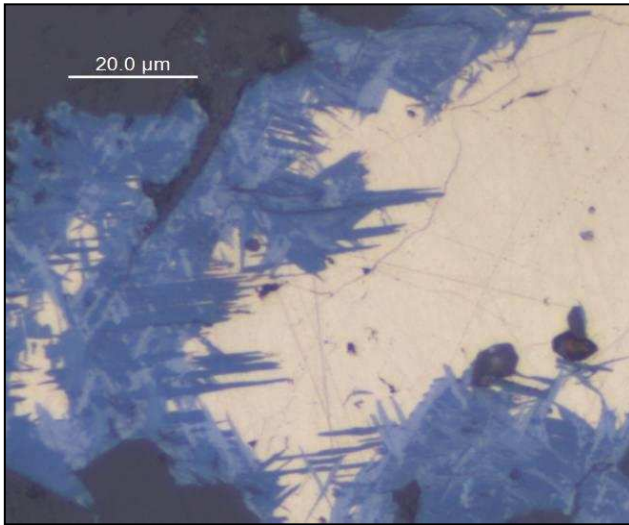
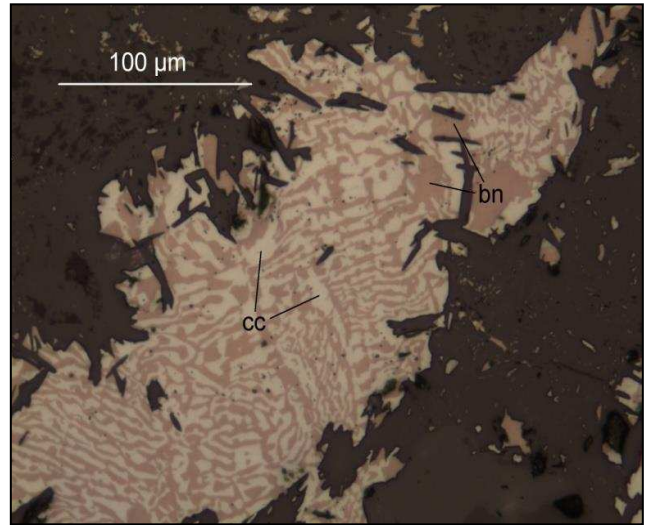


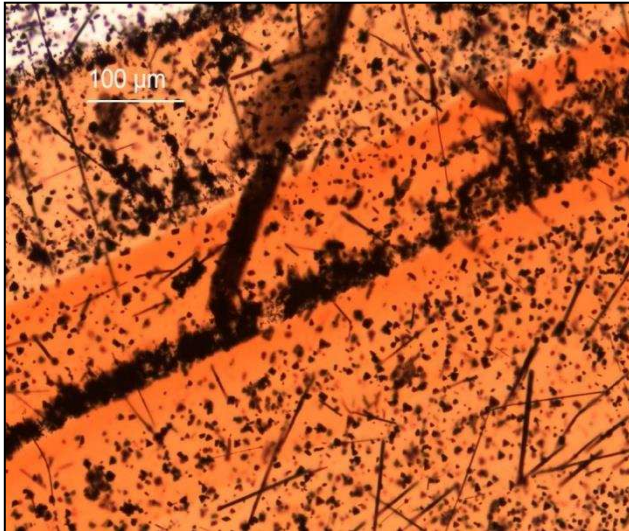
Ore Mineralogy & Microscopy



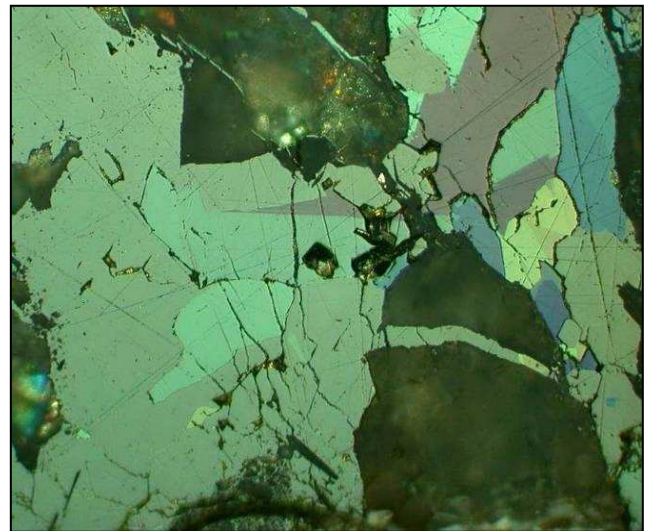
Rim replacement of chalcopyrite (yellow) by covellite. Morenci, Arizona. Reflected light.



Vermicular intergrowth of bornite (bn) and chalcocite (cc), Salobo, Brazil IOCG deposit. Reflected light. Polished section courtesy of Murray Hitzman, CSM.



Color-zoned sphalerite with interlayered pyrite (black) Mina Plomosas, Chihuahua, Mex. Transmitted light.



Marcasite, showing strong pleochroism. Bessie G mine, LaPlata, Colorado. Photo courtesy of Jim Paschis.

John L. Lufkin, Ph.D.

Ore Mineralogy & Microscopy

By John L. Lufkin, Ph.D

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Preface

This book is the outgrowth of teaching the subject of Ore Microscopy for many years, first at the University of Texas, Austin, in the early 1970s, and later at Colorado School of Mines in the early 1980s and presently at Metro State University of Denver. The subject is considered “a forgotten art” according to several of my colleagues. Nevertheless, I feel that it should still be taught to the benefit of many college students interested in pursuing a career in economic geology, as well as those “older folks” still laboring in the field of mineral exploration. Believe me, there is much to learn about an ore deposit through the microscope lens!

I took my first mineralogy course at CSM in 1961 during a summer school session from “Crystal” Paul Keating, a wonderful man and superb mineralogist. He was 65 at the time, I believe, and suffered a heart attack mid-way through the course, which was completed by Harry Kent. That course included a lot of ore minerals, and lit my fire for mineralogy and geology in general.

During my second year of teaching at the University of Texas at Austin, I was asked to teach a course in Ore Microscopy. In preparation for that experience, I was given the small sum of \$2,500 from the Geology Foundation for my request to tour the western United States to collect samples of ore deposits. During the summer of 1973, I collected samples from at least 15 deposits, including Climax, Homestake, Butte, Coeur d’Alene, Stillwater Complex, Carlin, Bingham Canyon, Bishop, Yerington, Ray, Morenci, Copper Cities, and Santa Rita, among others. It was a fantastic learning experience I will never forget. Much of the material presented here was derived from the study of thin sections cut from rock samples collected that summer.

In the fall of 1981, I renewed my connection with Mines again when Dr. Joseph Finney, Department Head, hired me specifically to teach a course in Ore Microscopy, as well as serve as his Assistant in the Department of Geology. Then, fast forward 26 years to March, 2007, when I asked Murray Hitzman, Forgy Professor of Economic Geology, and John Humphrey, Department Head, to return to Mines once again, this time to teach Ore Microscopy as a short course. After teaching the short course for two years, I soon realized that I had sufficient material to convert into a book that you are looking at now. I hope you enjoy what you find here.

Acknowledgments

A book of this magnitude could not have been done without the help of many colleagues. First of all, I am particularly grateful for the courtesy and help of Murray Hiltzman, not only for the frequent use of his lab facilities, but also for his contribution of many polished thin sections to the class.

Additional sample materials and photomicrographs were generously supplied by numerous geologists, including Dan Barker, Professor Emeritus, University of Texas, Austin; Karen Kelley, Al Hofstra, and Bob Rye, U.S. Geological Survey; Revell Phillips, BYU Emeritus Professor; David Gonzales, Ft. Lewis College; Sam Romberger, CSM; Glenn Scott and Helene Lukey, Cliffs Natural Resources; Peter Kurisoo, Galway Resources; Don Taylor, Doe Run Corp; David Oliver, Duluth, Metals; Tom Loomis, Dakota Matrix; Matt Knight, Chief Geologist, Stillwater Mining Company; Andrew Ware, Rudy Ganske, and Gerry Austin, Kennecott Corporation; and Steve Czuhera, Chief Geologist, Montana Resources; and Steve Hauck and Mark Severson, NRRI, Duluth, Minnesota.

I thank my several friends at the U.S. Geological Survey who have supported my work since returning to Colorado in 2001, including Bob Rye, Sharon Diehl, Al Hofstra, Gary Landis, and Richard Goldfarb. Ms. Sara Mellon, Arvada, did the formatting of this book.

And finally, I am grateful for the thoughtful reviews of this book provided by Bill Atkinson, University of Colorado, Boulder, retired; Phil Bethke, USGS (deceased); David Gonzales, Ft. Lewis College, Durango, CO; and Steve Scott, University of Toronto, retired.

Dedication

I wish to dedicate this book to two exceptional geoscientists, Dr. Murray W. Hitzman and Dr. William W. Atkinson. Murray was instrumental in my returning to teach at Colorado School of Mines in 2007. As an internationally known economic geologist, Charles W. Fogarty Professor of Economic Geology, and former Head of the Department of Geology and Geological Engineering at Colorado School of Mines, he recognized and supported the need to offer the subject of Ore Microscopy to students at Mines entering the field of economic geology. In support of my teaching efforts at Mines in past years, he made his microscope lab and polished sections available to me.

I met Bill Atkinson in 2009 for the first time, knowing of his outstanding reputation in the field of ore deposits, and his distinguished teaching career at the University of Colorado, Boulder for many years. Although “retired” from teaching for several years, he was interested in reviewing the first draft of this book. Since then, in spite of significant health problems, Bill has been a constant source of inspiration, constructive ideas, and encouragement for improving the manuscript. Moreover, he continues to review the Spanish translation of the book that is now underway.

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1.0 INTRODUCTION

Ore microscopy has been described by several of my colleagues as a “lost art”. I think that is an accurate description, and an unfortunate one because it still has an important role to play in the study of ore deposits. The study of ores in reflected light began many decades ago, but now only a few schools offer the subject, usually on an alternate year basis.

The purpose of this book is to introduce senior-level college and graduate students, as well as professional exploration geologists to the qualitative techniques of mineral identification in reflected light, since the vast majority of ores are opaque and do not transmit light. There are several disadvantages to studying ores, compared to the transparent silicate minerals. Over 35 years ago I heard Paul Barton, distinguished USGS scientist and authority on ore petrology, state at a Short Course on Sulfide Mineralogy at the GSA Meetings in Miami, Florida, “it is certain that ore textures present much information, but it is equally certain that there are few areas of scientific endeavor that are more subject to misinterpretation than the study of ore textures. The interpretation of ore textures is the most maligned, most difficult, and most important aspect of the study of these (sulfide) rocks” (Barton, 1973, p. B-3).

There are three main reasons for this pessimistic outlook on ore microscopy by a leading practitioner: 1) most sulfides and oxides are opaque to transmitted light, and therefore, have to be studied optically in reflected light; thus the important third dimension is lost to observation (Figures 1.1 and 1.2); 2) in reflected light we have fewer optical properties with which to identify the minerals, compared to transparent phases; the three main properties by which ore minerals are identified include color, relative hardness, and isotropic/ anisotropic effects. And these parameters can be anything but distinct in many of the opaque minerals; for example, most of the opaques are not distinctively colored, but shades of gray; and 3) the sulfides are much more reactive (ie., low refractability) and subject to change under changing T-P conditions than the oxide and silicate groups (Figure 1.3). (Refractability may be defined as a mineral’s resistance to change in texture and/or composition). Therefore, in many, if not most cases, we cannot observe the original texture that developed during ore deposition. For the above reasons then, the interpretation of ore textures becomes very challenging indeed, particularly when dealing with the wide variety of intergrowth textures that may develop, either by exsolution, replacement, or other processes.

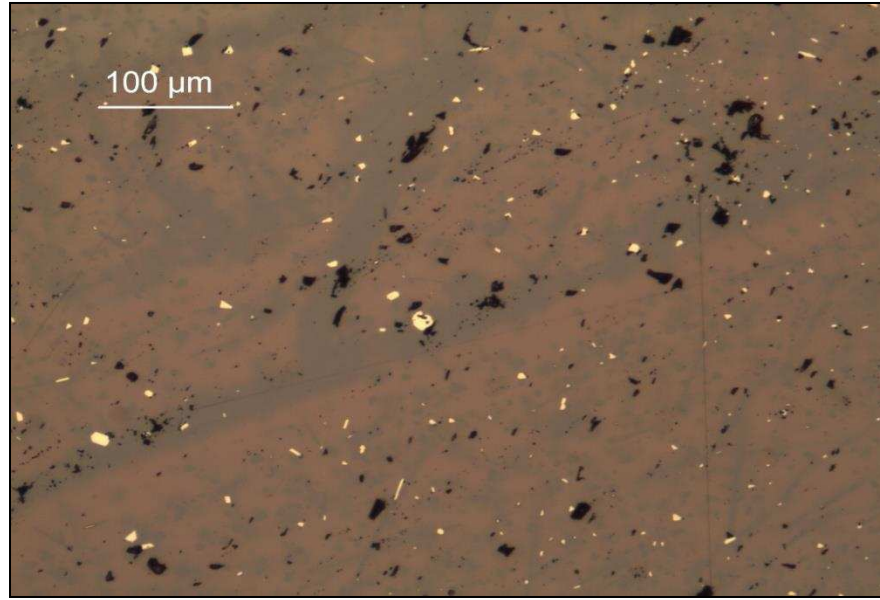


Figure 1.1 "Pyrite disease" in sphalerite. Mina Plomosas, Chihuahua, Mexico. Reflected light.

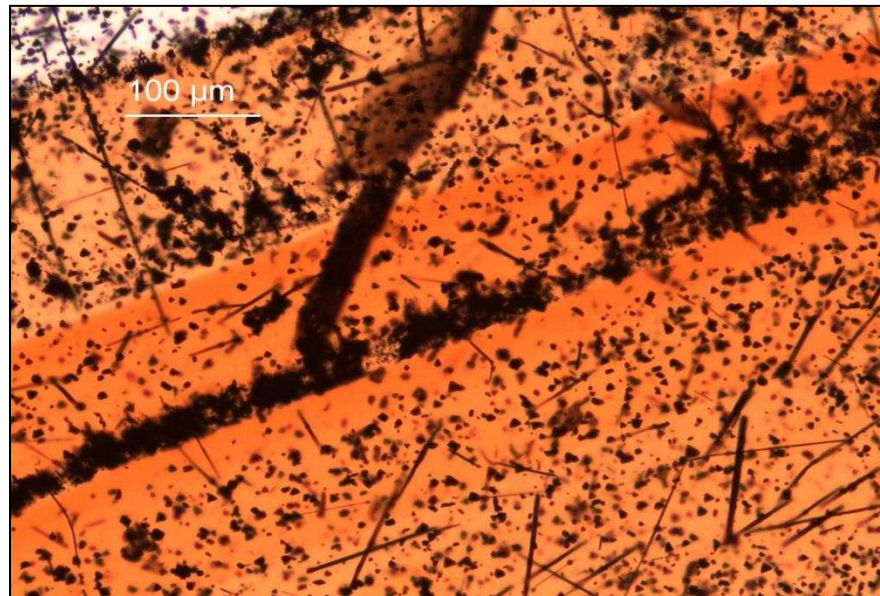


Figure 1.2 Same view, transmitted light. In transparent minerals like color-zoned, low Fe sphalerite shown here, the third dimension becomes much more visible, revealing pyrite as layers rather than as disseminated grains (black).

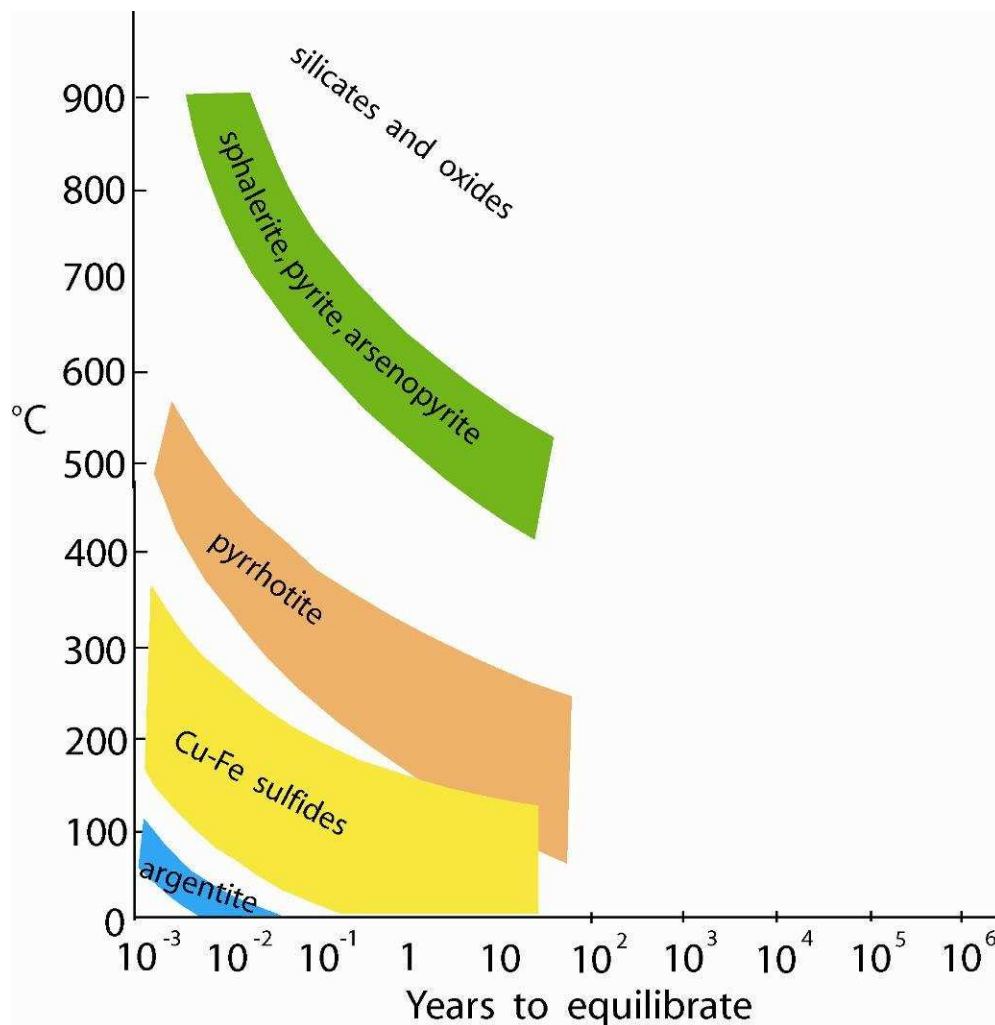


Figure 1.3 Refractability of sulfides (modified after Barton, 1974).

The greatest utilization of the microscope is that, with some practice, the economic geologist/mineralogist can readily learn to identify at least 50 of the most common ore minerals in a rather short period of time; in my course at Colorado School of Mines, I find that the typical student can identify at least 30 of the opaque minerals by sight after a week of concentrated study. With more study, the ore microscopist can take a good photomicrograph of the polished section, observe interesting textures, and work out a pretty detailed history of the deposit and the time sequence, or paragenesis of minerals that cannot be determined in any other way! At the same time, it should always be remembered that there are many occasions when the opaque mineral cannot be identified solely with microscopy, and one must resort to other techniques, such as x-ray diffraction (XRD), SEM, and/or electron microprobe.

2.0 THE ORE MICROSCOPE

The ore microscope is similar in construction to the conventional petrographic microscope, consisting of the same system of lenses, polarizer, analyzer, and various diaphragms to restrict the field of illumination. The main difference, however, is that the light path is passed vertically downward onto the mineral specimen, rather than transmitted upward from a source below the microscope stage. In the ore microscope, the light source is mounted in a horizontal column and light is reflected downward by a glass plate or prism (Figure 2.1).

When I was in graduate school almost 40 years ago, the typical ore microscope was equipped only with reflected-light optics. The microscopes in use today, however, have both transmitted and reflected light capabilities which allow for complete study of both transparent and opaque minerals in a single polished section—a tremendous improvement.

The principal components of the ore microscope include a rotatable stage, three or more objective lenses, the eyepiece system of two ocular lenses, an illuminating system, reflector plate or prism, two polarizers (called polarizer and analyzer), and accessory equipment (Figures 2.2, 2.3).

Rotatable Stage

The stage should be easily rotatable through 360 degrees and be perpendicular to the axis of light transmission. If you have ever used a fixed stage, then the value of a rotating stage becomes immediately apparent, for it allows the observer to quickly determine whether the mineral is isotropic or anisotropic, and if the mineral possesses bireflection pleochroism and/or anisotropic colors.

Objective Lenses

The objective lenses are usually classified as *achromat*, *apochromat*, or *fluorite*, and are screw-mounted into a turret head, whereby each lens can be rotated easily into focal position. The conventional turret can hold up to four objective lenses, typically ranging in magnification from 5x to 50x for most scopes (Craig and Vaughan, 1994).

The achromat lens is the most common and least expensive. Since it is corrected for spherical aberration for only green, color fringes may appear on the outer margin of the image.

The apochromat is more expensive, since it is corrected for both spherical and chromatic aberration of several colors. And it produces a sharper image and better photomicroscopy than any other lens.

Fluorite lenses ("semiapochromats") are a compromise in price and quality between the achromat and apochromat lenses, and should be used with compensation eyepieces (Craig and Vaughan, 1994).

Objective lenses are also classified as *dry* and *immersion* types. The dry objective is used in air, and the most commonly used. The immersion objective, which is used with a drop of oil ($n \sim 1.51$), or water has several advantages over the dry lens: 1) it enhances the color differences in the mineral, 2) reduces light scattering, and 3) the observation of subtle anisotropic and birefractance phenomena is much clearer. The two main drawbacks of the immersion lens are the need of frequent cleaning, and the very short working distance of the lens. Unless indicated otherwise, all the photomicrographs used in this book were taken in reflected light through a dry objective lens.

Ocular Lenses

The eyepiece or ocular system is designed to enlarge the primary image formed by the objective lens. Most microscopes are equipped with "Huygenian" oculars of between 5x and 12x magnification that consist of two lenses. The larger research scopes may have wide field oculars that enable a larger field of view (Craig and Vaughan, 1994).

Illuminating Systems

Ore microscopes employ two basic types of illuminating systems: an incandescent filament lamp and the gas discharge lamp. Most student models contain the incandescent tungsten filament lamp that ranges from 6-12V and 15-100W. A blue filter is commonly inserted between the lamp and the rest of the illuminating system which provides a more daylight-like color temperature. The standard illuminating system is comprised of two lenses, two or three diaphragms, and a polarizer in addition to the light source.

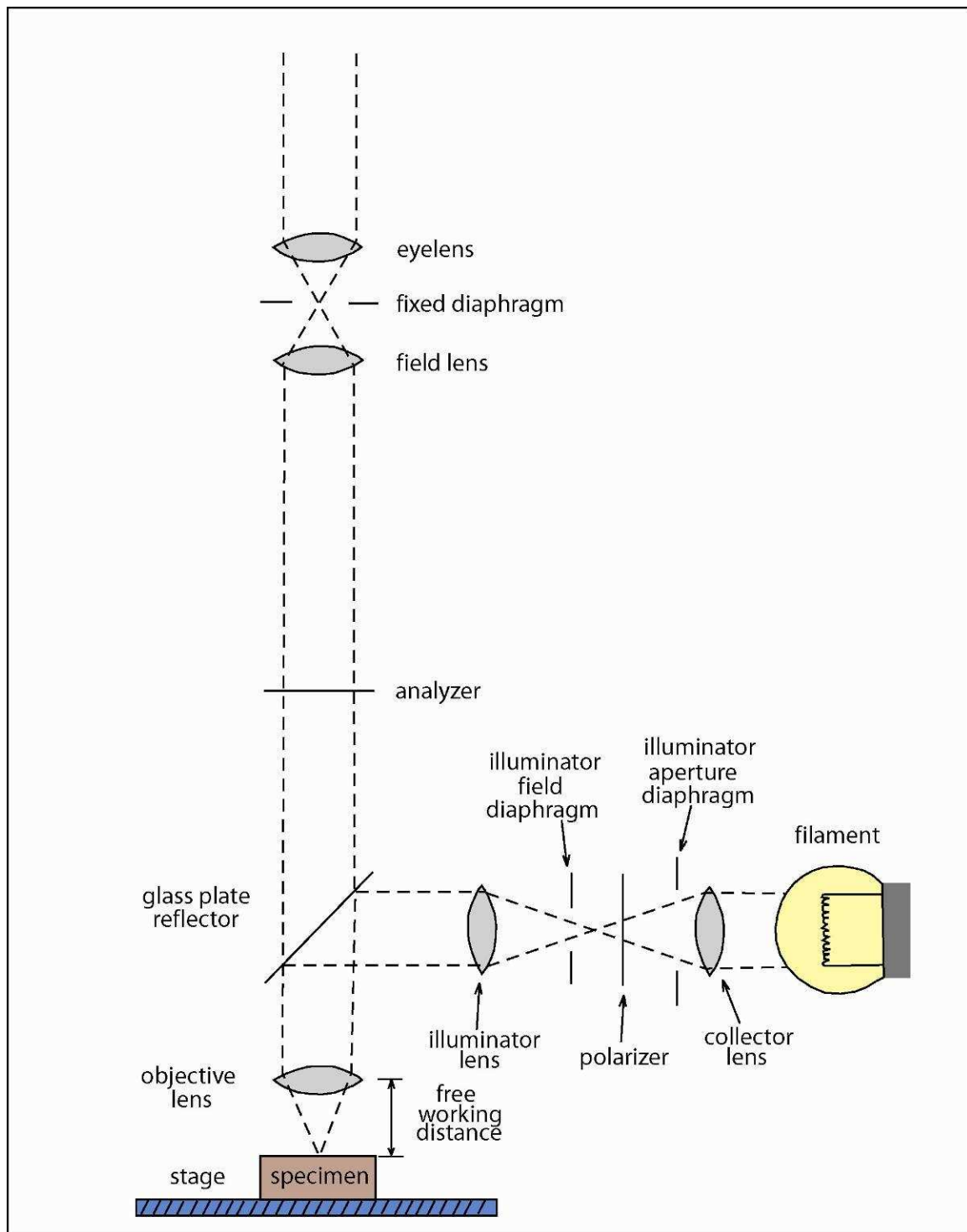


Figure 2.1 Schematic cross section of the ore microscope showing major components, glass plate reflector, and path of light through the system (modified after Craig and Vaughan, 1981, fig. 1.2).

The Reflector

A key component of the microscope is the *reflector* which brings light vertically downward onto the polished specimen (Figure 2.1). Two basic types of reflectors in use are the glass plate reflector and the half-field prism. The glass plate reflector is designed to both reflect light down on the specimen, and also to allow light to be reflected back up to the observer. “The coated glass plate reflectors of maximum efficiency result in only about 25% of the illuminator light that first reached the reflector ultimately reaching the ocular” (Craig and Vaughan, 1994). The alternative to this system is the totally reflecting prism in which light is reflected downward through one-half of the objective, and reflected back through the other half of the objective, which results in obliquely incident light and mirror aberrations. The advantage of the prism is that it allows a greater proportion of light to reach the ocular. Most workers find that the glass plate reflector is adequate or superior for most studies (Craig and Vaughan, 1994).

Polarizer and Analyzer

The polarizer is generally placed within the illuminating system and the analyzer is inserted in the microscope body just above the objective lenses. Both pieces of equipment consist of a polaroid plate that permits the passage of light in only one plane, hence the terminology, “plane or linearly polarized” light (PPL). In the crossed polar position, light that is reflected back to the observer is greatly reduced, so in order to better see anisotropic effects, it is best to rotate the analyzer a few degrees off of 90 degrees to allow more light to pass up to the oculars. This is accomplished by a *rotatable analyzer*, which costs around \$500. Therefore, most student microscopes are not equipped with this important piece of equipment. In the absence of a rotatable analyzer, the ocular head may be rotated a few degrees to produce a similar effect in letting more light through in the crossed polars position.

As a good test for seeing polarization colors, take a specimen of covellite and place it under crossed polars, with your analyzer inserted; you should then see the flash of orange to red colors as the stage is rotated. If not then your polarizer and analyzer are not in the proper alignment for the “crossed” position.

Centering the Microscope Stage and Objective Lenses

It is rather common for the microscope stage and/or the objective lenses to be thrown out of alignment from time to time. When this happens, your work becomes very frustrating indeed. Also, you cannot determine at first what is out of alignment, so you

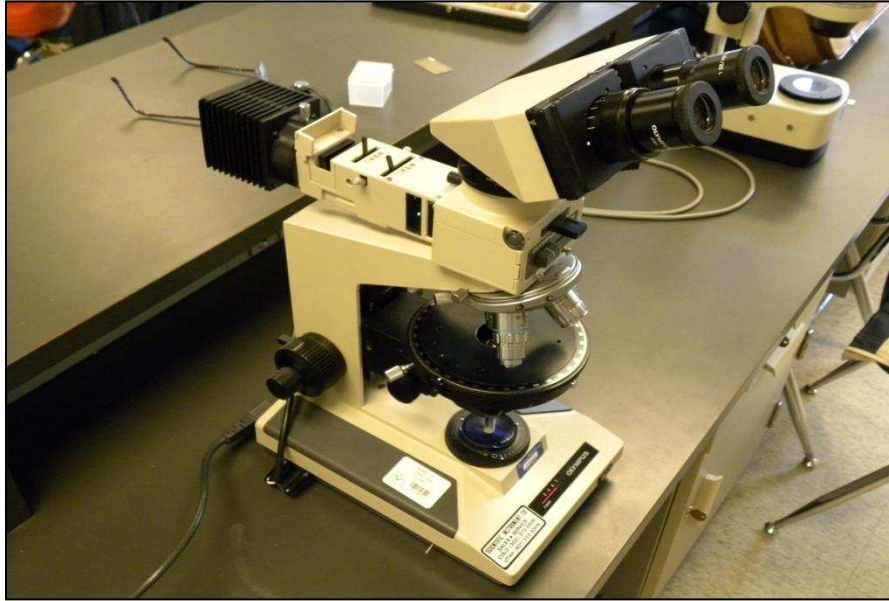


Figure 2.2 Olympus microscope, as used by students at Colorado School of Mines.

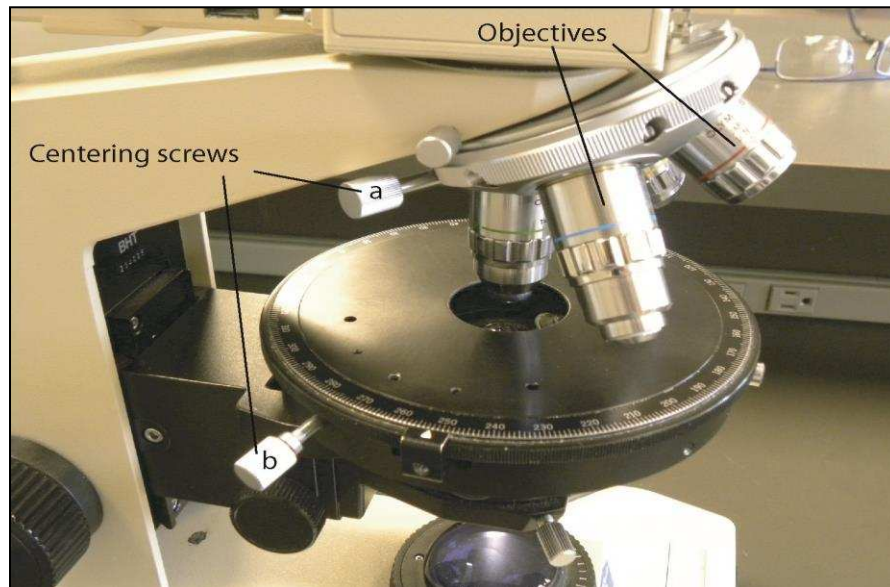


Figure 2.3 Olympus scope, showing the centering screws. (a) Objective centering screw in turret; a second screw on opposite side, out of view; (b) stage centering screw; second screw out of view on opposite side of stage.

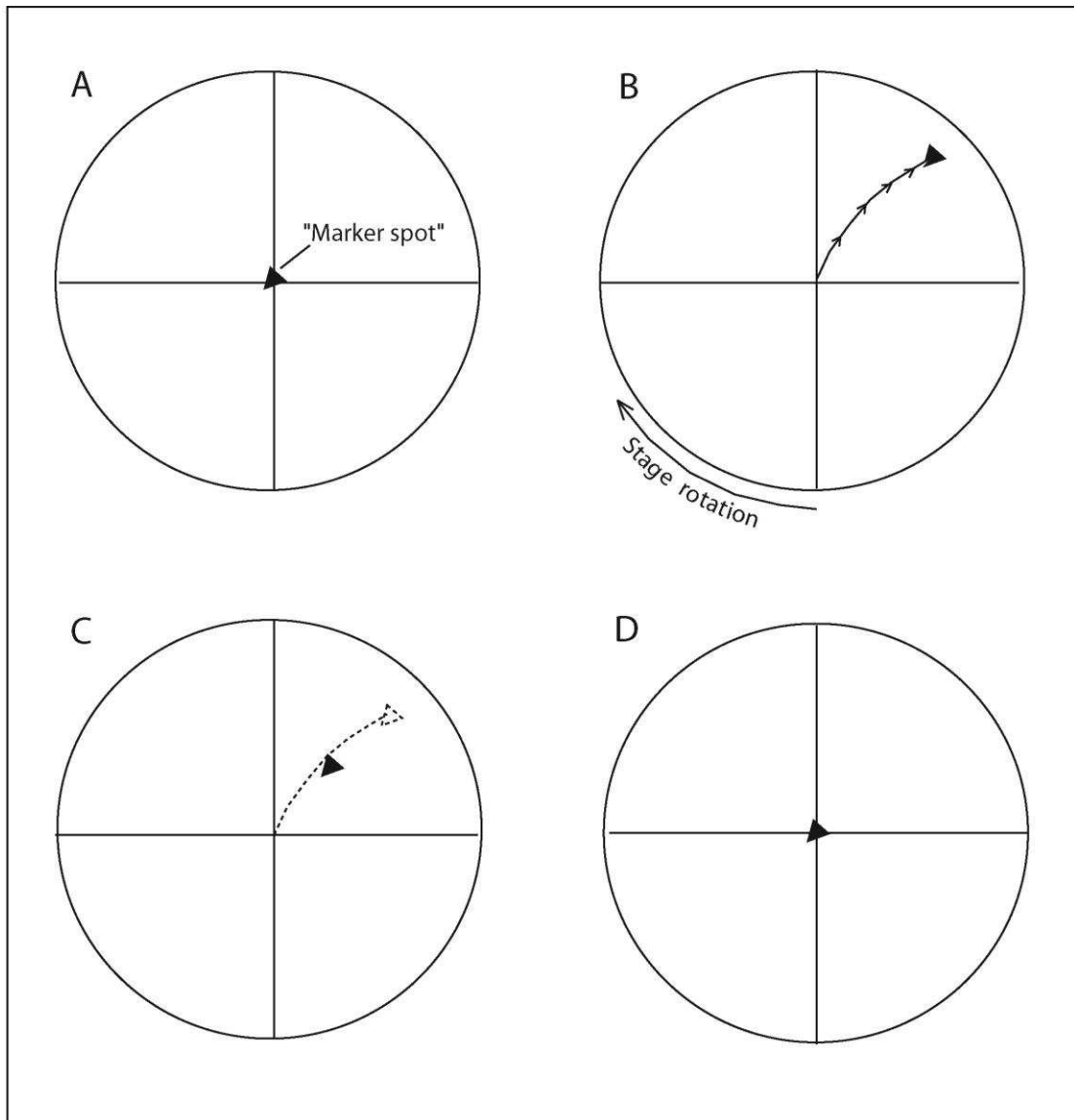


Figure 2.4 Diagrams to illustrate the procedures for centering the microscope stage and objective lenses.

should first check the microscope stage which is the easiest to do.

Centering screws for the stage are normally in place on either side of the stage perimeter (Figure 2.3). First, put a section on the stage, and place a small grain or imperfection (a "marker spot") under the cross-hairs (Figure 2.4A). Then, rotate the stage slowly about 90° clockwise, and you will observe the grain rotate out away from the cross-hairs, as shown in Figure 2.4B. Now, re-position the "marker spot" a distance halfway back to the cross-hairs you began with, working both of the centering screws at the same time (Figure 2.4C). Move the slide again, placing the "marker spot" under the

cross-hairs again (Figure 2.4D), and repeat this operation 4-5 times or until the marker spot remains centered under the cross-hairs during a full stage rotation. If this does not remedy the alignment problem, then you know that the objective lens is not centered!

To center the objective lens, a different set of screws have to be inserted into the body of the objective lens or turret (Figure 2.3). Working both screws together, repeat the same centering operation that you did for the stage. Once you have centered the objective lens, your alignment problem should now be corrected.

Microscope Dealerships

There are several dealerships of microscopes around the country. Here in Golden, Colorado we have an excellent company Leica dealer, North Central Instruments, who has been of service to the Colorado School of Mines for many years.

Several of the photomicrographs in this book were taken with the Leica DM2500P polarized light microscope equipped with both transmitted and reflected polarized light; Pol incident light illuminator (four positions), polarizer and rotating analyzer, Smith prism (Leica exclusive), N Plan EPI Pol objectives 5x/0.12, 10x/0.25, 20x/0.40, 50x/0.75 and eyepiece 10x/25 were used for reflected light pictures. The Leica DFC 290 digital color camera (3.0Mp, 2048 x 1536 pixels), not shown in Figure 2.5, was used for digital image capture using the Leica LAS software for capture, annotation, and measurement of images.



Figure 2.5 Leica petrographic microscope, Model DM2500P, equipped with both transmitted and reflected light capabilities.

3.0 PREPARATION OF POLISHED THIN SECTIONS

The preparation of polished thin sections is an art, and one of the best technicians in the business is Mark Mercer, petographics@montrose.net, who has done many for me, and whom I have asked to write this short chapter.

Introduction

The microscopic study of rocks and minerals is greatly enhanced with a well prepared polished or doubly-polished petrographic thin section. Both transmitted and reflected light microscopy benefit from a low relief, highly polished surface with minimal scratching and pitting. Additionally, fluid-inclusion, microprobe and other micro-analytical studies require properly polished surfaces for optimal results. The following is a brief description of the technique I have developed over the past 30 years in the thin-section laboratory to produce high quality polished rock and mineral surfaces.

Rock Sample Preparation

The first and critical step to successful thin-section preparation is the proper handling of the rock specimen to be sectioned. The rock must hold together well and not produce a plucking situation anytime throughout the thin-sectioning process or the quality of the end result will be comprised. One must judge the condition of the rock specimen and treat it in a manner that will stabilize and hopefully preserve the natural fabric of the rock.

Rocks that are well indurated are cut to size using a continuous diamond blade on a common tile cutting saw with water as a coolant (oil coolants are troublesome and contaminate the sample). The cut rock chip is known as a *billet* and is normally rectangular in shape (approximately 18 x 30 mm). Samples that are friable, fractured, strongly foliated, or that consist of loose particles (cuttings, mineral separates, etc.) must first be stabilized by impregnation with a low viscosity epoxy under vacuum and/or high-pressure conditions. The rock sample is placed in a disposable plastic mold (available in various sizes) prior to epoxy impregnation. Rocks must be thoroughly dried on a hot plate prior to impregnation as water degrades the integrity of the epoxy. In the case of samples to be used in fluid inclusion work where excessive heat may damage the inclusions, the samples must be air dried for 24-48 hours. The curing of epoxies produces an exothermic reaction and heat is generated that can damage the inclusions. As a consequence I use only epoxies that cure at room temperature and do not accelerate their cure times. Additionally, most petrographers like the epoxy to be colored (a blue tint is normally used) so as to highlight porosity and fractures that may be present in the sample.

Once the rock sample billet has been satisfactorily prepared (with or without epoxy impregnation) it is then lapped down on a cast iron lapidary wheel using a water-based slurry of aluminum oxide grits of 220 (rough grinding) and 600 (fine grinding) particle sizes. Care must be taken to get a flat surface on the finished billet as any concavity or convexity on the billet will create wedged edges on the final section. A flat billet to within tolerances of a few microns is essential for producing good quality thin sections. To help alleviate this common problem it is important to have the lapidary wheels routinely trued for flatness at a machine shop every few months. The lapped billets are then cleansed and allowed to dry overnight.

Thin Section Preparation

The rock billet is glued to a frosted petrographic-sized (26 x 46 mm) microscope slide using a high quality mounting epoxy. I use epoxy that is used in the aerospace industry that has excellent adhesion properties. Slides are frosted using the 600 grit aluminum oxide slurry discussed above rather than factory frosted slides because they tend to be deeply etched and produce undesirable air bubbles in the mount. After curing the slides overnight the excess rock billet is trimmed off using the diamond blade end of a double arbor thin section machine like the one shown in Figure 3.1. The remaining rock thickness after trimming (1-2 mm) is then ground down using the diamond cup wheel side of the machine. The rock is ground to a remaining thickness of approximately 120-150 microns. Any more removal of rock will result in fracturing of brittle mineral grains such as quartz and feldspar. It has been my experience that thin section machines that finish a thin section to final thickness (30 microns) using mechanically controlled diamond cup wheels usually damage the mineral grains, sometimes severely. I “hand finish” the slide to final thickness using the aforementioned lapidary wheel setup and 600 grit slurry as a cutting agent. The cast iron wheel and slurry are much “softer” on the minerals and man-induced damage is minimized. During this grinding phase I continuously check the section for correct thickness using a monocular polarized microscope. In fluid inclusion doubly-polished sections the procedures are the same except the section is usually left substantially thicker (80-200 microns) and the mounting agent is generally cyanoacrylate glue instead of epoxy. Once the thin section has been satisfactorily lapped to 30 microns, the section is cleaned in water and taken to the polishing room which should be separate from the cutting and grinding area of the laboratory (Figure 3.1).

Polishing Procedure

Polishing the thin section is normally done using synthetic diamond compounds that are oil-based and oil is used as a lubricant. I prefer synthetic diamond over natural diamond compounds which tend to polish slower, producing higher relief in the finished section. The diamond polishing method generates some heat and this is a problem with low-temperature fluid inclusion samples. When heat must be avoided aluminum oxide polishing compounds are used.

Polishing is simply the placing of successively finer and finer scratches across the rock surface of the thin section. Following the initial grind to 30-micron thickness the thin

section will have pervasive scratches of approximately 14 microns in size. A 3-step polishing process is initiated as follows:

Rough Polish Step

An 8-inch brass polishing lapidary wheel is tightly covered with a low-nap nylon polishing cloth. About one inch of 6-micron diamond paste is squeezed from a plastic syringe and dabbed in a checkerboard fashion across the cloth with several drops of polishing oil as a lubricant. (Isopropanol is used as a solvent when using oil-based compounds). The section is held in a special thin section holder that allows the technician to lap the section in a direction opposite of the rotating wheel while applying downward pressure. The holder itself should be rotated regularly to balance the polishing effort of the diamond-impregnated cloth across the rock surface. The section should be routinely checked under a reflected-light microscope during this rough polishing step. This step should be continued until the pits are smoothed out of the mineral grains. Quartz is typically the hardest mineral present and can be used to gauge the progress of the rough polish step. As the pitting disappears from the harder minerals it should be noted that the softer sulfides will still look relatively scratched. This step normally takes 6-12 minutes to complete for each section.

Fine Polish Step

Following the same procedures as in the first step, a 1-micron diamond paste is used in this step. Significant progress will be noticed during this procedure with all the minerals becoming smooth and their shared boundaries are much sharper and distinct. Very soft minerals such as native gold, copper, galena, and molybdenite will still look somewhat scratched, but much improved over the previous step. This step normally takes 3-6 minutes to complete.

Very Fine Polish Step

A medium-napped polish cloth is now placed on the brass wheel and a 0.05-micron water-based slurry of de-agglomerated aluminum oxide is used as the polish agent. This step finalizes the polishing procedure and the softer minerals will now appear well polished. This step should not be overdone as it can impart some relief to the overall polished thin section and is normally done for only 30 to 60 seconds. Longer periods of time will produce undesirable relief differences between soft and harder minerals.



Figure 3.1 Three steps in the preparation of a polished thin section 30 microns in thickness.

Summary

The polishing procedure described above should result in high quality polished thin sections which will satisfy most petrographers and mineral analysts. Shortcuts do not exist when polishing thin sections and the time and patience that are required to obtain the desired quality of polish naturally vary from one rock/mineral suite to another. As with all laboratory work, there is always a gremlin lurking about to befuddle the technician, and seemingly unexplainable problems arise from time to time. Normally these can be worked out by sticking to procedure and following clean laboratory techniques at all times. And lastly, the experience factor weighs heavily in this endeavor; the more polishing one does the better the results.

4.0 ORE MINERALOGY

In the broadest sense, ore consists of any solid that can be mined at a profit. In the more restricted sense, as used in this book, ore constitutes one or more minerals that are opaque to transmitted light, and therefore have to be studied with reflected light. Not all ore minerals are opaque, however; cassiterite, sphalerite, and a few others are notable exceptions. Furthermore, pyrite and marcasite are very common sulfides, yet

they are not considered ore in the normal sense, since they are not mined for their metallic content.

Ore minerals are commonly classified on the bases of chemical composition, crystal structure, and cation-anion ratio, such as MX, MX₂, M₂X, where M = metal cation, and X = the anion, S or O (Stanton, 1972). The major chemical groupings of ores include native metals, sulfides, sulfosalts, and oxides. The more important tellurides, tungstates, and arsenides are also included here.

NATIVE METALS

As the name suggests, the native metals represent single elements that are uncombined in nature. This group includes the precious metals, gold and silver, and copper. These metals are all of cubic symmetry (isometric), and show properties associated with metallic bonding. Their densities are high, ranging from 8.9 to 19.3 (gold). Gold and silver form a complete solid solution series, but the solubility of copper in gold is limited to about 20 weight percent. If gold contains 20 percent or more of silver, the compound is referred to as “electrum”. The greater the concentration of silver, the whiter the appearance of electrum. Microscopically, the diagnostic feature of this group is their high reflectivity. Silver has the highest reflectivity of all ores—about 95%; the reflectivity of gold is 74. Although these minerals are cubic, gold is anisotropic and silver may become anisotropic with substitution of antimony. These minerals are also soft and therefore easily scratched and require very careful polishing (Stanton, 1972).

SULFIDES AND SULFOSALTS

Chemically the sulfides represent ores where the metal cation is bonded to the sulfur anion. Sulfosalts, on the other hand, represent double-metal sulfides, where two metals are combined with sulfur, e.g., the ruby silvers, proustite and pyrargyrite. The sulfides may be further subdivided on the basis of crystal structure. Major sulfide structural groups are named after their common sulfide, and include argentite, sphalerite, wurtzite, niccolite, spinel, pyrite, marcasite, krennerite, and skutterudite groups.

Argentite Group

The most important members of this group are argentite, naumannite, hessite, digenite, eucarite, petzite and aguilarite (Figure 4.1). Since argentite, Ag₂S, inverts to acanthite below 179°C, acanthite is the more common phase in nature. Microscopically, the main features of this group are their softness and low to moderate reflectivity. Argentite/acanthite is the softest of all known naturally occurring sulfides. It is also the

most important primary source of silver, is a common component of lead-zinc sulfide ores, silver-silver sulfosalt veins, and copper sulfide ores.

Name	Formula	Crystal System	Density	Polishing Hardness	Reflectivity % (in air)
Argentite	Ag ₂ S	Cubic 179°C	7.0-7.4	Very soft	30-31
Acanthite	Ag ₂ S	Orthorhombic <179°C		Very soft	
Naumannite	Ag ₂ Se	Cubic 133°C			~35
Hessite	Ag ₂ Te	Cubic 149.5°C	8.2-8.5	Very soft	39-41
Digenite	Cu ₂ -xS	Cubic	5.55	~galena	21-24
Eucairite	CuAgSe	?Cubic at High T	7.6-7.8	Very soft	~30
Petzite	Ag ₃ AuTe ₂	?Cubic at High T	8.7-9.0	Very soft	37
Aguilarite	Ag ₄ SSe	Cubic at High T	7.6	Very soft	35

Figure 4.1 Chemical compositions and physical properties of the argentite group.

Chalcocite Group

This group includes chalcocite, stromeryite, and richardite (Figure 4.2). Chalcocite is by far the most abundant; both richardite and stromeryite are noted for their beautiful colors, particularly richardite. Chalcocite, however, is pale blue to white in color; under crossed polars, it may appear a very pale pink to light emerald green. Richardite features colors of bright orange, yellow, and blue.

Chalcocite is a very important ore found in supergene enrichment zones, particularly those of porphyry copper deposits worldwide. Richardite is commonly found in gold-silver telluride veins, while stromeyerite is not common.

Galena Group

The galena group includes the minerals galena, clausthalite, altaite, alabandite, and oldhamite; galena is the only common member of this series (Figure 4.3). All members are cubic, and feature six-fold coordination of anions about the cations; all members feature excellent cleavage parallel to the {001} plane. Galena is easily distinguished microscopically by its creamy white color, moderate reflectivity (44%), and triangular cleavage pits.

Galena is present in almost all base metal ores. Altaite and clausthalite are found in many gold and silver telluride and selenide deposits. Alabandite occurs with other manganese minerals in some sulfide ores.

Name	Formula	Crystal System	Density	Polishing Hardness	Reflectivity % (in air)
Chalcocite	Cu ₂ S	Orthorhombic	5.5-5.8	~galena	~30
Stromeyerite	CuAgS	Orthorhombic	6.2-6.30	<galena	26-30
Richardite	Cu ₂ Te	Tetragonal	7.5	very soft	~25

Figure 4.2 Chemical compositions and physical properties of the chalcocite group.

Name	Formula	Crystal System	Density	Polishing Hardness	Reflectivity % (in air)
Galena	PbS	Cubic	7.58	~chalcocite	44
Clausthalite	PbSe	Cubic	7.8	<<galena	26-30
Altaite	PbTe	Cubic	8.15	<galena	~25
Alabandite	MnS	Cubic	4.0	<sphalerite	~25
Oldhamite	CaS	Cubic	2.58		Translucent

Figure 4.3 Chemical compositions and physical properties of the galena group.

Sphalerite Group

Members of the sphalerite group are also cubic. Principal members include sphalerite, hawleyite, metacinnabar, tiemannite, and coloradoite; *derivative* phases include chalcopyrite, stannite, tetrahedrite-tennantite, famatinite, and enargite. Sphalerite and chalcopyrite are the most common members of this group (Figure 4.4).

All of these minerals are rather soft and of low reflectivity; sphalerite has the lowest reflectivity of 17-20%. Sphalerite, (Zn,Fe)S, features excellent 6-directional cleavage in hand specimen, however, this is never observed in reflected light. Iron substitutes easily in the sphalerite structure with increasing temperature, thereby affecting its physical properties, notably its light to dark brownish color. Sphalerite commonly features

internal reflections as well from yellow to red. The mineral becomes opaque with the substitution of about 10% Fe. Twinning is also common in sphalerite, which is enhanced with etching. Low Fe sphalerite is semi-transparent, and should be studied under transmitted light.

Chalcopyrite is a very common copper sulfide, found in all kinds of sulfide deposits. Microscopically it is distinguished by its pure yellow color and relative softness—much softer than pyrite.

Tetrahedrite-tennantite is usually a minor constituent of base metal sulfide deposits and is generally associated with arsenopyrite in lead-zinc ores. Stannite is a rare mineral, but may occur as intergrowths with chalcopyrite and tetrahedrite-tennantite in sphalerite.

Name	Formula	Crystal System	Density	Polishing Hardness	Reflectivity % (in air)
Sphalerite	ZnS	Cubic	4.09	>chalcopyrite	17-20
Hawleyite	CdS	Cubic	4.87	?	
Metacinnabar	HgS	Cubic	7.65	<cinnabar	25
Tiemannite	HgSe	Cubic	8.30-8.47	<<galena	~30
Coloradoite	HgTe	Cubic	8.04	<calaverite	34
"Derivative" members					
Chalcopyrite	CuFeS ₂	Tetragonal	4.1-4.3	>galena	44-49
Stannite	Cu ₂ FeSnS ₄	Tetragonal	4.3-4.5	>chalcopyrite	26-29
Tetrahedrite- Tennantite	(Cu,Ag,Fe) ₁₂ Sb ₄ S ₁₃ (Cu,Ag,Fe) ₁₂ As ₄ S ₁₃	Cubic	4.6-5.1	>>galena	31-33 27-31
Famatinite	Cu ₃ SbS ₄	Tetragonal	4.50-4.65	>galena	
Enargite	Cu ₃ AsS ₄	Orthorhombic	4.45	>galena	25-29

Figure 4.4 Chemical compositions and physical properties of the sphalerite group.

Wurtzite Group

Members of this group include the minerals wurtzite, the hexagonal dimorph of sphalerite, greenockite, cubanite, emplectite, chalcostibite, and sternbegite. All are quite rare, except cubanite, CuFe₂S₃, which is found in nickel sulfide ores, along with pyrrhotite and pentlandite.

Nickeline Group

The nickeline group (formerly niccolite) includes nickeline, NiAsS, breithauptite, NiSb, and pyrrhotite, Fe_{1-x}S (Figure 4.5). Members of the group are characterized by the nickel arsenide structure, a hexagonal close-packed arrangement in which the cations and anions are in six-fold coordination with each other. Pyrrhotite, the most common member of the group, is a non-stoichiometric compound which is deficient in Fe; in several nickel deposits, Ni may occupy the Fe vacancies and be considered a nickel ore. It also occurs in both hexagonal and monoclinic symmetries.

In reflected light, pyrrhotite is a distinct brownish pink, nickeline a light copper color, and breithauptite, reddish with a mauve tint. All three minerals feature a strong natural color with very strong anisotropism, and beautiful interference colors. Under crossed nicols, pyrrhotite ranges from brown to greenish gray, niccolite from bright tan to brilliant apple green, and breithauptite from bluish green to violet-red.

After pyrite, pyrrhotite is the most abundant sulfide in the Earth's crust. It is found in all rock types, and in a wide variety of base and precious metal deposits; it tends to be the iron sulfide of copper ore, while pyrite is the most common iron sulfide of lead-zinc ores (Stanton, 1972). Niccolite is most common in hydrothermal veins, particularly those with native silver, and Co-Ni arsenide assemblages. In massive sulfide deposits, niccolite is associated with chalcopyrite, cubanite, and other phases. Breithauptite is commonly associated with nickeline in hydrothermal vein ores.

Name	Formula	Crystal System	Density	Polishing Hardness	Reflectivity % (in air)
Niccolite	NiAs	Hexagonal	7.78	>chalcopyrite	49-53
Breithauptite	NiSb	Hexagonal	8.23	hard	37-48
Pyrrhotite	Fe_{1-x}S	Hexagonal	4.58-4.65	>>chalcopyrite	34-39

Figure 4.5 Chemical compositions and physical properties of the nickeline group.

Pyrite Group

The list of minerals with the pyrite structure totals 13 in number, but only pyrite is common and important (Figure 4.6). In this group that features cubic symmetry, sulfur atoms are in six-fold coordination about each iron atom, and iron is in six-fold

coordination with each sulfur pair. Many of these minerals, including pyrite, are hard, due to the combination of both metallic and covalent bonding.

Members of the group consistently develop crystal faces, ie., they are *idiomorphic*, or euhedral, and most are not strongly colored; pyrite is a clear pale cream, sperrylite a bright white, and cobaltite is white with a pale pinkish tint. For reasons unknown, pyrite may be anomalously anisotropic. Pyrite is common in all types of rocks, and is a common vein constituent along with precious metal and base-metal sulfides.

Name	Formula	Crystal System	Density	Polishing Hardness	Reflectivity (in air)
Pyrite	FeS ₂	Cubic	5.0	v.high	54
Cattierite	CoS ₂	Cubic	?		33
Vaesite	NiS ₂	Cubic	?		31
Hauerite	MnS ₂	Cubic	3.46		25
Sperrylite	PtS ₂	Cubic	10.58		55-56
Aurostibite	AuSb ₂	Cubic	9.98		?
Laurite	RuS ₂	Cubic	6.23		42-43
"Derivative" members					
Bravoite	(Ni,Fe,Co)S ₂	Cubic	4.62		31-52
Penroseite	(Ni,Cu,Pb)Se ₂	Cubic	7.56		31-52
Cobaltite	(Co,Fe)AsS	Cubic	6.33		56
Gersdorffite	(Ni,Fe,Co)AsS	Cubic	5.82		
Ullmanite	(Ni,Co,Fe)(Sb,As,Bi)S	Cubic	6.65		45
Willyamite	(Ni,Co)SbS	Cubic	6.87		?

Figure 4.6 Chemical compositions and physical properties of the pyrite group.

Marcasite Group

Members of the marcasite group are orthorhombic, and include marcasite, FeS₂, loellingite, FeAs₂, safflorite, (Co,Fe)As₂, rammelsbergite, NiAs₂, arsenopyrite, (Fe,Co)(As,Sb)S, glaucodot, (CoFe)AsS, and gudmundite, FeSbS (Figure 4.7). Marcasite and arsenopyrite are the most common members.

Marcasite is the dimorph of pyrite, with the S atoms in six-fold coordination about the Fe cations. It is a low-temperature form of FeS₂ and generally forms under acid conditions. At higher temperatures pyrite is the stable form. Marcasite forms in near surface, generally acidic conditions, commonly as encrustations, concretions, or as replacements of fossils. It may also result from inversion of pyrite, and is also a common low-temperature alteration product of pyrrhotite (Stanton, 1972). Microscopically,

marcasite is distinguished from pyrite by its whitish color, bireflection pleochroism, and bright green anisotropic colors.

Name	Formula	Crystal System	Density	Polishing Hardness	Reflectivity (in air)
Marcasite	FeS ₂	Orthorhombic	4.89	>pyrrhotite	47-53
Loellingite	FeAs ₂	Orthorhombic	7.40		55
Safflorite	(Co,Fe)As ₂	Orthorhombic	7.20		55-60
Rammelsbergite	NiAs ₂	Orthorhombic	7.10		60
"Derivative" members					
Arsenopyrite	(Fe,Co)(As,Sb)S	Orthorhombic	6.07		51-52
Glaucodot	(Fe,Co)AsS	Orthorhombic	5.90		50-52
Gudmundite	FeSbS	Orthorhombic	5.90		50-52

Figure 4.7 Chemical compositions and physical properties of the marcasite group.

Arsenopyrite is the most abundant and widespread arsenic mineral. It occurs most commonly as a hydrothermal vein mineral; it also occurs in granitic rocks and as a constituent of contact metamorphic zones, and in lead-zinc deposits. At Homestake, Lead, SD, it is a major constituent of the gold-bearing ore zones of the Homestake Formation. Under the microscope arsenopyrite is white, and shows strong shades of blue, green, and brownish-yellow anisotropic colors. Arsenopyrite also is quite hard, of moderate reflectivity (51-52) and has a strong tendency to form rhombic-shaped crystals, as seen in the Homestake ores and elsewhere.

OXIDES

The oxide ores are those in which one or more metal cations are joined with oxygen. The principal metals in this group include iron, manganese, chromium, tin, and uranium. Cassiterite, the main ore of tin, differs from the rest in being semi-transparent.

The oxide ores are further subdivided into four groups, based on crystal symmetry: spinel (cubic), with 3 series; hematite (hexagonal); rutile (orthorhombic); and uraninite (cubic).

Spinel Group

Natural spinels are subdivided into three end-member series: spinel, —Al₂O₃; magnetite, —Fe₂O₃; and chromite, —Cr₂O₃. Extensive solid solution is common within each series, but is uncommon between them (Figure 4.8).

The spinel series ($\text{MO} \cdot \text{Al}_2\text{O}_3$) consists of spinel, hercynite, gahnite, and galaxite, where $\text{M} = \text{Mg}^{+2}$, Al^{+2} , Zn^{+2} , or Mn^{+2} ; the magnetite series ($\text{MO} \cdot \text{Fe}_2\text{O}_3$) includes magnesioferrite, magnetite, franklinite, jacobsite, and trevorite; and the chromite series is comprised of chromite and magesiochromite. We will cover only the most common phases—magnetite and chromite (Figure 4.9).

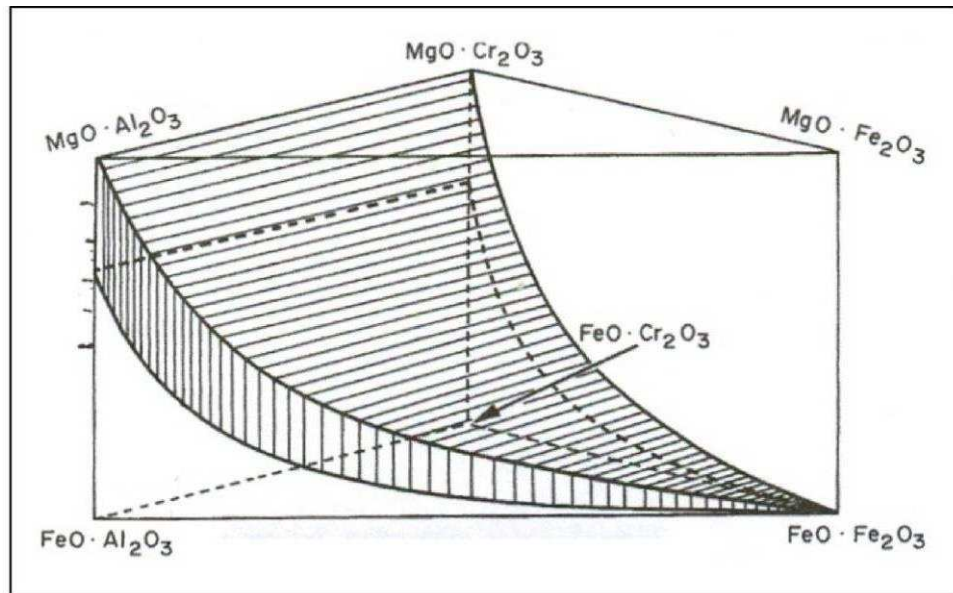


Figure 4.8 Solid solution fields of the spinels. Redrawn after Stevens, 1944.

Name	M^{+2}	Crystal System	Density	Polishing Hardness	Reflectivity (in air)
Spinel series ($\text{MO} \cdot \text{Al}_2\text{O}_3$)					
Spinel	Mg	Cubic	3.58	High	7-8
Hercynite	Al	Cubic	4.39	High	Low
Gahnite	Zn	Cubic	4.62	High	Low
Galaxite	Mn	Cubic	4.03	High	Low
Magneite series ($\text{MO} \cdot \text{Fe}_2\text{O}_3$)					
Magnesioferrite	Mg	Cubic	4.51	High	Low
Magnetite	Fe	Cubic	5.20	High	21
Franklinite	Zn	Cubic	5.07-5.22	High	18
Jacobsite	Mn	Cubic	4.0	High	19-20
Trevorite	Ni	Cubic	5.20	High	Low
Chromite series ($\text{MO} \cdot \text{Cr}_2\text{O}_3$)					
Chromite	Cr	Cubic	5.09	>magnetite	11-13
Magnesiochromite	Mg	Cubic	4.5-4.8	High	Low

Figure 4.9 Chemical compositions and physical properties of the spinel group.

In reflected light, both are isotropic; chromite is gray, but much darker than magnetite, which is pale gray. Magnetite is the most widespread oxide mineral and occurs in all rock types. Chromite, however, is restricted to ultramafic rocks—either dunites and peridotites of alpine-type intrusions, or the mafic and ultramafic layers of large differentiated bodies, such as the Stillwater Complex, MT, and the Bushveld Complex, South Africa.

Hematite Group

Members of the hematite group include hematite, Fe_2O_3 , ilmenite, FeTiO_3 , and corundum, Al_2O_3 . Corundum is not an ore mineral, so we will consider only hematite and ilmenite (Figure 4.10). Hematite and ilmenite are hexagonal; in ilmenite half the Fe atoms of hematite are replaced by Ti. The two minerals form a solid-solution pair, and both phases are characterized by low reflectivity and gray color. Ilmenite is the darker of the two. Hematite is commonly difficult to polish, whereas ilmenite usually takes a good polish.

Both minerals are anisotropic, with hematite producing gray-blue to yellow tints under crossed polars; ilmenite polarization colors are green to brownish gray. In addition, hematite usually exhibits intense red internal reflections (Stanton, 1972).

Name	Formula	Crystal System	Density	Polishing Hardness	Reflectivity % (in air)
Hematite	Fe_2O_3	Hexagonal	5.26	>>magnetite	26-30
Ilmenite	FeTiO_3	Hexagonal	4.79	>magnetite	16-20
Corundum	Al_2O_3	Hexagonal	3.98	very hard	transparent

Figure 4.10 Chemical compositions and physical properties of the hematite group.

Hematite is a common primary mineral in vein deposits, particularly epithermal deposits and porphyry systems. It is also very widespread in sedimentary rocks, and is also a very common alteration product of iron-bearing silicates and other minerals. Ilmenite is generally restricted to mafic rocks, such as gabbros and anorthosites, and is also found in beach sands.

Rutile Group

The rutile group includes the isostructural tetragonal minerals rutile, TiO_2 ; cassiterite, SnO_2 ; pyrolusite, MnO_2 , and plattnerite, PbO_2 , a rare lead oxide (Figure 4.11). Because of the large differences in cation sizes, there is little tendency to form solid-solutions in this group. Microscopic characteristics of this group include low reflectivity and colors from white (pyrolusite) to dark gray (cassiterite and tantalite-columbite). Both pyrolusite and rutile exhibit distinct pleochroism. Under crossed polars, rutile, cassiterite, and tapiolite all show internal reflections that are normally deep red-brown in rutile; yellow to red-brown in tapiolite; and pale yellow to yellow-brown in cassiterite.

Rutile is a common accessory mineral in igneous rocks, in veins, and in high-grade schists, gneisses, and contact-metasomatic rocks (Stanton, 1972). Pyrolusite is found in low-temperature, highly oxidizing conditions, such as lakes, bogs, and near-shore marine environments with other manganese and iron oxides.

Cassiterite is widely associated with granites, as topaz-cassiterite or “greisen” altered rock, and also occurs in high-temperature pegmatitic and hydrothermal veins.

The colloform variety of cassiterite is known as “wood tin”, in resemblance to growth rings in wood. Wood tin from the Black Range, New Mexico, which is best studied under transmitted light, commonly features cassiterite with intergrown hematite, and silica locally, in a wide variety of colors that have chemical significance; darker red and brown colors as seen in transmitted light reflect higher concentrations of Fe, apparently substituting for Sn in the crystal structure of the very fine-grained cassiterite (Lufkin, 1977).

Owing to its resistance to chemical weathering and its high specific gravity, cassiterite and wood tin form major accumulations of placer deposits, such as those found in southeast Asia.

Name	Formula	Crystal System	Density	Polishing Hardness	Reflectivity % (in air)
Rutile	TiO ₂	Tetragonal	4.25	~chalcocite	20-24
Pyrolusite	MnO ₂	Tetragonal	5.06	<<galena	27-47
Cassiterite	SnO ₂	Tetragonal	6.99	<galena	11-13
Plattnerite	PbO ₂	Tetragonal	9.42	hard	17
"Derivative" members					
Tapiolite	FeTa ₂ O ₆ - Fe(Nb,Ta) ₂ O ₆	Tetragonal	8.17	hard	15-18
Columbite	(Fe,Mn)(Nb,Ta) ₂ O ₆	Orthorhombic	5.48	hard	15-18

Figure 4.11 Chemical compositions and physical properties of the rutile group.

Uraninite Group

Uraninite, UO₂, and thorianite, ThO₂, are the only important members of the uraninite group. Both are cubic, with a fluorite structure, and form a complete solid-solution series. Furthermore, these minerals are not distinctive in reflected light. Reflectivities are very low, and both are dull gray in color, similar to magnetite. Both are isotropic but may show brown internal reflections (Stanton, 1972).

Uraninite most commonly occurs in granites, syenites, and related pegmatites, in veins, and in large stratiform disseminations. In veins it commonly develops a colloform texture, known as "pitchblende". Major ore bodies of uraninite have been developed in the Precambrian quartz-pebble conglomerates of the Witwatersrand in the Transvaal and Blind River, Ontario.

Thorianite is localized in granitic pegmatites, but its most common occurrence is in heavy mineral sands, along with monazite, zircon, rutile, and ilmenite (Stanton, 1972).

TELLURIDES

Unoxidized telluride minerals (henceforth referred to as tellurides) are rare, usually softer than gold, totally opaque, generally smaller than 1 mm in greatest dimension, but possibly more widespread than commonly believed because they have been understudied (Bruce Geller, pers. comm.). The best indications that tellurides are present in an ore sample are an anomalously high geochemical assay (generally >1 ppm Te), or the presence of fairly bright grains in freshly sawed ore slabs that exhibit numerous subparallel saw blade scratches under stereoscopic examination at

magnifications of 15x or greater. Chemical compositions of the gold-silver tellurides are shown in Figure 4.12.

The exact identification of telluride minerals in a given sample is usually difficult without preparing a polished section and studying it with micro-analytical techniques at magnifications of 50x to 400x. Furthermore, telluride-bearing polished sections commonly contain more than one telluride phase.

The optical properties that are particularly useful when discriminating tellurides include anisotropic intensity, colors under crossed polarizers, and extinction behavior; relative white light reflectivity and color; and the presence or absence of polishing cleavage pits, twinning, and grain shape. Chemical etch tests, micro-indentation tests, and micro-beam analyses are discouraged before careful petrographic examination and photomicrography because such tests mar carefully prepared polished surfaces.

A cursory literature search reveals that there is a decent correlation between the date when a telluride was first discovered and the number of deposits in which it has been reported. This being said, the seven most commonly reported tellurides on Earth (in increasing order of scarcity) are: hessite (Ag_2Te), tetradyte ($\text{Bi}_{14}\text{Te}_{13}\text{S}_8$), sylvanite (AuAgTe_4), altaite (PtTe), calaverite (AuTe_2 with minor Ag), petzite (Ag_3AuTe_2), and native tellurium, Te (Geller, 1993; Bruce Geller, pers. comm.)

Krennerite Group

The major gold-silver tellurides form the krennerite group, which includes krennerite, $(\text{Au},\text{Ag})\text{Te}_2$; calaverite, AuTe_2 ; and sylvanite, $(\text{Au},\text{Ag})\text{Te}_2$ (Figure 4.13). Krennerite is orthorhombic, and calaverite and sylvanite are monoclinic. There is a high degree of metallic bonding in this group, which results in softness and high reflectivity of each mineral. Under the microscope, all three tellurides are creamy white, and show weak to distinct bireflection pleochroism and strong anisotropism. Krennerite exhibits yellow to brown colors under crossed polars; sylvanite, light gray to dark brown, and calaverite, light to dark gray, with greenish and brown tints. Calaverite is commonly mispronounced; the accent is on the first syllable, since the mineral is named for Calaveras County, California..

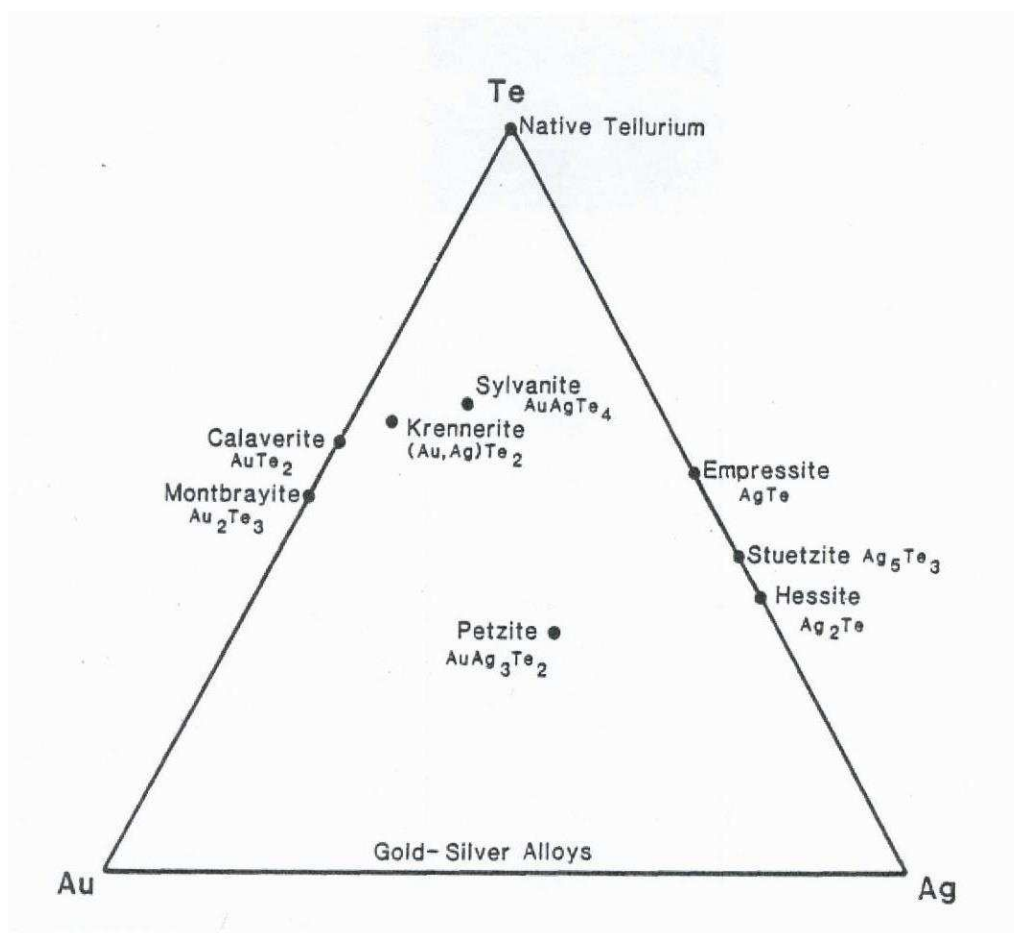


Figure 4.12 Compositions of the gold-silver tellurides. After Saunders, 1986.

Name	Formula	Crystal System	Density	Polishing Hardness	Reflectivity (in air)
Krennerite	(Au,Ag)Te ₂	Orthorhombic	8.62	>calaverite	72
Calaverite	AuTe ₂	Monoclinic	9.24	sl. <galena	64-65
Sylvanite	(Au,Ag)Te ₂	Monoclinic	8.16	>>argentite	50-58

Figure 4.13 Chemical compositions and physical properties of the krennerite group.

5.0 QUALITATIVE METHODS OF MINERAL IDENTIFICATION

There are two fundamental types of mineral identification in reflected light microscopy—*qualitative* and *quantitative*. My comments here are devoted only to the qualitative aspects of mineral identification, for several reasons. First, the equipment—

Microhardness Testor and Reflectometer—are very expensive. Secondly, they are difficult to obtain. For example, even the U.S. Geological Survey in Denver has not had this equipment in use since the retirement many years ago of Ben Leonard, a leading practitioner of the art. And thirdly, this book is designed for the student and exploration geologist who want to quickly learn the basic methods of mineral identification. For a very good discussion on the quantitative methods, however, the interested student is referred to the work of Craig and Vaughn (1994).

Minerals under the microscope are generally viewed in either linearly polarized, or plane polarized light, or under crossed polars (nicols). The older microscopes used carefully prepared optical grade calcite, or Nicol prisms to produce polarized light. More recently, thin sheets of polaroid film accomplish the same result and are much cheaper. Ore minerals may also be viewed through oil or water immersion objectives, which requires additional time.

Optical Properties

Optical properties include color, reflectance, birefractance, reflection pleochroism, anisotropism, and internal reflection. Color, reflectance, birefractance, reflection pleochroism are properties that are observed under linearly or plane-polarized light. Anisotropism and internal reflection, however, are best viewed under crossed polars.

Color

Only a few opaque minerals are distinctly colored in reflected light, eg., gold, bornite, chalcopyrite, and covellite. Other minerals are typically white, or shades of gray. The appearance of color is particularly influenced by proximity to other minerals. For example, chalcopyrite next to gold appears a greenish-yellow.

The beginning ore microscopist is often confused by “tarnishing”. Several ores, particularly native copper, silver, bornite, and a few others tarnish easily by oxidation. Native copper oxidizes to a brownish color; silver to black; and bornite, pink when fresh, but commonly tarnished to shades of blue, lavender, or purple. Overpolishing of mineral sections also may change the color of some minerals, such as chalcopyrite, which becomes white when overpolished.

Reflectance

Reflectance, or “brightness”, is defined as the ratio of intensity of reflected light to the intensity of incident light, where

$$\text{Reflectance (R\%)} = \frac{\text{Intensity of reflected light (x100)}}{\text{Intensity of incident light}}$$

The reflectance of an opaque mineral varies with 1) orientation, 2) wavelength of light, and 3) the angle of incidence of light (which is normally perpendicular to the specimen). For qualitative purposes, it is best to compare unknowns with minerals of known reflectivities. For example, magnetite R% ~20; galena R% ~43; pyrite R% ~55, etc. Transparent minerals and oxide phases have low reflectivities, eg., quartz, calcite, and other gangue minerals, R%~5.

Bireflectance and Reflection Pleochroism

All minerals crystallize in one of six crystal systems. These systems, in order of decreasing symmetry elements, are: isometric (cubic), hexagonal, tetragonal, orthorhombic, monoclinic, and triclinic. Minerals crystallizing in the cubic system, such as galena, sphalerite, chromite, and magnetite, remain unchanged in reflectance and color when the stage is rotated, regardless of mineral orientation. Most minerals that crystallize in the other five systems do show changes in reflectance and/or color upon stage rotation. The change in reflectance is called *bireflectance*, and the change in color is referred to as *reflection pleochroism*, or simply pleochroism. When looking down the c-crystallographic axis of hexagonal or tetragonal minerals, that particular orientation will yield an isotropic section, which produces no change in reflectance or color. The quality of change in either of these properties is generally described in terms of “very weak, weak, moderate, strong, and very strong”. Examples of minerals that feature strong bireflectance are graphite, molybdenite, stibnite, and covellite; ilmenite and arsenopyrite exhibit weak bireflectance.

Anisotropism

From your course in optical mineralogy, you will remember that isotropic minerals transmit light with equal velocity in all directions; the same is true for reflected light optics. Minerals that reflect light with different velocities, depending upon orientation, are called *anisotropic*.

With the polars crossed, isotropic minerals remain dark, or extinct, upon 360° rotation of the stage. Anisotropic minerals, however, under crossed polars, will exhibit variations in brightness and/or color, when the stage is fully rotated. Depending upon crystallographic orientation of the specimen, the anisotropic effects of both reflection and

color may range from nil to maximum. As before, these changes in anisotropic effects are termed “very weak, weak, moderate, strong, and very strong”.

As with bireflectance and pleochroism it is important to examine, where possible, a number of grains to see the maximum effect of anisotropism. Also, for reasons unknown, some isotropic minerals, like pyrite, feature “anomalous” anisotropism. Polishing scratches in soft, isometric metals like gold, silver, and copper, produce similar anomalous phenomena.

Internal Reflection

Several minerals, like sphalerite, cassiterite, and chromite are intermediate in their opacity, and allow vertically incident light to penetrate their surfaces along cracks or other flaws in the mineral, and reflect light back as characteristic colors. These colors are known as *internal reflections*. For example, sphalerite produces colored internal reflections of yellow to brown, commonly related to its iron content; cinnabar, deep red; cassiterite, yellow brown to yellow; and hematite, deep red.

Internal reflections are best observed under crossed polars and with high illumination. Not all grains of the same mineral species show this phenomenon, however. Internal reflections are enhanced with the aid of an oil immersion objective and high-power magnification (Craig and Vaughan, 1994).

Qualitative Hardness

Hardness of a mineral is its resistance to scratching, or abrasion. For qualitative determinations, there are two types of hardness—*polishing hardness* and *scratch hardness*. During the polishing process, harder minerals will stand out in relief, compared to softer phases that become “dished”, forming lower spots in the polished section. To determine the relative hardness between two adjacent grains, use is made of the *Kalb light line*, which is a line of “fuzzy” light that is produced upon reflection at the contact between two minerals of contrasting hardness. (Not to be confused with the *Becke line*, which is produced by refraction in transmitted light).

To observe the Kalb line, 1) focus on the boundary of two mineral grains, 2) lower the microscope stage slowly, as the specimen goes out of focus, and 3) observe the line of light that moves toward the softer mineral. It should be noted that this feature can be seen only where there is a significant relief and hardness difference between mineral grains.

Scratch Hardness

Scratches are invariably produced during the polishing process, and it takes considerable practice and patience to produce a scratch-free surface on opaque mineral specimens. Nevertheless, where scratches develop they can be useful in determining the relative hardness of different minerals in a given section. Naturally, softer minerals will exhibit deeper scratches than harder minerals. Where minerals of different hardness are in contact with each other, a scratch will commonly end at the contact of the softer mineral. If a scratch extends across the boundary of two phases, the softer mineral will show a deeper scratch than the harder one.

Structural and Morphological Properties

Structural and morphological properties of minerals include crystal form and habit; cleavage and parting; and twinning.

Crystal Form and Habit

Several ore minerals feature well-formed crystals, or *euhedra*, such as pyrite, hematite, magnetite, and arsenopyrite. Most opaques, however, do not feature crystal faces and are called *anhedral*. As with your previous studies in mineralogy, crystal habit is described in the familiar terms of cubic, octahedral, prismatic, colloform, etc.

Many opaque minerals feature characteristic habits, as follows.

Rhombic	arsenopyrite, marcasite
Acicular	hematite, stibnite, rutile
Isometric	cube—pyrite, galena octahedron—chromite, magnetite, pyrite
Tabular	covellite, molybdenite, graphite
Lath-shaped	ilmenite, hematite
Skeletal	magnetite, galena

Cleavage and Parting

Cleavage and parting generally are not seen in polished section, because the prime objective of the polishing process is to remove such imperfections in the mineral surface. Nevertheless, where cleavage and parting directions intersect, pits are commonly produced in the mineral surface due to plucking. The development of such pits depends both on the method of polishing and the orientation of the mineral grain relative to its

cleavage directions. For example, galena is readily identified by its characteristic triangular cleavage pits, due to the plucking that occurs at intersections of its perfect 3-directional cleavage directions. If a galena grain is polished parallel to one of its cleavage directions {100}, {010}, or {001}, however, the mineral will appear perfectly smooth, without any pits.

Twinning

The three major types of twinning in minerals are 1) growth, 2) inversion, and 3) deformation twins. Unlike the case with most transparent minerals, twinning in the ore minerals is generally obscured. Also, the mineral surface needs to be etched with various acids to see these features more clearly. Of the basic types of twinning, deformation twins probably are the most easily recognized. The interested student is referred to the classic works on experimental deformation of sulfide ores by Clark and Kelly (1973).

6.0 DECISION TREE FOR MINERAL IDENTIFICATION

Spry and Gedlinske (1987) have produced a very useful “decision tree” for the identification of ore minerals, and it is reproduced as Figure 6.1. Based both on optical and physical properties, the unknown mineral may be placed in one of twenty groups, listed below. Working through the branches of the tree, the observer first must decide whether or not the mineral is colored. If colored, the tree is followed downward along the left side of the diagram to the second decision—is the mineral pleochroic (bireflectant) under plane polarized light? If the mineral is strongly pleochroic, indicated by the symbol “+PL”, then the mineral falls into the Group 1 minerals listed in Table 6.1. If the mineral is weakly pleochroic or nonpleochroic (“-PL”), then the unknown mineral is placed downward into one of three groups, 2,3, or 4, based on the mineral’s anisotropism (either strongly, moderately, or weakly anisotropic) or isotropic. Thus, if the mineral is colored, it may wind up in one of four groups.

On the other hand, if the mineral is weakly- or non-colored, the choices are more abundant, depending further on the presence or absence of internal reflections (IR) and the mineral hardness (soft, S; medium, M, or hard, H). If the mineral is weakly- or non-colored, the mineral may be placed in any one of groups 6 through 20, depending upon the properties of pleochroism, anisotropism, internal reflections, and hardness.

The decision tree is far from infallible, and does not lead to a unique choice; it does narrow the field of choices considerably, however. For example, groups 4 and 5 still

CLASSIFICATION OF OPAQUE MINERALS

COLORED

- +PL**
 - 1
 - ++AN**
 - 2
 - +AN**
 - 3
 - AN**
 - 4
- PL**
 - AN**
 - 5
 - +IR**
 - 6 (S)
 - 7 (M)
 - 8 (H)
 - +IR**
 - 9 (S)
 - 10 (M)
 - 11 (H)
 - IR**
 - 12 (S)
 - 13 (M)
 - 14 (H)
 - +AN**
 - 15
 - +IR**
 - 16 (S)
 - 17 (M)
 - 18 (H)
 - IR**
 - 19
 - 20

WEAKLY COLORED

- PL**
 - AN**
 - 5
 - +IR**
 - 6 (S)
 - 7 (M)
 - 8 (H)
 - +IR**
 - 9 (S)
 - 10 (M)
 - 11 (H)
 - IR**
 - 12 (S)
 - 13 (M)
 - 14 (H)
 - +AN**
 - 15
 - +IR**
 - 16 (S)
 - 17 (M)
 - 18 (H)
 - IR**
 - 19
 - 20
 - +PL**
 - ++AN**
 - 15
 - +IR**
 - 16 (S)
 - 17 (M)
 - 18 (H)
 - IR**
 - 19
 - 20

NUMBERS IN CIRCLES = GROUP NUMBERS

PROPERTIES:

- + PL, strongly or moderately pleochroic
- PL, weakly pleochroic or nonpleochroic
- ++ AN, strongly anisotropic
- + An, moderately anisotropic
- An, weakly anisotropic or isotropic

- + IR, shows internal reflections
- IR, does not show internal reflections
- S, soft
- M, medium
- H, hard

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1	breithauptite covellite delafossite famatinite idaite luzonite mackinawite marcasite mawsonite niccolite valleriite	garnet jacobsite pyroxene quartz sphalerite tetrahedrite- tennantite uraninite wurtzite zincite	violarite	bournonite krennerite stromeyerite tetradymite
2	cubanite enargite millerite niccolite pyrrhotite	6 calaverite chalcocite djurleite freibergite galena silver tetradymite	9 pearcite realgar	17 antimony arsenic braggite cubanite enargite parar- ammelsbergite stannite
3	bornite chalcocite chalcopyrite bornite	7 allargentum carrolite coffinite cooperite maghemite maucherite pentlandite platinum tetrahedrite- tennantite	10 cuprite scheelite zincite	18 arsenopyrite ilmenite loellingite pyrolusite rammelsberite safflorite
4	bornite bravoite chalcopyrite copper digenite gold/electrum pyrite tetrahedrite- tennantite ulvospinel	8 bixbyite braunite carrolite chromite cobaltite gersdorffite jacobsite linnaeite magnetite pyrite seigenite skutterudite sperryite ullmannite	11 cassiterite columbite goethite hematite wolframite	19 cinnabar jamesonite lepidochrocite miargyrite orpiment pyrolusite- pyrargyrite psilomelane
5	alabandite amphibole biotite brannerite chromite columbite cuprite feldspar franklinite freibergite		12 acanthite argentite stephanite tetradymite	20 berthierite boulangerite calcite chalcophanite graphite mackinawite marcasite molybdenite stibnite tenorite valleriite
			13 bournonite chalcostibite dyscrasite gaucodot	
			14 braunite cobaltite	
			15 cassiterite cinnabar cuprite goethite hausmannite hematite manganite pearceite- polybasite realgar rutile zincite	
			16 bismuth bismuthinite boulangerite	

Table 6.1 Groups of ore minerals to fit into decision tree, previous figure. After Spry and Gedlinske, 1987, with permission.

7.0 ORE TEXTURES AND THEIR INTERPRETATION

Introduction

The study of textures is the most interesting and most important aspect of microscopic study, for it provides, if interpreted correctly, the most useful information in determining the origin and history of an ore deposit. As stated by Guilbert and Park (1986, p. 133), “Textural interpretation can assist greatly in determining the time relationships of successive mineral assemblages in the rock, and the overall environment of formation, and the manner of deposition. In epithermal deposits, textures can help define the sequence and nature of events...and they permit the distinction of mechanical and chemical controls...”

Texture is generally defined as the size, shape, and interrelationship of grains (in a rock). We will focus here on the interrelationships of grains. There is a wide range of textures discussed in the literature, and my remarks will be confined to the most common ones. The description of textures is commonly muddled by both students and experienced petrographers alike who use “time” words in their descriptions. For example, such “time words”, including *frequent*, *sometimes*, and *often*, should never be used in describing a rock texture. I chuckle when I remember the time when I used the term, *often*, in my Ph.D. thesis manuscript, and my supervisor at the time, Dick Jahns, remarked in red ink, “every third Tuesday?” Later, he rewarded me with the book, *Suggestions to Authors*, published by the U.S. Geological Survey—a very useful set of guidelines for writing geologic papers.

Also, there is the common tendency for petrographers and microscopists to *combine texture with process*. The literature is full of such erroneous descriptions as “exsolution texture”, or “replacement texture”, where process and texture are combined; they should always be separated from each other. For example, it is best to describe the texture first, e.g., intergrowth, disseminated, colloform, etc. ; then discuss the process, ie., exsolution, replacement, etc.

Before textures can be accurately assessed with any degree of confidence, the microscopist must be well grounded in several facets of mineral systems, including mineral refractability, pertinent experimental work, phase equilibria, and mineral solubility—all important topics that are not covered here.

Classification of Ore Textures

As pointed out by George Schwartz at the University of Minnesota over fifty years ago, the growth of the subject of ore microscopy has been rather haphazard since its beginning in the early 1900s. Little has changed since his time. In describing ores, texture and structure have been used interchangeably. In general texture refers to the size, shape, and arrangement of grains of one or more minerals which make up the ore mineral structure (in ore mineralogy); on the other hand, structure refers to the internal features of the mineral grain or single crystal, e.g., zoning of a crystal, or spherulitic structure (Schwartz, 1951).

The first paper to produce a classification of textures was published by Grigoriev in Russian with an English abstract. In his classification texture relates to features observed by the unaided eye and structure to the internal fabric.

In 1931 Schneiderhohn and Ramdor's book appeared, featuring a great range of textures and mineral structures in ores.

As also summarized by Schwartz, the classification of textures and structures of ore minerals is difficult because of the great variation in features resulting from complex processes involved in their origin and that many textures form in more than one way. Another complication is the fact that various investigators have used many different terms for similar looking textures (Schwartz, 1951).

In Schwartz' classification scheme, he recognized four categories: 1) primary, 2) secondary, 3) "exsolution textures", and 4) mineral structures. In his classification of primary textures, 22 types are listed, such as banded, caries, and cockade. In the secondary category, 17 terms are presented, including boxwork, brecciated, atoll, and so forth. For "exsolution textures", 6 examples are listed—cellular or mesh texture, emulsion, and eutectoid. In the fourth category involving mineral structures, 6 are identified, including cleavage, herringbone, and lamellar.

In this book I have followed much of Schwartz' original terminology and definitions of each texture. However, I prefer not to combine the description of texture with process, eg., "exsolution texture", or "replacement texture" which are commonly used in the literature. Most of these textures come under the heading of intergrowth textures, which I prefer. In any geologic report, texture should be described first, followed by the interpretation as to its origin.

The following terms for textures are descriptive, and most of the common textures in ore deposits are presented. They are listed in alphabetical order, and include atoll, botryoidal, colloform, caries, cumulate, deformed, dendritic, disseminations (also termed “emulsion”), flame, framboids, grain boundary segregations, lamellae/lamellar, lattice intergrowths, mutual boundary, net, symplectic (“chalcopyrite disease”), and vermicular (also termed myrmekitic or granophyric). Where known the definition of each texture is followed by a discussion of its commonly accepted mode of origin, and an appropriate photomicrograph or two.

Atoll texture

An atoll is an island consisting of a circular coral reef deposits that form on the rim of an underwater volcano. Thus, the texture describes the appearance of a ring of one mineral with another mineral, or minerals, within and without the ring; also known as a *core texture* (Figures 7.1). In the Mount Isa ore, cores of pyrite grains have been replaced by galena, sphalerite, and chalcopyrite, forming an atoll texture (Edwards, 1965).

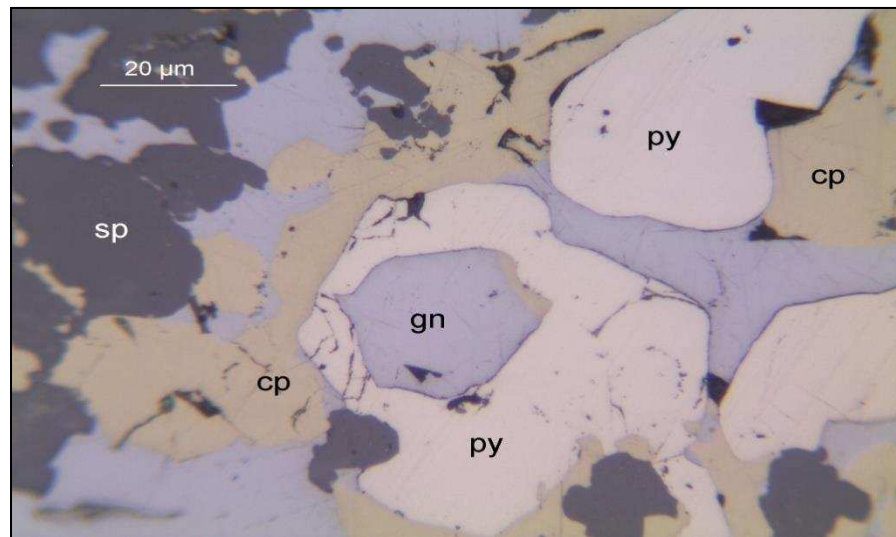


Figure 7.1 Atoll texture in pyrite, with core of galena (gn). Eskay Creek VMS deposit, BC. Polished section, ESC-19, courtesy of Murray Hitzman, CSM.

Banded, or layered texture

Generally a structure term, when developed on a large scale. Alternating bands of different minerals or variations in color within a mineral.

Botryoidal structure

Botryoidal is a structure term, referring to the outer surface of colloform textures that are smoothly convex outward, like a bunch of grapes (Figure 7.2). Similar terms include reniform and mammillary.



Figure 7.2 Botryoidal structure in goethite. Morocco.

Caries texture

Caries is a term derived from the French word for cavity. The terms, *cuspid* and *caries*, have been used to describe the concave reentrants, or indentations of one mineral against another (Figure 7.3). This texture is generally thought to result from replacement of the *host* mineral by the *guest* mineral, “as if the replacing mineral had bitten into the host” (Guilbert and Park, 1986, p. 141). I suppose it is possible that the cavity may result from incomplete growth of the host mineral, but there is no support for this notion in the literature. Caries texture is most commonly developed in pyrite, which is typically the first sulfide to form in ore deposits and has the very strong tendency to form euhedral, cubic outlines.

Cumulate texture

Cumulus or cumulate textures refer to grains that have settled out of a magma. Typical oxide ores include magnetite and chromite (Figure 7.4). Examples include the chromite ores of Stillwater Complex, the Bushveld Complex, and several others. Associated silicates, including olivine and pyroxene, also form cumulate textures.

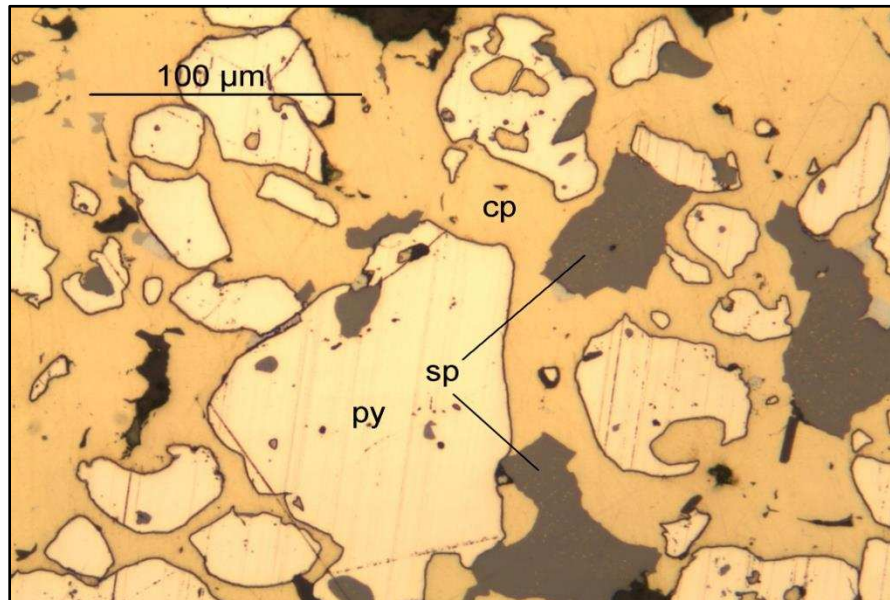


Figure 7.3 Caries texture in pyrite. Py, pyrite; cp, chalcopyrite, and sp, sphalerite. Specimen from Eskay Creek, courtesy of Murray Hitzman.

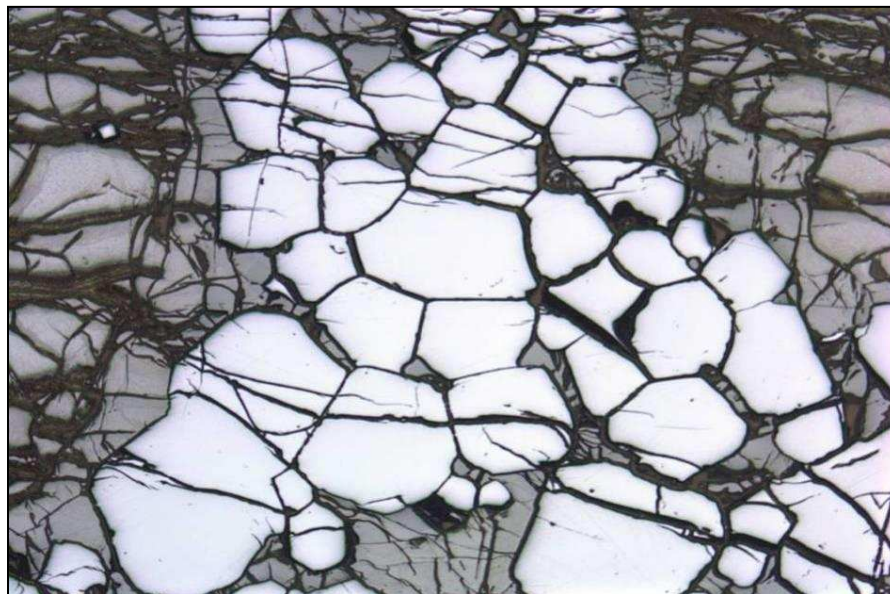


Figure 7.4 Annealed chromite cumulate grains with abundant triple junctions. Stillwater Complex, Montana. No. S2, 5x.

Cockade or ring texture

This texture is characterized by fragments of rocks or ore enclosed by successive crusts of other minerals.

Colloform

A word derived from the appearance of colloids or colloidal solutions. The texture describes both a radial and concentric growth of sub-microscopic to fine-grained minerals with a nodular or botryoidal surface (Figures 7.5 and 7.6). This texture is commonly developed in a number of minerals, including pyrite, sphalerite, wood tin (cassiterite), goethite, carbonates of copper, and many others.

Origin of Colloform Texture

The term “colloform” describes the mineral texture characterized by a series of concentric curved or scalloped layers, in which the curvature is always convex towards the younger or free surface (Edwards, 1954, p. 20). Although the grain size is not specified, the crystals may vary in length from microns to a few millimeters. Elongated crystals are oriented nearly perpendicular to growth layers. Outer surfaces of the texture are smoothly convex, reflecting the internal growth structure, and have been variously described as botryoidal, mammillary, or reniform. Other characteristics include the



Figure 7.5 Colloform and banded texture in wood tin, with interlayers of hematite (black). Black Range, New Mexico. Transmitted light.

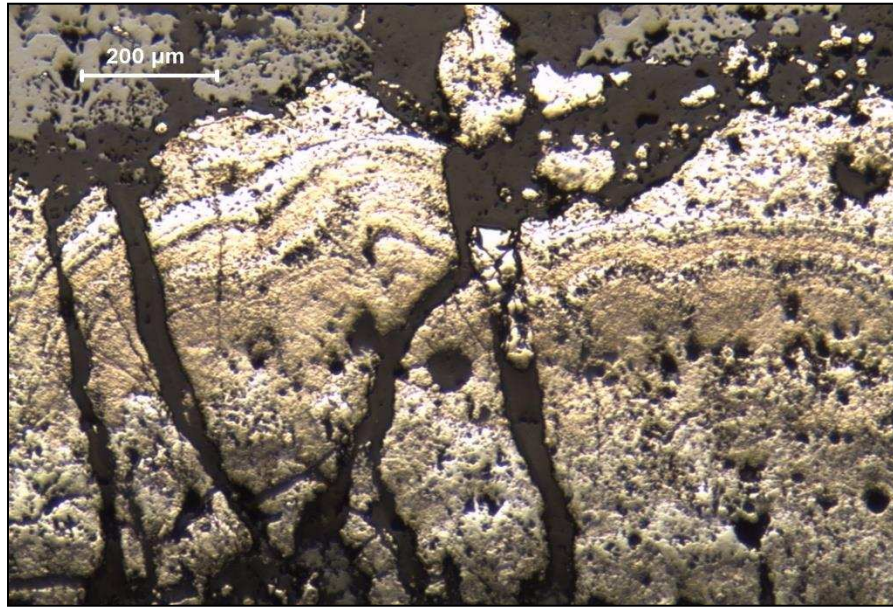


Figure 7.6 Colloform texture in pyrite. Reflected light.

common development of re-entrant angles between adjacent botryoids, and a fine layering, which is defined by variations in crystal size, mineral composition, and/or color (Roedder, 1968).

The term “colloform” was originally coined in reference to a presumed colloidal origin for this texture (Boydell, 1925), and the word has been used synonymously for colloidal deposition for many decades. For example, Knopf (1916, p. 658) interpreted the “broken ring-like forms” in wood-tin (colloform cassiterite) from Lander County, Nevada as having “resulted from the bursting of colloidal membranes by osmotic forces.” Much later, Roedder (1968) suggested that colloidal theory may not adequately explain this texture. Colloform texture as a non-genetic, descriptive term, however, still conveys a specific textural meaning to most geologists.

Colloform texture has been recognized and described in a variety of minerals. Edwards (1954) listed thirty-five hypogene and supergene minerals that may exhibit colloform texture. Common ore minerals of this listing are cassiterite (wood-tin), sphalerite, galena, pyrite, marcasite, psilomelane, and pyrolusite. Colloform gold was described by Zhirnov (1972), but this form of gold is rare.

The list of non-ore minerals developing a colloform texture is also extensive: silica, malachite, azurite, carbonates, speleothems, and others.

Colloform sphalerite is common in Mississippi Valley–type deposits (McLimens and others, 1980), and has been described from a number of localities world-wide (Roedder, 1968). In many instances, the colloform texture features intergrowths and layers of different minerals. For example, placer wood tin derived from veinlets in Tertiary rhyolite from the Black Range, New Mexico commonly exhibits hematite and silica interlayered with the cassiterite (Lufkin, 1977). In addition, color zoning in this wood tin correlates with iron content of the cassiterite. Similar deposits of wood tin are widespread in Mexico (Pan, 1974; Ypma and Simons, 1969).

Most of the controversy over the significance of colloform texture in ore minerals has centered on its mode of origin. For more than fifty years colloform texture was considered to have originated from colloidal systems (Knopf, 1916; Boydell, 1925; Bastin, 1950; Edwards, 1954; Park and MacDiarmid, 1975). The curved surfaces were considered to be “manifestations of surface tension effects in viscous material, and are therefore indicative, though not by any means exclusively, of colloidal origin” (Boydell, 1925). According to Edwards (1954), crystallization of a gel “results in the formation of radially arranged columnar crystals whose long axes are normal to the outer (free) surface of the layer. A free surface, if present, is typically smooth, commonly with a high gloss or luster, corresponding to the smooth ‘skin’ of a gel...This is evidence that crystallization proceeds from the free surface inwards.” Curvilinear cracks that are commonly associated with this texture have been cited as evidence for shrinkage of a gel during dehydration. Haranczyk (1962; 1971) has supported the role of colloids in the deposition of Silesian lead-zinc ores.

From a comprehensive study of numerous colloform lead-zinc ores from many localities around the world, Roedder (1969) cited evidence against a colloidal origin for most colloform textures. He questioned earlier conclusions about 1) surface tension, 2) the development of shrinkage cracks, and 3) concentric banding and radial structures.

According to Roedder, if surface tension causes the spheroidal shape, or botryoid, colloform layers should be of uniform curvature. Moreover, the effect of surface tension should also reduce re-entrant angles between adjacent botryoids. In fact, a wide range of radii of curvature do occur, and re-entrants are characteristic of colloform texture.

Regarding shrinkage cracks, Roedder noted that most gels contain 50 to 90 percent water, and upon drying, should reduce in volume by this much. The radial and/or concentric curvilinear cracks in colloform texture, however, rarely account for this much

contraction. Similar problems are encountered in explaining concentric banding and radial structure by some type of gel formation, or diffusion mechanism.

Roedder concluded that “the dominant parameter controlling the formation of colloform texture is a relatively high degree of supersaturation, resulting in relatively high rates of nucleation and crystallization” (1968, p. 468). In my opinion, I think that colloids and colloidal solutions have very little role, if any, to play in the transport and deposition of ore minerals.

Comb texture

This texture results from open-space crustification where crystals with long axes grow normal to walls of a vein. Quartz is a common example. Comb *structure* is used for larger-scale examples.

Deformed and Annealed Textures

Deformed ore, primarily sulfide ore, has been recognized and described since the early 1900s (Emmons, 1909, 1910; Lindgren and Irving, 1911; Ramdohr, 1928). However, widespread interest in these deposits did not begin until the 1950s. Since that time, a considerable number of both field and experimental studies has accumulated on the subject.

Experimental studies have played a vital role in the interpretational of deformed and annealed textures. The earliest experiments (Mügge, 1898; Adams, 1910) indicated that most of the common sulfides deform by brittle fracture at room temperatures and pressures. Later experiments at McGill University examined deformation mechanisms in sulfides at elevated temperature and pressure, and under variable strain rates (Gill, 1969; Davies, 1964; Krishnamurthy, 1967). More recent studies (Clark and Kelly, 1973; Kelly and Clark, 1975; Salmon et al., 1974; Rosco, 1975; Atkinson, 1975) have documented deformation mechanisms with compression tests on the common sulfides (pyrite, chalcopyrite, pyrrhotite, sphalerite, and galena) in terms of temperature, confining pressure, and strain rate and have established brittle-ductile transformations as functions of temperature and pressure. The role of fluids remains unknown in sulfide deformation, but probably is an important factor.

It wasn't until the 1960s that concepts already developed in metallurgy, e.g., interfacial free energy, grain boundary migration, work hardening, and annealing were applied to deformed sulfide deposits. Stanton and coworkers in Australia have made the

most substantial contributions in this area, particularly in the recognition of, and experimentation with, annealing and grain boundary migration in sediment-hosted base metal deposits (Stanton, 1964; Stanton and Gorman, 1968; and summarized in Lufkin, 1983.

Textures of Deformed and Annealed Ores

Textures that reflect deformation in ore minerals are readily recognized in polished section, provided the specimen has been properly etched. A list of common etchants is provided in several reference texts on ore microscopy (e.g., Cameron, 1961).

Brittle behavior, characterized by most sulfide and other ores at low temperature and pressure, is recorded by cataclastic, brecciated, or gangulated textures. Ore subjected to elevated temperature-pressure conditions deforms plastically, and these textures are featured by various combinations of twinning, translation gliding, and/or kinking.

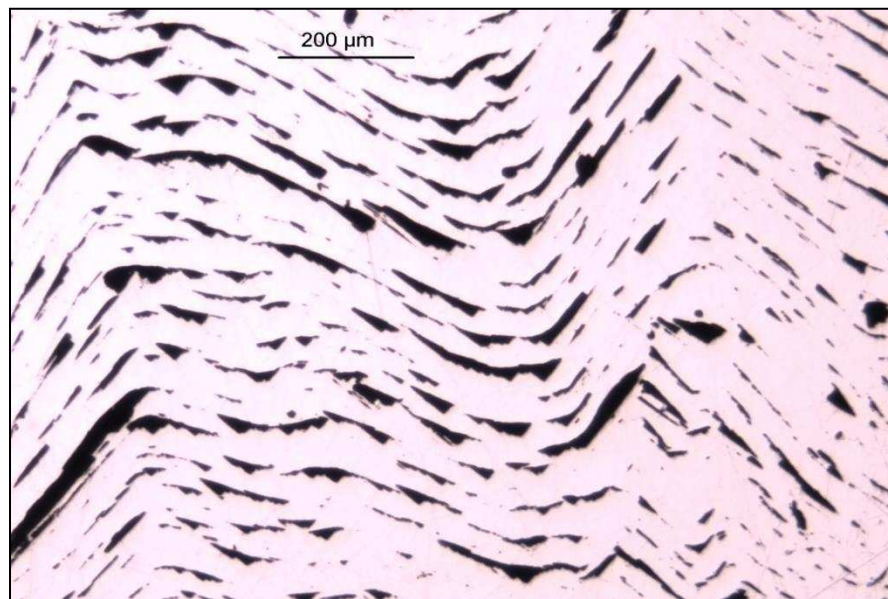


Figure 7.7 Plastic deformation with cleavage openings in galena. Specimen courtesy of Maritza Cantorin, Lima, Peru.

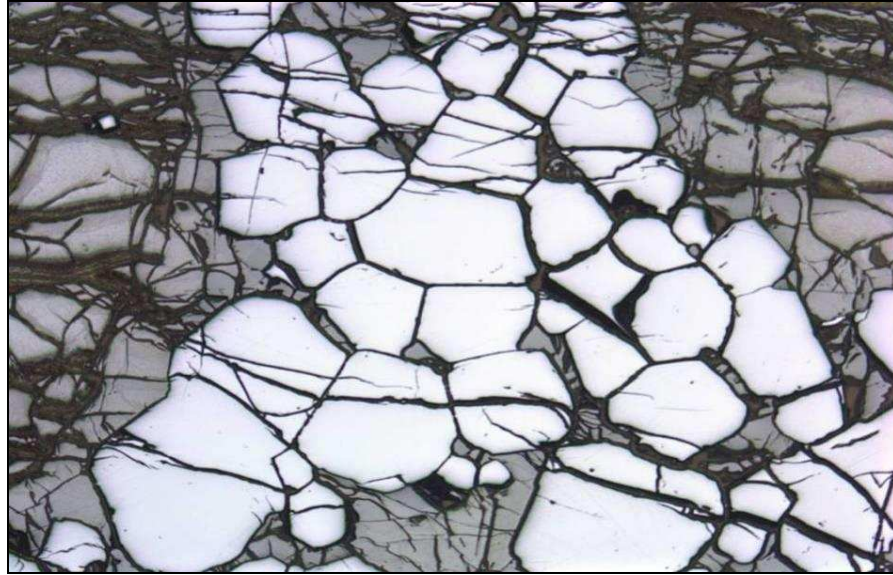


Figure 7.8 Annealed chromite cumulate grains with abundant triple junctions. Stillwater Complex, Montana. No. S2, 5x.

Differentiation of the different types of twins in sulfides may be difficult. The basic types have been clearly described and illustrated (Kelly and Clark, 1975; Clark and Kelly, 1973). Deformation twins developed experimentally in pyrrhotite {1012} form irregular, wavy or flame-like lenses, commonly at low angles to the maximum compression axis. These features form above 200°C, regardless of confining pressure. Sphalerite deformation twins {111} appear as straight, more elongate lens shapes, which commonly develop at high angles to the maximum stress direction. Chalcopyrite features thin, polysynthetic twins on {112} during deformation at 100°C, and higher. These twins, which typically develop at moderate angles to the principal stress orientation, commonly predate and truncate the thicker, lens-shaped twins parallel to {110} and {102} of non-deformational origin (Kelly and Clark, 1975).

Kink banding in sulfides results from the rotation of adjacent crystal domains by translation gliding. Kink bands form lamellae with generally straight, parallel borders. Kinking is common in pyrrhotite and galena, but not in sphalerite or chalcopyrite. In both experimentally and naturally deformed galena, cleavage openings in kink bands appear to be a unique deformation feature at low T-P conditions and are oriented subparallel to the maximum stress axis (Figure 7.7; Salmon and others, 1974).

The deformational textures discussed above are generally accompanied by changes in optical and physical properties as well. Deformed isotropic minerals become anisotropic, and commonly show variations in color, reflectivity, and microhardness.

Annealed textures are generally recognized by a) coarser grain size, b) smooth grain boundaries, c) development of near 120° interfacial angles, and d) little response to heat treatment, either in terms of grain boundary migration, or softening (Figure 7.8).

Approaches to textural equilibrium through the annealing process can be qualitatively determined by heating experiments. Ores that are not fully annealed will feature grain boundary migration during heating. In experiments on single phase sulfide aggregates, Stanton and Gorman (1968) measured triple-point junctions before and after heating galena, sphalerite, and chalcopyrite at different temperatures over different time periods. In all measurements after heating, the standard deviation from 120° angles was reduced, indicating grain boundary migrations toward the stable 120° triple-point configuration. Galena was annealed after 22 days at 300°C , and in only 10 days at 600°C .

Processes of Deformation and Annealing in Ores

The sulfide minerals pyrite, chalcopyrite, sphalerite, pyrrhotite, and galena, have received the most attention in deformation studies. My remarks are limited to this group of minerals. Numerous studies have established that sulfides may deform by several mechanisms, including slip, twinning, translation gliding, kinking, and lattice distortion. At low temperature and pressure, most of the common sulfides yield by brittle fracture; at elevated temperatures, the deformation is dominantly ductile, or plastic.

In the deformed state, as recorded by twins, kinks, etc., in sulfides, the crystal lattice is strained—a condition of high potential energy. In mineral aggregates, the process of eliminating this strain is called *annealing*.

Strength and the mechanism of deformation in the common sulfides are functions of several variables, including temperature, confining pressure, strain rate, porosity, and grain orientation. The nature and content of fluids and chemical composition probably are important factors as well. In general, the strength of sulfides decreases with increasing temperature and decreasing strain rate, but increases with increasing confining pressure. The presence of fluids probably reduces strength, but this parameter has not been studied (Kelly and Clark, 1973). Porosity reduces the strength of polycrystalline pyrite (Atkinson, 1975).

Studies of pyrite indicate that it generally exhibits brittle behavior over most T-P conditions. Confining pressure appears to be the main determinant of pyrite's strength (Graf and Skinner, 1970; Atkinson, 1975).

Deformation of pyrrhotite has been studied to 2,000 bars and 500°C (Clark and Kelly, 1973). Pyrrhotite deforms by microfracturing, translation gliding on {0001}, kinking, and twinning on {10 $\bar{1}$ 2}. At confining pressures of 1500 bars and above, pyrrhotite deforms at low temperatures by slip on {0001}. Its diagnostic deformation texture is twinning, which appears only above 200°C at all studied confining pressures. It becomes ductile above 1 kb pressure at room temperature, and above 240°C without stress.

Sphalerite deforms by microfracturing and by twinning and slip on {111} (Clark and Kelly, 1973). Kinking is rare. Deformation twins commonly form at 30-40° to the maximum compression axis; therefore, these features can be used to determine orientation of the stress field. Sphalerite may deform plastically in almost any direction, due to its 12 independent slip systems. The brittle-ductile transition of sphalerite is at lower pressure than that for pyrrhotite. It becomes ductile above 30°C at all pressures.

Chalcopyrite deforms by cataclasis with translation gliding on {112}. Perhaps the most diagnostic feature is polysynthetic twinning, also on {112}, which begins at 100°C at 500 bars, and increases in frequency at higher temperatures, with a loss of strength and increased ductility (Kelly and Clark, 1973). Kinking is also rare in chalcopyrite. The brittle-ductile transformation in chalcopyrite is similar to pyrrhotite; it becomes plastic above ~200°C at all pressures. Pure chalcopyrite will decompose in the 552° to 557°C range, depending upon composition (Barton, 1973).

The major deformation mechanisms in galena are translation gliding on {110} and associated kinking (Salmon and others, 1974). The most significant features are cleavage openings, which develop at low temperature and pressure, and are generally oriented parallel to subparallel to maximum stress (Figure 7.5). Kink bands commonly form below 300°C, and are oriented at high angles to the maximum stress direction. Thus, galena is a sensitive indicator in the low P-T environment. Galena is ductile, even at room temperature at 500 bars pressure (Salmon and others, 1974).

In the deformed state, the crystal lattice is strained—a condition of high potential energy. In mineral aggregates, the process of eliminating this strain is called annealing. As in metals, annealing in sulfides proceeds by sub-grain formation, *or polygonization*, in

which strain-free grains crystallize. This is commonly followed by grain coarsening and the tendency toward textural equilibrium. For fully annealed single-phase aggregates, textural equilibrium is expressed by interfacial angles (triple-point junctions) near 120° (Lawrence, 1972, 1973; Stanton, 1964; Stanton and Gorman, 1968).

Rates of annealing are functions of temperature, grain orientation, grain boundary impurities, and composition. Annealing is rapid in sulfides. For example, at 300°C, polycrystalline galena can be annealed in 23 days, sphalerite in 27 days, and chalcopyrite in 33 days (Stanton and Gorman, 1968). In terms of refractibility, then, chalcopyrite>sphalerite>galena. Equilibrium grain boundary configurations are attained by galena and sphalerite on the order of 100 days at only 100°C. Thus, given the relative ease of annealing common sulfides in the laboratory, one must wonder how deformed textures can be preserved over geologic time in the Earth's crust (Lufkin, 1983).

Problems of Interpretation

Although many common textures in deformed ores can be duplicated experimentally, e.g., twins, translation gliding, kinking, etc., most of these textures can form over a range of pressure and temperature, and therefore, are difficult to quantify in terms of these variables. Where preserved, some of these textures can be useful in determining stress orientations, e.g., open cleavages in galena, and deformation twins in pyrrhotite and chalcopyrite.

Experimental data have limited applications as well. Strengths and brittle-ductile transformations in sulfides determined experimentally must be viewed with caution, since experimental strain rates are about 8 orders of magnitude faster than those operating in nature (Clark and Kelly, 1973). Therefore, strengths determined in compression tests must be considered as maxima.

Another problem, particularly in the sulfide group, is *reequilibration*, both texturally and compositionally. Annealing processes in sulfides have been shown to be both common and rapid. Most ores that have been subjected to elevated temperature, therefore, will lose previous deformational fabrics through polygonization.

Furthermore, time sequences, or *parageneses*, cannot be determined in deformed sulfides. Embayments, caries, and infilling of softer sulfides around euhedral crystals, e.g., pyrite, arsenopyrite, magnetite, etc., are now to be expected, in light of the

crystalloblastic series developed for the sulfides (Stanton, 1964). Formerly, many if not most deformed textures were regarded as replacement features, and paragenetic relationships were established on the basis of idiomorphic development, i.e., minerals with well-developed crystal faces were considered paragenetically early, anhedral grains later in the sequence. As described well by Stanton (1964), the ability of a mineral to form crystal faces is related to packing density and bond strength. Thus, the degree of crystal face development reflects the mineral's place in the crystalloblastic series; in order of decreasing ability to form crystal faces, these are: magnetite-arsenopyrite, pyrite, pyrrhotite, sphalerite, chalcopyrite, and galena. In other words, magnetite and arsenopyrite have the greatest packing density and bond strength, and therefore, have the greatest ability to form crystal faces; galena has the least ability (Lufkin, 1983).

Dendritic texture

This texture is defined as a branching figure resembling a shrub or tree (Figure 7.9). A dendritic texture therefore is composed of branching limbs or dendrites. See Paul Barton, 1991, Mineralogical Magazine. Dendritic galena has been observed at Creede (Phil Bethke, pers. comm.)

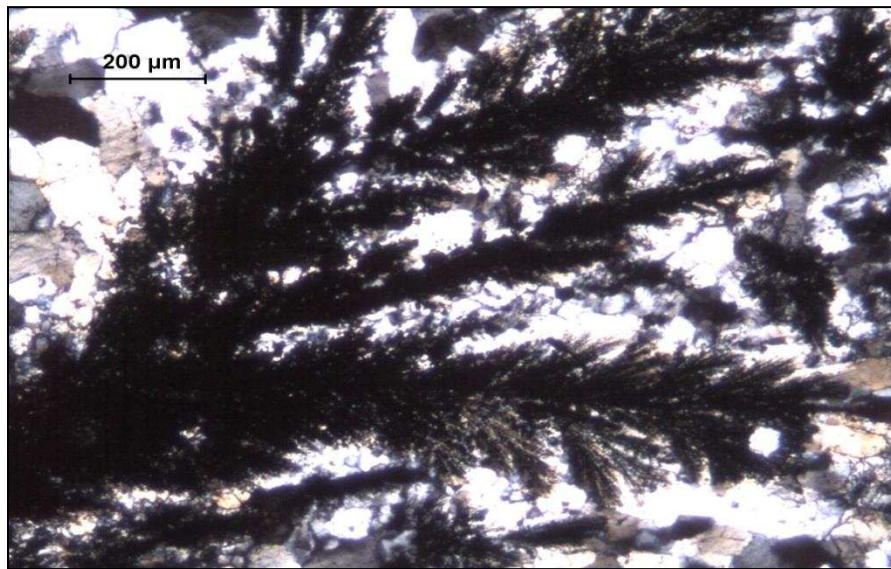


Figure 7.9 Dendritic sphalerite (black) from Red Dog, Alaska Pb-Zn-Ag deposit, Alaska. Polished thin section, RD698b, courtesy of Karen Kelley, USGS, Denver. Transmitted light.

Disseminated texture

A disseminated texture is one that features tiny grains scattered throughout the matrix of another mineral, or rock. Disseminated sulfides are very common in porphyry copper and magmatic Cu-Ni deposits. In Cu-Ni sulfide deposits, where the sulfides are not interconnected they are described as disseminated. The amount of sulfide present is generally between 1 and 33 modal percent (Barnes and Lightfoot, 2005). Another form of dissemination is known as “*chalcopyrite disease*.”

Chalcopyrite disease was first named by Paul Barton and Phil Bethke (Barton and Bethke, 1987), and refers to chalcopyrite disseminated in sphalerite. This texture has been described from several deposits, including MVT and Kuroko ores, but also known in some porphyry deposits (e.g., Butte Continental mine, Figure 7.10) and skarns (Figure 7.11). Disseminated pyrite in sphalerite (“pyrite disease”) is also known from the MVT deposit at Mina Plomosas, Chihuahua, Mexico (Figures 7.12 and 7.13).

The origin of chalcopyrite disease has been debated since the early 1980s, and the suggested processes of formation include exsolution, replacement, and epitaxial growth. In discussing only the sphalerite-chalcopyrite assemblage, the unmixing of chalcopyrite from sphalerite solid solution appears unlikely for low temperature ores, at least, due to

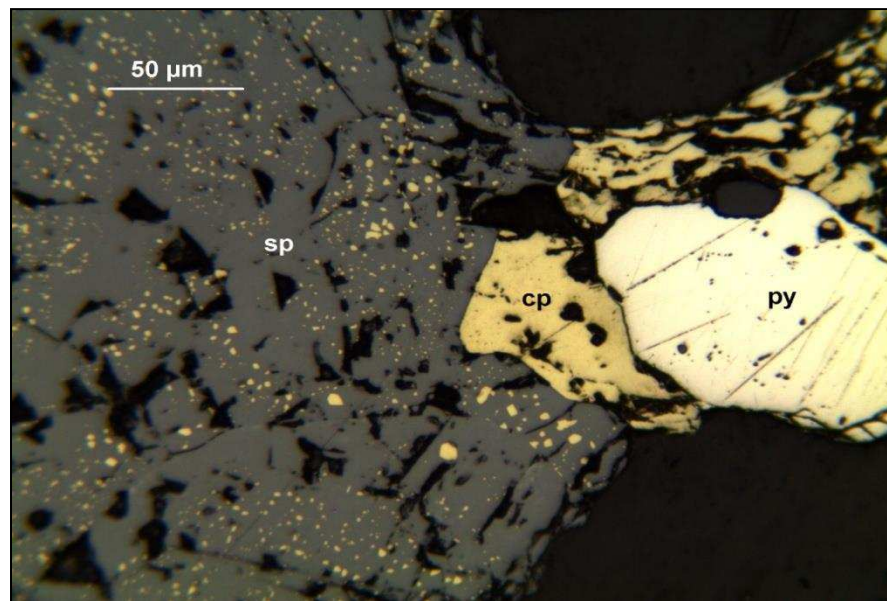


Figure 7.10 Chalcopyrite disseminated in sphalerite (sp); “chalcopyrite disease”. Continental Mine, Butte, Montana. Sample courtesy of Steve Czuhura, Montana Resources.

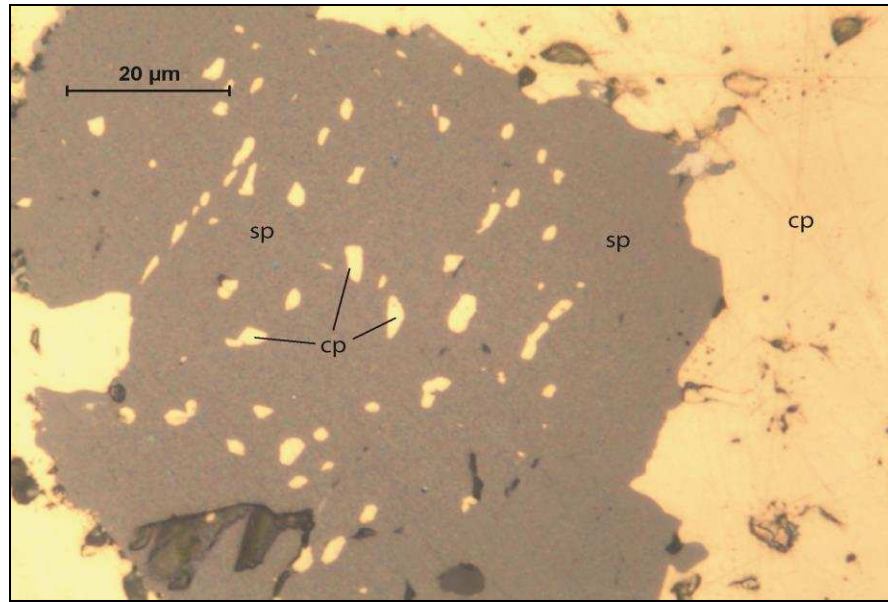


Figure 7.11 Oriented blebs of chalcopyrite (cp) in sphalerite (sp) from a porphyry copper skarn deposit, Arizona.

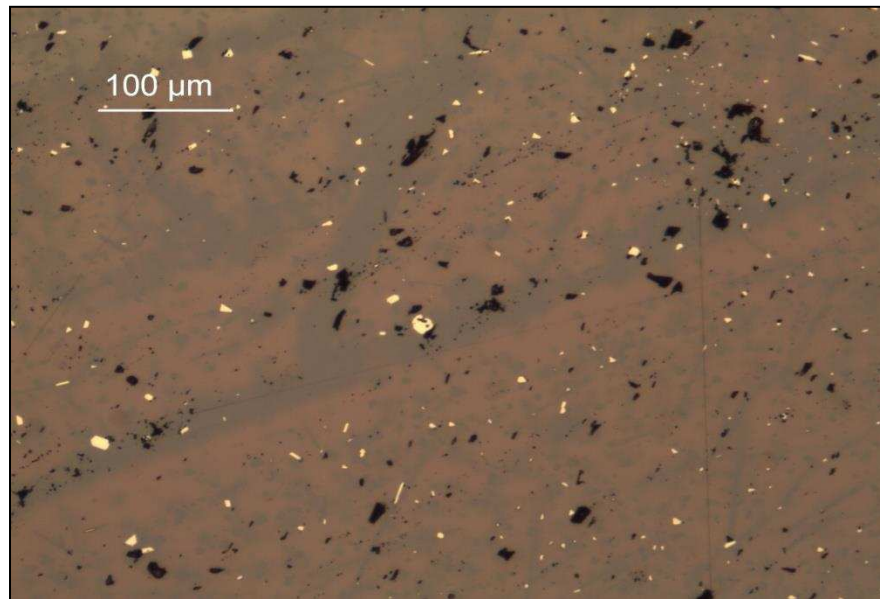


Figure 7.12 "Pyrite disease" in sphalerite. Mina Plomosas, Chihuahua, Mexico. Reflected light.

the low solubility of chalcopyrite in sphalerite (Wiggins and Craig, 1980; Hutchinson and Scott, 1980). Also, for low-Fe sphalerites common to MVT deposits, Barton and Bethke (1987) have shown, with the aid of doubly-polished thin sections and transmitted light,

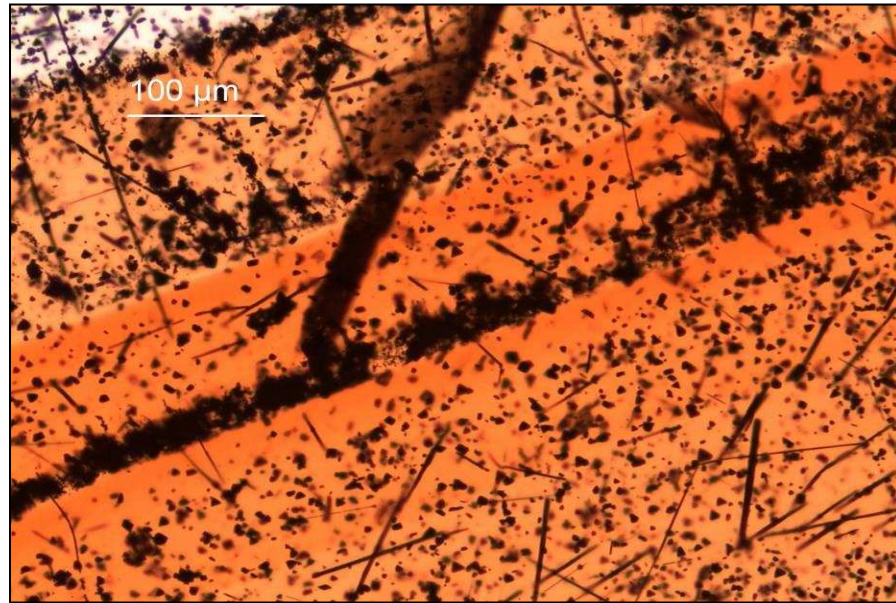


Figure 7.13 Same section, transmitted light. Notice that pyrite (black) now appears as discrete layers or as “needles” in this view, compared to “disseminations” shown in figure above.

that chalcopyrite blebs result either from epitaxial growth of chalcopyrite on sphalerite, or by replacement of sphalerite by copper-rich fluids after formation.

Steve Scott (pers. commun.) has also presented me with illustrations that indicate replacement of sphalerite by chalcopyrite adjacent a fracture in the host sphalerite (Figure 7.14).

The Replacement Process

Replacement processes have been recognized as characteristic phenomena in the formation of ore deposits. The results of replacement processes are dominant in a variety of mineral occurrences, including vein, skarn, and porphyry deposits (Figure 7.15).

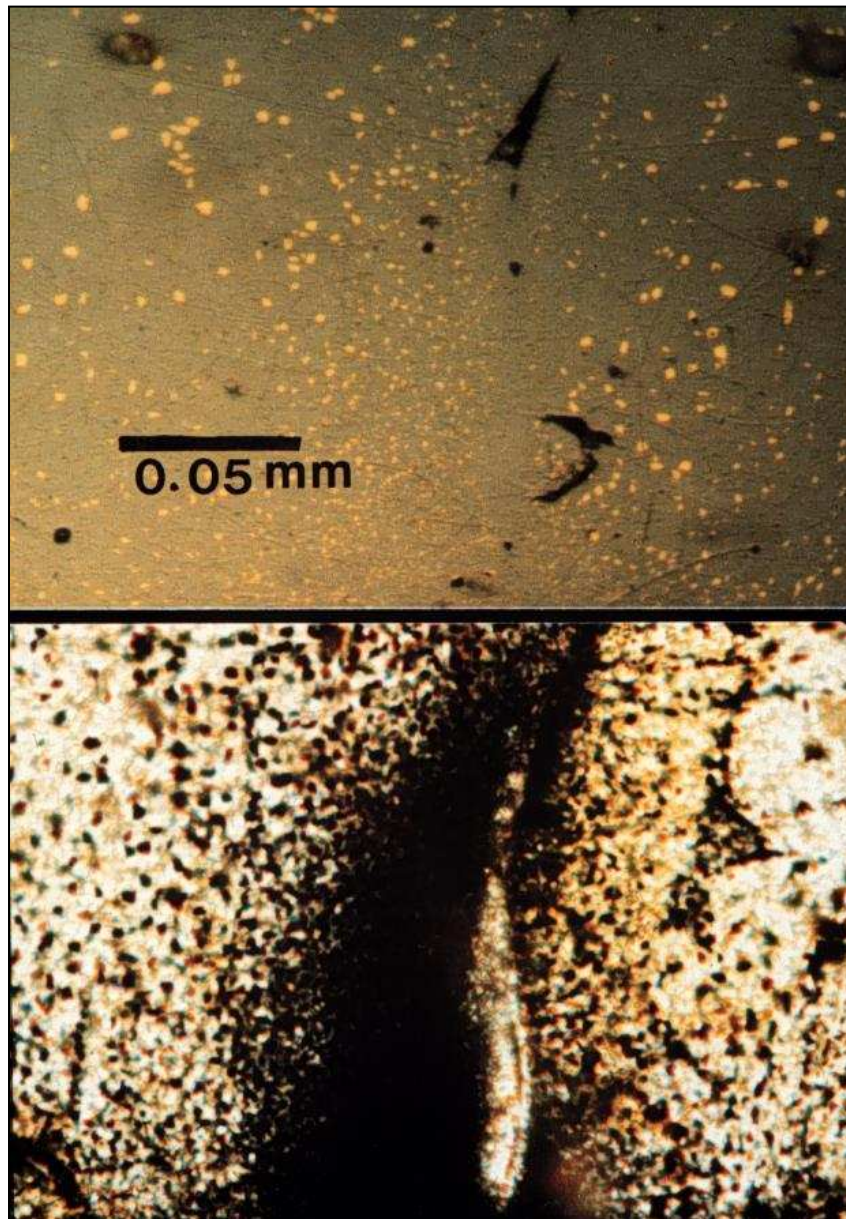


Figure 7.14 Disseminations of chalcopyrite in sphalerite. (Top) Disseminated chalcopyrite (yellow) in sphalerite, reflected light; (Bottom) Same view, transmitted light, showing prominent fracture in sphalerite, filled with chalcopyrite (black) that is disseminated outward from the crack; transmitted light. Photo courtesy of Steve Scott, University of Toronto.



Figure 7.15 Silver-bearing tetrahedrite veinlet in siderite, Crescent mine, Coeur d' Alene district, Idaho. Note selective replacement of carbonate by tetrahedrite, guided by rhombohedral cleavage. 5x.

Replacement occurs over a wide range of temperature, pressure, and depth, from hypogene to supergene environments. During the past seventy years, recognition of some replacement features in most types of ores has not been a problem, but understanding the processes of replacement and clearly distinguishing replacement from similar looking textures produced by exsolution and deformation remain as challenges to the petrographer and ore microscopist (Lufkin, 1983).

Criteria for Replacement

Many criteria for recognition of replacement features in ores have been advanced over the years. Perhaps the most complete list was compiled by Park and MacDiarmid (1975), who added to the earlier lists of Bastin and other (1931), Edwards (1954), and others. Included here is my "top 10" of the 20 criteria presented by Guilbert and Park (1986), with slight modification: 1) pseudomorphs—preservation of crystal form--the most diagnostic of all the criteria, 2) preservation of original structures and textures, 3) islands of unreplaced host mineral, 4) nonmatching walls of fractures or veinlets, 5) rims penetrating the crystallographic directions of the host mineral; easily confused with exsolution intergrowths, 6) metacrysts transecting original structures, e.g., pyrite in schist, 7) metacrysts deposited in obvious relation to fractures, cleavages, etc., 8) widening of fracture filling due to chemically reactive mineral grains, 9) metacrysts

deposited along advancing zone of alteration, and 10) no offset along the intersection of fractures. It should be emphasized that only where original crystal outlines, textures, or structures are preserved can one be certain that replacement has taken place.

One criterion commonly mentioned as evidence for replacement is the presence of concave surfaces into the host mineral, commonly referred to as “caries texture” (Lindgren, 1933). No single texture is more misinterpreted than this one! Recognizing that most sulfides do not develop good crystal faces, it is not surprising that sulfides will commonly exhibit embayments under normal growth conditions. Pyrite, arsenopyrite, and cobaltite are notable exceptions. Embayments may be produced by simultaneous growth with other sulfides, or by exsolution, as demonstrated experimentally by Brett (1964), and are particularly common in deformed sulfide deposits as well (Lufkin, 1983).

Flame texture

A flame texture derives its name from the wavy appearance of a fire flame. These intergrowth textural features are commonly observed in Cu-Ni deposits, and generally result from exsolution of Cu- and Ni-rich sulfide phases (Figures 7.16, 7.17).

Framboids

The word, framboid, is derived from *framboise*, the French word for raspberry, in allusion to its raspberry-like appearance (Rust, 1935). A framboid is a spherical to sub-spherical aggregate of equigranular pyrite microcrystals, and include a range of pyrite aggregate morphologies from irregular, nonspherical aggregates to spherical aggregates (Figure 7.18). In recent sediments and ancient sedimentary rocks the average diameter of spherical framboidal aggregates is about 5 microns (μm); framboids $>50\ \mu\text{m}$ are rare (Wilkin et al., 1996). Among different framboids, microcrystals vary in crystal form and are typically between 0.1 and 1 μm in diameter, ie., colloidal size. Within individual

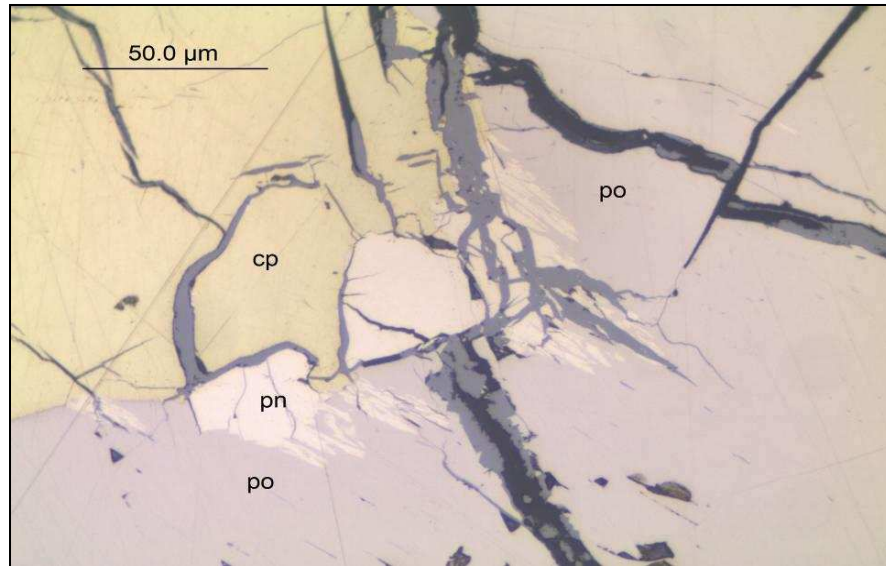


Figure 7.16 Pentlandite (pn) flames in pyrrhotite (po); an example of exsolluton. Eagle Cu-Ni deposit, Michigan. Specimen courtesy of Andrew Ware, Kennecott Corporation.

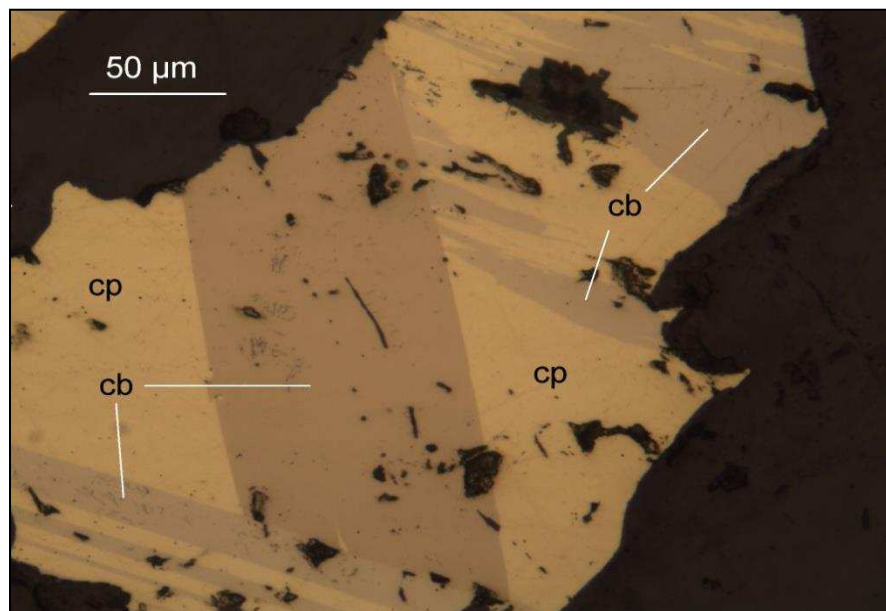


Figure 7.17 Flames of cubanite (cb) in chalcopyrite. Nokomis Cu-Ni deposit, Duluth Complex, MN. Specimen courtesy of David Oliver, Duluth Metals.

framboids, microcrystals are remarkably uniform in size and shape and usually arranged in ordered three-dimensional arrays. The ratio of the framboid diameter to the microcrystal diameter is generally between 5 and 30 (Wilkin et al., 1996).

Magnetite, magnesioferrite (MgFe_2O_4), and greigite (Fe_3S_4) also have been observed forming spherical and irregularly shaped aggregates, while marcasite framboids are extremely rare. Other mineralogies, including limonite, hematite, and chalcocite framboids likely represent oxidized or replaced pyrite framboids (Lougheed and Mancuso, 1973; Wilkin and Barnes, 1997).

Framboidal Growth and Formation

In spite of the voluminous literature on framboids, and the fact that greigite, Fe_3S_4 , is considered to be a key step in framboid formation, mechanisms that might form framboidal pyrite through the attraction of greigite microcrystals have not been critically evaluated. An aggregation model offers a process that could operate over a wide range of physical and chemical conditions (Wilkin and Barnes, 1997).

The Wilkin-Barnes model proposes four steps that are considered necessary for the formation of the pyrite framboids: (1) initial nucleation and growth of an iron monosulfide, (2) reaction of the initial monosulfide to greigite, (3) aggregation of the greigite microcrystals, and (4) replacement of the greigite by pyrite.

Nucleation and growth of very fine-grained textures is promoted by supersaturated conditions, as in colloform growth (Roedder, 1968), and most likely applies to framboid growth as well.

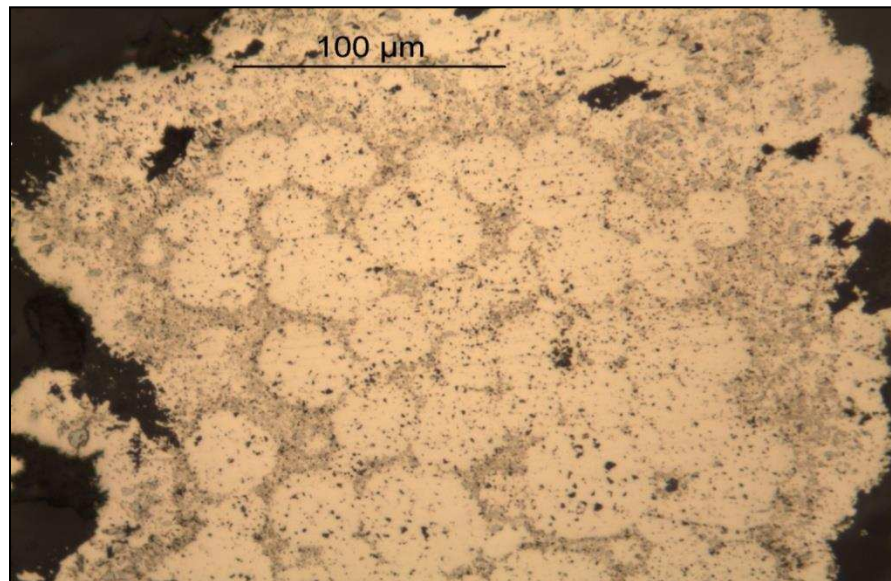


Figure 7.18 Coalescence of pyrite framboids. Polished section, ESC-1, from Escay Creek, BC VMS deposit. Polished section courtesy of Murray Hitzman.

Framboids are the dominant form of pyrite in modern anoxic environments, such as in argillaceous marine, lacustrine, and salt marsh sediments (Velentyn, 1963; Schallreuter, 1984; Oenema, 1990). Theories for the formation of framboidal pyrite range from biogenic, i.e., pyritic fossilization of bacterial colonies (Schneiderhöhn, 1923; Love, 1957) to inorganic, based on laboratory syntheses over a range of thermal conditions (Berner, 1969; Farrand, 1970; Sunagawa et al., 1971; Sweeney and Kaplan, 1973; Graham and Ohmoto, 1994). The morphology is commonly preserved in ancient sedimentary rocks, for example, in shales, carbonates, and coals since the Proterozoic (Honjo et al., 1965; Love and Amstutz, 1966; Weise and Fyfe, 1986; Sassano and Schrijver, 1989). Pyrite framboids are noted also in hydrothermal veins and other ore types (Steinike, 1963; Ostwald and England, 1977; Darling, 1987; Halback et al., 1993; Allen and Hahn, 1994).

Grain Boundary Segregations

Before the processes of exsolution were understood, grain boundary segregations were misinterpreted as “veinlets”. This texture is well-developed in Cu-Ni deposits, such as those at Sudbury, where pentlandite grains form “chainlike veinlets” around pyrrhotite grains---the stable end product of the exsolution of the mss (monosulfide solid solution; Figure 7.18). “In laboratory studies (Francis et al., 1976), the expulsion of nickel as pentlandite occurs as crystallographically oriented lamellae in the mss. However during the slow cooling from 400° down to ~100°C, the previously expelled chalcopyritelike phase would have tended to coalesce into anhedral masses and the pentlandite to diffuse and recrystallize into chainlike veinlets interstitial to mss grains” (Craig and Vaughn, 1981).

Intergrowth Textures

Lamellae

An intergrowth texture with lamellar or lamellae are lath-like features with parallel borders of variable thickness, but commonly measured in micron widths. These features, like lenses, are most commonly developed in sulfides and oxides as the result of exsolution (Figures 7.19, 7.20).

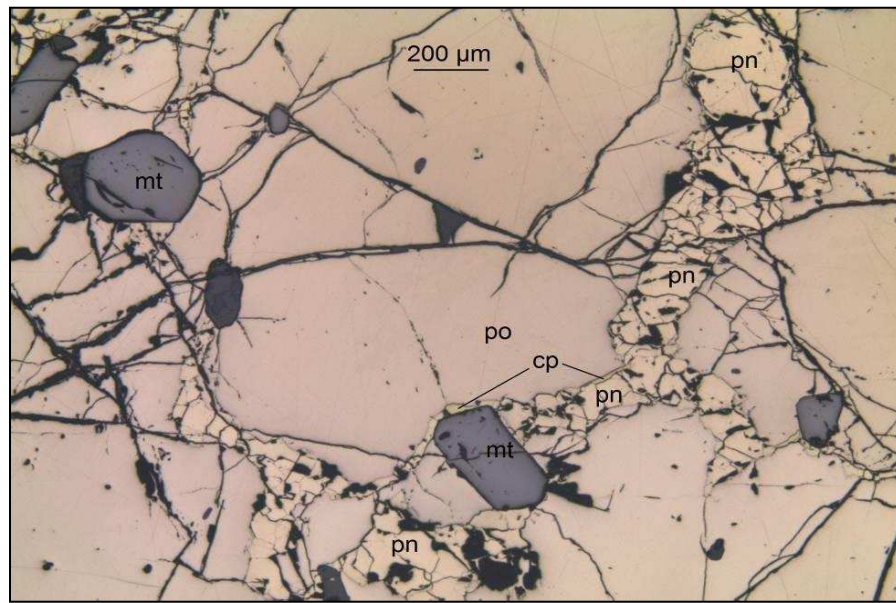


Figure 7.18 Exsolution of pentlandite (pn) to grain boundaries of pyrrhotite (po), with early magnetite (mt). Sudbury Cu-Ni deposit, Ontario.

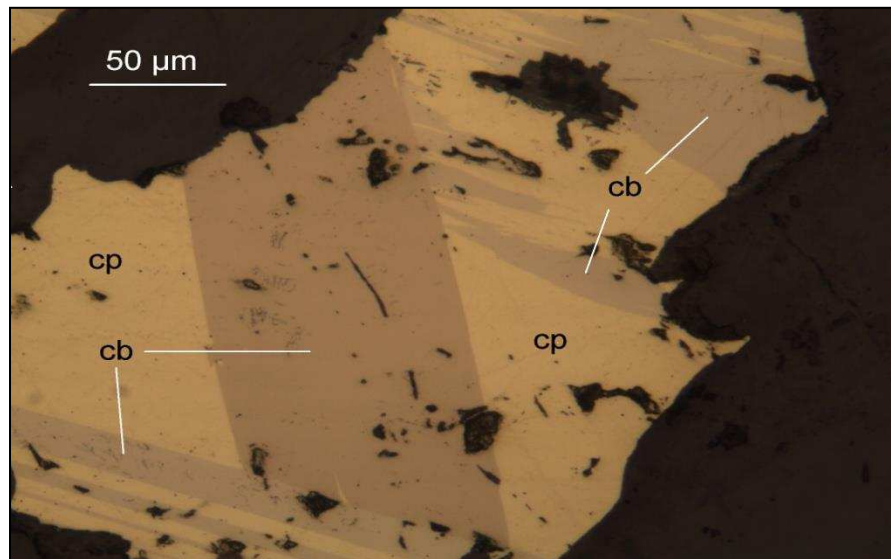


Figure 7.19 Lamellae of cubanite (cb) in chalcopyrite. Nokomis Cu-Ni deposit, Duluth Complex, MN. Sample courtesy of David Oliver, Duluth Metals.

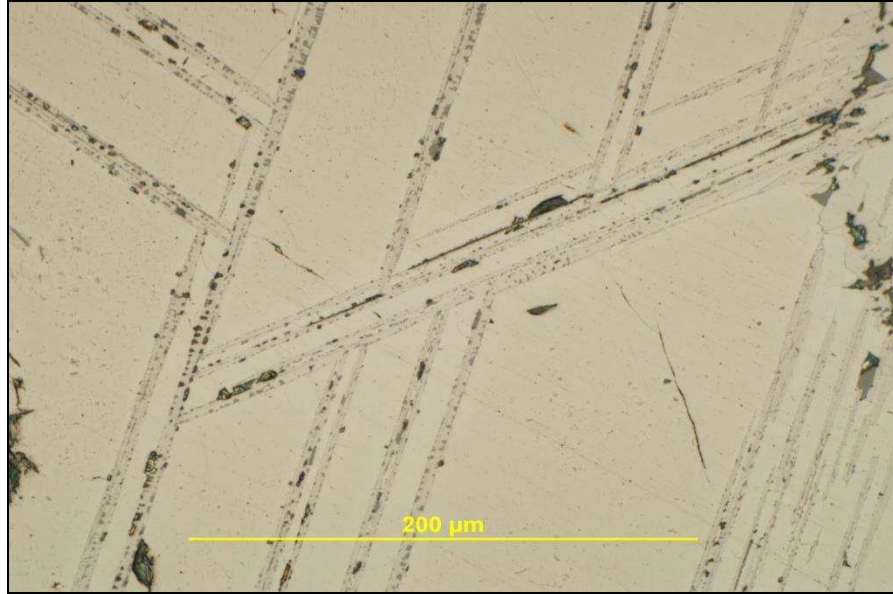


Figure 7.20 Magnetite? lamellae in ilmenite. Birch Lake deposit, Duluth Complex. Polished section BLDuW-2665.3, courtesy of Steve Hauck, NRRI, University of Minnesota, Duluth.

The Exsolution Process

Solid solutions in ore minerals are homogeneous, unstable mixtures of super-saturated components. In such a mixture, one phase, the solute, is dissolved in another, the solvent phase. The solid solution is generally accomplished either by a) substitution, or b) interstitial addition (Edwards, 1954). In substitution solid solution, the most common type, the solute metal ions substitute for the solvent ions in the crystal lattice. This is readily achieved when the metal ions are of compatible size and electrical charge. Interstitial solid solution involves the addition of ions or atoms to lattice vacancies in the solvent.

As a solid solution cools, the solute and solvent unmix, or exsolve. The kinetics and mechanisms of exsolution have been discussed by several authors (Yund and McCallister, 1970; Putnis and McConnell, 1980). As summarized by Brett (1964), exsolution is affected by nucleation and subsequent growth of exsolved particles from a supersaturated, originally homogeneous phase. The exsolution process is affected by numerous variables, including temperature, pressure, concentration, impurities, structure, grain size, coefficients of diffusion, and stress distribution. The driving force for exsolution is the tendency to reduce free energy of the system, which is high for a supersaturated solid solution. The exsolved phase most likely begins to nucleate at

imperfections in the solvent, such as dislocations, twin lamellae, grains boundaries, etc., and the rate of growth is dependent on the rate of diffusion (which is relatively high in metals, sulfides, and sulfosalts, compared to that in oxides and silicates).

Initial exsolution between a structurally compatible pair, for example, bornite and chalcopyrite, is coherent; that is, lattice continuity exists between the two phases. As exsolution progresses, growth of lattice distortions destroys the crystallographic continuity, and exsolution becomes noncoherent. For structurally similar pairs, the texture of the exsolved phase is crystallographically controlled by the host. Initially, lamellae form as a stable texture, but in an attempt to reduce surface free energy, the exsolved phase may grow to form lenses, or spheroids, or may migrate to form segregations at grains boundaries. According to Brett, lamellae are the most stable textural form in coherent exsolution. The degree of supersaturation, rate of cooling, crystal imperfection, crystallographic similarity, grain size, and initial concentration determine coherency during cooling. For noncoherent exsolution, the most stable configuration is an intergranular polyhedral texture (which was not observed in Brett's experiments on the Cu-Fe-S system) (Lufkin, 1983).

Experiments on bornite-chalcocite-chalcopyrite intergrowths were performed in the late 1920s and 1930s by George Schwartz, University of Minnesota (Schwartz, 1928; 1931; and 1939). The study of the bornite-chalcopyrite system was of particular significance because (1) natural intergrowths of bornite-chalcocite homogenized to form a solid solution above 475°C; (2) rapid cooling produced only a lattice intergrowth, and (3) slow cooling resulted in chalcopyrite segregation along bornite grain boundaries (Schwartz, 1931). These experiments provided the first strong evidence that lattice intergrowths were diagnostic of a rapid cooling rate (Lufkin, 1983).

During the 1950s, Sugaki and Japanese colleagues continued homogenization and exsolution experiments on sphalerite, chalcopyrite, and bornite (Sugaki, 1951; 1955; Sugaki and Tashiro, 1957). In experiments on chalcopyrite-bornite lattice intergrowths, Sugaki (1951) was able to homogenize chalcopyrite in bornite at temperatures from 300° to 460°C, with the rate of homogenization proportional to temperature. One hour was required to homogenize chalcopyrite at 460°C. A lattice intergrowth formed when the solid solution was held at 150° to 250°C for a period of time. From this he concluded that bornite--chalcopyrite intergrowths were not diagnostic of high temperature, as suggested earlier by Schwartz, but could form at temperatures of 200°C or lower.

The classic work of Robin Brett (1964) remains the modern standard of interpretation of intergrowth textures in copper sulfides produced by exsolution processes. Brett conducted 300 heating and cooling experiments on synthetic phases with compositions along the binary join of bornite-digenite, bornite-chalcopyrite, and bornite-chalcocite in the Cu-Fe-S system. All specimens were annealed at 600°C and then cooled at variable rates from above their solvus down to 50°C or below in the time period of 6½ minutes to 7 months. A variety of textures was produced, including lamellar, lenticular, "basket-weave", mutual boundary, wedge, myrmekitic, and vein. His experiments indicated that 1) lamellae may form from either fast or slow cooling; they may form after mutual boundary texture as a final stage of coherent exsolution, 2) confining pressure has little effect on preserving lamellae, 3) graphic, eutectic, and myrmekitic intergrowths may result from breakdown to "basket-weave" textures, 4) vein- and mutual-boundary textures may be exsolution products, and 5) homogenization of lamellae will give only a minimum temperature of formation of solid solution. He concluded that *no texture is diagnostic of any particular temperature or cooling rate (except maybe fine-grained textures), in the system he studied* (Brett, 1964).

The Role of Oxidation

The role of oxidation has been shown to be an important factor in the development of some intergrowth textures in Fe-Ti oxide minerals. Intergrowth lamellae of ilmenite in magnetite are suggestive of the exsolution process, however, Lindsley (1976) has demonstrated that this texture is the result of oxidation, whereby magnetite-ulvöspinel will undergo oxidation on cooling, and ilmenite lamellae will form on the {111} planes of magnetite. Conversely, iron-rich ilmenite, upon cooling may be reduced to produce lamellae of Ti-magnetite parallel to the {0001} planes of ilmenite (Craig and Vaughan, 1984).

Examples and Textural Criteria of Exsolution

Extensive lists of solid solution-exsolution pairs have been prepared by several investigators (Edwards, 1954; Ramdohr, 1969; Haggerty, 1976, and others). Common sulfide pairs include bornite-chalcocite, bornite-chalcopyrite, chalcopyrite-cubanite, sphalerite-chalcopyrite, sphalerite-pyrrhotite, and pyrrhotite-pentlandite. Oxide exsolution pairs feature magnetite-ulvöspinel, hematite-ilmenite, titanhematite-rutile, and cassiterite-tantalite, among others.

Depending upon a number of factors, unmixing of solid solutions leads to the development of a variety of textural forms. Most common of these are lamellae, lenses, spheroids, blebs, graphic and myrmekitic intergrowths, and grain boundary. The textural forms most diagnostic of the exsolution process are lamellae (Schwartz, 1931; Brett, 1964), which commonly constrict or thin at lamellae intersections. By contrast, lattice-controlled replacement textures typically enlarge at lamellae intersections. The other textures listed above may form either by replacement or exsolution processes.

Clearly, knowledge of phase relationships and solubilities of the mineral intergrowths is very important. For example, consider the common intergrowth of chalcopyrite-sphalerite. Intergrown chalcopyrite and sphalerite have been homogenized readily in the laboratory (Borchert, 1934; Nakano, 1934; Buerger, 1934; Sugaki and Tashiro, 1957; Lyon, 1959). Therefore, such an intergrowth has been attributed principally to exsolution, regardless of its temperature of formation. In studies of equilibrium assemblages in the Cu-Fe-Zn-S system from 500° to 800°C, Wiggins and Craig (1980) determined that the solubility of copper in sphalerite (as an intermediate solid solution, ISS) is a function of temperature and sulfur activity. Copper solubility increases with temperature, but decreases with increasing sulfur activity. Their results showed that copper content of sphalerite (ISS) may exceed 5 wt percent when coexisting with pyrrhotite, and 7 wt percent in equilibrium with bornite at 800°C. However, copper solubility decreases to less than 2 wt percent at 500°C. Thus, at much lower temperatures, for example, in the $\leq 150^\circ\text{C}$ Mississippi Valley-type ores, copper solubility in sphalerite may be quite low indeed. One may conclude from these data that exsolution probably is not the cause for all chalcopyrite intergrowths in sphalerite, particularly those present in low-temperature ores (Lufkin, 1983).

In view of the results of such experimental work, it is sobering to learn that we can confidently interpret little about the origin and temperature/cooling rate history of exsolution textures. Some textures are more stable than others, but only in a qualitative sense. If the compositions of sulfide exsolution pairs are determined, the temperature at which exsolution commenced can be approximated from the solvus; however, *neither the temperature of solid solution formation, nor its cooling history can be determined from its texture.*

Lattice intergrowth

The intersection of lamellae or lenses in two or more directions constitutes a lattice, or lattice intergrowth of two or more minerals. Lattice intergrowths are most commonly developed among sulfide and oxide minerals (Figure 7.21).

Lenses/Lensoid

As the name suggests, a lensoid feature looks like a lens, with convex surfaces on either side. Lensoid textures are very common among intergrowth textures, particularly involving the copper sulfides and iron-titanium oxides. This feature almost universally is the result of exsolution processes (Figures 7.24, 7.25).

Vermicular texture (also Graphic, Micrographic, Myrmekitic, Pseudoeutectic, Subgraphic, and Symplectic)

From the Latin *vermiculus* or *vermis*, meaning worm—the description of the “wavy” intergrowth of two minerals. “Curved lamellar intergrowth resembling some eutectic intergrowths found in metal alloys. In graphic granite partial crystallographic control makes a pattern suggesting cuneiform or runic characters. The textures are highly complex and have been described as twisting tongues of sulphides with smooth contacts and the embayments and tongues turn sharply to form hooks (Figure 7.29). Sub-graphic is used for poorly developed examples more or less resembling typical graphic intergrowths... The textures are considered by various authors to originate by simultaneous deposition, by unmixing and by replacement. True eutectics are probably rare or lacking in ores” (Schwartz, 1951).

Symplectic intergrowths (symplectites) are vermicular, or worm-like intergrowths of minerals that grow simultaneously in a solid-state reaction (Figure 7.30). Most common example is myrmekite—intergrowth of quartz and sodic plagioclase. Most symplectites are formed in solid-state reactions, but fluids may be involved in the transport (and deposition) of chemical components.

The word, myrmekitic, has also been applied to this intergrowth pattern, but should not, since it was first used to describe the wormy pattern of quartz-plagioclase intergrowths in granite.

A symplectic texture is also vermicular, and generally develops within silicate phases due to reaction during rapid cooling or metamorphism. More recently they have been

described as quenched melt textures in sulfosalt melts (Mavrogenes et al., 2010; Mavrogenes et al., 2001; Tomkins et al., 2004).

In conclusion, the vermicular texture is one of the most difficult to explain. In my opinion, simultaneous growth of two phases appears to fit the most common origin for this texture; I see no strong evidence for replacement.

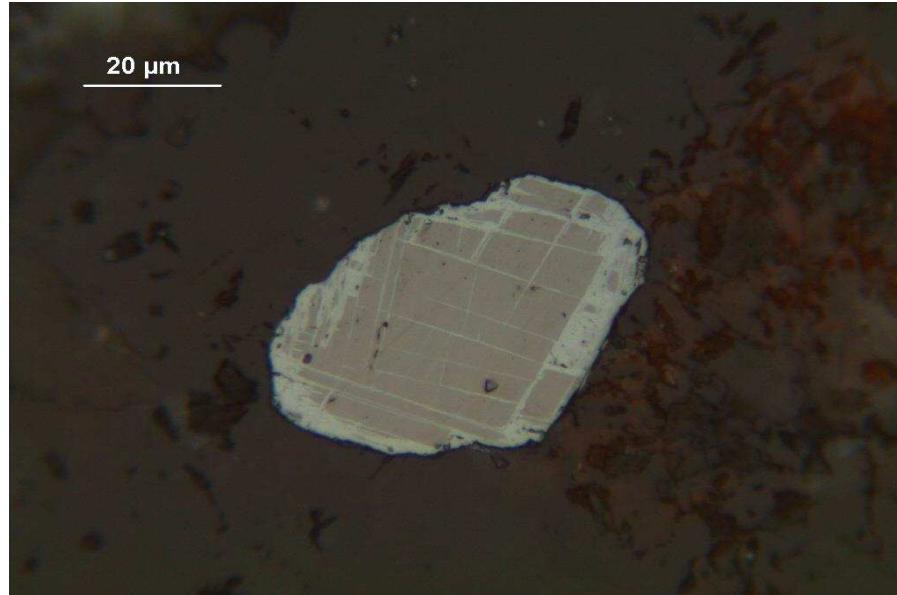


Figure 7.21 Lattice intergrowth. Magnetite oxidized to hematite (white) along {111} planes. Safford, AZ porphyry copper deposit.

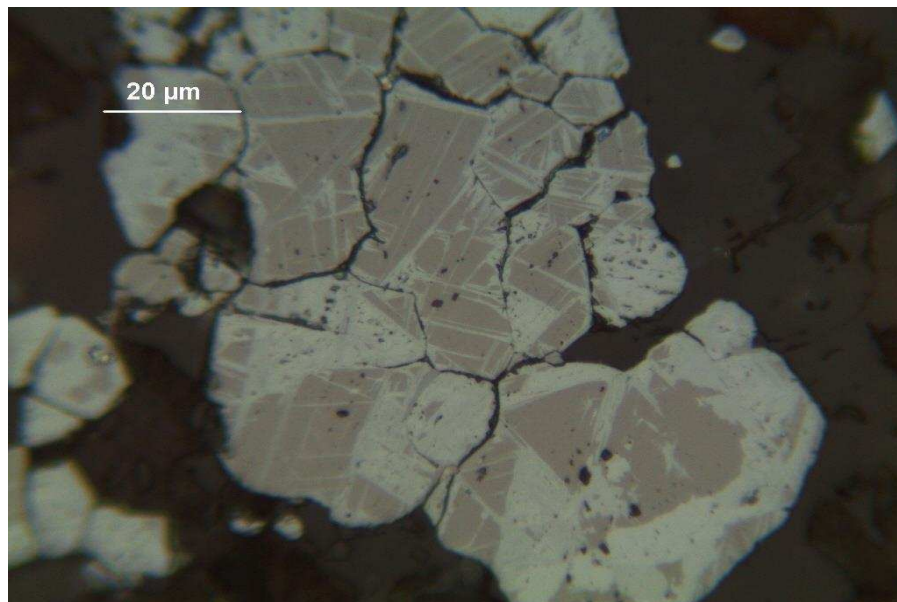


Figure 7.22 Advanced stage of oxidation of magnetite to hematite, Safford, AZ.

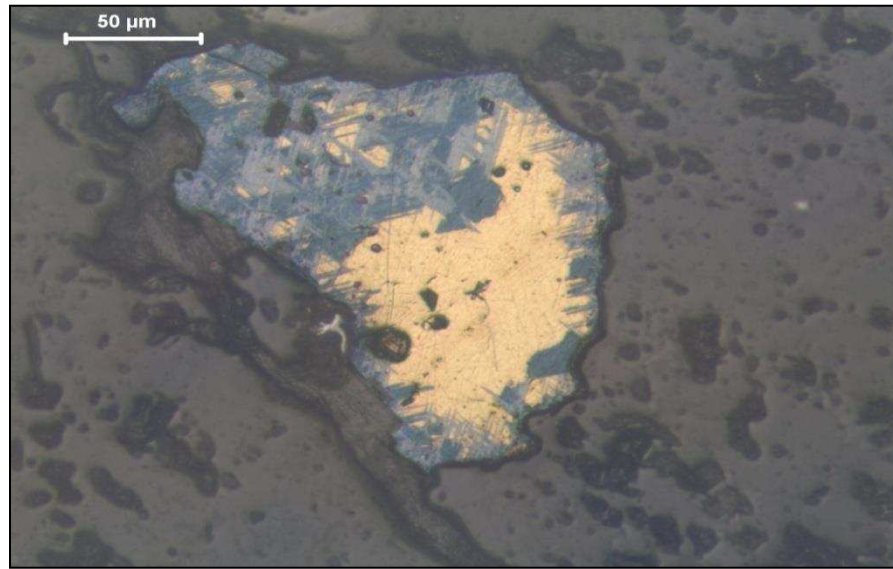


Figure 7.23 Lattice intergrowth of covellite (blue) and chalcopyrite (yellow), produced by rim replacement that advanced inward along crystallographic planes of host chalcopyrite. Morenci porphyry copper deposit, Arizona.

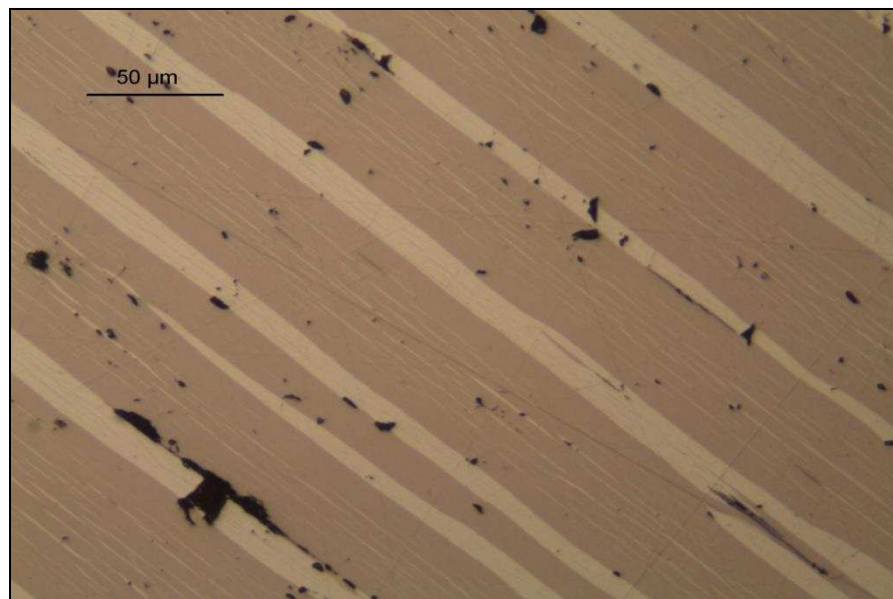


Figure 7.24 Hematite lenses in ilmenite; a process of exsolution.

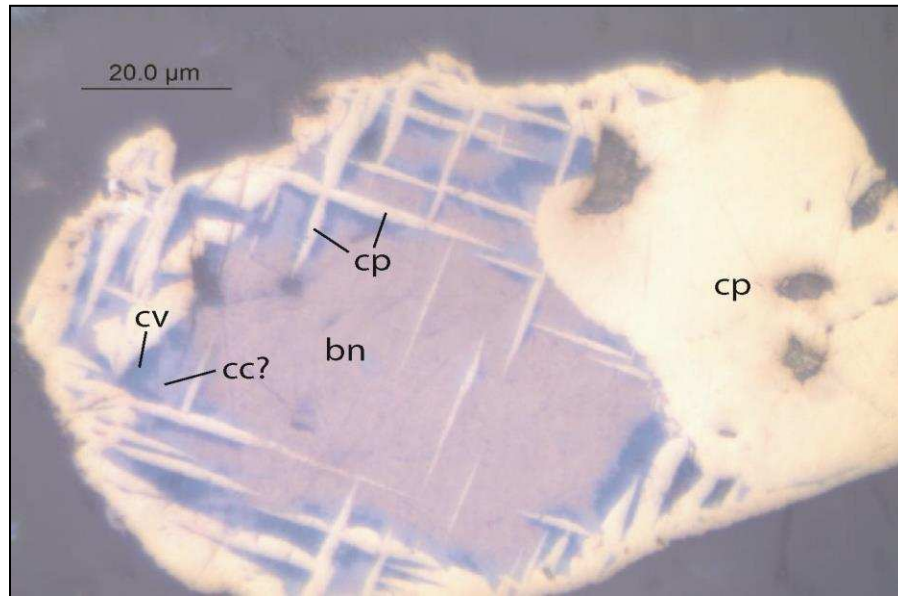


Figure 7.25 Lattice intergrowth of lenses, or “basket weave texture” of chalcopyrite (cp) and bornite (bn), with secondary alteration to covellite (cv) and chalcocite? (cc). Upper level of ore deposit, Bingham Canyon, Utah porphyry copper deposit. A process of exsolution, probably followed by rim replacement by chalcopyrite.

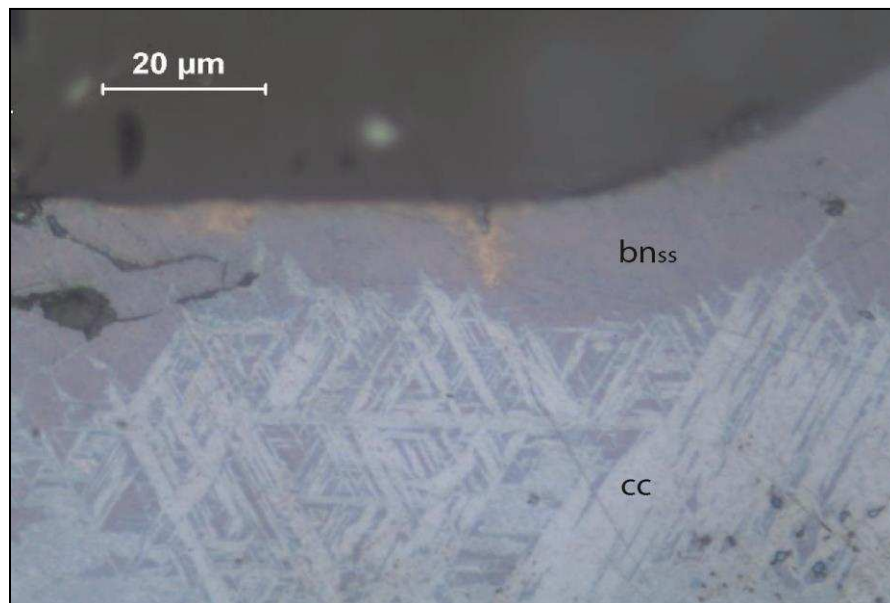


Figure 7.26 Lattice intergrowth of chalcocite and bornite, near bottom of present pit; sampled with Ganske, mine geologist, in May, 2009. A process of exsolution.

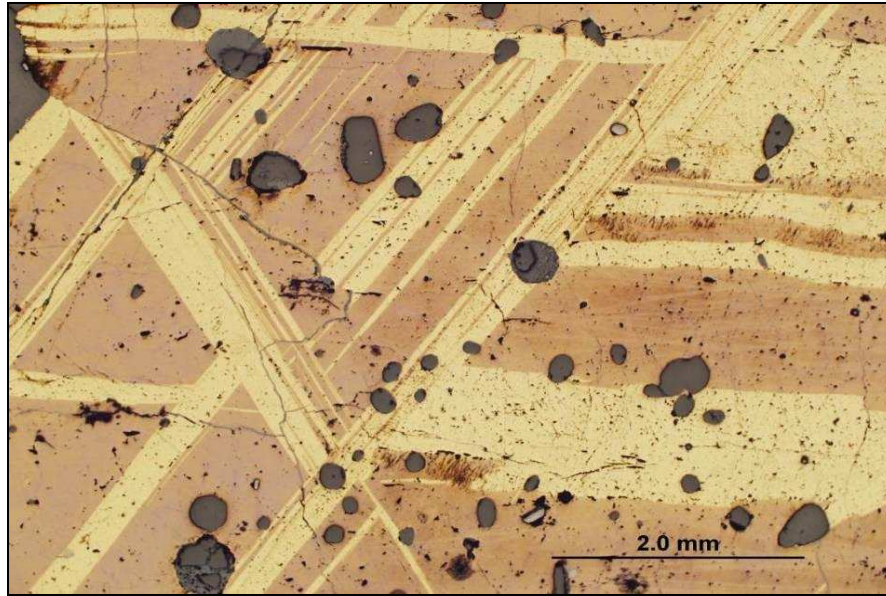


Figure 7.27 Lamellae of chalcopyrite (yellow) in talnakhite. Masaba deposit, Duluth Complex, Minnesota. Polished thin section courtesy of Steve Hauck, NRRI, University of Minnesota, Duluth.

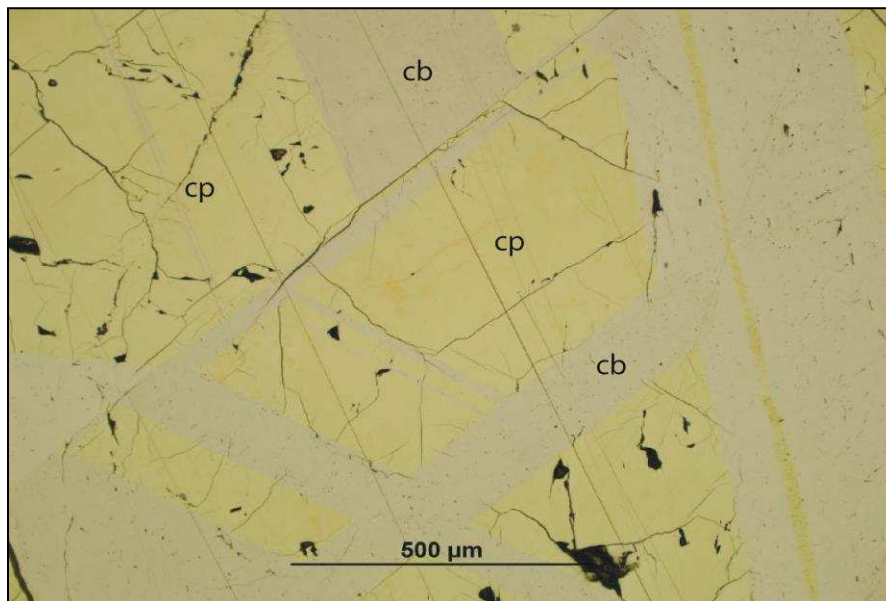


Figure 7.28 Lattice intergrowth of cubanite (cb) and chalcopyrite (cp). Mesaba Deposit, Duluth Complex. Polished section courtesy of Steve Hauck, NRRI, University of Minnesota, Duluth.

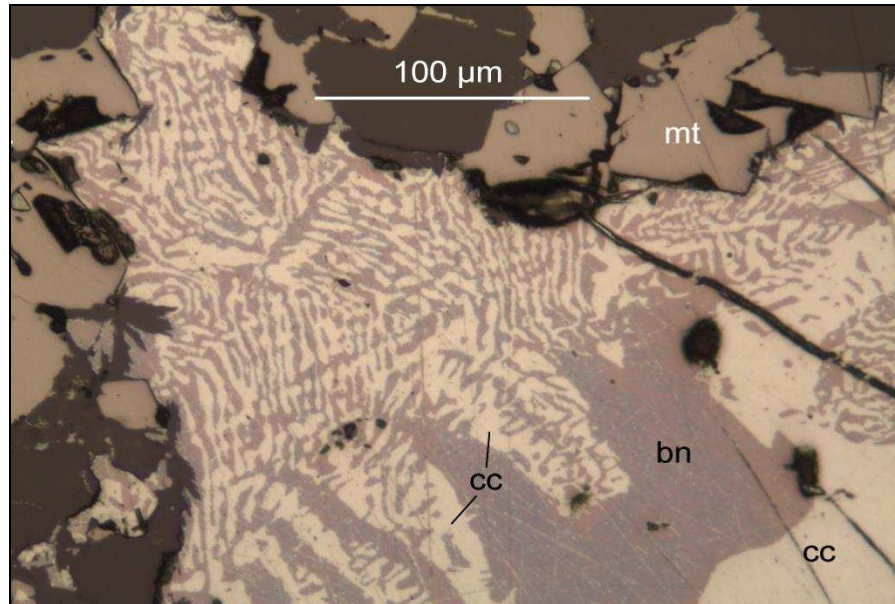


Figure 7.29 Vermicular intergrowth of bornite (bn) and chalcocite (cc). Intergrowth is quite possibly the result of simultaneous competitive growth of two phases, since these two phases typically form crystallographically controlled lattice intergrowths, ie., Bingham Canyon. Polished thin section made from Salobo, Brazil IOCG deposit, courtesy of Murray Hitzman, CSM.

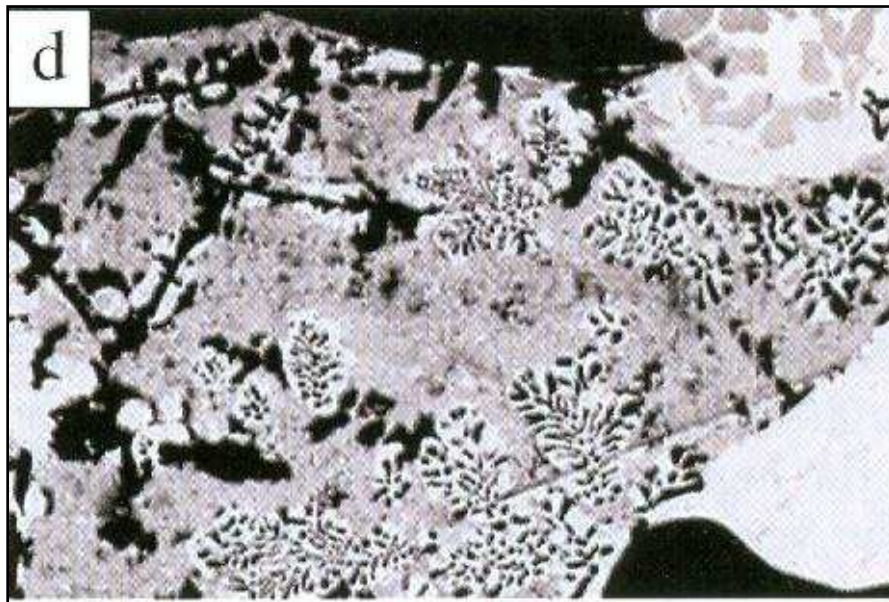


Figure 7.30 Symplectic intergrowths resembling quenched experimental sulfosalt melts (Mavrogenes, et al., 2010, p. 258).

Massive texture

Where the sulfide content exceeds 66 percent in magmatic Ni-Cu sulfide deposits, the texture is described as semimassive to massive (Barnes and Lightfoot, 2005).

Matrix or net textured

If sulfides in magmatic Ni-Cu sulfide deposits are interconnected and form a matrix to the silicates, they are described as matrix or net textured (Barnes and Lightfoot, 2005).

Mutual Boundary texture

This texture is characteristic of two or more minerals whose contacts are smooth, straight or curving that show no projections from one mineral into the other.

Open-Space Filling textures

“Open-space filling is common in shallow zones where brittle rocks yield by braking rather than by plastic flow. The openings in these zones tend to remain open because of low pressure transmitted through surrounding rock. At shallow depths, ore-bearing fluids have relatively free circulation, and their open connection with the surface permits deposition to be brought about by abrupt pressure and temperature changes—including retrograde boiling—as opposed to prolonged contact with surrounding rocks which undergo slow chemical changes in deeper environments.” (Guilbert and Park, 1986, p. 148).

Some of the common criteria that are suggestive of open-space filling include the following: 1) many vugs and cavities, 2) fine-grained minerals [and/or colloform textures] on walls of a cavity with coarser minerals in the center, 3) crustification, 4) comb structure, 5) symmetrical banding, 6) matching vein walls, 7) cockade structure, and 8) offset oblique structures (Guilbert and Park, 1986).

Spherulitic texture or structure

Groups of fibers, radiating from a central point or area, and these units embedded in a groundmass.

Zoning

Zoning refers to the distribution of geologic characteristics in space, such as chemical elements, minerals, structures, and the like. Sphalerite, cassiterite, and some

iron oxides are commonly zoned with respect to Fe content (Figure 7.31). In reflected light studies, zoning in ore minerals generally is not observed.

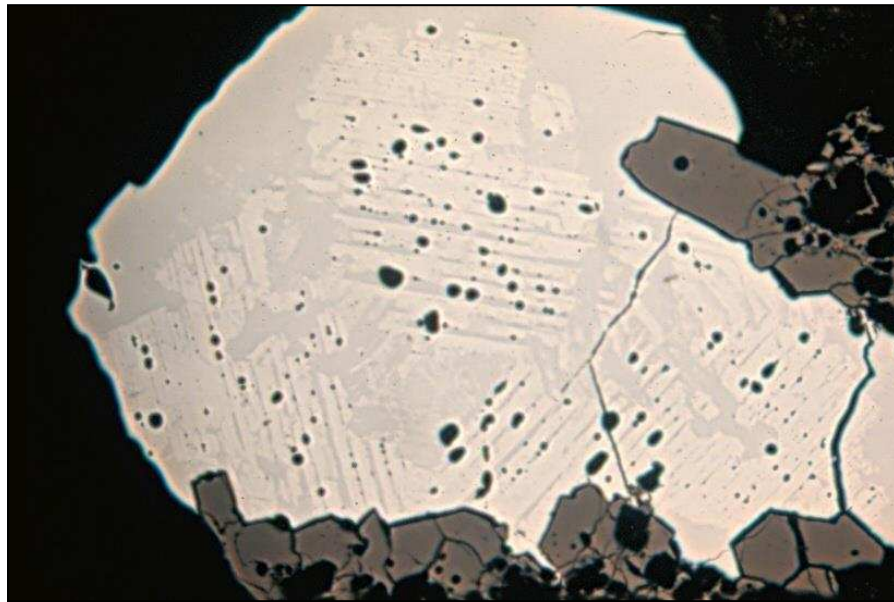


Figure 7.31 Bixbyite, $(\text{Fe,Mn})_3\text{O}_4$. Chemical zoning in a single crystal; white layers are more Fe rich. Paramount Canyon, Black Range, New Mexico.

8.0 PARAGENESIS AND ZONING

The concepts of paragenesis and zoning are very important to the mineral explorationist and the economic geologist, and should be covered in any text on ore deposits. *Paragenesis* refers to the time sequence of mineral deposition, while *zoning* describes the distribution of minerals and elements in space. Compositional zoning in minerals varies from the regional scale down to the microscopic level. On the microscopic scale, minerals commonly reflect changes in chemistry during growth, but this feature is not readily observed in reflected light. The ore microscope, however, is the principal tool for determining paragenesis in ore minerals, and that is the main concern of this chapter .

Paragenesis

Craig and Vaughn (1981) have done an excellent job describing the several aspects of paragenetic studies of ore deposits, and the many criteria by which the age of mineral deposition is determined in polished section. These criteria include: 1) cross-cutting

relationships, 2) crystal morphology, 3) mutual grain boundary relationships, 4) colloform texture, 5) replacement texture, and 6) exsolution phenomena.

Cross-cutting relationships

Without question cross-cutting relationships are probably the most reliable indicators of determining time sequence in mineral deposition. “The veinlet or other feature that cross-cuts another is younger than that which it cuts across...” (Craig and Vaughan, 1981, p. 149). A veinlet that cuts across another veinlet or crystal, therefore, is necessarily later, or younger in the paragenetic sequence whether it represents open space filling or replacement.

Crystal Morphology

The shapes of mineral grains have often been used as criteria for determining paragenesis. In general, euhedral crystals have been interpreted as forming early and growing unobstructed. Many many euhedral crystals are simply an indication of growth into open space, especially in vein deposits (Craig and Vaughan, 1981). Some sulfides, eg., pyrite and arsenopyrite, tend to form good crystal outlines regardless of their time sequence, due to their “force of crystallization”. Secondary pyrite resulting from exsolution of primary pyrrhoite in Fe-Cu-Ni ores commonly occurs as well formed cubes. Therefore, crystal morphology must be used with considerable caution, particularly when dealing with pyrite, arsenopyrite, and few other opaque minerals..

Mutual Grain Boundary Relationships

Mutual grain boundaries, or “equal degrees of mutual penetration”, are one of the most difficult textures facing the microscopist. “The equal interpenetration of minerals, the absence of characteristic first-formed crystals, and the absence of replacement features usually prevent determination of any paragenetic sequence and may indicate simultaneous crystallization of the minerals” (Craig and Vaughan, 1981, p. 146); the same thing can be said for deformed sulfide ores (Stanton, 1972)..

Colloform Texture

Colloform texture refers to the concentric growth of very fine-grained minerals about a nucleus or substrate. In a typical vein, the texture develops outward into open space from the vein wall, such that each successive layer is younger than the underlying layer. In hand specimen and in polished section, the outer surface of the colloform texture is seen as *botryoidal*, or convex, and may be mistaken as replacement embayments, or carries into adjacent minerals when in fact they result from open space deposition. The

colloform texture is commonly developed in a variety of minerals, including sphalerite, pyrite, marcasite, cassiterite, manganese oxides, and copper carbonates.

Replacement

Replacement textures are very common in ores, and play an important role in the paragenetic scheme. Simply put, the mineral that is replaced must predate the mineral that replaces it. The replacement process has been studied by numerous investigators, as discussed previously. In general, the replacement process is a surface chemical reaction taking place in a fluid that usually proceeds inward from the crystal boundary along permeable pathways, such as fractures and/or cleavage planes. This results in a texture where the replacing phase commonly possesses convex boundaries, and the replaced phase features concave boundaries that may remain as residual “islands” within a matrix of the later phase (Craig and Vaughan, 1981).

Exsolution

The exsolution process is also common in ores, particularly the Fe-Cu-Ni sulfide and the Fe-Ti oxide deposits. In the Fe-Cu-Ni ores, such as those at Sudbury, Ontario; Duluth Complex, Minnesota; and Eagle, Michigan, much of the nickel is first precipitated as the $(\text{Fe,Ni})_{1-x}$ monosulfide solid solution at temperatures of 900-1100°C. Upon cooling, the nickel unmixes, or exsolves as pentlandite, first to the grain boundaries of pyrrhotite, and later at lower temperatures as “flames” of pentlandite that are crystallographically controlled by the host pyrrhotite (Craig and Vaughan, 1981). Before these facts were established experimentally, the grain boundary migration phenomena were commonly misinterpreted as veining by later pentlandite.

Examples of Paragenesis

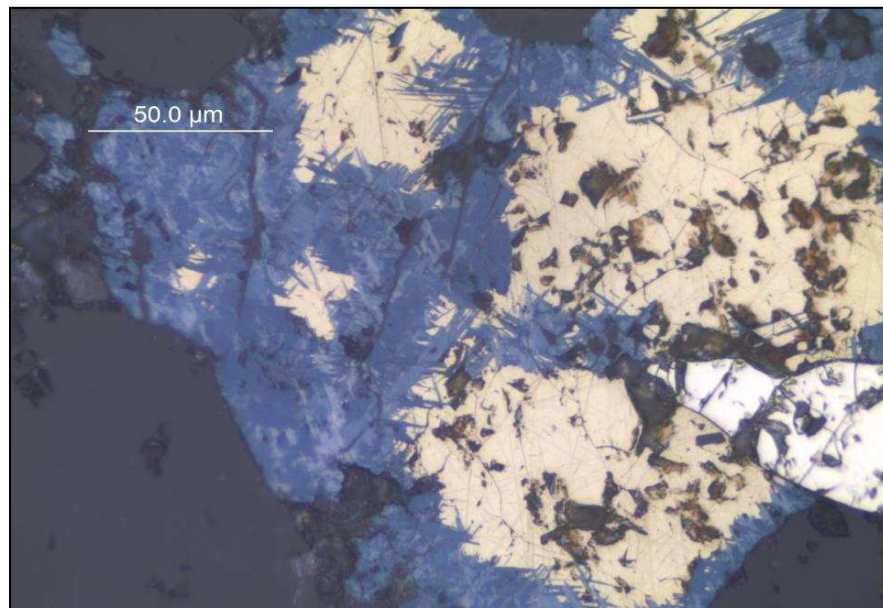


Figure 8.1 Morenci, Arizona. Paragenesis: early pyrite (white), followed by chalcopyrite (yellow), then rim replacement of chalcopyrite by covellite (blue).

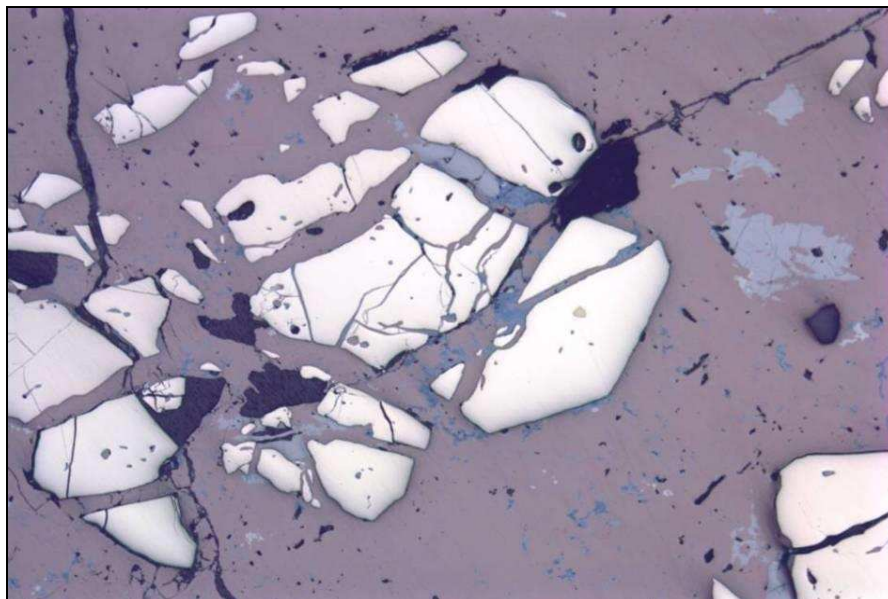


Figure 8.2 Pyrite, chalcocite (light blue), and covellite (dark blue) in matrix of bornite (lavender). Paragenesis: early pyrite, followed by bornite solid solution; later exsolution of chalcocite (gray), followed by local oxidation to covellite (blue).

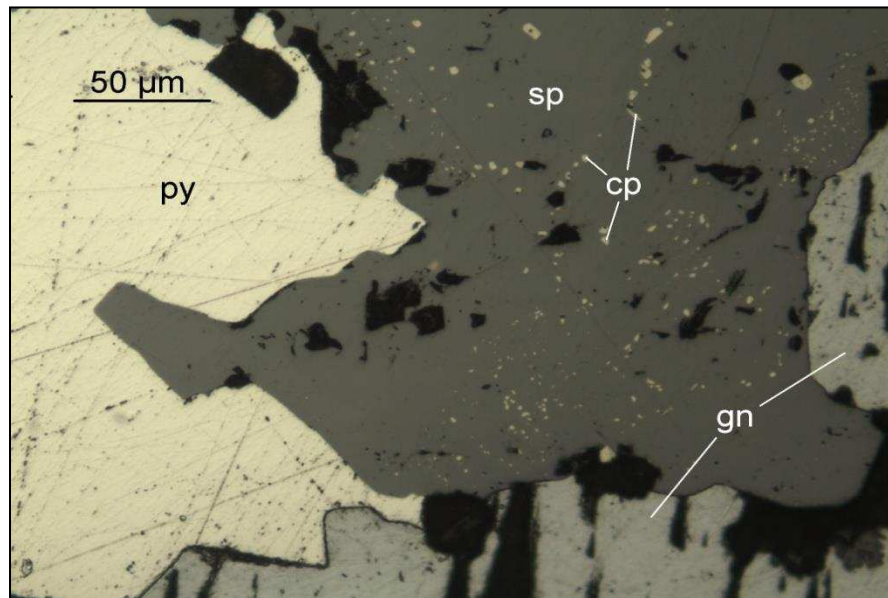


Figure 8.3 Paragenesis of pyrite (py), galena (gn), sphalerite (sp), and chalcopyrite (cp). Note the following features: emphyment of pyrite by sphalerite; embayment of galena by sphalerite, and oriented blebs of chalcopyrite intergrown with sphalerite. Therefore, the paragenesis is: pyrite→galena→sphalerite+chalcopyrite. Specimen MC-2b, courtesy of Maritza Cantorin, Lima, Peru.

9.0 DESCRIPTIVE ORE MINERALOGY

In this section the physical, chemical, and optical properties of more than fifty of the most common ore minerals are presented for both hand specimens and polished sections. In addition the details of their mineral associations, mode of occurrence, and origin are also described. The ore minerals are presented in alphabetical order, and grouped according to chemical class, which includes the common native metals, sulfides, sulfosalts, oxides, tungstates, arsenides, and tellurides, in that order. Most of the mineral specimens were photographed by a Nikon Coolpix P90 digital camera; the great majority of the photomicrographs were taken in air under plane polarized light, using a Leica DFC 290 digital color camera (3.0 MP, 2048 x 1536 pixels) and Leica LAS software.

Sources for data presented below have been derived from the following references:

Anthony, J.W., Bideaux, R.A., Bladh, K.W., and Nicols, M.C., Handbook of Mineralogy, vols. I-V: Mineral Data Publishing, Tucson, Arizona.

Craig, J.R., 1994, *Ore Microscopy and Ore Petrography*, 2nd edition: John Wiley & Sons, New York, 434 p.
Marshall, Dan, Anglin, C.D., and Mumin, Hamid, 2004, *Ore Mineral Atlas*: Geological Association of Canada, St. John's, Newfoundland, Canada A1B3X5.
Uytenbogaardt, W., and Burke, E.A.J., 1985, *Tables for Microscopic Identification of Ore Minerals*, 2nd edition: Dover Publication, New York, 430 p.

CHEMICAL CLASS: NATIVE METALS

Mineral Name: Copper

Composition: Cu

Characteristics in Hand Specimen

Crystal System: Cubic

Color: Light rose on fresh surface, quickly darkens to copper-red.

Cleavage: None

Fracture: Hackly

Tenacity: Highly malleable and ductile.

Mohs Hardness: 2.5-3

Density (meas.): 8.95

Streak: Reddish

Association: Silver, chalcocite, bornite, cuprite, malachite, azurite, tenorite, iron oxides, many other minerals.

Name: From the Latin *cuprum*, in turn from the Greek *kypriso*, *Cyprus*, from which island the metal was early produced.



Figure 9.1 Native copper, Keweenaw Peninsula, Michigan. CSM Geology Museum.

Characteristics in Polished Section

Color: Pink, tarnishes brown

Cleavage: Absent

Polishing Hardness: >chalcocite

Bireflectance: Weak

Anisotropy: Isotropic

Reflectance (in air): 43

IR: Absent

Distinguishing Features: Very reflective, pink, commonly with scratch marks.

Associated Minerals: Cuprite, malachite, and azurite in oxidized zones of copper sulfide deposits. Also in cavities of basalt with chalcocite, bornite, chalcopyrite, and pyrite.

Mode of Occurrence and Origin: Occurs as coarse to fine-grained disseminations and as aggregates. Typically found in oxidized zones of porphyry copper deposits. A major occurrence in basalt flows of the Keweenaw Peninsula, Michigan as cavity and fracture fillings, and as cement in conglomerates.

References:

Brown, A.C., 1971, Zoning in the White Pine copper deposit, Ontonagon County, Michigan: Economic Geology, v.66, p. 543-573.

Subias, I., Fanlo, I., Mateo, E., and Garcia-Veigas, J., 2003, A model for the diagenetic formation of sandstone-hosted copper deposits in Tertiary sedimentary rocks, Aragon (NE Spain): S/C ratios and sulphur isotope systematics: Ore Geology Reviews, v. 23, p. 55-70.

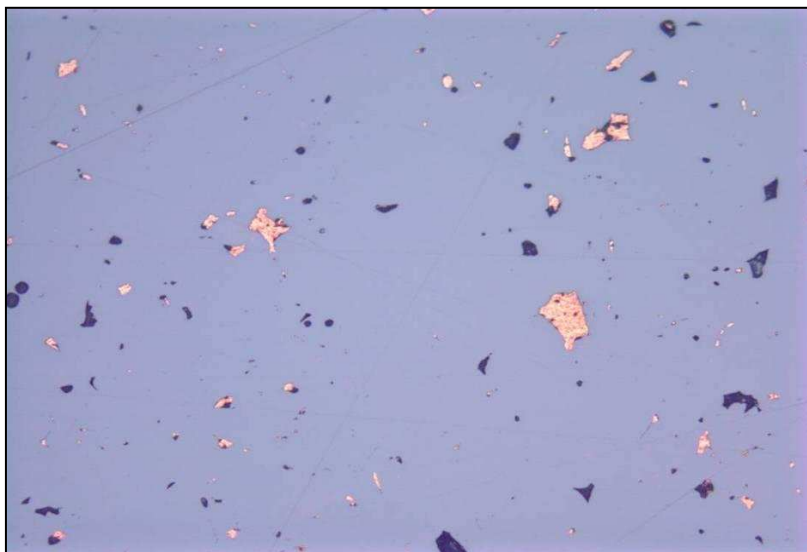


Figure 9.2 Disseminated native copper. No. 123, 5x.

CHEMICAL CLASS: NATIVE METALS

Mineral Name: Gold

Composition: Au

Characteristics in Hand Specimen

Crystal System: Cubic

Color: Gold-yellow when pure.

Cleavage: None

Fracture: Hackly

Tenacity: Very malleable and ductile.

Mohs Hardness: 2.5-3

Density (meas.): 19.3

Streak:

Association: Pyrite, chalcopyrite, arsenopyrite, pyrrhotite, sylvanite, krennerite, calaverite, altaite, scheelite, ankerite, tourmaline, quartz.

Name: An Old English word for the metal.



Figure 9.3 Gold, Central City, Colorado. CSM Geology Museum.

Characteristics in Polished Section

Color: Bright golden yellow

Cleavage: None

Polishing Hardness: ~chalcopyrite

Bireflectance: Absent

Anisotropy: Anisotropic (anomalous)

Reflectance (in air): 65-72

IR: Absent

Distinguishing Features: Yellow color, high reflectance, soft, lack of complete extinction under crossed nicols.

Associated Minerals: In quartz veins with numerous minerals, including stibnite, sphalerite, galena, arsenopyrite, pyrite, tellurides, chalcopyrite, pyrrhotite, silver-bearing minerals, bismuth-bearing minerals, scheelite.

Mode of Occurrence and Origin: Occurs in placers as irregular, rounded grains; as disseminations, wires, and rarely as crystals in hydrothermal deposits. Occurs in a wide variety of environments, including placers, porphyry, epithermal, mesothermal, VMS, and “noseum” Carlin, Nevada-type.

References:

- Barrett, T.J., and Sherlock, R.L., 1996, Geology, lithogeochemistry and volcanic setting of the Eskay Creek Au-Ag-Cu-Zn deposit, northwestern British Columbia: *Exploration and Mining Geology*, v. 5, p. 339-368.
- Kerrich, R., Goldfarb, R., Groves, D., and Garwin, S., 2000, S.G. Hageman and P.E. Brown, editors: *Reviews in Economic Geology*, v. 13, p. 501-551.
- Knight, J.B., Mortensen, J.K., and Mortensen, S.R., 1999, Lode and placer gold composition in the Klondike District, Yukon Territory, Canada: Implications for the nature and genesis of Klondike placer and lode gold deposits: *Economic Geology*, v. 94, p. 649-664.
- Michel, D., and Giuliani, G., 1996, Habit and composition of gold grains in quartz veins from greenstone belts: Implications for mechanisms of precipitation of gold: *Canadian Mineralogist*, v. 34, p. 513-528.

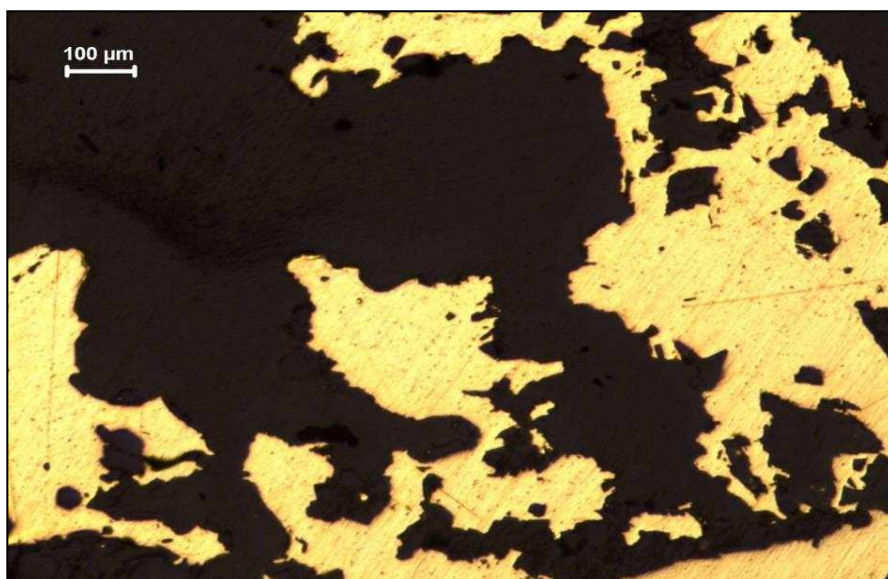


Figure 9.4 Gold in concentrate from the Manhattan mine, Nevada; Sample courtesy of Jae Stonehouse.

CHEMICAL CLASS: NATIVE METALS

Mineral Name: Silver

Composition: Ag

Characteristics in Hand Specimen

Crystal System: Cubic

Color: Silver-white, tarnishes gray to black.

Cleavage: None

Fracture: Hackly

Tenacity: Ductile, malleable.

Mohs Hardness: 2.5-3

Density (meas.): 10.1-11.1

Streak: Silver-white

Association: Acanthite, chlorargyrite, silver sulfosalts, copper.

Name: From an Old English word for the metal *soelfer*, related to the German *silber* and the Dutch *zilver*; the chemical symbol from the Latin *argentum*.



Figure 9.5 Native wire silver. Photo courtesy of Tom Loomis.

Characteristics in Polished Section

Color: Bright white, commonly tarnished black.

Polishing Hardness: >galena

Bireflectance: None

Anisotropy: Isotropic; false “anisotropism” due to scratches.

Reflectance (in air): 90-95

IR: Absent

Distinguishing Features: Highest reflectivity, very soft, isotropic, and very fine scratches are diagnostic.

Associated Minerals: Acanthite, pyrrargyrite, proustite, arsenopyrite, galena, sphalerite, tetrahedrite-tennantite.

Mode of Occurrence and Origin: Relatively rare, resulting from oxidation of silver-bearing sulfides, occurring as disseminations, wires, etc. Most common in hydrothermal vein deposits, such as those at Cobalt, Ont; Great Bear Lake, NWT; Konsberg, Norway; epithermal deposits in Mexico.

References:

Knight, J., and Leitch, C.H.B., 2001, Phase relations in the system Au-Cu-Ag at low temperatures, based on natural assemblages: *Canadian Mineralogist*, v. 39, p. 889-905.

Moller, S.A., Islas, F., Jorge, E., Davila, F., and Ramon, T., 2001, New discoveries in the La Colorado district, Zacatecas State, Mexico, *in* *New Mines and Discoveries in Mexico and Central America*: Society of Economic Geologists, Special Publication No. 8, p. 95-104.

Petruk, W., Harris, D.C., Cabri, L.J., and Stewart, J.M., 1971, Characteristics of the silver-antimony minerals: *Canadian Mineralogist*, v. 12, p. 187-195.

Raines, E., 1992, The geology, mineralogy, and history of four native silver localities in Colorado: *Rocks and Minerals*, v. 67, p. 230-254.

Sherlock, R.L., Roth, T., Spooner, E.T.C., and Bray, C.J., 1999, Origin of the Eskay Creek precious metal-rich volcanogenic massive sulfide deposit: fluid inclusion and stable isotope evidence: *Economic Geology*, v. 94, p. 803-824.

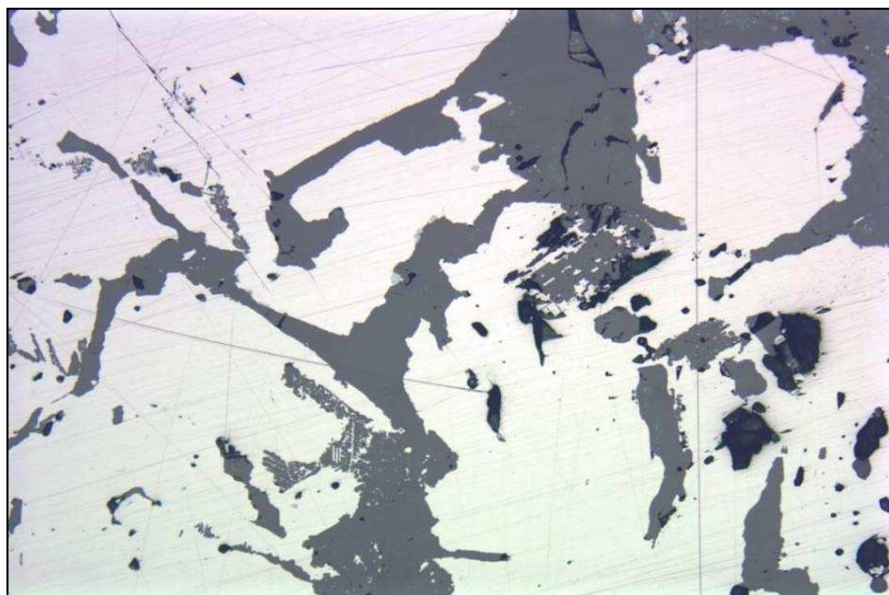


Figure 9.6 Native silver, No. 22.

CHEMICAL CLASS: SULFIDES

Mineral Name: Acanthite/Argentite

Composition: Ag_2S

Characteristics in Hand Specimen

Crystal System: Monoclinic

Color: Iron-black

Cleavage: Indistinct

Fracture: Uneven

Tenacity: Sectile

Mohs Hardness: 2.0-2.5

Density (meas.): 7.22

Streak: Black

Association: Silver, pyrargyrite, proustite, polybasite, stephanite, aguilarite, galena, chalcopryite, sphalerite, calcite, quartz.

Name: From the Greek for *thorn*, in allusion to the shape of the crystals.

Characteristics in Polished Section

Color: Gray, with greenish tint.

Cleavage: None

Polishing Hardness: Very low

Bireflectance: Very weak

Anisotropy: Distinct; bluish-gray

Reflectance (in air): 30-31

IR: Absent

Distinguishing Features: Gray with greenish tint, low reflectance, very weak bireflectance, distinct anisotropy.

Associated Minerals: Occurs with native silver, proustite, pyrargyrite, polybasite, galena, tetrahedrite, and cobalt-nickel ores.

Mode of Occurrence and Origin: Traditionally referred to as argentite, which is the stable form above 177°C. Acanthite commonly occurs in low-temperature vein deposits as inclusions in galena, as anhedral aggregates, or as pseudomorphs after argentite.

References:

- Greiffe', C., Bailly, L., and Milesi, J-P, 2002, Supergene alteration of primary ore assemblages from low-sulphidation Au-Ag epithermal deposits at Pongkor, Indonesia, and Nazareno, Peru: *Economic Geology*, v. 97, p. 561-571.
- Petruck, W., and staff, 1971, *Characteristics of the sulphides: Canadian Mineralogist*, v. 11, p. 196-231.

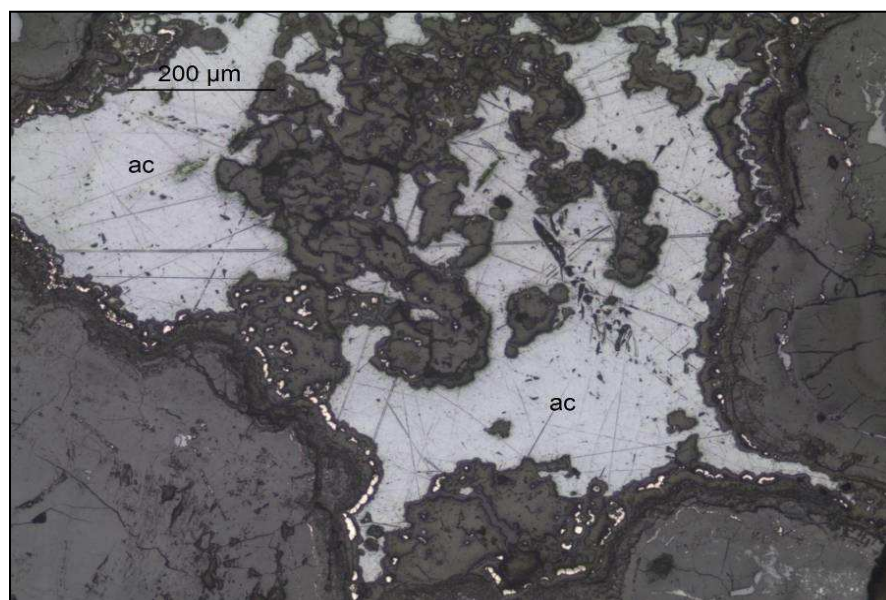


Figure 9.7 Acanthite (ac). R-29I, CSM Geology Collection.

CHEMICAL CLASS: SULFIDES

Mineral Name: Arsenopyrite

Composition: FeAsS

Characteristics in Hand Specimen

Crystal System: Monoclinic

Color: Silver-white to steel-gray.

Cleavage: Distinct on {101}; {010} in traces.

Fracture: Uneven

Tenacity: Brittle

Mohs Hardness: 5.5-6

Density (meas.): 6.05

Streak: Black

Association: Pyrrhotite, pyrite, chalcopyrite, galena, gold, scheelite, cassiterite, many other species.

Name: A contraction of *arsenical pyrites*.

Characteristics in Polished Section

Color: White

Cleavage: {110}, good

Polishing Hardness: <pyrite

Bireflectance: Weak

Anisotropy: Strong; blue, green



Figure 9.8 Arsenopyrite. CSM Geology Museum.

Reflectance (in air): 51-52

IR: Absent

Distinguishing Features: White color, strong anisotropism, and rhombic crystal form.

Associated Minerals: Gold, cassiterite, wolframite, galena, sphalerite, pyrite, and chalcopyrite.

Mode of Occurrence and Origin: Most common arsenic-bearing mineral. Euhedral to subhedral crystals with rhombic shape. Wide variety of hydrothermal environments, including tin ores at Cornwall, England; tin-tungsten veins at Panasqueira, Portugal; silver veins at Cobalt, Ont.; and Homestake gold deposits, Lead, South Dakota.

References:

- Fleet, M.E., and Mumin, A.H., 1997, Gold-bearing arsenian pyrite and marcasite and arsenopyrite from Carlin Trend gold deposits and laboratory synthesis: *American Mineralogist*, v. 82, p. 182-193.
- Kretschmar, U., and Scott, S.D., 1976, Phase relations involving arsenopyrite in the system Fe-As-S and their application: *Canadian Mineralogist*, v. 14, p. 364-386.
- Morimoto, N., and Clark, L.A., 1961, Arsenopyrite crystal-chemical relations: *American Mineralogist*, v. 46, p. 1448-1469.
- Scott, S.D., 1983, Chemical behavior of sphalerite and arsenopyrite in hydrothermal and metamorphic environments: *Mineralogical Magazine*, v. 47, p. 427-435.

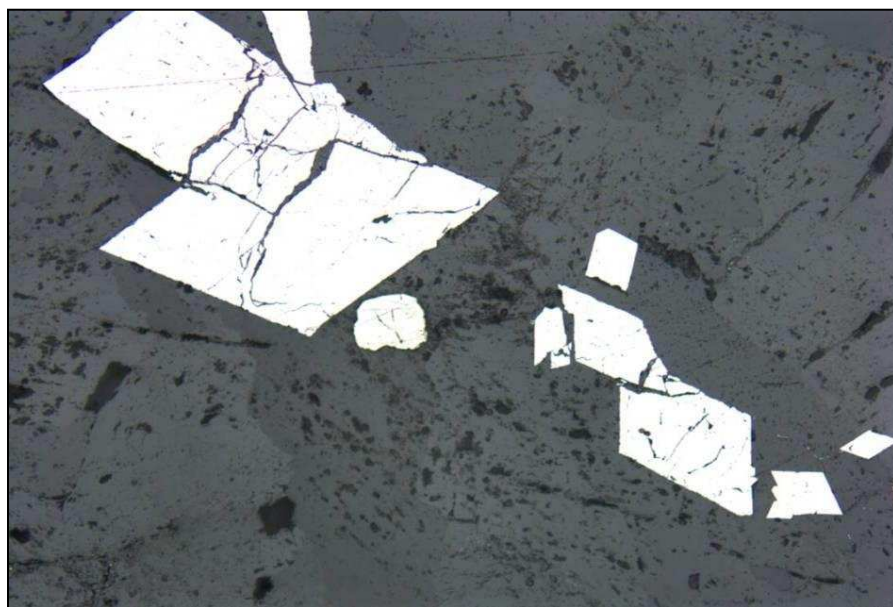


Figure 9.9 Rhombs of arsenopyrite. No. U7, 10x.

CHEMICAL CLASS: SULFIDES

Mineral Name: Bornite

Composition: Cu_5FeS_4

Characteristics in Hand Specimen

Crystal System: Orthorhombic

Color: Copper-red to brown on fresh surfaces, rapidly tarnishes iridescent purple.

Cleavage: {111} in traces.

Fracture: Uneven to subconchoidal.

Tenacity: Brittle

Mohs Hardness: 3.-3.25

Density (meas.): 5.06-5.08

Streak: Light grayish-black.

Association: Chalcopyrite, pyrite, other copper and iron sulfides, garnet, calcite, wollastonite, quartz.

Name: For Ignatius von Born (1742-1791), distinguished Austrian mineralogist.

Characteristics in Polished Section

Color: Pinkish-brown, tarnishing to lavender, blue, or purple.

Cleavage: {111} imperfect

Polishing Hardness: >galena

Bireflectance: Weak



Figure 9.10 Bornite. UCD Geology Collection.

Anisotropy: Very weak

Reflectance (in air): 18.5

IR: Absent

Distinguishing Features: Blue to purple tarnish, weak anisotropism, and common exsolution and replacement textures with chalcopyrite, chalcocite, covellite, digenite, enargite, and tetrahedrite-tennantite.

Associated Minerals: Pyrite, sphalerite, galena, magnetite, pyrrhotite, tetrahedrite-tennantite, and hematite.

Mode of Occurrence and Origin: Bornite, or “peacock ore”, occurs both as a hypogene and supergene mineral, in veinlets, or as disseminations, or granular masses. Very common in porphyry copper deposits as well as VMS, disseminations in mafic rocks, in contact metamorphic rocks, in replacement deposits, and less commonly in pegmatites.

References:

- Hannington, M.D., Bleeker, W., and Kjarsgard, I., 1999, Sulfide mineralogy, geochemistry and ore genesis of the Kidd Creek deposit: Part 2. The bornite zone, *in* The Giant Kidd Creek Volcanogenic Massive Sulfide Deposit, Western Abitibi Subprovince, Canada, (eds.) M.D. Hannington and C.T. Barrie: Economic Geology Monograph 10, Economic Geology Publishing Company, Littleton, CO, p. 225-266.
- Manske, S.L., and Paul, A.H., 2002, Geology of a major new porphyry copper center in the Superior (Pioneer) District, Arizona: Economic Geology, v. 97, p. 197-220.
- Maier, W.D., and Barnes, S.J., 1999, The origin of Cu sulfide deposits in the Curaca Valley, Bahia, Brazil: evidence from Cu, Ni, Se, and platinum-group element concentration: Economic Geology, v. 94, p. 165-183.

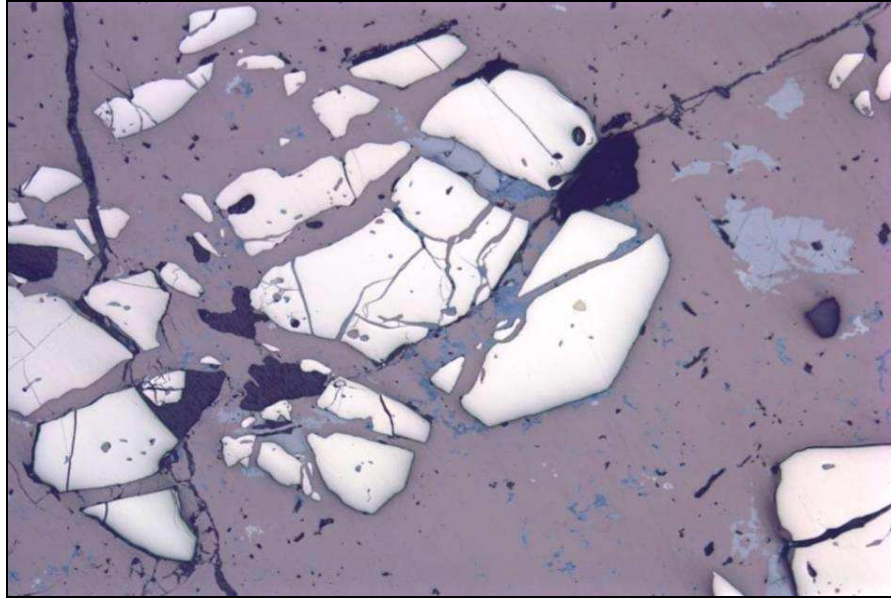


Figure 9.11 Pyrite, chalcocite (light blue), and covellite (dark blue) in matrix of bornite (lavender). No. 4, 5x.

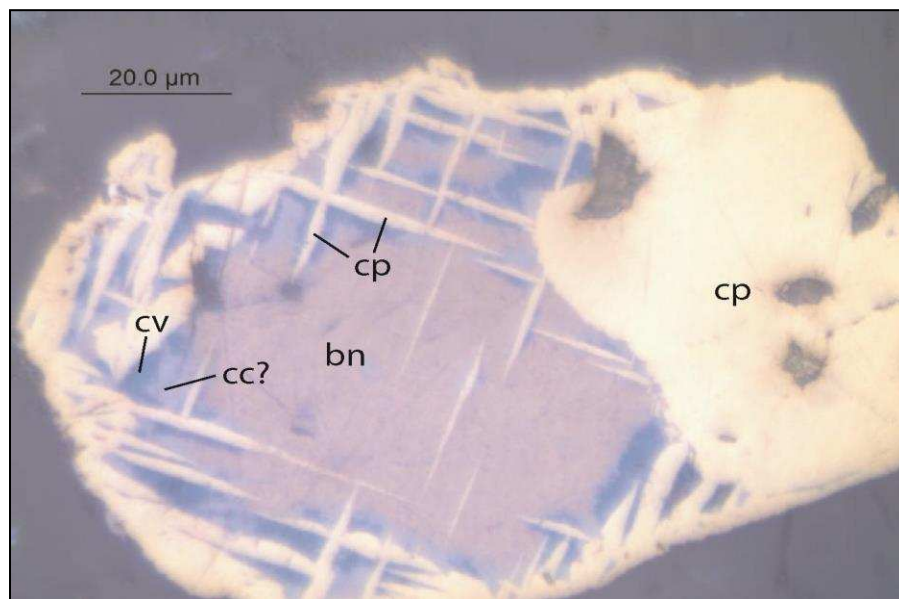


Figure 9.12 Lattice intergrowth of lenses, or "basket weave texture" of chalcopyrite (cp) and bornite (bn), with secondary alteration to covellite (cv) and chalcocite? (cc). Upper level of ore deposit, Bingham Canyon, Utah porphyry copper deposit. Notice the tapered ends of chalcopyrite lamellae, characteristic of exsolution, followed by rim replacement by chalcopyrite.

CHEMICAL CLASS: SULFIDES

Mineral Name: Chalcocite

Composition: Cu_2S

Characteristics in Hand Specimen

Crystal System: Monoclinic

Color: Blackish lead-gray.

Cleavage: Indistinct on {110}.

Fracture: Conchoidal

Tenacity: Brittle, somewhat sectile.

Mohs Hardness: 2.5-3

Density (meas.): 5.5-5.8

Streak: Blackish lead-gray.

Association: Pyrite, chalcopyrite, covellite, bornite, molybdenite, many other sulfides and their alteration products.

Name: For its composition, from the Greek for *chalkos*, copper.

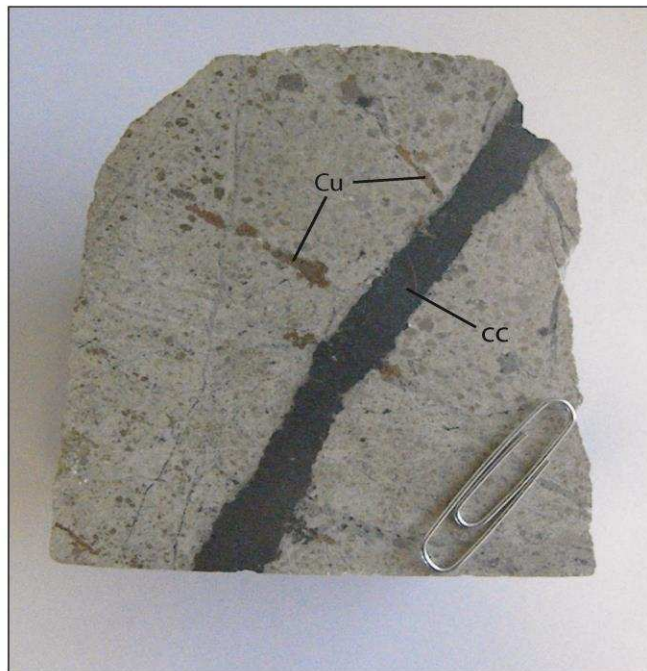


Figure 9.13 Veins of supergene chalcocite (cc) and native copper (Cu) in quartz monzonite. Specimen SR-10, Santa Rita, New Mexico.

Characteristics in Polished Section

Color: Bluish-gray to lead-gray.

Cleavage: {110}, poor

Polishing Hardness: ~galena

Bireflectance: Very weak.

Anisotropy: Weak

Reflectance (in air): 30

IR: Absent

Distinguishing Features: Typically bluish-gray, weakly anisotropic, very soft. Hypogene chalcocite is commonly coarse grained; supergene chalcocite may be massive, fine grained, or “sooty”.

Associated Minerals: Pyrite, chalcopyrite, bornite, covellite, copper, and digenite. Commonly present as exsolution intergrowths in bornite, and as pseudomorphs after chalcopyrite, galena, bornite, covellite, pyrite, digenite, and enargite.

Mode of Occurrence and Origin: Chalcocite may occur as a primary phase, but is most common and important as a supergene mineral, upgrading porphyry copper deposits to economic importance. It also occurs disseminated in mafic rocks, in contact metamorphic deposits, and in red-bed copper deposits, e.g., Keweenaw Peninsula, Michigan.

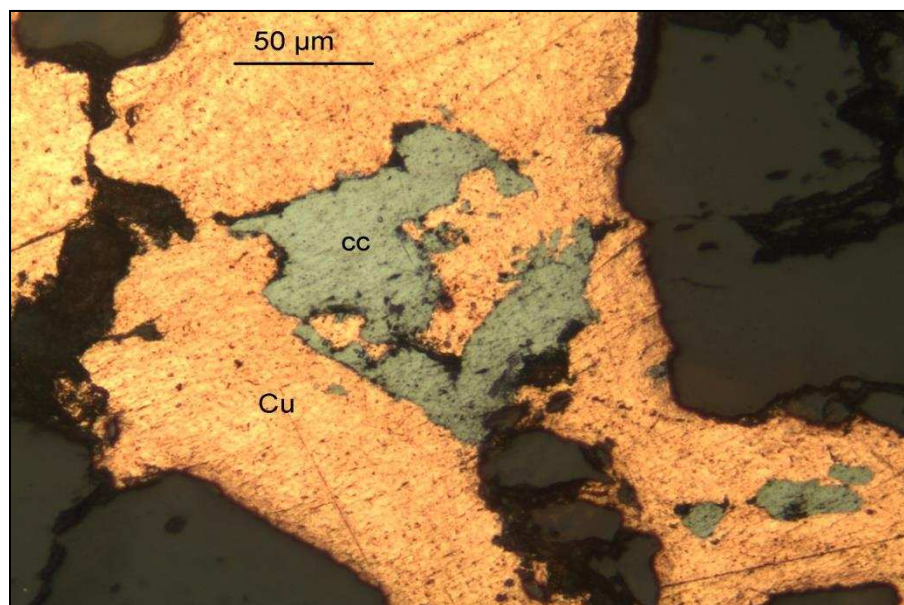


Figure 9.14 Polished section of specimen SR-10, showing inclusions and replacement of chalcocite (cc) by native copper (Cu). Therefore, native Cu veinlet postdates the chalcocite veinlet.



Figure 9.15 Supergene chalcocite (blue) replacement of pyrite. Santa Rita, NM.

References:

- Ossandon, G., Freraut, R., Gustafson, L.B., Lindsay, D.D., and Zentilli, M., 2001, Geology of the Chuquicamata mine: A progress report: *Economic Geology*, v. 96, p. 249-270.
- Sillitoe, R.H., Jaramillo, L., and Castro, H., 1984, Geologic exploration of a molybdenum-rich porphyry copper deposit at Mocoa, Colombia: *Economic Geology*, v. 79, p. 106-123.
- Alyanak, N., and Vogel, T.A., 1974, Framboidal chalcocite from White Pine, Michigan: *Economic Geology*, v. 69, p. 697-703.

CHEMICAL CLASS: SULFIDES

Mineral Name: Chalcopyrite

Composition: CuFeS_2

Characteristics in Hand Specimen

Crystal System: Tetragonal

Color: Brass-yellow, commonly tarnished and iridescent.

Cleavage: Poor on {011} and {111}.

Fracture: Brittle

Mohs Hardness: 3.5-4

Density (meas.): 4.1-4.3

Streak: Greenish-black

Association: Sphalerite, galena, tetrahedrite, pyrite, many copper sulfides.

Name: From the Greek for *brass* and *pyrite*.



Figure 9.16 Chalcopyrite and sphalerite. CSM Geology Museum.

Characteristics in Polished Section

Color: Yellow to brassy yellow.

Cleavage: {011}, {111} poor.

Polishing Hardness: >galena, <sphalerite.

Bireflectance: Weak

Anisotropy: Weak to distinct; gray-blue to yellow-green.

Reflectance (in air): 44-49

IR: Absent

Distinguishing Features: Color is similar to gold, but chalcopyrite is much harder, higher relief, and commonly fractured.

Associated Minerals: Pyrite, bornite, digenite, magnetite, molybdenite, pyrrhotite, pentlandite, and many others.

Mode of Occurrence and Origin: Chalcopyrite is the most common primary ore of copper and found in most sulfide deposits. It occurs as fine- to coarse-grained, anhedral disseminations, veinlets, and aggregates; widely distributed in copper porphyry, magmatic, sedex, epithermal, vein, and skarn deposits.

References:

- Barton, P.B., Jr., and Bethke, P.M., 1987, Chalcopyrite disease in sphalerite; pathology and epidemiology: *American Mineralogist*, v. 72, p. 451-467.
- Bortnikov, N.S., Genkin, A.D., Dobrovol, M.G., Muravitskaya, G.N., and Filimonova, A.A., 1991, The nature of chalcopyrite inclusions in sphalerite; exsolution, coprecipitation, or "disease"?: *Economic Geology*, v. 86, p. 1070-1082.

Mizuta, T., and Scott, S.D., 1997, Kinetics of iron depletion near pyrrhotite and chalcopyrite inclusions in sphalerite; the sphalerite speedometer: *Economic Geology*, v. 92, p. 772-783.

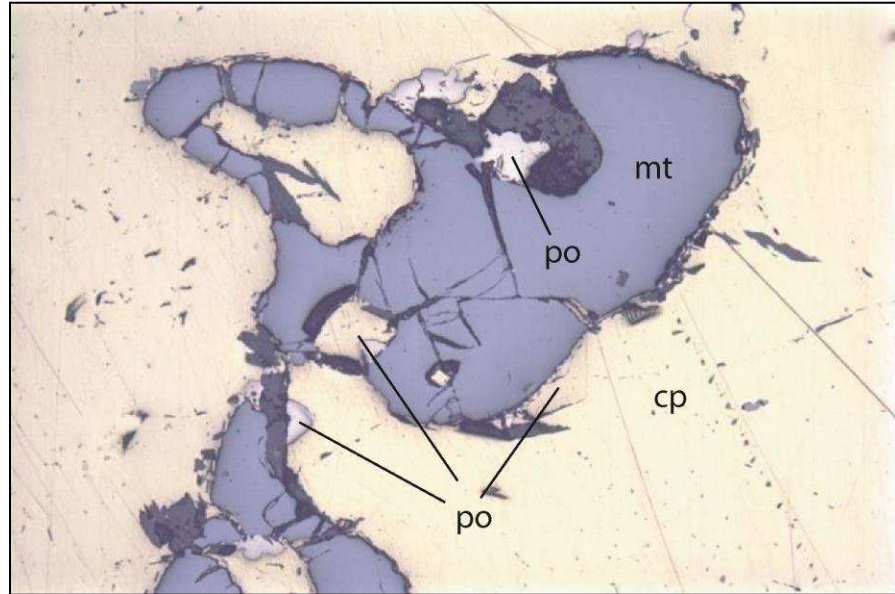


Figure 9.17 Chalcopyrite (cp), with magnetite (mt) and pyrrhotite (po), Sudbury, Ontario.

CHEMICAL CLASS: SULFIDES

Mineral Name: Cinnabar

Composition: HgS

Characteristics in Hand Specimen

Crystal System: Hexagonal

Color: Shade of red.

Cleavage: {10 $\bar{1}$ 0} perfect.

Fracture: Subconchoidal, uneven.

Tenacity: Slightly sectile.

Mohs Hardness: 2.-2.5

Density (meas.): 8.176

Streak: Scarlet

Association: Mercury, realgar, pyrite, marcasite, stibnite, opal, chalcedony, barite, dolomite, calcite.

Name: From the Medieval Latin *cinnabaris*, traceable to the Persian *zinjifrah*, apparently meaning *dragon's blood*, for the red color.



Figure 9.18 Cinnabar. UCD Geology collection.

Characteristics in Polished Section

Color: White with bluish-gray to reddish tint.

Cleavage: {1010} perfect.

Polishing Hardness: Slightly >antimony

Bireflectance: Weak to distinct.

Anisotropy: Strong; gray, blue, green, with internal reflections.

Reflectance (in air): 25-29

IR: Abundant, bright red.

Distinguishing Features: Cinnabar is white with grayish tints; anisotropism is strong, with red internal reflections.

Associated Minerals: Pyrite, marcasite, stibnite, realgar, gold, orpiment, galena, enargite, and numerous transparent minerals—chalcedony, calcite, quartz, and fluorite.

Mode of Occurrence and Origin: Most important ore of mercury. Occurs as vein fillings and disseminations in and near felsic volcanic rocks and hot springs; deposited from alkaline solutions. A common mineral in epithermal gold deposits. In the U.S., major deposits found in Nevada, California, and west Texas.

References:

Prol-Ledesma, R.M., Canet, C., Melgarejo, J.C., Tolson, G., Rubio-Ramos, M.A., Cruz-Ocampo, J.C., Ortega-Osoria, A., Torres-Vera, M.A., and Reyes, A., 2002, Cinnabar deposition in submarine coastal hydrothermal vents, Pacific margin of central Mexico: *Economic Geology*, v. 97, p. 1331-1340.

Wallace, A.R., 2003, Geology of the Ivanhoe Hg-Au district, northern Nevada: Influence of Miocene volcanism, lakes, and active faulting on epithermal mineralization: Economic Geology, v. 98, p. 409-424.

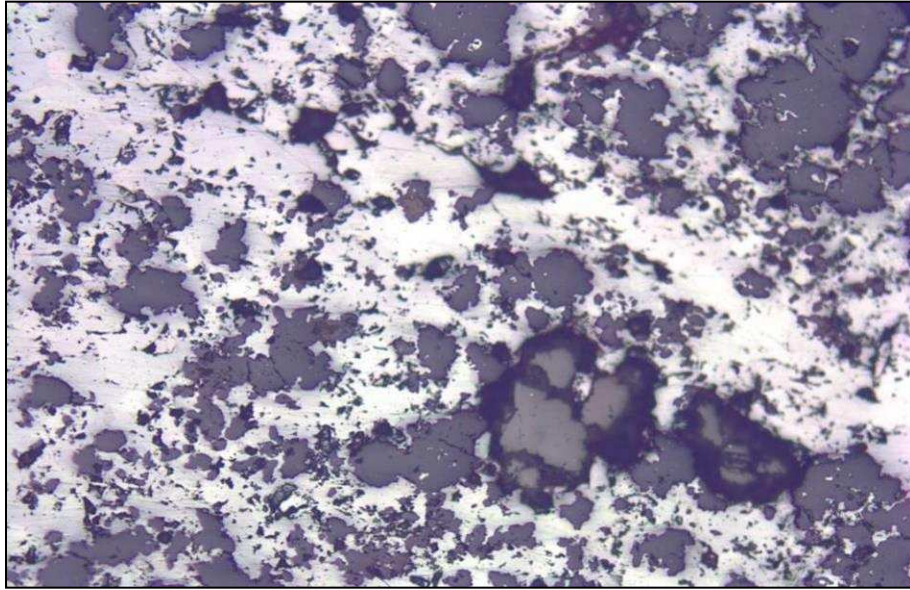


Figure 9.19 Cinnabar (white with grayish tint). No. 32, 10x.

CHEMICAL CLASS: SULFIDES

Mineral Name: Covellite

Composition: CuS

Characteristics in Hand Specimen

Crystal System: Hexagonal

Color: Indigo-blue, commonly highly iridescent.

Cleavage: Perfect on {0001}.

Tenacity: Flexible in thin leaves.

Mohs Hardness: 1.5-2

Density (meas.): 4.6-4.76

Streak: Lead-gray, shining.

Association: Chalcopyrite, chalcocite, djurleite, bornite, enargite, pyrite, other sulfides.

Name: For Niccolo Covelli (1790-1829), discoverer of Vesuvian covellite.



Figure 9.20 Covellite. UCD Geology Collection.

Characteristics in Polished Section

Color: Indigo-blue to bluish-white.

Polishing Hardness: Slightly <galena

Bireflectance: Strong blue-violet to bluish-white.

Anisotropy: Extreme, red-orange to brown.

Reflectance (in air): 7-24

IR: Absent

Distinguishing Features: Blue color and strong blue to bluish-white bireflectance and orange to brown anisotropism are most characteristic.

Associated Minerals: Pyrite, chalcopyrite, chalcocite, digenite, and bornite. Also occurs with many other minerals.

Mode of Occurrence and Origin: Commonly occurs as compact masses or micaceous plates, disseminations, and in veinlets as replacement of other copper sulfides. A common supergene mineral associated with porphyry copper deposits, and also as a primary hypogene mineral in the vein deposits at Butte, Montana.

References:

- Large, D.J., MacQuaker, J., Vaughan, D.J., Sawlwick, Z., and Gize, A.P., 1995, Evidence for low temperature alteration of sulfides in the Kupferschiefer copper deposits of southwestern Poland: *Economic Geology*, v. 90, p. 2143-2155.
- Landtwing, M.R., Dillenbeck, E.D., Leake, M.H., and Heinrich, C.A., 2002, Evolution of the breccia-hosted porphyry Cu-Mo-Au deposit at Agua Rica, Argentina: Progressive unroofing of a magmatic hydrothermal system: *Economic Geology*, v. 97, p. 1273-1292.

Moss, R., and Scott, S.D., 1996, Silver in sulfide chimneys and mounds from 13° N and 21° N, East Pacific Rise: Canadian Mineralogist, v. 34, p. 697-716.

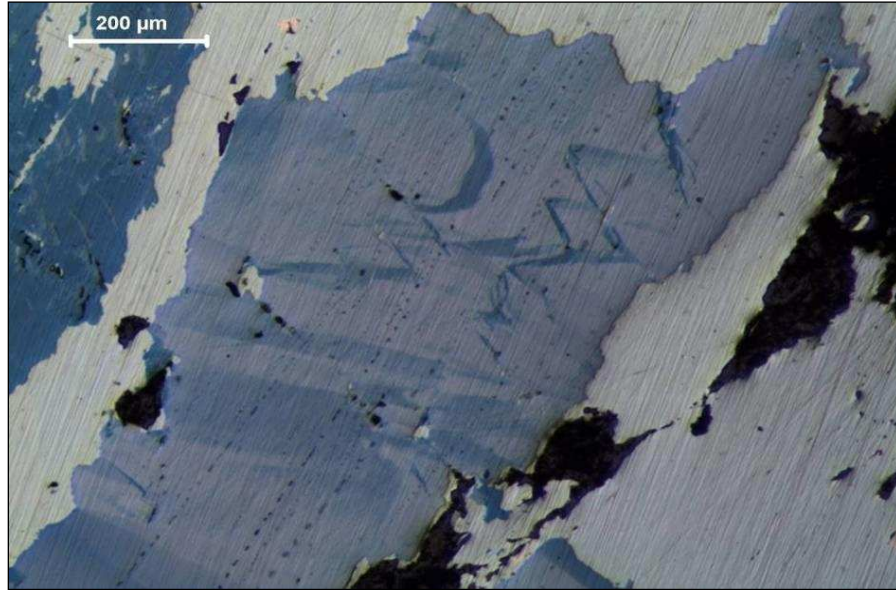


Figure 9.21 Blue and gray bireflection in covellite. Plane-polarized light.

CHEMICAL CLASS: SULFIDES

Mineral Name: Cubanite

Composition: CuFe_2S_3

Characteristics in Hand Specimen

Crystal System: Orthorhombic or cubic.

Color: Brass- to bronze-yellow.

Cleavage: None; parting on $\{110\}$ and $\{\bar{1}30\}$.

Fracture: Conchoidal

Mohs Hardness: 3.5

Density (meas.): 4.03-4.18

Streak: Black

Association: Chalcopyrite, pyrite, pyrrhotite, sphalerite.

Name: For its occurrence in Cuba.

Characteristics in Polished Section

Color: Creamy gray or pale brown.

Cleavage: None

Polishing Hardness: Slightly >chalcopyrite

Bireflectance: Gray to brownish gray

Anisotropy: Strong; brownish to blue

Reflectance (in air): 39-40

IR: Absent

Distinguishing Features: Distinct bireflectance and anisotropy

Associated Minerals: Pyrrhotite, sphalerite, galena, mackinawite, pentlandite, magnetite, and arsenopyrite.

Mode of Occurrence and Origin: Most commonly as sharply bounded laths within coarse-grained chalcopyrite.

References:

Cabri, L.J., Hall, R.S., Szymanski, J.T., and Stewart, J.M., 1973, On the transformation of cubanite: Canadian Mineralogist, v. 12, p. 33-38.

Caye, R., Cervelle, B., Cesbron, F., Oudin, E., Picot, P., and Pillard, F., 1988, Isocubanite, a new definition of the cubic polymorph of cubanite CuFe_2S_3 ; Mineralogical Magazine, v. 52, p. 509-514.

Leveques, A., 1983, Cubanite from Chibougamau, Quebec: Mineralogical Record, v. 14, p. 151-155.

Naldrett, A.J., Singh, J., Krstic, S., and Li, C., 2000, The mineralogy of the Voisey's Bay Ni-Cu-Co deposit, northern Labrador, Canada: Influence of oxidation state on textures and mineral compositions: Economic Geology, v. 95, p. 889-900.

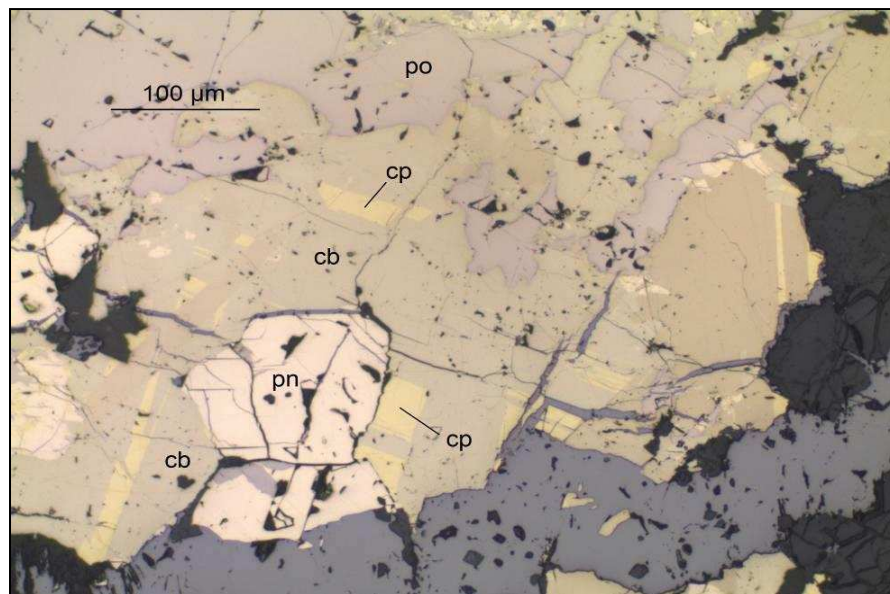


Figure 9.22 Cubanite (cb), with pyrrhotite (po), pentlandite (pn), chalcopyrite (cp), and sphalerite (medium gray). Eagle deposit, Michigan Cu-Ni deposit.

CHEMICAL CLASS: SULFIDES

Mineral Name: Digenite

Composition: Cu_9S_5

Characteristics in Hand Specimen

Crystal System: Hexagonal

Color: Blue to black.

Cleavage: {111} (synthetic).

Fracture: Conchoidal

Tenacity: Brittle

Mohs Hardness: 2.5-3

Density (meas.): 5.546

Streak: Grayish black.

Association: Chalcocite, djurleite, bornite, chalcopyrite, other copper sulfides, pyrite.

Name: From the Greek for *two kinds or sexes*, in reference to the presumed presence of both cuprous and cupric ions.

Characteristics in Polished Section

Color: Blue

Cleavage: {111} good

Polishing Hardness: ~galena, chalcocite.

Bireflectance: None

Anisotropy: Anomalous, weak.

Reflectance (in air): 21-24

IR: Absent

Distinguishing Features: Bluish color, good polish, and moderate reflectance distinguish it from bornite. Easily confused with chalcocite!

Associated Minerals: Chalcocite, covellite, bornite, chalcopyrite, enargite, tetrahedrite-tennantite, pyrite, galena, and sphalerite.

Mode of Occurrence and Origin: Generally occurs in massive or granular aggregates with other copper sulfides. May be primary or secondary in origin; found in veins, stratabound, and porphyry copper deposits.

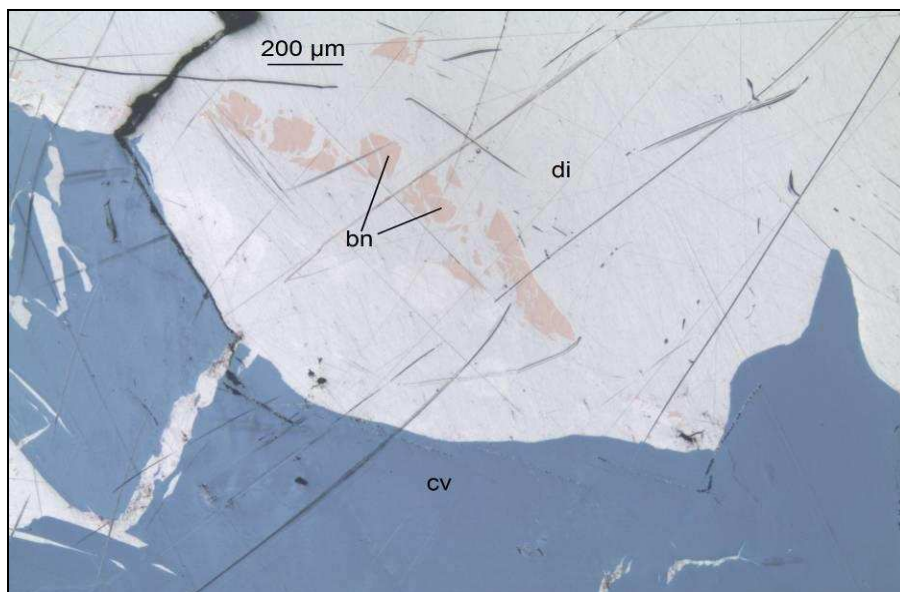


Figure 9.23 Digenite (di), with covellite (cv) and bornite (bn). CSM Geology collection, R-55.

References:

- Kojima, S., Astudillo, J., Rojo, J., Trista, D., and Hayashi, K., 2003, Ore mineralogy, fluid inclusion, and stable isotopic characteristics of stratiform copper deposits in the coastal Cordillera of northern Chile: *Mineralium Deposita*, v. 38, p. 208-216.
- Morimoto, N., and Gyobu, A., 1971, Composition and stability of digenite: *American Mineralogist*, v. 56, p. 11-12.
- Ossandon, G.I., Freraut, R., Gustafson, L.B., Lindsay, D.D., and Zentilli, M., 2001, Geology of the Chquicamata mine: A progress report: *Economic Geology*, v. 96, p. 249-270.

CHEMICAL CLASS: SULFIDES

Mineral Name: Galena

Composition: PbS

Characteristics in Hand Specimen

Crystal System: Cubic

Color: Lead-gray

Cleavage: Perfect, {001}; parting or cleavage on {111}.

Fracture: Subconchoidal

Tenacity: Brittle

Mohs Hardness: 2.5-2.75

Density (meas.): 7.58

Streak: Lead-gray

Association: Sphalerite, marcasite, pyrite, chalcopyrite, tetrahedrite, silver minerals, siderite, calcite, dolomite, barite, quartz, many other hydrothermal minerals.

Name: A Latin word *galena*, given to lead ore or the dross from melted lead.



Figure 9.24 Galena. Gift from Maritza Cantorin, Lima, Peru.

Characteristics in Polished Section

Color: Creamy white.

Cleavage: {100} perfect, leaving triangular pits.

Polishing Hardness: ~chalcocite, <chalcopyrite.

Bireflectance: None

Anisotropy: Isotropic

Reflectance (in air): 44

IR: Absent

Distinguishing Features: White color, perfect cubic cleavage expressed by triangular pits, softness, and moderate reflectance.

Associated Minerals: Sphalerite, pyrite, chalcopyrite, tetrahedrite-tennantite, argentite, and lead sulfosalts. Common gangue minerals include barite, fluorite, quartz, and calcite.

Mode of Occurrence and Origin: The principal ore of lead. A very widespread and common sulfide, occurring in MVT, VMS, and SEDEX deposits. In hydrothermal vein deposits, commonly associated with silver minerals.

References:

Bortnikov, N.S., Dobrovolskaya, M.G., Genkin, A.D., Naumov, V.B. and Shapenko, V.V., 1995, Sphalerite-galena geothermometers: Distribution of cadmium, manganese, and fractionation of sulphur isotopes: *Economic Geology*, v. 90, p. 155-180.

Fowler, A.D., 1996, Self-organized banded sphalerite and branching galena in the Pine Point ore deposit, Northwest Territories: Canadian Mineralogist, v. 34, p. 1211-1222.
Huston, D.L., Jablonski, W., and Sie, S.H., 1996, The distribution and mineral hosts of silver in eastern Australian volcanogenic massive sulfide deposits: Canadian Mineralogist, v. 34, p. 529-546.

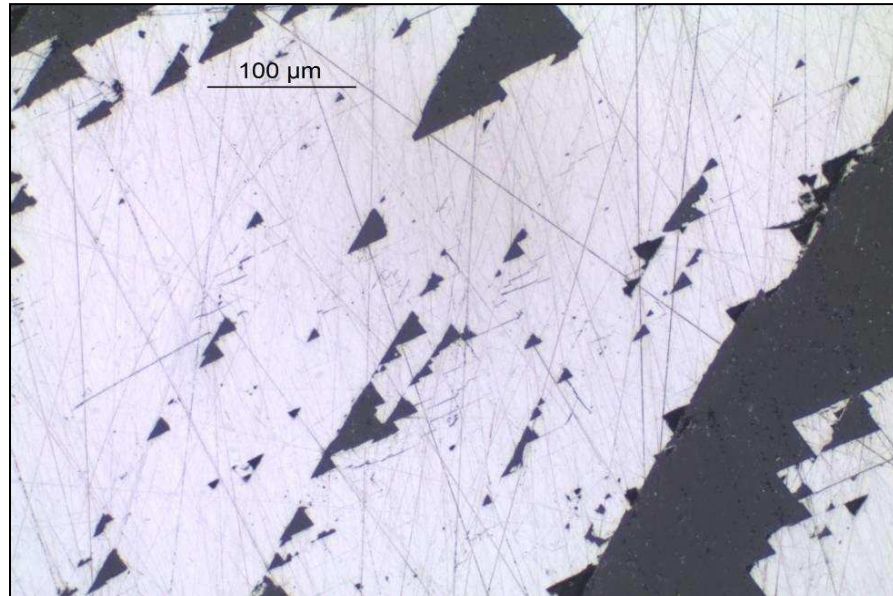


Figure 9.25 Galena with cleavage pits.

CHEMICAL CLASS: SULFIDES

Mineral Name: Heazlewoodite

Composition: Ni_3S_2

Characteristics in Hand Specimen

Crystal System: Trigonal

Color: Light bronze or brass-yellow.

Mohs Hardness: 4

Density (meas.): 5.82

Streak: Light bronze.

Name: For the locality at Heazlewood, Tasmania, Australia.

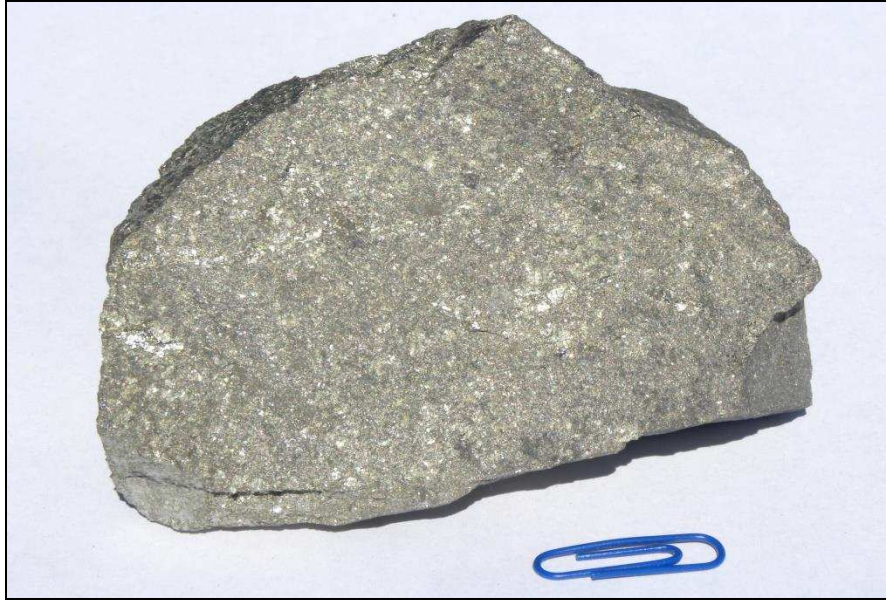


Figure 9.26 Heazlewoodite. McWatters nickel mine, Timmons, Ontario. Gift of Gary Nash, CEO, Liberty Mines.

Characteristics in Polished Section

Color: Yellowish-cream

Cleavage: Parallel to $\{10\bar{1}1\}$ may be visible.

Polishing Hardness: slightly <pentlandite, slightly >chalcopyrite.

Bireflectance: Very weak.

Anisotropy: Strong; brown to bluish-gray.

Reflectance (in air): 52.5

IR: Absent

Distinguishing Features:

Associated Minerals:

Mode of Occurrence and Origin:

References:

CHEMICAL CLASS: SULFIDES

Mineral Name: Marcasite

Composition: FeS_2

Characteristics in Hand Specimen

Crystal System: Orthorhombic

Color: Tin-white on fresh surface, pale bronze-yellow.

Cleavage: {101} rather distinct, {110} in traces.

Tenacity: Brittle

Mohs Hardness: 6-6.5

Density (meas.): 4.887

Streak: Grayish- to brownish-black.

Association: Pyrite, pyrrhotite, galena, sphalerite, fluorite, dolomite, calcite.

Name: A word of Arabic or Moorish origin, early applied to pyrite and other substances.

Characteristics in Polished Section

Color: Yellowish-white

Cleavage: {110} poor

Polishing Hardness: <pyrite, >pyrrhotite

Bireflectance: Strong; brown, yellowish-green

Anisotropy: Strong; blue, greenish-yellow, gray

Reflectance (in air): 47-53

IR: Absent

Distinguishing Features: Bireflectance, strong blue to yellowish anisotropism, lamellar texture, and common twinning.

Associated Minerals: Pyrite, galena, sphalerite, bornite, carbonates, and fluorite.

Mode of Occurrence and Origin: A low temperature mineral, occurring as granular to massive aggregates, concretions, and pseudomorphs. Commonly found as replacement deposits in carbonate rocks.

References:

- Drapela, T., and Beran, A., 1993, Reflected light examination of marcasite and löllingite: Mineralogy and Petrology, v. 48, p. 269-274.
- Fleet, M.E., and Mumin, A.H., 1997, Gold-bearing arsenian pyrite and marcasite and arsenopyrite from Carlin Trend gold deposits and laboratory synthesis: American Mineralogist, v. 82, p. 182-193.
- Murowchick, J.B., 1992, Marcasite inversion and the petrographic determination of pyrite ancestry: Economic Geology, v. 87, p. 1141-1152.
- Pichler, T., Giggenbach, W.F., McInnes, B.I.A., Buhl, D., and Duck, B., 1999, Fe sulfide formation due to seawater-gas-sediment interaction in a shallow-water hydrothermal system at Lihir Island, Papua, New Guinea: Economic Geology, v. 94, p. 281-288.

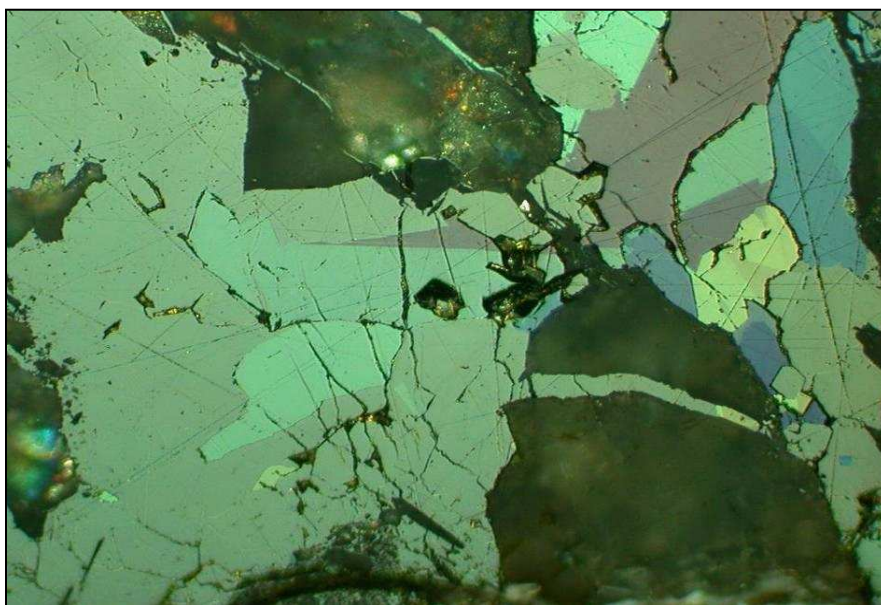


Figure 9.27 Marcasite, showing strong pleochroism. Bessie G mine, La Plata, CO; crossed polars. Photo courtesy of Jim Paschis.

CHEMICAL CLASS: SULFIDES

Mineral Name: Millerite

Composition: NiS

Characteristics in Hand Specimen

Crystal System: Hexagonal

Color: Pale brass-yellow to bronze-yellow.

Cleavage: Perfect on $\{10\bar{1}1\}$ and $\{01\bar{1}2\}$.

Fracture: Uneven

Tenacity: Brittle; capillary crystals are elastic.

Mohs Hardness: 3-3.5

Density (meas.): 5.5

Streak: Greenish-black.

Association: Gersdorffite, nickeline, galena, sphalerite, pyrite, pyrrhotite.

Name: For William Hallows Miller (1801-1880), British mineralogist, Cambridge University, who first studied crystals of the mineral.

Characteristics in Polished Section

Color: Pure yellow.

Cleavage: None

Polishing Hardness: >chalcopyrite, <sphalerite, pentlandite.

Bireflectance: In oil, bright yellow to grayish yellow.

Anisotropy: Strong; straw- or lemon-yellow to a pronounced iris-blue and violet.

Reflectance (in air): 51-56

IR: Absent

Distinguishing Features:

Associated Minerals:

Mode of Occurrence and Origin:

References:

Ballhaus, C., Tredous, M., and Spath, A., 2001, Phase relations in the Fe-Ni-Cu-PGE-S system at magmatic temperatures and application to massive sulphide ores of the Sudbury Igneous Complex: *Journal of Petrology*, v. 42, p. 1911-1926.

Kojima, S., Hanarmuro, T., Hayeashi, K., Haruna, M., and Ohmoto, H., 1998, Sulphide minerals in Early Archean chemical sedimentary rocks of the eastern Pilbara district, Western Australia: *Mineralogy and Petrology*, v. 64, p. 219-235.

Molnar, F., Watkinson, D.H., and Jones, P.C., 2001, Multiple hydrothermal processes in footwall units of the North Range, Sudbury Igneous Complex, Canada, and implications for the genesis of vein-type Cu-Ni-PGE deposits: *Economic Geology*, v. 96, p. 1645-1670.

CHEMICAL CLASS: SULFIDES

Mineral Name: Molybdenite

Composition: MoS_2

Characteristics in Hand Specimen

Crystal System: Hexagonal

Color: Bluish-gray

Cleavage: Perfect on {0001}.

Tenacity: Lamellae flexible, not elastic.

Mohs Hardness: 1-1.5

Density (meas.): 4.62-4.73

Streak: Bluish

Association: Chalcopyrite, other copper sulfides, tin and tungsten minerals, quartz.

Name: A word derived from the Greek *molybdos*, lead.



Figure 9.28 Molybdenite (bluish gray) in quartz vein, Leon deposit, Canada.

Characteristics in Polished Section

Color: White to gray, with pinkish tint.

Cleavage: {0001} perfect

Polishing Hardness: Slightly >chalcopyrite

Bireflectance: Very strong; white to gray.

Anisotropy: Very strong; pinkish-white.

Reflectance (in air): 22-42

IR: Absent

Distinguishing Features: Soft (with poor polish), bireflectance, and anisotropism are characteristic. Also, bent basal cleavage, straight extinction, and polysynthetic twinning are common.

Associated Minerals: Pyrite, chalcopyrite, bornite, cassiterite, wolframite, bismuthinite, and other sulfides.

Mode of Occurrence and Origin: Major ore of molybdenum (“moly”); most common as disseminations and in quartz veinlets and stockworks with chalcopyrite, chalcocite, bornite, and sphalerite in Arizona porphyry coppers, and in rhyolite porphyries, as noted at Climax and Henderson, Colorado. Also found in tin-tungsten veins and in some copper-gold and tungsten skarn deposits.

References:

Carten, R.W., White, W.H., and Stein, H.J., 1993, High-grade granite-related molybdenum systems: Classification and origin: Geological Association of Canada, Special Paper 40, p. 521-554.

Maughan, D.T., Keith, J.D., Christiansen, E.H., Pulsipher, T., Hatori, K., and Evan, N.J., 2002, Contributions from mafic alkaline magmas to the Bingham porphyry Cu-Au-Mo deposit, Utah, USA: *Mineralium Deposita*, v. 37, p. 14-37.

White, W.H., Bookstrom, A.A., Kamilli, R.J., Ganster, M.W., Smith, R.P., Ranta D.E., and Steininger, R.C., 1981, Character and origin of the Climax-type molybdenum deposits: *Economic Geology*, 75th Anniversary Volume, p. 270-316.

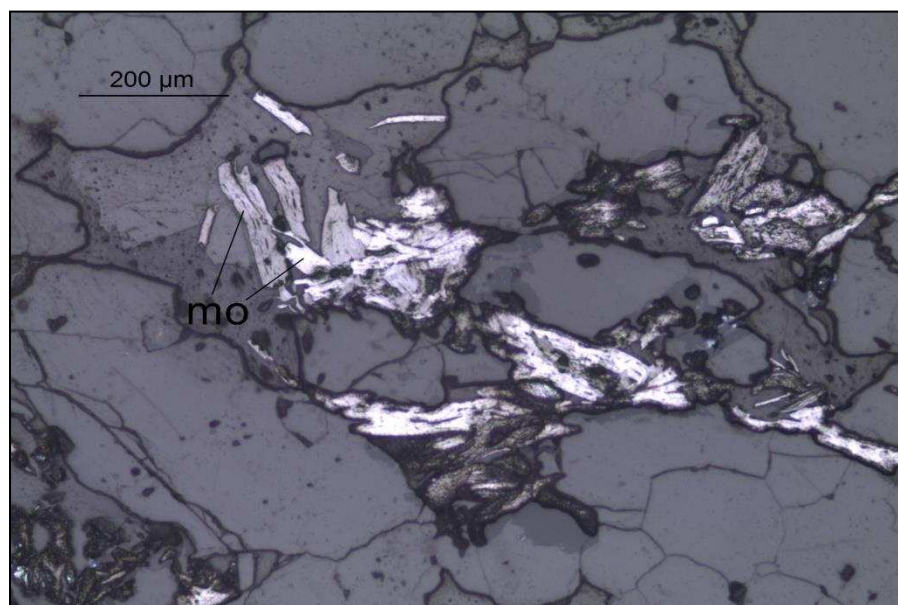


Figure 9.29 Molybdenite. Questa, New Mexico moly porphyry.

CHEMICAL CLASS: SULFIDES

Mineral Name: Orpiment

Composition: As_2S_3

Characteristics in Hand Specimen

Crystal System: Monoclinic

Color: Lemon-yellow to golden or brownish-yellow.

Cleavage: {2010} perfect, {100} imperfect.

Tenacity: Sectile

Mohs Hardness: 1.5-2

Density (meas.): 3.49

Streak: Pale lemon-yellow.

Association: Stibnite, realgar, calcite, barite, gypsum.

Name: From the Latin *auripigmentum*, golden paint, in allusion to the color.

Characteristics in Polished Section

Color: Gray

Polishing Hardness:



Figure 9.30 Orpiment (yellow) and realgar (red) from the Carlin Trend, Nevada. Specimen courtesy of Al Hofstra, USGS.

Bireflectance: Strong; white to gray.

Anisotropy: Masked by abundant internal reflections.

Reflectance (in air): 25

IR: Abundant and intense; white to yellow.

Distinguishing Features: Color, strong anisotropy, internal reflections.

Associated Minerals: Realgar, stibnite, arsenopyrite, enargite, proustite, and Fe-hydroxides.

Mode of Occurrence and Origin: Cavity fillings between other minerals; as tabular interlocking anhedral masses and as needle- or lathlike crystals in epithermal deposits, commonly associated with gold deposits.

References:

- Asadi, H.H., Voncken, J.H.L., Kuhnelt, R.A., and Hale, M., 2000, Petrography, mineralogy, and geochemistry of the Zarshuran Carlin-like gold deposit, northwest Iran: *Mineralium Deposita*, v. 35, p. 656-671.
- Ferrini, V., Martarelli, L., DeVito, C., and Deda, T., 2003, The Koman dawsonite and realgar-orpiment deposit, northern Albania: Inferences on processes of formation: *Canadian Mineralogist*, v. 41, p. 413-427.

Groff, J.A., Campbell, A.R., and Norman, D.I., 2002, An evaluation of fluid inclusion microthermometric data for orpiment-realgar-calcite-barite-gold mineralization at the Betze and Carlin mines, Nevada: *Economic Geology*, v. 97, p. 1341-1346.

Powell, W.G., and Pattison, D.R.M., 1997, An exsolution origin for low-temperature sulfides at the Hemlo gold deposit, Ontario, Canada: *Economic Geology*, v. 92, p. 569-577.

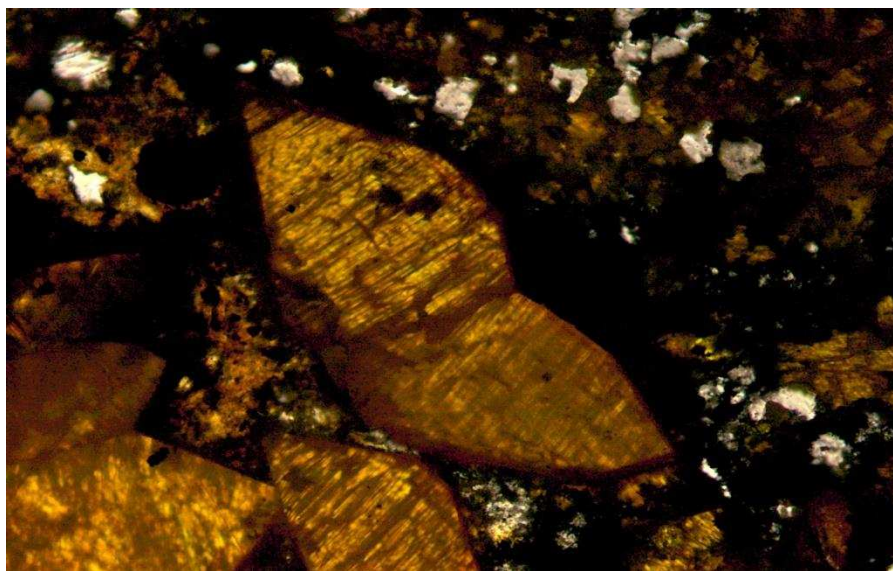


Figure 9.31 Orpiment. Post-ore generation. Getchell mine, Nevada. Transmitted light, crossed polars. Photo courtesy of Al Hofstra, USGS.

CHEMICAL CLASS: SULFIDES

Mineral Name: Pentlandite

Composition: $(\text{Fe}, \text{Ni})_9\text{S}_8$

Characteristics in Hand Specimen

Crystal System: Cubic

Color: Light bronze-yellow.

Cleavage: None; parting on {111}.

Fracture: Conchoidal

Tenacity: Brittle

Mohs Hardness: 3.5-4

Density (meas.): 4.6-5

Streak: Light bronze-brown.

Association: Pyrrhotite, chalcopyrite, cubanite, mackinawite, magnetite.

Name: For Joseph Barclay Pentland (1797-1873), Irish natural scientist, who first noted the mineral.

Characteristics in Polished Section

Color: Light cream to yellowish.

Cleavage: {111} parting

Polishing Hardness: >chalcopyrite, slightly <pyrrhotite

Bireflectance: None

Anisotropy: Isotropic

Reflectance (in air): 44

IR: Absent

Distinguishing Features: Creamy color, good polish, moderate reflectance, isotropism, and common association with pyrrhotite.

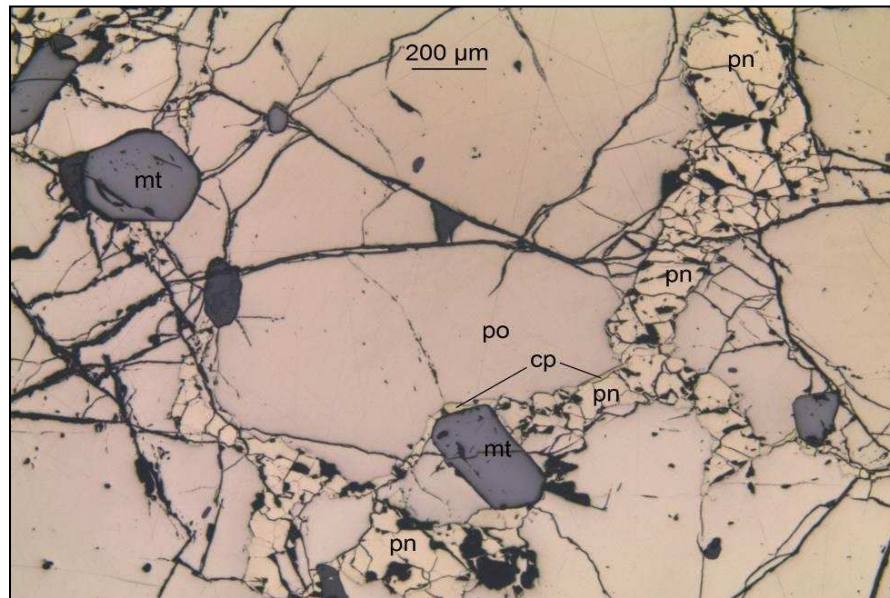


Figure 9.32 Pentlandite (pn) along grain boundaries of pyrrhotite (po), and early magnetite (mt). Sudbury Cu-Ni deposit, Ontario.

Associated Minerals: Pyrrhotite, chalcopyrite, pyrite, violarite, millerite, cubanite, chromite, ilmenite, and magnetite.

Mode of Occurrence and Origin: Major ore of nickel. Most common in magmatic segregation deposits where it forms flames and grain boundary exsolution intergrowths with pyrrhotite. Major deposits include those at Sudbury, Ont; Thomson, Manitoba; Voisey's Bay, Labrador, and Kambalda, West Australia.

References:

Craig, J.R., and Solberg, T.N., 1999, Compositional zoning in ore minerals at the Craig mine, Sudbury, Ontario, Canada: Canadian Mineralogist, v. 37, p. 1163-1176.

Kelly, D.P., and Vaughan, D.J., 1983, Pyrrhotite-pentlandite ore textures: A mechanistic approach: *Mineralogical Magazine*, v. 47, p. 453-463.
Naldrett, A.J., Singh, J., Krstic, S., and Li, C.S., 2000, The mineralogy of the Voisey's Bay Ni-Cu-Co deposit, northern Labrador, Canada: Influence of oxidation state on textures and mineral compositions: *Economic Geology*, v. 95, p. 889-900.
Riley, J.F., 1977, The pentlandite group $(\text{Fe,Ni,Co})_9\text{S}_8$: New data and an appraisal of structure composition relationships: *Mineralogical Magazine*, v. 41, p. 345-349.

CHEMICAL CLASS: SULFIDES

Mineral Name: Pyrite

Composition: FeS_2

Characteristics in Hand Specimen

Crystal System: Cubic

Color: Pale brass-yellow, tarnishes darker and iridescent.

Cleavage: Indistinct on {001}; partings on {011} and {111}, indistinct.

Fracture: Conchoidal to uneven.

Tenacity: Brittle

Mohs Hardness: 6-6.5

Density (meas.): 5.02

Streak: Greenish-black to brownish-black.

Association: Pyrrhotite, marcasite, galena, sphalerite, arsenopyrite, chalcopyrite, many other sulfides and sulfosalts, hematite, fluorite, quartz, barite, calcite.

Name: From the Greek for *fire*, as sparks may be struck from it.



Figure 9.33 Pyritohedral pyrite. CSM Geology Museum.

Characteristics in Polished Section

Color: Yellowish-white

Cleavage: None

Polishing Hardness: Very high; >marcasite.

Bireflectance: Absent

Anisotropy: Weak (anomalous), blue-green to reddish.

Reflectance (in air): 54

IR: Absent

Distinguishing Features: Yellowish white, high relief (very hard), high reflectance.

Associated Minerals: With most common ores, particularly chalcopyrite, sphalerite, galena, arsenopyrite, and pyrrhotite.

Mode of Occurrence and Origin: Occurs as euhedral cubes, pyritohedra, anhedral crystalline masses; less commonly in colloform growths. Most common of the sulfide minerals, associated with gold, VMS, and porphyry deposits. Also occurs in hydrothermal veins, sedimentary, igneous, and metamorphic rocks.

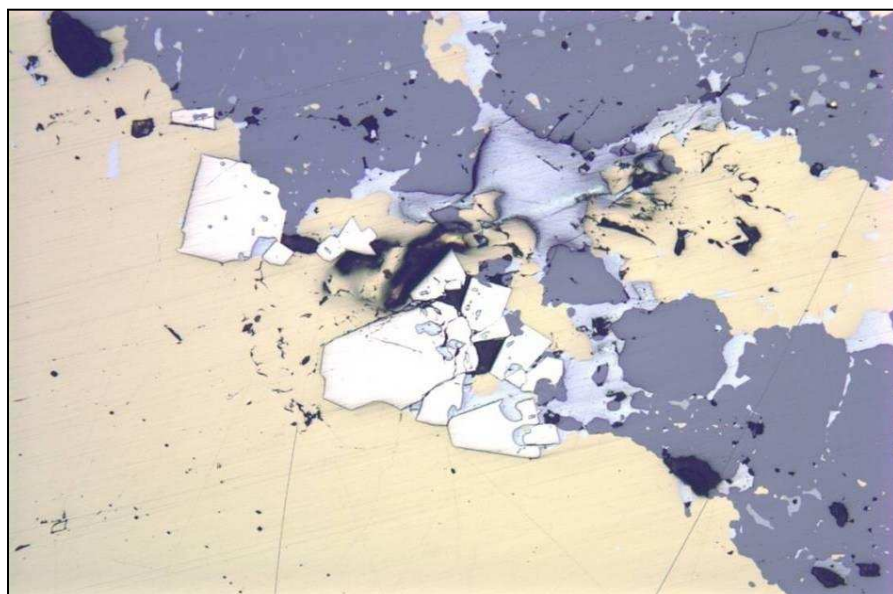


Figure 9.34 Pyrite (whitish), with chalcopyrite, sphalerite, galena, and chalcocite. No. 11, 10x.

References:

- Booker, D.D., Craig, J.R., and Rimstidt, J.D., 1987, Ore metamorphism and pyrite porphyroblast development at the Cherokee Mine, Ducktown, Tennessee: *Economic Geology*, v. 82, p. 72-86.
- Craig, J.R., Vokes, F.M., and Solberg, T.N., 1998, Pyrite: physical and chemical textures: *Mineralium Deposita*, v. 34, p. 82-101.

- England, B.M., and Ostwald, J., 1993, Framboid-derived structures in some Tasman fold belt base-metal sulphide deposits, New South Wales, Australia: *Ore Geology Reviews*, v. 7, p. 381-412.
- Foley, N., Ayuso, R.A., and Seal, R.R., 2001, Remnant colloform pyrite at the Haile gold deposit, South Carolina: A textural key to genesis: *Economic Geology*, v. 96, p. 891-902.
- Simon, G., Kesler, S.E., and Chryssoulis, S., 1999, Geochemistry and textures of gold bearing arsenian pyrite, Twin Creeks, Nevada: Implications for deposition of gold in Carlin-type deposits: *Economic Geology*, v. 94, p. 405-421.

CHEMICAL CLASS: SULFIDES

Mineral Name: Pyrrhotite

Composition: Fe_{1-x}S

Characteristics in Hand Specimen

Crystal System: Monoclinic

Color: Bronze-yellow to brown; tarnishes quickly.

Cleavage: None; distinct {0001} parting.

Fracture: Uneven to subconchoidal.

Mohs Hardness: 3.5-4.5

Density (meas.): 4.58-4.65

Streak: Dark grayish black.

Association: Pyrite, marcasite, chalcopyrite, pentlandite, many other sulfides, magnetite, calcite, dolomite.

Name: From the Greek for *redness*, in allusion to its color.

Characteristics in Polished Section

Color: Creamy pinkish-brown.

Cleavage: None

Polishing Hardness: ~pentlandite

Bireflectance: Distinct; creamy brown to reddish-brown.

Anisotropy: Very strong; red to yellowish-brown.

Reflectance (in air): 34-39

IR: Absent

Distinguishing Features: Distinct bireflectance, strong anisotropism, and basal cleavage.



Figure 9.35 Pyrrhotite. CSM Geology Museum.

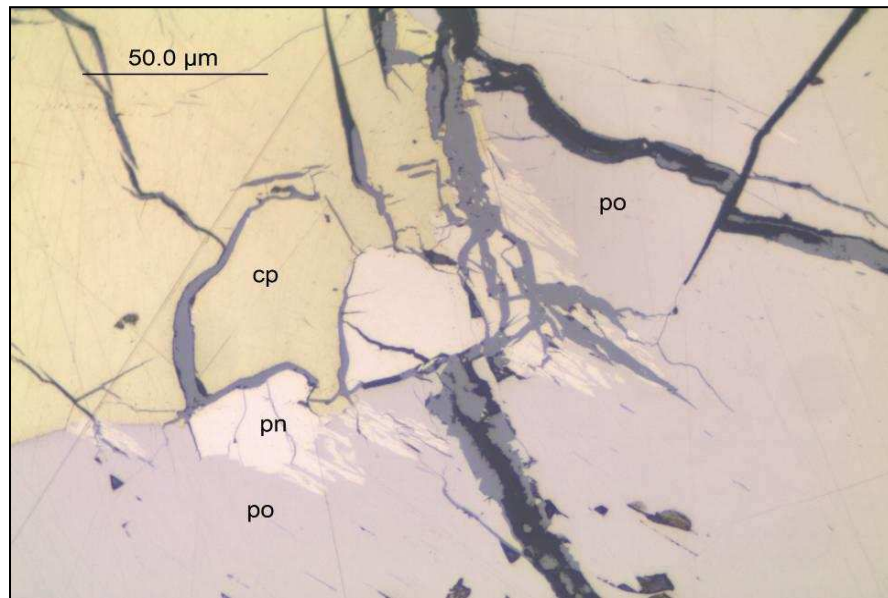


Figure 9.36 Pyrrhotite (po), with chalcopyrite (cp), pentlandite (pn), and sphalerite (medium gray). Note pentlandite flames. Eagle Cu-Ni deposit, Michigan.

Associated Minerals: Chalcopyrite, pentlandite, marcasite, arsenopyrite, pyrite, and magnetite. Intergrowths with pentlandite are very common in nickel ores.

Mode of Occurrence and Origin: Commonly associated with mafic and ultramafic rocks. Occurs as large masses in magmatic nickel deposits associated with pentlandite, chalcopyrite, and other sulfides. Also found in VMS, skarns, veins, and pegmatites.

References:

- Durazzo, A., and Taylor, L.A., 1982, Exsolution in the Mss-pentlandite system: textural and genetic implications for Ni-sulfide ores: *Mineralium Deposita*, v. 17, p. 313-332.
- Kelly, D.P., and Vaughan, D.J., 1983, Pyrrhotite-pentlandite ore textures: A mechanistic approach: *Mineralogical Magazine*, v. 47, p. 453-463.
- Li, C., Naldrett, A.J., Rucklidge, J.C., and Kilius, L.R., 1993, Concentrations of platinum-group elements and gold in sulfides from the Strathcona Deposit, Sudbury, Ontario: *Canadian Mineralogist*, v. 1, p. 523-531.
- Zhou, T., Phillips, G.N., Dong, G., and Myers, R.E., 1995, Pyrrhoite in the Witwatersrand gold fields, South Africa: *Economic Geology*, v. 90, p. 2361-2369.

CHEMICAL CLASS: SULFIDES**Mineral Name:** Realgar**Composition:** AsS**Characteristics in Hand Specimen****Crystal System:** Monoclinic**Color:** Red to orange-yellow.**Cleavage:** Good on {010}; less so on several other directions.**Tenacity:** Sectile**Mohs Hardness:** 1.5-2**Density (meas.):** 3.56**Streak:** Orange-red to red.**Association:** Orpiment, other arsenic minerals, calcite, barite.**Name:** From the Arabic for *powder of the mine*.**Characteristics in Polished Section****Color:** Dull gray**Bireflectance:** Weak, but distinct; gray with reddish to gray with bluish tint.**Anisotropy:** Strong**Reflectance (in air):** 20-21**IR:** Abundant and intense; yellowish red.**Distinguishing Features:** Color, strong anisotropy, internal reflections.**Associated Minerals:** Orpiment, stibnite, arsenopyrite, enargite, proustite, and Fe-hydroxides.**Mode of Occurrence and Origin:** Cavity fillings between other minerals; as tabular interlocking anhedral masses and as needle- or lathlike crystals in epithermal deposits, commonly associated with gold deposits.



Figure 7.37 Realgar on quartz. Specimen is a gift from Professor Enrique Guadalupe Gomez, University of San Marcos, Lima, Peru.



Figure 7.38 Realgar, Jerritt Canyon. SDrm, reflected light, 10x. Photo courtesy of Al Hofstra.

References:

Ferrini, V., Martarelli, L., DeVito, C., and Deda, T., 2003, The Koman dawsonite and realgar-orpiment deposit, northern Albania: Inferences on processes of formation: Canadian Mineralogist, v. 41, p. 413-427.

Groff, J.A., Campbell, A.R., and Norman, D.I., 2002, An evaluation of fluid inclusion microthermometric data for orpiment-realgar-calcite-barite-gold mineralization at the Betze and Carlin mines, Nevada: *Economic Geology*, v. 97, p. 1341-1346.
Marquez-Zavalia, F., Craig, J.R., and Solberg, T.N., 1999, Duranusite, product of realgar alteration, Mina Capitalis, Argentina: *Canadian Mineralogist*, v. 37, p. 1255-1259.
Xiong, X.X., 2000, Classification, minerogenic models and prospecting of realgar/orpiment deposits in China: *Acta Geologica Sinica*, v. 74, p. 618-622.

CHEMICAL CLASS: SULFIDES

Mineral Name: Sphalerite

Composition: (Zn,Fe)S

Characteristics in Hand Specimen

Crystal System: Cubic

Color: Highly variable, ranging from colorless to dark brown, gray, black.

Cleavage: Perfect on {011}.

Fracture: Conchoidal

Tenacity: Brittle



Figure 9.39 Sphalerite. UCD Geology collection.

Mohs Hardness: 3.5-4

Density (meas.): 3-4.1

Streak: Brownish to light yellow and white.

Association: Galena, chalcopyrite, marcasite, pyrite, fluorite, barite, quartz, many other hydrothermal minerals.

Name: From the Greek for *treacherous*, the mineral sometimes being mistaken for galena, but yielding no lead.

Characteristics in Polished Section

Color: Gray

Cleavage: Not observed.

Polishing Hardness: >chalcopyrite, <pyrrhotite

Bireflectance: None

Anisotropy: Isotropic

Reflectance (in air): 17-20

IR: Common, yellow-brown to reddish-brown.

Distinguishing Features: Gray color, isotropism, commonly with abundant yellow-brown to reddish-brown internal reflections. In copper sulfide deposits tiny inclusions of chalcopyrite are very common. Low-iron sphalerite is transparent and should be studied in transmitted light.

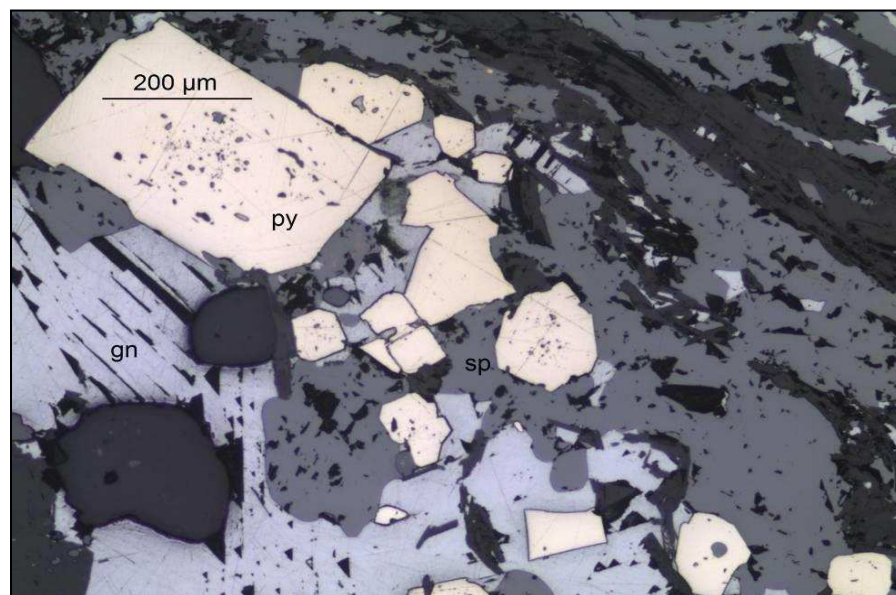


Figure 9.40 Sphalerite (sp), with pyrite (py) and galena (gn). Kidd Creek massive sulfide deposit, Timmins, Ontario.

Mode of Occurrence and Origin: Major ore of zinc, commonly associated with galena. Occurs as euhedral to subhedral crystals, or as colloform texture. Common in many deposits including MVT, VMS, and SEDEX. Also occurs in veins and in contact metamorphic (skarn) deposits. High-temperature polymorph is wurtzite (hexagonal).

References:

Scott, S.D., 1983, Chemical behavior of sphalerite and arsenopyrite in hydrothermal and metamorphic environments: *Mineralogical Magazine*, v. 47, p. 427-435.

Hutchison, M.N., and Scott, S.D., 1981, Sphalerite geobarometry in the Cu-Fe-Zn-S System: Economic Geology, v. 76, p. 143-153.

Mizuta, T., and Scott, S.D., 1997, Kinetics of iron depletion near pyrrhotite and chalcopyrite inclusions in sphalerite: The sphalerite speedometer: Economic Geology, v. 92, p. 772-783.

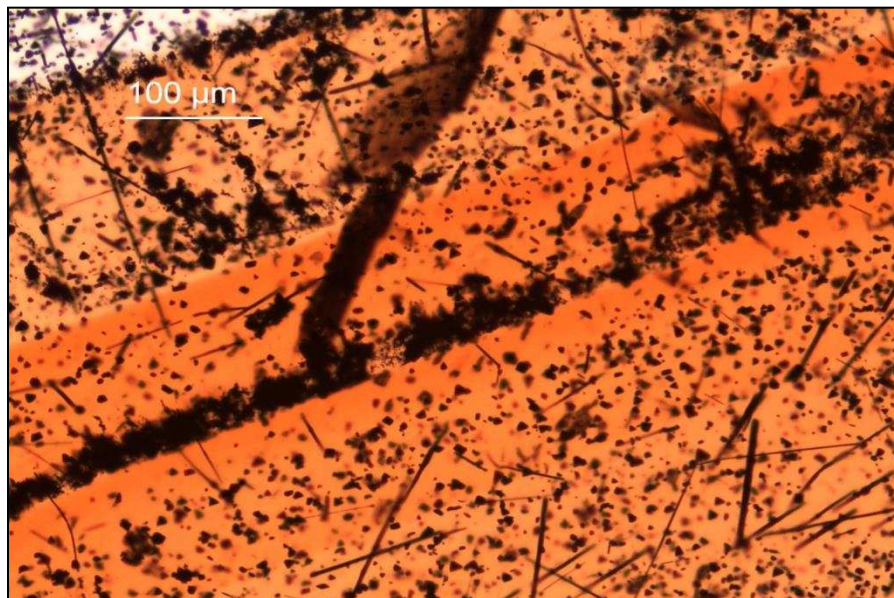


Figure 9.41 Color-zoned, low Fe sphalerite, with interlayered pyrite (black). Mina Plomosas, Chihuahua, Mexico. Transmitted light.

CHEMICAL CLASS: SULFIDES

Mineral Name: Stibnite

Composition: Sb_2S_3

Characteristics in Hand Specimen

Crystal System: Orthorhombic

Color: Lead-gray, tarnishing blackish or iridescent.

Cleavage: Perfect on {010}; imperfect on {100} and {110}.

Fracture: Subconchoidal

Tenacity: Highly flexible but not elastic; slightly sectile.

Mohs Hardness: 2

Density (meas.): 4.63

Streak: Lead-gray

Association: Realgar, orpiment, cinnabar, galena, lead sulfantimonides, pyrite, marcasite, arsenopyrite, calcite, ankerite, barite, chalcedonic quartz.

Name: From the Greek *stibi*, then Latin *stibium*, an old name for the mineral.



Figure 9.42 Stibnite. China.

Characteristics in Polished Section

Color: White to gray.

Cleavage: {010} perfect

Polishing Hardness: ~galena, <<chalcopyrite

Bireflectance: Strong; white to grayish-white.

Anisotropy: Very strong; blue, gray, brown, pink.

Reflectance (in air): 31-47

IR: Absent

Distinguishing Features: Softness, strong bireflectance, very strong anisotropism, and undulatory extinction.

Associated Minerals: Galena, sulfosalts, cinnabar, pyrite, marcasite, chalcopyrite, arsenopyrite, realgar, orpiment, and gold.

Mode of Occurrence and Origin: Occurs as radiating to granular or compact aggregates. In low temperature hydrothermal veins or in replacement, or hot spring deposits. Significant deposits occur in the Hunan province, China; Giant Mine, NWT, and at Hemlo, Ont.

References:

- Bailly, L., Bouchot, V., Beny, C., and Milesi, J-P., 2000, Fluid inclusion study of stibnite using infrared microscopy: an example from the Brouzils antimony deposit (Vendee, Armorican Massif, France): *Economic Geology*, v. 95, p. 221-26.
- Fan, D., Zhang, T., and Ye, J., 2003, The Xikuangshan Sb deposit hosted by the Upper Devonian black shale series, Hunan, China: *Ore Geology Reviews*, v. 24, p. 121-133.

Wagner, T., and Cook, N.J., 2000, Late-Variscan antimony mineralization in the Rheinisches Schiefergebirge, NW Germany: evidence for stibnite precipitation by drastic cooling of high-temperature fluid systems: *Mineralium Deposita*, v. 35, p. 206-222.

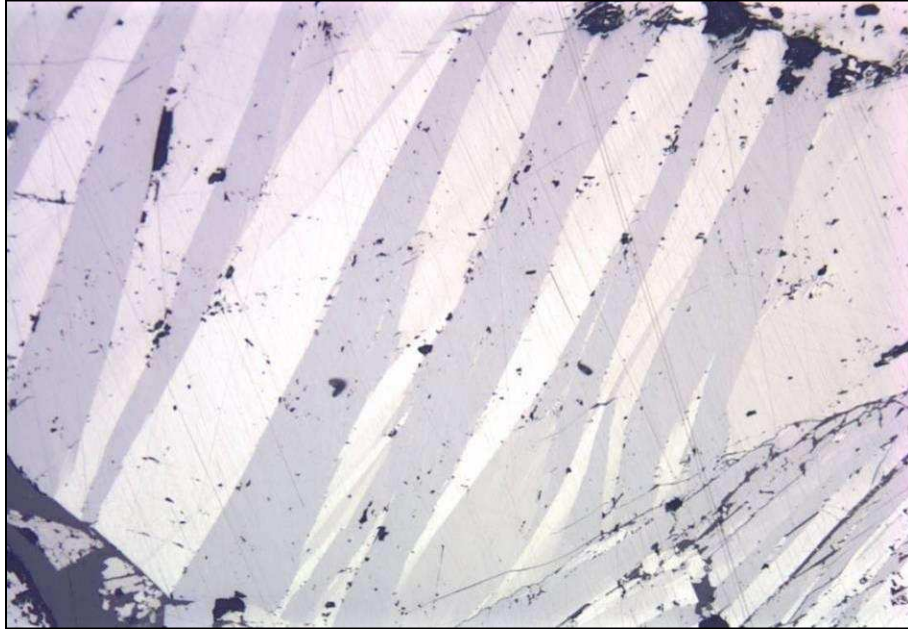


Figure 9.43 Growth twinning in stibnite. No. 17, 10x.

CHEMICAL CLASS: SULFIDES

Mineral Name: Talnakhite

Composition: CuFeS_2

Characteristics in Hand Specimen

Crystal System: Cubic

Color: Chalcopyrite-yellow, tarnishes rapidly to hues of pink and brown.

Mohs Hardness: 4-4.5

Density (meas.): 4.29

Streak: Black

Association: Chalcopyrite, cubanite, pentlandite, valleriite, mackinawite, magnetite, Ag-Au alloy, Pd-Pb alloy (Talnakh area, USSR).

Name: For the Talnakh area, USSR, in which it occurs.



Figure 9.44 Tarnished talnakhite in core from Local Boy ore zone, Mesaba deposit, Duluth Complex. Photo courtesy of Mark Severson, NRRI, University of Minnesota, Duluth.

Characteristics in Polished Section

Color: Chalcopyrite yellow; tarnishes rapidly to hues of pink and brown.

Cleavage: None

Polishing Hardness:

Bireflectance: None

Anisotropy: None

Reflectance (in air): 39

IR: Absent

Distinguishing Features: Dark yellow color, tarnishing to brown; generally intergrown with fine plates and mesh structures of chalcopyrite.

Associated Minerals: Cubanite, pentlandite, magnetite, sphalerite, pyrrhotite, and chalcopyrite.

Mode of Occurrence and Origin:

References:

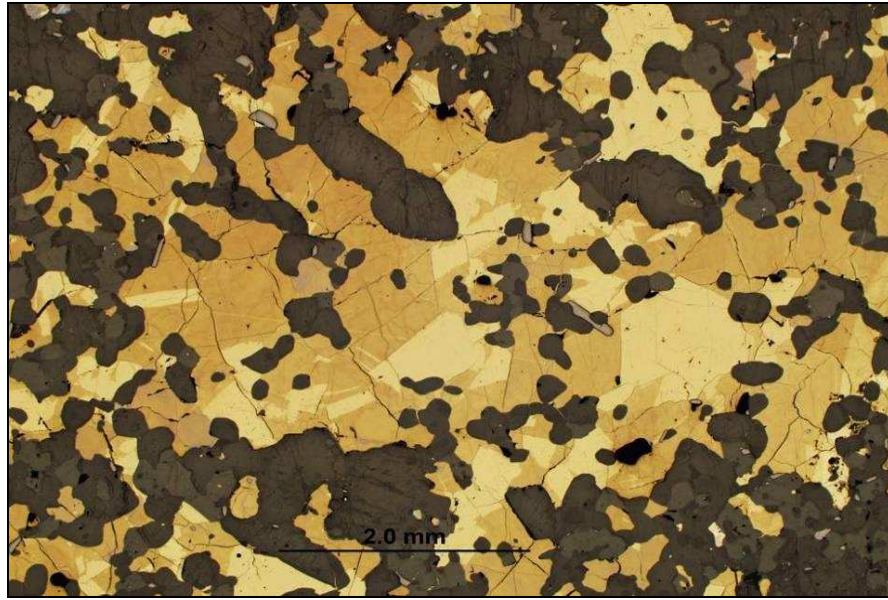


Figure 9.45 Talnakhite (tarnished yellowish-tan), intergrown with chalcopryite (yellow) and gangue (brown). Mesaba deposit, Duluth Complex, Minnesota. Polished section courtesy of Steve Hauck.

CHEMICAL CLASS: SULFOSALTS

Mineral Name: Boulangerite

Composition: $\text{Pb}_5\text{Sb}_4\text{S}_{11}$

Characteristics in Hand Specimen

Crystal System: Monoclinic

Color: Dull lead-gray.

Cleavage: Distinct on {100}.

Tenacity: Brittle; flexible in thin crystals.

Mohs Hardness: 2.5-3

Density (meas.): ~6.2

Streak: Brownish

Association: Lead sulfosalts, galena, stibnite, sphalerite, pyrite, arsenopyrite, siderite, quartz.

Name: For Charles Louis Boulanger (1810-1849), French mining engineer.

Characteristics in Polished Section

Color: White with bluish-gray tint.

Cleavage: {001} indistinct, {010} indistinct.

Polishing Hardness: <galena



Figure 9.46 Boulangerite needles. Photo courtesy of Tom Loomis, Dakotamatrix.com.

Bireflectance: Distinct; gray white to green gray.

Anisotropy: Distinct; tan, brown, bluish gray.

Reflectance (in air): 37-42

IR: Rare; red.

Distinguishing Features: Color, softness, and distinct anisotropism.

Associated Minerals: Galena, sphalerite, chalcopyrite, tetrahedrite, or other Pb-Sb sulfosalts.

Mode of Occurrence and Origin: Granular or fibrous aggregates.

References:

- Mulshaw, S.C., Puig, C., Spiro, B., and Buchanan, D.L., 1997, Genesis of epizonal Ag vein mineralization at San Bartolome in Central Ecuador; textural evidence, fluid inclusions, and stable isotope geochemistry: *Economic Geology*, v. 92, p. 210-227.
- Wagner, T., and Schneider, J., 2002, Lead isotope systematics of vein-type antimony mineralization, Rheinisches Schiefergebirge Germany: a case history of complex reaction and remobilization processes: *Mineralium Deposita*, v. 37, p. 185-197.
- Wagner, T., and Cook, N.J., 1997, Mineral reactions in sulphide systems as indicators of evolving fluid geochemistry: A case study from the Apollo Mine, Siegerland, FRG. *Mineralogical Magazine*, v. 61, p. 573-590.

CHEMICAL CLASS: SULFOSALTS

Mineral Name: Bournonite

Composition: PbCuSbS_3

Characteristics in Hand Specimen

Crystal System: Orthorhombic

Color: Steel-gray to iron-black.

Cleavage: {010}, imperfect; {100} and {001}, less perfect.

Fracture: Subconchoidal to uneven.

Tenacity: Brittle

Mohs Hardness: 2.5-3

Density (meas.): 5.83

Streak: Steel-gray to iron-black.

Association: Galena, tetrahedrite, sphalerite, chalcopyrite, pyrite, stibnite, siderite, quartz, rhodochrosite, barite.

Name: After Count Jacques Louis de Bournon (1751-1825), French crystallographer and mineralogist.



Figure 9. 47 Bournonite from China. Photo courtesy of Tom Loomis.

Characteristics in Polished Section

Color: Grayish white with a distinct blue or bluish green tint.

Cleavage: {010} imperfect; {100}, {001} less perfect.

Polishing Hardness: >boulangerite, galena; <chalcopyrite, sphalerite.

Bireflectance: Weak

Anisotropy: Weak

Reflectance (in air): 35-39

IR: Absent

Distinguishing Features: Twinning, color, and anisotropy.

Associated Minerals: Galena, bornite, bournonite, chalcopyrite, arsenopyrite.

Mode of Occurrence and Origin:

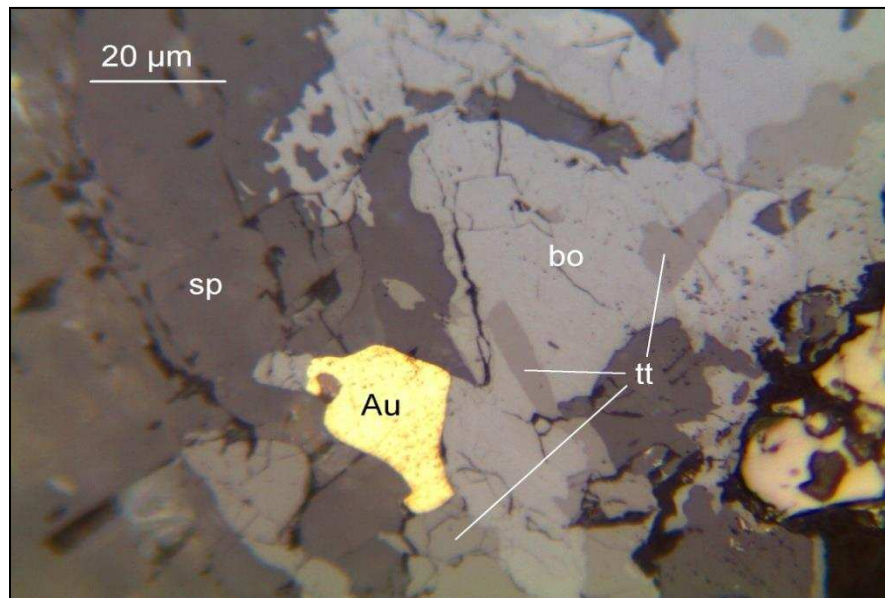


Figure 9. 48 Bournonite (bo), sphalerite (sp), tetrahedrite (tt), and gold (Au), Eskay Creek, BC gold deposit. Polished section ESC-17, courtesy of Murray Hitzman, CSM.

References:

- Wagner, T., and Cook, N.J., 1997, Mineral reactions in sulphide systems as indicators of evolving fluid geochemistry: a case study from the Apollo Mine, Siegerland, FRG: Mineralogical Magazine, v. 61, p. 573-590.
- Wagner, T., and Jonsson, E., 2001, Mineralogy of sulfosalt-rich vein-type ores, Boliden massive sulfide deposit, Skellefte District, northern Sweden: Canadian Mineralogist, v. 39, p. 855-872.
- Wu, I.J., and Birnie, R.W., 1977, The bournonite-seligmannite solid solution: American Mineralogist, v. 62, p. 1097-1100.

CHEMICAL CLASS: SULFOSALTS

Mineral Name: Enargite

Composition: Cu_3AsS_4

Characteristics in Hand Specimen

Crystal System: Orthorhombic

Color: Grayish black to iron-black.

Cleavage: {110} perfect; {100} and {010} distinct.

Fracture: Uneven

Tenacity: Brittle

Mohs Hardness: 3

Density (meas.): 4.45

Streak: Grayish-black

Association: Pyrite, sphalerite, galena, bornite, tetrahedrite-tennantite, chalcocite, covellite, barite, quartz.

Name: From the Greek for *distinct*, in allusion to its cleavage.



Figure 9.49 Enargite. Gift of Professor Enrique Guadalupe Gomez, University of San Marcos, Lima, Peru.

Characteristics in Polished Section

Color: Pinkish-gray to pinkish-brown.

Cleavage: {110} perfect; {100}, {010} distinct.

Polishing Hardness: >galena, chalcocite

Bireflectance: Distinct in oil.

Anisotropy: Strong; blue, green, red, and orange.

Reflectance (in air): 25-29

IR: Deep red possible.

Distinguishing Features: Pinkish-brown color, strong anisotropism, moderate reflectance and cleavage are characteristic.

Associated Minerals: Chalcopyrite, pyrite, bornite, tetrahedrite-tennantite, covellite, digenite, galena, sphalerite, and arsenopyrite.

Mode of Occurrence and Origin: Occurs as anhedral to subhedral grains. Found in vein and replacement deposits of moderate temperature. Import ore at Butte, Montana; Chuquicamata, Chile; and at several Peruvian copper deposits.

References:

Sillitoe, R.H., 1983, Enargite-bearing massive sulfide deposits high in porphyry copper systems: *Economic Geology*, v. 78, p. 348-352.

Springer, G., 1969, Compositional variations in enargite and luzonite: *Mineralium Deposita*, v. 4, p. 72-74.

Taylor, L.G., and Bornhorst, T.J., 1998, A boiling model for the formation of enargite-bearing veins in the Central City district, Colorado: *The Mountain Geologist*, v. 35, p. 15-22.

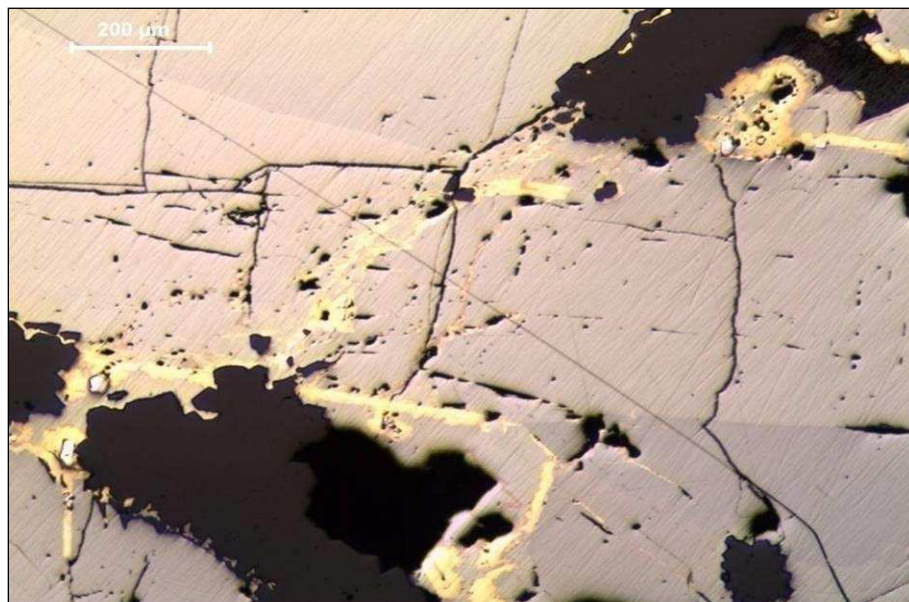


Figure 9.50 Enargite, showing characteristic cleavage. CSM Geology Collection, R30.

CHEMICAL CLASS: SULFOSALTS

Mineral Name: Gersdorffite

Composition: NiAsS

Characteristics in Hand Specimen

Crystal System: Cubic

Color: Silver-white to steel-gray; may tarnish.

Cleavage: Perfect on {100}.

Fracture: Uneven

Tenacity: Brittle

Mohs Hardness: 5.5

Density (meas.): 5.9

Streak: Grayish black.

Association: Nickeline, skutterudite, ullmannite, other sulfides, siderite.

Name: For the von Gersdorffs, owners of the nickel mine at Schladming, Austria (ca. 1842).

Characteristics in Polished Section

Color: White with yellow or pink tint.

Cleavage: {100} good.

Polishing Hardness: ~skutterudite, <<pyrite

Bireflectance: None

Anisotropy: Isotropic; (may have anomalous anisotropism).

Reflectance (in air): 47-54

IR: Absent

Distinguishing Features: White with pink tints, isotropic, and high reflectance.

Associated Minerals: Pyrrhotite, pentlandite, magnetite, chalcopyrite, silver, skutterudite, arsenopyrite, nickeline, and cobaltite.

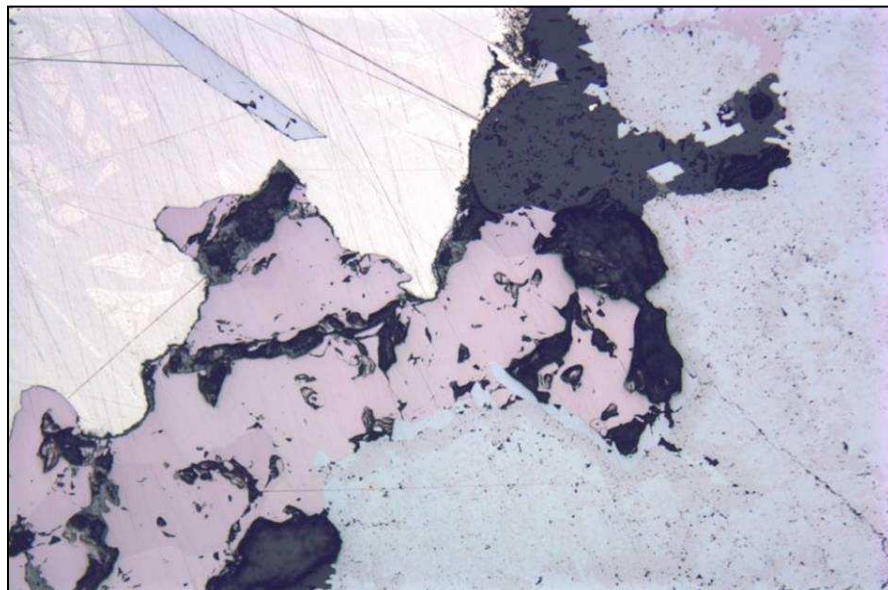


Figure 9.51 Gersdorffite (white) and nickeline (pink). No. 24, CSM Geology Collection.

Mode of Occurrence and Origin: Occurs as single euhedral to subhedral crystals and as massive aggregates with pyrrhotite, pentlandite, and magnetite. Commonly found both in vein and magmatic sulfide deposits in Canada (Sudbury, Thompson, and Cobalt).

References:

- Vokes, F.M., and Strand, G.S., 1982, Atoll texture in minerals of the cobaltite-gersdorffite series from the Raipas Mines, Finmark, Norway, in Ore Genesis: The State of the Art, G. Arnstute et al., editors: Springer-Verlag, Berlin, Germany, p. 118-130.
- Wagner, T., and Lorenz, J., 2002, Mineralogy of complex Co-Ni-Bi vein mineralization, Bieber Deposit, Spessart, Germany: Mineralogical Magazine, v. 66, p. 385-407.
- Yund, R.A., 1962, The system Ni-As-S: phase relations and mineralogical significance: American Journal of Science, v. 260, p. 761-782.

CHEMICAL CLASS: SULFOSALTS

Mineral Name: Proustite

Composition: Ag_3AsS_3

Characteristics in Hand Specimen

Crystal System: Hexagonal

Color: Scarlet-vermilion.

Cleavage: Distinct on $\{10\bar{1}1\}$.

Fracture: Conchoidal to uneven.

Tenacity: Brittle

Mohs Hardness: 2.-2.5

Density (meas.): 5.57

Streak: Vermilion

Association: Silver, arsenic, stephanite, acanthite, tetrahedrite, chlorargyrite.

Name: For Joseph Louis Proust (1754-1826), celebrated French chemist.

Characteristics in Polished Section

Color: Bluish-gray

Cleavage: $\{1011\}$ good.

Polishing Hardness: ~pyrargyrite

Anisotropy: Strong

Reflectance (in air): 25-28

IR: Common, scarlet-red.

Distinguishing Features: Bluish-gray, distinct bireflectance, low reflectance, strong anisotropy, and abundant red internal reflections.

Associated Minerals: Nickel-cobalt minerals, sulfosalts, galena, sphalerite, and pyrite.

Mode of Occurrence and Origin: Proustite forms a solid solution pair with pyrargyrite, which is more abundant. This pair is called the “ruby silvers”, which are low temperature vein and epithermal minerals found in Zacatecas, Mexico; Cobalt, Ont; and in Chile and Bolivia.

References:

Kracek, F.C., 1946, Phase relations in the system silver-sulfur and the transitions in silver sulfide: Transactions of the American Geophysical Union, v. 27, p. 367-374.
Petruk, W., 1975, Mineralogy and geology of the Zgounder silver deposit in Morocco: Canadian Mineralogist, v. 13, p. 43-54.
Petruk, W., and staff, 1971, Characteristics of the sulphides: Canadian Mineralogist, v. 11, p. 196-231.

CHEMICAL CLASS: SULFOSALTS

Mineral Name: Pyrargyrite

Composition: Ag_3SbS_3

Characteristics in Hand Specimen

Crystal System: Hexagonal

Color: Deep red.

Cleavage: Distinct on $\{10\bar{1}1\}$.

Fracture: Conchoidal to uneven.

Tenacity: Brittle.

Mohs Hardness: 2.5

Density (meas.): 5.82

Streak: Purplish red.



Figure 9.52 Pyrargyrite. Guanajuato, Mexico. CSM Geology Museum.

Association: Silver, acanthite, tetrahedrite, other silver sulfosalts, calcite, dolomite, quartz.

Name: From the Greek for *fire* and *silver*, in allusion to its composition and color.

Characteristics in Polished Section

Color: Bluish-gray

Polishing Hardness: ~proustite

Bireflectance: Distinct

Anisotropy: Strong; gray to dark-gray.

Reflectance (in air): 28-31

IR: Intense red.

Distinguishing Features: Bluish-gray color, distinct bireflectance, low reflectance, strong anisotropy, and red internal reflections.

Mode of Occurrence and Origin: Occurs as irregular grains and aggregates. May be twinned and zoned; complete solid solution with proustite; found in low temperature vein and epithermal deposits.

References:

Kracek, F.C., 1946, Phase relations in the system silver-sulfur and the transitions in silver sulfide: Transactions of the American Geophysical Union, v. 27, p. 367-374.

Petruck, W., 1975, Mineralogy and geology of the Zgounder silver deposit in Morocco: Canadian Mineralogist, v. 13, p. 43-54.

Petruck, W., and staff, 1971, Characteristics of the sulphides: Canadian Mineralogist, v. 11, p. 196-231.

CHEMICAL CLASS: SULFOSALTS

Mineral Name: Tennantite

Composition: $\text{Cu}_{12}\text{As}_4\text{S}_{13}$

Characteristics in Hand Specimen

Crystal System: Cubic

Color: Flint-gray to iron-black.

Cleavage: None

Fracture: Subconchoidal to uneven.

Tenacity: Somewhat brittle.

Mohs Hardness: 3-4.5

Density (meas.): 4.62

Streak: Reddish gray.

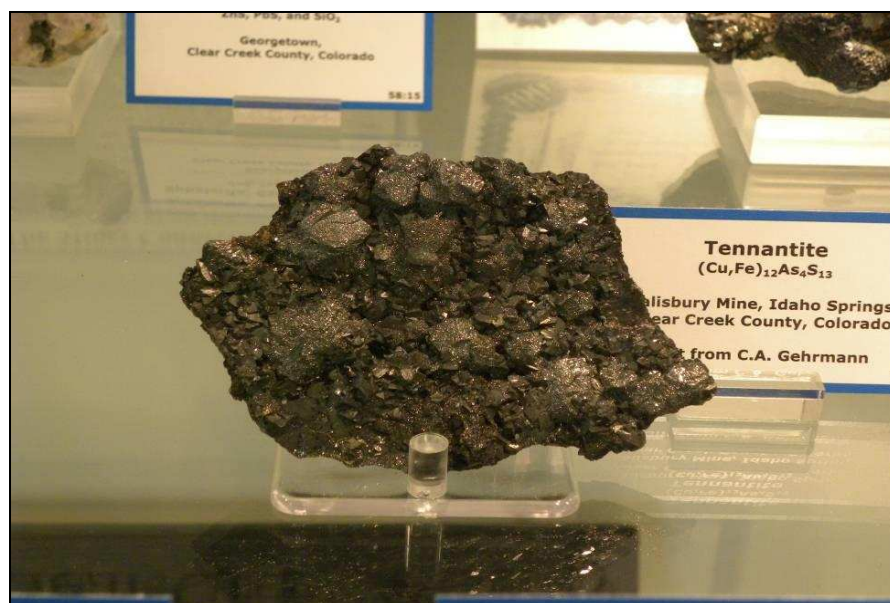


Figure 7.53 Tennantite. Clear Creek Co., Colorado. CSM Geology Museum.

Association: Cu-Pb-Zn-Ag sulfides and sulfosalts, pyrite, calcite, dolomite, siderite, barite, fluorite, quartz.

Name: For Smithson Tennant (1761-1815), English chemist.

Characteristics in Polished Section

Color: Gray with green or blue tint.

Cleavage: Absent

Polishing Hardness: ~chalcopyrite, <sphalerite

Anisotropy: Isotropic

Reflectance (in air): 27-31

IR: Common, reddish.

Distinguishing Features: Moderate reflectance, isotropic, and good polish are characteristic.

Associated Minerals: Sphalerite, galena, arsenopyrite, chalcopyrite, pyrite, silver-bearing minerals, and other sulfosalts.

Mode of Occurrence and Origin: Forms a complete solid solution with tetrahedrite. A relatively rare mineral, occurring in low to moderate temperature vein deposits with Cu, Ag, Pb, and Zn minerals.

References:

Foit, F.F., and Ulbrich, M.E., 2001, Compositional variation in mercurian tetrahedrite-tennantite from the epithermal deposits of the Steens and Pueblo Mountains, Harney County, Oregon: Canadian Mineralogist, v. 39, p. 819-830.

Johnson, N.E., Craig, J.R., and Rimstidt, J.D., 1988, Crystal chemistry of tetrahedrite: American Mineralogist, v. 73, p. 389-397.
Lynch, J.V.G., 1989, Large-scale hydrothermal zoning reflected in the tetrahedrite-freibergite solid solution, Keno Hill, Ag-Pb-Zn district, Yukon: Canadian Mineralogist, v. 27, p. 383-400.

CHEMICAL CLASS: SULFOSALTS

Mineral Name: Tetrahedrite

Composition: $\text{Cu}_{12}\text{SbS}_{13}$

Characteristics in Hand Specimen

Crystal System: Cubic

Color: Flint-gray to iron-black to dull black.

Cleavage: None

Fracture: Subconchoidal

Tenacity: Somewhat brittle.

Mohs Hardness: 3-4.5

Density (meas.): 4.97

Streak: Black to brown.

Association: Chalcopyrite, galena, sphalerite, pyrite, bornite, acanthite, calcite, dolomite, siderite, barite, fluorite, quartz.

Name: In allusion to the tetrahedral crystal shape.



Figure 9.54 Tetrahedrite, Casapalca mine. Gift of Professor Enrique Guadalupe Gomez, University of San Marcos, Lima, Peru.

Characteristics in Polished Section

Color: Gray with brownish tint.

Cleavage: None

Polishing Hardness: ~chalcopyrite, <sphalerite

Bireflectance: None

Anisotropy: Isotropic

Reflectance (in air): 31-33

IR: As arsenic content increases, the color becomes reddish.

Distinguishing Features: Moderate reflectance, isotropic, and good polish.

Associated Minerals: Associated minerals include sphalerite, galena, arsenopyrite, chalcopyrite, pyrite, and sulfosalts.

Mode of Occurrence and Origin: Same as tennantite. Both minerals occur in low to medium temperature hydrothermal veins of Cu, Ag, Pb, and Zn. Tetrahedrite may contain significant silver values, as in the Coeur d'Alene district, Idaho and Broken Hill, Australia.

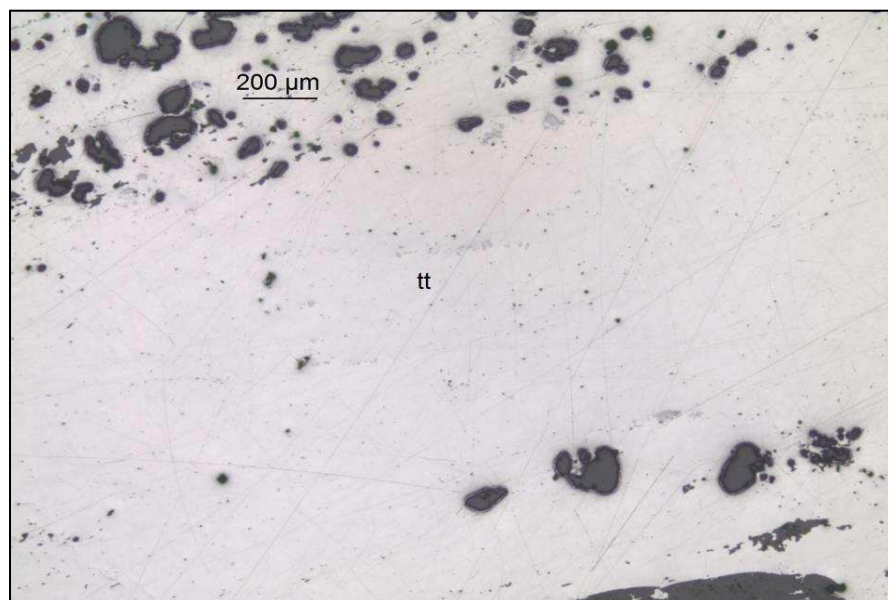


Figure 7.55 Tetrahedrite. Lucky Boy mine, Nevada.

CHEMICAL CLASS: OXIDES

Mineral Name: Cassiterite

Composition: SnO_2

Characteristics in Hand Specimen

Crystal System: Tetragonal

Color: Usually brown to black.

Cleavage: {100} imperfect, {110} indistinct; parting on {111} or {011}.

Fracture: Subconchoidal to uneven.

Tenacity: Brittle

Mohs Hardness: 6-7

Density (meas.): 6.98-7.01

Streak: White, pale brown, pale gray.

Association: Quartz, muscovite, wolframite, tourmaline, topaz, fluorite, scheelite, lepidolite, arsenopyrite, bismuth, molybdenite.

Name: From the Greek for *tin*.



Figure 7.56 Cassiterite crystals. CSM Geology Museum.

Characteristics in Polished Section

Color: Brownish gray.

Polishing Hardness: Very high.

Bireflectance: Distinct; brownish to gray.

Anisotropy: Distinct; gray.

Reflectance (in air): 11-13

IR: Common, yellow to yellow-brown.

Distinguishing Features: Gray color, low reflectance, distinct anisotropism, internal reflections common.

Mode of Occurrence and Origin: Major ore of tin. Occurs as compact anhedral masses and as subhedral to euhedral crystals that are commonly twinned or zoned. Strong affiliation with granitic rocks; in high temperature veins, greisens, skarns, and in

pegmatites. Also an accessory mineral in massive sulfide deposits, such as at Kidd Creek, Canada.

Wood tin: The main variety of cassiterite, in allusion to its wood-like “growth rings”. Wood tin is the colloform variety of cassiterite, consisting of finely crystalline cassiterite, commonly intergrown with hematite and silica polymorphs. Widespread occurrences are found in the rhyolitic rocks of northern Mexico, and southwestern New Mexico, and elsewhere.

References:

- Halter, W.E., Williams-Jones, A.E., and Kontak, D.J., 1996, The role of greisenization in cassiterite precipitation at the East Kemptville tin deposit, Nova Scotia: *Economic Geology*, v. 91, p. 368-385.
- Hennigh, Q., and Hutchinson, R.W., 1999, Cassiterite at Kidd Creek; An example of volcanogenic massive sulfide-hosted tin mineralization, *in* the Giant Kidd Creek Volcanogenic Massive Sulfide Deposit, Western Abitibi Subprovince, Canada, (eds.) M.D. Hannington and C.T. Barrie, *Economic Geology Monograph 10*, Economic Geology Publishing Company, Littleton, CO, p. 431-440.
- Linnen, R.L., Williams-Jones, A.E., and Martin, R.F., 1992, Evidence of magmatic cassiterite mineralization at the Nong Sua aplite-pegmatite complex: *Canadian Mineralogist*, v. 30, p. 739-761.
- Lufkin, J.L., 1977, Chemistry and mineralogy of wood tin, Black Range, New Mexico: *American Mineralogist*, v. 62, p. 100-106.



Figure 7.57 Wood tin, Durango, Mexico. UCD Geology collection.

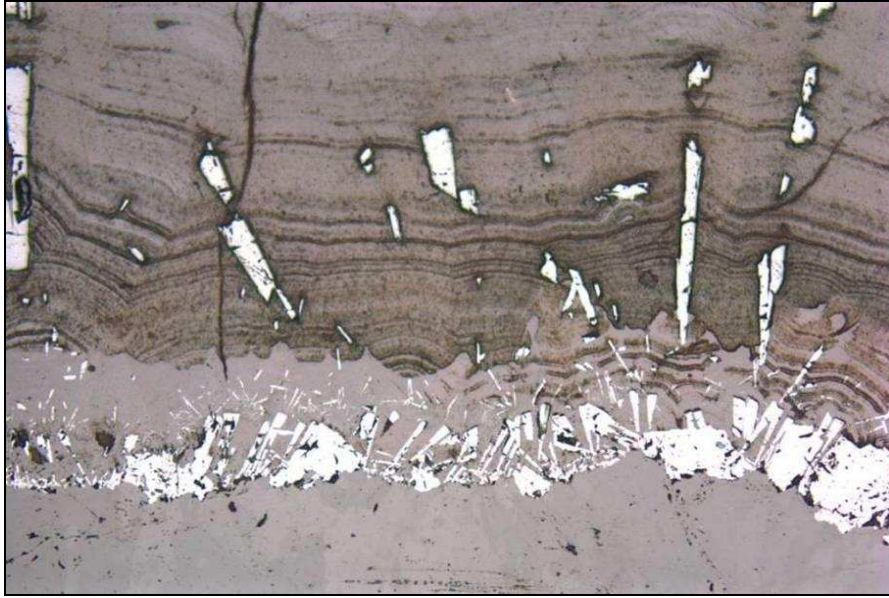


Figure 7.58 Wood tin with plates and needles of hematite (white), Black Range, New Mexico.



Figure 7.59 Same view, transmitted light, crossed polars, 10x.

CHEMICAL CLASS: OXIDES

Mineral Name: Chromite

Composition: $(\text{Fe,Mg})(\text{Cr,Al})_2\text{O}_4$

Characteristics in Hand Specimen

Crystal System: Cubic

Color: Black

Cleavage: Parting may develop along {111}.

Fracture: Uneven

Tenacity: Brittle

Mohs Hardness: 5.5

Density (calc.): 5.12

Streak: Brown

Association: Olivine, enstatite, plagioclase, serpentine, magnetite, ilmenite, pyrrhotite, pentlandite, ulvöspinel.

Name: After the element.



Figure 7.60 Chromite. Stillwater Complex, Montana.

Characteristics in Polished Section

Color: Dark-gray to brownish-gray.

Cleavage: None

Polishing Hardness: >magnetite, <hematite

Bireflectance: Absent

Anisotropy: Isotropic

Reflectance (in air): 11-13

IR: Common, red-brown.

Distinguishing Features: Darker than magnetite, euhedral to rounded grains, good polish, low reflectance, and isotropic.

Mode of Occurrence and Origin: Main ore of chromium. Usually as euhedral, subhedral, or rounded crystals or aggregates. Major deposits are magmatic segregations in ultramafic complexes, such as those at Bushveld, South Africa; Great Dyke, Zimbabwe; and the Stillwater Complex, Montana.

References:

Stowe, C.W., 1994, Compositions and tectonic settings of chromite deposits through time: *Economic Geology*, v. 89, p. 528-546.

Zingg, A.J., 1996, Recrystallization and the origin of layering in the Bushveld Complex: *Lithos*, v. 37, p. 15-37.

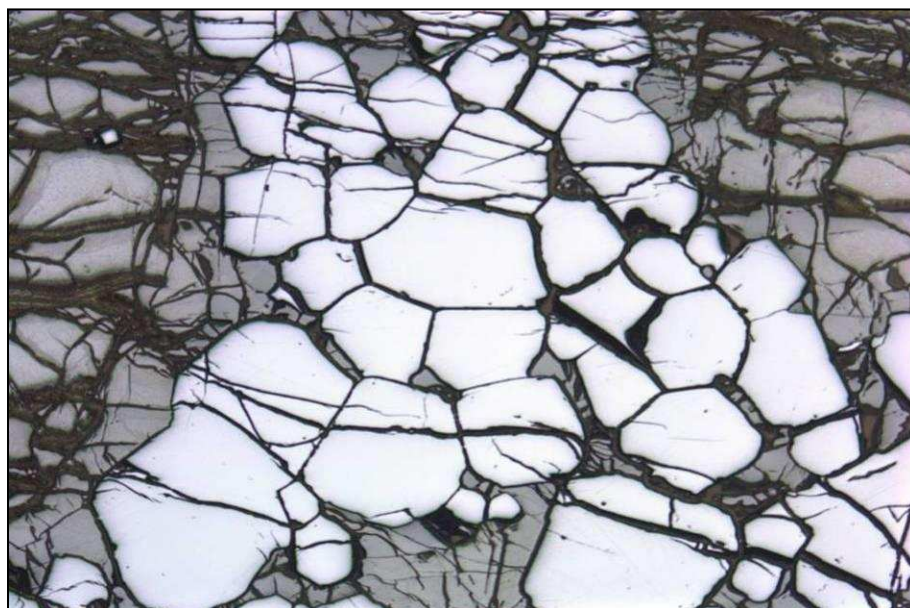


Figure 7.61 Annealed chromite cumulate grains with abundant triple junctions. Stillwater Complex, Montana. No. S2, 5x.

CHEMICAL CLASS: OXIDES

Mineral Name: Franklinite

Composition: $(\text{Zn,Fe,Mn})(\text{Fe,Mn})_2\text{O}_4$

Characteristics in Hand Specimen

Crystal System: Cubic

Color: Black

Cleavage: Parting on {111}, fair.

Fracture: Uneven to subconchoidal.

Tenacity: Brittle

Mohs Hardness: ~6

Density (meas.): 5.05-5.22

Streak: Reddish-brown to black.

Association: Zincite, willemite, calcite, andradite, rhodochrosite, gahnite, magnetite, and others.

Name: Named for Franklin Furnace (now Franklin), New Jersey, and in honor of Benjamin Franklin (1706-1790).



Figure 7.62 Franklinite (black), with willemite and calcite. Sterling Hill, New Jersey. Gift of Bill Keiser, Westminster, MD.

Characteristics in Polished Section

Color: Gray with a faint greenish tint.

Cleavage: May be distinct.

Polishing Hardness: >zincite

Bireflectance: Isotropic

Anisotropy: Isotropic

Reflectance (in air): 18

IR: Deep red.

Distinguishing Features: Color, isotropism, and red internal reflections. Twinning on {111} and {100} may occur. Exsolution intergrowths may be present with magnetite, hematite, gahnite, or other spinels.

Associated Minerals: Magnetite, hematite, gahnite, manganite, and zincite.

Mode of Occurrence and Origin: The unusual zinc deposit at Franklin and Sterling Hill, New Jersey is generally recognized as a folded, tabular body of Franklin limestone, Precambrian in age, that was replaced by sulfides, and later metamorphosed to form franklinite, willemite, zincite, and a wide variety of gangue minerals, including carbonates, sulfates, oxides, and silicates.

References:

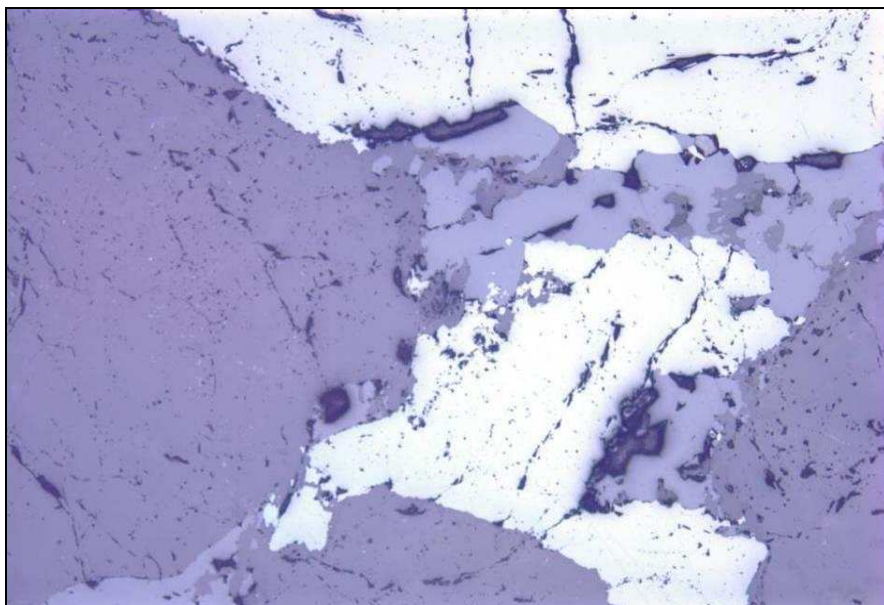


Figure 7.63 Franklinite (white), zincite, and willemite, Franklin, New Jersey. No. 1, 5x.

CHEMICAL CLASS: OXIDES

Mineral Name: Goethite

Composition: $\text{FeO} \cdot \text{OH}$

Characteristics in Hand Specimen

Crystal System: Orthorhombic

Color: Blackish-brown; yellowish to reddish brown in massive aggregates.

Cleavage: {010}, perfect; {100}, less perfect.

Fracture: Uneven

Tenacity: Brittle

Mohs Hardness: 5-5.5

Density (meas.): 4.28

Streak: Brownish-yellow, yellow-orange, ocher-yellow.

Association: Lepidocrocite, hematite, pyrite, siderite, pyrolusite, manganite, many other iron- and manganese-bearing species.

Name: Honors the German poet, philosopher, Johann Wolfgang von Goethe (1749-1832).



Figure 7.64 Goethite. Botryoidal structure, and colloform texture. Morroco.

Characteristics in Polished Section

Color: Gray, with bluish tint.

Cleavage: {010} perfect.

Polishing Hardness: Variable; for crystalline material, <magnetite, hematite

Bireflectance: Weak

Anisotropy: Distinct; gray-blue to gray-yellow, brown.

Reflectance (in air): 15-20

IR: Brownish yellow or reddish brown.

Distinguishing Features: Gray, low reflectance, distinct anisotropism, with abundant red, brownish, or yellow internal reflections.

Associated Minerals: Siderite, hematite, pyrite, pyrrhotite, Mn oxides, sphalerite, galena, fluorite, limonite, and chalcopyrite.

Mode of Occurrence and Origin: An ore of iron. Found under oxidizing conditions as a weathering product of iron sulfides and other iron-bearing minerals. Commonly forms botryoidal habit with colloform layers of radiating fibers, or as pseudomorphs after pyrite and other Fe-bearing minerals.

References:

- Dorr, J., 1964, Supergene iron ores of Minas Gerais, Brazil: *Economic Geology*, v. 59, p. 1203-1240.
- Schweigart, H., 1965, Genesis of the iron ores of the Pretoria series, South Africa: *Economic Geology*, v. 60, p. 269-298.

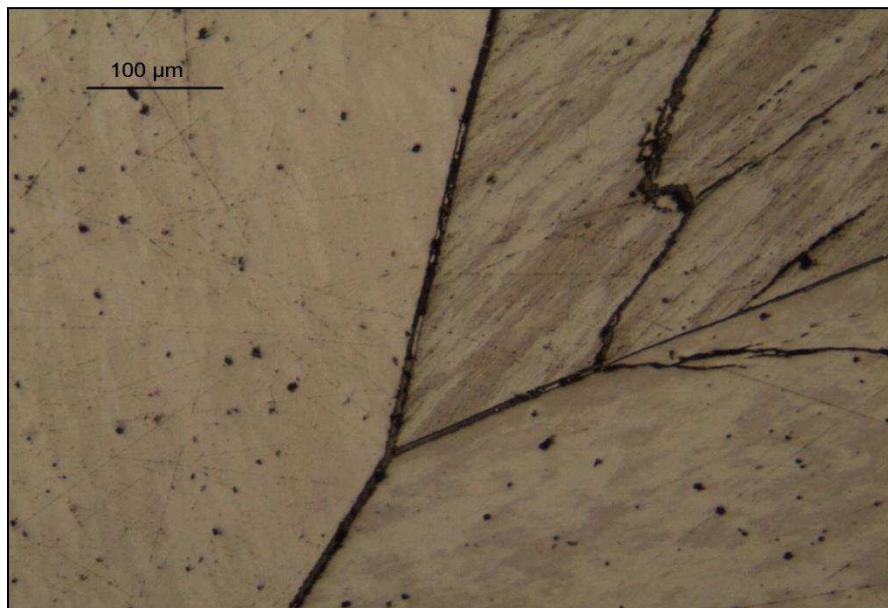


Figure 7.65 Goethite. The “Y” marks the contact between 3 segments of the colloform texture. Note the bireflection between adjacent segments.

CHEMICAL CLASS: OXIDES

Mineral Name: Hematite

Composition: Fe_2O_3

Characteristics in Hand Specimen

Crystal System: Hexagonal

Color: Steel gray.

Cleavage: Parting on $\{0001\}$ and $\{10\bar{1}1\}$ due to twinning.

Fracture: Uneven to subconchoidal.

Tenacity: Brittle; elastic in thin laminae.

Mohs Hardness: 5-6

Density (meas.): 5.26

Streak: Cherry-red or reddish-brown.

Association: Ilmenite, rutile, magnetite, goethite, siderite.

Name: From the Greek for *blood*, in allusion to its color.



Figure 7.66 Archean Banded Iron Formation (BIF), consisting of hematite (gray), jasper (red), and tiger eye (yellow, silicified crocidolite or blue asbestos). Ord Ranges, Western Australia, about 1,000 miles north of Perth.

Characteristics in Polished Section

Color: Gray-white with bluish tint.

Cleavage: None

Polishing Hardness: Very high, variable; >magnetite, ilmenite.

Color: Gray-white with bluish tint.

Cleavage: None

Bireflectance: Weak

Anisotropy: Distinct; gray-blue.

Reflectance (in air): 26-30

Distinguishing Features: Variable, due to habit. Commonly white to grayish-white, with moderate reflectance and distinct anisotropism. May contain internal reflections.

Associated Minerals: Ilmenite, magnetite, pyrite, chalcopyrite, bornite, rutile, chromite, cassiterite, goethite, and sphalerite.

Mode of Occurrence and Origin: Occurs as bladed or needle-like, radiating aggregates; lamellar twinning is common. Also, as lenses/lamellae in ilmenite or magnetite, or as host to same. Most important ore of iron; found in Precambrian banded iron formations (BIF) throughout the world. Also occurs in skarn deposits, and as a common alteration of iron-bearing silicates, sulfides, and oxides.

References:

- Beukes, N.J., Gutzmer, J., and Mukhopadhyay, J., 2003, The geology and genesis of high-grade hematite iron ore deposits: Institution of Mining and Metallurgy, Transactions, v. 112, p. 18-25.
- Gross, G.A., 1965, Geology of iron deposits in Canada. Volume I. General Geology and Evaluation of Iron Deposits: Geological Survey of Canada, Economic Geology Report No. 22, 181 p.
- Rosiere, C.A., Siemes, H., Quade, H., Brokmeier, H.G., and Jansen, E.M., 2001, Microstructures, textures, and deformation mechanisms in hematite: Journal of Structural Geology, v. 23, no. 9, p. 1429-1440.

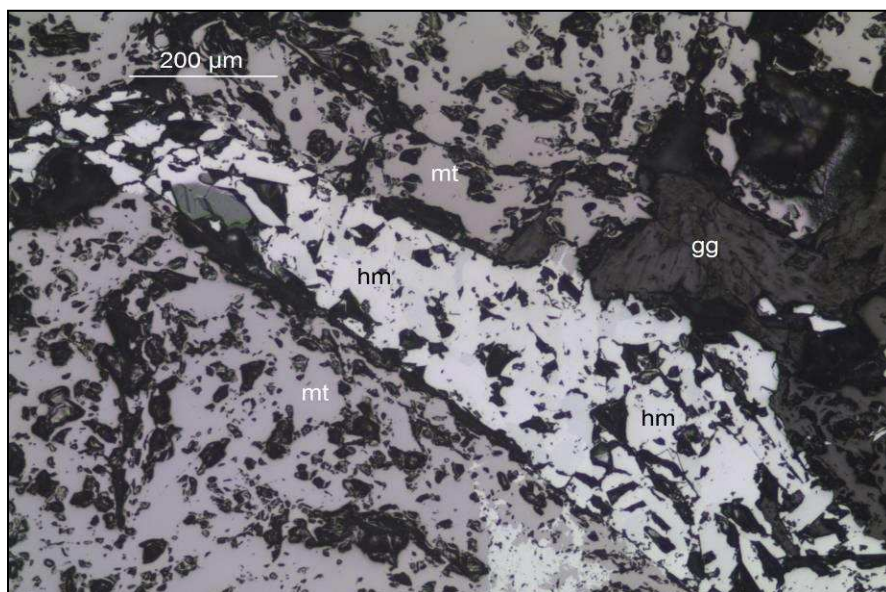


Figure 7.67 Hematite (hm) veinlet cutting magnetite (mt).

CLASS: OXIDES

Mineral Name: Ilmenite

Composition: FeTiO_3

Characteristics in Hand Specimen

Crystal System: Hexagonal

Color: Iron-black

Cleavage: $\{0001\}$ and $\{10\bar{1}1\}$ partings.

Fracture: Conchoidal

Tenacity: Brittle

Mohs Hardness: 5-6

Density (meas.): 4.72

Streak: Black to reddish-brown.

Association: Magnetite, hematite, rutile, ulvöspinel, pyrrhotite, apatite.

Name: For the early-noted occurrence in the Ilmen Mountains, Russia.



Figure 7.68 Ilmenite. St. Urban, Quebec, Canada.

Characteristics in Polished Section

Color: Pinkish-brown

Cleavage: None

Polishing Hardness: >magnetite, <hematite

Bireflectance: Distinct; pinkish-brown to dark-brown.

Anisotropy: Strong; greenish-gray to brownish-gray.

Reflectance (in air): 16-20

IR: Rare, dark brown.

Distinguishing Features: Pinkish-brown to dark-brown, anisotropic, and common as exsolution lamellae in hematite.

Associated Minerals: Magnetite, hematite, pyrite, pyrrhotite, chromite, apatite, and rutile.

Mode of Occurrence and Origin: Major ore of titanium. Occurs as subhedral to anhedral grains, and as lamellae or lenses in hematite. Forms as magmatic segregations in anorthosites and ultramafic rocks. Also found in kimberlites, as an accessory in igneous and metamorphic rocks, and with magnetite in placer deposits.

References:

- Barksdale, J., 1966, *Titanium: Its Occurrence, Chemistry and Technology*: Ronald Press, New York, 691 p.
- Buddington, A.F., and Lindsley, D.H., 1964, Iron-titanium oxide minerals and synthetic equivalents: *Journal of Petrology*, v. 5, p. 310-357.
- Jang, S.Y., Palmer, M.R., and Slack, J.F., 1996, Mn-rich ilmenite from the Sullivan Pb-Zn-Ag deposit, British Columbia: *Canadian Mineralogist*, v. 34, p. 29-36.

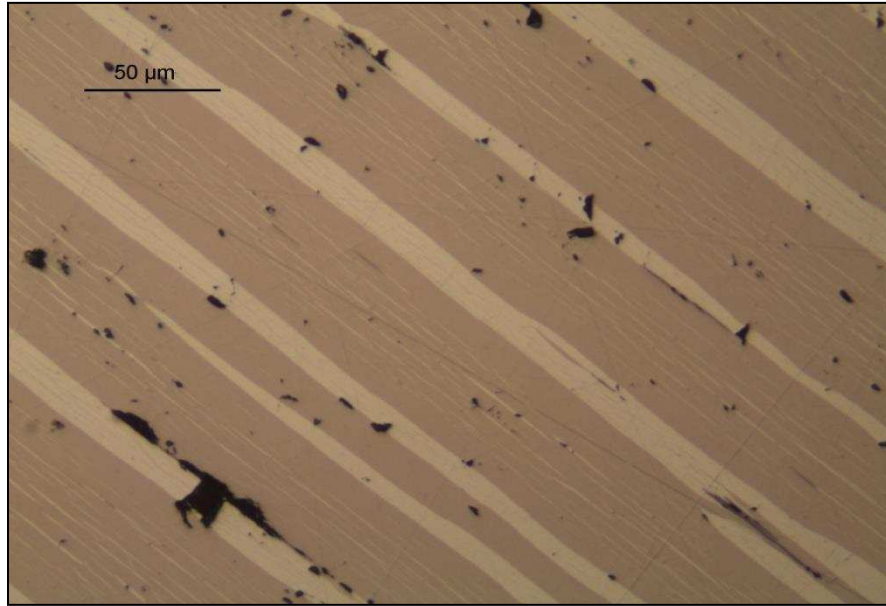


Figure 7.69 Hematite lamellae (lighter color) in ilmenite.

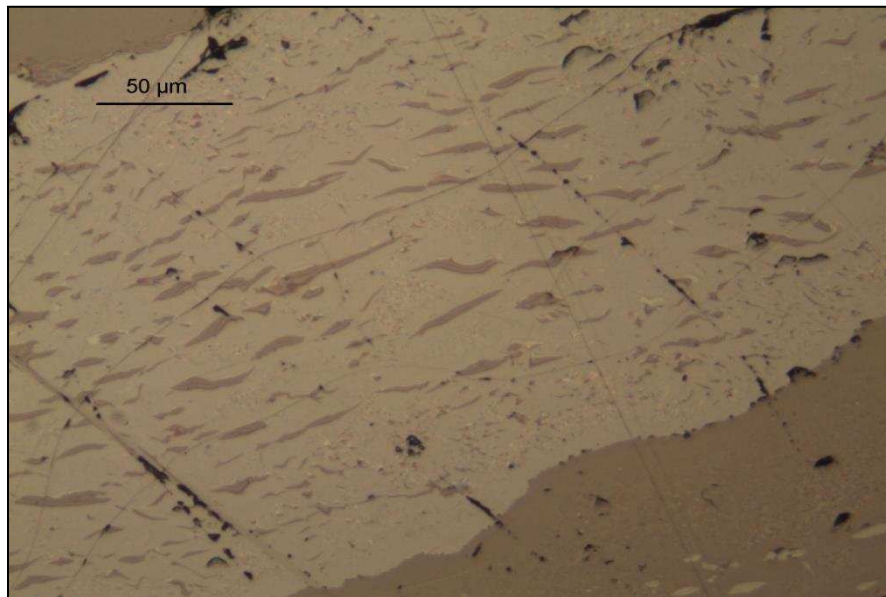


Figure 7.70 Wavy ilmenite lamellae (dark) in hematite.

CHEMICAL CLASS: OXIDES

Mineral Name: Magnetite

Composition: Fe_3O_4

Characteristics in Hand Specimen

Crystal System: Cubic

Color: Black

Cleavage: Parting on {111} very good.

Fracture: Uneven

Tenacity: Brittle

Mohs Hardness: 5.5-6.5

Density (meas.): 5.175

Streak: Black

Association: Chromite, ilmenite, ulvöspinel, rutile, apatite, pyrrhotite, pyrite, chalcopyrite, pentlandite, sphalerite, hematite, silicates.

Name: An ancient term, possibly an allusion to the locality, *Magnesia*, Greece.

Characteristics in Polished Section

Color: Gray with brownish to violet tint.

Cleavage: Parting on {111}, imperfect.

Polishing Hardness: <ilmenite, <<hematite

Bireflectance: None

Anisotropy: Isotropic

Reflectance (in air): 21

IR: Absent

Distinguishing Features: Granular aggregates with good polish, and high relief. Hydrothermal varieties commonly oxidized to hematite along fractures and {111} parting planes.

Associated Minerals: Ilmenite, hematite, pyrrhotite, pyrite, pentlandite, chalcopyrite, bornite, sphalerite, and galena.

Mode of Occurrence and Origin: Occurs as euhedral to subhedral crystals and anhedral polycrystalline aggregates. Usually found in magmatic, skarn, epithermal, and sedimentary (BIF) deposits. Occurs as magmatic segregations (Bushveld, South Africa); with anorthosite at Balmat Edwards, NY; as contact limestone replacements at Iron Springs, Utah; as disseminations in potassic alteration zones of porphyry copper deposits; and as BIF with hematite and silica in northern Minnesota and Michigan, and other parts of the world.



Figure 7.71 Magnetite, Brazil.

References:

- Barker, D.S., 1995, Crystallization and alteration of quartz monzonite, Iron Springs Mining District, Utah: Relation to associated iron deposits: *Economic Geology*, v. 90, p. 2197-2217.
- Hoatson, D.M., and Sun, S.S., 2002, Archean layered mafic-ultramafic intrusions in the west Pilbara Craton, Western Australia: A synthesis of some of the oldest orthomagmatic mineralizing systems in the world: *Economic Geology*, v. 97, p. 847-872.
- Sillitoe, R.H., and Burrows, D.R., 2002, New field evidence for bearing on the origin of the El-Laco magnetite deposit, northern Chile: *Economic Geology*, v. 97, p. 1101-1109.
- Travisany, V., Henriquez, F., and Nystroem, J.O., 1995, Magnetite lava flows in the Pleito-Melon District of the Chilean iron belt: *Economic Geology*, v. 90, p. 438-444.

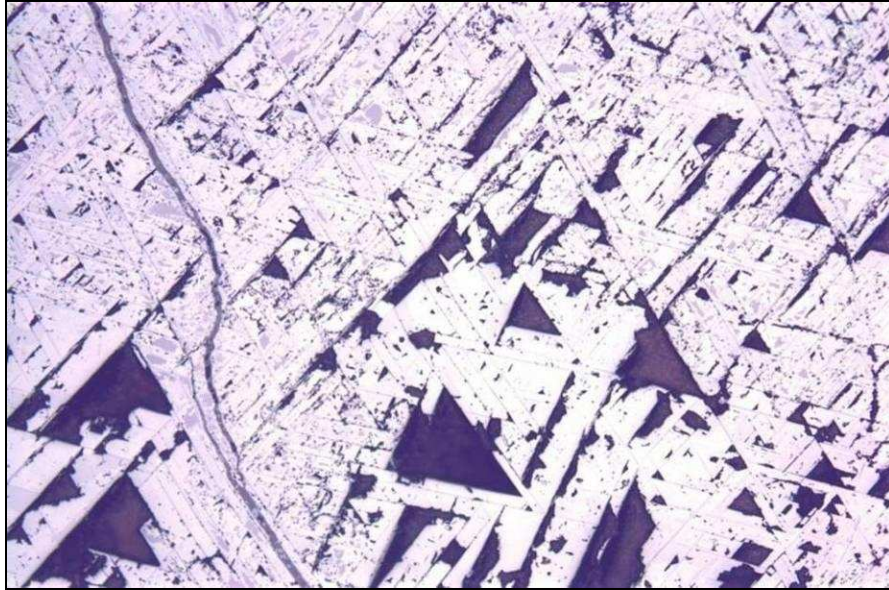


Figure 7.72 Magnetite with {111} parting pits, oxidized to hematite (white). Iron Springs, Utah; No. 117, 10x.

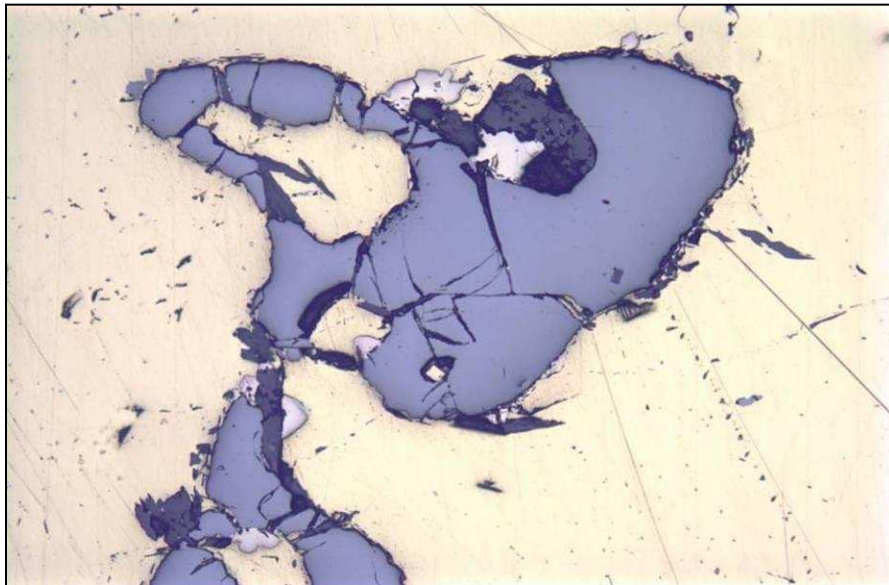


Figure 7.73 Magmatic magnetite (gray), with chalcopyrite, pyrrhotite, and pentlandite. Sudbury, Ont., No. 51, 10x.

CHEMICAL CLASS: OXIDES

Mineral Name: “Psilomelane”

Composition: Mixture of manganese oxides.

Characteristics in Hand Specimen

Characteristic properties are not listed here, since psilomelane is not a single mineral.



Figure 7.74 Psilomelane. UCD Geology collection.

Characteristics in Polished Section

Color: Bluish-gray to grayish-white.

Cleavage: None

Polishing Hardness:

Bireflectance: Strong; white to bluish-gray.

Anisotropy: Strong; white to gray.

Reflectance (in air): 15-30

IR: Brown, but not common.

Distinguishing Features: Color, bireflectance, strong anisotropism, and colloform texture are distinctive.

Associated Minerals: Pyrolusite, goethite, hausmanite, and cryptomelane.

Mode of Occurrence and Origin: Typically a secondary mineral formed under surface conditions of temperature and pressure; may be found as large residual deposits resulting from weathering of manganese carbonates or silicates; also as concretionary or botryoidal masses in clays and in lake and swamp deposits.



Figure 7.75 Colloform psilomelane, 5x.

CHEMICAL CLASS: OXIDES

Mineral Name: Pyrolusite

Composition: MnO_2

Characteristics in Hand Specimen

Crystal System: Tetragonal

Color: Light steel-gray, iron-gray to iron-black.

Cleavage: {110} perfect.

Fracture: Uneven

Mohs Hardness: 2 to 6-6.5

Density (meas.): 5.06

Streak: Black, bluish-black.

Association: Manganite, hollandite, hausmannite, braunite, chalcophanite, goethite, hematite.

Name: From the Greek for *fire* and *to wash*, as it is used to remove tints from glass.



Figure 7.76 Pyrolusite. UCD Geology Collection.

Characteristics in Polished Section

Color: Creamy white

Cleavage: {110} perfect.

Polishing Hardness: Variable

Bireflectance: Distinct; yellowish-white to grayish.

Anisotropy: Very strong; yellowish, brown, blue.

Reflectance (in air): 27-47

IR: Absent

Distinguishing Features: White color with very strong anisotropism.

Associated Minerals: Psilomelane, manganite, vanadinite, goethite, hematite, and iron hydroxides.

Mode of Occurrence and Origin: Major ore of manganese. Occurs as coarse-grained tabular crystals or as fine-grained, banded aggregates. Major sources are sedimentary in origin, as well as supergene occurrences from deeply weathered manganese-bearing rocks. Also occurs as alteration of manganese minerals, in bogs, on lake bottoms, and on the seafloor.

References:

Burns, R.G., and Burns, V.M., 1979, Manganese oxides: Marine Minerals, v. 6, p. 1-46.

Gutzmer, J., and Beukes, N.J., 1996, Mineral paragenesis of the Kalahari manganese field, South Africa: Ore Geology Reviews, v. 11, p. 405-428.

Miura, H., and Hariya, Y., 1997, Manganese mineralization: geochemistry and mineralogy of terrestrial and marine deposits: Geological Society Special Publication 119, p. 281-299.

CHEMICAL CLASS: OXIDES

Mineral Name: Ulvöspinel

Composition: TiFe_2O_4

Characteristics in Hand Specimen

Crystal System: Cubic

Color: Black

Mohs Hardness: 5.5-6.0

Density (meas.): 4.78

Association: Iron, magnetite, troilite, graphite, ilmenite, pyrrhotite, chalcopyrite, olivine, pyroxene, biotite, plagioclase, apatite.

Name: For the occurrence on Ulvö Island, Sweden, and as a member of the spinel group.

Characteristics in Polished Section

Color: Brown to reddish brown.

Reflectance (in air): Not reported.

Distinguishing Features: Commonly forming a fine network along {100} in magnetite, or in ilmenite.

Mode of Occurrence and Origin: It is common in titaniferous magnetite iron ore deposits, kimberlites, some reduced iron-bearing basalts, and lunar basalts. Ulvöspinel tends to oxidize to magnetite plus ilmenite during subsolidus cooling, and the ilmenite may form lamellae in magnetite. Ilmenite and magnetite do not form a solid solution.

References:

Buddington and Lindsley, 1964, Journal of Petrology, v. 5, p. 310-357.

Ramdohr, Paul, 1953, Ulvöspinel and its significance in titaniferous iron ores: Economic Geology, v. 48, p. 677-688.

Stout, M.V., and Bayliss, P.I., 1980, Crystal structure of two ferrian ulvöspinels from British Columbia: Canadian Mineralogist, v. 18, p. 339-341.

Picol, P., and Johan, Z., 1982, Atlas of ore minerals: B.R.G.M., Orleans, France, and Elsevier, Amsterdam, Holland, p. 378.

CHEMICAL CLASS: OXIDES

Mineral Name: Uraninite/Pitchblende

Composition: UO_2

Characteristics in Hand Specimen

Crystal System: Cubic

Color: Steel-black to velvet-black, brownish black, grayish, greenish.

Cleavage: {111}, {100} imperfect.

Fracture: Uneven to conchoidal.

Tenacity: Brittle

Mohs Hardness: 5-6

Density (meas.): 10.63-10.95, decreasing markedly with oxidation.

Streak: Brownish black, gray, olive-green, shining.

Association: Zircon, monazite, tourmaline, mica, feldspar, pyrite, chalcopyrite, galena, bismuth, silver, nickeline, barite, fluorite, carbonates.

Name: For uranium in the composition.

Characteristics in Polished Section

Color: Brownish-gray

Cleavage: {111}, {100} imperfect.

Polishing Hardness: Very high; >magnetite

Bireflectance: Absent

Anisotropy: Isotropic

Reflectance (in air): 17

IR: Dark brown or reddish-brown.

Distinguishing Features: Dark-brown internal reflections, isotropism, low reflectance. Commonly zoned and produces radiometric haloes in adjacent minerals.

Associated Minerals: Uranophane, brannerite, coffinite, molybdenite, bismuth, galena, pyrite, fluorite, vanadates, silver, and gold.

Mode of Occurrence and Origin: Occurs as growth-zoned crystals and as colloform, oolitic, and dendritic masses. Found as accessory grains in granites, pegmatites, and high-temperature sulfide veins; as clastic grains in quartz-pebble conglomerates; and as tabular to roll-front deposits in sandstones. Pitchblende is the massive, fine-grained colloform variety of uraninite.

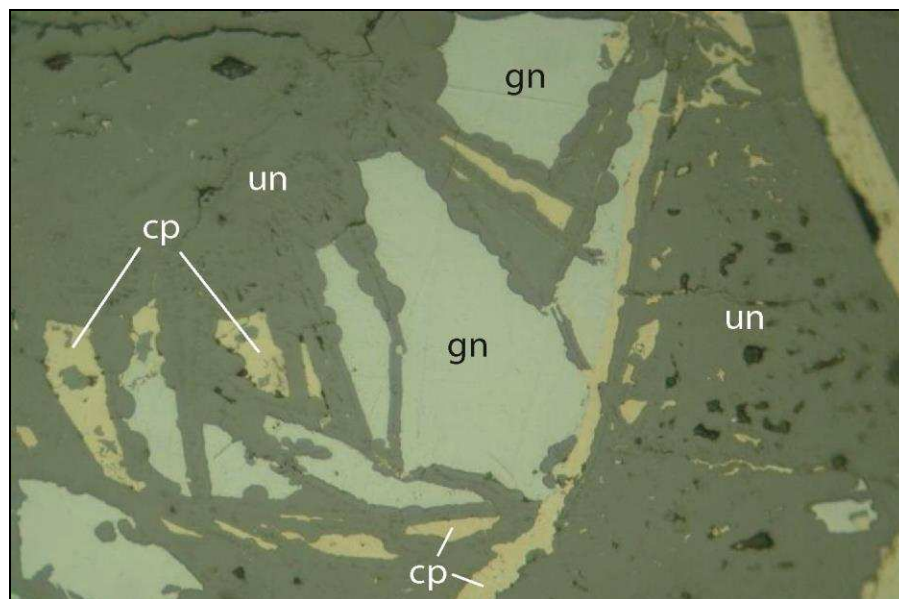


Figure 7.77 Uraninite (un), with chalcopyrite (cp), and galena (gn).
Schwartzwalder mine, Colorado; 100x. Photo courtesy of Jim Paschis.

CHEMICAL CLASS: TUNGSTATES

Mineral Name: Scheelite

Composition: CaWO_4

Characteristics in Hand Specimen

Crystal System: Tetragonal

Color: Colorless, white, gray, brown, and pale shades of orange, red, and green.

Cleavage: On {101}, distinct; also on {112} and {001}.

Fracture: Irregular, uneven.

Mohs Hardness: 4.5-5

Density (meas.): 6.10(2)

Streak: White

Association: Cassiterite, wolframite, topaz, fluorite, apatite, and many others.

Name: For Karl Wilhelm Scheele (1742-1786), who determined that the mineral contained tungsten.

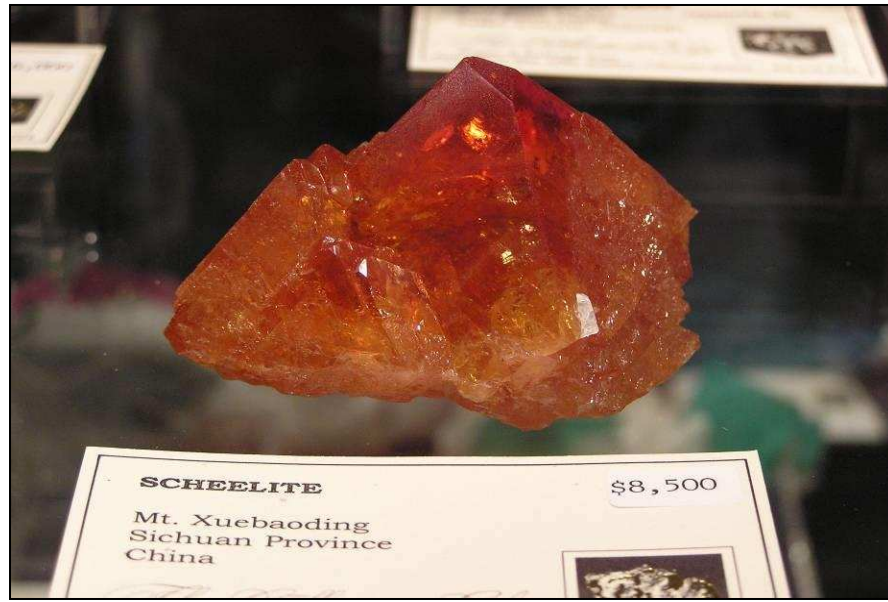


Figure 7.78 Scheelite. Mt. Xuebaoding, Sichuan Province, China. CSM Geology Museum.



Figure 7.79 Scheelite in core under the black light. Cantung skarn deposit, Cantung, Canada.

Characteristics in Polished Section

Color: Variable; gray-white, yellow, brown, and green.

Cleavage: {010}, distinct.

Polishing Hardness: High

Bireflectance: None

Anisotropy: Distinct, but masked by internal reflections.

Reflectance (in air): 10

IR: Abundant, white.

Distinguishing Features: Low reflectance, white internal reflections, high relief.

Associated Minerals: Carbonates, garnet, diopside, and amphibole in skarn deposits. In hydrothermal vein deposits with wolframite, pyrrhotite, arsenopyrite, molybdenite, fluorite, and tourmaline.

Mode of Occurrence and Origin: Occurs as equant to lath-like polycrystalline aggregates. Occurs as granular disseminations in skarn deposits, or as granular aggregates in pegmatites and quartz veins. Scheelite forms a solid solution with powellite, the molybdenum endmember. Fluoresces pale bluish white to yellow under ultraviolet light, depending upon moly content.

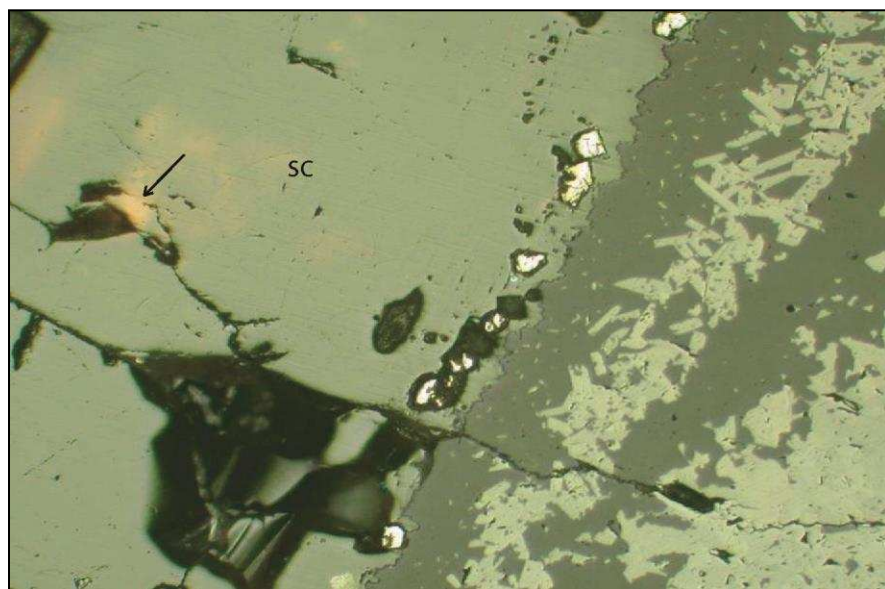


Figure 7.80 Scheelite (sc) showing internal reflections (arrow). Eureka mine, Boulder Co., CO. Photo courtesy of Jim Paschis.

References:

- Anglin, C.D., Franklin, J.M., and Jonasson, I.R., 1996, Sm-Nd dating of scheelite and tourmaline: Implications for genesis of Archean gold deposits, Val d'Or, Canada: *Economic Geology*, v. 1, p. 1372-1382.
- Brugger, J., Maas, R., Lahaye, Y., McRae, C., Ghaderi, M., Costa, S., Lambert, D., Bateman, R., and Prince, K., 2002, Origins of Nd-Sr-Pb isotopic variations in single scheelite grains from Archean gold deposits, Western Australia: *Chemical Geology*, v. 182, p. 203-225.
- Kempe, U., Belyatsk, B.V., Kyrmsky, R.S., Kremenetsky, A.A., and Ivanov, P.A., 2001, Sm-Nd and Sr isotope systematics of scheelite from the giant Au(-W) deposit Muruntau (Uzbekistan): Implications for the age and sources of Au mineralization: *Mineralium Deposita*, v. 36, p. 379-392.

Miguel, G.L., and Inverno, C.M.C., 2000, Mineralogy and metasomatic evolution of distal strata-bound scheelite skarns in the Riba de Alva Mine, Northeastern Portugal: Economic Geology, v. 95, p. 1259-1275.

CHEMICAL CLASS: TUNGSTATES

Mineral Name: Wolframite

Composition: $(\text{Fe}, \text{Mn})\text{WO}_4$. Forms a complete series between ferberite (FeWO_4) and huebnerite (MnWO_4).



Figure 7.81 Wolframite in quartz, Hunan province, China. Specimen courtesy of Jim Elliott, USGS retired.

Characteristics in Hand Specimen

Crystal System: Monoclinic

Color: Brownish-black to iron-black. Huebnerite is reddish brown, with a resinous luster, and is translucent; ferberite is black, with a nearly black streak and an almost metallic luster.

Cleavage: $\{010\}$ perfect.

Fracture: Irregular, uneven.

Tenacity: Brittle

Mohs Hardness: 4-4.5

Density (meas.):

Streak: Reddish-brown to brownish-black.

Association:

Name: Derived from “wolf” and “ram” for “froth” or “soot” (Agricola), perhaps in allusion to objectionable scum or substance formed during the smelting of tin ores containing tungsten.

Characteristics in Polished Section

Color: Light gray to white.

Cleavage: {010} distinct.

Polishing Hardness: >magnetite, scheelite

Bireflectance: Weak, with red-brown internal reflections.

Anisotropy: Distinct; gray-yellow.

Reflectance (in air): 15-20

IR: Deep red.

Distinguishing Features: Lamellar form, internal reflections, oblique extinction, cleavage, and low reflectance.

Associated Minerals: Pyrite, chalcopyrite, sphalerite, molybdenite, bismuth, cassiterite, scheelite, hematite, and arsenopyrite.

Mode of Occurrence and Origin: Wolframite is a solid solution of Fe and Mn endmembers. Huebnerite is the Mn endmember; ferberite is the Fe-rich endmember. Wolframate occurs as euhedral platelets and as masses of intergrown laths. Found in high-temperature quartz veins, pegmatites, and greisen zones. Examples include deposits at Cornwall, England; Panasqueira, Portugal; and Colorado molybdenum porphyries.

References:

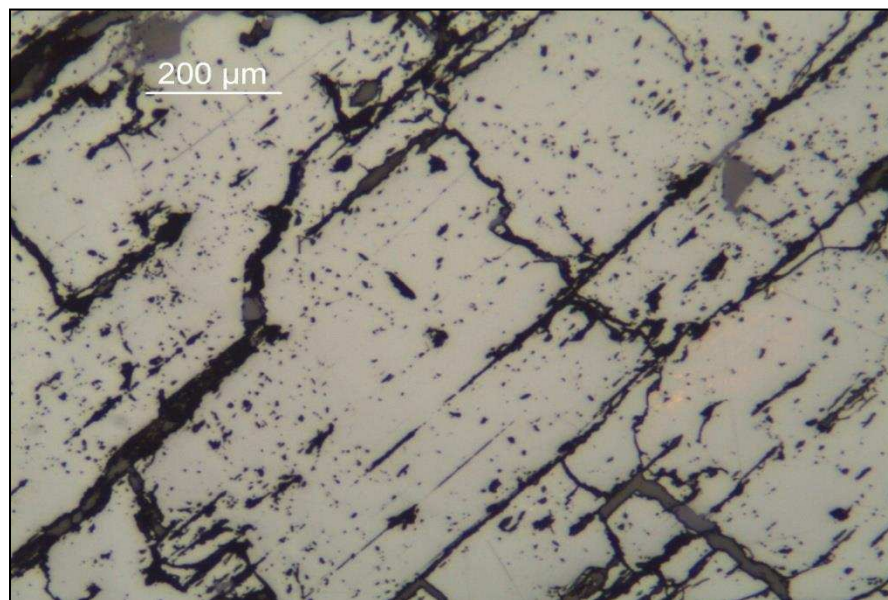


Figure 7.82 Wolframite, showing cleavage. Reflected light.

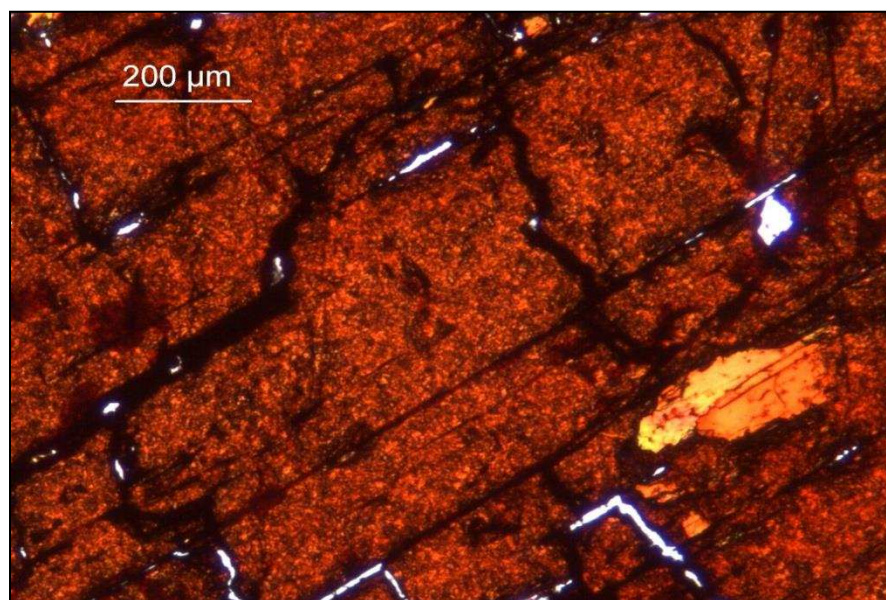


Figure 7.83 Wolframite, same view. Transmitted light.

CHEMICAL CLASS: ARSENIDES

Mineral Name: Nickeline (formerly Niccolite)

Composition: NiAs

Characteristics in Hand Specimen

Crystal System: Hexagonal

Color: Pale copper-red, tanishes gray to blackish.

Cleavage:

Fracture: Conchoidal

Tenacity: Brittle

Mohs Hardness: 5-5.5

Density (meas.): 7.784

Streak: Pale brownish-black.

Association: Skutterudite-nickel-skutterudite, safforite, rammelsbergite, maucherite, briethauptite, bismuth, bismuthinite, silver minerals.

Name: From the German *kupfernickel*, or Devil's copper.

Characteristics in Polished Section

Color: Yellow, pink, to brownish

Cleavage: (1010), (0001) imperfect.

Polishing Hardness: >chalcopyrite, ~pyrrhotite

Bireflectance: Strong; yellowish-pink to brownish-pink.



Figure 7.84 Nickeline. Specimen provided courtesy of Tom Loomis.

Anisotropy: Very strong; yellowish, gray, violet-blue, blue-gray.

Reflectance (in air): 49-53

IR: Absent

Distinguishing Features: Color, strong bireflectance, very strong anisotropism, and high reflectance are characteristic.

Associated Minerals: Ni-Co-Fe arsenides, Ag minerals, or with pyrrhotite and chalcopyrite.

Mode of Occurrence and Origin: Occurs as isolated subhedral to euhedral crystals, as anhedral aggregates, concentric layers, and as intergrowths with pyrrhotite and chalcopyrite.

References:

- Abzalov, M.Z., Brew, T.S., and Polezhaeva, L.I., 1997, Chemistry and distribution of accessory Ni, Co, Fe arsenic minerals in the Pechenga Ni-Cu Deposits, Kola Peninsula, Russia: *Mineralogy and Petrology*, v. 61, p. 145-161.
- Barrie, C.T., Corfu, F., Davis, P., Coutts, A.C., and MacEachern, D., 1999, Geochemistry of the Dundonald komatiite-basalt suite and genesis of Dundee Ni deposit, Abitibi Subprovince, Canada: *Economic Geology*, v. 94, p. 845-866.
- Chen, Y., Fleet, M.E., and Pan, Y., 1993, Platinum-group minerals and gold in arsenic-rich ore at the Thompson Mine, Thompson Nickel Belt, Manitoba, Canada: *Mineralogy and Petrology*, v. 49, p. 127-146.

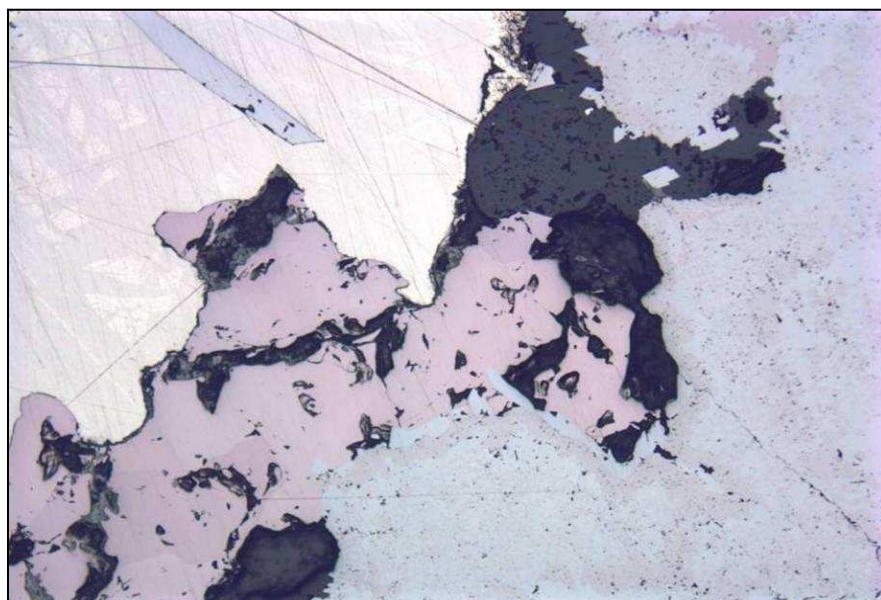


Figure 7.85 Nickeline (pink) and gersdorffite (white). No. 24, 10x.

CHEMICAL CLASS: ARSENIDES

Mineral Name: Safflorite

Composition: $(\text{Co,Fe,Ni})\text{As}_2$

Characteristics in Hand Specimen

Crystal System: Orthorhombic

Color: Tin-white, readily tarnishes to dark gray.

Cleavage: Distinct on $\{100\}$.

Fracture: Uneven to conchoidal.

Tenacity: Brittle

Mohs Hardness: 4.5-5

Density (meas.): 7.2

Streak: Grayish-black

Association: Skutterudite, rammelsbergite, nickeline, silver, bismuth, löllingite.

Name: From safflower, in allusion to its use as a pigment.

Characteristics in Polished Section

Color: White with a bluish tint.

Polishing Hardness: >skutterudite, <loellingite

B/P: Very weak, bluish to gray.

Anisotropy: Very strong

Reflectance (in air): 55-60

IR: Absent

Distinguishing Features:

Associated Minerals:

Mode of Occurrence and Origin:

References:

www.mindat.org

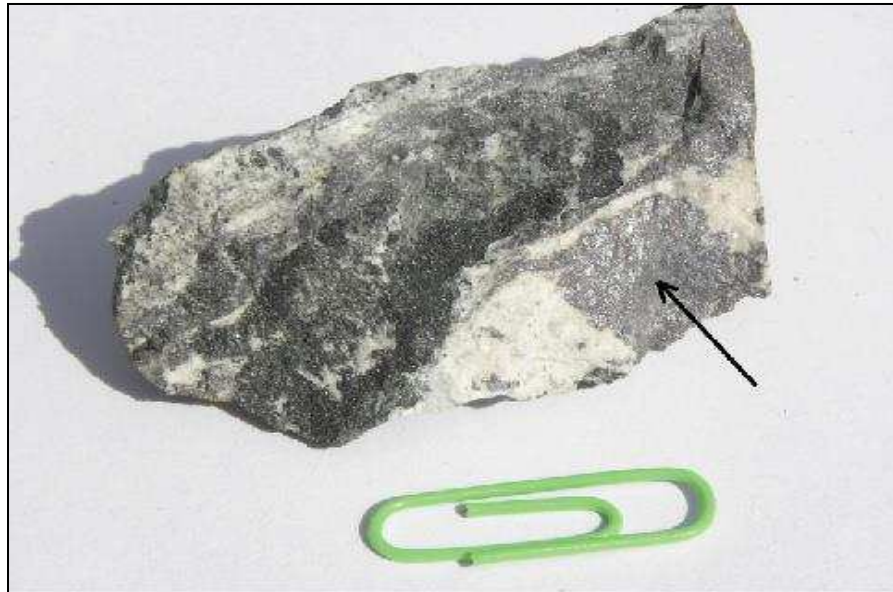


Figure 7.86 Safflorite (arrow). Keeley mine, Timiskaming, Ontario, Canada.

CHEMICAL CLASS: ARSENIDES

Mineral Name: Skutterudite

Composition: $(\text{Co}, \text{Ni})\text{As}_{2-3}$. This series comprises three minerals: skutterudite, $(\text{Co}, \text{Ni})\text{As}_3$; smaltite, $(\text{Co}, \text{Ni})\text{As}_{3-x}$; chloanthite, $(\text{Ni}, \text{Co})\text{As}_{3-x}$. These mineral names are applied to portions of a continuous solid solution series. The name smaltite, the oldest and best known, is generally preferred and applies to the most common occurrences (Mason and Berry, 1968).

Characteristics in Hand Specimen

Crystal System: Cubic

Color: Tin-white to silver-gray, tarnishes to gray or iridescent.

Cleavage: Distinct on $\{001\}$ and $\{111\}$; in traces on $\{011\}$.

Fracture: Conchoidal to uneven.

Tenacity:

Mohs Hardness: 5.5-6

Density (meas.): 6.5

Streak: Black

Association:

Name: For the Norwegian locality at Skutterud.



Figure 7.87 Skutterudite. Cobalt, Ontario, Canada.

Characteristics in Polished Section

Color: Creamy white to grayish white, commonly zoned.

Cleavage:

Polishing Hardness:

B/P: Absent

Anisotropy: Isotropic

Reflectance (in air): 53

IR: Absent

Distinguishing Features:

Associated Minerals:

Mode of Occurrence and Origin:

References:

www.mindat.org

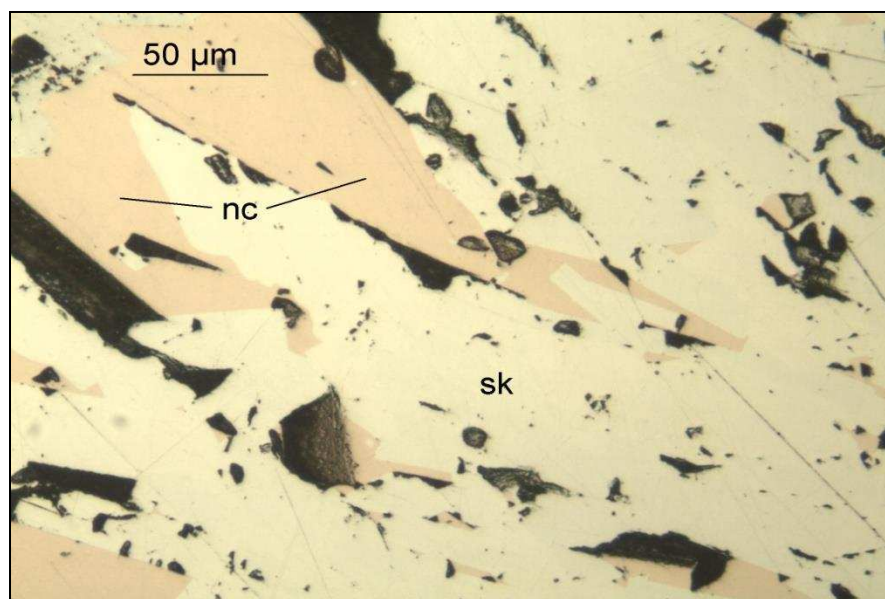


Figure 7.88 Skutterudite (sk) and nickeline (nc). Cobalt, Ontario, Canada.

CHEMICAL CLASS: TELLURIDES

In working with the telluride group, first determine whether or not the grains display any anisotropy. The seven most commonly reported tellurides on Earth, in decreasing order of abundance, are: hessite (Ag_2Te), tetradymite ($\text{Bi}_{14}\text{Te}_{13}\text{S}_8$), sylvanite (AuAgTe_4), altaite (PbTe), calaverite (AuTe_2 with minimum Ag), petzite (Ag_3AuTe_2), and native tellurium, Te (Geller, 1993; and personal communication). Four of these are at least distinctly anisotropic. Under crossed polars, note the following polarization colors for the following minerals:

hessite- in shades of orange and blue with distinct inversion twinning in patchwork patterns.

tetradymite- shades of cream/gray/dark tan, with undulatory to corrugated to patchy birdseye extinction).

sylvanite- dramatic dark brown extinction at maximum position, usually with polysynthetic twinning.

Calaverite features weak to strong anisotropy that is weaker than sylvanite's, and in colors paler than sylvanite, which make it hard to discriminate from untwinned sylvanite and certain other tellurides. Both altaite and petzite are isotropic, although micro-scratches often lend an apparent anisotropy to certain altaite grains. However, altaite is a bright, an unmistakable pure white, while petzite is dark gray-blue.

Secondly, observe the white light reflectivity of the tellurides in plane polarized light. The seven most common tellurides [and some non-tellurides, in brackets] from brightest to darkest, are: altaite, calaverite, [gold], native tellurium, sylvanite, tetradymite, [pyrite], [chalcopyrite], [galena], hessite, petzite, [tetrahedrite], and [sphalerite].

Third, of the most common tellurides, only native tellurium and petzite commonly display microscopic triangular cleavage after polishing. Hessite is one of the softest minerals known and usually retains micro-scratches made during the polishing process. Only hessite and sylvanite display obvious twinning, the latter as polysynthetic blades.

Finally, in terms of shape, many tellurides are anhedral, but calaverite grains generally display “jigsaw puzzle” outlines under crossed nicols, whereas native tellurium usually occurs in large mosaic aggregates. Sylvanite and tetradymite are commonly bladed.

Note that petrography may not be able to discriminate the telluride species, but it should be able to separate them from sulfides and other mineral species, which will facilitate further studies with micro-beam techniques (microprobe and SEM). Of the most common species, the most difficult to identify petrographically are calaverite and tetradymite (Bruce Geller, pers. comm.)

CHEMICAL CLASS: TELLURIDES

Mineral Name: Altaite

Composition: PtTe

Characteristics in Hand Specimen

Crystal System: Cubic

Color: Tin-white with yellowish tint, tanishes bronze.

Cleavage: {001} perfect.

Fracture: Subconchoidal

Tenacity: Sectile

Mohs Hardness: 3

Density (meas.): 8.19

Streak:

Association: Gold, silver, antimony, tellurium, galena, pyrite, tellurides, and many others.

Name: After the locality in the Altai Mountains, USSR.



Figure 7.89 Altaite. Gift of Tom Loomis, Dakotamatrix.com

Characteristics in Polished Section

Color: Bright white.

Cleavage: Commonly visible.

Polishing Hardness: <galena

Bireflectance: Absent

Anisotropy: Absent

Reflectance (in air): 70-71

IR: Absent

Distinguishing Features: Common as granular aggregates.

Associated Minerals: Other tellurides, tetrahedrite, tennantite, chalcocopyrite, sphalerite, chalcocite, covellite, enargite, and many others.

Mode of Occurrence and Origin:

References:

www.mindat.org

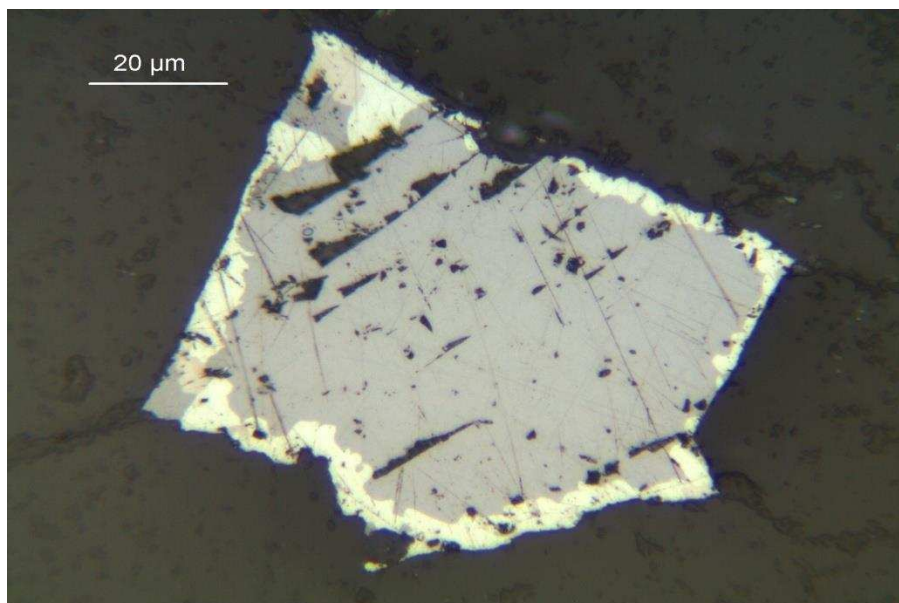


Figure 7.90 Rim replacement of galena (gray with cleavage pits) by altaite? Alpine Horn mine, Sugarloaf District, Colorado.

CHEMICAL CLASS: TELLURIDES

Mineral Name: Calaverite

Composition: AuTe_2

Characteristics in Hand Specimen

Crystal System: Monoclinic

Color: Grass-yellow to silver-white.

Fracture: Uneven to subconchoidal.

Tenacity: Brittle

Mohs Hardness: 2.5-3

Density (meas.): 9.10-9.40

Streak: Greenish to yellowish gray.

Association: Altaite, coloradoite, krennerite, richardite, other tellurides, pyrite, arsenopyrite, tetrahedrite, tennantite, sphalerite, stibnite, other sulfides.

Name: For its occurrence in Calaveras Co., California, USA.

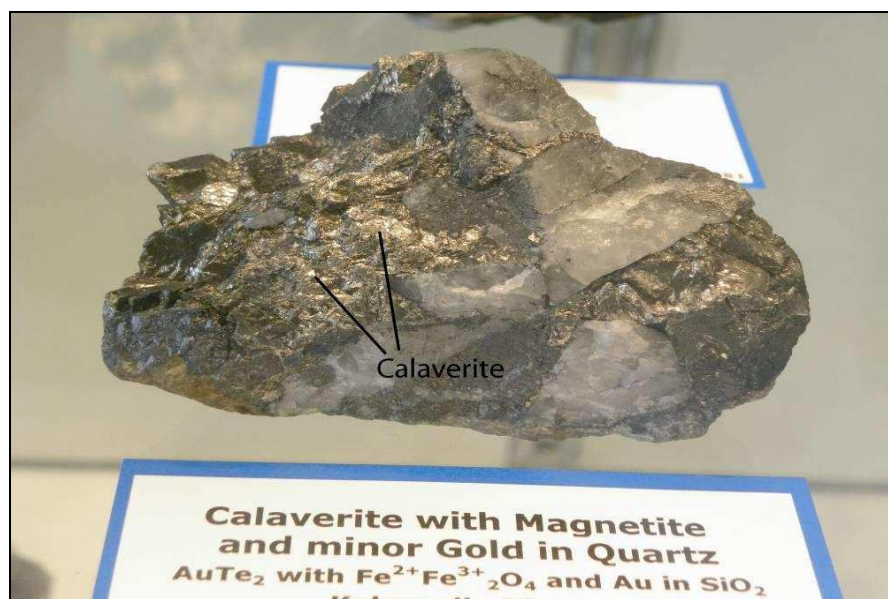


Figure 7.91 Calaverite. CSM Geology Museum.

Characteristics in Polished Section

Color: White with a creamy or yellowish tint.

Cleavage: Generally absent.

Polishing Hardness: Slightly less than galena.

Bireflectance: Weak to distinct.

Anisotropy: Grayish red, green, or greenish brown

Reflectance (in air): 64-65

IR: Absent

Distinguishing Features: Usually occurs as idiomorphic needle-shaped crystals, or as irregular lath-shaped crystals.

Associated Minerals: Other tellurides, freibergite, and sulfides of Fe, Cu, Pb, and Zn

Mode of Occurrence and Origin:

References:

www.mindat.org

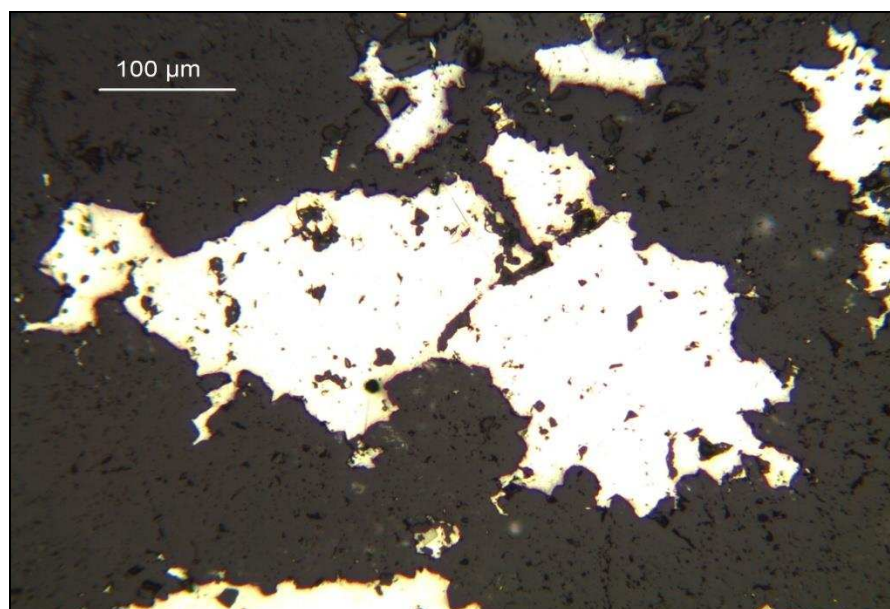


Figure 7.92 Calaverite, Cash mine, Magnolia District, Colorado.

CHEMICAL CLASS: TELLURIDES

Mineral Name: Hessite

Composition: Ag_2Te

Characteristics in Hand Specimen

Crystal System: Monoclinic

Color: Lead-gray to steel-gray, tarnishing to black.

Cleavage: {100} indistinct.

Fracture: Even, smooth.

Tenacity: Sectile

Mohs Hardness: 2-3

Density (meas.): 8.24-8.45

Association: Calaverite, sylvanite, altaite, petzite, empressite, richardite, gold, tellurium, pyrite, galena, tetrahedrite, chalcopyrite.

Name: For Germain Henri Hess (1802-1850), Swiss-Russian chemist, of Leningrad (St. Petersburg), Russia.



Figure 7.93 Hessite. Specimen courtesy of Tom Loomis?

Characteristics in Polished Section

Color: Gray-white

Cleavage: Not observed.

Polishing Hardness: Lowest of all tellurides; >argentite, <<galena

Bireflectance: Barely visible.

Anisotropy: Strong; dark gold-brown or dark orange to dark blue-gray

Reflectance (in air): 39-41

IR: Absent

Distinguishing Features: Occurs as rounded aggregates or as allotriomorphic crystals; also as skeleton-shaped crystals. When deposited above 155°C, inversion twin lamellae in 1,2, or 3 sets are present. .

Associated Minerals: Other tellurides, chalcopyrite, pyrite, sphalerite, galena, tennantite, argentite, electrum, antimony, and many others.

Mode of Occurrence and Origin:

References:

www.mindat.org

CHEMICAL CLASS: TELLURIDES

Mineral Name: Petzite

Composition: Ag_3AuTe_2

Characteristics in Hand Specimen

Crystal System: Cubic

Color: Bright steel-gray to iron-black, commonly tarnished.

Cleavage: {001}

Fracture: Subconchoidal

Tenacity: Slightly sectile to brittle.

Mohs Hardness: 2.5-3

Density (meas.): 8.7-9.4

Association: Gold, hessite, sylvanite, krennerite, calavarite, altaite.

Name: After W. Petz, who first analyzed the mineral.

Characteristics in Polished Section

Color: Grayish-white with a creamy or yellowish tint.

Cleavage: Cubic cleavage less perfect than galena.

Polishing Hardness: <sylvanite, coloradoite, hessite, altaite, calaverite.

Bireflectance: Weak to distinct.

Anisotropy: Grayish-red, green, or greenish-brown.

Reflectance (in air): 37

IR: Absent

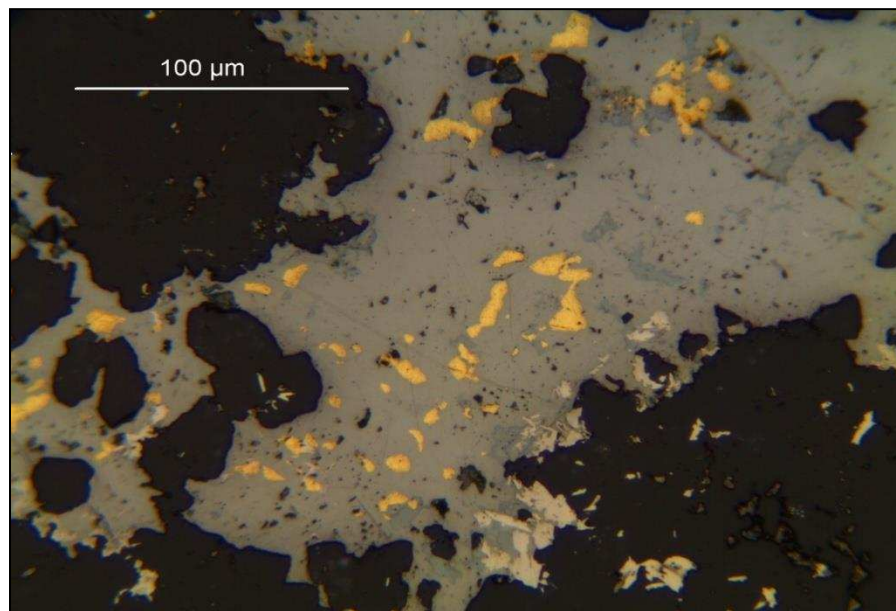


Figure 7.94 Petzite with gold inclusions. Cash mine, Magnolia district, Colorado.

Distinguishing Features: Usually occurs as idiomorphic needle-shaped crystals, or as irregular lath-shaped crystals.

Associated Minerals: Other tellurides, freibergite, and sulfides of Fe, Cu, Pb, and Zn.

Mode of Occurrence and Origin:

References:

www.mindat.org

CHEMICAL CLASS: TELLURIDES

Mineral Name: Sylvanite

Composition: $(\text{Au,Ag})_2\text{Te}_4$

Characteristics in Hand Specimen

Crystal System: Monoclinic

Color: Gray, white, or pale yellow.

Cleavage: Perfect on {010}.

Fracture: Uneven

Tenacity: Brittle

Mohs Hardness: 1.5-2

Density (meas.): 8.16

Streak: Steel-gray to silver-white.

Association: Gold, calaverite, krennerite, altaite, hessite, petzite, acanthite, pyrite, galena, sphalerite, chalcopyrite, quartz, chalcedony, fluorite.

Name: From Transylvania, for the part of Romania where it was first found, and in allusion to the element, tellurium (*sylvanium*, a name early proposed for the element), which the mineral contains.

Crystal System: Monoclinic

Mohs Hardness: 1.5-2



Figure 7.95 Sylvanite. Photo courtesy of Tom Loomis
Dakotamatrix.com.

Characteristics in Polished Section

Color: Creamy white

Cleavage: (010) perfect, (100) less distinct.

Polishing Hardness: Greater than altaite, Bi-tellurides.

Bireflectance: Distinct

Anisotropy: Strong; light bluish gray to dark brown.

Reflectance (in air): 50-58

IR: Absent

Distinguishing Features: Skeleton-shaped crystals are common; a characteristic polysynthetic twinning is always present.

Associated Minerals: Other tellurides, gold, galena, argentite, sphalerite, bornite, pyrite, chalcopyrite, and several others.

Mode of Occurrence and Origin:

References:

www.mindat.org

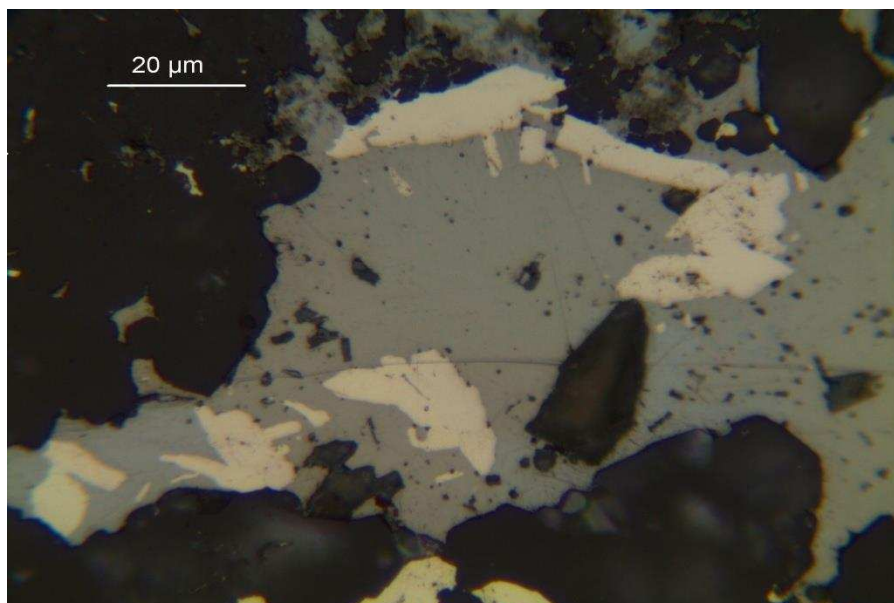


Figure 7.96 Sylvanite (white) and petzite (gray). Cash mine, Magnolia district, Colorado.

CHEMICAL CLASS: TELLURIDES

Mineral Name: Tetradyomite

Composition: $\text{Bi}_{14}\text{Te}_{13}\text{S}_8$

Characteristics in Hand Specimen

Crystal System: Hexagonal

Color: Pale steel-gray, tarnishes dull or iridescent.

Cleavage: Perfect on {0001}.

Tenacity: Laminae flexible but not elastic; slightly sectile.

Mohs Hardness: 1.5-2

Density (meas.): 7.3

Streak: Pale steel-gray.

Association: Gold, bismuth, hessite, petzite, calaverite, matildite, altaite, pyrite, pyrrhotite, galena, sphalerite, arsenopyrite, hematite.

Name: From the Greek for *fourfold*, an allusion to the twin crystals.



Figure 7.97 Tetradyomite.

Characteristics in Polished Section

Color: White with a creamy or light yellow tint.

Cleavage: Perfect basal cleavage.

Polishing Hardness: Soft

Bireflectance: Weak, in grayish-green tints.

Anisotropy: Distinct; bluish-gray or yellow-gray.

Reflectance (in air): 50-52

IR: Absent

Distinguishing Features: Forms idiomorphic needle-shaped crystals with straight extinction and hexagonal cross-sections. May show anhedral granular texture, or spindle-like texture due to folding.

Associated Minerals: Other tellurides, gold, bismuth, chalcopyrite, gersdorffite, scheelite, rutile, magnetite, galena, pyrite, tetrahedrite, and many others.

Mode of Occurrence and Origin:

References: www.mindat.org

REFERENCES

- Adams, E.F., 1910, An experimental investigation into the action of differential pressure on certain minerals and rocks employing the process suggested by Professor Kick: *Journal of Geology*, v. 18, p. 489-535.
- Allen, K.D., and Hahn, G.A., 1994, Geology of the Sunbeam and Grouse Creek gold-silver deposits, Yankee Fork mining district, Eocene Challis volcanic field, Idaho: A volcanic dome- and volcanoclastic-hosted epithermal system: *Economic Geology*, v. 89, p. 1964-1982.
- Anthony, J.W., Bideaux, R.A., Bladh, K.W., and Nicols, M.C., *Handbook of Mineralogy*, vols. I-V: Mineral Data Publishing, Tucson, Arizona.
- Atkinson, B.K., 1975, Experimental deformation of polycrystalline pyrite: Effects of temperature, confining pressure, strain rate, and porosity: *Economic Geology*, v. 70, p. 473-487.
- Barnes, H.L., Editor, 1997, *Geochemistry of Hydrothermal Ore Deposits*, 3rd edition: John Wiley & Sons, New York, 972 p.
- Barnes, S.-J., and Lightfoot, P.C., 2005, *Economic Geology 100th Anniversary Volume*, p. 179-213.
- Barton, P.B., Jr., 1970, Sulfide petrology: *Mineralogical Society of America Special Paper 3*, p. 187-198.
- _____, 1973, Solid solution in the system Cu-Fe-S. Part I: The Cu-S and CuFe-S joins: *Economic Geology*, v. 68, p. 455-465.
- _____, 1974, Sulfide Petrology, *in* *Sulfide Mineralogy: Mineralogical Society of America Short Course Notes*, v. 1, P.H. Ribbe, editor, p. B1-B11.
- Bastin, E.S., 1950, Interpretation of ore textures: *Geological Society of America Memoir 45*, 101 p.
- _____, Graton, L.C., Lindgren, W., Newhouse, W.H., Schwartz, G.M., and Short, M.N., 1931, Criteria of age relations of minerals, with special reference to polished sections of ores: *Economic Geology*, v. 26, p. 561-610.
- Boydell, H.C., 1925, The role of colloidal solutions in the formation of mineral deposits: *Institute of Mining and Metallurgy Transactions*, v. 34, p. 145-337.
- Brett, Robin, 1964, Experimental data from the system Cu-Fe-S and their bearing on exsolution textures in ores: *Economic Geology*, v. 59, p. 1241-1269.
- Brobst, D.A., and Pratt, W.P., editors, 1973, *United States Mineral Resources: U.S. Geological Survey Professional Paper 820*, 722 p.
- Buddington and Lindsley, 1964, *Journal of Petrology*, v. 5, p. 310-357
- Cameron, E.N., 1961, *Ore microscopy*: New York, John Wiley and Sons, Inc., 293 p.
- Clark, B.R., and Kelly, W.C., 1973, Sulfide Deformation Studies: I. Experimental deformation of pyrrhotite and sphalerite to 2,000 bars and 500°C: *Economic Geology*, v. 68, p. 332-352.
- Craig, J.R., and Vaughan, D.J., 1981, *Ore Microscopy & Ore Petrography*: John Wiley & Sons, New York, 406 p.
- _____, 1994, *Ore Microscopy and Ore Petrography*, 2nd edition: John Wiley & Sons, New York, 434 p.
- Criddle, A.J., and Stanley, C.J., editors, *Quantitative data file for ore minerals*: Chapman and Gall, New York, 635 p.
- Darling, R.S., 1987, The geology and ore deposits of the Carriatown silver-lead-zinc deposit, Blaine and Camus counties, Idaho: Masters thesis, Idaho State University.
- Davies, R., 1964, Chalcocite recrystallization and solid state mobility at high temperature and pressure: Masters thesis, McGill University, Montreal, Canada.

- Edwards, A.B., 1954, Textures of the ore minerals and their significance: The Australian Institute of Mining and Metallurgy, Melbourne, Australia, 242 p.
- Emmons, W.H., 1909, Some regionally metamorphosed ore deposits and so-called segregation veins: *Economic Geology*, v. 4, p. 755-781.
- _____, 1910, Some ore deposits in Maine and the Milan Mine, N.H.: U.S. Geological Survey Bulletin, v. 432, p. 1-62.
- Farrand, M., 1970, Framboidal sulphides precipitated synthetically: *Mineralium Deposita*, v. 5, p. 237-247.
- Geller, B.A., 1993, Mineralogy and origin of telluride deposits: Ph.D. dissertation, University of Colorado at Boulder, Boulder, Colorado, 731 p.
- Gill, J.E., 1969, Experimental deformation and annealing of sulfides and interpretation of ore textures: *Economic Geology*, v. 64, p. 500-508.
- Graf, J.L., and Skinner, B.J., 1970, Strength and deformation of pyrite and pyrrhotite: *Economic Geology*, v. 65, p. 206-215.
- Graham, U.M., and Ohmoto, Hiroshi, 1994, Experimental study of formation mechanisms of hydrothermal pyrite: *Geochim. Cosmochim. Acta*, v. 58, p. 2187-2202.
- Guilbert, J.M., and Park, C.F., Jr., 1986, The geology of ore deposits: W.H. Freeman and Company, New York, 985 p.
- Halback, P., Pracejus, B., and Märten, A., 1993, Geology and mineralogy of massive sulfide ores from the central Okinawa trough, Japan: *Economic Geology*, v. 88, p. 2210-2225.
- Haranczyk, C., 1971, Colloidal transport phenomena of zinc sulfide (brunckite) observed in the Olkusz Mine in Poland, *in* Geochemistry and crystallography of sulphide minerals in hydrothermal deposits: Int. Mineral. Assoc.-Genesis of Ore Deposits, Joint Symp. Vol. Soc. Min. Geol. Japan, Special Issue, No. 2.
- _____, 1962, Ore minerals of Silesia—Cracow zinc and lead deposits: *Polish Acad. Sci. Geol. Trans.*, No. 8, 96 p.
- Honjo, S., Fischer, A.G., and Garrison, R., 1965, Geopetal pyrite in fine-grained limestones: *Journal of Sedimentary Petrology*, v. 35, p. 480-488.
- Hutchinson, M.N., and Scott, S.D., 1980, Sphalerite geobarometry in the Cu-Fe-n-S system, *Economic Geology*, v.
- Ineson, P.R., 1989, Introduction to Practical Ore Microscopy: Longman Scientific & Technical and John Wiley & Sons, Inc., New York, 181 p.
- Kelly, W.C., and Clark, B.R., 1975, Sulfide deformation studies: III. Experimental deformation of chalcopyrite to 2000 bars and 500°C: *Economic Geology*, v. 70, p. 431-453.
- Knopf, Adolf, 1916, Wood tin in the Tertiary rhyolites of northern Nevada: *Economic Geology*, v. 11, p. 652-661.
- Krishnamurthy, P., 1967, Experimental deformation of sulphide ores: Masters thesis, McGill University, Montreal, Canada.
- Lindgren, W., and Irving, J.D., 1911, The origin of Rammelsberg ore deposit: *Economic Geology*, v. 6, p. 303-313.
- Lindsley, D.H., 1976, Experimental studies of oxide minerals, *in* D. Rumble, editor, *Oxide Minerals: Mineralogical Society of America Short Course Notes*, v. 3, L61-L88.
- Lufkin, J.L., 1983, Interpretation of ore-mineral textures: Progress and problems in the past fifty years, *in* Boardman, S.J., editor, *Revolution in the Earth Sciences: Advances in the Past Half Century*, Kendall/Hunt Publishers, p. 268-280.
- _____, 1977, Chemistry and mineralogy of wood-tin, Black Range, New Mexico: *American Mineralogist*, v. 62, p. 100-106.

- _____, 1976, Oxide minerals in miarolitic rhyolite, Black Range, New Mexico: *American Mineralogist*, v. 61, p. 425-430.
- Loughheed, M.S., and Mancuso, J.J., 1973, Hematite framboids in the Negaunee iron formation, Michigan: Evidence for their biogenic origin: *Economic Geology*, v. 68, p. 202-209.
- Love, L.G., and Amstutz, G.C., 1966, Review of microscopic pyrite from the Devonian Chattanooga Shale and Rammelsberg Banderz: *Fortschr. Mineral.*, v. 43, p. 273-309.
- Marshall, Dan, Anglin, C.D., and Mumin, Hamid, 2004, *Ore Mineral Atlas*: Geological Association of Canada, St. John's, Newfoundland, Canada A1B3X5.
- Mason, Brian, and Berry, L.G., 1968, *Elements of Mineralogy*: W.H. Freeman and Company, San Francisco, 550 p.
- Mavrogenes, J., Henley, R.W., Reyes, A.G., and Berger, B., 2010, Sulfosalt melts: Evidence of high-temperature vapor transport of metals in the formation of high-sulfidation lode gold deposits: *Economic Geology*, v. 105, p. 257-262.
- Mavrogenes, J.A., MacIntosh, I.W., and Ellis, D.J., 2001, Partial melting of the Broken Hill galena-sphalerite ore: Experimental studies in the system PbS-FeS-ZnS-(Ag₂S): *Economic Geology*, v. 96, p. 205-210.
- McLimens, R.K., Barnes, H.L., and Ohmoto, H., 1980, Sphalerite stratigraphy of the Upper Mississippi Valley zinc-lead district, southwest Wisconsin: *Economic Geology*, v. 75, 351-361.
- Moore, W.J., and Lanphere, M.A., 1971, The age of porphyry-type copper mineralization in the Bingham mining district, Utah—A refined estimate: *Economic Geology*, v. 66, p. 331-334.
- Mügge, O., 1898, Über translationen und veränderte erscheinungen im krystallen: *Neues Jahrbuch für Min. Geol. U. Pal.*, I., p. 123-138.
- Oenema, O., 1990, Pyrite accumulation in salt marshes in the eastern Scheldt, southwest Netherlands: *Biogeochemistry*, v. 9, p. 75-98.
- Ohmoto, Hiroshi, and Skinner, B.J., editors, 1983, *The Kuroko and related volcanogenic massive sulfide deposits*: *Economic Geology Monograph* 5, 604 p.
- Ostwald, J. and England, B.M., 1979, The relationship between euhedral and framboidal pyrite in base-metal sulfide ores: *Mineralogical Magazine*, v. 43, p. 297-300.
- Pan, Y., 1974, The genesis of the Mexican type tin deposits in acid volcanics: Ph.D. dissertation, Columbia University, New York, N.Y.
- Park, C.F., and MacDiarmid, R.A., 1975, *Ore deposits*, 3rd edition: W.H. Freeman and Company, San Francisco, 529 p.
- Picot, P., and Johan, Z., 1982, *Atlas of Ore Minerals*.
- Pracejus, Bernhard, editor, 2008, *The ore minerals under the microscope: An optical guide*: Elsevier, Amsterdam, 875 p.
- Putnis, A., and McConnell, J.D.C., 1980, *Principles of Mineral Behavior*: Elsevier, New York.
- Ramdohr, Paul, 1980, *The ore minerals and their intergrowths*, v. 1-2: Pergamon Press, Oxford, England, 1205 p.
- _____, 1928, Über den mineralbestand und die strukturen der erze des Rammelsbergs: *Neues Jahrb. Mineral. Geol. Palaeontol., Abh., Abt. A.*, v. 57(2), p. 1013-1068.
- Roedder, Edwin, 1968, The non-colloidal origin of "colloform" textures in sphalerite ores: *Economic geology*, v. 63, p. 451-471.
- Rosco, W.E., 1975, Experimental deformation of natural chalcopyrite at temperatures up to 300°C over the strain rate range
- Rosso, Jodi, editor, 2006, *Sulfide mineralogy and geochemistry: Reviews in mineralogy and geochemistry*, v. 61, 714 p.

- Rumbel III, Douglas, editor, 1976, Oxide minerals, v. 3: Mineralogical Society of America Short Course Notes.
- Rust, G.W., 1935, Colloidal primary copper ores at Cornwall mines, southeastern Missouri: *Journal of Geology*, v. 43, p. 398-426.
- Salmon, B.C., Clark, B.R., and Kelly, W.C., 1974, Sulfide deformation studies: II. Experimental deformation of galena to 2000 bars and 400°C: *Economic Geology*, v. 69, p. 1-16.
- Sassano, G.P., and Schrijver, K., 1989, Framboidal pyrite: Early-diagenetic, late diagenetic, and hydrothermal occurrences from Acton Vale quarry, Cambro-Ordovician, Quebec: *American Journal of Science*, v. 289, p. 167-179.
- Schallreuter, R., 1984, Framboidal pyrite in deep sea sediments: *Initial Reports DSDP*, v. 75, p. 875-891.
- Schneiderhöhn, H., 1923, Chalkographische Untersuchung des Mansfelder Kupferschiefer: *Neus Jahrbuch Mineralogie, Geologie, und Paläeontologie*, v. 47, p. 1-38.
- Schwartz, G.M., 1951, Classification and definitions of textures and mineral structures in ores: *Economic Geology*, v. 46, p. 578-591.
- _____, 1939, Significance of bornite-chalcocite microtextures: *Economic Geology*, v. 34, p. 399-418.
- _____, 1928, Experiments bearing on bornite-chalcocite intergrowths: *Economic Geology*, v. 23, p. 381-397.
- _____, 1927, Intergrowths of chalcopyrite and cubanite: *Economic Geology*, v. 22, p. 44-61.
- Shouten, C., 1962, Determinative tables for ore microscopy: Amsterdam, Elsevier, 242 p.
- Spry, P.G., and Gedlinske, B.L., 1987, Tables for the determination of common opaque minerals: The Economic Geology Publishing Company, 52 p.
- Stanton, R.L., 1972, Ore petrology: McGraw-Hill, Inc., 713 p.
- _____, 1964, Mineral interfaces in stratiform ores: *Transactions of the Institute of Mining and Metallurgy*, v. 74, p. 45-79.
- _____, and Gorman, 1968, A phenomenological study of grain boundary migration in some common sulfides: *Economic Geology*, v. 63, p. 907-923.
- Sunagawa, I., Endo, Y., and Nakai, N., 1971, Hydrothermal synthesis of framboidal pyrite: *Society of Mining Geologists of Japan (Spec. Issue)*, v. 2, p. 10-14.
- Sweeney, R.E., and Kaplan, I.R., 1973, Pyrite framboid formation: laboratory synthesis and marine sediments: *Economic Geology*, v. 68, p. 618-634.
- Tomkins, A.G., Pattison, D.R.M., and Zaleski, E., 2004, The Hemlo gold deposit, Ontario: An example of melting and mobilization of precious metal-sulfosalt assemblage during amphibolite facies metamorphism and deformation: *Economic Geology*, v. 99, p. 1063-1084.
- Uytendogaardt, W., and Burke, E.A.J., 1985, Tables for Microscopic Identification of Ore Minerals, 2nd edition: Dover Publication, New York, 430 p.
- Weise, R.G., and Fyfe, W.S., 1986, Occurrences of iron sulfides in Ohio coals: *International Journal of Coal Geology*, v. 6, p. 251-276.
- Wiggins, L.B., and Craig, J.R., 1980, Reconnaissance of the Cu-Fe-Zn-S system: Sphalerite phase relationships: *Economic Geology*, v. 75, p. 742-752.
- Wilkin, R.T., and Barnes, H.L., 1996, Pyrite formation by reactions of iron monosulfide with dissolved inorganic and organic sulfur species: *Geochim. Cosmochim. Acta*, v. 60, p. 4167-4179.
- _____, Barnes, H.L., and Brantley, S.L., 1996, The size distribution of framboidal pyrite: an indicator of redox conditions: *Geochim. Cosmochim. Acta*, v. 60, p. 3897-3912.

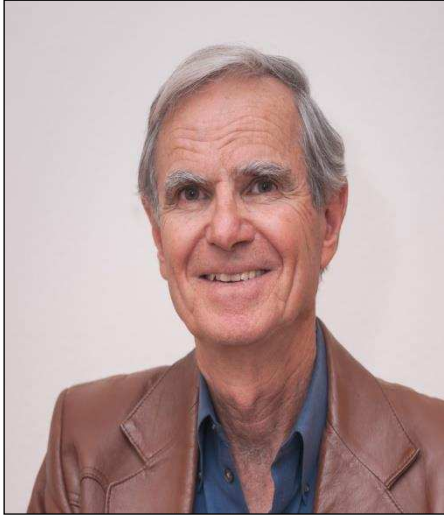
- Yund, R.A., and McCallister, R.H., 1970, Kinetics and mechanisms of exsolution: Chemical Geology, p. 5-30.
- Ypma, P.J.M., and Simons, J.H., 1969, Genetical aspects of the tin mineralization in Durango, Mexico: International Tin Council, London, and Department of Mineral Resources, Bangkok, 14 p.
- Zhirnov, A.M., 1972, Hypogene colloform gold in the Kauldy gold deposit, Central Asia: Uzbek. Geol. Zh., no. 1, p. 93-96.

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