CHAPTER 3

MINERAL IDENTIFICATION—QUALITATIVE METHODS

3.1 INTRODUCTION

When a polished section or a polished thin section is placed on the stage of a standard reflected-light microscope, the first objective of any examination of the section is usually the identification of the minerals present. A variety of properties exhibited by each phase can be studied using the microscope without any modification of the instrument or ancillary apparatus. However, in contrast with the study of thin sections in transmitted light, these properties are qualitative[1] and may not be sufficient for unequivocal identification. The extent to which individual phases can be identified using these qualitative methods depends considerably on the knowledge and experience of the microscopist. To the beginner, very few minerals are immediately identifiable, and, although the experienced microscopist can identify many more minerals, there will still be certain phases (or groups of phases) that cause confusion. The tendency to rely on experience has led to the view (an unfortunate misconception, in the opinion of the present authors) that ore microscopy is a "difficult art." The developments in quantitative methods of reflectance and microhardness measurement discussed in Chapters 5 and 6 and the more widespread availability of such ancillary methods as electron microprobe analysis and X-ray diffraction have done much to dispel this view. There is still much to be gained by a careful qualitative examination of minerals in polished section; however, given a moderate amount of experience, an appreciable number of phases can be identified routinely without the use of elaborate ancillary equipment.

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[1] The study of rotation properties further discussed in Chapter 4 are an exception, but the techniques have not been proved satisfactory for routine work in most laboratories.

In this chapter, the qualitative properties of value in mineral identification are discussed. There are four major categories: (1) optical properties; (2) properties dependent on hardness; (3) properties dependent on the structure and morphology of phases; and (4) textures that are characteristic of some phases when they occur in association with certain other phases. As noted at the end of this chapter, information can also be derived from the associated minerals. The importance of spending as much time as possible looking at different minerals in various associations cannot be overemphasized for the beginning student. Appendix 1 incorporates data on qualitative properties for the more common minerals; additional detail or information on uncommon minerals may be found in such reference texts as Ramdohr's *The Ore Minerals and Their Intergrowths* (1980) and Uytenbogaardt and Burke's *Tables for the Microscopic Identification of Ore Minerals* (1971).

3.2 QUALITATIVE OPTICAL PROPERTIES

Observations with the ore microscope are usually made either with (1) only the polarizer inserted (i.e., using linearly or "plane" polarized light) or with (2) both polarizer and analyzer inserted (i.e., under "crossed polars," the analyzer being at 90° to the polarizer). Observations are also made using air and oil immersion objectives. Color, reflectance, bireflectance, and reflection pleochroism are observed using linearly ("plane") polarized light; anisotropism and internal reflections are observed under crossed polars.

3.2.1 Color

A very small number of ore minerals are strongly and distinctively colored (e.g., covellite, bornite, gold; see Table 3.1), but most are only weakly colored and may appear to the beginner as white through various shades of gray.

TABLE 3.1 Minerals Distinctly Colored in Reflected Light

Color	Mineral Phases	Other Observations
Blue	Covellite	Intense pleochroism
	Chalcocite, Digenite	Weakley anisotropic
Yellow	Gold	Very high reflectance
	Chalcopyrite	Very weak anisotropy
	Millerite, Cubanite	Strong anisotropy
	Mackinawite, Valleriite	Strong pleochroism
Red-brown to brown	Bornite	Weak anisotropy
	Copper	Very soft, high reflectance
	Nickeloan Pyrite, Violarite	Isotropic
	Breithauptite	Anisotropic

However, with some practice, many of the subtle color differences become apparent. Although the eye is generally good at distinguishing minor color differences between associated phases, it has a poor "memory" for colors. A further problem is that the apparent color of a mineral depends on its surroundings (e.g., the mineral chalcopyrite appears distinctly yellow against a white or gray phase but a greenish-yellow when seen next to native gold). This phenomenon of "mutual color interference" means that it is important to see a mineral in a range of associations. Accordingly, the colors of minerals are best described in comparison with other common minerals with which they are often associated.

It is important for observers to make their own descriptions of colors, because of differences in the perception of color by different microscopists. It is also difficult to rely only on other observers' descriptions of colors; thus, the information given in Appendix 1 should be regarded as only a rough guide. Another reason for caution in using qualitative color descriptions is that colors are also dependent on the illumination employed (see Section 1.2.4) and will show subtle differences when different microscopes are used. When you begin work with a new instrument, it is necessary to "get your eye in" by examining a few common and easily identifiable minerals, some of which you may even recognize before you place the section under the microscope.

Two other cautionary notes regarding color concern the effect of tarnishing on color (e.g., bornite may appear purple rather than brown after a section has been left exposed to air) and of incorrect polishing procedures, particularly "overpolishing" (e.g., chalcopyrite, if overpolished, may appear white, although it will still exhibit its characteristic yellow color at grain margins and along fractures). Both these types of error are best eliminated by repetition of the final stages of polishing.

In Section 5.5, the problem of quantitatively representing color differences is discussed, and this both highlights the limitations of the qualitative approach and shows a direction in which future discussions of colors of minerals in polished section will probably progress. Reference to the chromaticity diagram shown as Figure 5.18, on which are plotted all of the common opaque minerals, again emphasizes the very limited range of color variation exhibited by them. However, as also further discussed in Chapter 5, the level at which the eye of the "average observer" can discriminate between such color differences is such that a separation can be achieved under ideal conditions.

3.2.2 Reflectance

The amount of incident light on a polished surface of a particular mineral that is reflected back to the observer depends on an important property of that mineral, its reflectance. The reflectance of a phase (what could colloquially be termed its "brightness") is a fundamental property that will be discussed in much greater detail in Chapters 4 and 5; it is a property that can be accurately measured using equipment added to the standard reflecting microscope and is defined on a percentage scale as

$$\text{Reflectance (R\%)} = \frac{\text{Intensity of reflected light } (\times 100)}{\text{Intensity of incident light}}$$

The reflectance of a phase may vary with its orientation (see the following), with the wavelength of light being reflected (i.e., the mineral may preferentially reflect certain wavelengths and hence be colored) and with the angle of incidence of the light (although in ore microscopy, illumination is always at effectively normal incidence).

Although the eye cannot "measure" reflectance, it is easy to arrange the minerals in a section in order of increasing reflectance by visual inspection. Given one or two readily identifiable phases, the reflectances of which can be easily checked (e.g., magnetite R% ~20; galena R% ~43; pyrite R% ~55), it is possible with a little experience to estimate the reflectances of "unknown" phases by comparison with these visual "standards." It is useful also to note that quartz gangue and many mounting plastics have reflectance values of ~5%. The reflectance values of the common ore minerals are given in Appendix 1.

A number of factors can cause confusion in the estimating of reflectance. Minerals that take a poor polish will appear of lower reflectance than those that polish well, even though reflectance values may be similar. Color, not surprisingly, may cause difficulties, since it arises as a result of the sampling by the eye of a range of light wavelengths of differing reflectances (see Chapter 4). One solution to this problem is to insert a filter to limit the light illuminating the section to a narrow range of wavelengths (say of "green" or "yellow" light). However, provided these problems are kept in mind, reflectance can be estimated by eye with sufficient accuracy to aid identification considerably.

3.2.3 Bireflectance and Reflection Pleochroism

Cubic minerals remain unchanged in reflectance and color on rotation of the stage, whatever the orientation of the grains. Most minerals of other crystal symmetries show changes in reflectance or color (or both) when sections of certain orientations are rotated. The change of reflectance is a property termed *bireflectance*, and the change of color (or tint) is a property called *reflection pleochroism*. However, the isometric (basal) sections of hexagonal and tetragonal crystals do not exhibit either of these properties and appear the same as cubic minerals. In addition to noting that either of these (or both) properties are shown by a mineral, it is usual to note the intensity with which the property is exhibited (very weak, weak, moderate, strong, very strong) and, in the case of reflection pleochroism, to note the colors observed in different orientations. Examples of minerals that show reflection pleochroism are listed in Table 3.2 and are illustrated in Figure 3.1.

The difference in maximum and minimum values of the percent reflectance is, of course, a measure of the bireflectance. Examples of minerals exhibiting strong bireflectance are graphite, molybdenite, covellite, stibnite, valleriite; moderate bireflectance is exhibited by marcasite, hematite, niccolite, cubanite, pyrrhotite; weak bireflectance is exhibited by ilmenite, enargite, arsenopyrite (see Appendix 1 and Table 3.2).

It is important to remember that both properties are a function of the orientation of the crystal relative to the polarized light beam, with various orientations showing anything from the maximum to no effect. When you are searching for weak to moderate bireflectance or pleochroism, it is useful to examine closely adjacent grains (e.g., along a twin plane) where the eye can distinguish small differences, less than 2% in reflectance under ideal circumstances.

TABLE 3.2 Examples of Minerals That Exhibit Reflection Pleochroism (in Air) and Bireflectance

Mineral	Color Range (Darker–Lighter)	Bireflectance Range (Approximate R% at 546 nm)
Covellite	Deep blue to bluish white	6–24
Molybdenite	Whitish grey to white	19–39
Bismuthinite	Whitish grey to yellowish white	37–49
Pyrrhotite	Pinkish brown to brownish yellow	34–40
Niccolite	Pinkish brown to bluish white	46–52
Cubanite	Pinkish brown to clear yellow	35–40
Valleriite	Brownish grey to cream yellow	10–21
Millerite	Yellow to light yellow	50–57
Graphite	Brownish grey to greyish black	6–27

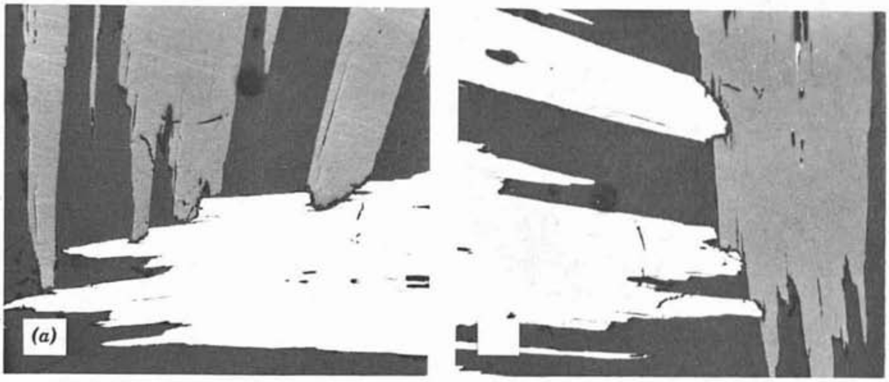

FIGURE 3.1 The properties of bireflectance and reflection pleochroism illustrated by the mineral covellite photographed in two orientations at 90° to one another in plane (linearly) polarized light. The darker gray blades in the black-and-white photographs are actually deep blue; the light blades are pale bluish white (width of field = 400 μm).

3.2.4 Anisotropism

When a polished surface of a cubic mineral is examined under crossed polars, it is found to remain dark (in *extinction*) in all positions of the stage, whatever the crystallographic orientation of the polished surface (in some cases, the section may not be completely dark but will nevertheless remain unchanged on rotation).[2] Such minerals are termed *isotropic*. Minerals that form crystals of lower-than-cubic symmetry will not remain unchanged as the stage is rotated for polished surfaces of most orientations; that is, they are *anisotropic*. Sections of certain special orientations of anisotropic phases may be isotropic (e.g., the basal sections of hexagonal and tetragonal crystals), but most will show variations in brightness or color, or in both, as the stage is rotated through 360°. As with bireflectance and pleochroism, the anisotropy can range from a maximum to zero (i.e., isotropic), depending on which section through the crystal has been polished. In a section showing anisotropy, there will be four positions, 90° apart, in one 360° rotation where the section is dark (in extinction) or at least shows minimum brightness. Between these (at ~45° to extinction positions) lie the positions of maximum brightness. Having noted that a mineral exhibits anisotropism, the first observation of the microscopist is of its intensity; again, the terms "very weak," "weak," "moderate," "strong," "very strong" are commonly used.

The colors exhibited by an anisotropic mineral on rotating the stage (*anisotropic colors*) may be of value in identification when used with caution, and some are quite distinctive (e.g., the deep green colors of marcasite). However, the colors are constant only if the polars are exactly crossed and change in a characteristic manner on uncrossing the polars for a particular mineral. Aside from the problems of qualitative color description discussed in Section 3.2.1, anisotropic colors may be sensitive to differences between microscopes and illumination systems. However, used carefully and with the microscopist maintaining consistent viewing conditions and compiling a set of personal observations, they are of value in identification.

As with bireflectance and pleochroism, it is important to examine a number of grains in a polished section to obtain orientations of maximum anisotropy; when the rock itself has an oriented fabric, it may be necessary to cut and polish further sections. Sometimes the combined effects of stage rotation and the anisotropism of adjacent grains make it difficult to determine whether a given grain is isotropic or weakly anisotropic. Such a determination may be more easily accomplished if the specimen is left stationary and the analyzer is slowly rotated 5–10° back and forth through its crossed position at 90° from the polarizer; this eliminates the distraction of movements while the microscopist is trying to observe minor variations in color or reflectance. A well-centered objective and the use of the field diaphragm to eliminate extraneous grains from the field of view also help.

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[2] Unfortunately there are occasional exceptions to this rule for reasons that remain obscure. A weak "anomalous anistropism" is sometimes shown by cubic minerals such as pyrite.

Note also that fine, parallel scratches left from incomplete polishing or careless buffing can produce effects that are similar to anisotropism and bireflectance. Such scratches are especially common in grains of soft minerals, such as gold and silver.

3.2.5 Internal Reflections

Some minerals examined in polished section are transparent, and others are completely opaque, with some being intermediate in their "opacity." Transparent phases are, of course, best studied in transmitted light. In polished sections, such phases may allow light to penetrate deep below the surface and to be reflected back to the observer from cracks or flaws within the crystal. Such light will appear as diffuse areas or patches, known as *internal reflections*. Both the occurrence of internal reflections and their colors may be of diagnostic value, the latter because certain wavelengths of the incident white light (see Section 4.1.1) are preferentially absorbed by the crystal that exhibits a characteristic "body color." For example, cassiterite shows yellow or yellow-brown internal reflections, and proustite shows ruby-red internal reflections. The nonopaque phases in a polished section may, under certain illumination conditions, be a mass of internal reflections.

Internal reflections are best seen under crossed polars with intense illumination; they may also be visible in linearly ("plane") polarized light. It is important to realize that many grains of a phase that could show internal reflections may not exhibit them and that a careful search must be made over the entire section. Isolated grains of magnetite and sphalerite have very similar optical properties and are often mistaken by students. The common presence of internal reflections in sphalerite and their absence in magnetite is a very useful aid in distinguishing between them. The visibility of internal reflections is also enhanced by using oil immersion objectives and by using high-power magnification; they are often best seen at the edges of grains or in small grains. Some examples of common ore minerals exhibiting internal reflections are given in Table 3.3, and the internal reflections exhibited by sphalerite are shown in Figure 3.2.

3.3 QUALITATIVE EXAMINATION OF HARDNESS

A detailed discussion of hardness and its quantitative determination is the subject of Chapter 6. As will be explained further, hardness is a complex property of a mineral, and the term "hardness" as used in ore mineralogy may refer to a number of phenomena. Three types of hardness are particularly important:

1. Polishing hardness
2. Scratch hardness
3. Microindentation hardness

TABLE 3.3 Examples of Minerals That Exhibit Internal Reflections

Mineral	Color of Internal Reflection
	Often Seen in Air, Strong in Oil
Sphalerite	Yellow to brown (more rarely to green to red)
Cinnabar	Blood red
Proustite-pyrargyrite	Ruby red
Rutile	Clear yellow to deep red-brown
Anatase	White to blue
Azurite	Blue
Malachite	Green
Cassiterite	Yellow brown to yellow
	Sometimes Seen in Air, Often in Oil
Hematite	Blood red
Wolframite	Deep brown
Chromite	Very deep brown

The third of these will be dealt with in Chapter 6 and forms the basis of quantitative hardness determination; the first two can be examined with the standard ore microscope by comparing the relative hardness of adjacent phases and can be very helpful in mineral identification. It is important to realize that these three forms of hardness are not entirely equivalent, being the response of the material to different kinds of deformation or abrasion.

3.3.1 Polishing Hardness

Polishing hardness is the resistance of a particular mineral to abrasion during the polishing process. The fact that hard minerals are worn away more slowly than soft minerals means that they may stand slightly above the surfaces of softer grains in the section—an effect known as *polishing relief*. Although in the preparation of a polished section (see Section 2.2) every attempt is made to minimize the amount of relief, the presence of some relief enables relative hardness to be estimated rapidly. This determination involves a simple test using the *Kalb light line*, which is a phenomenon analogous to the Becke line used in transmitted light work, although it is of *wholly different origin*. The procedure is as follows:

1. Focus on a clear boundary line between two mineral grains.
2. Lower the stage (or raise the microscope tube) so that the sample begins to go out of focus as the distance between the specimen and the objective increases.
3. Observe a "line" of light (cf. the Becke line) that will move toward the softer mineral, provided there is significant relief.

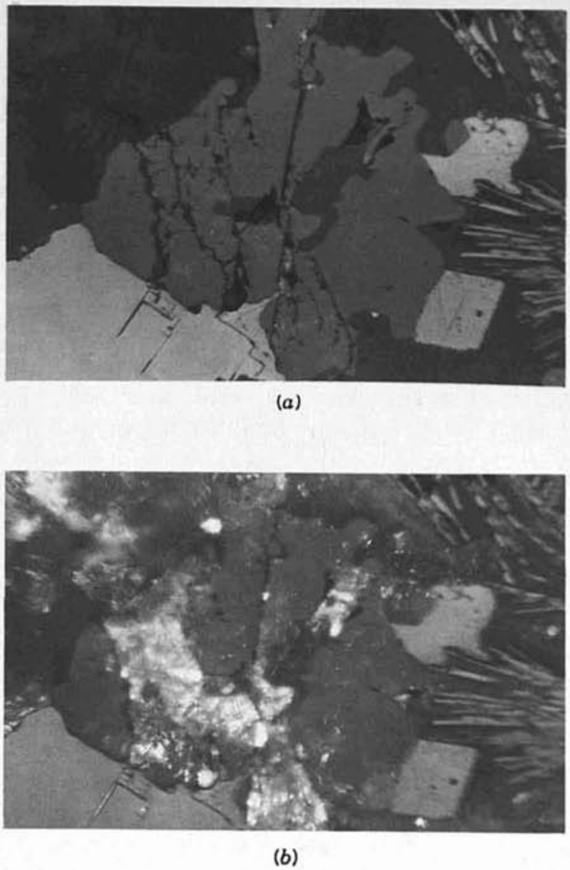

FIGURE 3.2 Internal reflections in sphalerite. (*a*) View in plane polarized light reveals a uniformly homogeneous sphalerite (light gray). (*b*) The same view under crossed polars reveals many internal reflections of variable intensity. (Madan District, Bulgaria (width of field = 1,200 μm).

The origin of the Kalb light line can be considered using Figure 3.3. At the junction between the soft and hard minerals, light can be reflected at non-normal incidence. This light is not apparent when the boundary area is in focus (focal plane F_1) but during defocusing to F_2 is seen as a line of light moving toward the softer mineral. It is important to realize that this effect will only be seen when there is significant relief and that this depends on the relative hardness of the adjacent grains and the method of polishing. Indeed, significant relief is only likely to be developed at boundaries between phases that show appreciable differences in hardness, (perhaps 50% or more). The ore minerals can be arranged in a sequence of increasing polishing hardness, although factors such as polishing method and state of aggregation of the mineral may slightly influence its position in such a table. Commonly, the

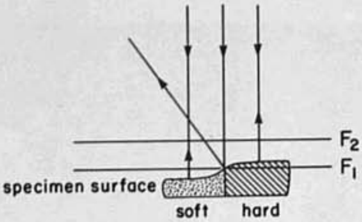

FIGURE 3.3 Cross section (schematic) of polished section surface showing origin of Kalb line at the boundary of two minerals of different hardness.

polishing hardness of a mineral is compared to one or several relatively abundant minerals (e.g., a sequence in which minerals are described as "less hard," "as hard," or "harder than" galena, chalcopyrite, or pyrite is sometimes used).

In favorable circumstances, polishing hardness can enable a fairly accurate estimate of the hardness of an unknown phase to be made.

3.3.2 Scratch Hardness

Although the perfect polished section is completely scratch-free, in practice the surface of a section always has some scratches. The relative amount of surface scratching and the depth of scratches that cross grain boundaries may, however, be used in favorable circumstances to estimate relative hardness. Although some soft minerals can acquire a smooth, brilliant polish (covellite, bismuthinite), others nearly always retain a scratched appearance (graphite, molybdenite, gold, silver). Some hard minerals readily acquire a smooth polish (arsenopyrite, ilmenite, niccolite), while others require much longer polishing (magnetite, wolframite, pyrite), although this also depends on the crystallographic orientation of the surface being polished. A scratch extending across the boundary between two minerals may indicate relative hardness by being more deeply incised in the softer mineral (Figure 3.4a). However, this test must be applied with caution, because deep scratches from an early stage of polishing may remain in a hard phase (pyrite, marcasite; see Figure 3.4b), even after they have been removed in an adjacent soft phase by later stages.

3.4 STRUCTURAL AND MORPHOLOGICAL PROPERTIES

Structural and morphological properties depend chiefly upon the crystal structure of the minerals and comprise (1) crystal form and habit, (2) cleavage and parting, and (3) twinning. They are, of course, an essential aspect of the textures of ore minerals and mineral assemblages, and are further discussed in Chapter 7. Their importance in mineral identification will be briefly considered here.

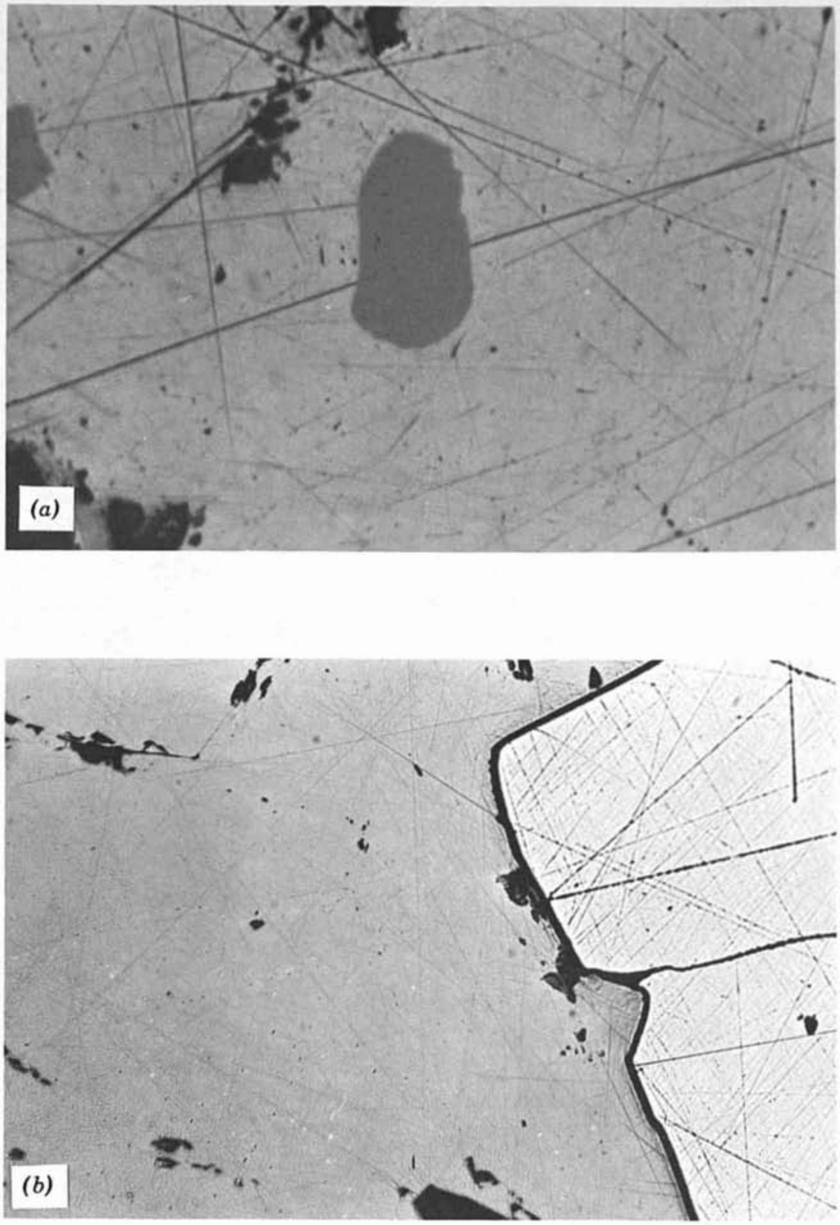

FIGURE 3.4 (*a*) Example of scratch hardness as a scratch extends from a softer mineral (galena) across a harder one (tetrahedite) and back to the softer one (width of field = 1,000 μm). (*b*) Residual scratches in pyrite (white) remaining after the scratches in the adjacent sphalerite have been removed in the last polishing steps (width of field = 2,000 μm).

3.4.1 Crystal Form and Habit

The full range of crystal forms and habits encountered in the study of minerals in hand specimen and thin section can also be seen in polished section, and the same terminology can be applied. Some minerals commonly develop well-formed crystals or *euhedra* (e.g., pyrite, arsenopyrite, magnetite, hematite, wolframite), whereas others are characteristically *anhedral* (e.g., chalcopyrite, bornite, tetrahedrite). In the average ore, the majority of minerals are not bounded by crystal outlines. It is important to remember that a polished surface only gives a two-dimensional view of a three-dimensional object; thus, for example, a cube may appear on a polished surface as a square, a rectangle, a triangle, or even an irregular pentagon.

All of the standard mineralogical terms used to describe crystal habit can be employed in ore microscopy (e.g., cubic, octahedral, tabular, acicular, columnar, bladed, fibrous, colloform, micaceous, prismatic; see Figures 3.1, 7.5, 7.9, etc.), and the observation of characteristic habit is a considerable aid in identification. Some common examples are

Acicular	Hematite, stibnite, jamesonite, rutile
Lath-shaped	Ilmenite, hematite
Tabular	Covellite, molybdenite, graphite, hematite
Rhombic	Arsenopyrite, marcasite
Skeletal	Magnetite (due to fast crystallization), galena
Isometric forms	Cube—galena, pyrite Octahedron—chromite, spinel, pyrite, magnetite, galena Pentagonal dodecahedron—pyrite, bravoite

Crystal habit can also be used to advantage in the identification of commonly associated gangue minerals (e.g., octahedra or cubes of fluorite, rhombs of dolomite and siderite, quartz euhedra of characteristic trigonal morphology).

3.4.2 Cleavage and Parting

Although cleavage or parting is a mineral property that is often readily seen in hand specimen or in a thin section of a translucent mineral, it is not as commonly observed in a polished section. It may often be more readily seen at an early stage of section preparation (say, after polishing with 6 μm diamond paste) than in the final specimen. Cleavage or parting is seen in polished section as one or more sets of parallel cracks, and, if three or more cleavage directions are present, parallel rows of triangular pits may be observed. Such pits are particularly characteristic of galena (see Figures 3.5a and 7.22) but may also be observed in magnetite, pentlandite, gersdorffite, and other minerals. The development of such pits depends not only on the method of polishing but also on the orientation of the section surface relative to the cleavage directions.

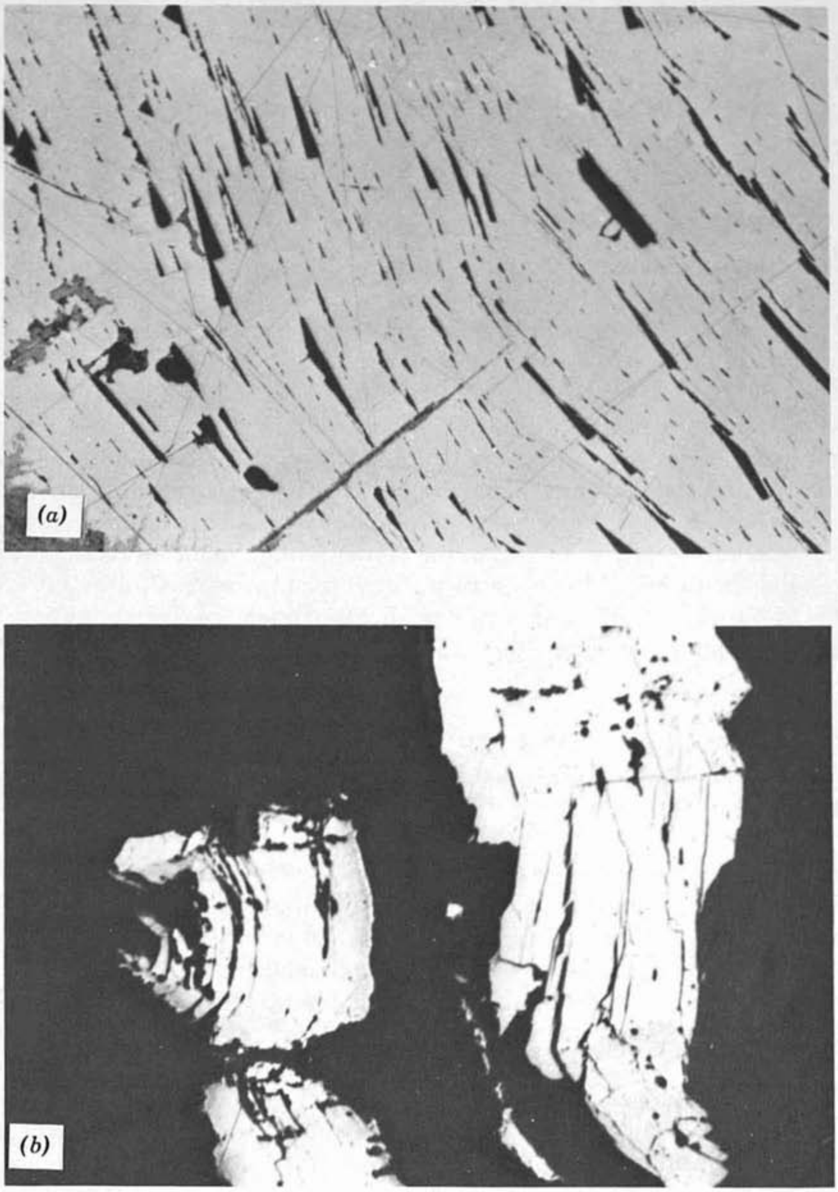

FIGURE 3.5 (*a*) Cleavage in galena shown by rows of triangular pits (width of field = 2,000 μm). (*b*) Cleavage in stibnite (width of field = 2,000 μm).

A prismatic cleavage gives diamond-shaped, triangular, or rectangular patterns; a pinacoidal cleavage gives a set of parallel cracks (see Figure 3.5b).

The cleavage of a mineral may not be evident at all in a carefully polished grain, and, if the material is fine-grained, it is unlikely to be evident at any stage of polishing. Cleavage is often more evident at the margins of grains and in certain cases may be beautifully brought out by weathering, some other form of alteration, or by etching. Fine examples of this include the alteration along cleavages of galena to cerussite, sphalerite to smithsonite, and chalcopyrite to covellite (see Figure 7.10b).

3.4.3 Twinning

As further discussed in Section 7.6, three major types of twinning—growth, inversion, and deformation—can be observed in opaque minerals. Generally, they cannot be seen in isotropic minerals unless the surface is etched (although they may often be evident in early stages of polishing) and are best observed in anisotropic minerals under crossed polars. Sometimes twinning may be evident from abrupt changes in the orientation of cleavages or lines of inclusions, or in cubic phases that show internal reflections under crossed polars. The crystallographic planes involved in twinning are usually not determinable in polished section; nevertheless, the twin patterns in some minerals are characteristic and of considerable value in identification. Examples include the "arrowhead" twins (growth twins) seen in marcasite, the lamellar twins (deformation twins) seen in hematite and chalcopyrite, and the inversion twins seen in stannite and acanthite (see Figure 7.19).

3.5 OTHER AIDS TO IDENTIFICATION (PHASE EQUILIBRIA, MINERAL ASSEMBLAGES, CHARACTERISTIC TEXTURES, AND ANCILLARY TECHNIQUES)

The properties discussed in this chapter as the basis for identification by visual inspection under the ore microscope are all essentially the properties of individual grains. However, the samples normally studied in polished section are made up of assemblages of minerals, and identification is greatly helped by considering the minerals as an assemblage rather than as isolated individual phases. Ore mineral assemblages can be profitably considered in terms of (1) known phase equilibria and (2) characteristic ore types. For example, numerous studies of sulfide phase equilibria have demonstrated that most sulfide ores have re-equilibrated on cooling and now represent assemblages that are stable at less than 100–200°C. The refractory sulfides—pyrite, sphalerite, arsenopyrite—are notable exceptions and often retain compositional and textural features from higher formational temperatures. For most copper, lead, silver, and nickel ores, however, the low-temperature phase diagrams provide a hint as to likely mineral associations. Thus, using the copper-iron-sulfur system (Figure 8.14) as an example, if pyrite and chalcopyrite are identified in a polymineralic mass, one might expect also to find one of the adjacent phases—either pyrrhotite or bornite—but not both (as this would violate the phase rule; see Vaughan and Craig, 1978). Oxide minerals, although more refractory than sulfides, also generally occur in assemblages similar to those shown in phase diagrams. Thus, one can reasonably expect to find hematite with magnetite or ilmenite, or both, but not with ulvöspinel (see Figure 9.12). The phase diagrams, therefore, provide a guide as to possible, but not necessary, mineral assemblages. They also provide an understanding of some textures (e.g., pentlandite exsolved from pyrrhotite, bornite exsolved from chalcopyrite, the growth of pyrite crystals in pyrrhotite) by revealing the extent and temperature dependence of mineral solid solutions.

The characteristic ore mineral associations and textural relationships discussed in Chapters 7–10 also provide valuable guides to mineral assemblages. For example, galena, sphalerite, and pyrite constitute a common assemblage in carbonate-hosted deposits, but tin minerals are virtually unknown in such ores. Pentlandite and chalcopyrite commonly occur with pyrrhotite, magnetite, and pyrite, but sphalerite and galena are rarely present. The recognition of one unusual mineral (e.g., a telluride or selenide) should prompt the observer to be on the lookout for others.

The weathering of ores may result in equilibrium assemblages (e.g., hexagonal pyrrhotite altering to monoclinic pyrrhotite or bornite altering to covellite) or disequilibrium ores (e.g., pentlandite altering to violarite or chalcopyrite altering to covellite). In the former case, phase diagrams and characteristic assemblages are useful guides; in the latter case, equilibrium phase diagrams are less useful but the characteristic assemblages are still useful.

3.6 CONCLUDING STATEMENT

The qualitative methods of identification discussed in this chapter enable many minerals to be recognized without recourse to other methods, given a little experience on the part of the microscopist. It is important to emphasize that undue reliance should not be placed on any single property, or any single grain, but that all of the information should be considered in attempting to reach a decision. To confirm an identification or to choose between a number of remaining alternatives, the quantitative methods discussed in Chapters 4 and 5 may be used. Before we turn to these methods, we will consider the origin of the optical effects seen using the reflected-light microscope.

REFERENCES

Ramdohr, P. (1980). *The Ore Minerals and Their Intergrowths*, 2nd ed. Pergamon Press, Oxford.

Uytenbogaardt, W., and Burke, E. A. J. (1971). *Tables for the Microscopic Identification of Ore Minerals.* Elsevier, Amsterdam. (Reprinted 1985 by Dover Publications, New York).

Vaughan, D. J., and Craig, J. R. (1978). *Mineral Chemistry of Metal Sulfides.* Cambridge University Press, Cambridge, England.

BIBLIOGRAPHY

Cameron, E. N. (1961). *Ore Microscopy*. John Wiley & Sons, New York.

Criddle, A. J., and Stanley, C. J. (eds.) (1986). *The Quantitative Data File for Ore Minerals of the Commission on Ore Microscopy of the International Mineralogical Association.* British Museum (Nat. Hist.), London.

Galopin, R., and Henry, N. F. M. (1972). *Microscopic Study of Opaque Minerals.* McCrone Research Association, London.

Ixer, R. A. (1990). *Atlas of Opaque and Ore Minerals in Their Associations.* Van Nostrand Reinhold, New York.

Picot, P., and Johan, Z. (1982). *Atlas of Ore Minerals.* BRGM, Orleans. (English translation by J. Guilloux and D. H. Watkinson.)