studied in plane-polarized light. When the analyser is inserted the sample is said to be observed with crossed polars. When there is no thin section on the microscope stage no light can be seen on looking down the microscope when the polars are crossed because the polarized light emerging from the polarizer is blocked by the analyser.

A polarizing microscope is illustrated opposite. This model, produced by Carl Zeiss mainly for student use, has all the facilities required for petrographic study of rock sections in transmitted light. The parts of the microscope with which the beginner must become familiar are marked on the photograph.

This instrument has a nosepiece carrying four objectives each having a different magnification: rotation of the nosepiece permits a change in magnification by bringing one objective into a vertical position directly above the thin section. The objectives are designed to be parfocal: thus when an objective is changed only a small adjustment in focus is necessary.

Focusing a microscope involves adjusting the distance between the objective and the object being examined. In this instrument focusing is achieved by altering the height of the stage and the focusing controls can be seen at the lower end of the arm of the microscope.

The substage assembly carries, in addition to the lower polarizer, a condensing lens and an iris diaphragm. These facilities permit observation of minerals in a strongly converging beam of polarized light, as well as in a non-converging (i.e. parallel) beam. Examination of minerals in convergent light is beyond the scope of this text. The iris diaphragm is also used in restricting the aperture:

• To obtain improved contrast between minerals of slightly different refractive indices.

• For observing the Becke Line (see page 20) to determine the relative refractive indices of adjacent minerals or a mineral and the mounting material.

An inexpensive biological microscope can be obtained much more readily than a polarizing microscope and by incorporating two pieces of polaroid in the light path such a microscope may be used for the study of thin sections of rocks provided that the polaroid above the thin section can be easily removed and re-inserted. The facility of rotating the microscope stage will not normally be available in a biological microscope and in such a case it would be necessary to be able to rotate the lower polarizer. There are two reasons why it is desirable to be able to rotate the stage or the lower polarizer. These are :

• To observe pleochroism (i.e. change in colour of a mineral as seen in plane-polarized light, when the mineral is rotated with respect to the plane of polarization of light.)

• To measure extinction angles (see page 26).

Description of minerals

To describe a mineral and so identify it correctly a student must be able to:

• Describe the shape of the crystals.

• Note their colour and any change in colour on rotation of the stage in plane-polarized light.

• Note the presence of one or more cleavages.

• Recognize differences in refractive index of transparent minerals and determine which has the higher refractive index of two adjacent minerals.

• Observe the interference colour with crossed polars and identify the maximum interference colour.

• Note the relationship between the extinction position and any cleavages or traces of crystal faces.

• Observe any twinning or zoning of the crystals.

These properties are treated in some detail below and are illustrated where possible.

Shape and habit of crystals

In a completely crystalline rock it is unlikely that the faces of all the crystals will be well-developed because they interfere with one another during growth. In an igneous rock the first crystals to grow are likely to have well formed crystal faces since they have probably grown freely in a liquid. In some metamorphic and sedimentary rocks, crystals with well-developed crystal faces are presumed to have grown in an environment consisting mainly of solids but with fluid in the interstices.
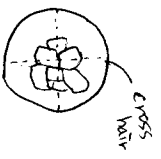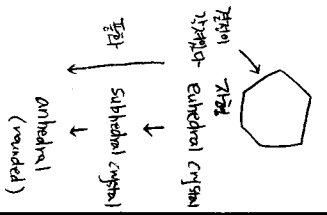
1 Euhedral crystals of garnet in a metamorphic rock (× 40).

2 Euhedral crystals of nepheline in an igneous rock (× 11).
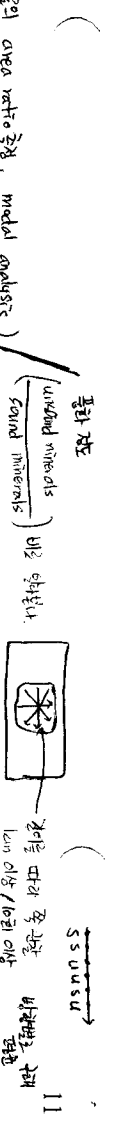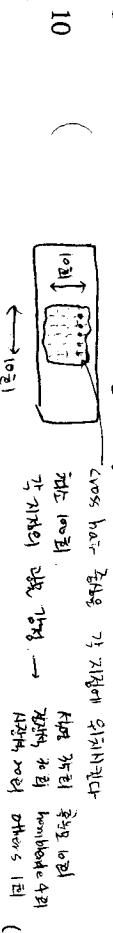
Crystals whose outlines in thin section show well defined straight edges, which are slices through the faces of the crystal, are described as *euhedral* crystals (**1, 2**); crystals which have no recognizable straight edges are *anhedral* and crystals with some straight edges and others curved are *subhedral*.

In an igneous rock, large crystals in a matrix or groundmass of much smaller crystals are described as *phenocrysts* (**3**). In a metamorphic rock similar large crystals embedded in a mass of smaller crystals are termed *porphyroblasts* (**4**). In some rocks it is not certain whether the large crystals grew from an igneous magma or in a later stage metamorphic event. In these cases it is perhaps better to describe the crystals as *megacrysts*.

To describe the outlines of crystals as seen in thin section, such words as rectangular, square, hexagonal, diamond-shaped, or rounded are self-explanatory.
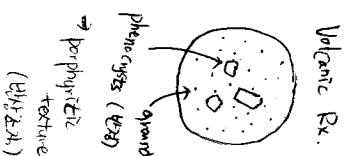
The term *habit* is used to indicate the shape of crystals as seen in hand specimen or deduced from several cross-sections in a thin slice. The following terms are used: *needle-shaped*, (or *acicular*), *prismatic* and *tabular*. The first of these terms is self-explanatory (**5**).

Prismatic is the term used to describe crystals which have similar dimensions in two directions and are elongated in the third dimension (**6**). Tabular habit is used to describe crystals which are flat in one plane.
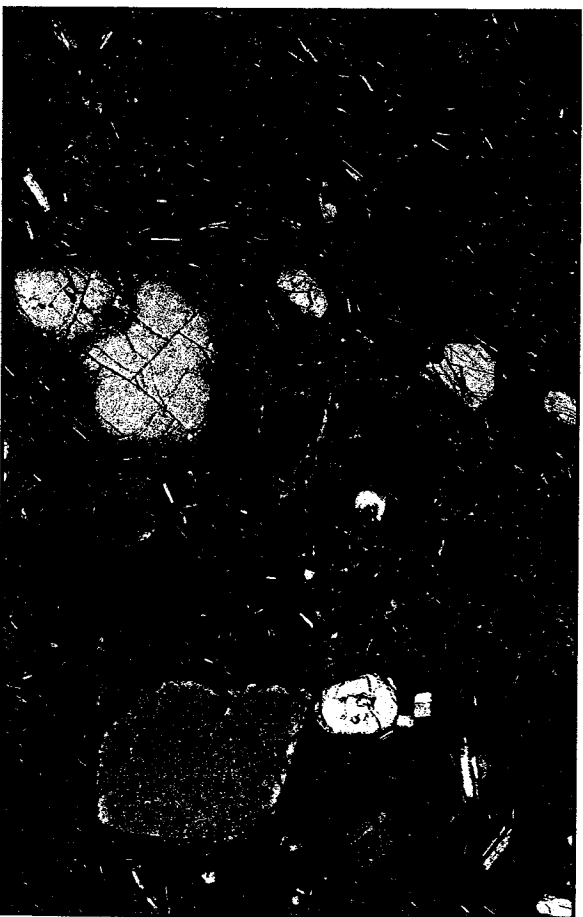
A mineral may be characterized by a particular habit but in some rocks one mineral may display two different habits.

3 Phenocrysts of olivine in an igneous rock (x 9).
반점 감람석

4 Porphyroblasts of albite in a metamorphic rock (x 13).

**5** Needle-shaped or acicular crystals of tourmaline (x 48).

Colour and pleochroism

Many minerals, although coloured in hand specimen, may be nearly colourless in thin section. A few common minerals are easily recognized by their colour in thin section e.g. the mineral biotite is usually brown (**8**). Some minerals are opaque in thin section and their properties can only be studied with a reflected light microscope. A mineral which is coloured in thin section may show a different colour or shades of one colour as the microscope stage is rotated. Because crystals in a rock are usually randomly arranged and hence cut in different directions in a thin section, they are likely to show different colours or shades of one colour in a section. The colour of a mineral when observed in plane-polarized light is termed its *absorption colour* and the phenomenon of variation in colour depending on the orientation of a crystal with respect to the plane of polarization of the light is known as *pleochroism* (**7**, **8**). This is a very useful diagnostic property for some minerals.
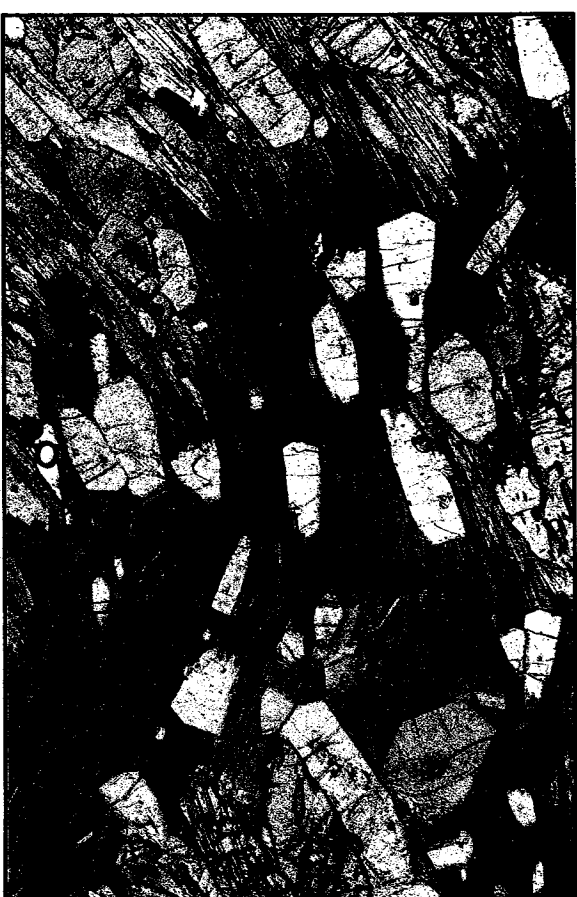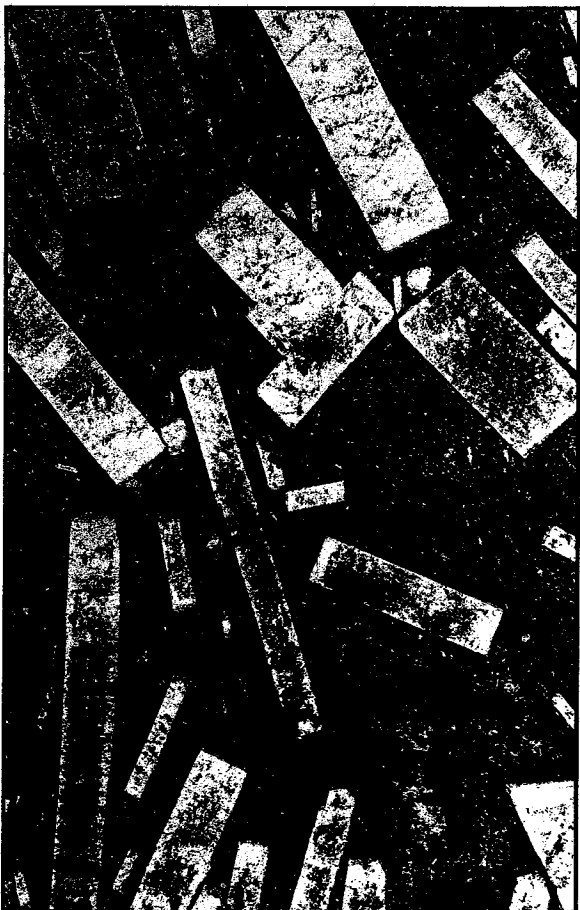
6 Prismatic crystals of sanidine (x7).

14

7 & 8 In **7**, olive-green crystals of tourmaline, a complex boron aluminium silicate, are intergrown with pale yellow biotite. In **8**, taken after rotating the polarizer through 90°, many of the tourmaline crystals have changed and are colourless and much of the biotite is brown. The orientation of the polarizer is shown by the double headed arrow beside each figure. The extent to which the crystals change colour depends on their orientation (x 16).

Cleavage 벽개

Many minerals break or cleave along certain planes, the positions of which are controlled by the atomic structure of the minerals. Between cleavage planes the atomic bonding is weak compared to that within the planes. The presence or absence of cleavage and the angles between cleavages if more than one cleavage is present, may be of diagnostic value.

Crystals of mica can be easily separated into thin sheets because micas have a perfect cleavage in one plane. In crystals cut at right angles to the cleavage plane, the cleavage is visible in thin section as a set of thin straight, parallel, dark lines, whereas if the crystal is cut nearly parallel to the cleavage it is not visible. Some minerals cleave parallel to more than one plane and the angle between two cleavages can be diagnostic of certain minerals; thus in the pyroxene group of minerals two cleavages are at 90^0 (9), whereas in the amphiboles the cleavages intersect at an angle of 120^0 (10). In a thin section the angle between two cleavages can only be measured with accuracy when the thin section is cut at, or nearly at, right angles to both cleavages. Cleavages tend to be parallel to crystal faces although this is not always the case. In 9 and 10 crystal boundaries are parallel to both cleavages in the pyroxene and the amphibole.

9 Clinopyroxene crystals showing two cleavages at approximately 90^0 There are crystal faces parallel to both cleavages (x42).


10 Amphibole crystals with two cleavages at approximately 120^0 In this rock the crystal faces parallel to the cleavages are not as easily seen as in the pyroxenes (x70).
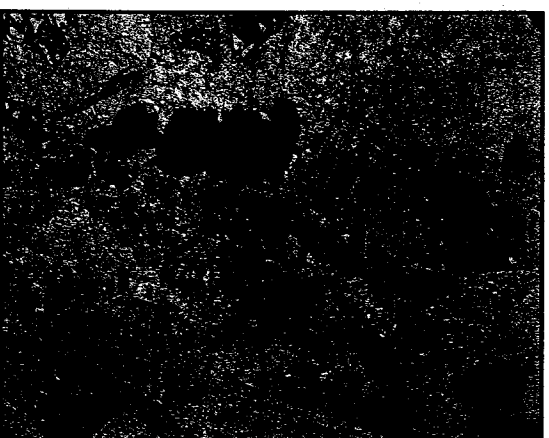
Relief

Colourless minerals of similar refractive index and having refractive indices close to that of the mounting medium do not show distinct boundaries when seen under the microscope. The greater the difference between the refractive index of a mineral and its surrounding material the greater its *relief* (11, 12). When differences in the refractive index are small it is necessary to partially close the substage diaphragm to detect differences in relief and if the microscope is not equipped with a substage diaphragm it may be difficult or impossible to detect differences in refractive indices or relief (see discussion of Becke line below).

Minerals have one, two or three refractive indices, depending on their symmetry. On viewing a mineral in thin section in polarized light, its relief may change when rotating the microscope-stage since the refractive index of the mineral which is being compared with the mounting medium may change. A few minerals have very large differences between their maximum and minimum refractive index and in such cases the change in relief may be considerable; this is known as *twinkling* and is characteristic of the carbonate minerals (13, 14).


11

12
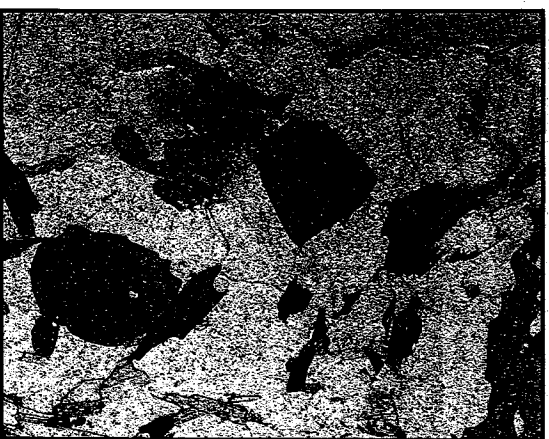
11 Crystals having higher refractive indices than others stand out in relief against the background which is mainly quartz. The two minerals showing very high relief in this figure are kyanite and garnet; the brown mineral is biotite and shows moderate relief against quartz (x 8).

12 The elongated crystals shown here are of corundum (Al₂O₃). They have much higher refractive indices than the feldspar in which they are embedded and hence stand out in relief (x 7).

→
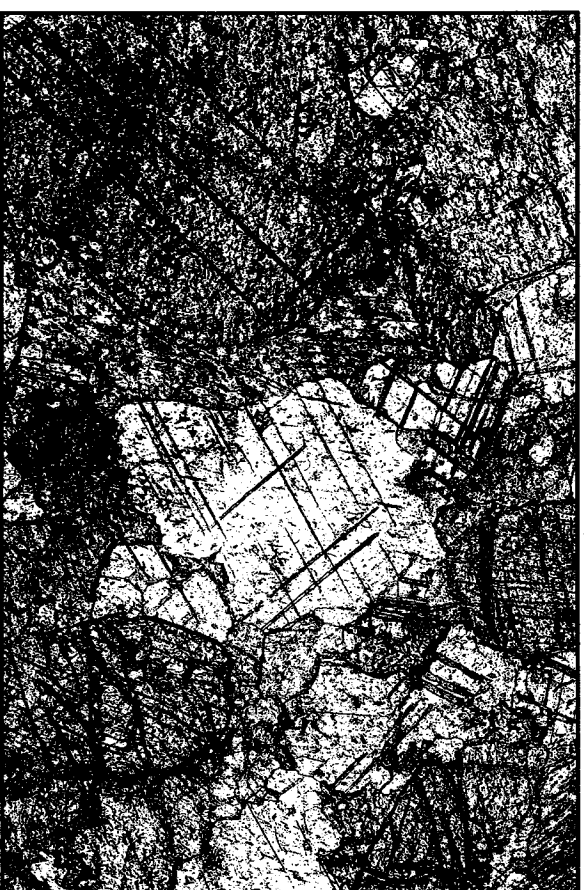
14

↕

13 & 14 These two figures show calcite crystals in a marble. The orientation of the polarizer is shown by the double headed arrows adjacent to the figures and we can see that the relief of each of the calcite crystals relative to its neighbouring crystals changes with rotation of the polarizer (x 50).

In attempting to identify minerals, it is often desirable to know which of two adjacent materials has the higher refractive index. The boundary between materials of differing refractive index is characterized by a bright line which can be enhanced by partially closing the sub-stage diaphragm and defocusing the image slightly; this bright line is known as the *Becke line*. If the tube of the microscope is raised or the stage lowered (depending on the method of focusing), it is observed that the Becke line moves into the material which has the higher refractive index and on lowering the tube, or raising the stage, the bright line moves into the lower refractive index material (**15–17**).

If instead of a bright line the boundary between two minerals is marked by a faint blue and yellow fringe this is an indication that the two minerals have very similar refractive indices and only in the light of a given colour or wavelength could an observer specify which mineral has the higher index of refraction.


15

16

17

15–17 *The Becke line:* In **15** the right hand side of the field of view is occupied by a few crystals of muscovite whereas the left side is the mounting medium. This figure was taken with the analyser inserted: the mounting medium appears black since it is isotropic (see page 24) whereas the muscovite shows bright interference colours. In **16** and **17** the analyser has been removed and the same field of view can be seen in plane-polarized light. To compare the refractive index of muscovite with that of the mounting medium it is necessary to defocus the microscope—in **16** the microscope tube has been lowered below the position of sharp focus and in **17** the tube has been raised above the position of sharp focus. The bright line, which marks the boundary between the muscovite and the mounting medium, can be seen to have transferred from within the mounting medium in **16** into the muscovite in **17**—the rule is: on raising the microscope tube the Becke line moves into the material of higher refractive index. Thus it can be seen that muscovite has a higher refractive index than the mounting medium. (x 96).
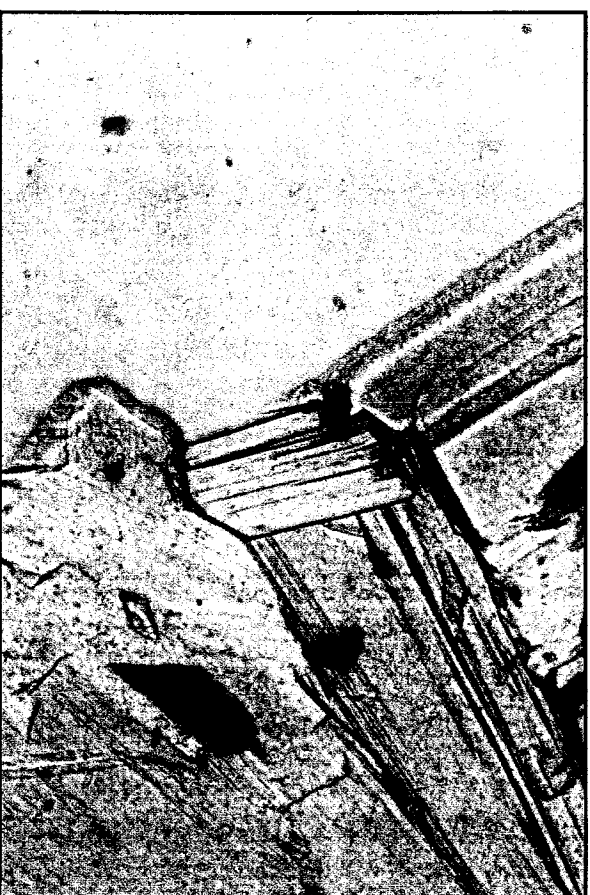
Birefringence 복굴절(이?)

Although values of refractive indices of minerals are of great diagnostic value, it is very difficult to measure them accurately, especially in the case of minerals which have three refractive indices and when the indices are greater than 1·70.

Most mineralogists know how to measure a refractive index using liquids of known refractive index, but very rarely do so except in the case of a new mineral where it is necessary to report its physical constants. Minerals which have more than one refractive index have a property which is known as *double refraction*. A quantitative measure of double refraction is *birefringence*, defined as the difference between the maximum and minimum refractive indices of a mineral. Birefringence can be measured fairly readily and with considerable accuracy.

When polarized light enters most crystals, it is split into two components each having a different velocity; the two light waves become out of phase as they travel through the crystal because of their differing velocities. On emerging from the mineral the two rays interfere with one another and, when observed with the analyser inserted in the light path, show what are known as *interference colours*. These colours are similar to those seen when a thin film of oil is observed on a wet street.
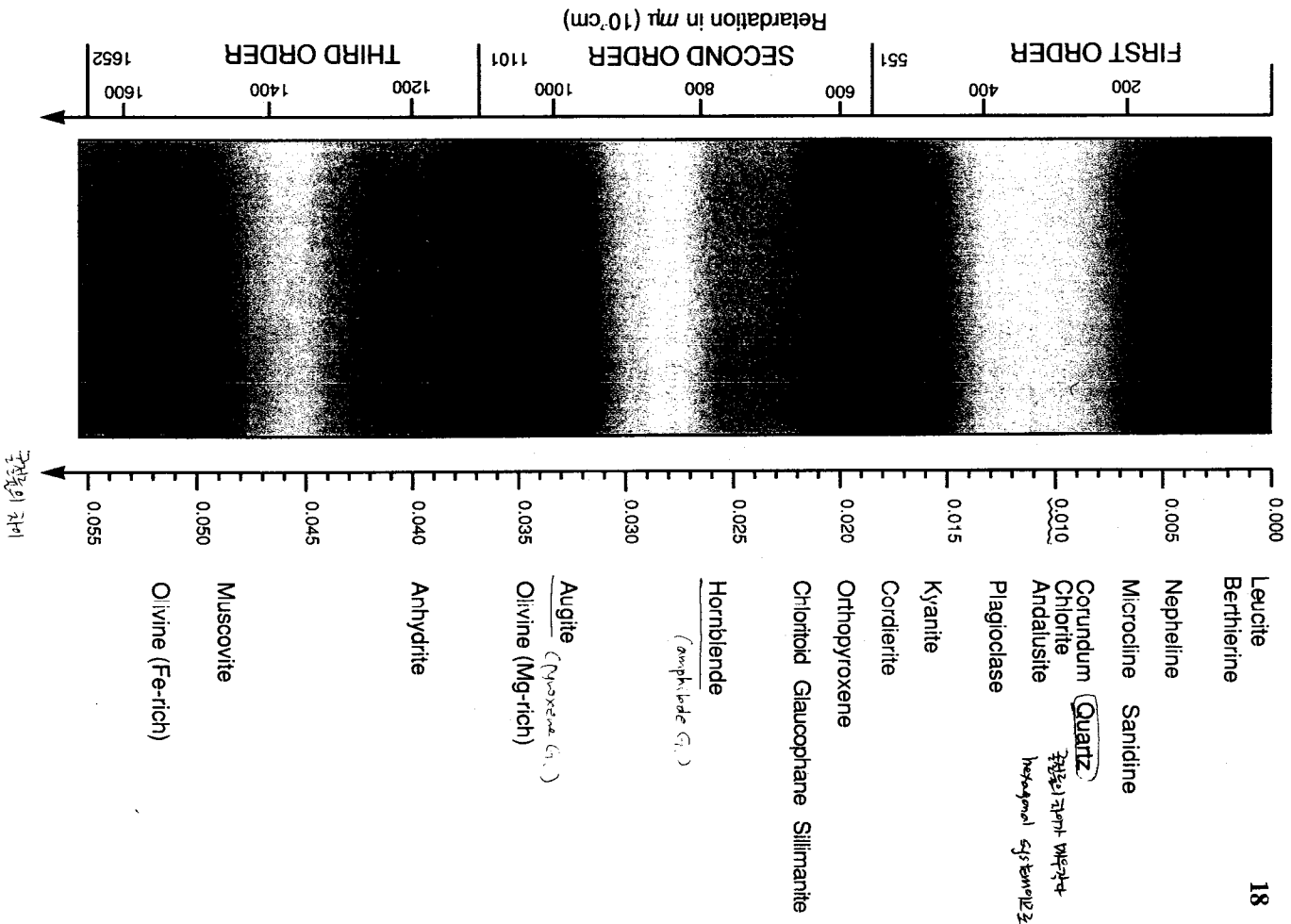
The interference colours shown by a mineral in thin section chiefly depend on three factors:
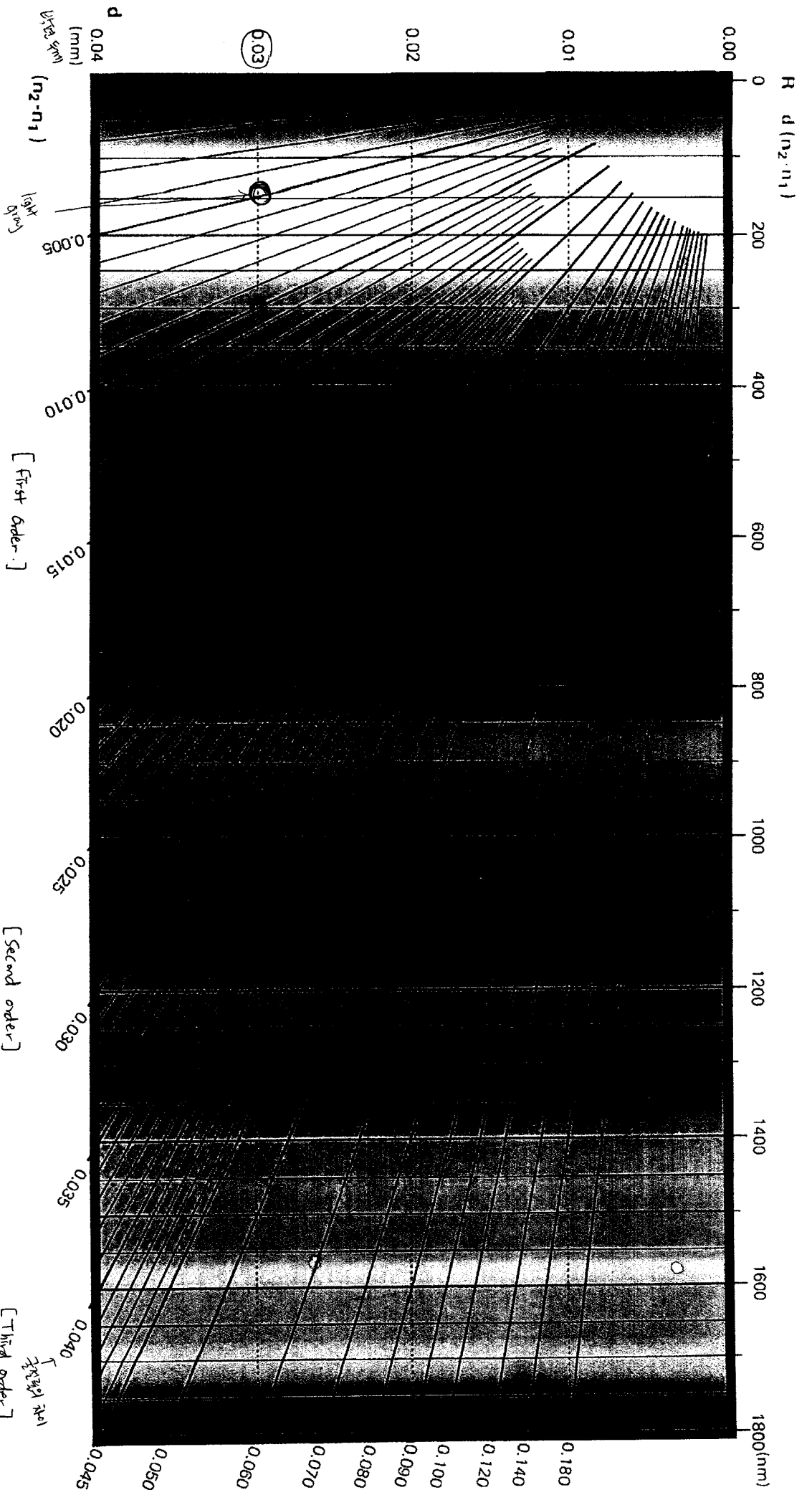
- the birefringence of the mineral,
- the thickness of the section,
- the orientation in which the mineral is cut.

The second variable is eliminated by cutting all rock sections to a standard thickness of 0.03mm. To allow for differences in orientation and so eliminate the third variable only the *maximum* value of the interference colour is considered and the value of the birefringence is obtained from the accompanying chart (18). This *birefringence chart* shows the interference colours in a section of standard thickness of a colourless mineral corresponding with the value of its birefringence. The common minerals illustrated in this book are indicated at the appropriate birefringence value.

The low interference colours are grey and white and these are at the top of the chart. The chart is divided into *orders*; the first three orders are shown. Most common minerals are covered by the range of birefringence shown, except for the carbonates in which the birefringence is nearly 0.18. The high-order colours shown by the carbonates are illustrated in 63.

18 *Birefringence Chart*. The chart was made from a photograph of a crystal of quartz, viewed between crossed polars, ground so that its thickness changes gradually from 'zero' at the top of the figure to a thickness of about 0.15mm at the lower end. (We cannot grind a crystal of quartz to zero thickness without producing a very ragged edge so that the black colour corresponding to zero birefringence is produced by addition of the same small amount of birefringence along the entire length of the wedge-shaped quartz crystal.) This chart shows the birefringence of some of the common minerals.

Retardation in mμ (10⁷cm)

FIRST ORDER	SECOND ORDER	THIRD ORDER
200 400 551	600 800 1000 1101 1200	1400 1600 1652

Mineral birefringence scale (0.000 – 0.055):

- Leucite / Berthierine
- Nepheline
- Microcline / Sanidine
- Corundum / Chlorite / Andalusite / Quartz
- Plagioclase
- Kyanite / Cordierite
- Orthopyroxene
- Chloritoid / Glaucophane / Sillimanite
- Hornblende (amphibole G.)
- Augite (pyroxene G.)
- Olivine (Mg-rich)
- Anhydrite
- Muscovite
- Olivine (Fe-rich)

Interference Color Chart. (Courtesy Nikon.)

A single crystal of a mineral may show any colour between that corresponding to its maximum birefringence colour and black corresponding to zero birefringence, depending on the orientation of the crystal. For a given mineral in a thin section of standard thickness only the maximum colour is of diagnostic value and defines the birefringence (**19**).

Some minerals show interference colours which are not represented on the birefringence chart. These colours are shades of blue, yellow or brown and are known as *anomalous* colours. If the birefringence of a mineral varies appreciably with the wavelength of light, some colours may be reduced in intensity and so the resultant interference colours are anomalous. If the absorption colour of a mineral is strong, it may affect the interference colour and thus also produce an anomalous colour. A few common minerals are characterized by anomalous interference colours and this may help in identification—e.g. chlorite (**44**).

It was noted above that minerals may have one, two or three refractive indices. Those which have only one refractive index have structures made up of very regular arrangements of atoms so that light passes through a crystal with the same velocity irrespective of the direction in which it travels. Such minerals show no double refraction and appear black when viewed with crossed polars: these minerals are said to be *isotropic*.

Materials such as glass and liquids are also isotropic but for a very different reason: they are isotropic because they usually have a very disordered arrangement of atoms and in consequence light passes through such materials with the same velocity irrespective of its direction. The mounting materials used for making thin sections are isotropic.

Minerals which have two refractive indices possess one unique direction in which they show no double refraction and minerals which have three refractive indices have two directions in which they show no double refraction and so appear black when observed between crossed polars. In a thin section the proportion of crystals which have been cut exactly at right angles to one of these directions is small but for more advanced optical techniques it may be desirable to look for such sections.
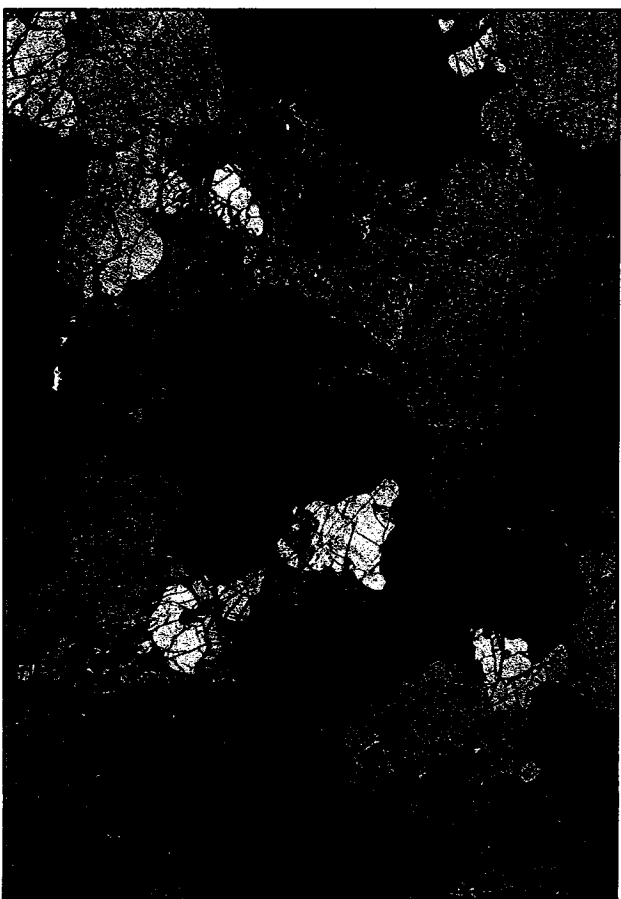
19 This view is of a rock consisting of a number of crystals of the same mineral showing a range of interference colours when viewed between crossed polars. A few crystals show grey or white first-order interference colours, one large crystal to the left of centre of the field of view shows a first-order red colour. The crystal just below the centre of the field of view shows a blue colour and below that the green colour could be a third-order colour. Thus the birefringence of this mineral on the basis of the highest order colour seen in this view is about 0.040, provided that the section is of the correct thickness. The rock is a dunite which is a monomineralic rock consisting almost entirely of olivine (x11).

Extinction angles

가동이 각도.

The interference colour of each mineral grain in thin section, observed with crossed polars, changes in intensity as the stage is rotated and the intensity falls to zero at every 90° of rotation (i.e. no light is seen by the observer from this crystal). The positions in which a particular grain is black are known as the *extinction positions* for that crystal. The angle between an extinction position and some well defined direction in a crystal is known as the *extinction angle* for that crystal: it is usually quoted as less than 45°, although sometimes the complementary angle is given. Since an extinction angle for a given orientation of a crystal or a maximum extinction angle, obtained by measurements from a number of crystals of the same mineral, may be of diagnostic value, the method of measuring an extinction angle is described briefly below and illustrated in **20–22**.

The thin section should be held in place by one of the spring clips on the microscope stage. Either a straight edge, representing a crystal face, or a cleavage direction of the crystal being studied is set parallel to one of the cross-hairs in the eyepiece and the angular position of the stage read from the fixed vernier scale. This should be done with the analyser removed from the light path. The analyser is then inserted and the stage rotated slowly to one of the extinction positions and the angular position read from the vernier scale. The difference in the two readings is the extinction angle for this particular crystal. If the angle is zero the crystal has *straight extinction*—non zero values are described as *oblique extinction*. An extinction position which bisects the angle between two cleavages is known as *symmetrical extinction*.

관측 방법 / cleavage 있는 방향

Stage 회전시키면 light → dark 0; extinction angle → 각도 변화 가능
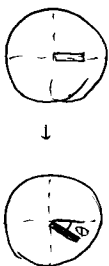
20–22 The main part of the field of view is occupied by a crystal of kyanite; a cleavage has been set parallel to the long edge of **20**. The interference colour shown by the kyanite is a first-order pale yellow. In **21** the microscope stage has been rotated through 150 and the brightness of the interference colour has become less intense. In **22** the microscope stage has been rotated through 30° and here the mineral is completely black—it is in the extinction position and only the inclusions of other minerals show interference colours. In this orientation the extinction angle of kyanite is 30°—a value which is characteristic of this mineral when measured from the cleavage shown here (x 38).

21

22

Extinction angle이 다른 맹도의 단이 둘이와는 것 (4개씨)

Twinning and zoning — 한개의 근 광물가 안에 다른 광물들이 둘이와는 것 (대응분인)
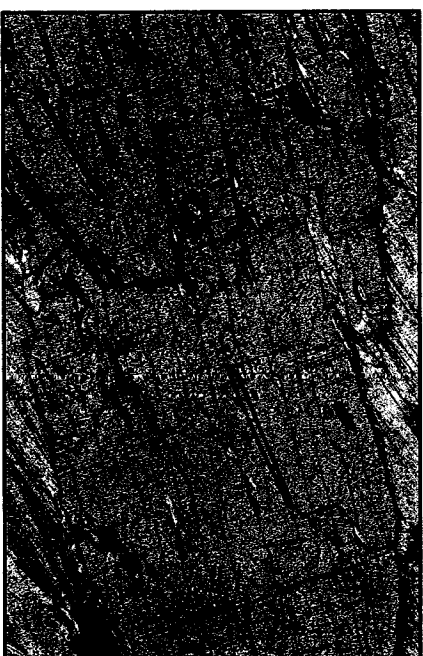
Many minerals occur in what are known as *twins*. Twins are crystals of the same mineral in which the orientations of the two or more parts have a simple relationship to each other, e.g. a rotation through 180° around one of the crystallographic axes, or reflection across a plane in the crystal (23). When this twin operation is repeated a number of times the crystals are described as *polysynthetically twinned* or as showing *multiple twinning*: in this case alternate lamellae show the same orientation.

The commonest rock-forming minerals in the earth's crust are the feldspars and certain types of twinning are characteristic of the different feldspars. The sodium-calcium or plagioclase feldspars invariably show polysynthetic twinning and an estimate of the sodium to calcium ratio may sometimes be obtained from a measurement of the extinction angle or of the maximum extinction angle depending on the orientation of the crystals. In Part 2 we describe a method of determining the sodium to calcium ratio of the plagioclase feldspars from extinction angle measurements of twinned crystals.

23 *Twinning.* This figure shows a few crystals of pyroxene taken with polars crossed. Some of the crystals have a dividing line and a change of interference colour across this line: this is due to twinning. If the crystal consists of only two parts it is simply twinned. Very often two different orientations are intergrown so that alternate lamellae have different orientations and so different interference colours (x 16).

24 & 25 *Zoning.* These figures show a phenocryst of plagioclase feldspar in a lava. The innermost zone, commonly referred to as the core, encloses small crystals of other minerals. This is surrounded by a second zone (or mantle) in which there is a high concentration of very small inclusions. Finally the outermost zone (or rim) shows numerous sub-zones or banding, because some bands are nearer their extinction position than others. Notice the zoning caused by the difference in extinction angle can only be seen in the view with crossed polars (25) (x 15).