CHAPTER 11

APPLICATIONS OF ORE MICROSCOPY IN MINERAL TECHNOLOGY

11.1 INTRODUCTION

The extraction of specific valuable minerals from their naturally occurring ores is variously termed "ore dressing," "mineral dressing," and "mineral beneficiation." For most metalliferous ores produced by mining operations, this extraction process is an important intermediate step in the transformation of natural ore to pure metal. Although a few mined ores contain sufficient metal concentrations to require no beneficiation (e.g., some iron ores), most contain relatively small amounts of the valuable metal, from perhaps a few percent in the case of base metals to a few parts per million in the case of precious metals. As Chapters 7, 9, and 10 of this book have amply illustrated, the minerals containing valuable metals are commonly intergrown with economically unimportant (gangue) minerals on a microscopic scale.

It is important to note that the grain size of the ore and associated gangue minerals can also have a dramatic, and sometimes even limiting, effect on ore beneficiation. Figure 11.1 illustrates two rich base-metal ores, only one of which (11.1b) has been profitably extracted and processed. The McArthur River Deposit (Figure 11.1a) is large (> 200 million tons) and rich (> 9% Zn), but it contains much ore that is so fine grained that conventional processing cannot effectively separate the ore and gangue minerals. Consequently, the deposit remains unmined until some other technology is available that would make processing profitable. In contrast, the Ruttan Mine sample (Fig. 11.1b), which has undergone metamorphism, is relatively coarse grained and is easily and economically separated into high-quality concentrates.

Most mineral beneficiation operations involve two principal stages. The first of these is reduction in size of the particles of mined ore (which may
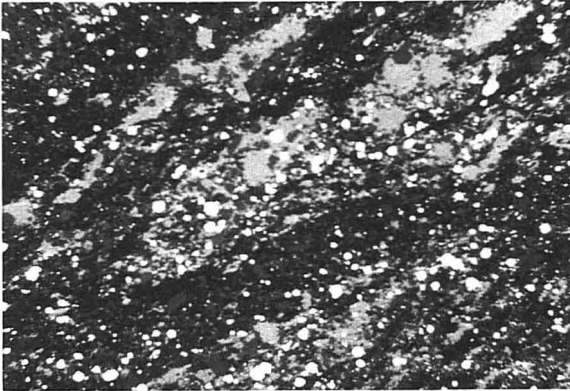
(a)

(b)

FIGURE 11.1   Differences in grain size reflect the origin and history of a deposit and may affect the comminution and recovery of an ore. (a) Very fine-grained sphalerite and pyrite that are difficult to separate and recover prevented efficient processing of the rich (9% Zn) and large (>220 million tons) but unmetamorphosed McArthur River Deposit, Australia. (b) Metamorphism recrystallized and coarsened the pyrite, sphalerite, and galena in the ores of the Ruttan Mine, Canada, and permitted easy separation and recovery (width of field = 1,200 μm, the same in both photographs).

initially be blocks up to several meters in diameter) to a size that is as close as possible to that of the individual metal-bearing mineral particles. This process of *comminution* achieves the *liberation* of valuable minerals from the gangue and, in the case of complex ores, liberation of different valuable minerals from one another. Since the size reduction required to achieve liberation is commonly down to a few hundreds of microns or less in diameter, extensive crushing followed by grinding (or *milling*) of the ores is required. The second stage in beneficiation is that of *mineral separation*, in which the valuable minerals are removed as a *concentrate* (or *concentrates*) and the remaining, commonly value-

less materials (the *tailings*) are discarded. This separation is usually achieved by exploiting differences in the physical, chemical, or surface properties of ore and gangue minerals. For example, the fact that many metalliferous ores are more dense than associated gangue minerals can be exploited by using heavy media for separation or other methods of gravity concentration, such as mineral jigs or shaking tables. The fact that certain ore minerals are strongly attracted by magnetic fields (e.g., magnetite, monoclinic pyrrhotite) or exhibit metallic or semiconducting electrical properties can be exploited in certain magnetic and electrical methods of separation. However, the most widely employed method of separation is *froth flotation*, in which the surface chemistry of fine ore particles suspended in an aqueous solution is modified by addition of conditioning and activating reagents to be selectively attracted to fine air bubbles that are passed through this suspension or *pulp*. These air bubbles, with the associated mineral particles, are trapped in a froth that forms on the surface of the pulp and can be skimmed off to effect the separation.

The technical details of the various comminution and separation methods are beyond the scope of this book and can be obtained from works by Pryor (1965), Gaudin (1957), and Willis (1992). However, in the study of the mined ores and the products of various stages of the comminution and separation processes, ore microscopy has a very important industrial application. It facilitates the identification of the valuable minerals and of minerals that may prove troublesome during beneficiation or during later stages of extraction. It also provides information on the sizes of particles, the nature of their intergrowth, and the nature of the boundaries ("locking") between them. The efficiency of comminution and separation techniques can be monitored at any stage by the examination of mounted and polished products under the ore microscope. Thus, from the initial assessment of the commercial exploitability of a prospective ore through the planning of a processing plant, the setting up of a pilot plant, and the first efficient operation of the full-scale beneficiation scheme, a vital role is played by the ore microscopist.

Certain ores, rather than undergo the complete processes of comminution and physical particle separation described previously, may have the valuable metals removed from them by chemical dissolution. For example, gold may be dissolved by cyanide solutions, or copper in the form of copper sulfides may be dissolved (*leached*) by acid solutions. When crushing and grinding of the ores is required to expose the minerals to the action of the solutions, ore microscopy is again important in planning and monitoring efficient cyanidation or acid leaching. The technologies of such processes lie more in the general field of metallurgy than that of mineral beneficiation, although the term *mineral technology* can be taken to embrace all of them. In this chapter, the applications of ore microscopy in mineral technology will be considered. Although the products of the roasting and smelting of ores that follow beneficiation are sometimes substances with no natural (mineral) equivalents, the techniques of ore microscopy remain applicable.

Further information on the subject discussed in this chapter may be found in works by Schwartz (1938), Edwards (1954), Gaudin (1957), Amstutz (1961), Rehwald (1966), Ramdohr (1969), and Hagni (1978). The range of textural information that is required in mineral beneficiation and obtainable primarily from ore microscopy is summarized in Table 11.1.

11.2 MINERAL IDENTIFICATION IN MINERAL BENEFICIATION

The techniques described in earlier chapters of this book (Chapters 3, 5, and 6) can all, of course, be applied in the identification of opaque minerals in both untreated ores and products of various stages of comminution or separation. The first concern in the untreated ore is identification of phase(s) that carry the valuable metal(s), since the initial information available is commonly only a bulk chemical analysis of the ore. This analysis provides no information on the mineral phases present nor on their sizes and textural relations; it is possible for different mineral associations to yield very similar bulk analyses. For example, nearly all zinc ores contain sphalerite as the only or principal zinc-bearing phase. In rare, but sometimes important deposits (e.g., Sterling Hill, New Jersey), the zinc is held as zincite (ZnO) or willemite (Zn_2SiO_4), or both. Another possible significant zinc phase is gahnite ($ZnAl_2O_4$). Each of these zinc minerals has the potential to form ores, but their different physical properties make their processing and the extraction of zinc very different. Hence, the determination of the type of metal-bearing phase(s) is critical.

As outlined by Schwartz (1938) and by Ramdohr (1969), the precise identification and characterization of the ore minerals can save a great deal of work in the establishment of an efficient beneficiation system. Examination of the untreated ore will enable the assessment of the feasibility of using density, magnetic, or electrical methods of separation, since such properties are well characterized for most minerals. However, fine intergrowths of dense ore minerals with gangue phases can result in ranges in specific gravity and loss of valuable metals or dilution of concentrate.[1] Similar problems can arise from fine intergrowths of "magnetic" and "nonmagnetic" phases (e.g., removal of ferrimagnetic magnetite and pyrrhotite from the nickel-bearing pentlandite in the Sudbury ores may result in nickel losses due to fine pentlandite flames in the pyrrhotite). The flotation properties of most ore minerals have also been extensively studied, so identification is an important first step in the application of this separation method. However, flotation behavior can be very adversely affected by oxide coatings or by tarnishing of ore mineral grains; such coatings may be detected under the microscope and either removed by acids prior to flotation or subjected to flotation using different reagents. Inefficient

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[1] When certain methods of separation are used, such material may appear in a third, intermediate fraction that is between concentrate and tailings in composition and is termed the "middlings."

TABLE 11.1   Information Available from Mineralogic Studies

Compositional or Mineralogic Data

Subdivided into
    Metallic ore minerals (and/or)
    Nonmetallic ore minerals
    Nonore metallic (pyrite, etc.)
    Gangue minerals
With special reference to (selection of examples)
    Specific gravity
    Solubility
    Radioactivity
    Magnetic properties
    Cleavability (sliming properties, sheeting and coating properties, such as sericite, clays, talc, covellite, etc.)
    New phases in artificial products (slags, mattes, speisses, sinters, etc.)
    State of oxidation
    Objectionable minerals (minerals with P, S, As in certain iron ores or Bi in lead ores, etc.)
    Chemical composition of minerals (other elements contained in solid solution, like Fe in sphalerite, Ag in tetrahedrite, etc.)
    On the basis of the aforementioned information, the best method of concentrating can be chosen.
    Compositional changes to be expected in the wall rock, in adjacent zones (oxidation, enrichment, leaching, etc.), or at depth, which will bear on the milling operations, as mining proceeds

Geometric Data (Textures and Structures)

Of
    Metallic ore minerals (and/or)
    Nonmetallic ore minerals
    Nonore metallic minerals
    Gangue minerals
With special information on
    Locking types (including such data as tarnish, coating, veining, etc.), porosity, pitting, etc.
Quantitative data
    Amounts of metallic ore minerals (and/or)
    Amounts of nonmetallic ore minerals (and/or)
    Amounts of nonore metallic minerals (and/or)
    Amounts of gangue minerals
With quantitative information on the qualitative and geometric properties listed above, for example,
    Relative grain size or particle size
    Relative size of locking
   Relative amounts of locking (as a whole)
    Relative proportions of individual minerals in the locked particles (middlings)
Chemical analyses of samples (tailings, ores, concentrates, etc.), estimated or computed on the basis of the particle counting data

separation by flotation also occurs when the particles consist of grains of more than one mineral phase that are "locked" (bound in some manner) together; the result is either loss of ore mineral or contamination by the attached grains (Figure 11.2). Special problems may also arise with ores that contain complex minerals (e.g., minerals of the tetrahedrite group, although dominantly copper sulfosalts, may contain high contents of zinc, mercury, or silver that will appear in the concentrate). As well as assessment of the problems of mineral separation following mineral identification, the efficiency of separation can be monitored by examination of products at the various stages of beneficiation. In this regard, it is important that tailings as well as concentrates be thoroughly studied. Identification and characterization of the ore minerals is also important for subsequent metallurgical processing; for example, titanium is more difficult to extract from ilmenite than from rutile.

The identification and characterization of the gangue minerals, which may include worthless opaque phases, is also very important. These materials may have economic potential, and their behavior during ore processing must be assessed. Particularly important is the identification (and subsequent removal, in some cases) of impurities that may adversely affect the efficiency of later concentration or refining processes or may lower the quality of the final product. An example of the former is the presence of iron sulfides, stibnite, or copper sulfides in gold ores that are to be treated by dissolution in cyanide solution; such materials also react with the cyanide solution, resulting in both its consumption and contamination. An example of the latter is the presence of phosphorus-bearing minerals in iron ores that reduce ore quality below that required for steel making. Problems can also arise from the presence of fine-layer silicates such as kaolin, talc, or sericite when flotation is used for ore concentration. These minerals also tend to float and thus reduce the grade of the concentrate. Even the presence of inert gangue phases such as quartz may be important in assessing efficient comminution. When such hard materials
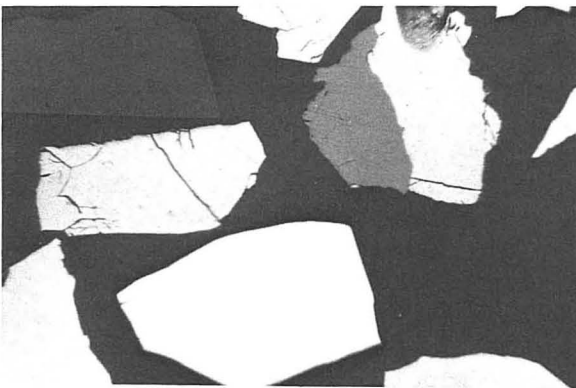
FIGURE 11.2 Locked and unlocked numeral grains. A locked grain of sphalerite and pyrrhotite coexisting in a mill product with unlocked grains of pyrite and pyrrhotite, Ducktown, Tennessee (width of field = 600 µm).

are associated with soft sulfides (e.g., galena), the gangue is ground to a given size more slowly, so there is a danger of overgrinding the galena-producing fine materials (*slimes*), which are difficult to recover. Also of great importance is the identification of waste materials that are likely to have an adverse effect on the environment if they are allowed to disperse into the air or rivers (e.g., asbestos minerals).

In some instances, identification of the ore minerals can even allow prediction of the grade of a concentrate that can be prepared from the ore. Thus, Craig, Ljokjell, and Vokes (1984) applied the available phase equilibrium data on coexisting iron sulfides with sphalerite (Figure 10.28) to point out the inherent compositional limitations of the zinc content of the sphalerite concentrate of numerous ores. The activity of sulfur (generally expressed in terms of S_2) during formation and subsequent equilibration of an ore determines what iron sulfide(s) (pyrrhotite and/or pyrite) are present and the amount of iron in the sphalerite. If the only iron sulfide present is pyrite, the iron content of a sphalerite formed in equilibrium with it will be less than 1 wt % and a concentrate can be prepared with a zinc content close to that of pure ZnS (67 wt %). If an ore contains pyrrhotite and pyrite, the iron content of the sphalerite formed in equilibrium with these two iron sulfides depends somewhat on pressure (see Section 10.10) but generally lies in the range of 8–12 wt %. Accordingly, the maximum zinc content of a sphalerite concentrate is reduced to 55–59 wt %. If the only iron sulfide present with the sphalerite is pyrrhotite, then the iron content of the sphalerite is even higher, further reducing the maximum zinc content of the concentrate.

Following identification of ore and gangue phases, the next important step is quantitative determination of their relative amounts in the untreated ores and in the ores after comminution and at the various stages of mineral separation. Such determinations must be statistically sound, and it is most important to study sufficient samples of ores and mill products to ensure that the material examined is representative. Furthermore, one must be careful not to allow any layering or schistosity of samples to bias estimation of either total or individual ore mineral contents. The quantitative determination of mineral ratios from polished sections can be undertaken using point counting or various methods of image analysis by electronic scanning equipment. The detailed applications of such methods and their reliability have been discussed by Petruk (1990) and by Jones (1977).

The combination of the various methods of quantitative mineralogical analysis with bulk chemical analysis and chemical analysis of various mineral fractions (and, where possible, of individual mineral grains) makes possible the determination of relative amounts of ore and gangue minerals, percentages of each ore mineral, and the average composition of each ore mineral. In the untreated ores, it is also very important to know the sizes and size distributions of the various ore minerals and to monitor the distribution of ore minerals in various size fractions during comminution. Measurement may be accomplished under the microscope (e.g., using a micrometer or grating eyepiece) or through the use of various electronic devices (see Petruk, 1976 and Jones, 1977).

The question of the sizes and size distributions of ore (and gangue) particles is closely linked to the important role of studies of ore textures in relation to beneficiation problems, which will now be discussed.
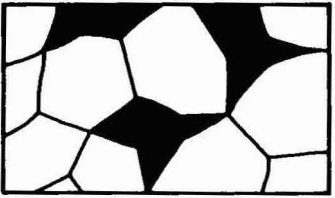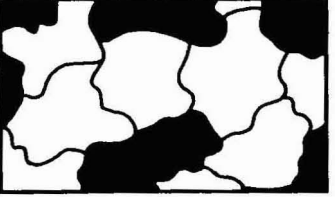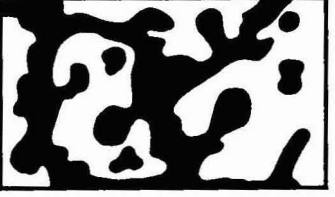
11.3   ORE TEXTURES IN MINERAL BENEFICIATION

Since the first stage in the beneficiation of ores in order to liberate the particles of valuable minerals from each other and from the gangue is comminution, knowledge of the sizes and intergrowth relationships of ore mineral grains is of great importance. Only through careful examination of the ores in polished section can the optimum grain size for effective liberation be determined. Insufficient grinding may result in loss of valuable minerals in the tailings; overgrinding wastes energy and may produce slimes that are difficult to treat later in the processing stage. The efficiency of the grinding methods employed at the pilot stage must also be monitored by the examination of polished grain mounts of their products.

The great variety of intergrowths that may occur between ore and gangue minerals and between different ore minerals that may eventually require separation has been well illustrated already (see Chapters 7, 9, and 10). As we consider the problems of liberation of the ore minerals, it is useful to outline a fairly simple classification based on the geometry of the intergrowths and locking textures, without any genetic implications. Such a classification of textures has been suggested by Amstutz (1961). This classification forms the basis of Figure 11.3, which also incorporates some information on the liberation characteristics of the ore types illustrated.

As well as the type and scale of the intergrowths, the nature of the boundaries between intergrown particles is important. This will show whether or not the rupturing of larger particles during grinding is likely to occur at grain boundaries. For similar reasons, information regarding fractures and fissures in the ore minerals, as well as the porosity of the material, is important data that is derived from examination under the microscope. In addition to the influence that such textural features have on the comminution process, they have importance in the flotation and leaching methods of ore treatment.

The extent to which liberation has been achieved at each stage in grinding can, of course, be assessed by quantitative determination under the ore microscope. This may be seen in the photomicrographs of ground ores in Figure 11.4. Even if the desired ore minerals are more or less randomly distributed in an ore, their distribution into different size fractions during comminution may be controlled by their textures. Table 11.2 presents quantitative microscopic data showing the distribution of ore and gangue minerals as functions of size fractions during grinding of the massive pyrite and pyrrhotite ores of the Ducktown, Tennessee, deposits. The data demonstrate that the valued ore minerals—chalcopyrite and sphalerite—are strongly concentrated in the finest fractions, whereas the pyrite is dominant in the coarse fraction. The cause lies in the initial ore texture, where chalcopyrite and sphalerite occur as small grains and film along the margins of the coarse pyrite crystals in a pyrrhotite

Texture and Nature of Interlocking	Diagram	Liberation Properties in Relatively Large Particles, Examples of Ores
Equigranular. Straight, rectilinear, cuspate margins. Simple locking.		Fairly easy liberation. Common occurrence especially in orthomagmatic and highly metamorphosed and recrystallized ores. Also in ores showing successive depositional sequence.
Mutually curving boundaries with negligible interpenetration. Simple locking.		Fairly easy liberation. Common occurrence in simultaneously crystallized ores where interfacial free energies are similar.
Mottled, spotty, careous, with partial penetration. Relatively simple locking.		Fairly easy liberation. Common occurrence in ores where interreplacement processes have been active.
Graphic, myrmekitic, visceral locking. Deep micropenetration.		Complete liberation difficult or impossible. Not common as a major texture in ores. Produced by exsolution and replacement. Examples: galena/sphalerite and chalcocite/bornite.

FIGURE 11.3 Geometric classification of ore mineral textures and their liberation characteristics.
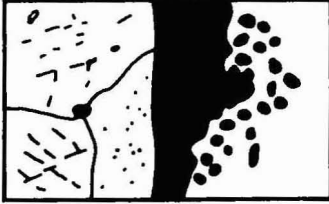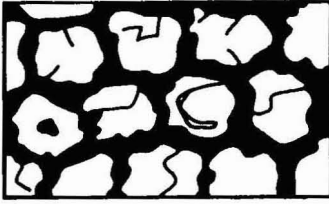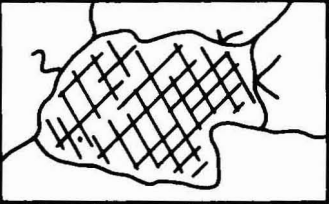
Texture and Nature of Interlocking	Diagram	Liberation Properties in Relatively Large Particles, Examples of Ores
Disseminated, droplike, emulsion, eutectoidal locking. Finely dispersed phases.		Complete liberation difficult or impossible; chemical treatment often required. Common occurrence by exsolution (left) Au/arsenopyrite chalcopyrite/sphalerite; by replacement (right) pyrite/sphalerite.
Intergranular rim; coating mantled, enveloped, atoll-like locking.		Liberation may be difficult if free grain is continously enveloped by layer. Not uncommon; often formed by replacement reaction. Examples: hematite film on gold; chalcocite or covellite on pyrite, galena, or sphalerite.
Concentric, spherulitic, scalloped, colloform-layered locking.		Liberation fairly difficult or difficult; common occurrence in Fe, Mn, and Al ores. Also U (pitchblende) intergrained with sulfide. Usually associated with colloidal precipitation.
Planar, lamellar, sandwich-type locking. Lamellae may vary in size.		Liberation fairly easy to variable. Produced by exsolution (examples: cubanite/chalcopyrite, ilmenite/magnetite). Also by replacement. Examples: magnetite and hematite.
Reticulate (net-like) boxwork. Finely interpenetrating locking.		Liberation variable to difficult. Common occurrence by replacement. Examples: bornite/chalcopyrite, anglesite/covellite/galena. Also by exsolution. Examples: hematite/ilmenite/magnetite.

FIGURE 11.3 (*Continued*)
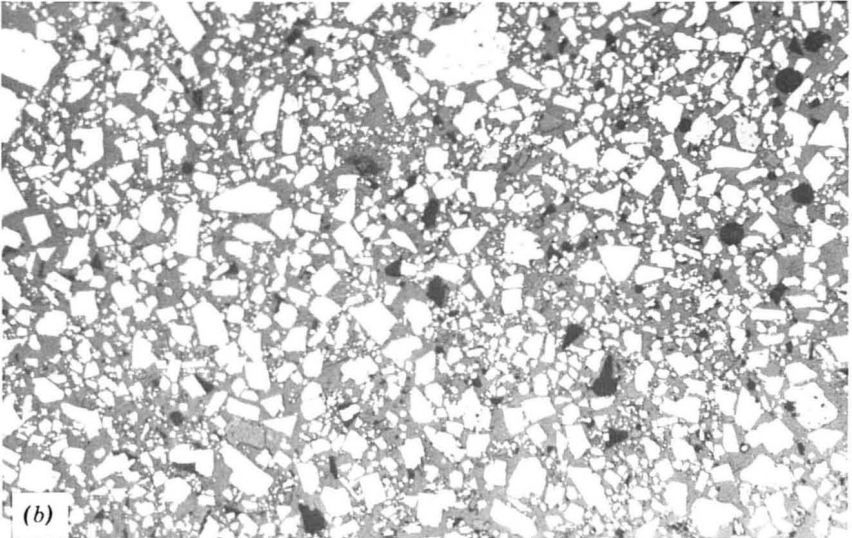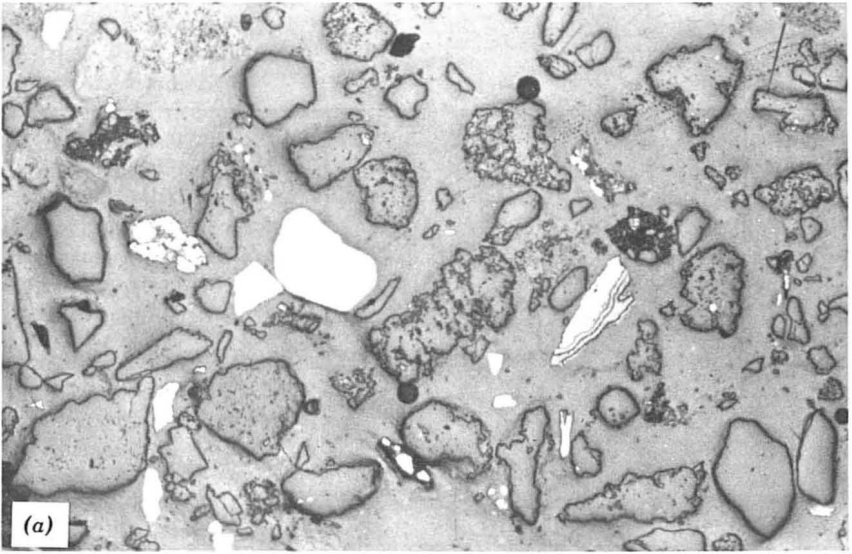
FIGURE 11.4 Photomicrographs of grain mounts of ground ores. (*a*) Ground ore prior to concentration (width of field = 520 μm). (*b*) Lead concentrate from Viburnum Trend, southeast Missouri; dominantly galena fragments with minor sphalerite (darker gray) (width of field = 520 μm).

TABLE 11.2 Microscopic Determination of Ore and Gangue Minerals from Massive Metal-bearing Sulfide Ore at Ducktown, Tennessee, as Functions of Size Fraction During Grinding

Mesh Size	Microns (Approx.)	Minerals[a] (in %)					
		Po	Py	Cpy	Mt	Sph	Gangue
+35	>420	32	61	0.9	1.0	0.0	4.4
35–48	420–290	47	44	1.6	0.9	0.2	6.0
48–65	290–200	49	36	2.6	1.0	0.2	10.0
65–100	200–130	50	28	3.3	2.1	0.5	16.0
100–150	130–95	50	24	5.9	2.9	0.7	16.6
150–200	95–75	49	23	5.0	3.9	1.0	18.4
200–250	75–55	56	21	4.6	4.8	1.0	12.8

Source: Craig, J. R., Yoon, R. H., Haralick, R. M., Choi, W. Z., and Pong, T. C. (1984). *Mineralogical Variations During Comminution of Complex Sulfide Ores in Process Mineralogy III,* W. Petruk, ed., *Soc. of Mining Engineers,* New York, pp. 51–63.

[a] po = pyrrhotite; py = pyrite; cpy = chalcopyrite; mt = magnetite; sph = sphalerite.

matrix. During grinding, the ores fracture along the weakest zones, that is, through the chalcopyrite and sphalerite, yielding numerous small fragments of these minerals and leaving the harder pyrite crystals in large grains or fragments. Detailed examination of each size fraction of an ore during communication can reveal information on the concentration of phases during grinding as well as determine the degree to which the grains are liberated from other minerals.

## 11.4 EXAMPLES OF APPLICATIONS OF ORE MICROSCOPY IN MINERAL BENEFICIATION

A number of contrasting examples can be used to illustrate this application of ore microscopy.

11.4.1 Gold Ores

Economic occurrences of gold generally consist of very small amounts of dispersed native gold or gold-silver alloys. Even in the well-known ores of the Witwatersrand in South Africa, the average concentration of gold is only about 16 ppm (0.5 troy oz/ton). The ores containing native gold may contain large amounts of quartz and minor (uneconomic) sulfides; little quartz but large amounts of valueless sulfides (pyrite, pyrrhotite, arsenopyrite); or valuable base-metal sulfides of antimony, arsenic, copper, lead, or zinc. Although some coarser gold particles may be separated from gangue by utilizing the high density of gold (cf. the "panning" of early prospectors), much gold is

removed from ore by dissolution in a cyanide solution (*cyanidation*) or in mercury amalgam (now rarely used and illegal in many places). For density separation, the gold particles must be liberated from gangue; for cyanidation or amalgamation, the gold must be sufficiently exposed to permit attack by the cyanide solution (or mercury). This is shown by two of the examples of gold ores illustrated in Figures 11.5a and 11.5b. In the first case, gold occurs along grain boundaries and fractures, and, in the second, as minute particles within the sulfide. An equivalent amount of grinding will produce a much greater "effective liberation" of gold in the first ore because of the tendency to break along fractures and boundaries. This ore can be subjected to cyanidation after (or during) grinding, whereas the second ore may need roasting to release the gold before it can be successfully cyanided. Many ores will, of course, contain a certain amount of both types of intergrowth; the relative amounts and size ranges can then be determined by microscopic examination. If gold particles occur largely as inclusions in a particular phase (e.g., pyrite), it may be possible to concentrate this phase by flotation and subject only this to fine grinding or roasting in order to liberate the gold.

When the cyanidation process is to be employed in gold extraction, it is particularly important that microscopic studies be made to determine the presence of deleterious minerals. The dissolution process depends on an adequate supply of oxygen; pyrrhotite, marcasite, and some pyrites consume oxygen, thus inhibiting the process. Other minerals, notably stibnite, copper sulfides, and some arsenopyrites and pyrites may dissolve in the cyanide solution, resulting in excessive consumption of cyanide and even reprecipitation of the gold in extreme cases. In cases in which the concentration of deleterious

(a)
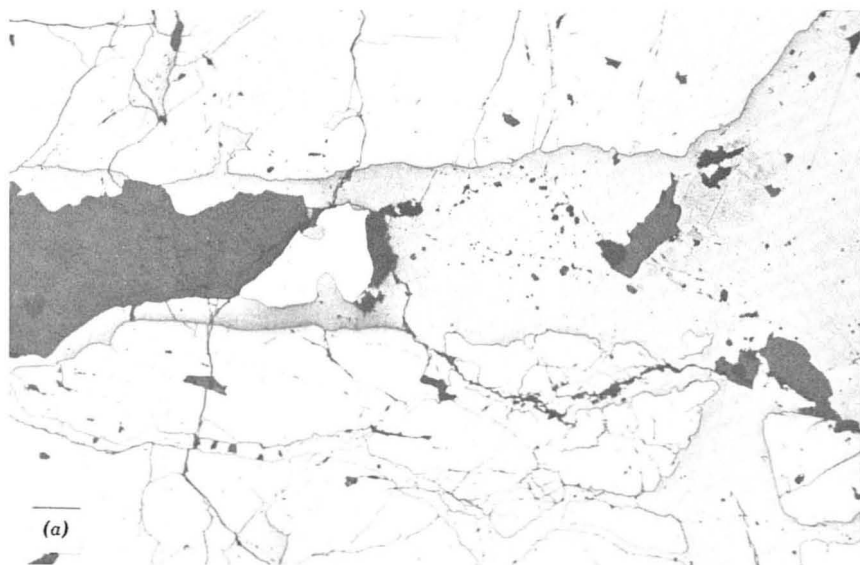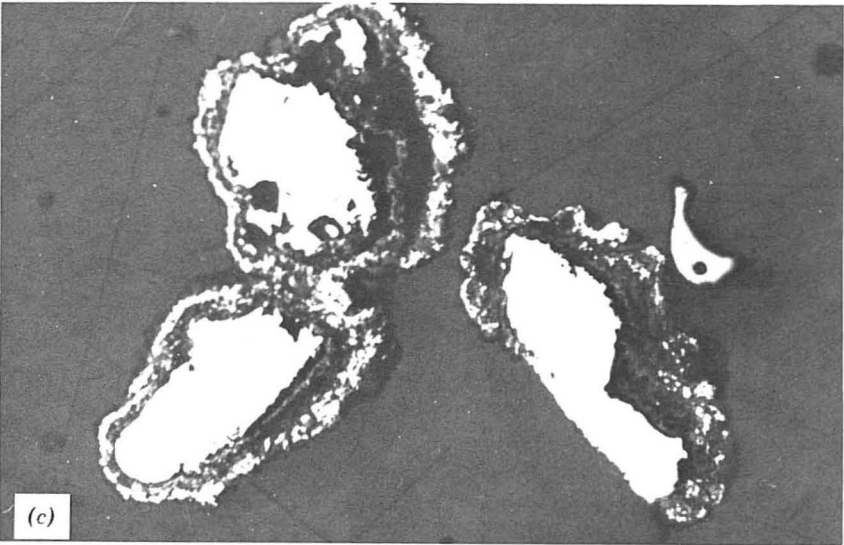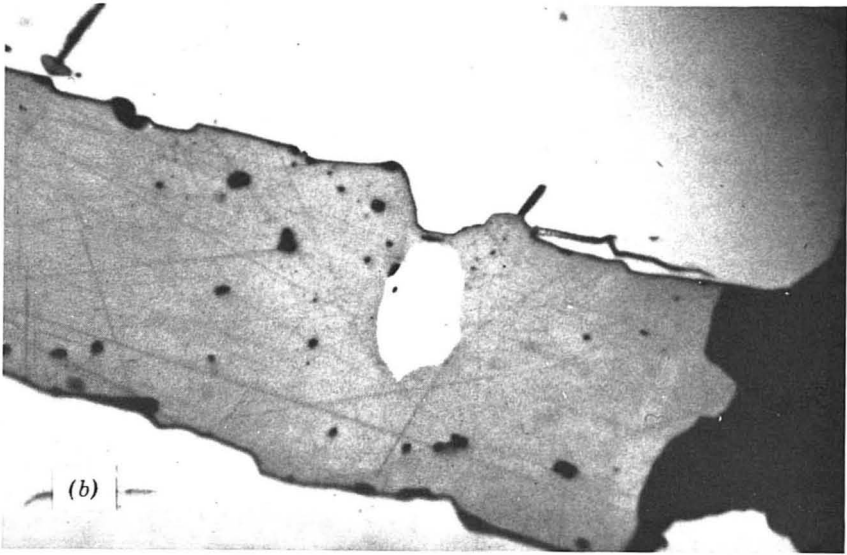
FIGURE 11.5 Examples of gold ores. (*a*) Gold occurring along grain boundaries and fractures in pyrite, Witwatersrand, South Africa (width of field = 2,000 μm). (*b*) Gold occurring within chalcopyrite, Witwatersrand, South Africa (width of field = 210 μm). (*c*) Gold grain coated with magnetite and goethite, Alaska (width of field = 2,000 μm).

minerals is such that it seriously affects the efficiency of the process, it may be necessary to remove the minerals by flotation prior to cyanidation. As with cyanidation, certain minerals can adversely affect amalgamation (e.g., stibnite, enargite, realgar, tetrahedrite, pyrrhotite, arsenopyrite, and pyrite react with amalgam) and may have to be removed.

Other problems in the processing of gold ores may result from the presence of a coating on the surface of the gold particles (commonly of iron oxide, as shown in Figure 11.5c). This can result in losses of gold during separation (especially if a magnetic process is employed to remove oxide impurities that may then carry gold with them) and can prevent dissolution of the gold unless it is removed by grinding. Other coatings that inhibit dissolution may form during processing. With an ore as valuable as gold, an important aspect of microscopic studies for efficient extraction is the examination of tailings. If losses are occurring in the tailings, the reasons for such losses can then be determined.

11.4.2 Copper Ores

Copper is obtained largely from sulfide ores, and chalcopyrite is the single most important copper ore.mineral. The chemistry and metallurgy of chalcopyrite have been reviewed by Habashi (1978). Other copper-iron (bornite, cubanite, talnakhite, mooihoekite) and copper (covellite, chalcocite, digenite, djurleite) sulfides are often associated with chalcopyrite and may be locally important. The copper content of each of these phases is different, and a careful quantitative determination of the mineralogy is an important step in the assessment of ore grade. Many of these phases (particularly bornite, chalcocite, and covellite) may result from the alteration of chalcopyrite in processes of secondary enrichment (see Figure 7.11). Examples of major copper deposits are the *porphyry coppers* (see Section 9.5), large deposits that are often mined at average copper concentrations of less than 0.5%. Such deposits contain large amounts of pyrite as well as chalcopyrite; some copper may occur as sulfosalts (tetrahedrite, enargite), and silver and gold may also occur in small but economically important quantities. Quartz, feldspars, biotite, chlorite, sericite, anhydrite, clay minerals, and other layer silicates are the dominant gangue minerals.

As Gaudin (1957) has pointed out, the sulfide copper ores are particularly well suited to flotation recovery methods. When the ore is largely chalcopyrite and pyrite, liberation of chalcopyrite can usually be achieved by normal grinding methods. Flotation can then be carried out to selectively concentrate the chalcopyrite. The preparation of a copper concentrate may be more difficult if chalcopyrite, pyrite, and other copper sulfides are intimately intergrown. Another problem may arise in recovering the gold or silver, which may well follow pyrite into a "tailings fraction." Solutions to all of these problems require careful study of mined ores and mill products by ore microscopy.

When the ores have been partly oxidized, some of the copper may be present as easily soluble oxides, basic sulfates, or carbonates from which copper can be easily extracted by acid leaching. Such methods are being more widely employed also as a method of extraction of copper from sulfides in *dump leaching* of very low-grade ores (Fletcher, 1970). Here again, microscopic study of textures to estimate the efficiency of the leaching process is important.

Another major source of copper is the volcanogenic massive sulfide deposit (Section 10.9). The chalcopyrite in these ores occurs as anhedral interstitial grains and to a variable but significant extent as very small ($<5\,\mu m$) blebs and veinlets within sphalerite ("chalcopyrite disease," Figure 7.18). This finely dispersed chalcopyrite can create separation problems and may result in appreciable copper reporting in the zinc concentrate. It may also be desirable to remove, during beneficiation, certain phases that cause problems during smelting (e.g., arsenopyrite in order to reduce arsenic emissions). Such problems are readily anticipated if detailed ore microscopic work has first been undertaken.

11.4.3 Chromium Ores

The only significant ore mineral of chromium is chromite (ideal composition, $FeCr_2O_4$), which occurs in ultramafic and mafic igneous rocks (see Section 9.2). Although chromite often occurs in a silicate matrix (see Figures 9.1 and 9.2) as single-phase euhedral-subhedral grains that can be readily separated by grinding and gravity concentration, deficiencies in the grade of a concentrate may result from intimate intergrowths with gangue minerals or variation in chromite composition. The former is often a result of severe fracturing of the chromite and infilling of the fractures with serpentine; the latter results from the substitution of Fe^{3+} and Al^{3+} for Cr^{3+} in the chromite, the composition of which may even vary within a single grain, producing a zonal distribution of chromium concentration. Variations in magnetic properties of chromites as a function of iron content may permit selective magnetic concentration of chromium-rich fractions in some cases. The efficient gravity concentration of low-grade chromite ore from Cyprus described by Mousoulos and Papadopoulos (1976) involved a combination of heavy media, jigs, and shaking tables.

11.4.4 Iron-Titanium Oxide Ores

Some iron-titanium oxide ores present particular milling problems because of the intimate association of the mineral phases. Figure 11.6 illustrates two extreme examples of ores: in Figure 11.6a, the separation is readily achieved; in Figure 11.6b, the separation is difficult to achieve. In the former case, ilmenite and magnetite coexist in a coarse equigranular aggregate and can
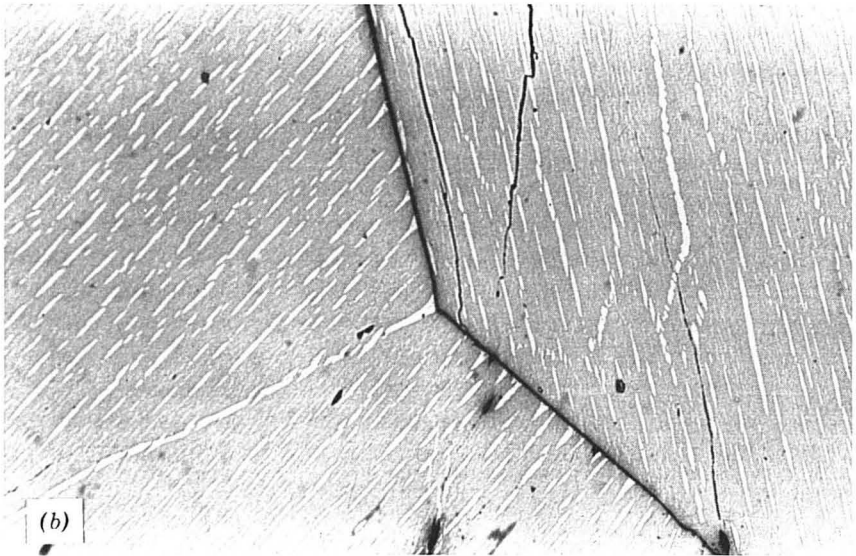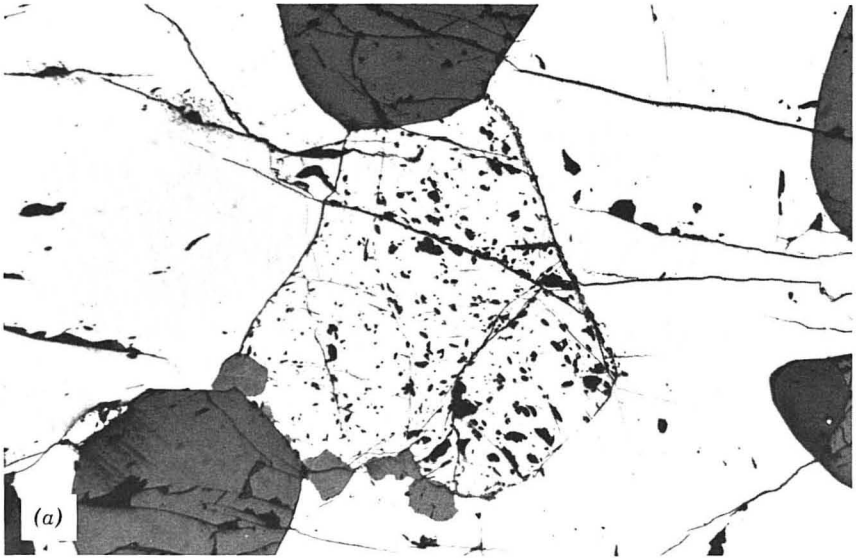
FIGURE 11.6 Examples of iron-titanium oxide ores. (*a*) Coarse magnetite grain (dark gray, pitted) flanked by coarse ilmenite grains, Storgangen, Norway (width of field = 2,000 μm). (*b*) Fine lamellae of hematite within ilmenite, Blasfjell, Norway (width of field = 520 μm).

readily be separated magnetically after grinding. In the latter case, however, the intimate intergrowth of ilmenite with hematite, down to a submicroscopic scale, makes a clean mechanical separation of the phases impossible.
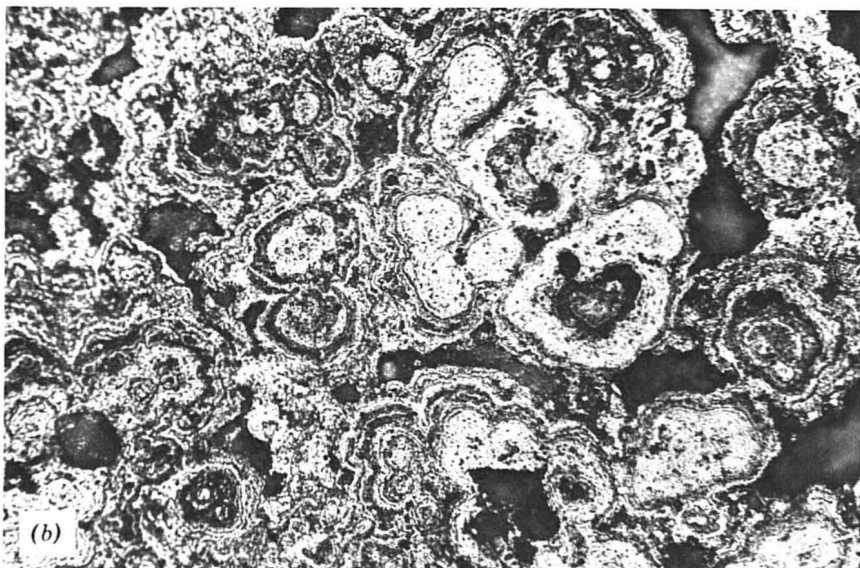
11.4.5   Manganese Nodules

The manganese nodules of the deep ocean floors are an important potential source of not only manganese but also of other base metals; nodule deposits being considered for mining assay as high as 2.3% Cu, 1.9% Ni, 0.2% Co, and 36% Mn (dry weight) (Fuerstenau and Han, 1977). Study of the nature and distribution of the phases containing these valuable metals in the nodules is an important step toward their economic exploitation. Although their detailed mineralogy is complex, the predominant minerals in the nodules are manganese (IV) oxides related to the terrestrial minerals todorokite, birnessite, and δ-MnO_2; also present is crystallographically poorly ordered goethite ("incipient goethite") (Burns and Burns, 1977; 1979). The nickel, copper, and cobalt are taken up by todorokite in postdepositional processes. The textural relationships between mineral phases in a nodule are shown in Figures 11.7a and 11.7b.

Brooke and Prosser (1969) examined the mineralogy and porosity of several such nodules and investigated the problem of selective extraction of copper and nickel. Tests showed that selective leaching of copper and nickel using dilute sulfuric acid is a possible method of extraction. A whole range of possible extraction methods (acid leaching, ammonia leaching, smelting, chlorination, and segregation roasting) have also been reviewed by Fuerstenau and Han (1977).

### 11.5   THE STUDY OF MATTES, SLAGS, ASHES, SINTER, AND OTHER SMELTER AND INCINERATOR PRODUCTS

The compositions and textural relationships of the products of sintering and smelting (mattes, slags, etc.) can be studied by using the techniques outlined in Chapters 1–6. Although these are not minerals, many do closely resemble ore minerals in composition and optical properties and sometimes in texture. Their history of crystallization may also be followed using textural interpretations similar to those outlined for ores.

Slags (Figure 11.8), the waste products of smelting, are intended to remove impurities from the desired metals. Ideally, all of the metal remains in a melt, whereas all impurities segregate into the slag. In reality, the separation is never perfect, and studies of the slags and matter are used to reveal the quantities and nature of phases either lost or serving as contaminants. The loss of some iron during smelting (Figure 11.8b) is generally of little economic consequence, but the loss of copper (Figure 11.8d) is of concern, and the loss of electrum (Figure 11.8a) in the smelting of gold and silver ores can be very serious.

FIGURE 11.7 Textural relationships between mineral phases in manganese nodules sectioned in different orientations. (*a*) Blake Plateau, Atlantic Ocean (width of field = 2,000 μm). (*b*) Pacific Ocean (width of field = 520 μm).

The mining and smelting of iron is much larger and widespread than that of any other metal. The study by Basta, El Sharkowi, and Salem (1969) provides an example of iron slags. They studied the mineralogy of fluxed sinters of fines from the Aswan iron ore. These oolitic ores are mainly hematite, with some goethite, quartz, carbonate, and chlorite; some minor sulfur, phosphorus, and manganese are also present. Sintering was at ~1,200°C, with limestone, pyrite cinders, and coke as a fuel. Studies of such sinters show iron, iron oxides

(a)

(b)
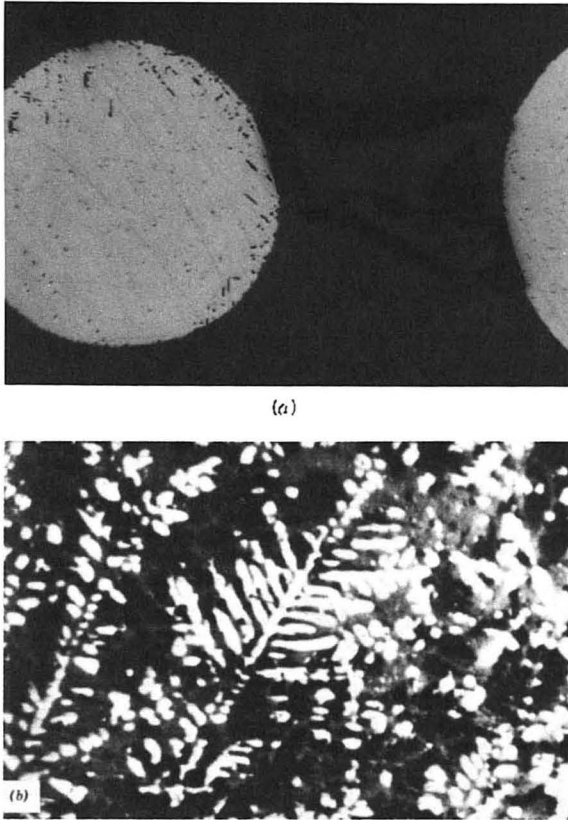
FIGURE 11.8 (a) Spheres of electrum occurring in slag from the smelting of gold-silver ores. Such entrapment requires remelting of the slag to recover all of the precious metals, Morning Star Mine, California (width of field = 1,200 μm). (b) Dendritic crystals of magnetite in a matrix of glass; sinter from Aswan iron ore (width of field = 200 μm). (Reproduced from E. Z. Basta et al., *Trans. I.M.M.* **78**, C3, 1969; used with permission.) (c) Copper-nickel matte with small euhedral crystals of Fe, Ni disulfide in a matrix of Cu_2S (dark gray) and NiS (light gray). A large subhedral grain of metallic nickel is visible in the upper-left-hand corner (width of field = 2,000 μm). (d) Dendritic crystals of magnetite with interstitial pyrrhotite and chalcopyrite in ancient slags produced by the Romans as they worked the copper ores on Cyprus (width of field = 1,200 μm).
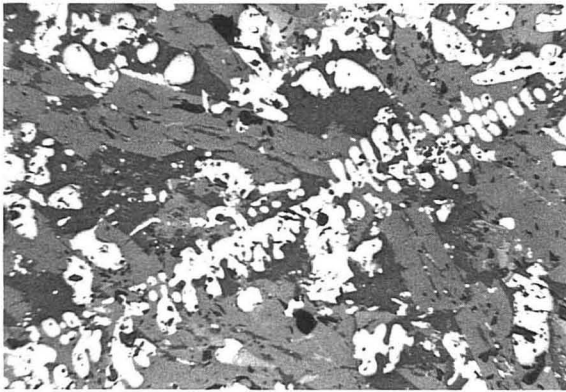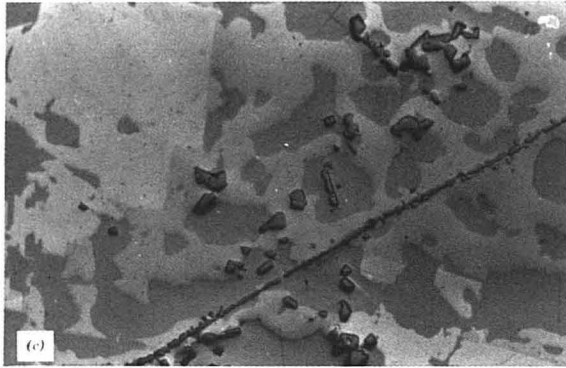
(d)

FIGURE 11.8   (*Continued*)

(magnetite, hematite, wüstite), and calcium ferrites as spherules, dendrites, and crystals in a matrix of silicates—both crystalline (gehlenite, olivine, wollastonite) and glassy (Figure 11.8b). Minor sulfides may also be present (pyrrhotite, chalcopyrite). The effect of varying the amounts of limestone added is related to mineralogical variations that are, in turn, related to such properties as strength and reducibility of the sinters.

The reduction of ilmenite has been studied by Jones (1974). At temperatures less than $1,000°C$, natural ilmenites are reduced by carbon monoxide to metallic iron and reduced rutiles ($Ti_nO_{2n-1}, n \geqslant 4$), but minor magnesium or manganese prevent the reaction from going to completion. These problems are lessened at higher temperatures, and at $1,200°C$ the products of reduction are metallic iron and anosovite ($Fe_{3-x}Ti_xO_5$) solid solution. These reaction products were characterized at various stages of reduction by ore microscopy (and electron probe microanalysis).

The mattes produced in copper smelters vary considerably in composition but include many of the phases familiar from mineralogical studies in the Cu-Fe-S and Cu-Ni-S systems. Figure 11.8c illustrates the nature of a copper-

nickel matte containing 40% Cu and 40% Ni. The matte contains an early crystallized iron-nickel alloy phase, dispersed small grains of an Fe-Ni disulfide and a matrix of NiS (millerite), and a copper sulfide solid solution. This last phase has exsolved on cooling to give a basket weave texture of two copper sulfide phases. Figure 11.8d is a Roman-period copper mining slag from Cyprus; it reveals the loss of copper and chalcopyrite associated with magnetite and pyrrhotite in the slag.

The combustion of coal, oil, and even municipal solid waste concentrates metals and generates ashes and slags that contain mineral-like phases. Coals generally contain significant quantities of clays and quartz in addition to trace to minor amounts of metals and metal-bearing phases (especially pyrite). During combustion, the metals and other nonflammable materials become concentrated by factors of about 10 times, with the resultant formation of spinel-type oxides, several silicate phases, and occasional iron sulfides in a glassy silicate matrix.

The distillation of petroleum to leave a solid coke-like phase, and the subsequent combustion of that material, results in a much greater degree of concentration (approximately 1,000 times) of metals and sulfur, but with much less silica. The resulting slag may contain a complex variety of iron, nickel, and vanadium sulfides and oxides, as well as much free metal (usually as iron-nickel alloys), as shown in Figure 11.9. Microscopic analysis has revealed much about the phases present and their potential for reuse or disposal (Craig, Najjar, and Robin, 1990; Groen, 1992).
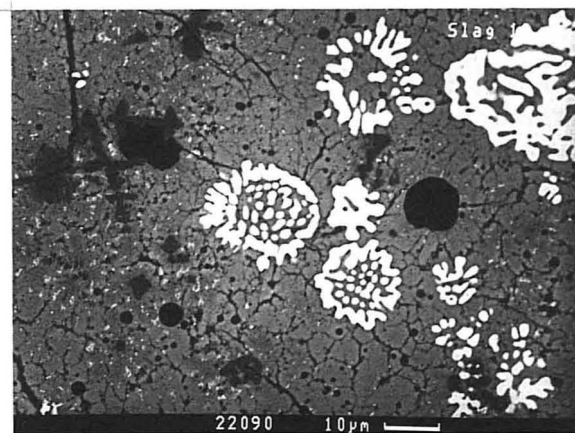
(a)

FIGURE 11.9 Scanning electron microscope images of petroleum coke slags. (a) Atoll-like structure of native iron and some cruciform spinel crystals in a fine matrix of intergrown FeS and FeO in slag produced during production of synthesis gas from petroleum coke (width of field = 100 μm). (b) Equant and skeletal crystals of iron- and nickel-rich aluminate spinels in a matrix of glass from a petroleum coke gasifier. The coarser crystals were probably stable at the temperature of the gasifier, whereas the very fine crystals formed during rapid cooling of the glass (width of field = 360 μm).
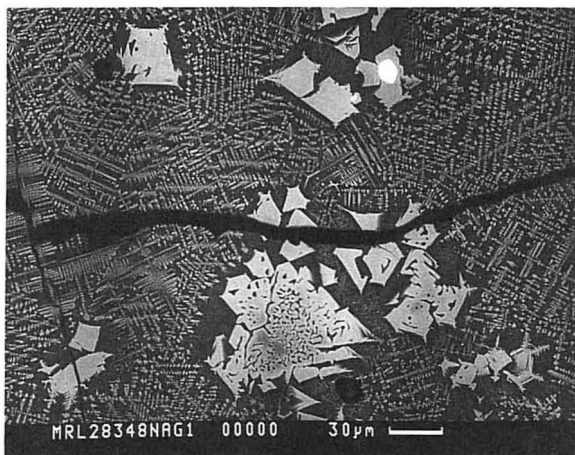
(b)

FIGURE 11.9   (*Continued*)

The incineration of municipal solid waste is being undertaken more widely to generate heat and to effect volume reduction. As one might expect, the ashes and slags produced are rich in silicates and glasses but contain a wide variety of metallic mineral-like oxide phases (Brock, 1993; Kirby and Rimstidt, 1993). Much more study is needed to characterize all of the phases present and to identify potential uses or problems related to their ultimate disposal.

11.6   CONCLUDING REMARKS

This very brief outline of the applications of ore microscopy in mineral technology serves only to illustrate the great importance of this area of application. The increasing world demand for metals necessitates the economic extraction of metals from ores of lower and lower grades, which requires efficient, skilled beneficiation. Thus, careful study under the reflected-light microscope of the ore and of the products of various comminution and separation processes is necessary. If, following initial discovery; exploratory drilling to determine overall size, grade, and geological setting; mineralogical analysis to establish feasibility of metal extraction; and pilot testing of the extraction processes, it is decided to proceed with a mining operation, the ore microscopist is still needed to monitor variations in the mineralogy of the ore and the effects of such variations on processing. Variations laterally or vertically in the orebody may call for changes in beneficiation procedures or mixing of ores mined from different areas; the microscopic study of the ores may also be of great value as a guide to mine exploration and development. In all of these applications, the ore mineralogy has to be related to the geological and engineering problems of mining, on the one hand, and to the problems of beneficiation and metallurgical treatment, on the other.

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