9

Identification of Minerals

Rapid identification of minerals in thin section, polished section, or grain mount requires a systematic approach tempered with common sense and familiarity with a variety of common rocks and minerals. This chapter provides some general information to aid in identification. Identification tables and charts are located in Appendix B.

Chapters 10 through 16 provide descriptions of a variety of common minerals, and experience has shown that this selection covers the large majority of minerals found in most rocks. The reader is cautioned, however, that about 4000 different minerals have been identified and described and no assurance can be given that an uncommon mineral may not be present in any given rock. More complete compilations of optical data are provided by Troger (1979), Fleischer and others (1984), and Phillips and Griffen (1981). The reader is also directed to the excellent compilations of mineral data provided by Anthony and others in a series of volumes (1990, 1995, 1997, 2000) and by Gaines and others (1997).

Descriptive Features

A prodigious amount of terminology has been developed to describe minerals. Some commonly used terms are as follows.

Crystal Shape

acicular elongate needle-like grains

anhedral without regular crystal faces

bladed elongate, slender

columnar shaped like a column—moderately elongate grains with equidimensional cross section

equant equidimensional grains

euhedral has well-formed crystal faces

fibrous individual grains are long slender fibers

lathlike flat elongate grains

prismatic the dominant faces are those of a prism

subhedral has crystal faces but they are poorly formed or irregular

tabular shaped like a book

Mode of Aggregation

columnar parallel arrangement of columnar grains

foliated more or less parallel tabular or platy grains

granular equant grains, all about the same size

matted elongate grains in a random pattern

radiating elongate grains that radiate out from a center

Cleavage

In grain mount, the planar sides to the individual grains indicate the presence of cleavage, and, with careful observation, the number and approximate angular relation between the cleavages can be determined. In thin section, cleavage may be difficult to recognize in minerals with low relief, but careful examination with the aperture diaphragm set to enhance the relief may reveal the presence of fine parallel cracks. The angle between the traces of different cleavages in thin section depends on how the mineral has been cut, and examples are shown in Chapters 6 and 7.

Twinning

Many minerals are twinned, and the nature of the twinning is often easily seen. Simple twins consist of two segments that usually go extinct at different points with stage rotation. Contact twins are joined by a smooth twin plane separating the segments, while penetration twins are generally joined on irregular contacts. Polysynthetic twinning consists of numerous twin segments joined on parallel twin planes. If the successive twin planes are not parallel, a cyclic twin may result.

Alteration

Most minerals are subject to alteration from weathering, hydrothermal processes, or other causes. All too often, the alteration obscures the identity of the original mineral, but, in some cases—such as pinite after cordierite, or iddingsite after olivine—the alteration is a useful diagnostic property. If the alteration is severe, the optical properties of the remnants of the original mineral may be significantly changed.

Association

Some minerals are commonly associated in certain rocks or mineral deposits and other minerals are rarely found together. A knowledge of common mineral associations in a variety of rock types can aid in making educated guesses as to the possible identity of an unknown mineral. In addition, a knowledge of associations may suggest the presence of a mineral that might otherwise be overlooked.

While the use of association is valuable, it contains a subtle trap, because it tends to blind the observer to the possibility of an unusual or hitherto unidentified mineral. When making a choice between what "ought" to be present versus what the evidence seems to indicate, the evidence should be heeded.

The tables in Appendix C show minerals likely to be found in a variety of common rocks and mineral deposits. This compilation is far from complete and does not include any of the unusual associations that both frustrate and delight petrographers, nor does it include any of the myriad products of alteration or weathering that may be present.

Tactics for Mineral Identification

To identify and describe minerals optically, proceed as follows:

1. Examine the hand sample of the mineral to determine as many of the following characteristics as possible: color, luster, streak, hardness, cleavage/fracture, specific gravity, mineral habit. Provide a tentative identification or list of possibilities based on this information.

2. Based on the identity of associated minerals, rock type, or type of mineral deposit, modify the tentative list of minerals that the unknown might be. Appendix C lists common mineral associations in different rock types and mineral deposits.

3. Prepare a thin section, polished section, or grain mount. For spindle stage work, refer to Chapters 6 and 7.

THIN SECTION IDENTIFICATION

Thin sections are most valuable when rock textures and mineral intergrowth relations are of interest. Indices of refraction can only be estimated based upon relief, and measurement of 2V is approximate. A thin section takes substantially more time to prepare than grain mounts, but the time is often well spent. Proceed as follows:

1. Scan the slide to examine different grains of the unknown mineral. Color, relief, twinning, crystal shape, textures, and alteration usually provide the basis for distinguishing different minerals. Cross and uncross polarizers, and rotate the stage as needed. Record the following information:
   a. Color and pleochroism (if any)
   b. Relief relative to cement
   c. Mineral habit, textures, and alteration
   d. Whether the mineral is isotropic or anisotropic
   e. Nature of twinning, if present
   f. Nature of cleavage and/or fracture

2. If isotropic, go to the identification tables (Appendix B) and mineral descriptions.

ported here. If in doubt about a cement's index of refraction, consult the manufacturer, or prepare a grain mount of fragments of cured cement and measure it using the immersion method.

3. If anisotropic:
a. Scan the slide to find a grain of the unknown displaying the lowest interference color.
(1) *Uniaxial.* Obtain an interference figure and determine optic sign and record the relief associated with ω and the relief associated with n_ω.
(2) *Biaxial.* Obtain an interference figure and determine 2V, and dispersion characteristics, if any. Rotate the stage to place the optic plane at right angles to the lower polarizer direction. Return to orthoscopic illumination and observe the color associated with Y and record the relief of the mineral associated with n_β. Check the Becke line to determine if n_β is greater or less than the index of refraction of cement.

b. Scan the slide to find a grain of the unknown displaying the highest interference color.
(1) Determine maximum birefringence based on interference color and thin section thickness using Plate 1.
(2) Record the color and relief associated with n_ϵ (uniaxial) or n_α and n_γ (biaxial). Use the accessory plate to distinguish the appropriate vibration directions. Refer to Chapters 6 and 7 for information on vibration directions.
(3) If crystallographic directions can be recognized, determine optic orientation of biaxial minerals.

c. If the mineral is elongate or has cleavage
(1) Measure extinction angles on a number of grains. Often the diagnostic extinction angle is measured on grains with maximum birefringence.
(2) Determine sign of elongation (length fast or length slow).

d. Go to identification tables and mineral descriptions to determine identity of the mineral. For minerals in thin section, The chart printed on the back side of the interference color chart (Plate 2) provides a convenient starting point. Use the other figures and tables in Appendix B as needed to help refine the possibilities. Note that Plate 2, Table B.6, and the mineral descriptions in the latter part of the text all refer to relief in thin section. It is assumed that the cement used in thin section has an index of refraction of 1.540. Some cements may have an index of refraction either higher or lower than 1.540, so relief seen with these cements may be different than re-

GRAIN MOUNT IDENTIFICATION

Grain mounts of an unknown mineral are useful because they are quicker to prepare than a thin section of cleavage, and they provide accurate numerical values of indices of refraction, birefringence, and related optical variables. From these data, it may be possible to estimate chemical composition or confirm an identity that was uncertain in thin section or hand sample. It is generally necessary to separate grains of the unknown mineral from others that may be in the sample, prior to preparing the mount. In handling grain mounts, be careful to avoid getting immersion oil on lenses and working parts of the microscope. To identify an unknown mineral in grain mount, proceed as follows:

1. Scan the slide to observe as many of the following properties about the unknown mineral as possible: relief relative to immersion oil, whether isotropic or anisotropic, nature of cleavage and fracture, and alteration.
2. If isotropic, compare the indices of refraction of immersion oil and mineral using the Becke line. Prepare additional grain mounts using different immersion oils until an index of refraction match is obtained between the mineral and oil. Use the bracketing technique described in Chapter 3.
3. If anisotropic:
a. Scan the slide to find a grain of the unknown with the lowest interference color.
(1) *Uniaxial.* Obtain an interference figure and determine optic sign. Return to orthoscopic illumination and record the color associated with ω, and record the relief associated with n_ω. Check the Becke line to determine if n_ω is greater or less than the index of refraction of the oil.
(2) *Biaxial.* Obtain an interference figure and determine optic sign, 2V, and dispersion characteristics, if any. Rotate the stage to place the optic plane at right angles to the lower polarizer direction. Return to orthoscopic illumination and observe the color associated with Y and record the relief of the mineral associated with n_β. Check the Becke line to determine if n_β is greater or less than the index of refraction of oil.

b. Scan the slide to find a grain of the unknown displaying the highest interference color.
(1) If the mineral forms elongate fragments because of cleavage, measure the extinction angle and determine sign of elongation.
(2) Record the color and relief associated with n_ϵ (uniaxial) or n_α and n_γ (biaxial). Use the accessory plate to distinguish the appropriate vibration directions.
c. Prepare additional grain mounts to find index of refraction matches for n_ω and n_ϵ (uniaxial) or n_α, n_β, and n_γ (biaxial) following the procedures described earlier.
d. Go to identification tables (Appendix B) and mineral descriptions to identify the unknown.

POLISHED SECTION IDENTIFICATION

Proficiency in identification of minerals with a standard reflecting light microscope depends on gaining experience based on having looked at many samples. Unless equipment is available to make reflectance measurements, most of the items to be observed in reflective light are qualitative. Begin by scanning the polished section in both plane light and with crossed polarizers to note intergrowth textures, colors, alteration, or other features that distinguish among different opaque minerals in the sample. Then proceed systematically to observe the following for each mineral:

1. In plane light (analyzer removed)
a. Reflectance: Try to distinguish among very low (like quartz or epoxy), low (like magnetite), moderate (like galena), and high (like pyrite).
b. Bireflectance: Rotate the stage and note whether the reflectance varies.
c. Color and reflectance pleochroism
d. Polishing hardness relative to other minerals in the sample
2. With crossed polarizers (analyzer inserted)
a. Polarization colors
b. Internal reflections

Based on these observations, refer to Tables B.13, B.14, and B.15 in Appendix B, and refer to the mineral descriptions to work out the identification.

USE OF THE IDENTIFICATION TABLES

The optical data for minerals described in Chapters 10 through 16 are presented in Appendix B and selected optical data are shown on Plate 2 (back of interference color chart, Plate 1). The contents of Appendix B are:

Figure B.1	Values of 2V and birefringence (δ) for biaxial minerals
Table B.1	Color of minerals in thin section and grain mount
Table B.2	Index of refraction of isotropic or nearly isotropic minerals
Table B.3	Indices of refraction of uniaxial minerals
Table B.4	Indices of refraction of biaxial negative minerals arranged in order of increasing n_β
Table B.5	Indices of refraction of biaxial positive minerals arranged in order of increasing n_β
Table B.6	Birefringence
Table B.7	Minerals that may display anomalous interference colors
Table B.8	Isometric minerals that may display anomalous birefringence
Table B.9	Tetragonal and hexagonal minerals that may be anomalously biaxial
Table B.10	Normally birefringent minerals that may be sensibly isotropic
Table B.11	Biaxial minerals that may be sensibly uniaxial
Table B.12	Minerals that may produce pleochroic halos in surrounding minerals
Table B.13	Colors exhibited by opaque minerals in polished section viewed in air
Table B.14	Reflectance values (percent) for selected minerals in air
Table B.15	Polishing hardness

Table B.6, Plate 2, and the mineral descriptions in the chapters that follow all refer to the relief in thin section. It is assumed that the cement used in thin section has an index of refraction of 1.540, which is the index of refraction of Canada balsam and many commercially available epoxies and ultraviolet-curing cements in common use. However, some cements have an index of refraction either higher or lower than 1.54. If the cement is significantly different than 1.54, the relief of minerals in thin section may be different than what is reported in this book. If the index of refrac-

tion of a mineral is being compared with the cement in a thin section, it is important to know what the index of refraction of the cement actually is. If in doubt, consult the manufacturer.

If grain mount or spindle stage techniques are employed, the most useful data are the tabulations of the indices of refraction (Tables B.2 through B.5). A cross-check of color, birefringence, and 2V, as appropriate, may help narrow the list of possibilities.

For isotropic minerals in thin section, the tabulations of color (Table B.1) and index of refraction (Table B.2), supplemented by Plate 2, are typically most useful. Note, however, that only a rough estimate of index of refraction can be made from the relief in thin section.

For anisotropic minerals in thin section, Plate 2 is a useful starting points. The tabulations of birefringence (Table B.6) and color (Table B.1) help narrow the list of possibilities. For biaxial minerals, Figure B.1, which shows the optic angle, can be quite useful.

Nonminerals

Imperfectly prepared thin sections may contain a variety of materials that can be mistaken for minerals or that complicate the identification process. Some of the more common are bubbles, grinding abrasive, and textile fibers (Figure 9.1).

Unless care is taken in preparing thin sections, bubbles trapped in the cement are almost inevitable. If a bubble has been trapped where a grain has been plucked out, it can be mistaken for a high-relief isotropic mineral. Small spherical bubbles may display what looks like a uniaxial cross in orthoscopic illumination between crossed polarizers. Larger bubbles may be quite irregular, but typically display curved or rounded boundaries due to the surface tension of the cement.

Silicon carbide grinding abrasive appears as fine, angular opaque grains distributed throughout the slide, or concentrated in cracks or void spaces in the sample. If the cement is not entirely cured before grinding, abrasive may be embedded in the cement.

Textile materials from paper towels, clothing, and other sources appear as elongate fibers that are typically kinked. These materials may display interference colors between crossed polars because many varieties are anisotropic. By carefully adjusting the focus, it can usually be determined that these fibers are in the cement either above or below the sample.
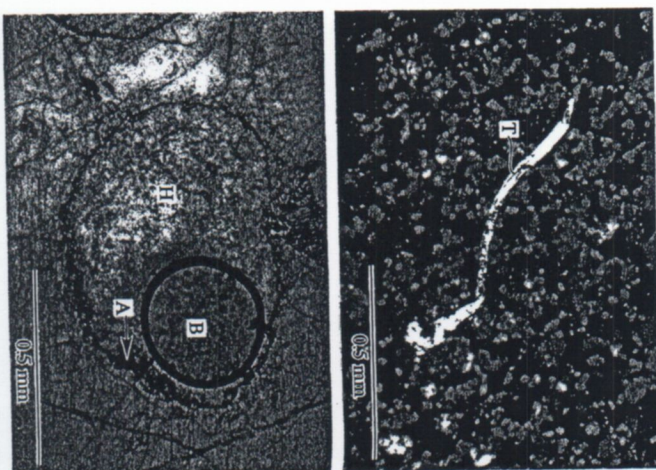
Figure 9.1 Nonminerals found in thin sections. (*Bottom*) Textile fiber (crossed polarizers). (*Bottom*) Hole (H) in a thin section partially occupied by a bubble (B) (plane light). The dark material around the edges of the hole and scattered through the epoxy in the hole is grinding abrasive (A).

Problems in Paradise

It would be nice if mineral identification and description could be accomplished by measuring a number of properties that unambiguously lead to an answer. The reality, as students soon learn, is subject to ambiguity and uncertainty. Different minerals have similar properties, some minerals have a wide range of properties, and properties may be incorrectly measured. Samples may also be too small or in inconvenient orientations, thereby precluding some measurements or observations.

These problems, while very real, become more manageable as experience is gained by studying many different suites of rocks and mineral deposits and learning to recognize the subtle characteristics of each mineral. That experience is gained most rap-

idly if a systematic approach is used. In this chapter and elsewhere, step-by-step instructions are provided to guide the student through the process of obtaining optical data on an unknown mineral. Students are encouraged to follow those instructions and to clearly define and understand what they are looking for before spending time peering down the microscope tube.

The quality of mineralogical data also can cause problems. Two issues, in particular, require comment.

INCONSISTENCIES IN CRYSTALLOGRAPHIC SETTINGS

In orthorhombic, monoclinic, and triclinic minerals, crystal axes may be assigned in several different ways. This has led to a substantial amount of confusion in the literature, where optical and physical properties are described using one crystal axis setting, and the structure is described using another setting. A concerted effort has been made to use a consistent crystal-axis setting for all properties in the mineral descriptions that follow, but the reader is cautioned that problems may persist and should exercise caution when comparing data from different sources.

POOR DATA

Most of the optical and physical properties reported in this and other standard sources on minerals are based on observations and reports from over a century ago. These data are uncritically repeated in each new text or reference work, with a few additions or modifications based on new measurements gleaned from the literature. Old errors are thereby perpetuated and new, often unrepresentative data are thereby added. As a general rule, data from the reference works by Deer and others (1962–2001, 1992) and/or Anthony and others (1990, 1995, 1997, 2000) are used here, but other sources were used where it seemed appropriate. Because the time required to systematically verify and update the data on each mineral is very large, it has not been attempted here. Reader beware.

◆ REFERENCES AND SUGGESTIONS FOR ADDITIONAL READING

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Deer, R. A., Howie, R. A., and Zussman, J 1962–2001, *Rock-forming minerals*, 1st edition, 5 vols, John Wiley & Sons, New York; 2nd edition, vols. 1A, 2A, 2B, 4A, and 5B, The Geological Society, London; vol. 5B, Longman Scientific and Technical, New York.

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Fleischer, M., Wilcox, R. E, and Matzko, J. J., 1984, *Microscopic determination of the nonopaque minerals*: U.S. Geological Survey Bulletin 1627, 453 pp.

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4/n

Physical properties of one minerals in polished section

① Crystal form
② Zoning
③ Cleavage and Parting
④ Twinning
⑤ Inclusions and intergrowths
⑥ Hardness

## 1.5 The reflected-light microscope

The light source A high-intensity source (Fig. 1.4) is required for reflected-light studies, mainly because of the low brightness of crossed polar images. Tungsten-halogen quartz lamps, similar to those in transparency projectors, are used and the tungsten light (A source) gives the field a yellowish tint. Many microscopists prefer to use a blue correction filter to change the light colour to that of daylight (C source) A monochromatic light source (coloured light corresponding to a very limited range of the visible spectrum) is rarely used in qualitative microscopy, but monochromatic filters for the four standard wavelengths (470 nm, 546 nm, 589 nm and 650 nm) could be useful in comparing the brightness of coexisting minerals, especially now that quantitative measurements of brightness are readily available.

The polarizer Polarized light is usually obtained by using a polarizing film, and this should be protected from the heat of the lamp by a glass heat filter. The polarizer should always be inserted in the optical train. It is best fixed in orientation to give east–west-vibrating incident light. However, it is useful to be able to rotate the polarizer on occasion in order to correct its orientation, or as an alternative to rotating the analyser.

The incident illuminator The incident illuminator sits above the objective, and its purpose is to reflect light down through the objective onto the polished specimen. As the reflected light travels back up through the objective to the eyepiece it must be possible for this light to pass through the incident illuminator. Three types of reflector are used in incident illuminators (Fig. 1.5):

(a) The cover glass or coated thin glass plate (Fig. 1.5a). This is a simple device, but it is relatively inefficient because of light loss both before and after reflection from the specimen. However, its main disadvantage when at 45° inclination is the lack of uniform extinction of an isotropic field. This is due to rotation of the vibration direction of polarized reflected light, which passes asymmetrically through the cover glass on returning towards the eyepiece. This disadvantage is overcome by decreasing the angle to about 23°, as on Swift microscopes.

(b) The mirror plus glass plate or Smith illuminator (Fig. 1.5b). This is slightly less efficient than the cover glass but, because of the low angle (approaching perpendicular) of incidence of the returning reflected light on the thin glass plate, extinction is uniform and polarization colours are quite bright. This illuminator is used on Vickers microscopes.

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Figure 1.5
Incident illuminators.

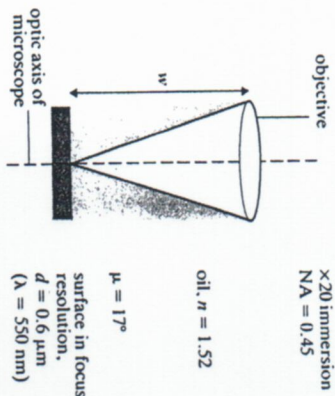(a) Cover glass illuminator   (b) Smith illuminator   (c) Prism illuminator
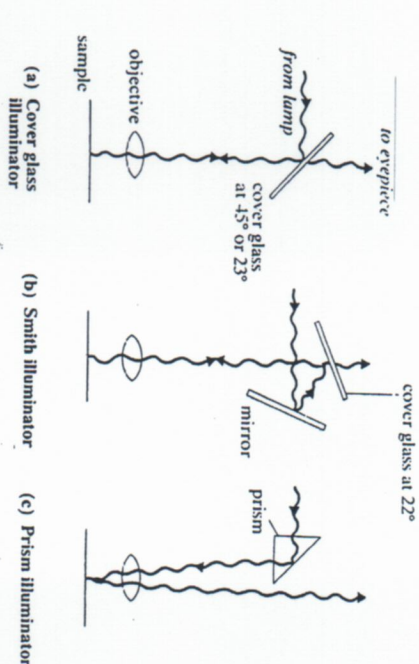
(c) The prism or total reflector (Fig. 1.5c). This is more efficient than the glass plate type of reflector but it is expensive. It would be 100 per cent efficient, but half of the light flux is lost because only half of the aperture of the objective is used. One disadvantage is the lack of uniform extinction obtained. A special type is the triple prism or Berek prism, with which very uniform extinction is obtained (Hallimond 1970, p. 103). Prism reflectors are usually available only on research microscopes, and are normally interchangeable with glass plate reflectors. One disadvantage of prisms is that the incident light is slightly oblique, and this can cause a shadow effect on surfaces with high relief. Colouring of the shadow may also occur.

Objectives Objectives are magnifiers and are therefore described in terms of their magnification power, e.g. × 5. They are also described using numerical aperture (Fig. 1.6), the general rule being the higher the numerical aperture the larger the possible magnification. It is useful to remember that, for objectives described as being of the same magnification, a higher numerical aperture leads to finer resolved detail, a smaller depth of focus and a brighter image. Objectives are designed for use with either air (dry) or immersion oil between the objective lens and the sample. The use of immersion oil between the objective and sample leads to an increase in the numerical aperture value (Fig. 1.6). Immersion objectives are usually engraved as such.

Low-power objectives can usually be used for either transmitted or reflected light, but at high magnifications (> × 10) good images can be obtained only with the appropriate type of objective.

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objective
×20 immersion
NA = 0.45

oil, n = 1.52

μ = 17°

surface in focus
resolution,
d = 0.6 μm
(λ = 550 nm)

optic axis of
microscope

Figure 1.6 The numerical aperture and resolution. NA = $n \sin \mu$, where NA is the numerical aperture, n is the refractive index of the immersion medium, and μ is half the angle of the light cone entering the objective lens (for air, n = 1.0). d = 0.5λ/NA, where d = the resolution (the distance between two points that can be resolved) and λ is in μm (1 μm = 1000 nm). The working distance (w in the diagram) depends on the construction of the lens: for the same magnification, oil immersion lenses usually have a shorter distance than dry objectives.

Reflected-light objectives are also known as metallurgical objectives. Achromatic objectives are corrected for chromatic aberration, which causes colour fringes in the image due to dispersion effects. Planochromats are also corrected for spherical aberration, which causes a loss in focus away from the centre of a lens; apochromats are similarly corrected but suffer from chromatic difference of magnification, which must be removed by the use of compensating eyepieces.

Analyser The analyser may be moved in and out of the optical train and rotated through small angles during observation of the specimen. The reason for rotation of the analyser is to enhance the effects of anisotropy. It is taken out to give plane polarized light (PPL), the field appearing bright, and put in to give crossed polars (XPOLS), the field appearing dark. Like the polarizer, it is usually made of polarizing film. On some microscopes the analyser is fixed in orientation and the polarizer is designed to rotate. The effect is the same in both cases, but it is easier to explain the behaviour of light if a rotating analyser is assumed (Section 5.3).

The Bertrand lens The Bertrand lens is little used in reflected-light microscopy, especially by beginners. The polarization figures

obtained are similar to the interference figures of transmitted-light microscopy, but differ in origin and use.

Isotropic minerals give a black cross, which is unaffected by rotation of the stage but splits into two isogyres on rotation of the analyser. Lower-symmetry minerals give a black cross in the extinction position, but the cross separates into isogyres on rotation of either the stage or the analyser. Colour fringes on the isogyres relate to dispersion of the rotation properties.

Light control Reflected-light microscopes are usually designed to give Kohler-type critical illumination (Galopin & Henry 1972, p. 58). As far as the user is concerned, this means that the aperture diaphragm and the lamp filament can be seen using conoscopic light (Bertrand lens in) and the field diaphragm can be seen using orthoscopic light (Bertrand lens out).

A lamp rheostat is usually available on a reflected-light microscope to enable the light intensity to be varied. A very intense light source is necessary for satisfactory observation using crossed polars. However, for PPL observations the rheostat is best left at the manufacturer's recommended value, which should result in a colour temperature of the A source. The problem with using a decreased lamp intensity to decrease image brightness is that this changes the overall colour of the image. Ideally, neutral density filters should be used to decrease brightness if the observer finds it uncomfortable. In this respect, binocular microscopes prove less wearisome on the eyes than monocular microscopes.

Opening of the *aperture diaphragm* decreases resolution, decreases the depth of focus and increases brightness. It should ideally be kept only partially open for PPL observation, but opened fully when using crossed polars. If the aperture diaphragm can be adjusted, it is viewed using the Bertrand lens or by removing the ocular (eyepiece). The aperture diaphragm is shown correctly centred for glass plate and prism reflectors in Figure 1.7.
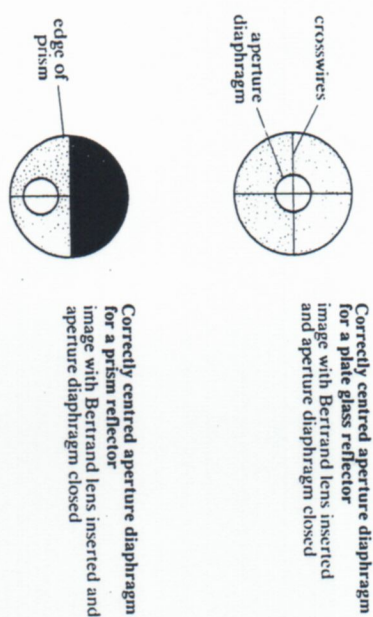
The *illuminator field diaphragm* is used simply to control scattered light. It can usually be focused and it should be in focus at the same position as the specimen image. The field diaphragm should be opened until it just disappears from the field of view.

1.6 The appearance of polished sections under the reflected-light microscope

On first seeing a polished section of a rock or ore sample, the observer often finds that interpretation of the image is rather difficult. One reason for this is that most students use transmitted light

Figure 1.7
Centring of the aperture diaphragm

crosswires
aperture diaphragm

Correctly centred aperture diaphragm for a plate glass reflector image and aperture diaphragm closed

edge of prism

Correctly centred aperture diaphragm for a prism reflector image with Bertrand lens inserted and aperture diaphragm closed

for several years before being introduced to reflected light, and they are conditioned into interpreting bright areas as being transparent and dark areas as being opaque (see Plates 4a & b); for polished sections the opposite is the case! It is best to begin examination of a polished section such as that illustrated in Figure 1.8 by using *low-power magnification* and *plane polarized light*, under which conditions most of the following features can be observed:

(a) Transparent phases appear dark grey, because they reflect only a small proportion of the incident light, typically 3–15%. Bright patches are occasionally seen within areas of transparent minerals, and are due to reflection from surfaces under the polished surface.

(b) Absorbing phases (opaques or ore minerals) appear grey to bright white, as they reflect much more of the incident light, typically 15–95%. Some absorbing minerals appear coloured, but colour tints are usually very slight.

(c) Holes, pits, cracks and specks of dust appear black. Reflection from crystal faces in holes may give peculiar effects, such as very bright patches of light.

(d) Scratches on the polished surfaces of minerals appear as long straight or curving lines, often terminating at grain boundaries or pits. Severe fine scratching can cause a change in the appearance of minerals. Scratches on native metals, for example, tend to scatter light and cause colour effects.

(e) Patches of moisture or oil tend to cause circular dark or iridescent patches, and indicate a need to clean the polished surface.

(f) Tarnishing of minerals is indicated by an increase in colour intensity, which tends to be rather variable. Sulphides, such as

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1 mm

Figure 1.8 A diagrammatic representation of a polished section of a sample of lead ore. *Transparent phases*, e.g. fluorite (A), barite (B) and the mounting resin (D) appear dark grey. Their brightness depends on their refractive index. The fluorite is almost black, the barite (B) and the mounting resin (D) appear dark grey. *Absorbing* (opaque) phases, e.g. galena (C), appear white. *Holes, pits and cracks* appear black. Note the black triangular cleavage pits in the galena and the abundant pits in the barite which result not from poor polishing but from the abundant fluid inclusions. *Scratches* appear as long straight or curving lines; they are quite abundant in the galena, which is soft and scratches easily.

bornite, tend to tarnish rapidly. Removal of tarnishing usually requires a few minutes of buffing and repolishing.

(g) Polishing relief, due to the differing hardnesses of adjacent minerals, causes dark or light lines along grain contacts. Small soft bright grains may appear to glow, and holes may have indistinct dark margins because of polishing relief.

1.7 Systematic description of minerals in polished section using reflected light

Most of the ore minerals described in Chapter 3 have a heading 'polished section'. The properties presented under this heading are in a particular sequence, and the terms used are explained briefly below. Not all properties are shown by each mineral, so only properties which might be observed are given in Chapter 3.

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1.7.1 Properties observed using plane polarized light (PPL)

The analyser is taken out of the optical path to give a bright image (see Frontispiece).

Colour Most minerals are only slightly coloured when observed using PPL, and the colour sensation depends on factors such as the type of microscope, the light source and the sensitivity of an individual's eyes. Colour is therefore usually described simply as being a variety of grey or white, e.g. bluish-grey rutile or pinkish-white cobaltite.

Pleochroism If the colour of a mineral varies from grain to grain and individual grains change in colour on rotation of the stage, then the mineral is pleochroic. The colours for different crystallographic orientations are given when available. Covellite, for example, shows two extreme colours, blue and bluish light grey. Pleochroism can often be observed only by careful examination of groups of grains in different crystallographic orientations. Alternatively, the pelochroic mineral may be examined adjacent to a non-pleochroic mineral, e.g. ilmenite against magnetite.

Reflectance This is the percentage of light reflected from the polished surface of the mineral and, where possible, values are given for each crystallographic orientation. The eye is not good at estimating absolute reflectance but is a good comparator. The reflectance values of the minerals should therefore be used for the purpose of comparing minerals. Reflectance can be related to a grey scale of brightness in the following way (however, although followed in this book it is not a rigid scale). A mineral of reflectance ~ 15% (e.g. sphalerite) may appear to be light grey or white compared with a low-reflectance mineral (such as quartz) or dark grey compared with a bright mineral (such as pyrite):

R (%)	Grey scale
0–10	dark grey
10–20	grey
20–40	light grey
40–60	white
60–100	bright white

Bireflectance Bireflectance is a quantitative value, and for an anisotropic grain it is a measure of the difference between the maximum and minimum values of reflectance. However, bireflectance is usually assessed qualitatively, e.g.

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(a)

(b)
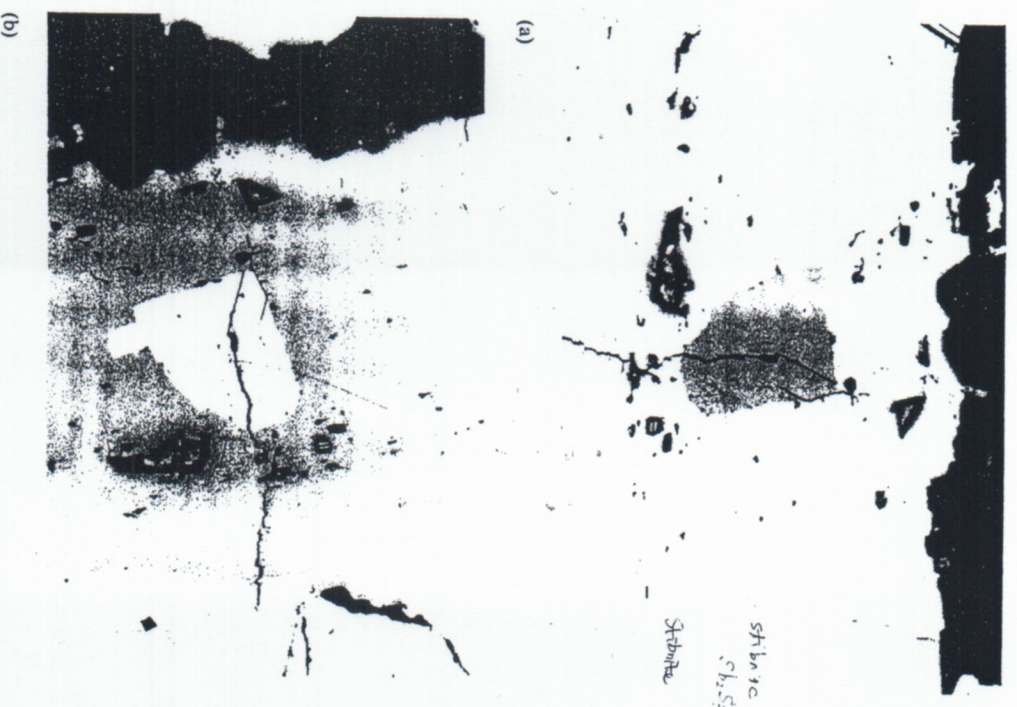
Figure 1.9(a) A reflected-light photomicrograph (PPL) of an elongate stibnite crystal (light grey) oriented east–west and containing an inclusion of stibnite (grey) in a different crystallographic orientation. **(b)** As (a), but the elongate stibnite crystal has been rotated to north–south. The inclusion is now white. Stibnite exhibits a distinct bireflectance which depends on the crystallographic orientation of the section.

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weak: observed with difficulty, $\Delta R < 5\%$ (e.g. hematite)
distinct: easily observed, $\Delta R > 5\%$ (e.g. stibnite, Figs 1.9a & b)

Pleochroism and bireflectance are closely related properties; the term pleochroism is used to describe change in tint or colour intensity, whereas bireflectance is used for a change in brightness.

1.7.2 Properties observed using crossed polars

The analyser is inserted into the optical path to give a dark image.

Anistropy: Anistropy varies markedly with the crystallographic orientation of a section of a non-cubic mineral. It is assessed as follows:

(a) Isotropic mineral: all grains remain dark on rotation of the stage, e.g. magnetite.
(b) **Weakly anisotropic mineral:** slight change on rotation, seen only on careful examination using slightly uncrossed polars, e.g. ilmenite.
(c) Strongly anisotropic mineral: pronounced change in brightness and possible colour seen on rotating the stage when using exactly crossed polars, e.g. hematite.

Remember that some cubic minerals (e.g. pyrite) can appear to be anisotropic, and weakly anisotropic minerals (e.g. chalcopyrite) may appear to be isotropic. Anisotropy and bireflectance are related properties; an anisotropic grain is necessarily bireflecting, but the bireflectance in PPL is always much more difficult to detect than the anisotropy in crossed polars (see Plates 4c & d).

Internal reflections Light may pass through the polished surface of a mineral and be reflected back from below. Internal reflections are therefore shown by all transparent minerals. When one is looking for internal reflections, particular care should be paid to minerals of low to moderate reflectance (semi-opaque minerals), for which internal reflections might be detected only with difficulty and near grain boundaries or fractures. Cinnabar, unlike hematite which is otherwise similar, shows spectacular red internal reflections. (Plates 4e & f).

1.7.3 The external nature of grains

The grain shapes of minerals are determined by complex variables acting during deposition and crystallization, and subsequent recrystallization, replacement or alteration. Idiomorphic (a term used by reflected-light microscopists for well shaped or euhedral) grains are unusual, but some minerals in a polished section will be found to

have a greater tendency towards a regular grain shape than others. In the ore mineral descriptions in Chapter 3, the information given under the heading "crystals" is intended to be an aid to recognizing minerals on the basis of grain shape. Textural relationships are sometimes also given.

1.7.4 Internal properties of grains

Twinning Twinning is best observed using crossed polars, and is recognized when areas with differing extinction orientations have planar contacts within a single grain (Plate 4d). Cassiterite is commonly twinned.

Cleavage Cleavage is more difficult to observe in reflected light than in transmitted light, and is usually indicated by discontinuous alignments of regularly shaped or rounded pits. Galena is characterized by its triangular cleavage pits (Plate 4b). Scratches sometimes resemble cleavage traces. Further information on twinning and cleavage is given under the "crystals" heading in the descriptions of Chapter 3.

Zoning Compositional zoning of chemically complex minerals, such as tetrahedrite, is probably very common but rarely gives observable effects such as colour banding. Zoning of micro-inclusions is more common.

Inclusions The identity and nature of inclusions commonly observed in the mineral are given, as this knowledge can be an aid to identification. Pyrrhotite, for example, often contains lamellar inclusions of pentlandite.

1.7.5 Vickers hardness number (VHN)

The Vickers hardness number is a quantitative value of hardness, knowledge of which is useful when comparing the polishing properties of minerals (see Section 1.10).

1.7.6 Distinguishing features

Distinguishing features are given for the mineral compared with other minerals of similar appearance. The terms harder or softer refer to comparative polishing hardness (see Section 1.9).

1.8 Observations using oil immersion in reflected-light studies

Preliminary observations on polished sections are always made simply with air ($RI = 1.0$) between the polished surface and the microscope objective, and for most purposes this suffices. However, an increase in useful magnification and resolution can be achieved by using immersion objectives which require oil (use the microscope manufacturer's recommended oil, e.g. Cargille oil type A) between the objective lens and the section surface. A marked decrease in glare is also obtained with the use of immersion objectives. A further reason for using oil immersion is that the ensuing change in appearance of a mineral may aid its identification. Ramdohr (1969) states: 'It has to be emphasised over and over again that whoever shuns the use of oil immersion misses an important diagnostic tool and will never see hundreds of details described in this book.'

Oil immersion nearly always results in a decrease in reflectance (Table 1.1), the reason being evident from examination of the Fresnel equation (Section 5.1.1), which relates the reflectance of a mineral to its optical properties *and* to the refractive index (N) of the immersion medium. Because it is the $n - N$ and $n + N$ values in the equation that are affected, the decrease in reflectance resulting from the increase in N is greater for minerals with a lower absorption coefficient (see Table 1.1).

Table 1.1 The relationship between the reflectances of minerals in air (R_{air}) and oil immersion (R_{oil}) and their optical constants, refractive index (n) and absorption coefficient (k). Hematite is the only non-cubic mineral represented, and two sets of values corresponding to the ordinary (o) and extraordinary (e) rays are given. N is the refractive index of the immersion medium.

		n	k	R_{air} (%) ($N = 1.0$)	R_{oil} (%) ($N = 1.52$)
Transparent minerals					
fluorite CaF$_2$		1.434	0.0	3.2	0.08
sphalerite ZnS		2.38	0.0	16.7	4.9
Weakly absorbing minerals					
hematite Fe$_2$O$_3$	(o)	3.15	0.42	27.6	12.9
	(e)	2.87	0.32	23.9	9.9
Absorbing (opaque) minerals					
galena PbS		4.3	1.7	44.5	28.9
silver Ag		0.18	3.65	95.1	93.2

The colour of a mineral may remain similar or may change markedly from air to oil immersion. The classic example of this is covellite, which changes from blue in air to red in oil, whereas the very similar blaubleibender covellite remains blue in both air and oil. Other properties, such as bireflectance and anisotropy, may be enhanced or diminished by the use of oil immersion.

To use oil immersion, lower the microscope stage so that the immersion objective is well above the area of interest on the horizontal polished section. Place a droplet of the recommended oil on the section surface, and preferably also on the objective lens. Slowly raise the stage using the coarse focus control, viewing from the side, until the two droplets of oil just coalesce. Continue to raise the stage very slowly using the fine focus, looking down the eyepiece until the image comes into focus. Small bubbles may drift across the field, but they should not cause any inconvenience. Larger bubbles, which tend to be caused by moving the sample too quickly, may be removed satisfactorily only by complete cleaning.

To clean the objective, lower the stage and immediately wipe the end of the objective with a soft tissue. Alcohol on a tissue may be used, but not a solvent such as acetone, which may result in loosening of the objective lens. The polished section can be carefully lifted from the stage and cleaned in the same way.

Most aspects of qualitative ore microscopy can be undertaken without recourse to oil immersion, and oil immersion examination of sections which are subsequently to be carbon coated for electron-beam micro-analysis should be avoided. The technique is most profitably employed in the study of small grains of low-reflectance materials such as graphite or organic compounds, where the benefits are a marked increase in resolution and image quality at high magnification.

1.9 Polishing hardness

During the polishing process, polished sections inevitably develop some relief (or topography) owing to the differing hardness of the component minerals (see Fig. 1.10). Soft minerals tend to be removed more easily than hard minerals. Also, the surfaces of hard grains tend to become convex, whereas the surfaces of soft grains tend to become concave. One of the challenges of the polishing technique is totally to avoid relief during polishing, because of the detrimental effect of polishing relief on the appearance of the polished section, as well as the necessity for optically flat polished surfaces for reflectance measurements. As some polishing relief is often advantageous in *qualitative* mineral identification, it is often
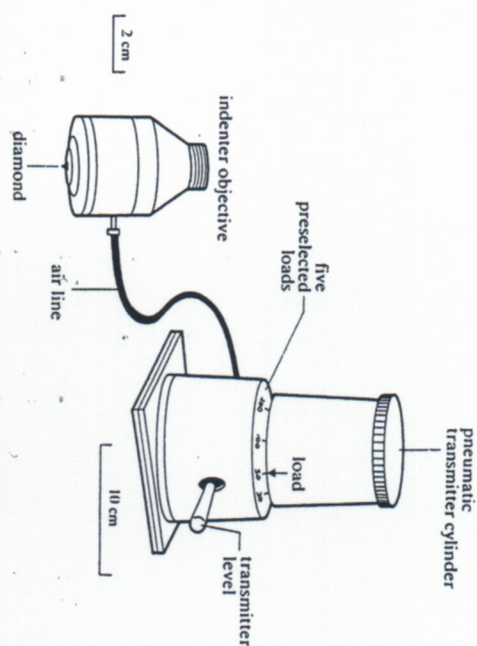
Figure 1.12 The Vickers micro-indentation hardness tester.

The size of the resulting square-shaped impression depends on the hardness of the mineral:

$$\left(VHN = \frac{1854 \times load}{d^2} \quad kg/mm^2 \right)$$

where the load is in kilograms and d is the average length of the diagonals of the impression in microns.

Hardness is expressed in units of pressure; that is, force per unit area. Thus the micro-indentation hardness of pyrite is written:

$$\text{pyrite, } VHN_{100} = 1027\text{–}1240 \text{ kg/mm}^2$$

The subscript 100 may be omitted, as this is the standard load. As VHN values are always given in kg/mm^2, the unit is also often omitted.

The determination of hardness is a relatively imprecise technique, so an average of several indentations should be used. Tables of VHN usually give a range of values for a mineral, due to compositional variations, anisotropy of hardness, and uncertainty. Brittleness, plasticity and elasticity control the shape of the indentations and, as the shape can be useful in identification, the COM recommends that indentation shape (using the abbreviations given in Fig. 1.13) be given with VHN values.

There is a reasonable correlation between VHN and Mohs' scratch hardness, as shown in Table 1.2

Table 1.2 Relation between VHN and Mohs' hardness.

| Mohs' hardness (H)		~ VN
1	talc	10
2	gypsum	40
3	calcite	100
4	fluorite	200
5	apatite	500
6	orthoclase	750
7	quartz	1300
8	topaz	1700
9	corundum	2400
[10	diamond]	

1.11 Practical points on the use of the microscope (transmitted and reflected light)

Always focus using low power first. It is safer to start with the specimen surface close to the objective and *lower* the stage or raise the tube to achieve the position of focus.

Thin sections must always be placed on the stage with the cover slip on top of the section; otherwise, high-power objectives may not focus properly.

Polished samples must be level. Blocks may be mounted on a small sphere of plasticine on a glass plate and pressed gently with a levelling device. Carefully machined polished blocks with parallel faces can usually be placed directly on the stage. A level sample should appear uniformly illuminated. A more exact test is to focus on the samples, and then close the aperture diaphragm (seen using

Figure 1.13 Indentation shapes.

p (perfect)

sf (slightly fractured)

f (fractured)

cc (concave)

cv (convex)
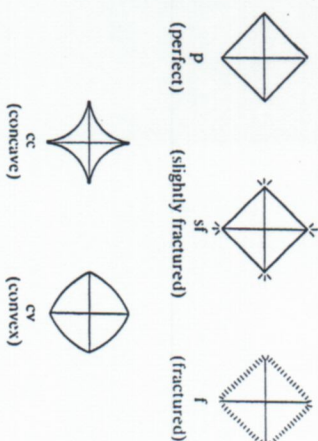
the Bertrand lens) and rotate the stage. If the sample is level, the small spot of light seen as the image should not wobble.

Good polished surfaces require careful preparation and are easily ruined. Never touch the polished surface or wipe it with anything other than a clean soft tissue, preferably moistened with alcohol or a proprietary cleaning fluid. Even a dry tissue can scratch some soft minerals. Specimens not in use should be kept covered.

The analyser is usually fixed in orientation on transmitted-light microscopes, but the polarizer may be free to rotate. There is no need to rotate the polarizer during normal use of the microscope, and it should be positioned to give east–west-vibrating polarized light. To check that the polars are exactly crossed, examine an isotropic substance such as glass and adjust the polarizer to give maximum darkness (complete extinction).

The approximate alignment of polarizer and analyzer for reflected light can be set fairly easily. Begin by obtaining a level section of a bright isotropic mineral such as pyrite. Rotate the analyzer and polarizer to their zero positions, which should be marked on the microscope. Check that the polars are crossed, i.e. the grain is dark. Rotate the analyser slightly to give as dark a field as possible. View the polarization figure (see Section 1.5). Adjust the analyzer (and/or polarizer) until a perfectly centred black cross is obtained. Examine an optically homogeneous area of a uniaxial mineral such as ilmenite, nicolite or hematite. Using crossed polars it should have four extinction positions at 90°, and the polarization colours seen in each quadrant should be identical. Adjust the polarizer and analyzer until the best results are obtained (see Hallimond 1970, p. 101).
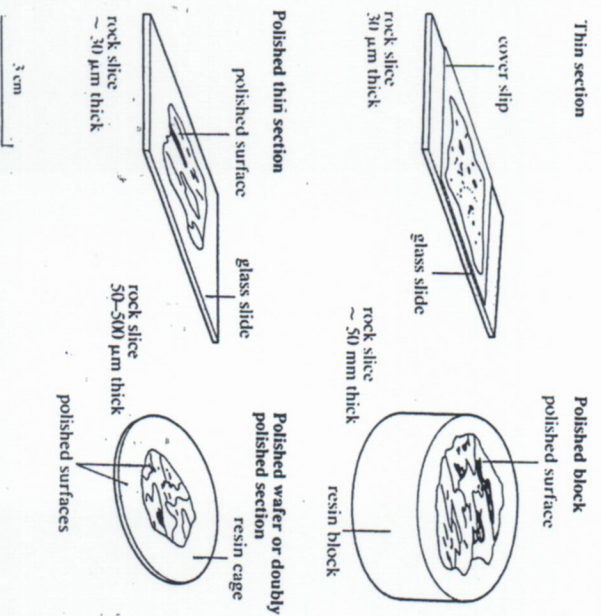
Ensure that the stage is well centred using the high-power objective before studying optical figures.

1.12 Preparation of thin and polished sections

Thin sections are prepared by cementing thin slices of rock to glass, and carefully grinding using carborundum grit to produce a paper-thin layer of rock. The standard thickness of 30 μm is estimated using the interference colours of known minerals in the section. A cover slip is finally cemented on top of the layer of rock (Fig. 1.14).

The three common types of polished section are shown in Figure 1.14. Preparation of a polished surface of a rock or ore sample is a rather involved process which involves five stages:

(1) Cutting the sample with a diamond saw.
(2) Mounting the sample on glass or in a cold-setting resin.
(3) Grinding the surface, flat, using carborundum grit and water on a glass or a metal surface.

Figure 1.14 Sections.

Thin section
cover slip
rock slice 30 μm thick
glass slide
rock slice ~50 mm thick

Polished block
polished surface
resin block

Polished thin section
polished surface
glass slide
rock slice ~30 μm thick

rock slice 50–500 μm thick
polished surfaces

Polished wafer or doubly polished section
resin cage

3 cm

(4) *Polishing* the surface, using diamond grit and an oily lubricant on a relatively hard "paper" lap.
(5) *Buffing* the surface, using gamma alumina powder and water as lubricant on a relatively soft "cloth" lap.

There are many variants of this procedure, and the details usually depend on the nature of the samples and the polishing materials, and the equipment that happen to be available. Whatever the method used, the objective is a flat, relief-free, scratch-free polished surface. The technique used by the British Geological Survey is outlined by Lister (1978).

While *covered thin sections* continue to be popular for the study of rocks and *polished blocks* for ores, the *polished thin section* is undoubtedly the most versatile preparation, and is particularly suited to the study of samples containing a variety of minerals of low to high RI and of variable absorption (see Plates 4a & b). Variants include doubly polished thin sections, which reveal the zoning of sphalerite, and ultra-thin (preferably doubly polished) sections, which reveal textural details in fine-grained carbonates. Partially polished (to coarse diamond grade) uncovered thin sections are popular for petrographic work using cathodoluminescence microscopy. *Polished wafers* are difficult and time-consuming to prepare,

but are necessary for the study of fluid inclusions in transparent minerals (Shepherd et al. 1985). Examination of minerals using cathodoluminescence, ultraviolet fluorescence, lasers and electron-beam X-ray micro-analysis all require polished sections, and the use of these techniques therefore benefits from the preliminary reflected-light study of samples.

2

Silicate minerals

2.1 Crystal chemistry of silicate minerals

All silicate minerals contain silicate oxyanions $[SiO_4]^{4-}$. These units take the form of a tetrahedron, with four oxygen ions at the apices and a silicon ion at the centre. The classification of silicate minerals depends on the degree of polymerization of these tetrahedral units. In silicate minerals, the system of classification commonly used by mineralogists hinges upon how many oxygens in each tetrahedron are shared with other similar tetrahedra.

Nesosilicates Some silicate minerals contain independent $[SiO_4]^{4-}$ tetrahedra. These minerals are known as nesosilicates, orthosilicates or *island silicates*. The presence of $[SiO_4]$ units in a chemical formula of a mineral often indicates that it is a nesosilicate, e.g. olivine $(Mg,Fe)_2SiO_4$ or garnet $(Fe,Mg$ etc.$)_3Al_2Si_3O_{12}$, which can be rewritten as $(Fe,Mg$ etc.$)_3Al_2[SiO_4]_3$. Nesosilicate minerals include the olivine group, the garnet group, the Al_2SiO_5 polymorphs (andalusite, kyanite and sillimanite), zircon, sphene, staurolite, chloritoid, topaz and humite group minerals.

Cyclosilicates Cyclosilicates or *ring silicates* may result from tetrahedra sharing two oxygens, linked together to form a ring, the general composition of which is $[Si_xO_{3x}]^{2x-}$, where x is any positive integer. The rings are linked together by cations such as Ba^{2+}, Ti^{4+}, Mg^{2+}, Fe^{2+}, Al^{3+} and Be^{2+}, and oxycomplexes such as $[BO_3]^{3-}$, may be included in the structure. A typical ring composition is $[Si_6O_{18}]^{12-}$, and cyclosilicates include tourmaline, cordierite and beryl, although cordierite and beryl may be included with the tektosilicates in some classifications.

Sorosilicates Sorosilicates contain $[Si_2O_7]^{6-}$ groups of two tetrahedra sharing a common oxygen. The $[Si_2O_7]^{6-}$ groups may be linked together by Ca^{2+}, Al^{3+}, Mg^{2+}, Fe^{2+} and some rare earth ions $(Ce^{2+}, La^{2+}$ etc.), and also contain $(OH)^-$ ions in the epidote group of minerals. In addition to the epidote group, sorosilicates include the melilites, vesuvianite (or idocrase) and pumpellyite.