CHAPTER 1

THE ORE MICROSCOPE

1.1 INTRODUCTION

The ore microscope is the basic instrument for the petrographic examination of the large and economically important group of minerals referred to collectively as "ore" or "opaque" minerals. Although neither term is strictly correct (inasmuch as pyrite is opaque but rarely, if ever, constitutes an economically viable ore and sphalerite and cassiterite are important ore minerals but are not opaque), both terms are frequently used synonymously. The ore microscope is similar to conventional petrographic microscopes in the systems of lenses, polarizer, analyzer, and various diaphragms employed, but differs in that its primary method of illumination is a light source above the sample to allow examination by light reflected from polished surfaces. The increasing interest in ore-gangue relationships and the recognition that much textural information can be derived from the examination of translucent ore minerals in polished thin sections now commonly leads to the use of microscopes equipped for both reflected- and transmitted-light study. The discussion below is concerned specifically with the design and use of the standard components of the reflected-light microscope; further details of the transmitted-light and reflected-light microscopes are described by Cameron (1961), Bloss (1961), Galopin and Henry (1972), Piller (1977), Bowie and Simpson (1977), and Criddle (1990).

The variety of commercially available reflected-light microscopes tends to mask the basic similarities between them in terms of the arrangement of light source, lenses, diaphragms, reflector, objectives, and oculars. Some of this variety is evident in Figure 1.1, which shows research and student model microscopes. Modern microscopes are deliberately designed to be "modular,"

and commonly both reflected-light and transmitted-light components can be combined in one instrument. Each manufacturer incorporates unique design features into the ore microscopes they produce, and it is necessary for the reader to refer to the instruction manual accompanying a particular microscope for the exact placement and employment of the components described below and for information regarding other accessories.

1.2 COMPONENTS OF THE ORE MICROSCOPE

The components of the ore microscope and the light path from the illuminator to the observer's eye are summarized in Figures 1.2a–1.2c. Conventional orthoscopic examination may be conducted by using various types of reflec-

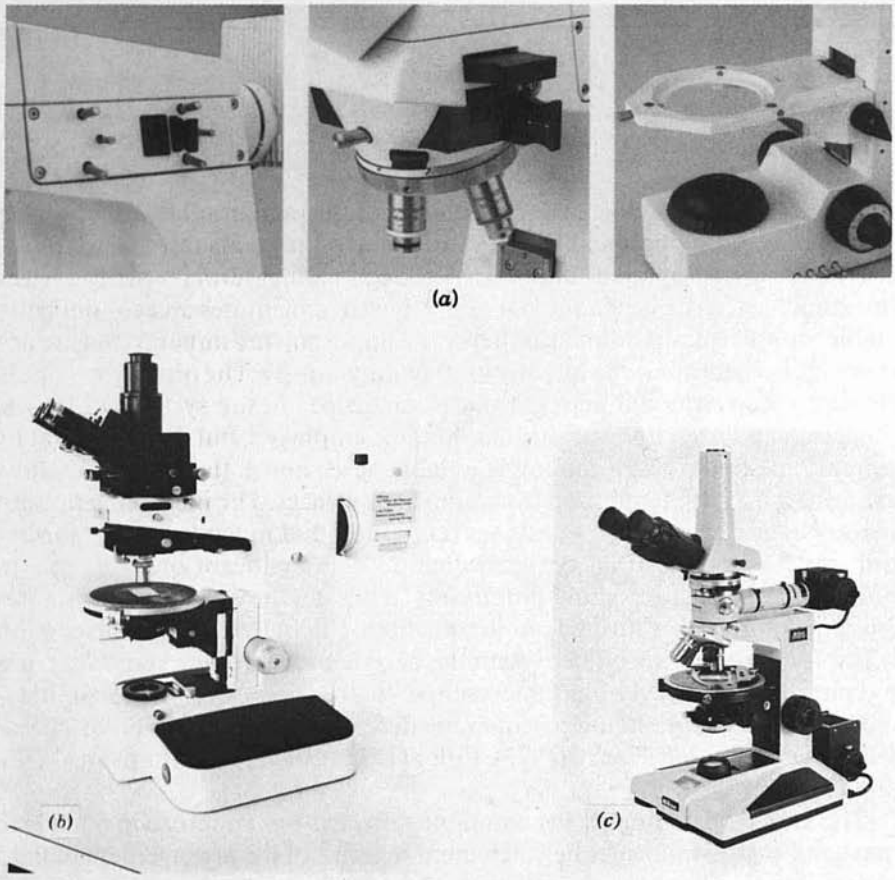
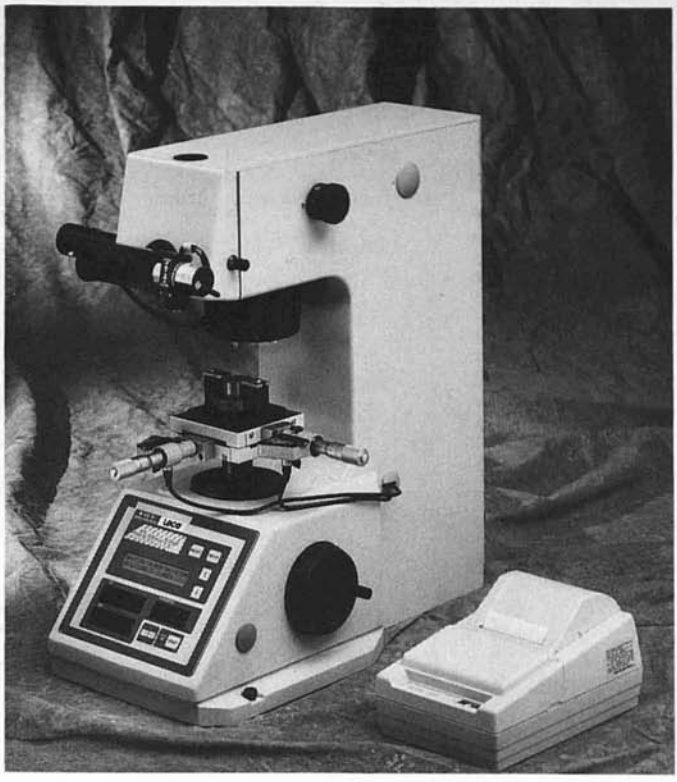


FIGURE 1.1 Representative instruments used in ore microscopy (all photographs courtesy of manufacturers): (*a*) Zeiss Axioplan universal research microscope; (*b*) Leitz Orthoplan-Pol microscope; (*c*) Nikon Optiphot-Pol microscope; (*d*) Leco M-400-H1 Automatic microhardness tester.



(d)

FIGURE 1.1 (*Continued*)

tors as shown in Figures 1.2a and 1.2b and further discussed in Section 1.2.5. Initial observations are made in plane-polarized light (better described in this work as linearly polarized; see Section 4.1), with only the polarizer inserted, and then under crossed polars when the analyzer is also inserted into the light path at right angles to the polarizer. Conoscopic observation may also be undertaken, by inserting the analyzer and the Bertrand lens (Figure 1.2c). If the microscope is not equipped with a Bertrand lens, the same effects may be observed by substituting a pinhole eyepiece for the ocular.

1.2.1 Rotatable Stage

The microscope stage, on which the polished sections are placed, should rotate freely, be perpendicular to the axis of light transmission through the microscope, and be centered relative to the objectives. Angular measurements can be made by means of the degree markings at the edge of the stage and the verniers provided. Most microscopes accept a mechanical stage equipped with X and Y movement for systematic examination or point counting of grains in specimens.

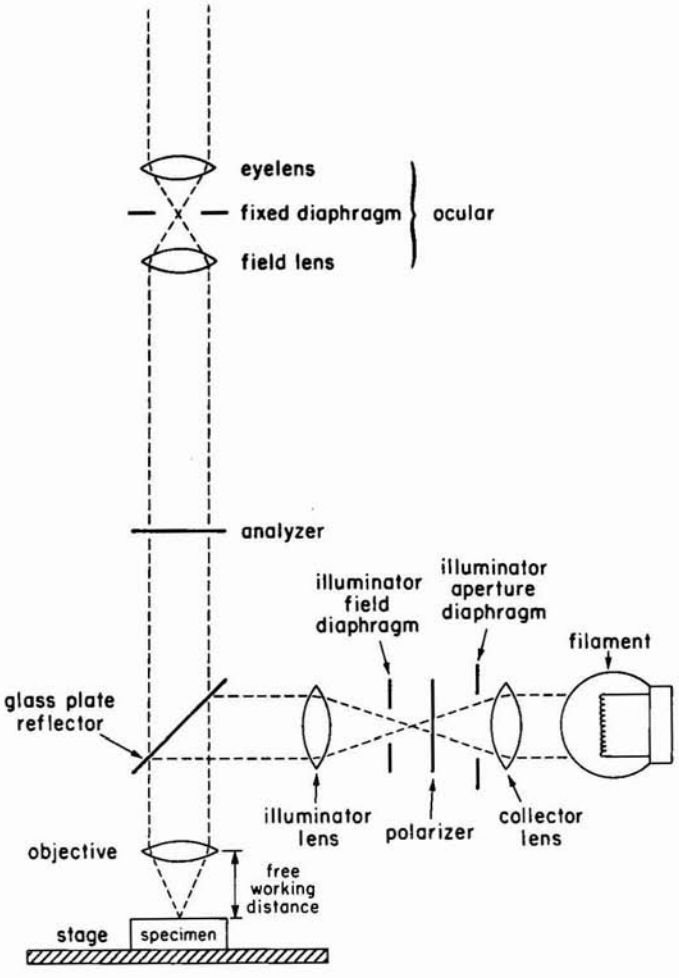


FIGURE 1.2 Schematic cross sections of microscopes illustrating essential components and the path of light through the systems involving (*a*) whole-field glass plate reflector; (*b*) half-field prism; (*c*) whole-field glass plate reflector for conoscopic viewing.

1.2.2 Objective Lenses

Microscope objectives may be classified in terms of lens type (achromat, apochromat, or fluorite), their magnification and numerical aperture, and whether they are for oil immersion or air usage. Occasionally, the focal length or working distance is also considered.

The *achromat* is the most common and least expensive lens found on most microscopes. It is corrected for spherical aberration for only one color, usually

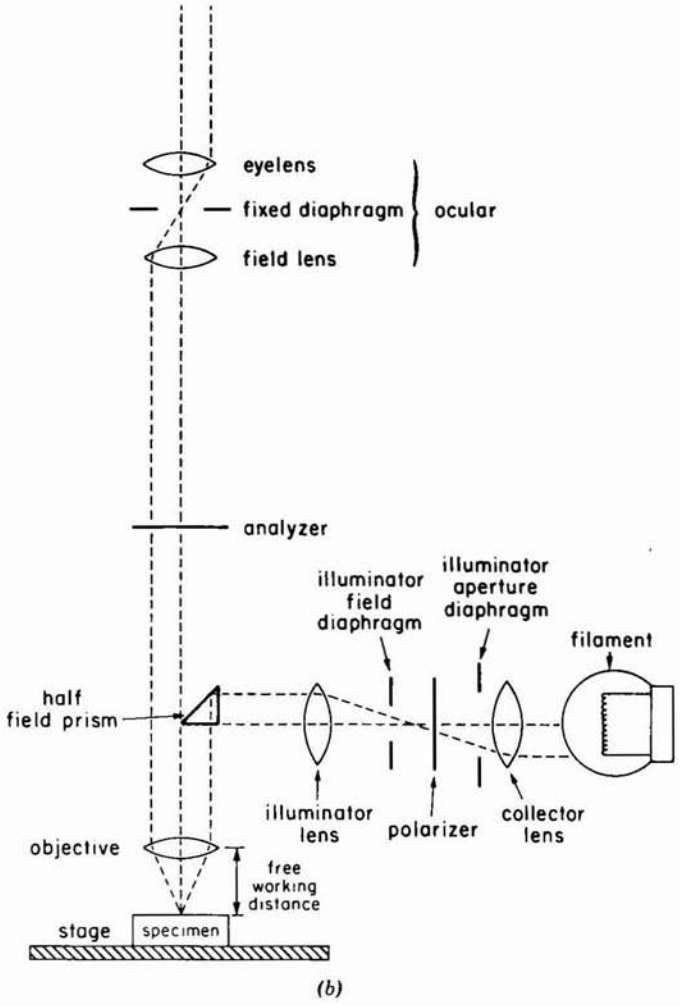
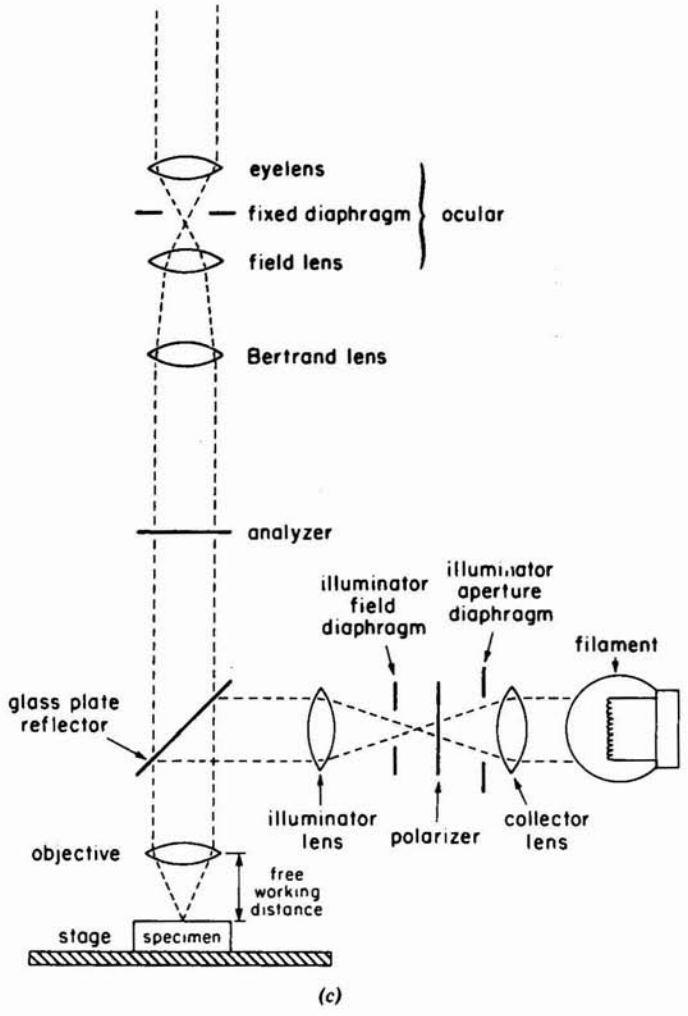


FIGURE 1.2 (*Continued*)

yellow-green, and for chromatic aberration for two colors. Thus, when used with white light, color fringes may appear at the outer margins of the image; when black-and-white film is used in photomicroscopy, the fringes may contribute to some fuzziness. However, if monochromatic light (especially green light) is used, the image, either to the eye or on a black-and-white film, is sharper.

The *apochromat* is a better and more expensive microscope objective. It is corrected for spherical aberration for two colors (blue and green) and for chromatic aberration for the primary spectral colors of red, green, and blue. Thus, the apochromat presents a sharper image and is better for color photo-



(c)

FIGURE 1.2 (*Continued*)

microscopy than any other lens. It can also be used for microscope photometry (see Chapter 5). To achieve the finest performance from apochromats, it is necessary to use them in conjunction with "compensating" eyepieces.

Fluorite lenses (also known as "semiapochromats") are a compromise in terms of price and quality between the other two types of lenses. Fluorite objectives must be used with compensating eyepieces for best performance.

Most objectives give a primary image in a curved plane; however, with additional corrections, these may be made to give a flat primary image. Such lenses are indicated by the prefix "flat-field" or "plan" and are especially useful for large fields of view and for photomicroscopy. In reflected-light micro-

scopy, it is also important to use objectives that are free from strain, as this can cause depolarization (or rotation; see Chapter 4) of the incident and reflected beam of polarized light. These objectives (designated "Pol" or by some other appropriate abbreviation) are necessarily expensive.

The *magnification* of an object is the degree by which the image is enlarged as light passes through the objective. The magnification is classified as 5X, 10X, 20X . . . up to about 125X. The projection of the primary image takes place within the body tube of the microscope, and the distance from the back focal plane of the objective to the primary image is the "optical tube length."

The *numerical aperture* (NA) is a measure of ability to distinguish fine structural details in a specimen and determines the depth of focus and the useful range of magnification. Mathematically this lies in the range 0.04–1.3 and is equivalent to the product of the refractive index (n) for the medium in which the lens operates and the sine of the angle (μ) equal to one-half of the angular aperture of the lens:

$$NA = n \sin \mu$$

The value of the NA is imprinted on the side of each objective, along with information on the magnifying power, type of correction applied, and whether it is an oil immersion lens. A 10X achromatic objective usually has an NA of 0.20 and a 20X objective of 0.40. Apochromatic objectives have higher NA values than achromats. The upper limit of the NA of a dry objective is 0.95, which corresponds to an angle of 70° as the maximum angle of incidence on the stage object (= 140° angular aperture). The maximum NA of immersion objectives that use an oil with a refractive index of 1.5 is about 1.4. Examples of the relationship between the angular aperture, initial magnification, and free working distance (FWD) of objectives are shown in Figure 1.3 and are summarized in Table 1.1.

The most commonly used low- and medium-magnification objectives for ore microscopic work are "*dry*" or *air* lenses, which are designed to have only air between the objective and the sample. It should be noted that objectives intended for transmitted light observation are corrected for use with specimens covered by a 0.17 or 0.18 mm "cover glass." These lenses may yield poor or distorted images if they are used for reflected-light microscopy.

Immersion objectives are commonly used for reflected-light microscopy, especially when high magnification and high resolution are required. Such lenses require a drop of immersion oil (usually with a refractive index of 1.515) between the sample and the objective; some objectives are designed for use with water instead of oil. The presence of the immersion medium (oil or water) reduces the reflectance of the minerals (see Section 4.1.2) but enhances color differences, reduces diffuse light scattering, and generally permits the observation of weak anisotropism and bireflectance (see Sections 3.2.3 and 3.2.4), which are not visible with dry objectives. The slight inconvenience of cleaning objectives and samples when using immersion objectives is generally more

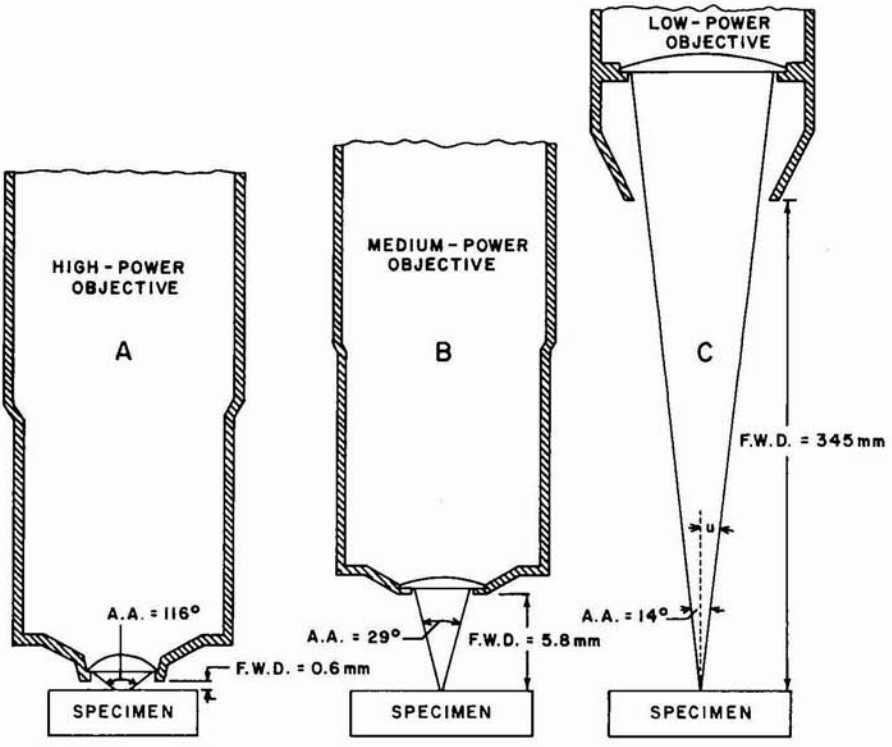


FIGURE 1.3 Comparison of the free working distances (FWD), angular apertures (AA), and one-half angular aperture (u) for typical objectives used in ore microscopy. (Reproduced from *An Introduction to the Methods of Optical Crystallography* by F. D. Bloss, Copyright © 1961, Holt, Rinehart and Winston, Inc., with the publisher's permission.)

than compensated by the increased information derived. Ramdohr (1969, p. 297) has summed up the value of immersion lenses in this statement: "It has to be emphasized 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." All immersion objectives have very short working distances; hence, great care must be taken in focusing so as not to damage the objective through collision with the sample. The immersion oils should be removed from lenses with solvents to prevent their gathering dust, and particular care should be taken to avoid unsuitable solvents that might damage the lenses. Water immersion objectives, which are so labeled, are especially convenient because of their ease in cleaning.

1.2.3 Ocular Lenses

The ocular or eyepiece system of the microscope serves to enlarge the primary image formed by the objective and to render it visible to the eye. Most micro-

TABLE 1.1 Properties of Five Objectives* Commonly Used in Ore Microscopy

Initial Magnification	Angular Aperture (AA)	Numerical Aperture (NA)	Free Working Distance (FWD) in mm	Focal Length in mm
5 × (oil)	7°	0.09	0.35	50
5 × (air)	10°	0.09	12	50
10 × (oil)	23°	0.20	14	25
20 × (oil)	31°	0.40	0.23	12.5
50 × (oil)	69°	0.85	0	2.0

*Ordinary objectives, separated by an air space from the object being viewed, are called "dry" objectives. This is in contrast to the more powerfully magnifying oil immersion objectives in which an immersion oil fills the gap between objective and object being viewed.

scopes are equipped with "Huygenian" oculars, of between 5X and 12X magnification, that consist of two lenses and an intermediate fixed diaphragm. The diaphragm commonly contains perpendicular crosshairs but may instead be equipped with a micrometer disk or a grid with a fixed rectangular pattern that is useful for particle size measurement or estimation. Oculars designed for photography do not contain crosshairs and are often designed to be of the "compensating" type to correct for chromatic aberration. Large research microscopes may have "wide-field" oculars, which are designed to give a larger, clear field of view.

1.2.4 Illuminating Systems

Two main types of lamp are commonly used in ore microscopes: the incandescent filament lamp and the gas discharge lamp. For most routine work, especially on student microscopes, the incandescent tungsten filament lamp is adequate. These lamps range from 6–12 V and 15–100 W, with minimum bulb lifetimes of 100–300 hours, and are generally operated by a variable rheostat. If the lamp is operated at too low a wattage, if the bulb is old, or if the microscope is misaligned, filament images and variably colored filament-shaped zones may be visible. Insertion of a frosted glass screen helps to eliminate the image, but microscope adjustment or even servicing may be required. The lamp should provide adequate light, evenly distributed throughout the field of view, without being uncomfortable to the eyes. The color temperature of tungsten filament lamps varies from about 2850°K for 6 V, 15 W bulbs to about 3300°K for halogen gas-filled 12 V, 100 W bulbs. These temperatures are far below the approximately 6100°K color temperature of xenon discharge lamps and, if used without filters, tend to bias the colors observed under the microscope toward the yellows and reds. Accordingly, most workers insert a pale blue filter between the lamp and the remainder of the illuminating system to provide a more daylight-like color temperature. The minor variations in the colors of the same minerals when viewed through different microscopes is due in large part to small differences in the effective color tem-

perature of the light source. Knowledge of the actual color temperature of the lamp is not important in routine polished-section examination, but it is important in photomicroscopy because of the specific requirements of different types of film. It is also important when measuring the color of minerals quantitatively, since the color observed is partly a function of the light source (see Chapter 5).

The standard illuminating system (Figures 1.2a–1.2c) contains two lenses, two or three diaphragms, and a polarizer, in addition to the light source. The illuminator aperture diaphragm is used to reduce stray scattered light. The illuminator field diaphragm controls the angle of the cone of light incident on the specimen and should be set to just enclose the field of view; this restricts the light to the most parallel rays, minimizes elliptical polarization (see Chapter 4), and maximizes the contrast. In many microscopes, a third diaphragm helps sharpen the image.

Reflectance measurement, although sometimes carried out using standard low-wattage incandescent filament lamps, usually requires either high-intensity halogen filament incandescent lamps or xenon discharge lamps to provide sufficient light intensity through monochromators in the range 400–700 nm (see Chapter 5).

1.2.5 The Reflector

The reflector is a critical component of the ore microscope, being the means by which light is brought vertically onto the polished specimen surface. Reflectors are of three types: the coated 45° plane-glass reflector (Figure 1.2a; Figure 1.4a), the Smith reflector (Figure 1.4b), and the totally reflecting prism (Figure 1.2b; Figure 1.4c).

When the coated 45° plane-glass reflector is employed (Figure 1.4a), part of the light from the illuminator is reflected downward through the objective onto the sample and part of the light passes through the reflector and is lost. The light that passes downward is then reflected back up through the objective until it reaches the reflector again. At this point, some of the light passes through the reflector up the microscope tube to the ocular and some is reflected back toward the illuminator and is lost. Ideally, the glass plate, coated with a semireflecting material of high refractive index, should reflect all of the light from the illuminator down onto the specimen but then should let all of the light reflected from the specimen pass through on its way up to the ocular. In fact, coated 45° plane-glass reflectors of maximum efficiency result in only about 19% of the illuminator light that first reached the reflector ultimately reaching the ocular. This efficiency is sufficient for most light sources; moreover, only with this type of reflector is there truly vertically incident light and illumination over the full aperture of the objective. However, reflectors of this

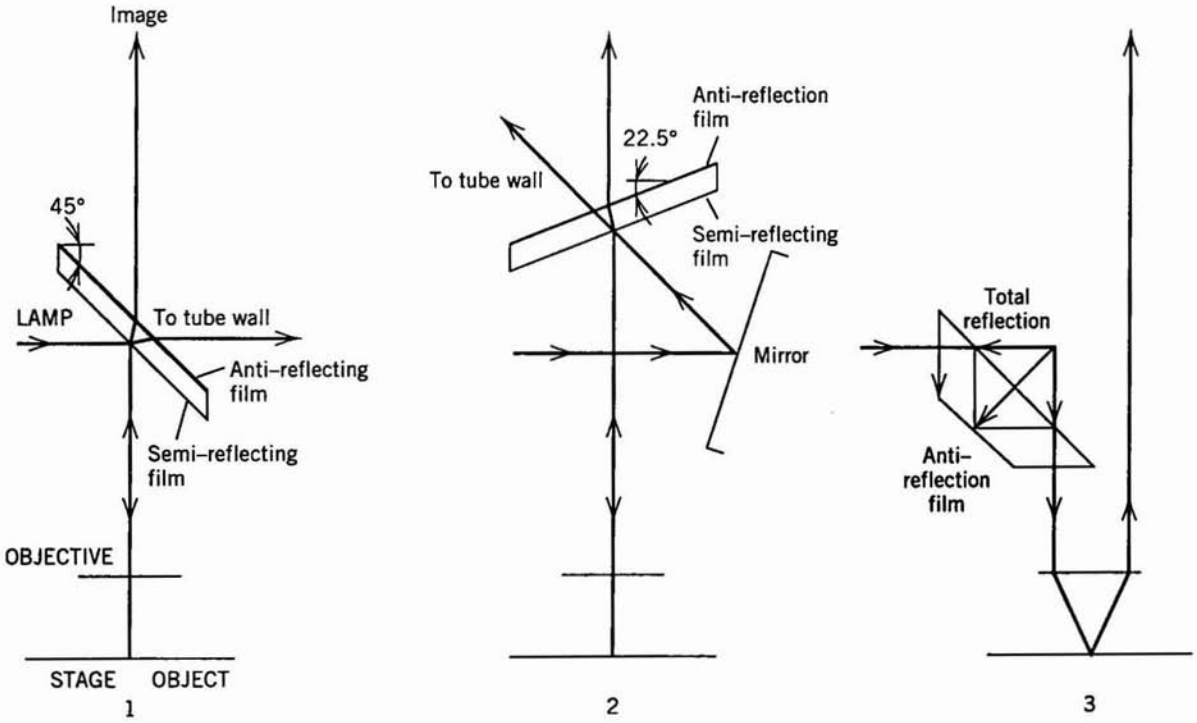


FIGURE 1.4 Schematic illustration of the three reflector units: 45° plane-glass (1); Smith (2); totally reflecting prism (3).

kind do not produce a perfectly dark field when the polars are crossed on isotropic specimens due to some rotation of the incoming beam of polarized light (see Chapter 4).

The Smith reflector (Figure 1.4b) involves light entering so as to fall on a mirror at an angle of 22.5°, from which it is reflected at the same angle onto a glass plate. This plate functions in the same way as the coated 45° plane-glass reflector, although its efficiency as a reflector is slightly less. However, the incident beam of polarized light is subject to less rotation (see Chapter 4), and an isotropic sample between crossed polars appears uniformly dark.

The totally reflecting prism system is one in which light is reflected downward through one-half of the aperture of the objective, strikes the specimen, is reflected back upward through the other half of the objective, and passes behind the prism on its path to the ocular (Figure 1.4c). In this situation, light is obliquely incident on the specimen. In conoscopic observation, only half of the polarization figure is visible, because half of the optical path is occupied by the prism. The advantage of the prism is that it permits a greater proportion of light (up to ~50%) to reach the ocular. Modern intense light sources now make the use of the prism less important. In addition, the early models of totally reflecting prisms and mirrors introduced some elliptical polarization, but these problems have been overcome by the development of multiple reflecting prisms and the introduction of polaroid plates on the lower face of the prism. Most workers find the plane-glass reflector adequate or superior for routine studies.

1.2.6 Polarizer and Analyzer

The polarizer in a standard ore microscope is usually positioned within the illuminating system between the lamp and the collector lens but may be located between the diaphragms. It is either a calcite prism or, more commonly, a polaroid plate that permits only the passage of light that is plane (or "linearly," see Chapter 4) polarized, usually in a North–South orientation. In standard transmitted-light thin-section or grain mount petrography, the polarizer and analyzer are perpendicular to one another. However, many ore microscopists find that polarization effects are more readily observed if the polars are a few degrees from the true 90° position. This is especially true of very weakly anisotropic minerals and even some moderately anisotropic grains if they occur in a matrix of more strongly anisotropic minerals. The slight uncrossing may be accomplished either by having a rotatable analyzer or by slightly adjusting (by 3–5°) the polarizer from the crossed position. Rotation of the microscope stage to observe anisotropism and extinction is not always unambiguous, because of the combination of movement and the variable anisotropism of adjacent grains. Alternatively, the stage may be left stationary and the analyzer rotated back and forth through the extinction position. This eliminates the distraction of movement of the specimen and may allow an unequivocal determination of the presence or absence of anisotropism (see Chapter 3).

1.3 ACCESSORIES

1.3.1 Monochromators

Because the optical properties of minerals vary as a function of wavelength, it is frequently necessary to provide incident light of specified wavelength. The operable range of most microscopes extends several hundred nanometers above and below the visible light range of approximately 400–700 nm wavelength. The two most commonly employed means of providing light of specified wavelength through this region are fixed monochromatic interference filters and continuous-spectrum monochromators (see Figure 1.5). Fixed interference filters consist of a glass substrate on which alternating layers of low-reflecting transparent dielectric substances and higher-reflecting semitransparent metal films or dielectrics of high refractive index have been deposited. The light that passes through such filters is not truly monochromatic but lies within a specified bandwidth, usually <15 nm if "narrow" band type and 15–50 nm if "broad" band type. The difficulty with such interference filters is that a separate filter is needed for each wavelength to be investigated.

The continuous-spectrum monochromator is an interference filter for which the wavelength of light transmitted varies continuously along the filter. A window, the width of which may be varied to control the passband width, is employed so that the monochromator may be slid along to whatever wavelength is desired. In this way, a single device may be used to provide monochromatic light over the entire visible range and even beyond. Some commercially available units for reflectance measurement are designed to fit directly onto the microscope and have built-in adjustable monochromators. Otherwise, the monochromator must be installed in the light path, usually immediately after the illumination source or immediately before a photometer that attaches to, or replaces, the ocular (see Chapter 5).

1.3.2 Photometers

Photometers, either built into large research microscopes or available as attachments to standard microscopes (Figure 1.5), are used to measure the reflectance of mineral grains. Most photometers consist of a photomultiplier tube that has high sensitivity throughout the visible spectrum. To achieve meaningful results, photometers must be used in conjunction with stabilized light sources, high-quality monochromators, and reflectance standards. The use of photometers in quantitative reflectance measurement is treated in detail in Chapter 5.

1.3.3 Stage Micrometers

All textural studies of ore minerals, mill products, and industrial materials require the accurate measurement of grain sizes. The stage micrometer, usu-

ally a 1 mm scale subdivided into hundredths, is invaluable in estimating grain sizes and in the calibration of a scale or grid set within an ocular. Stage micrometers are commercially available as small mounted metal disks on which the scale has been inscribed; they are positioned and observed in the same way as the polished section.

1.3.4 Sample Holders

Observation under the ore microscope requires that the sample surface be perpendicular to the incident light beam. This can be accomplished by carefully machining samples so that the top and bottom surfaces are flat and parallel or by using simple mechanical leveling devices (Figure 1.6a) that press the sample down on a lump of molding clay on which it then is held level (Figure 1.6b). More sophisticated devices include spring-loaded cylinders (Figure 1.6c), in which the specimen is held against a lip that is machined parallel to the microscope stage, and more elaborate rapid specimen changers, in which specimens are spring-loaded into holders that are held by leveling screws. The means of securely holding a specimen with its polished surface normal to the incident light beam is a matter of personal convenience and equipment availability.

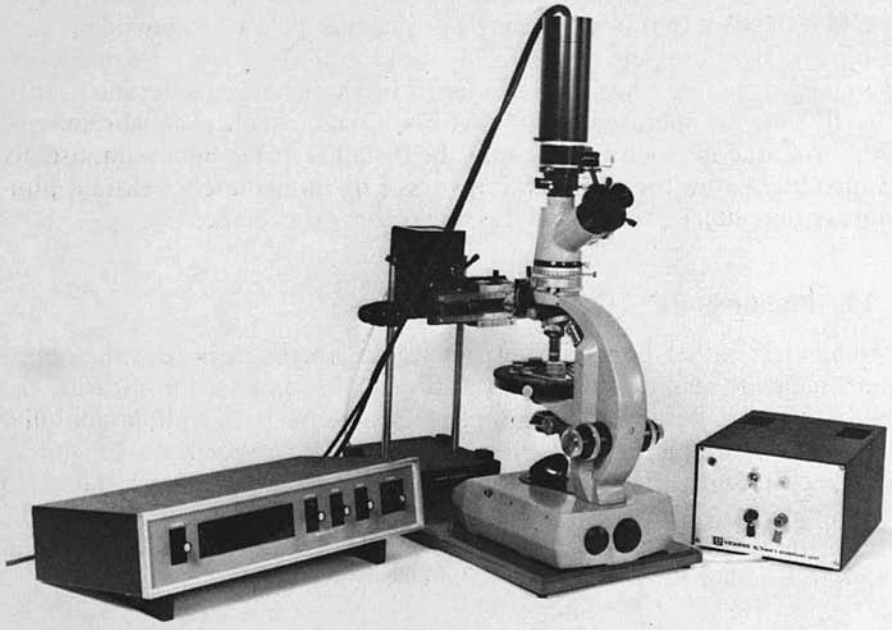
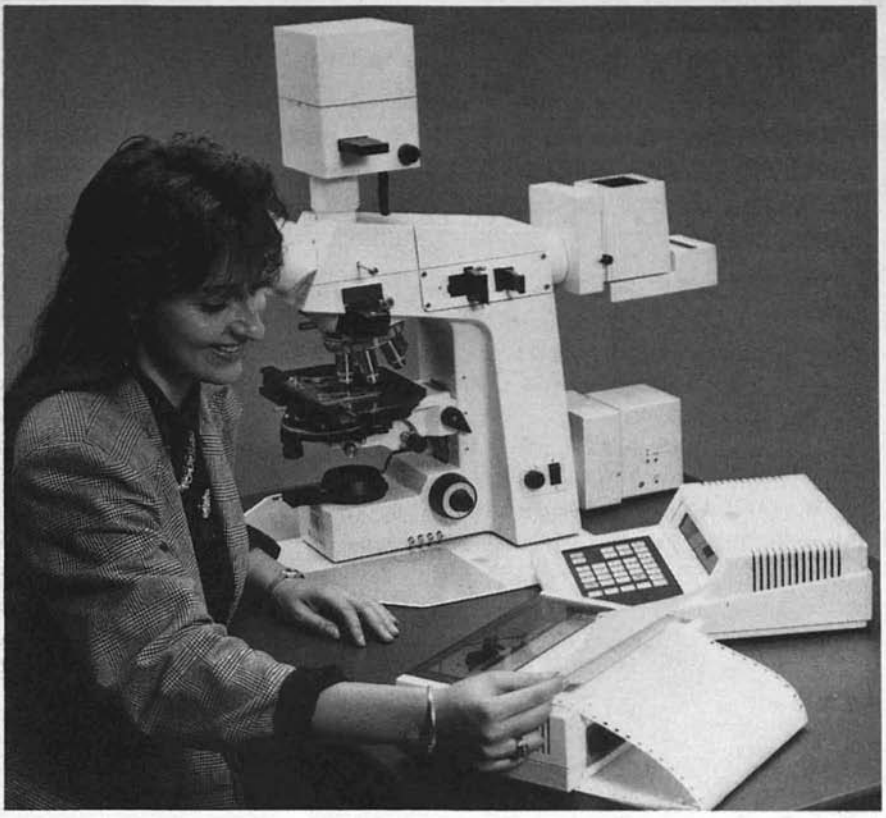


FIGURE 1.5 (*a*) Microphotometer system mounted on Vickers M74c microscope; also shown is continuous-spectrum monochromator mounted in front of the light source. (*b*) Zeiss microscope photometer system MPM mounted on the universal research microscope. (Photographs courtesy of manufacturers.)



(*b*)

FIGURE 1.5 (*Continued*)

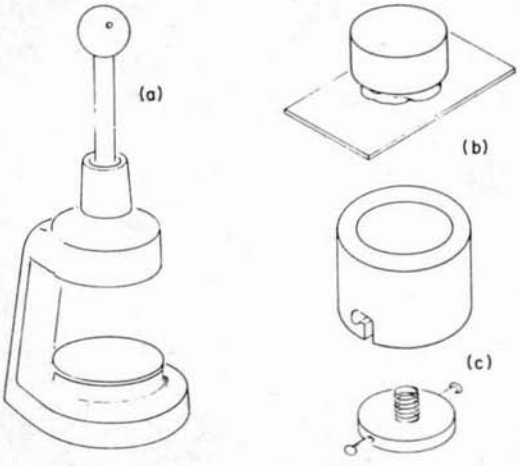


FIGURE 1.6 Specimen-mounting systems: (*a*) hand press for specimen mounting; (*b*) clay on glass plate system; (*c*) spring-loaded holder.

REFERENCES

Bloss, F. D. (1961). *An Introduction to the Methods of Optical Crystallography*. Holt, Rinehart and Winston, New York.

Bowie, S. H. U., and Simpson, P. R. (1977). Microscopy: Reflected Light. In J. Zussman (ed.), *Physical Methods in Determinative Mineralogy*, 2nd ed. Academic, London, pp. 109–166.

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

Criddle, A. J. (1990). The Reflected-Light Polarizing Microscope and Microscope Photometer. In J. L. Jambor and D. J. Vaughan (eds.), *Advanced Microscopic Studies of Ore Minerals*. Mineralogical Association of Canada Short Course Handbook, Vol. 17, pp. 1–36.

Galopin, R., and Henry, N. F. M. (1972). *Microscopic Study of Opaque Minerals*. W. Heffer and Sons, Ltd., Cambridge, England.

Piller, H. (1977). *Microscope Photometry*. Springer-Verlag, Berlin.

Randohr, P. (1969). *The Ore Minerals and Their Intergrowths*, Pergamon, New York.