DAVE
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7

Description of Skarns Associated With Porphyry Copper Plutons

SOUTHWESTERN NORTH AMERICA

Marco T. Einaudi

The invariable association of porphyry copper plutons emplaced in carbonate-rich sedimentary rocks with mineralized calc-silicate or siliceous replacement bodies is well known. Numerous examples of this association occur in southwestern North America; the importance of this type of deposit as an exploration target has increased over the years due to the fact that porphyry deposits with carbonate ores commonly display higher hypogene copper grades than those lacking carbonate wall rocks.

In spite of the economic importance and scientific interest of carbonate-hosted ores, knowledge of their critical field relations and petrology has lagged behind knowledge of these aspects in the porphyries themselves. Of the thirteen deposits summarized in this chapter, only three have had fairly extensive published coverage (Christmas, Bingham, and Ely) in which details of paragenesis, zoning, and approximate phase compositions have been laid out. This gap is only partially closed by the present volume; Twin Buttes is described for the first time by Barter and Kelly (see Chapter 20). One of the main aims of this chapter, then, is to summarize the better-known deposits and to describe the lesser-known occurrences. Unpublished data acquired by the author are presented for Yerington, Bingham, and Palo Verde; descriptions of Cananea, Silver Bell, Twin Buttes, Mission, Continental, and Ely are colored by knowledge gained during field visits and discussions with geologists who have extensive personal knowledge of these deposits; descriptions of Christmas, Santa Rita, Morenci, and Bisbee are based entirely on the published record. The general features and origin of ores in carbonate wall rocks of porphyry plutons are discussed in Chapter 8 of this book.

SKARN TERMINOLOGY

The terminology applied to altered and mineralized carbonate-bearing rocks often is misleading, and different terms have evolved to describe identical features. Descriptive and genetic terms must, therefore, be clearly differentiated. For a broader discussion, the reader is referred to Burt (1977).

Skarn refers to coarse-grained calc-silicates which replace carbonate-rich rocks during regional or contact metamorphism. Skarns tend to consist of a sequence of monomineralic or bimineralic layers which are zoned relative to sedimentary or igneous contacts and fissures or fractures. Two broad categories of skarn are recognized. Skarn formed over a few millimeters or meters along shale-limestone contacts during high-grade metamorphism, and whose bulk composition reflects that of the reacting rocks, is termed *reaction skarn.* Reaction skarns can be shown to be the result of bimetasomatic diffusion of locally derived components in a possibly stagnant, intergranular hydrothermal fluid. Of greater interest here are the larger *ore skarns,* which may contain significant quantities of ore minerals, and whose bulk composition bears no simple relation to the enclosing rocks. Ore skarns normally are thought to result from infiltration of an iron-rich hydrothermal fluid derived from dominantly magmatic processes. Clearly, gradations between reaction skarns and ore skarns are possible. However, a distinction often can be made within a given district on the basis of age relations (reaction skarn tends to be early) and composition of calc-silicates (reaction skarn tends to be more aluminous); this is an important point, and will be discussed in greater detail in later sections. In the present chapter, the term *skarn* is reserved for calc-silicate gangue which is spatially and temporally related to ore deposition. The term *tactite* would be roughly synonymous with this usage.

Metamorphism is commonly defined as recrystallization, often accompanied by mineralogical transformations, which involves no transfer of matter into or out of the system other than volatile components such as H_2O and CO_2. In contrast, *metasomatism* involves changes in the amounts of nonvolatile components such as Fe, Mg, and Si. Whether a particular rock is considered to be of metamorphic or metasomatic origin may depend on how the system is defined; for example, reaction skarns may be considered metasomatic if only the carbonate bed is considered, or metamorphic if the system is defined as the total sequence of interbedded carbonate-shale. In terms of processes, however, reaction skarns display the hallmark of the metasomatic process: abrupt discontinuities in bulk composition across monomineralic or bimineralic zonal boundaries. Metamorphic rocks, on the other hand, show no such compositional discontinuities across mineral zoning boundaries; the boundaries simply reflect thermal or volatile fugacity gradients.

Skarns can be classified according to the type of rock replaced: *endoskarns* replace an intrusive or other aluminous rock; *exoskarns* replace carbonate rocks. Endoskarns generally are only weakly developed in porphyry-related deposits. In the present chapter the term "skarn" is synonymous with "exoskarn." Further classification of exoskarn can be based on the calc-silicate mineral association. *Calcic skarns,* which generally replace non-magnesian limestone, display relatively high Ca/Mg ratios and consist of garnet, clinopyroxene, and wollastonite; one or more iron-rich calc-silicates always are present. *Magnesian skarns,* which generally replace dolomitic rocks, display relatively low Ca/Mg ratios and consist of foresterite, talc, tremolite, and serpentine; iron-rich calc-silicates generally are absent and magnetite is abundant. Due to the paucity of dolomite in sedimentary strata associated with porphyry copper deposits in southwestern North America, magnesian skarns are less important than calcic skarns in the deposits considered here.

Hornfels is a term generally applied to massive, fine-grained rocks resulting from contact metamorphism. A qualifier may be used to denote the dominant mineralogy or composition: calc-silicate hornfels or biotite hornfels. Although the term "hornfels," as used in the literature, generally implies an origin through metamorphism, it is clear that some hornfelses in porphyry-copper districts are metasomatic rocks. In this chapter, the term "hornfels" is used in a descriptive sense only.

The distinction between metamorphism and metasomatism becomes increasingly difficult if a sequence of impure carbonate and shale beds is replaced on a large scale by garnet-rich assemblages. Such assemblages may consist of coalesced reaction skarns or bedded sequences of coarse reaction skarn and finger-grained garnet hornfels resulting from metamorphic recrystallization of calcareous shale or marl. The term *skarnoid* is used in the present chapter to denote such garnet-rich rocks of uncertain origin.

The carbonate-hosted ores considered here are associated with highly fractured, hypabyssal granodiorite to quartz monzonite porphyry stock complexes that exhibit varying degrees of potassium silicate and/or sericitic alteration associated with Cu-Fe sulfide mineralization. With regard to alteration types in the stocks, the terms "propylitic," "potassium-silicate," "intermediate argillic," "sericitic," and "advanced argillic" are used in the sense defined by Meyer and Hemley (1967, p. 171–178).

CHARACTERISTICS OF SEDIMENTARY ROCKS IN SOUTHWESTERN NORTH AMERICA

Sedimentary rocks of porphyry copper districts in southwestern North America range from the carbonate-dominated cratonic deposits of southeastern Arizona to the sandstone-dominated subsident basin deposits of western Utah and eastern Nevada, to the basinal marine volcanic-arc deposits of western Nevada. A brief summary of sedimentary environments and lithologies is given here to set the context for the section dealing with individual deposits.

Carbonate Rocks of Arizona, New Mexico, and Sonora

The Paleozoic strata of southern Arizona, western New Mexico, and northeastern Sonora consist of a thin (1–2 km) sequence of shallow marine cratonic shelf deposits in which carbonate typically constitutes 65 percent of the whole (Figs. 7.1 and 7.2). The section thickens abruptly in the northwestern corner of Arizona toward the Cordilleran miogeosyncline and more gradually to the southeast toward the Sonoran embayment. Minor warping, faulting and eustatic changes in sea level characterized the central Arizona shelf during much of Early and Middle Paleozoic time. Increasing tectonic activity during Late Paleozoic time is correlated by Ross (1978) with the final closure of the Marathon geosyncline during collision of Gondwana and Laurasia during Pennsylvanian and Early Permian time. Patterns of sedimentation were controlled in part by a positive region in central Arizona and by northwest-trending, fault-bounded basins in the south (Butler, 1971; Titley, 1976).

Pronounced facies changes compound the difficulties involved in determining the origin of skarn minerals. For example, the Colina Limestone and Epitaph Formation, of Permian age, consist of dark-colored limestone, dolomite, marl, and gypsum; considerable variation in the proportions of these lithologies reflects the abrupt changes from a shallow lagoonal-evaporating pan (dolomite and gypsum) to deeper water (limestone) environments in the Pedregosa basin (Butler, 1971). The Silver Bell-Mission-Twin Buttes-Bisbee trend lies parallel to the northwest-trending basin axis and near its southwestern shoreline (Fig. 7.1), where the limestone:dolomite + gypsum ratio defined by Butler (1971) varies from 1:1 to 8:1. In areas where fresh equivalents of altered strata are not exposed, the determination of the source of magnesium in skarn and of the sedimentary or metasomatic origin of anhydrite is difficult at best.

Broader facies variations in other formations yield more predictable variations in calc-silicate associations. Where the Martin Formation is dominantly sandy dolomite to dolom-

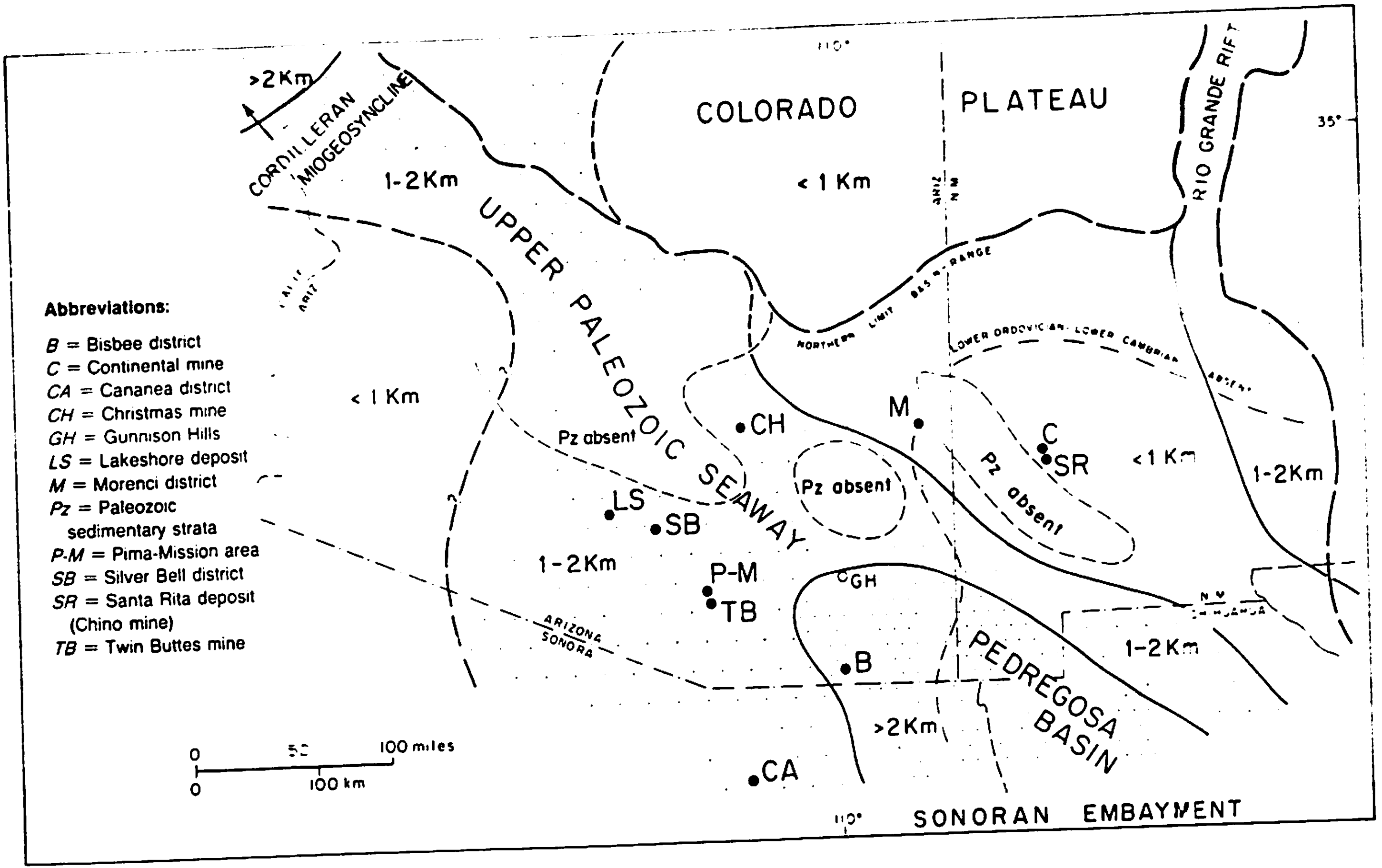


Figure 7.1. Paleothickness (in km) of Paleozoic sedimentary rocks in southeastern Arizona, southwestern New Mexico, and northernmost Sonora and Chihuahua. Porphyry-related skarn deposits are located mostly in areas of greatest thickness of carbonate-bearing strata that extend northwestward from the Pedregosa Basin. The absence of Paleozoic strata in some of the areas is due in part to non-deposition, in part to erosion. Information based on McKee (1951), Peirce (1976), and Greenwood and others (1977).

itic limestone, it yields magnetite-rich magnesian skarn at Christmas and Twin Buttes; to the southeast, toward the basin, the Martin consists of silty limestone and yields calcic skarn. The Abrigo and Earp formations consist of interstratified limestone, sandstone, siltstone, and shale; dolomitic members, which are characteristic of the Abrigo to the north and northeast are generally absent in southeastern Arizona (Hayes, 1978). During the early metamorphic stages of contact alteration, these formations typically yield layered hornfels-skarnoid-marble, which may be overprinted by calcic skarn; magnesian skarn generally is not developed. The Escabrosa, Horquilla, and Concha limestones consist of massive, thick-bedded cherty limestone, with shale and silty beds prominent only near the base of the Horquilla; during the metasomatic stages of alteration, these units typically yield massive calcic skarn.

Sandstone-Dominated Successions of Utah and Eastern Nevada

Farther north, in Utah and eastern Nevada, the Paleozoic section is more than an order of magnitude thicker than the shelf-margin of Arizona and includes thick sections of clastic rocks accumulated in subsident basins of Middle to Late Paleozoic age. Late Mississippian basins, forerunners of the Oquirrh basin, accumulated a thick section of black shales (Chainman Shale at Ely; Manning Canyon Formation near Bingham). In Pennsylvanian and Permian time extensive downwarping of the Cordilleran miogeosyncline occurred along the Cortez-Uinta trend from the Antler orogenic belt on the west to the Utah-Wyoming shelf margin (Roberts et al, 1965). The area of maximum sedimentation, near the Bingham district, received 8 km of predominantly sandy clastic deposits (Oquirrh Group). The middle portion of the Oquirrh Group constitutes the country rocks of the Bingham stock and locally is designated the Bingham Mine Formation (Fig. 7.3). The formation consists predominantly of quartz sandstone, with lesser amounts of clastic limestone and calcareous siltstone. Shaly interbeds constitute less than 1 percent of the whole and dolomite is virtually absent (Atkinson and Einaudi, 1978). The overall composition of the Pennsylvanian strata, thus, was not conducive to the generation of metamorphic calc-silicate hornfels with local skarnoid interbeds which, in contrast, characterize the Arizona-New Mexico-Sonora occurrences. Early metamorphic effects consist of recrystallization to orthoquartzite and local development of wollastonite-bearing marble.

To the southwest, the Oquirrh Group grades into a calcareous and silty facies, which in the Robinson district (Ely) is represented by the ore-bearing Ely Limestone. The thinner, ore-bearing limestone beds of the Bingham Mine Formation and the thicker Ely Limestone are very similar in overall composition: 25 to 30 percent SiO_2 (as chert and quartz silt),

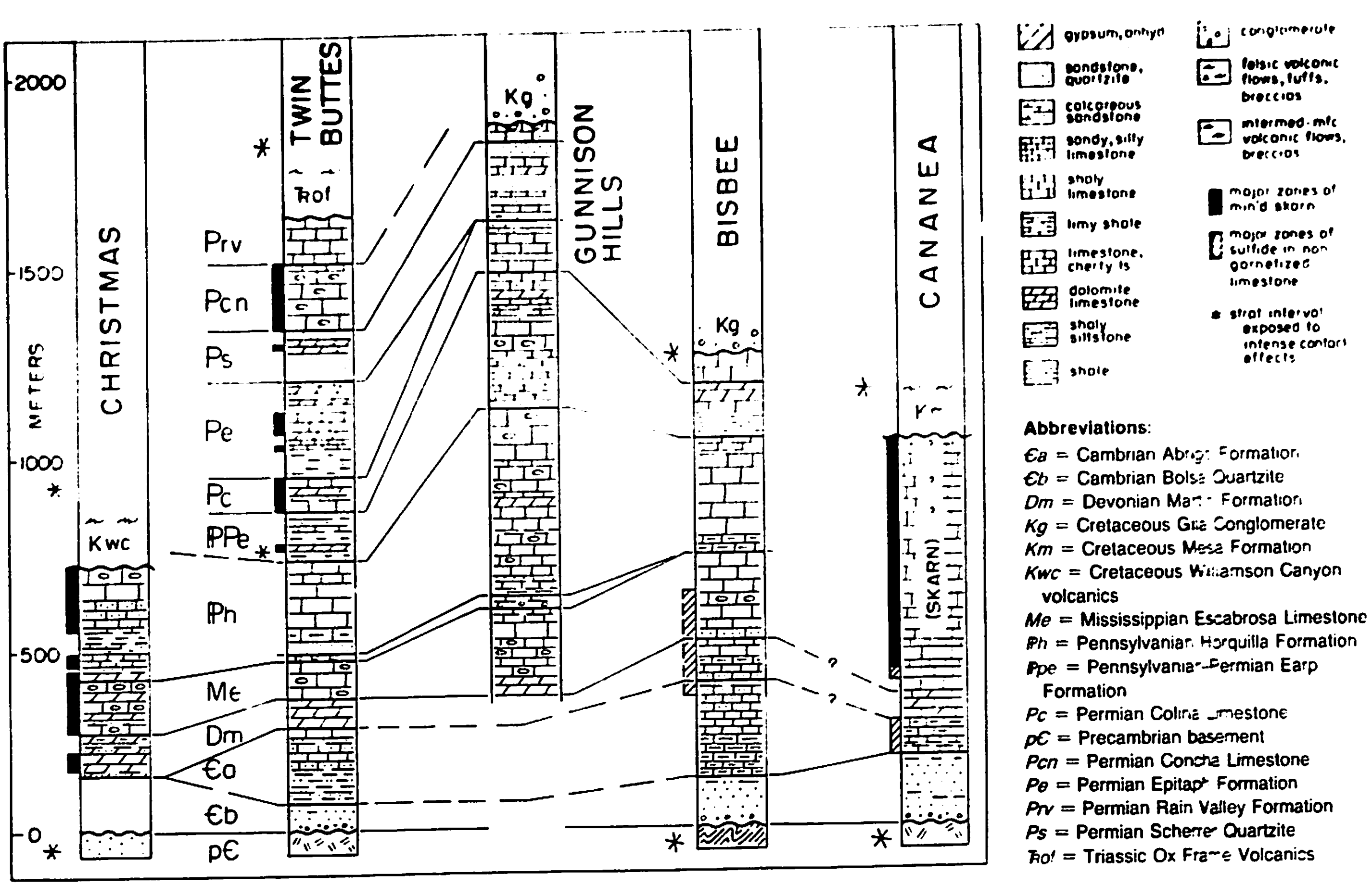


Figure 7.2. Paleozoic stratigraphic sections from southeastern Arizona and northernmost Sonora (localities shown in Fig. 7.1), illustrating lithologic variability within formations, dominance of carbonate lithology, and restriction of skarn (black bars) to purer carbonate beds. The stratigraphic interval occurring within the immediate contact aureole is indicated by stars for each locality. Source of data: Christmas (Perry, 1968); Twin Buttes (Barter and Kelly, 1982); Gunnison Hills (Gilluly et al., 1954); Bisbee (Bryant and Metz, 1966); Cananea (Mulchay and Velasco, 1954).

less than 1 percent MgO, and less than 1 percent Al_2O_3 (Reid, 1978; James, 1976).

Volcanic and Clastic Successions of Western Nevada

Further west, the strata of the western Great Basin consist of submarine volcanic arc deposits of Triassic age; lying west of the Paleozoic continental shelf, they are overlain by deposits which reflect the dominantly emergent continental margin terrain of Early to Middle Jurassic age (Speed, 1978). In the Yerington district, volcanic-sedimentary rocks consist of a Middle Triassic, andesite-rhyolite, volcanic-arc assemblage, which is overlain by Upper Triassic to Lower to Middle (?) Jurassic sedimentary rocks (Proffett, Livingstone, and Einaudi, in preparation). The sedimentary rocks consist of interstratified volcaniclastic rocks, black calcareous shale, argillite, and limestone of intermediate to shallow marine origin, overlain by evaporites and windblown (?) quartz sandstone (See Fig. 7.3). Middle Jurassic plutonism gave rise to dacite and quartz latite volcanic rocks, which unconformably overlie sandstone, and to porphyry copper and skarn deposits. The presence of intimately interbedded carbonate-argillaceous beds in the Triassic sedimentary section resulted in widespread development of calc-silicate hornfels and reaction skarns during the early metamorphic stages of Jurassic plutonism; metasomatic skarns were superimposed on this early metamorphic event and preferentially replaced pure limestone beds.

ALTERATION AND SKARN FORMATION

The correlation between potassium-silicate alteration in plutons and skarn formation, and between intense hydrolytic alteration in plutons and skarn destruction or silica-pyrite replacement of limestone has been documented at Santa Rita (Nielsen, 1970), Ely (James, 1976), and Bingham (Atkinson and Einaudi, 1978). In order to expand systematically on this theme, the twelve deposits considered in this chapter are discussed in a sequence which trends toward decreasing relative volumes of known potassium-silicate alteration and increasing relative volumes of known hydrolytic (sericitic and advanced argillic) alteration. Table 7.1 lays out this sequence for deposits where data are available; no implication as to relative depth of erosion is implied by the sequence. Two types of potassium-silicate alteration can be recognized in igneous rocks of most deposits. (1) Biotitization of hornblende and augite appears as a pervasive overprint on fresh rocks and is unrelated to distinct veinlets. Sulfide content is low (<1 wt. %) and grades of less than 0.2 percent Cu are typical. Where age/zonal relations are evident, this type predates and/or encompasses the second type. (2) Zones of sec-

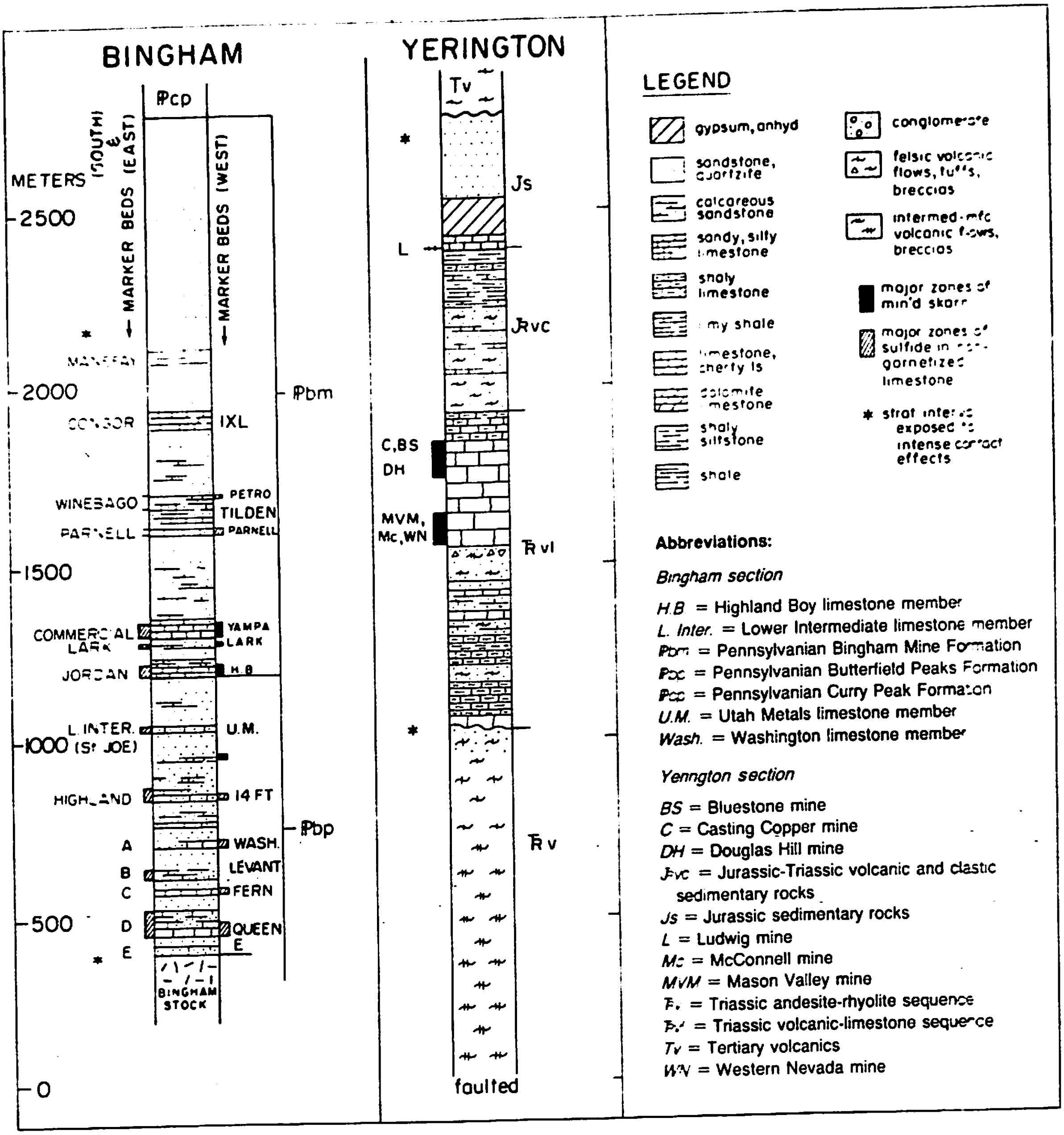


Figure 7.3. Stratigraphic sections at Bingham, Utah (based on Hansen, 1961; and Lanier, John, et al., 1978) and Yerington, Nevada (based on Proffett and Einaudi, unpublished). At Bingham, the skarn copper ores in the Carr Fork mine are localized in the Highland Boy and Yampa limestone members of the Bingham Mine Formation; these are the only major limestone beds in a sequence dominated by non-reactive quartzite. At Yerington, the skarn copper ores are localized at the lower and upper contacts of a thick-bedded limestone unit in a sequence of black shales, silicic tuffs, and siltstones.

ondary biotite and orthoclase are closely related to quartz-sulfide veinlets or microfractures and contain 1 to 4 weight percent sulfides displaying high Cu: Fe ratios and low sulfur (chalcopyrite + bornite, or pyrite:chalcopyrite <1). Grades range from 0.1 to 1.0 percent Cu. Magnesian and calcic skarn appear to be spatially and temporally related to both types of potassium-silicate alteration.

In Table 7.1, the column headed "sericitic" includes only quartz-sericite-pyrite alteration in which both orthoclase and plagioclase are replaced, and which in most cases forms as distinct envelopes on pyritic veins and veinlets. Where these envelopes coalesce, zones of pervasive sericite-quartz-pyrite develop, accompanied by 5 to 10 weight percent sulfides and very high pyrite:chalcopyrite ratios (10–40). This type of sericitic alteration is thought by many workers (e.g., Gustafson and Hunt, 1975) to represent the main influx of meteoric water into the cooling, sulfur-rich stock environment at hydrostatic pressures (<500 bars) and low temperatures (<350°C). Vein-related skarn destruction is the carbonate analogue of sericitic alteration superimposed on potassium silicate alteration. Silica-pyrite replacement of limestone is thought to be the carbonate analogue of pervasive sericite alteration superimposed on rocks not previously altered to potassium silicate assemblages. Minor lead-zinc-silver mineralization may accompany pyrite-quartz or occur as veins in peripheral limestone.

Not included in the sericite alteration type is the common, pervasive "wash" of sericitic-argillic alteration of

TABLE 7.1
Relative Volume of Alteration Types and Associated Mineralization in Ten Porphyry Copper Deposits

Porphyry Copper Deposit	Potassium Silicate Alteration					Sericitic (K-spar–destructive) Alteration				Advanced Argillic Alteration				Limestone	
	Pervasive Secondary Biotite	Biotite-Orthoclase Veinlets	Chalcopyrite: Bornite	Pyrite: Chalcopyrite	Weight % Total Sulfide	Vein-Related Quartz-Sericite-Pyrite	Pervasive Quartz-Sericite-Pyrite	Pyrite: Chalcopyrite	Weight % Total Sulfide	Presence	Silicate Mineral Assemblage	Sulfide Mineral Assemblage (ratios)	Weight % Total Sulfide	Skarn	Silica-Pyrite
Christmas	XXX	X	>1	ND	<0.5	X	?	ND	ND	?				*XXX*	?
Twin Buttes	XX	X	rare bornite	<1	1–2	X	?	>1	1–3	?				*XXX*	?
Mission	XXX	X	rare bornite	ND	ND	XX	?	1.5–3	ND	?				*XXX*	?
Bingham	XXX	*XXX*	1 to >1	<<1	2.5	XX	?	2	3.5	?				*XXX*	?
Silver Bell	XXX	XXX	rare bornite	0.5–2	3–4	XX	X	4–15	5–9	?				*XXX*	X
Santa Rita	?	XXX	ND	3	1–5	XX	XX	40	4–8	?				*XXX*	?
Morenci	?	?	ND	ND	ND	XXX	XXX	7–25 (+sphalerite)	3.5–8	?				XX	?
Ely	XX	*XXX*	rare bornite	~1	1	XXX	XXX	4–10	5–10	X	kaolinite-gibbsite-zunyite	pyrite	ND	*XXX*	XXX
Cananea	present (?)	absent (?)	ND	>>1	<1	XX?	XXX	>>1	ND	XX	alunite-sericite-clay	pyrite-enargite	ND	??	*XXX*
Bisbee	present (?)	absent (?)	ND	ND	ND	X	XXX	>1 (+sphalerite)	ND	XXX	sericite-dickite-pyrophyllite-alunite	pyrite: chalcopyrite >20	15–18	absent (?)	*XXX*

Sources. Santa Rita (Nielson, 1970); Ely (James, 1976); Bingham (Atkinson and Einaudi, 1978).

KEY:
ND = no data
X = present in very minor (relative) volumes of rock
XX = present in moderate (relative) volumes of rock
XXX = constitutes a major portion of the total volume of altered and mineralized rocks
XXX = constitutes a major portion of the total volume and contains a significant tonnage of greater than 0.4 percent copper

? = not reported at present surface or in deeper exposures; no data on which presence or absence can be inferred for any level of the original pattern
absent (?) = some data available which imply absence of alteration type
present (?) = some data imply presence of the alteration type in deep exposures
?? = skarn in Capote Basin at Cananea may not be related to quartz porphyries

Production and Mineralization in Porphyry, Skarn, and Breccia-Vein Deposits, Yerington District, Nevada

Deposit	Type	Years of Production	Production (In Thousands of Tons)	Percent Copper	Mineralization
Yerington	porphyry copper	1953–1978	162,400	0.55	oxide & sulfide: bornite-chalcopyrite-magnetite, chalcopyrite-pyrite
Ann Mason	porphyry copper	none	495,000 (resource)	0.40	sulfide: chalcopyrite, chalcopyrite-pyrite
Bear-Lagomarsino	porphyry copper	none	>500,000 (resource)	0.40	sulfide: chalcopyrite, chalcopyrite-pyrite
MacArthur	porphyry copper	none	13,000 (resource)	0.43	oxide: tenorite, chrysocolla
Bluestone	skarn-breccia pipe; garnet-epidote	1917–1930	~1,500	~1.5–3.5	sulfide: chalcopyrite >> pyrite
Douglas Hill	skarn, garnet	1911–1914?	~70	~5	oxide & sulfide: chalcopyrite >> pyrite
Mason Valley	skarn, garnet-pyroxene	1912–1930	~1,500	~1.5–3.5	sulfide: pyrite > chalcopyrite
McConnell	skarn, garnet-pyroxene	1912–1914, 1945	~20	~3	oxide & sulfide: pyrite > chalcopyrite
Casting Copper	skarn; garnet-pyroxene	1912–?	~450	~3	oxide & sulfide: pyrite > chalcopyrite
Western Nevada	skarn; garnet-pyroxene	1944–1945	~4	~3	oxide & sulfide: pyrite > chalcopyrite (pyrrhotite)
Ludwig	replacement lode, breccia vein; quartz-pyrite	1906–1923	~200	~2–6	oxide: tenorite, malachite; sulfide: pyrite >> chalcopyrite

Source: Data from Knopf (1918); Stoddard and Carpenter (1950); Proxy Statement, The Anaconda Co. (1976); Einaudi, personal notes (1970–71).

plagioclase, sometimes accompanied by chloritization of biotite, in which orthoclase commonly is unaltered. This type of alteration generally is widespread in porphyry deposits and bears little obvious temporal or spatial relation to sulfides or other alteration types. This suggests that it is the result of many processes, including: (1) oxidation of H_2S by the dissociation of magmatic H_2O at the higher P-T conditions of potassium silicate alteration; (2) increase in K^+:H^+ ion activity ratio in fluids permeating the wall rocks beyond quartz-sericite-pyrite alteration envelopes developed during the main sericite stage; and (3) supergene processes.

Advanced argillic alteration as defined by Meyer and Hemley (1967) represents a greater degree of alkali-cation-leaching (thus, lower temperatures and/or lower K^+:H^+ activity ratios in the fluid) than sericitic alteration. The key mineralogical feature is the absence of feldspar, and the replacement of sericite by kaolinite, pyrophylite, or related aluminosilicates. Pyrite is ubiquitous and abundant, and if Cu-Fe sulfides are present, they represent sulfidation states higher than the chalcopyrite + S_2 = pyrite + bornite reaction; thus, pyrite-bornite, pyrite-digenite, or pyrite-covellite assemblages are characteristic, and enargite and low-Fe sphalerite are common associates. Relative to sericitic alteration, advanced argillic alteration is rare in porphyry copper deposits; this rarity may be due to the fact that advanced argillic alteration would be expected to occur at high structural levels which, in most cases, are removed by erosion. Alternatively, fluids in porphyry copper environments may only rarely evolve to the extremes of high sulfidation-oxidation states and low pH required. Of the deposits listed in Table 7.1, only Cananea and Bisbee contain important volumes of advanced argillic alteration. Both deposits contain the majority of ore in mineralized breccias associated with feldspar-destructive alteration. The carbonate analogue of advanced argillic alteration is massive sulfide ores associated with vein, manto, or pipe-like bodies of silica-pyrite breccias in limestone.

The relative volumes of alteration-mineralization types in known portions of individual deposits are relatively unambiguous in the deposits listed near the top of Table 7.1, but these volumes become difficult to evaluate as the degree of hydrolytic alteration increases. For example, the presence or absence of potassium silicate alteration in deeper portions of the Morenci, Cananea, and Bisbee deposits appears to be unknown, in spite of the fact that rocks with stable feldspar and biotite are known to occur at depth in underground mine workings or deep drill holes. Even if such rocks turn out not to show evidence of potassium-silicate alteration, the possibility must be considered that such alteration was present in upper levels, where hydrolytic alteration may have destroyed the evidence.

Yerington is not included in Table 7.1 because carbonate rocks—and hence skarn deposits—are located a considerable distance (3–4 km) from porphyry copper occurrences. The characteristics of Yerington skarns are similar to many "nonporphyry" skarns; thus, they serve to illustrate the link between such skarns and the larger, more complex skarns which are located at immediate contacts with mineralized porphyry copper stocks.

THE YERINGTON DISTRICT

The Yerington district, located in Lyon County, western Nevada, recently has been recognized as a major porphyry copper district with a future resource of greater than 1 billion tons of 0.4 percent Cu. Table 7.2 shows a breakdown of these figures by deposit. The Yerington mine, which closed in June 1978, produced about 162 million tons of 0.55 percent Cu. Skarn deposits represent a very minor portion of the district ore potential with recorded production of approximately 3.7 million tons of 1.5 to 6 percent Cu.

The geology of the Yerington district was first summarized in a comprehensive study by Knopf (1918). Since 1918, published accounts of district geology and mineral deposits have resulted from detailed studies by the geological staff of The Anaconda Company, including: Wilson (1963) on the Yerington porphyry copper deposit; Proffett and Proffett (1976) on the stratigraphy of the Tertiary ash-flow tuffs; Proffett (1977) on Basin and Range structure; and Einaudi (1977*a*) on skarn at the Mason Valley mine. The summary that follows is based on these and unpublished reports.

General Setting

The Yerington district is located 80 km east of the Sierra Nevada batholith in the western Great Basin province within a belt of Jurassic intrusives. One of these intrusives, the Yerington batholith, occupies much of the northern end of the Singatse Range. Strongly folded and faulted Lower Mesozoic volcanic and sedimentary rocks, with a total thickness of about 3,000 m, form an east-west–trending septum 8 km long and up to 3 km wide between the Yerington batholith and the batholith to the south (Fig. 7.4). The lower half of the volcanic-sedimentary section is composed of metamorphosed andesite and rhyolite flows, breccias, and sediments; the upper portion largely consists of massive limestone, thin-bedded black calcareous shale, and silicic volcaniclastic rocks (see Fig. 7.3). Limestone beds constitute the host rock for numerous, small, copper-bearing skarn deposits located on the outer fringe of a hornfels-skarnoid aureole extending 600 to 1,800 m from the Yerington batholith.

The Yerington batholith consists of granodiorite intruded by quartz monzonite and, later, by quartz monzonite porphyry dike swarms. Known porphyry copper mineralization is restricted to the core of the batholith and is associated with the porphyry dike swarms. Basin and Range normal faulting resulted in an average 70° westward tilt of all pre-Miocene rocks; the surface, therefore, approximates a series of fault-bounded cross sections, with their upper portions to the west.

Alteration of Sedimentary Rocks

The distribution of metasomatic and metamorphic rocks and the zoning of mineral assemblages indicate that the Yerington batholith, rather than the southern batholith, was responsible for the alteration. Alteration of sedimentary

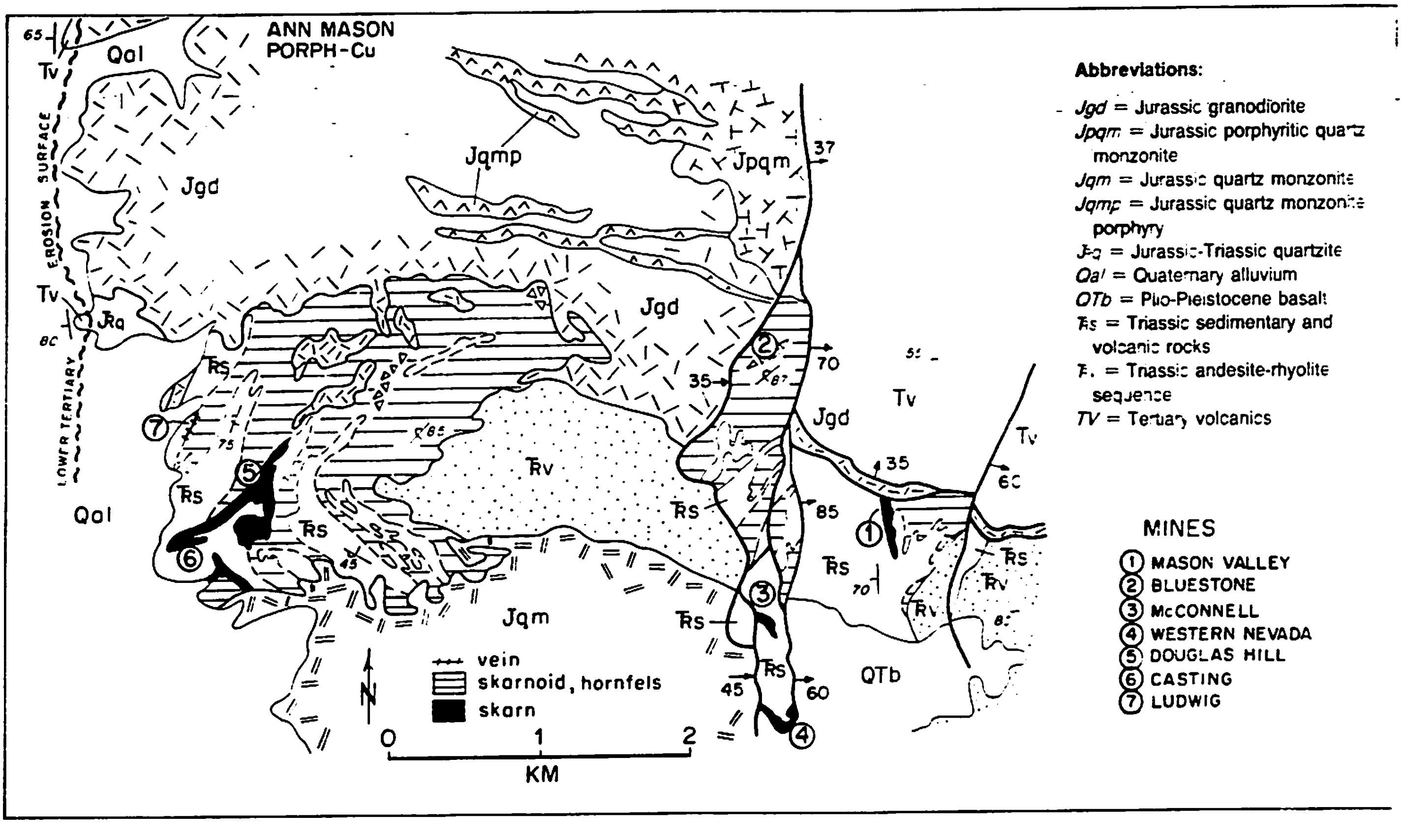


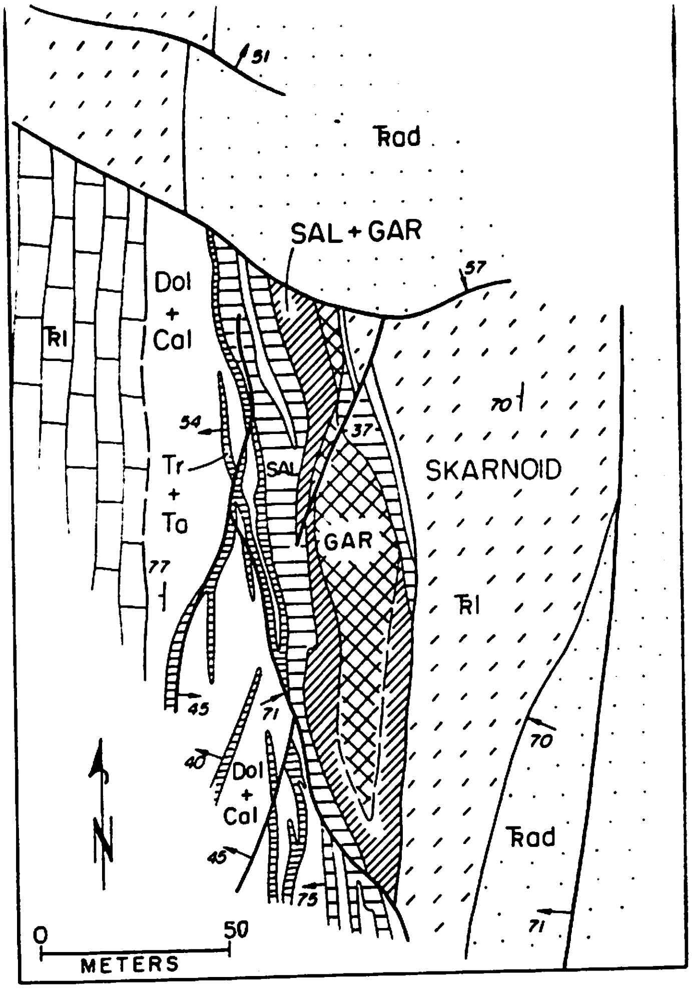
Figure 7.4. Geologic sketch map of the Yerington district, Nevada, showing septum of Triassic volcanic and Triassic-Jurassic volcaniclastic-sedimentary rocks between a southern quartz monzonite batholith and a northern granodiorite batholith. The Ann Mason and Yerington porphyry copper deposits are associated with quartz monzonite porphyry dikes and their porphyritic quartz monzonite roots within the granodiorite batholith. Yerington deposit is located 1 km northeast of the upper right corner of figure. Skarn copper deposits are located on the outer fringe of a skarnoid/garnet hornfels aureole. Based on mapping by J. M. Proffett and M. T. Einaudi.

(1918).

Hornfels-Skarnoid. An early stage produced garnet (Ad_{25-70})*-pyroxene (Hd_{0-15}) hornfels and skarnoid near the batholith contact and recrystallization in hornblende hornfels facies rocks farther out. The district-wide formation of skarnoid probably represents a metamorphic event synchronous with the emplacement of the granodiorite batholith.

Skarn. Brecciation of early hornfels and skarnoid was followed by formation of chalcopyrite-pyrite–bearing skarns. Iron-rich garnets (Ad_{50-75}), locally accompanied by clinozoisite, formed near the batholith, and andradite (Ad_{80-100})-salite (Hd_{30-60}) skarns formed on the fringe of the skarnoid aureole in dolomitized marbles. Six skarn deposits are located in the Triassic septum west of Mason (see Fig. 7.4). Two of these, the Douglas Hill and Bluestone deposits, are located relatively close to the Yerington batholith, within the zone of early garnet-pyroxene skarnoid. Both are characterized by: (1) relatively low total sulfides, generally less than 5 volume percent; (2) relatively low pyrite:chalcopyrite ratios, generally less than 0.1; (3) absence of magnetite or hematite; (4) a gangue dominated by andradite, with minor epidote at the Bluestone mine; and (5) strong brecciation. A lack of zoning of calc-silicate and sulfide minerals is characteristic. Local limestone pods, which survived the earlier skarnoid stage, are replaced by massive andradite with disseminated chalcopyrite. In general, however, andradite was deposited as open-space fillings in veins or breccias, and it cemented skarnoid. The Bluestone mine shows evidence of several episodes of brecciation, with the final event forming a heterolithologic breccia composed of partially epidotized skarnoid, hornfels, and chalcopyrite fragments set in a matrix of finely comminuted garnet cemented by calcite and quartz. A quartz monozonite porphyry dike, intensely epidotized and broken into large blocks where it cuts the breccia zone, yields evidence that the porphyry cycle was broadly synchronous with breccia-skarn formation.

Four former producers (Mason Valley, Western Nevada, Casting Copper, and McConnell mines) are located in a fringe position relative to the andradite-chalcopyrite skarns. All four deposits formed in dolomitized marble in contact with skarnoid, 1 to 2 km from the Yerington batholith contact. These skarns are characterized by: (1) relatively high total sulfides, in the range 10 to 25 volume percent; (2) high pyrite:chalcopyrite ratios, generally greater than 1; (3) presence of trace quantities of magnetite, talc, and tremolite on the marble contact; (4) a gangue dominated by coarse, bladed salite and andradite, with salite near marble and andradite more centrally located; and (5) little or no evidence of large-scale brecciation. Zoning of calc-silicate and sulfide minerals is characteristic of these skarns; the general zonal sequence toward marble, as exemplified by the Mason Valley mine (Einaudi, 1977*a*) is: andradite, andradite-salite-chalcopyrite-pyrite, salite-actinolite-pyrite ± magnetite, chalcopyrite, tremolite-magnetite ± pyrite, talc-calcite ± magnetite, dolomite-calcite (Fig. 7.5). Cross-cutting vein and overgrowth relations indicate that inner zones encroached on outer zones during the process of skarn growth. However, in some localities, the process was not arrested at the end of pro-grade growth; at the Casting Copper mine, local brecciation of skarn was followed by the inward collapse of the above sequence. Actinolite-calcite-quartz ± magnetite, pyrite, chalcopyrite veins and breccia fillings cement rotated andradite blocks up to 1 m in diameter (Fig. 7.6); actinolite is separated from andradite by coarse-grained bladed salite, which grew outward from, and locally veined, the garnetite fragments.



Abbreviations:

Cal = calcite
Dol = dolomite
GAR = garnet
SAL = salitic pyroxene
Ta = Talc
Tr = tremolite
Ŧad = Triassic andesite-dacite tuff breccia
Ŧl = Triassic limestone

Figure 7.5. Plan map of 300-ft. level, Mason Valley mine, Yerington district, Nevada, illustrates zoning of skarn from garnet center to salite-garnet, salite, and tremolite-talc, toward dolomitic marble. Zones developed contemporaneously with garnet overgrowing salite, and salite overgrowing tremolite-talc. Skarnoid and dolomitization may represent an early event. Based on Einaudi (1977*a*).

Silica-Pyrite. In addition to skarn deposits, another type of ore occurrence in sedimentary rocks is illustrated by silica-pyrite rock at the Ludwig lode, located at a faulted contact between limestone and skarnoid north of the Casting Copper mine (see Fig. 7.4 for location). Intense supergene leaching resulted in a quartzose gossan at the surface and rich

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*Mineral compositions are given as the mole percentage of iron endmembers.

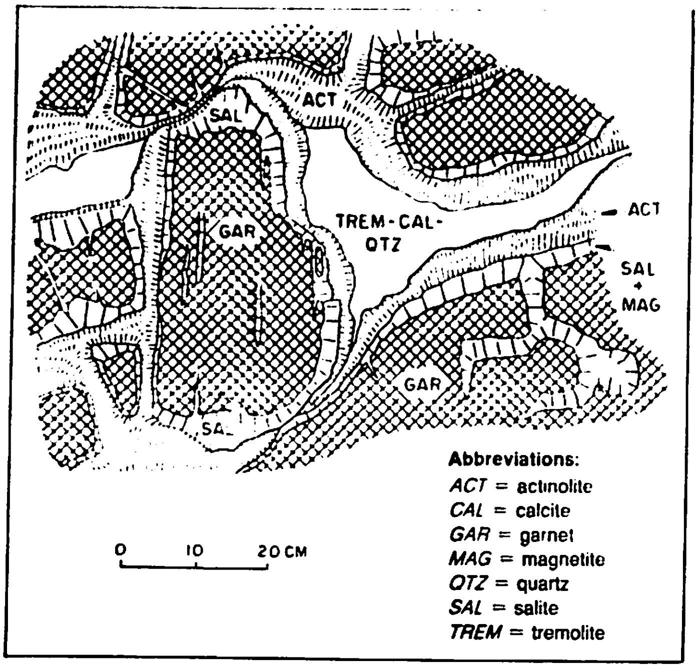


Figure 7.6. Sketch of skarn outcrop near Casting Copper mine, Yerington district, Nevada, illustrates reversal of mineral-age sequence following brecciation of garnet center.

tenorite ores up to 250 m thick below the surface. According to Knopf (1918), the protore at Ludwig below the 700-ft. level consists largely of pyrite and quartz which replaced a fault breccia consisting of marble and porphyry fragments cemented by carbonate. Large pyritic masses also occur in intensely silicified and quartz-veined porphyry dikes. The Ludwig deposit is the only known major sulfide accumulation in carbonate rocks of the Yerington district which is not directly associated with skarn minerals. The presence of brecciated, altered, and mineralized porphyry in the fissure zone, and of unaltered porphyry which cuts the fissure north of the mine area, indicates that the Ludwig mineralization was contemporaneous with the porphyry intrusive event.

Conclusions

An important aspect of the Yerington district, which contrasts with the southern Arizona-New Mexico-Sonora province, is the presence of a thick section of interbedded calcareous shale and felsic volcaniclastic rocks with relatively minor limestone. Intrusion of a batholith of granodiorite–quartz monzonite generated a metamorphic aureole which includes large volumes of garnet-rich skarnoid, a feature generally not present in other districts. Furthermore, the large mass of granodiorite effectively shielded the carbonate rocks from direct contact with the porphyry copper plutons; the ore-bearing skarns are located some 3 to 4 km distant from the outermost edge of significant porphyry copper alteration-mineralization in igneous rocks. The spatial separation of skarn and porphyry deposits resulted in a relatively mild retrograde event in the skarns, because these were not directly subjected to the long-lived hydrothermal activity and repeated fracturing which characterizes porphyry copper centers. Although there can be little doubt that the skarns and the porphyry copper deposits represent one metallogenic event, their extreme spatial separation introduces significant uncertainties in detailed correlation of alteration-mineralization events between igneous and sedimentary rocks.

THE CHRISTMAS MINE

The Christmas mine is located in the Banner mining district, southwestern Gila County, 43 km south of Globe, Arizona. It is a small porphyry-skarn copper deposit, which has produced 4.6 million tons of 2 percent Cu from underground ore in skarn from 1905 to 1966 and 15.8 million tons of open-pit ore averaging 0.6 percent Cu from 1965 to 1976. Ninety-five percent of the latter ore occurred in calc-silicate rocks. The ore zone presently being mined by open-pit methods contains an additional 80 million tons of ore reserves (Koski and Cook, 1982). The geological setting of the Christmas mine has been described by Ross (1925), Willden (1964), and Eastlick (1968); details of alteration-mineralization in igneous and sedimentary rocks have been provided by Koski (1978), Koski and Cook (1982), and D. V. Perry (1968, 1969).

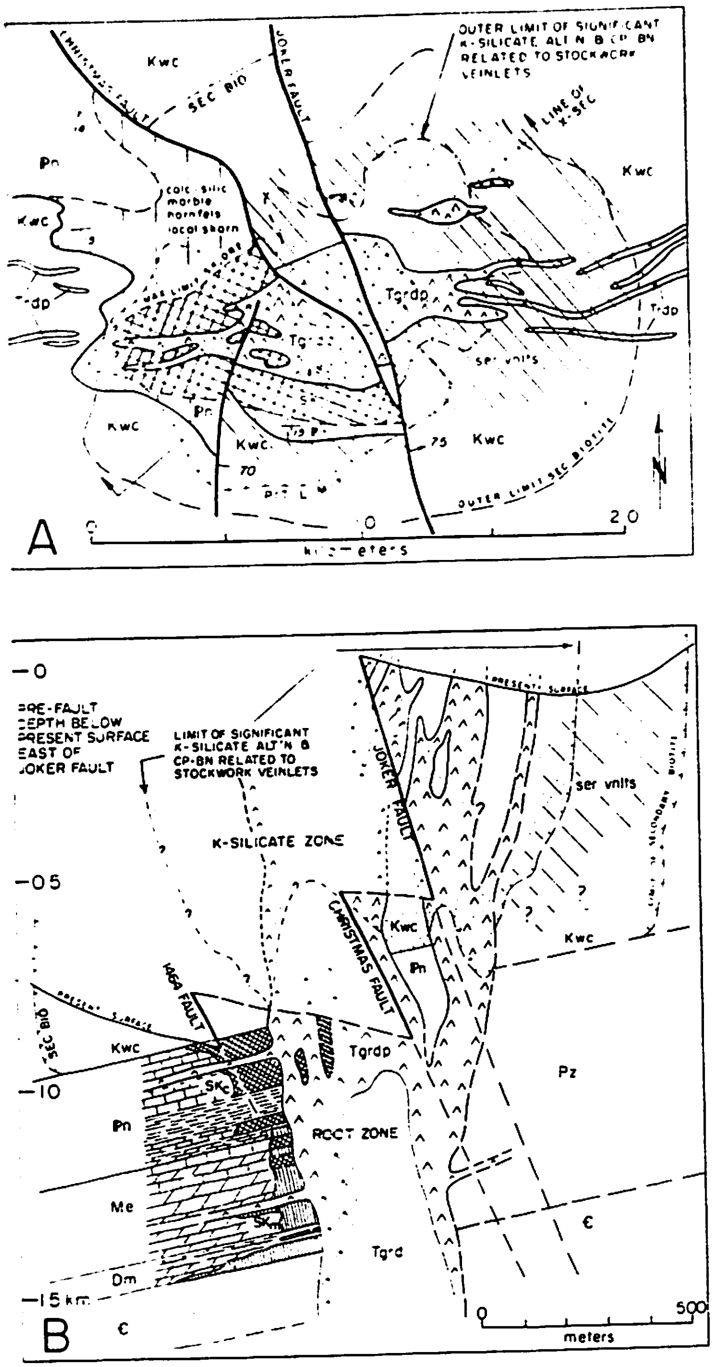
General Setting

Ore-bearing skarns are associated with an elongate plug-dike complex of granodiorite and granodiorite porphyry, measuring 900 X 450 m in horizontal dimension. The stock and an associated dike swarm of rhyodacite porphyry, intruded a 1,000-m-thick sequence of Precambrian, Paleozoic, and Cretaceous sedimentary and volcanic rocks (see Fig. 7.2) along an east-west–trending fault zone. The sedimentary rocks are broadly folded, forming a southeasterly-plunging anticline; in the ore zone west of the Christmas stock, the beds dip 15°S.

A major post-ore normal fault system (Christmas-Joker), striking north-northwest and dipping 75°E, bisects the stock (Fig. 7.7*A*); cumulative normal displacement is estimated to be approximately 1 km (Eastlick, 1968; Koski and Cook, 1982). As a result of this fault displacement, two different levels of exposure in the porphyry system are preserved: on the west, a relatively deep core environment with weakly altered and mineralized porphyry in contact with high-grade skarns in Paleozoic carbonate rocks; and, on the east, a relatively higher-level environment with potassium-silicate alteration and disseminated sulfides in porphyry and Cretaceous andesite (Fig. 7.7*B*).

Porphyry

Alteration-mineralization in the porphyry stock complex is described by Koski and Cook in Chapter 17 of this volume. Early potassium-silicate alteration, characterized by a stockwork of orthoclase-quartz-chalcopyrite-bornite veinlets, and partial to complete biotitization of hornblende, is best developed in the higher-level portion of the stock east of the Christmas-Joker fault. Quartz-sulfide veinlets and secondary biotite extend 100 to 200 m into the basaltic volcanic rocks; recent drilling indicates a large tonnage of 0.2 to 0.6 percent Cu mineralization. Fracture-controlled alteration of quartz-sericite and quartz-sericite-chlorite, accompanied by chalcopyrite and pyrite, is superimposed on the outer portion of the stockwork potassium-silicate zone.



Abbreviations:

ALT'N = alteration
BN = bornite
€ = Cambrian Bolsa Quartzite
CP = chalcopyrite
calc silic = calc-silicate
Dm = Devonian Martin Formation
Kwc = Cretaceous Williamson Creek volcanics
Me = Mississippian Escabrosa Limestone
Pn = Pennsylvanian Naco Group
Pz = Paleozoic sedimentary rocks
SEC BIO = secondary (hydrothermal) biotite
ser vnlts = sericite veinlets
SK$_c$ = calcic skarn
SK$_s$ = skarn, undifferentiated
SK$_m$ = magnesian skarn
Tgrd = Tertiary granodiorite
Tgrdp = Tertiary granodiorite porphyry
Trdp = Tertiary rhyodacite porphyry

Figure 7.7. Christmas mine, Banner mining district, Arizona: *A*, surface geology and alteration; *B*, reconstructed cross section, looking northwest. The cross section illustrates location of mineralized skarn in contact with the deep root zone of the porphyry system and selective replacement of sedimentary strata. Based on Perry (1968), Eastlick (1968), Koski (1978), and Koski and Cook (1982).

According to Perry (1968, 1969) and Koski and Cook (1982), granodiorite porphyry west of the Joker fault also displays potassium-silicate alteration accompanied by sulfides, but the intensity of alteration-mineralization is lower than in the down-dropped block; copper grades range from 0.05 to 0.1 percent. Plagioclase is fresh and hornblende is only partially biotitized. The dominant opaque mineral assemblage is composed of less than 0.5 percent bornite and chalcopyrite, accompanied by 1 percent magnetite. Perry (1968) has described two types of sulfide-bearing veinlets: (1) thin, discontinuous, biotite veinlets that contain accessory quartz, K-feldspar and anhydrite; and (2) thicker, vuggy, quartz-lined veinlets that contain accessory K-feldspar, biotite, and rare molybdenite. Thus, the characteristics of alteration and mineralization in the westernmost fault block of the Christmas stock suggest a fairly deep exposure of a porphyry copper system.

Sedimentary Rocks

Copper-bearing skarn has been mined from the Martin Formation, Escabrosa Limestone, and Horquilla Formation in contact with porphyry west of the Joker fault. The following summary of contact metamorphism and metasomatism is based on descriptions by Perry (1968).

Contact Metamorphism. At distances greater than 1 km from the stock, hornfelses occur in shaly beds only at contacts with diorite-granodiorite sills. Within 750 m of the stock on the north, and 450 m on the west, shale, siltstone, and impure carbonate beds are converted to hornfels; cherty marble contains wollastonite with local garnet and diopside; sandy dolomitic marble is characterized by the assemblage tremolite-calcite; Martin dolomite locally contains brucite after periclase; and calcareous quartzite contains interstitial diopside-quartz with local wollastonite or phlogopite. Although Perry (1968, 1969) believes that these contact effects are largely metamorphic, he suggests that some local metasomatism must have occurred, particularly in the case of the monomineralic diopside hornfels beds which are characteristic of the Beckers Butte member of the lower Martin Formation.

Skarn. In general, skarn occurs in the purer carbonate units of the Paleozoic section (see Fig. 7.7) and extends farthest from the stock in carbonate beds which are interbedded with siltstone or shale. Thus, skarn in the thick-bedded, relatively pure Escabrosa Limestone extends only tens of meters from the stock, whereas skarn in the Martin and Horquilla Formations extends up to 120 to 200 m outward (see Fig. 7.7 *B*). Perry (1968) describes three dominant skarn types: (1) endoskarn in porphyry, (2) calcic skarn in limestone units of the Escabrosa and Horquilla Formations, and (3) magnesian skarn in dolomitic units of the Horquilla and Martin Formations. The major skarn orebodies occur in the upper Horquilla (calcic skarn) and lower Martin (magnesian skarn). The following summary is based on descriptions of these two ore zones; garnet compositions are based on cell-edge determinations. The zonal mineralogy of calcic skarn in the Horquilla Formation is summarized in Table 7.3.

Porphyry in contact with skarn is converted to endoskarn consisting of pale brown grossularitic garnet (Ad$_{10-50}$)

TABLE 7.3
Zonal Mineralogy of Calcic Skarn and Endoskarn at Horquilla-Porphyry Contact, Christmas Mine

Rock Type	Distance From Igneous-Sedimentary Contact	Background Alteration	Veinlets, Veins	Late Alteration	Garnet Color	Volume Percent Magnetite	Volume Percent Sulfides	Major Sulfides	Minor Sulfides
limestone	>120 m	marble	garnet with local pyroxene envelopes	?	pale yellow-green	0	locally high	bornite, sphalerite	chalcopyrite, galena
exoskarn	variable (15–120 m)	garnet, calcite, minor pyroxene	calcite-sulfide	calcite	pale yellow-green	0	~3	bornite > chalcopyrite	sphalerite
exoskarn	erratic (near stock)	garnet	chalcopyrite-epidote-calcite-quartz	calcite	pale yellow-green	?	?	chalcopyrite, pyrite magnetite	sphalerite
exoskarn	< 10 m	garnet, minor pyroxene & epidote	?	calcite	reddish brown	~3–8	5–10	pyrite > chalcopyrite	sphalerite
endoskarn	few cm to 1 m	local pyroxene in mafic sites; garnet (with minor pyroxene, idocrase, wollastonite) in plagioclase sites	calcite, zeolite	?	pale brown	0	"not common"	chalcopyrite > pyrite	?
endoskarn	few m	pyroxene, sphene (minor chlorite & epidote) in mafic sites; minor pyroxene, epidote in plagioclase sites	pyroxene	?	—	0	"not common"	?	?
granodiorite porphyry	>few m	minor biotite in hornblende	quartz-sulfide-biotite-anhydrite	?	—	1	<0.5	bornite-chalcopyrite, chalcopyrite-pyrite	molybdenite

Source: Data from Perry (1968).

and pale green clinopyroxene over widths of a few centimeters to several meters. Accessory minerals include wollastonite-idocrase or phlogopite-chlorite. Vugs and veinlets are filled with chalcopyrite, stilbite, and calcite; at greater depths, anhydrite-chalcopyrite veinlets with epidote alteration envelopes occur in endoskarn related to the Martin magnesian skarn.

Calcic exoskarn occurring as xenoliths in the stock, or within 10 m of the stock contact, consists of reddish-brown andradite (Ad_{92}) and minor diopside and epidote, with abundant magnetite and pyrite, lesser chalcopyrite, and magnetite pseudomorphous after specular hematite. Locally high chalcopyrite concentrations occur in irregular orbicular structures with calcite and garnet; these structures are cut by chalcopyrite-epidote-calcite-quartz veinlets and quartz-rich pods with disseminated sulfides. Copper grades are generally low in this zone and increase with distance from the stock (Petersen and Swanson, 1956; Eastlick, 1968). In the ore zones, granular, yellow-green garnetite (Ad_{72-91}), with local diopside, contains chert nodules; precursor wollastonite is suggested by local calcite-quartz textures. Bornite and lesser chalcopyrite occur interstitial to garnet, apparently as replacements of calcite, and in infrequent quartz veinlets. The outer skarn contact is marked by a zone of garnet veins (some with diopside-sulfide envelopes) cutting marble. Erratic concentrations of sphalerite-chalcopyrite, with traces of galena, are found along garnet-marble contacts and in veins.

Magnesian skarn is characterized by forsterite and abundant magnetite (5–25%) accompanied by brucite, anhydrite, and sulfides. Tremolite-talc masses and nodules of brown and green garnet (Ad_{85}, one sample)-diopside-anhydrite-sulfides occur locally. Perry (1968) describes orbicular growths and veinlet relations which indicate that forsterite, magnetite, anhydrite, and sulfides were broadly synchronous. Late serpentine replaces most of the forsterite.

Although the calc-silicates in magnesian skarn display no obvious zonal pattern, the sulfides are well zoned. The assemblage chalcopyrite-bornite (with local chalcocite) gives way laterally, toward the marble contact, to chalcopyrite-pyrite-pyrrhotite. Sphalerite abundance increases outward and toward the hanging wall and footwall of the skarn bed.

The hanging-wall contact of magnesian skarn with dolomitic marble reveals the fracture control of metasomatic fluid movement and of skarn growth; magnetite-calcite veinlets (with anhydrite, chalcopyrite, and sphalerite) are encased in zone envelopes consisting of (1) forsterite or forsterite-magnetite near the veinlet filling and (2) coarse calcite near the dolomitic marble wall.

Mineralization in Hornfels. Hornfelses locally are extensively veined and mineralized; they contain copper grades in the neighborhood of 1 percent, especially where they occur in contact with mineralized skarn. The Beckers Butte member of the Martin Formation, converted to light gray granular diopside hornfels in the early stages, is cut by veinlets of anhydrite-pyrite-chalcopyrite (± magnetite) that are 1 mm wide, with 0.5-mm-wide, dark green actinolite alteration envelopes. Other hornfelses higher in the Martin Formation contain similar veinlets, with epidote in addition to actinolite, or with biotite in inner zones near the sulfide veinlet-filling and with actinolite as an outer alteration product. Molybdenite, a rare mineral in skarn, occurs in quartz-rich hornfelses, containing interstitial actinolite and/or biotite.

Conclusions

The essentially synchronous development of skarn and magnetite-sulfide mineralization, in contrast with the multistage model of Eastlick (1968), is supported by observations reported by Perry (1968) and also by analogy with other porphyry skarn deposits. Some sulfide mineralization continued after main skarn formation, as evidenced by anhydrite-sulfide veinlets in calcic skarn, but Perry concludes that the quasi-pervasive serpentinization of magnesian skarn and the local replacement of calcic skarn minerals by calcite postdate most of the sulfide deposition.

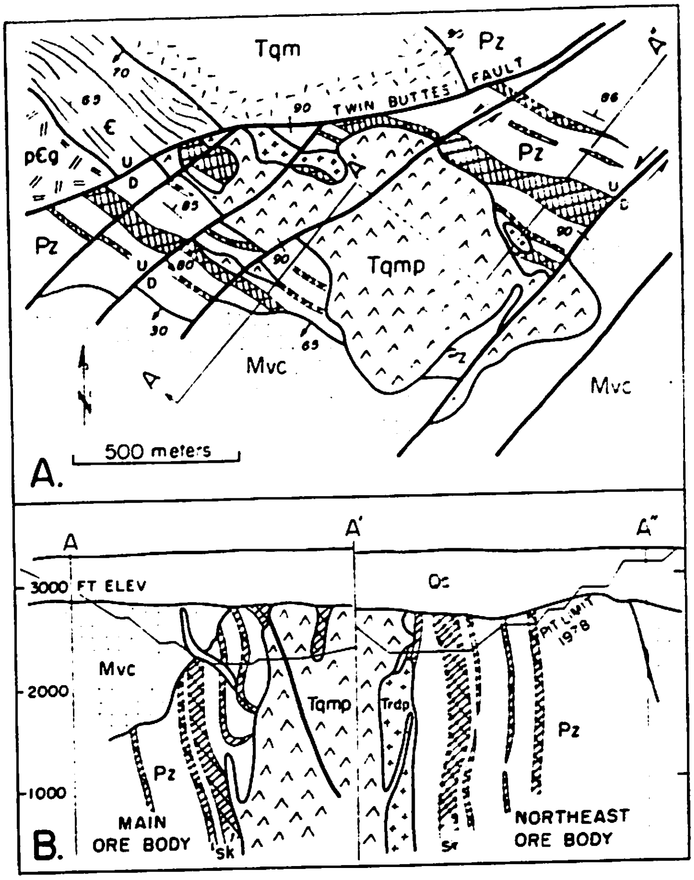
The contemporaneity of the formation of both magnesian and calcic skarn with potassium-silicate alteration in the stock is suggested, but not proved, by the data. Sulfide-actinolite veining of hornfels is probably also synchronous with skarn formation and does not appear to represent a major retrograde event, such as might occur during hydrolytic alteration of the associated stock. This probability is supported not only by the fact that sericitic alteration is weak or absent at the relatively deep structural levels of the western fault block, but also by veinlet relations at contacts between hornfelses and biotite granodiorite porphyry dikes; here, veinlets with biotite alteration halos in porphyry cut into hornfels, where they display actinolite alteration halos (Einaudi, 1978, personal notes).

THE TWIN BUTTES MINE

The main and northeast ore zones at Twin Buttes are located in metasedimentary rocks of Permian age separated by a low-grade, northwest-trending quartz monzonite stock of Eocene age (Fig. 7.8). Ore reserves at the end of 1970 were approximately 475 million tons of 0.78 percent Cu; 20 percent of this reserve was oxide ore averaging 1.0 percent Cu and 80 percent was sulfide ore averaging 0.73 percent Cu and 0.03 percent Mo (Proxy Statement, The Anaconda Company, 1976). The following summary is based on Barter and Kelly (1982) and discussions with R. C. Baker and C. F. Barter, formerly of The Anaconda Company.

General Setting

The mineralized sedimentary rocks south of the Twin Buttes fault consist of a 400-m-thick section of Pennsylvanian and Permian strata correlated with the Earp, Colina, Epitaph, and Scherrer Formations; bedding is vertical and strikes N60°W. Arkosic siltstone, conglomerate, and interbedded rhyolitic flows and tuffs of Mesozoic age are exposed in the southern wall of the West Pit, where they unconformably overlie Paleozoic strata (see Fig. 7.8). A complex series of Eocene porphyries intrude the Paleozoic and Mesozoic strata. Mineralization and alteration of the sedimentary rocks is spatially related to these intrusions and to west-northwest–trending faults which also guided the emplacement of the intrusions.



€ = Cambrian Abrigo Formation
Mvc = Mesozoic volcaniclastic rocks
p€g = Precambrian granite
Pz = Paleozoic sedimentary rocks
Qal = Quaternary alluvium
sk = skarn
Trdp = Tertiary rhyodacite porphyry
Tqm = Tertiary quartz monzonite
Tqmp = Tertiary quartz monzonite porphyries

Figure 7.8. Twin Buttes mine, Pima mining district, Arizona: *A*, schematic geology at 2,100-ft. elevation; *B*, schematic cross section, looking northwest. Cross section illustrates steep bedding control of mineralized skarn. Based on Barter and Kelly (1982).

Porphyry

Rhyodacite porphyry occurs as a dike-like body, 75 m wide, emplaced parallel to bedding. The rhyodacite porphyry is pervasively biotitized, displays pyrite:chalcopyrite ratios of less than 1, and contains 0.1 to 0.5 percent Cu; it is thought to represent the first of the Laramide porphyries and was emplaced either prior to, or during, the main period of mineralization.

A complex of quartz monzonite porphyries comprise the main mass of Laramide intrusive rocks; the porphyries form an irregular, steep-walled, northwest-trending stock up to 600 m wide, terminated at its southeast end by a steep northwest-striking fault zone. Potassium-silicate alteration of the porphyries locally is developed along quartz veinlets; sericitic alteration of feldspars and chloritic alteration of mafic minerals are also present. Pyrite, chalcopyrite, and molybdenite are the principal sulfides; pyrite:chalcopyrite ratios generally are greater than 1, and primary copper grades range from 0.01 to 0.25 percent.

Sedimentary Rocks

The bulk of the hypogene ore and zones of high sulfide content in the Twin Buttes pit occur in altered carbonate beds within the Colina Limestone and Epitaph Formation; lesser amounts of ore, generally of lower grade, occur in altered carbonate and siltstone beds of other Permian formations (see Fig. 7.2), in Mesozoic arkosic rocks, and in Eocene porphyries.

Hornfels. Hornfelses are present throughout the Permian section and are extremely variable in mineralogy. Some, representing original silty limestone or silty dolomitic limestone, consist of fine-grained, granular diopside-quartz hornfels with local patches of fine-grained garnet. In the higher sulfide zones near the center of the mine, diopside hornfelses contain 1.5 to 5 volume percent sulfides in abundant pyrite-chalcopyrite-quartz-epidote veinlets with dark green actinolite alteration envelopes. Flinty, aphanitic hornfelses containing recrystallized quartz, and variable amounts of diopside, tremolite, biotite, and feldspar are particularly common in the Earp and Abrigo Formations.

Quartzite and siltstone beds, with a variable but minor content of interstitial tremolite, biotite, sericite, and feldspar occur in the Earp, lowermost and uppermost Epitaph, and Scherrer formations. Sulfide-bearing fractures have sericitic envelopes in biotitic siltstones and biotite envelopes in tremolitic siltstones.

Calcic Skarn. Calcic skarn formed through metasomatic replacement of limestone beds in the lower Earp Formation, Colina Limestone, upper Epitaph Formation, and Concha Limestone. Near the stock and along contacts with interbedded siltstone, these limestone beds yielded granular to massive, dark reddish-brown garnet and clinopyroxene skarn with interstitial quartz, calcite, chalcopyrite, pyrite, and local magnetite. Dark brown garnet replaces both diopside and paler garnet, and forms overgrowths on pale garnet. Preliminary wet chemical analyses (Harold Vincent, 1973, personal communication) indicate that: (1) garnets are nearly pure endmember andradite, with 0.5 to 1.4 weight percent Al_2O_3, and (2) clinopyroxenes are nearly pure endmember diopside, with 1.9 to 2.1 weight percent total Fe as Fe_2O_3. The garnetite is cut by abundant quartz-sulfide and quartz-epidote-sulfide veinlets and patches, especially within 30 m of the stock. Sulfides in the quartz veins are pyrite, chalcopyrite, and molybdenite. The most persistent zones of +1.5 percent Cu occur in the Colina skarn; these contain 4 to 6 volume percent sulfides, with local zones containing up to 15 to 20 volume percent.

Garnetite pervasively replaces limestone beds in the center of the mine, but some limestone remnants are present farther from the stock. In these cases brown garnetite with chalcopyrite and pyrite replace limestone or an intervening wollastonite-bearing marble. In addition to wollastonite with local bornite-chalcocite, marble at the skarn contact contains: (1) pale brown and green garnet and idocrase in wollastonite with disseminated chalcopyrite, bornite, sphalerite, and local anhydrite; and (2) patches of massive sphalerite-chalcopyrite-pyrrhotite-magnetite in marble.

Magnesian Skarn. Magnesian skarn formed in dolomitic beds of the Colina Limestone, middle Epitaph Formation, and middle Scherrer Formation. It is characterized by the association of serpentine and tremolite, with high magnetite and high chalcopyrite contents. Forsterite, or serpentine after forsterite, are common in magnetite-rich zones, and coarse green mica is present in some areas. Farther from the central zone, unsilicated dolomitic beds contain magnetite-pyrite veinlets with serpentine envelopes.

Discussion

Barter and Kelly (1982) have implied that much of the anhydrous skarn and hornfels formation pre-dated the emplacement of the central porphyry complex. This early skarn-forming event may have been synchronous with the emplacement of the biotitized rhyodacite porphyry, and probably was accompanied by some copper mineralization. Local zoning in calcic skarn was developed primarily relative to sedimentary contacts or to northwest-striking bedding faults. Most of the molybdenite mineralization and, presumably, additional copper and pyritic hydrous alteration of skarn and hornfelses accompanied the later porphyries.

The overall zoning of sulfides in any given rock-alteration type appears to reflect distance from this late porphyry complex. Table 7.4, compiled on the basis of Figure 20.6 of Barter and Kelly (1982), presents the average copper and molybdenum grades, total sulfide content, and pyrite:chalcopyrite ratios of the four dominant rock-alteration types. Although calcic and magnesian skarn maintains a high level of total sulfides and copper grades irrespective of distance from the stock, a trend toward decreasing pyrite:chalcopyrite ratios with distance is clearly illustrated by all four rock types. Presumably, this reflects the late stage overprinting of pyrite near the stock.

THE MISSION AREA

It has been suggested that the Mission area represents a faulted upper portion of the Twin Buttes area, having moved relatively northward 10 km on a flat decollement structure—the San Xavier fault (Lacy, 1959; Cooper, 1960, 1971; Shafiqullah and Langlois, 1978). The stratigraphic section and the association of mineralized skarn, hornfelses, and arkoses with a relatively weakly mineralized quartz monzonite porphyry stock at Pima-Mission is virtually the same as just described for Twin Buttes.

General Setting

The structural setting at Pima-Mission is complex. As described by Gale (1965), the quartz monzonite was emplaced in the core of an east-plunging, asymmetrical, faulted antiform whose core consists of Paleozoic sedimentary rocks (Fig. 7.9). The flanks of the antiform consist of Mesozoic argillite and arkose resting unconformably or in fault contact with the underlying carbonate rocks. The fold is cut by steep, south-dipping faults which strike parallel to the fold axis and which pre-date mineralization. These structures are cut by

TABLE 7.4
Grade and Sulfide Content of Sedimentary Rocks at Twin Buttes
(In Weighted Means)

Alteration Type	Distance from Stock (m)	Length of Sample (m)	Weight % Cu	Weight % Mo	Cu:Mo	Volume % Chalcopyrite and Pyrite	Chalcopyrite: Pyrite
Magnesian Skarn[a]	< 200	41	1.55	0.050	31	5.5	0.6
	≥ 200	105	1.04	0.019	55	3.4	0.4
Weighted Average			1.18	0.028	42	4.0	0.5
Calcic Skarn[b]	< 200	212	1.30	0.053	25	6.8	1.1
	≥ 200	64	1.20	0.035	34	4.1	0.5
Weighted Average			1.28	0.049	27	6.2	1.0
Hornfels[c]	< 200	109	0.43	0.034	13	2.4	1.7
	≥ 200	47	0.70	0.023	30	2.4	0.8
Weighted Average			0.51	0.031	15	2.4	1.4
Quartzite[d]	< 200	299	0.17	0.032	5.3	1.0	2.1
	≥ 200	154	0.10	0.015	6.7	0.4	1.2
Weighted Average			0.15	0.026	5.8	0.8	1.8
Overall Average			0.65	0.033	18	2.9	1.3

Source Data from Barter and Kelly (1982), Figure 20.6.

[a] Serpentine-tremolite-magnetite, minor diopside or forsterite.

[b] Garnet-diopside, minor quartz, actinolite, magnetite (wollastonite-bearing calcic skarn not included). Contains approximately 0.37 oz. Ag/ton.

[c] Diopside-quartz hornfels, with actinolite alteration, minor garnet; or, siliceous aphanitic hornfels.

[d] Siltstone and quartzite, with sericite-biotite or biotite-actinolite.

steeply dipping, north-northeast–striking faults which postdate the skarn-forming event (Fig. 7.10).

The stratigraphic identity of Paleozoic rocks at Mission is obscured by extensive faulting and alteration. Sedimentary rocks which underlie Mesozoic arkose consist of an upper section of quartzite, with interbedded diopside hornfels, and a lower section of skarn-bearing marble (see Fig. 7.10). Richard and Courtright (1959) and Gale (1965) have suggested a correlation of the quartzite with the Scherrer Formation and a tentative correlation of the marble with the Colina Limestone. However, further investigation has suggested that the section is overturned and that the skarn unit is developed in Concha Limestone (Einaudi, 1974; L. R. Jansen, 1976, quoted in Langlois, 1978). The limestone unit is separated from underlying volcaniclastic rocks and Precambrian granite by flat faults which belong to the San Xavier fault system (Richard and Courtright, 1959).

Large copper-bearing skarn bodies and disseminated lower-grade ore zones in hornfels, arkose, and porphyry are located within a 3-km-wide, northwest-trending zone of pyritic mineralization (see Fig. 7.9), which encompasses the porphyry stock, Pima and Mission pits, and Palo Verde Mine (Kinnison, 1966). At Mission mineralized skarn extends eastward 800 m from sill-like bodies of quartz monzonite porphyry largely emplaced along unconformable contacts between Paleozoic and Mesozoic rocks (Gale, 1965). North of the antiform axis the skarn beds dip 20 to 40° north under Mesozoic cover and are continuous with skarn exposed underground in the Palo Verde mine (MacKenzie, 1963; Einaudi, 1974). The Pima mine, which produced 146 million tons of copper ore between 1955 and 1978 (Langlois, 1978), is located in the southern limb of the fold. According to Journeay (1959) and Langlois (1978), southeast-dipping Mesozoic and Paleozoic rocks at Pima are in fault contact with underlying Tertiary granite. Ore-bearing skarn and hornfels in carbonate rocks, mineralized by fluids related to the emplacement of quartz monzonite porphyry (Himes, 1973; Langlois, 1978), extend over 500 m along strike, with an average thickness of 60 m. Although the average grade of skarn-hornfels is 0.81 percent Cu, 75 percent of the production in the late 1970s came from mineralized Mesozoic arkose which averaged 0.38 percent Cu (Langlois, 1978); the average grade of ore mined at Pima at that time was 0.47 percent Cu and 0.015 percent Mo (Parkinson, 1976).

Lesser ore occurrences located a few kilometers west and southwest of the Pima mine could be considered related to the same intrusion-mineralization episode. The Mineral Hill and Daisy Mines (see Fig. 7.9 for locations) described by MacKenzie (1959), occur along pre-ore, east-striking faults. These orebodies are small-scale duplications of the Pima-Mission-Palo Verde skarn ore zone: copper ore occurs dominantly in garnetite close to igneous contacts, molybdenite (and minor scheelite) is restricted to the porphyry or its immediate wall rocks, and sphalerite and galena occur at the marble contact. In contrast with the Pima-Mission orebodies, however, some ore at the Mineral Hill and Daisy mines occurs in manto replacement bodies. Although no details of the manto ores are published, massive replacement of limestone by sulfides, carbonates, and quartz can generally be taken to represent lower temperatures and/or higher sulfidation states (such as would dominate in areas peripheral to a major heat source).

A trend toward larger amounts of lead and zinc relative to copper is seen further south at the San Xavier mine (see Fig. 7.9 for location) which produced lead-zinc-silver ore with lesser amounts of copper (Irvin, 1959). Here,

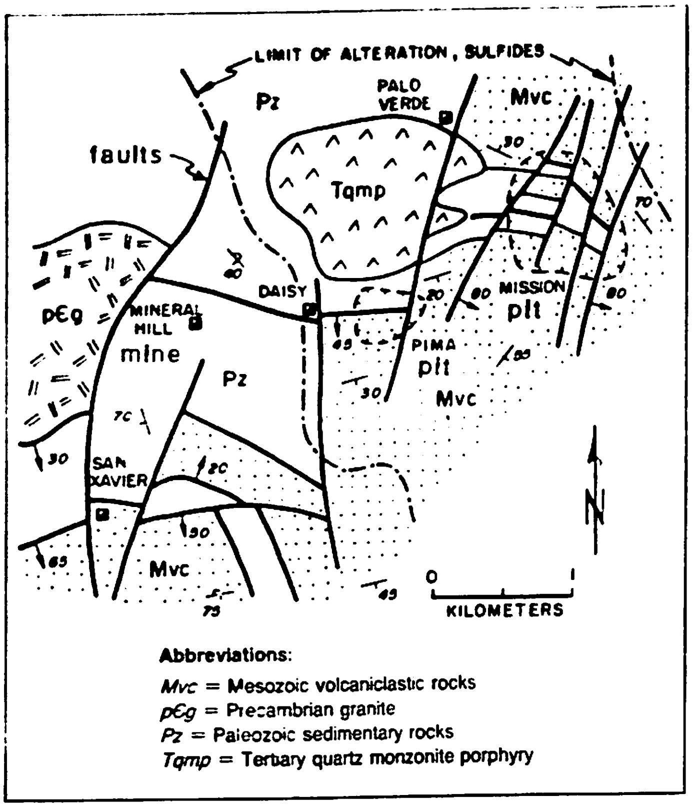


Figure 7.9. Location of Palo Verde shaft, Mission and Pima pits, and Daisy, Mineral Hill, and San Xavier mines relative to central porphyry complex of the Pima-Mission area, Pima mining district, Arizona. Generalized surface geology redrawn from Gale (1965). Limit of alteration and sulfides based on Kinnison (1966).

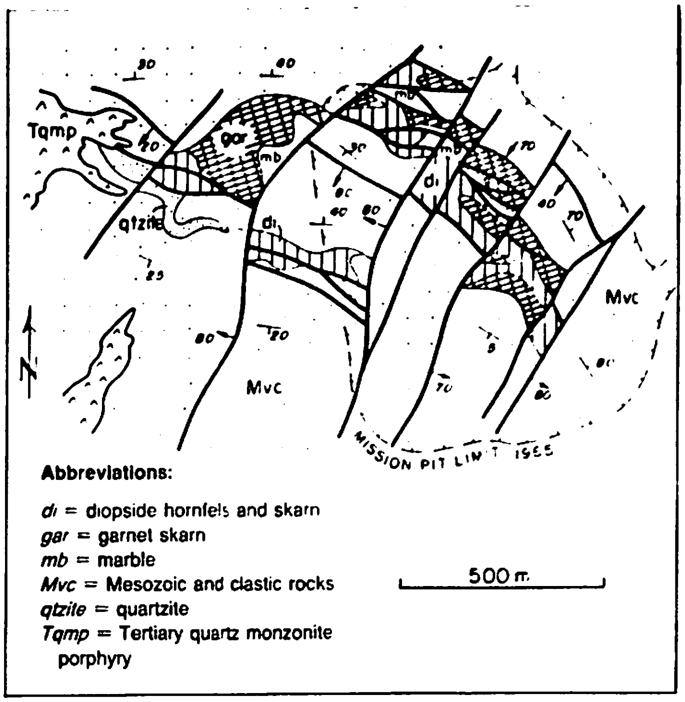


Figure 7.10. Distribution of garnet skarn, diopside hornfels, and marble in core of faulted antiform at Mission mine, Pima mining district, Arizona. Skarn extends down-dip under Mesozoic volcaniclastic rocks. Generalized surface geology redrawn from Gale (1965).

structurally controlled ore pipes and flat ore shoots consist of galena, sphalerite, and chalcopyrite with specularite, magnetite, pyrite, calcite and quartz. The ores are associated with some calc-silicate minerals, dominantly clinopyroxene.

Porphyry

The general setting of the Mission and related Palo Verde orebodies suggests that these are genetically related to the quartz monzonite porphyry stock exposed to the west. Detailed studies of calc-silicate and sulfide mineral zoning clearly support this contention (Gale, 1965; MacKenzie, 1963; Einaudi, 1974).

The quartz-monzonite at Mission is described by Gale (1965) as typical of porphyry copper plutons in general. Phenocrysts of 10 percent orthoclase, 30 percent plagioclase, and 5 percent biotite are set in a sub-graphic, fine-grained, K-feldspar-quartz groundmass. Potassium-silicate alteration generally is weakly developed, with ragged wisps of secondary biotite and replacement veinlets of quartz and K-feldspar. Gale (1965) has indicated that weak sericitic alteration is the most widespread alteration type: quartz-muscovite-pyrite-chalcopyrite veinlets locally are accompanied by pervasive replacement of plagioclase (but not of K-feldspar) by sericite; biotite remains fresh or is partly replaced by muscovite-chlorite-apatite-rutile and pyrite. Although primary copper grades and sulfide ratios have not been summarized by Gale, nor by Kinnison (1966), various lines of evidence indicate that overall the porphyry exposed at the Mission mine contains 0.15 to 0.3 percent Cu, rarely exceeds 0.4 percent Cu, and displays pyrite:chalcopyrite ratios of 3:2 to 3:1 (Gale, 1965, Table 12, p. 118; Kinnison, 1966, Figs. 5 and 6, p. 285). At Palo Verde (Einaudi, 1974) the copper grade in porphyry increases from 0.2 percent on the west to 0.4 percent on the east (Fig. 7.11). The average grade in porphyry at the Pima mine is 0.15 percent Cu (Langlois, 1978). Thus, rock type, alteration, copper grade, and sulfide ratios in the Pima-Mission area are strikingly similar to those exhibited by the porphyry stock complex at Twin Buttes.

Sedimentary Rocks at the Mission Pit

The major tonnage of ore-grade copper mineralization occurs in garnet and diopside skarn, with highest grades in skarn near marble contact and in west-northwest–striking fissures which contain massive sulfides. A lesser amount of open-pit ore occurs in Mesozoic argillite-arkose (Gale, 1965). Metal grades in three drill holes in the Mission pit are summarized in Table 7.5.

Alteration-mineralization in sedimentary rocks in the Mission pit has been studied by Gale (1965), who has suggested that early thermal metamorphism formed diopside in dolomitic siltstone and wollastonite in siliceous limestone. Later metasomatic alteration superimposed ore-bearing skarns. Gale has described three major types of skarn and their locations: (1) fine-grained, granular, diopside skarn (hornfels) largely occurs in a 10- to 30-m-thick bed within the Scherrer quartzite and in underlying carbonate beds at the contact with quartzite; (2) garnet (calcic) skarn, with variable garnet:pyroxene ratios and an outer wollastonite zone against marble, is zoned relative to quartzite-carbonate contacts or fissure zones; (3) epidote skarn (endoskarn), in Mesozoic argillite and arkose at contacts with calcic skarn, consists of epidote, K-feldspar, quartz, and tremolite, with lesser garnet and clinopyroxene.

According to Gale (1965) the major sulfide mineral associations and zonal distribution include: (1) pyrite-chalcopyrite-molybdenite in and near porphyry; (2) chalcopyrite-bornite dominant in skarn at the west end of the pit near porphyry; (3) chalcopyrite-pyrite as the dominant skarn sulfide assemblage, especially at the east end of the pit some distance from porphyry; (4) sphalerite most abundant at skarn-marble contacts; and (5) bornite-pyrite-sphalerite-galena-tetrahedrite in late quartz-calcite veins at the eastern periphery of the pit. On the basis of sulfide mineral zoning, Gale has concluded that there was a direct genetic link between the porphyries and mineralization.

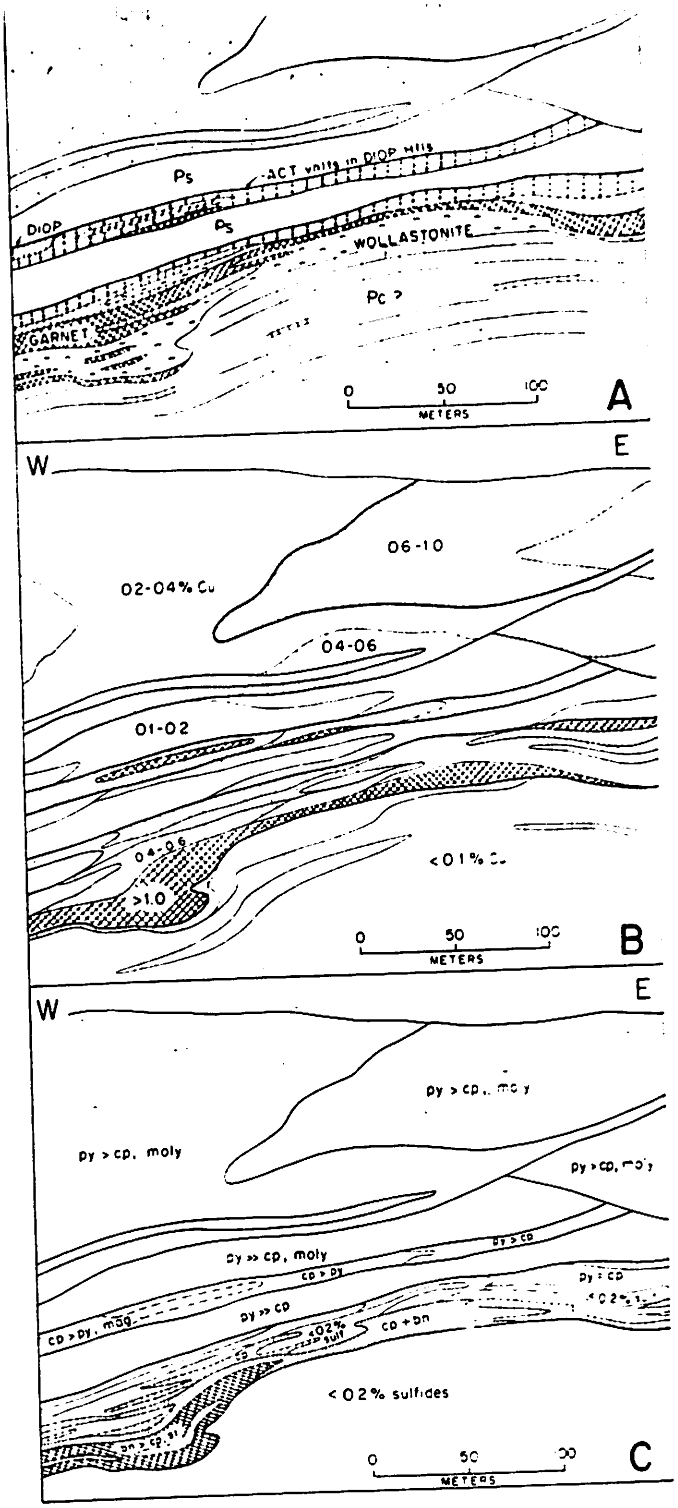
Sedimentary Rocks at the Palo Verde Mine

The Palo Verde mine is a portion of the extensive Pima-Mission alteration zone, and, as in the Mission orebody, the majority of > 0.4 percent Cu mineralization is in Paleozoic and Mesozoic sedimentary rocks located east of and beneath a northwest-dipping, low-grade porphyry sill. High-grade zones are restricted to skarn in Paleozoic limestone on the contact with either Paleozoic quartzite or Mesozoic arkose. The skarn is separated from low-grade porphyry on the west by 30 to 60 m of quartzite and hornfels. The geology of the Palo Verde mine briefly has been described by MacKenzie (1963); the following is summarized from a more detailed study by Einaudi (1974). Rock type and alteration, copper grades, and sulfide assemblages are illustrated in Figure 7.11, an east-west cross section located north of the Mission pit, and summarized in Table 7.6.

Sedimentary rocks at Palo Verde are tentatively correlated with Scherrer Formation and Concha Limestone.

Quartzite-Hornfels. The bulk of the lower Scherrer Formation consists of glassy, white quartzite with very few impurities. The upper Scherrer Formation has a pale buff cast and contains 5 to 20 percent interstitial biotite, feldspar-mica, diopside-montmorillonite, or dolomite. Sulfide mineralization, with pyrite:chalcopyrite ratios ranging from 50:1 to 10:1, generally is fracture-controlled. Copper grades increase systematically from 0.1 percent on the west to 0.25 percent on the east.

The dominant rock type in the mid-Scherrer carbonate beds is diopside-quartz hornfels. Flinty to sandy, white to pinkish-white hornfels occurs at most contacts between quartzite and diopside hornfels. The white hornfelses consist largely of dolomite, with 5 to 20 percent recrystallized quartz; calcite is generally present in minor to trace amounts. Coarse green mica and white termolite may be present, especially near the contact with diopside hornfels. Very fine grained pyrite, chalcopyrite, and sphalerite are disseminated and in veinlets without visible alteration envelopes. Medium-grained, sugary-textured pale green diopside rock contains sparse, disseminated magnetite and pyrite. Chalcopyrite-pyrite (± quartz, magnetite) veinlets display dark green alteration envelopes which consist of actinolite-quartz with minor calcite. The intensity of veining is uniform from west to east and copper grades range from 0.4 to 0.6 percent.



Abbreviations:

ACT vnlts = actinolite veinlets
bn = bornite
cp =chalcopyrite
DIOP Hfls = diopside hornfels
mag = magnetite
moly = molybdenite
Mvc = Mesozoic volcaniclastic rocks
Pc = Permian Concha Limestone
Ps = Permian Scherrer Formation
py = pyrite
Qal = Quaternary alluvium
sl = sphalerite
sulf = sulfides
Tqmp = Tertiary quartz monzonite porphyry

Figure 7.11. East-west cross section (looking north) of the Palo Verde mine in the Mission area of the Pima mining district, illustrating *A*, rock types and alteration; *B*, copper grades; and *C*, sulfide associations. Approximate pre-fault configuration is shown. Mid-Scherrer carbonate beds contain local serpentized magnesian skarn with magnetite. Concha Limestone contains calcic skarn. Based on diamond drill hole data (Einaudi, 1974).

TABLE 7.5
Grade of Skarn Ore in the Mission Pit

Drill Hole Number	Length of Sample (m)	Weight Percent			Oz./Ton	Cu:Mo	Cu:Pb
		Cu	Mo	Pb	Ag		
51	19	0.85	.013	.041	0.29	65	21
106	45	0.60	.008	.035	0.29	75	17
130	39	0.74	.009	.002	0.24	82	370

Source Data from Gale (1965).

NOTE Skarn type not specified.

Magnesian Skarn. The core of the mid-Scherrer diopside hornfels locally contains magnesian skarn characterized by patches and specks of brown serpentine rimmed with magnetite and set in a pale green, coarse tremolite-calcite matrix. Talc is a trace constituent in some areas. Chalcopyrite, with only minor pyrite, is disseminated throughout. No forsterite was noted in thin section, but the textures, and comparison with Twin Buttes samples, suggest that serpentine replaced original forsterite grains. Copper grades are generally greater than 1 percent.

Calcic Skarn. Immediately below the Scherrer quartzite in the western portion of Palo Verde, and below arkoses in the eastern portion, is a thick carbonate unit (Concha Limestone?) which consists largely of dark colored, locally cherty limestone. This unit is converted to garnet-diopside-wollastonite skarn along the contact with arkose and quartzite. The skarn zone varies in thickness from 20 to 45 m; post-skarn normal faulting has increased the thickness of skarn in some areas.

The metasomatic alteration of limestone may be described under three headings: (1) an inner zone, next to quartzite or arkose, consists dominantly of diopside hornfels; (2) an outer skarn zone consists of garnet-diopside-wollastonite; and (3) a marble zone consists largely of bleached and recrystallized limestone (see Fig. 7.11).

The inner skarn zone is similar in most respects to the mid-Scherrer carbonate unit, except that it lacks magnesian skarn; diopside constitutes over 80 percent of the rock. Disseminations and veinlets of chalcopyrite and pyrite are invariably rimmed with dark green actinolite halos. The contact of the inner skarn zone with the outer skarn zone is defined as the point at which actinolite halos disappear and garnet patches and veins appear in diopside. The contact generally is sharp; actinolite and garnet do not occur together, and no crosscutting relations between the two minerals were noted.

The outer skarn consists of garnet-diopside, garnet, and garnet-wollastonite, generally zoned toward marble in the order listed. Age relations between fine-grained diopside hornfels and garnet are generally lacking, but the presence of a number of garnet veins in diopside near the inner skarn zone suggests that garnet at any given point formed later than fine-grained diopside. In outer garnet-diopside zones, the two minerals show no discernable age relations. In wollastonite zones coarse, green diopside and garnet occur largely as patches, but veins of both diopside and garnet have been observed to cut wollastonite.

Garnet in the outer skarn zone varies from pale brown to green in color. There is a marked tendency for pale brown garnet to occur with diopside; locally this garnet is overgrown or veined by reddish brown garnet. Green garnet tends to occur on the marble side of the skarn zone and is associated with wollastonite.

An X-ray study of garnet compositions suggests a small, but systematic, increase in Al_2O_3 content with outward progression toward the marble contact. Eight garnet samples, selected from two drill holes, showed a change from 100 mole percent andradite to about 95 mole percent andradite in both sets of samples.

Sulfides consist of pyrite, chalcopyrite, bornite, and sphalerite; magnetite is absent. Fine hematite dusting in garnet is common, but probably is later than both andradite and sulfides. Pyrite and bornite do not occur in contact and generally do not occur in the same hand specimen. A general zoning is noted outward, from chalcopyrite-pyrite associated

TABLE 7.6
Grade and Sulfide Content in Sedimentary Rocks in the Palo Verde Mine, Pima-Mission Area
(Data in Weighted Means)

Drill Hole Sample Alteration Type	Length of Sample (m)	Weight % Copper	Volume % Sulfide (Chalcopyrite + Pyrite or Bornite)	Ore Assemblage
Quartzite[a]	—	0.15	1.5	pyrite : chalcopyrite = 5–10, molybdenite
Hornfels[b]	82	0.45	1.5	pyrite : chalcopyrite = 0.1–2, trace magnetite
Magnesian Skarn[c]	6	2.08	5.0	pyrite : chalcopyrite = 0.1, 5–10 magnetite
Calcic Skarn[d]	32	0.30	1.5	pyrite : chalcopyrite = 10
Calcic Skarn[d]	27	1.47	3.5	chalcopyrite, minor pyrrhotite
Calcic Skarn[d]	23	1.86	3.2	chalcopyrite, bornite; minor pyrrhotite
Calcic Skarn[e]	53	1.89	2.5	chalcopyrite, bornite, sphalerite; minor chalcocite, tennantite

Source Data from Einaudi (1974).

[a] Scherrer quartzite.

[b] Diopside-quartz hornfels veined by sulfides-actinolite or sulfides-garnet, mid-Scherrer Formation.

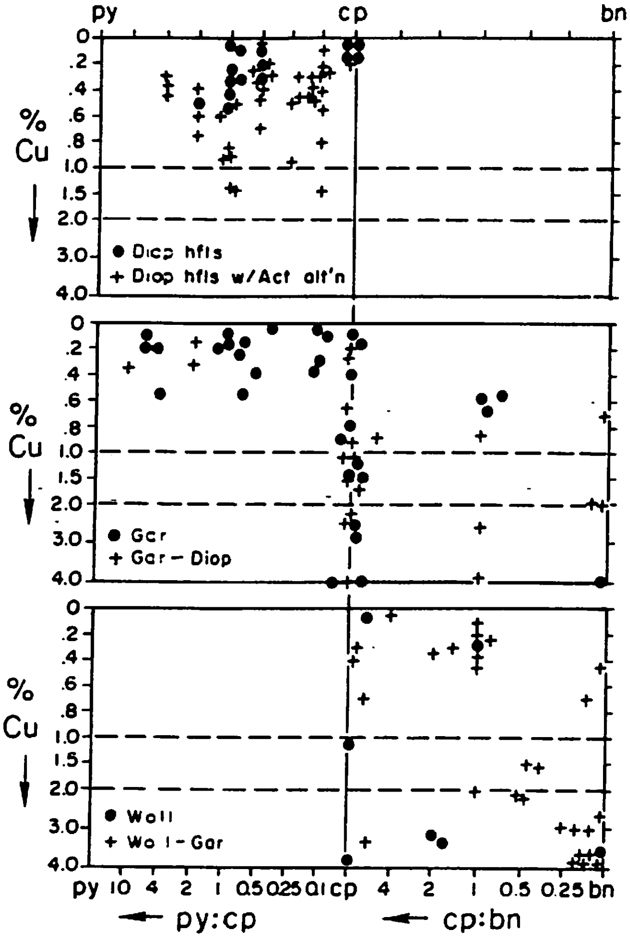
[c] Serpentine-tremolite-calcite-magnetite skarn, mid-Scherrer Formation.

[d] Garnet-diopside skarn, Concha Limestone.

[e] Garnet-wollastonite skarn at marble contact, Concha Limestone.

with diopside and garnet-diopside to chalcopyrite-bornite (± sphalerite, pyrrhotite) associated with garnet-wollastonite. This relation is illustrated in Figures 7.11 and 7.12. Pyrite does not occur with wollastonite. Sulfides occur as streaks and disseminations in fresh garnet, diopside, and wollastonite. In massive garnet zones, sulfides—particularly chalcopyrite and bornite—preferentially replace calcite, which occurs as patches interstitial to garnet. Sphalerite and sphalerite-bornite (± chalcocite, tennanite) tend to occur with green garnet in wollastonite, whereas chalcopyrite-bornite tends to occur with brown garnet.

Within a few feet of the marble contact and within the marble itself, there is generally an increase in sulfide abundance. Chalcopyrite and chalcopyrite-sphalerite occur as massive bedding streaks in white calcite marble, a few centimeters to 1 meter beyond wollastonite-garnet, or in dolomite-quartz envelopes in dolomitic marble beyond diopside-garnet.



Abbreviations:

bn = bornite
cp = chalcopyrite
Diop = diopside
Diop hfls = diopside hornfels

Gar = garnet
py = pyrite
w/Act alt'n = with actinolite alteration
Woll = wollastonite

Figure 7.12. Plot of pyrite:chalcopyrite and chalcopyrite:bornite ratios, and copper grade as a function of calc-silicate assemblage at the Palo Verde mine, Pima mining district, Arizona. Each datum point represents visual estimate of sulfide ratio over core intervals of 1 to 2 m from cross section shown in Fig 7.11. Plot shows decreasing Fe:Cu ratio in sulfides and increasing copper grades from diopside ± actinolite to garnet ± diopside and wollastonite ± garnet. Based on Einaudi (1974).

Copper grades within the inner 7 to 15 m of the outer skarn zone average around 0.4 percent. In the outer 5 to 7 m, as the marble contact is approached, copper grades increase to 2.5 to 4.0 percent.

Marble Zone. The marble zone has a highly variable sulfide and silicate mineralogy, dependent to a large degree on original dolomite content. Wollastonite is not an abundant mineral; it characteristically occurs as rims on chert nodules; locally along fractures; and over short, apparently bedding-controlled intervals in calcite marbles. Idocrase is present in such intervals.

Two types of alteration envelope assemblages occur on sulfide veinlets in dolomite. Chalcopyrite-pyrite-magnetite veinlets have serpentine envelopes, and sphalerite-chalcopyrite (± pyrite) veinlets have white dolomite-quartz (± calcite) envelopes. The dolomite content in the envelopes is generally higher than in the enclosing marble. Similar veins with dolomite envelopes also occur in calcite marble.

The most abundant type of alteration in marbles consists of soft, pale buff to greenish, altered diopside hornfels, with minor garnet and idocrase. Talc-serpentine alteration of diopside is often pervasive and the enclosing rock may be partly replaced by talc-serpentine, which yields a pale yellowish marble. In thin section talc appears to replace both diopside and idocrase. Montmorillonite generally is less abundant than talc-serpentine, and tremolite is absent. Sulfides consist of pyrite-chalcopyrite and sphalerite-chalcopyrite; bornite is absent.

Late Alteration. Alteration of wollastonite and garnet to a variety of assemblages—including the minerals calcite, quartz, hematite, siderite, and chlorite—is widespread in the outer skarn zone. These late minerals occur in alteration envelopes on calcite-siderite veins and on post-skarn fault breccias cemented by calcite-hematite-siderite. Skarn fragments within fault breccias are pervasively altered to carbonate-hematite. Pervasive alteration extends up to 1 m beyond strong fault zones and into the skarn along fractures.

Wollastonite is the first mineral affected by late recarbonation; it is replaced by a pale gray mixture of calcite-quartz. Andradite is next affected; abundant thin fractures of calcite-hematite darken the color of garnet to a deep carmine red and any associated wollastonite is completely destroyed. Within and near breccia zones, andradite may be completely replaced by dark purple calcite-quartz-hematite, with local siderite and traces of chlorite. Skarn textures are preserved and the above assemblage pseudomorphously replaces andradite grains. Diopside associated with andradite appears to undergo the same alteration. Bornite does not survive this late alteration; it is converted to chalcopyrite.

THE LAKESHORE DEPOSIT

In May, 1968, El Paso Natural Gas Company announced the discovery of a major copper deposit on the Lakeshore property, located on the southwest flank of the

Slate Mountains in Pinal County, 28 miles south of Casa Grande, Arizona. The following summary of the geology is based on studies of the mine area by Harper and Reynolds (1969) and Barron (1969), as reported in Hallof and Winniski (1971), and by South (1972); discussions with J. J. Quinlan and Craig Hansen of Hecla Mining Company also were helpful.

General Setting

The southern end of the Slate Mountains consists largely of Precambrian Pinal Schist intruded by a large stock of equigranular quartz monzonite of Laramide age, known as the Lakeshore stock. This stock extends 4 km in a northwesterly direction and is bounded on the west by the Lakeshore fault, a major, west-dipping, range-front normal fault with a west-side-down normal displacement of several thousand meters.

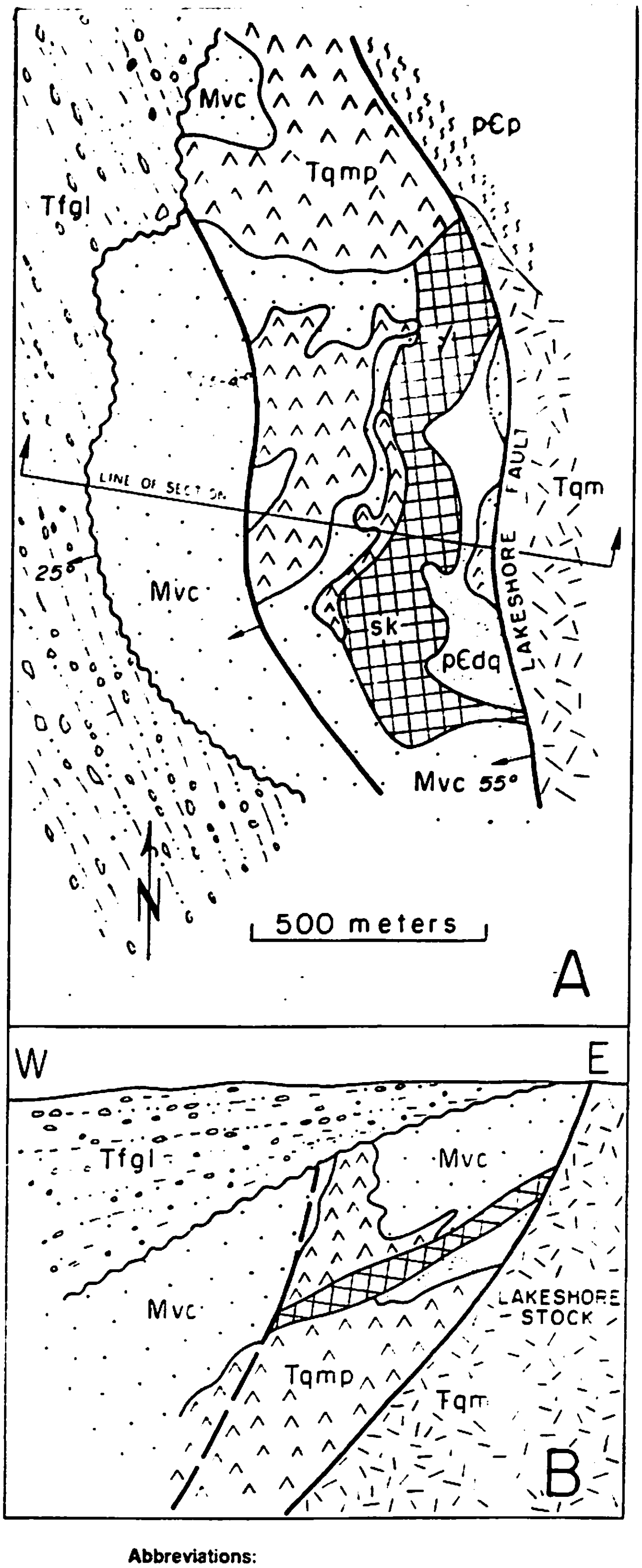
West of the fault, in the block containing the Lakeshore deposit, are scattered pediment outcrops of younger Precambrian Apache Group rocks overlain disconformably, or in fault contact with, volcanic and sedimentary rocks of Cretaceous age. Irregular sills and stocks of quartz monzonite porphyry, presumably representing the preserved cupola portions of the Lakeshore stock, occur at depth. A plan view of the 400-ft. level and cross section at the Lakeshore mine are presented in Figure 7.13.

Primary copper mineralization is spatially associated with the upper portions of the porphyry bodies and includes: (1) lower grade (0.5–0.8% Cu), disseminated chalcopyrite in porphyry, Precambrian diabase, skarn, and Cretaceous volcanic sedimentary rocks; and (2) higher grade (~1.7% Cu) tabular bodies of chalcopyrite mineralization in skarn. The skarn ore occurs in a limestone unit which may be either Precambrian (Mescal Limestone?) or early Paleozoic in age.

Skarn

The skarn bed dips 20° west, has an average thickness of 20 m, and is terminated on the east and west by normal faults (see Fig. 7.13). Low-angle shears disrupt the bed on a local scale; many contacts between higher-grade and lower-grade mineralization and between differing calc-silicate assemblages are fault surfaces. The base of the skarn bed is also locally faulted.

In spite of the structural disruptions and local lithological controls of calc-silicate mineralogy within the limestone unit, the following dominant mineral associations are roughly arranged from northwest to southeast with increasing distance from the main porphyry mass: (1) garnet, with generally low sulfide content and high pyrite:chalcopyrite ratios; 2) diopside, with patches of garnet, relatively higher sulfide content and high pyrite:chalcopyrite ratios, containing abundant, sulfide-bearing fractures with dark green (actinolite?) alteration envelopes; and (3) talc-tremolite with relatively low pyrite:chalcopyrite ratios, and with magnetite ranging up to 25 percent. Zones dominated by garnet or tremolite-magnetite contain the highest copper grades; the most persistent zones of high-grade ore occur in the latter assemblage. Overall, the skarn contains 1 to 6 percent pyrite,



Abbreviations:

Mvc = Mesozoic volcaniclastic rocks
pЄdq = Precambrian diabase and quartzite
pЄp = Precambrian Pinal schist
sk = skarn
Tfgl = Tertiary fanglomerate
Tqm = Tertiary quartz monzonite
Tqmp = Tertiary quartz monzonite porphyry

Figure 7.13. Plan view of 400-ft. level (*A*) and cross section, looking north (*B*) at the Lakeshore mine, Slate Mountains, Arizona, illustrating the location of skarn and quartz monzonite porphyry stock in down-dropped block west of Lakeshore fault. Redrawn from South (1972).

[illegible] range from 1:2 to 4:1.

THE BINGHAM MINING DISTRICT

The Bingham mining district has been the subject of intense geological study for many years; advances in geological knowledge are documented in *Economic Geology*, v. 73, no. 7 (1978). The Bingham district is unique; not only does it contain the largest known porphyry copper deposit in North America, with a production of 1.3 billion tons of 0.85 percent Cu ore from 1904 to 1976, but also it contains the world's largest known skarn Cu deposits and is the only porphyry copper system from which major lead-zinc-silver ore tonnages (47 million tons from 1870–1971) have been mined. With a high-grade skarn-ore preserve of greater than 60 million tons of approximately 2 percent Cu, a lower-grade skarn-ore resource of 150 million tons of 1.3 percent Cu (Proxy Statement, The Anaconda Co., 1976), and additional reserves for which tonnage and grade figures are unavailable, the district promises to maintain its premier position in metal production for many decades to come. In addition, 2 km of vertical exposure due to mining and deep drilling in an essentially continuous structural block is unparalleled in any other porphyry-skarn system. A unique opportunity exists, therefore, to document the changes in skarn mineralogy as a function of depth, from deep zones, spatially related to a low-grade root zone in igneous rocks, to relatively higher-level environments, spatially related to well-mineralized porphyry dominated by potassium silicate alteration (Table 7.7).

General Setting

Sedimentary rocks in the contact aureole are of Pennsylvanian age and consist of quartzite, with lesser amounts of calcareous siltstone and limestone (see Fig. 7.3). The relatively small volume of carbonate-rich rocks in the Pennsylvanian section at Bingham—in contrast with southern Arizona, New Mexico, and Sonora—is noteworthy and may be one of the key factors which led to the immense tonnage of highly mineralized skarn.

Compressive deformation from the southwest during Mesozoic time formed east-west–trending folds, bedding plane faults, and a set of northwest-striking, imbricated, thrust or right lateral, strike-slip faults. A system of northeast-striking faults, which were later to serve as major ore solution conduits (especially in the southwestern and southern portion of the district, Fig. 7.14*a*), originated largely as tension fissures parallel to the direction of maximum principal stress. Intrusion of quartz monzonite during mid-Tertiary time was controlled to a large degree by the zone of northeast faults and by steep bedding.

Porphyry

The Bingham stock—composed of a multiple intrusive sequence of early monzonite, followed by quartz monzonite porphyry and late quartz latite porphyry—contains a relatively high-grade primary ore assemblage (≃0.65% Cu) of biotite-orthoclase [illegible] stage of quartz-sericite-montmorillonite alteration of plagioclase, with stable orthoclase and biotite, occurs along a structurally permeable zone along the northwestern contact of the stock (Moore and Nash 1974; Moore, 1978). The configuration of disseminated and stockwork copper mineralization has been described by James (1971) as an inverted, cup-shaped volume which is draped over a low-grade core zone. The alteration-mineralization pattern, clearly centered on the quartz monzonite porphyry phase, indicates that the hydrothermal activity responsible for this pattern was synchronous with the emplacement and cooling of the porphyry. This relation is particularly clear in the cross sections shown in Figure 7.15, which illustrate the assymetry of the pattern relative to the stock as a whole.

The contrast in alteration-mineralization in the stock near the surface and 1,000 m below the surface is largely one of intensity, rather than kind. At the surface (see Fig. 7.14) the copper ore zone is centered on the porphyry, and the outer limit of >0.35 percent Cu extends a few hundred meters eastward and westward beyond the monzonite stock contact into biotite and actinolite-bearing quartzite (John, 1978; Atkinson and Einaudi, 1978). Copper grade decreases southward in the monzonite stock as potassium-silicate alteration and stockwork veinlets decrease in intensity and grade out through secondary actinolite to unaltered augite-hornblende monzonite (Lanier, Raab, et al, 1978). At depths of 1,000 m below the surface (See Fig. 15), however, the porphyry contains less than 0.25 percent sulfides, although the intensity of potassium-silicate alteration remains high; at these depths the zone of >0.35 percent Cu is located 450 m from the porphyry contact on the south and east sides, where the wall rock is monzonite, containing only minor secondary biotite (John, 1978). On the west side of the porphyry, where the wall rock is quartzite, the better-grade zone appears as a mirror image of the eastern ore zone, although grades reach only 0.1 to 0.4 percent Cu (Atkinson and Einaudi, 1978).

Timing of Cu Versus Pb-Zn-Ag

The zonation of ores and alteration in the sedimentary wall rocks of the Bingham stock was first documented by R. N. Hunt (1924); Table 7.8 shows that copper ores are restricted to garnetized limestone beds near the intrusion, whereas lead-zinc-silver ores occur principally in limestone and monzonite outside the zone of skarn minerals (see also Fig. 7.14). Although there exists a clear zonal relation between the copper and lead-zinc-silver zones, the timing of these two zones relative to each other and relative to alteration-mineralization events in the stock is not so clear. Atkinson and Einaudi (1978) concluded that deposition of garnet-copper-iron sulfides was essentially synchronous with garnetization of limestone and with actinolite alteration of diopside in hornfels and quartzite; both were broadly synchronous with biotite-orthoclase alteration of igneous rocks. The contemporaneity of actinolite alteration of diopside and biotite-orthoclase alteration of igneous rocks is clearly documented by veinlet relations at igneous-sedimentary rock contacts.

TABLE 7.7
Changes in Alteration-Mineralization with Depth at Carr Fork, Bingham Mining District

	Alteration-Mineralization	Skarn		Quartzite		Porphyry	
		Surface	1 km Depth	Surface	1 km Depth	Surface	1 km Depth
< 100 m from intrusive contact	% Copper	0.6–1.0	0.2–0.6	0.4	< 0.1	0.65	< 0.1 locally high molybdenum
	Volume % Sulfide	0.5–4	0.5–1	1–2	< 0.25	1.5	0.5
	Sulfide Assemblage	chalcopyrite= pyrite	chalcopyrite > bornite	chalcopyrite > pyrite	molybdenite > chalcopyrite	chalcopyrite > bornite	molybdenite > chalcopyrite
	Volume % Iron Oxide	1–2	2–5	0	0	0	trace
	Iron Oxide Assemblage	magnetite, hematite	magnetite	—	—	—	magnetite
	Main Stage Alteration	garnet (clinopyroxene)	garnet (clinopyroxene)	interstitial actinolite; actinolite-biotite veinlets	interstitial biotite	(actinolite-epidote)[a] biotite-orthoclase	(actinolite-epidote?)[a] biotite-orthoclase
	Late Alteration	clay after clinopyroxene; opaline silica, pyrite	garnet (clinopyroxene) clay after clinopyroxene	chlorite, sericite, montmorillonite	local sericite	(chlorite) sericite, montmorillonite, pyrite	weak sericite, montmorillonite
100–400 m from intrusive contact	% Copper	1–4	1–4	0.2–0.4	0.1–0.4	↑	↑
	Volume % Sulfide	5–15	2–8	1	0.25–1		
	Sulfide Assemblage	pyrite > chalcopyrite	chalcopyrite >> bornite chalcopyrite= pyrite	chalcopyrite= pyrite	chalcopyrite > pyrite; chalcopyrite >> bornite		
	Volume % Iron Oxide	1–2	2–10	0	0	porphyry not found	prophyry not found
	Iron Oxide Assemblage	magnetite, hematite	magnetite	—	—		
	Main Stage Alteration	garnet-pyroxene	garnet-pyroxene	interstitial clinopyroxene, actinolite; actinolite-biotite veinlets	interstitial actinolite; actinolite-biotite veinlets		
	Late Alteration	clay after clinopyroxene; local opaline silica, pyrite	absent	chlorite; montmorillonite	absent	↓	↓
>400 m from intrusive contact	% Copper	< 0.1	erratically very high	< 0.1	< 0.1	↑	↑
	Volume % Sulfide	trace–1	erratically very high	trace–1	trace–0.5		
	Sulfide Assemblage	bornite, chalcopyrite (sphalerite, galena)	pyrite > chalcopyrite	pyrite > chalcopyrite	pyrite= chalcopyrite		
	Volume % Iron Oxide	0	erratically very high	0	0	porphyry not found	porphyry not found
	Iron Oxide	—	magnetite	—	—		
	Main Stage Alteration	garnet replaces wollastonite	magnetite and sulfide replace marble	interstitial clinopyroxene; actinolite veinlets	interstitial clinopyroxene, actinolite; actinolite (biotite) veinlets		
	Late Alteration	clay, chalcedony replace limestone; pyrite-sphalerite-galena	?	only on northeast fissures	absent	↓	↓

[a] Endoskarn.

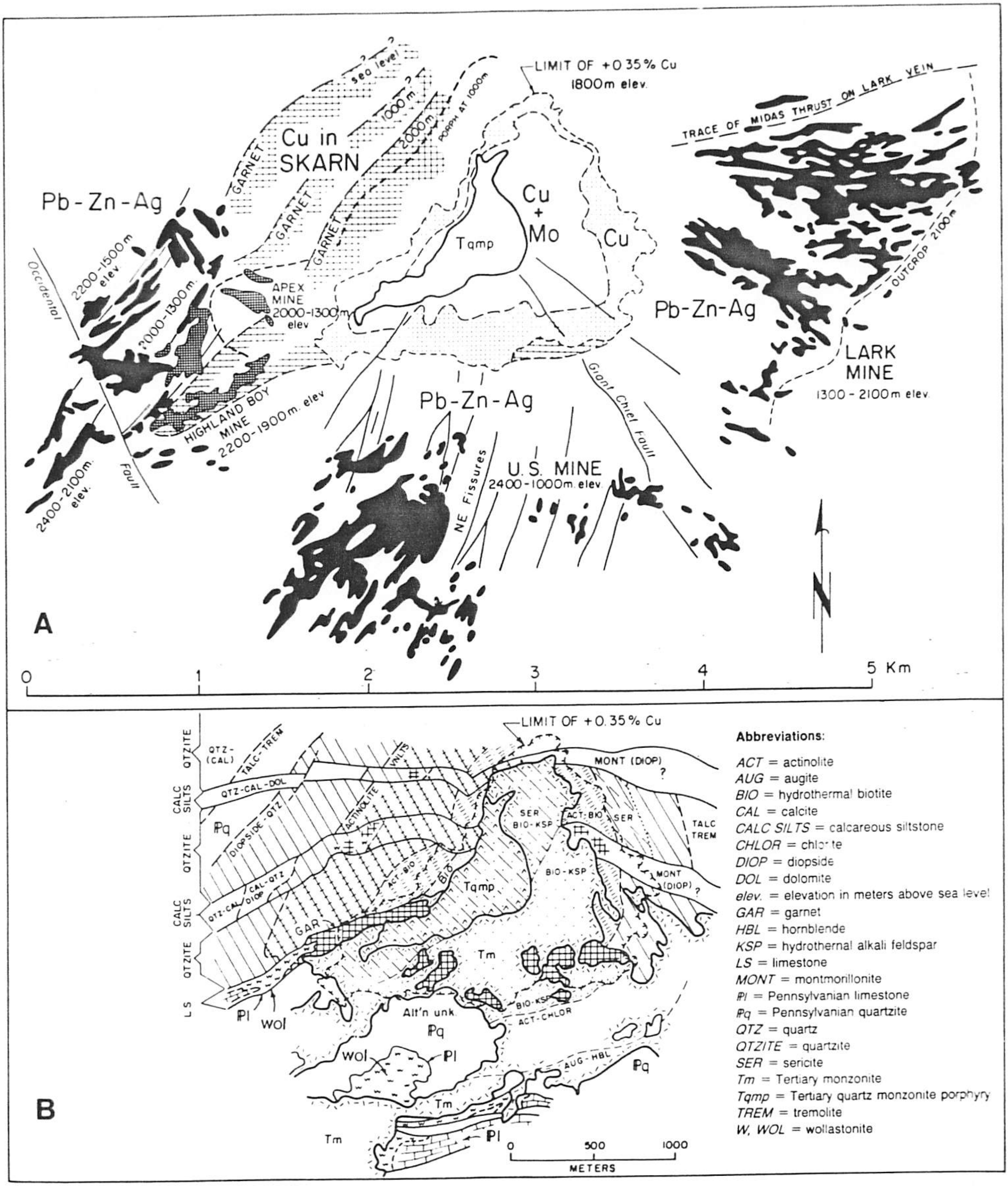


Figure 7.14. Mineral zoning and alteration in the Bingham mining district, Utah. *A*, metal zoning relative to central quartz monzonite porphyry projected to a horizontal plane: Cu + Mo and Cu disseminated in igneous rocks and peripheral sediments at 1,800-m elevation; Cu in skarn (garnet, cross-hatched) on west and northwest from 2,200- to 0-m elevation; Pb-Zn-Ag replacement and fissure ores (black) in limestone, quartzite, and monzonite from 2,400- to 1,000-m elevation. *B*, alteration in igneous and sedimentary rocks at the surface. Based on Lanier, John, and others (1978), John (1978), Moore (1978), Lanier, Raab, and others (1978), Atkinson and Einaudi (1978).

J. P. Hunt (1957) has concluded that much of the lead-zinc-silver mineralization was associated with a later hydrogen metasomatizing environment which produced sericite in igneous rocks, clays (not actinolite) in calc-silicate rocks, and carbonate-silica in limestone.

Sedimentary Rocks

The following summary of alteration-mineralization in sedimentary rocks is based on the study of the western contact aureole by Atkinson and Einaudi (1978). An early stage of magnesium-silica metasomatism produced diopside in quartzite and in silty limestone beds up to 1,500 m from the stock and wollastonite, with minor idocrase and garnet, in thick, cherty limestone up to 600 m from the porphyry (see Figs. 7.14 and 7.15). A trace amount of sulfides accompanied this early metasomatic-metamorphic event, which was synchronous with emplacement of monzonite and continued during the initial emplacement of quartz monzonite porphyry.

Actinolite-biotite alteration of diopside along sulfide-

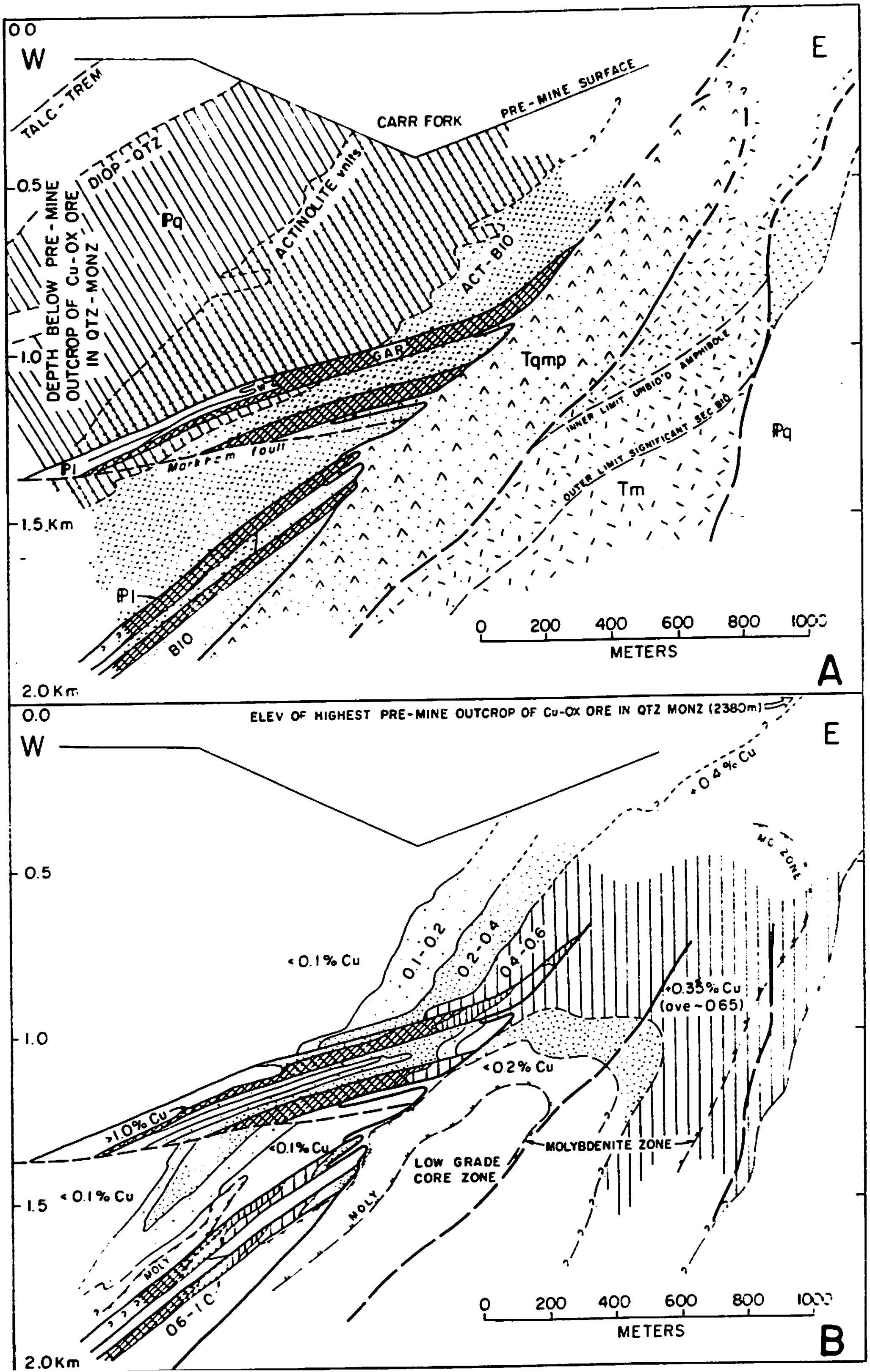


Figure 7.15. Cross section (looking north) of the Bingham mining district, Utah, illustrating alteration (*A*), copper grade (*B*), and sulfide ratios (*C*) in the western contact zone (Carr Fork area) of Bingham stock. Relations at depth east of the porphyry in monzonite and quartzite are semi-schematic and based on John (1978) and Lanier, John, and others (1978); relations at depth in porphyry and west of porphyry are based on Atkinson and Einaudi (1978) and Einaudi (unpublished data)

bearing fractures in quartzite, and garnetization of wollastonite-bearing marble, represent the beginning of main-stage mineralization and are synchronous with biotite-orthoclase alteration of igneous rocks. Pyrite:chalcopyrite ratios decrease toward the stock in the zone of actinolite envelopes. Crosscutting veinlet relations indicate that the biotite zone expanded from the stock onto the outer actinolite zone during a trend toward decreasing pyrite:chalcopyrite and Cu-Fe sulfide:molybdenite ratios. Late pyritic veinlets with actinolite envelopes represent the waning of main-stage mineralization in quartzite.

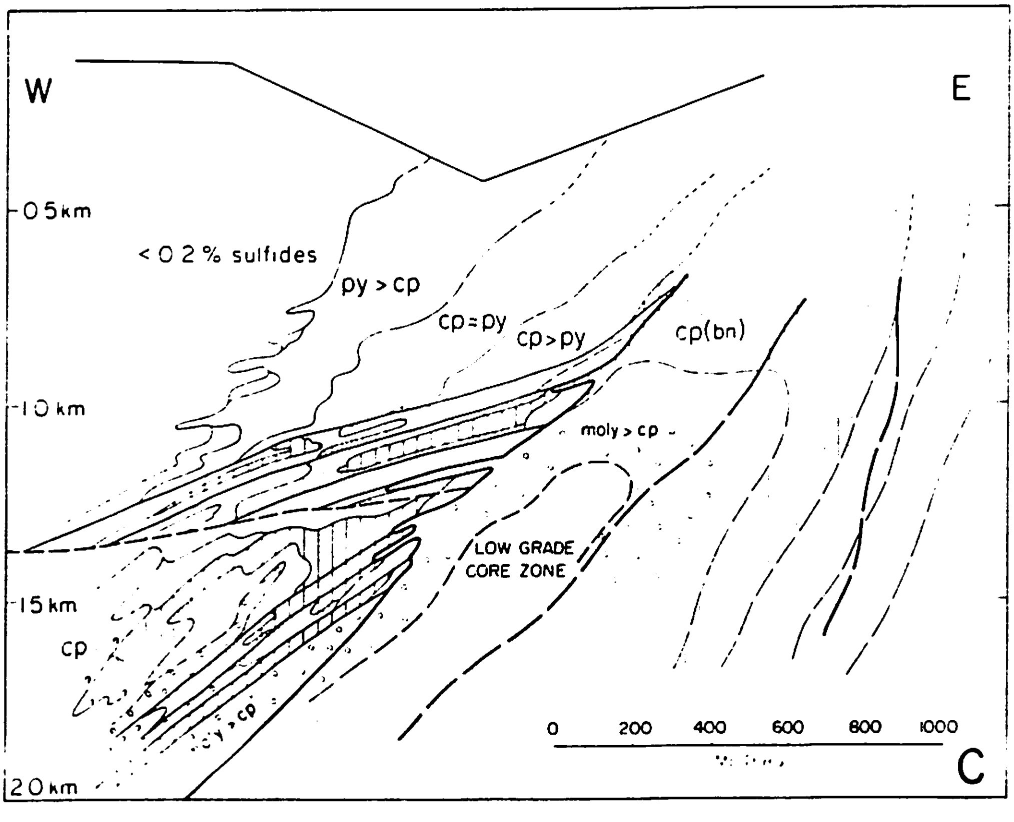
Two cherty limestone beds, 15 to 60 m thick and separated by 100 m of quartzite, contain the major copper-bearing skarns in the district. Zoning in these skarn beds is summarized in Table 7.9. Main-stage alteration consists of brown andradite (average Ad_{95} by chemical analysis), diopside, magnetite, and chalcopyrite superimposed on early-stage wollastonite up to 450 m from the porphyry. In the wollastonite zone, yellow-green garnet (average Ad_{72} by X-ray) is accompanied by chalcopyrite and bornite, with minor galena and sphalerite. Pyrite:chalcopyrite ratios decrease from the outer edge of the andradite-diopside zone toward the intrustive contact; they also decrease with depth. Massive magnetite locally replaces garnet at lower elevations; at higher elevations, the skarns have a lower iron-oxide content, hematite appears, and the hematite-magnetite ratio increases to unity near the surface.

The main stage of ore deposition in skarn culminated with alteration of andradite to variable mixtures of calcite, quartz, hematite, magnetite, siderite, and sulfides. In the more diopside-rich skarn of the outer zones, alteration assemblages accompanying some sulfide deposition include andradite-actinolite or actinolite in addition to the minerals listed above. These reactions may have been largely the result of declining temperatures; it is unclear whether any new copper, iron, or sulfur was introduced at this stage.

A late stage of alteration produced pyrite, chlorite, montmorillonite, sericite, talc, and opal from earlier calcsilicates and locally redistributed chalcopyrite. Lead-zinc and gold deposits, accompanied by arsenic-bearing minerals such as tennantite and arsenopyrite, also belong to this time frame. The late stage is believed to be contemporaneous with sericite-pyrite alteration of intrusive rocks, and largely is restricted to higher elevations.

THE SANTA RITA DEPOSIT

The Santa Rita deposit is located on the east side of the Central mining district, about 20 km east of Silver City, New Mexico. The general geology of the Santa Rita quadrangle has been described by Jones and others (1967). Copper-bearing skarns related to the Santa Rita stock, which have been described by Nielsen (1970), display the characteristic mineralogy of skarns related to porphyry copper intrusive systems: they are copper-dominant and contain an association of andraditic garnet and diopsidic clinopyroxene with zinc present in minor, uneconomic concentrations near the marble contact. These skarns are in marked contrast with the zinc-bearing skarns located north of Santa Rita (Fig. 7.16) on the southern fringe of the Hanover-Fierro stock at the Kearney, Oswaldo, Empire, and Pewabic mines (Schmitt, 1939; Hernon and Jones, 1978). The zinc-bearing skarns are characterized by the association of manganhedenbergite, bustamite, rhodonite, and local ilvaite located on the marble side of andraditic garnet zones. It is likely that this association, which has not been reported from porphyry-copper-related skarns, is unrelated to the emplacement of the Santa Rita stock and to the formation of its associated copper-bearing



Abbreviations:

ACT = actinolite
BIO, SEC BIO = secondary (hydrothermal) biotite
bn = bornite
cp = chalcopyrite
DIOP = diopside
GAR = garnet
Mo = molybdenum
MOLY = molybdenite
Pl = Pennsylvanian limestone
Pq = Pennsylvanian quartzite
py = pyrite
QTZ = quartz
QTZ MONZ = quartz monzonite
Tm = Tertiary monzonite
Tqmp = Tertiary quartz monzonite porphyry
TREM = tremolite
UNBIO'D = unbiotized
vnlts = veinlets
w = wollastonite

TABLE 7.8

Metal Grades and Zones of Limestone Replacement-Fissure Ores and Skarn in the Bingham Mining District

Mineralization Alteration Type	Location	Distance From Porphyry (m)	Elevation (m)	Weight %				Oz./Ton		Pb:Cu	Pb:Zn	Cu:Mo
				Cu	Mo	Pb	Zn	Au	Ag			
Pb-Zn-Ag Fissure and Replacement	Carr Fork	2,300–500	2,190–1,860	1.0	ND	14.4	10.7	0.05	4.9	16.4	1.2	—
Pb-Zn-Ag Concordant and Replacement	Lark	2,700–900	2,120–1,300	0.7	ND	12.1	8.5	0.03	4.0	18.7	1.5	—
Pb-Cu Fissure Ore	Carr Fork	900–240	1,680–1,310	2.6	ND	3.9	(9.0)[a]	0.08	2.1	1.7	(1.0)[a]	—
Cu Ore, Garnet Skarn	Highland Boy Mine	670–0	2,200–1,910	2.2	ND	ND	ND	0.07	0.7	—	—	—
Wollastonite Skarn	Yampa Limestone outcrop, Carr Fork	750–300	2,240–2,075	0.017	0.0004	0.023	0.055	ND	0.04	1.4	.42	43
Open-Pit Cu Ore, Garnet Skarn	Yampa Limestone, Utah pit	300–0	2,000–1,820	0.65	0.009	0.002	0.02	ND	0.15	0.003	0.10	72
Cu Ore, Garnet Skarn	Carr Fork Mine[b]	450–120	1,760–970	1.9	0.008	ND	ND	0.02	0.4	—	—	238
Cu Ore, Garnet Skarn	Carr Fork Mine[b]	450–120	1,420–1,000	2.2	0.021	ND	ND	0.02	0.4	—	—	105
Cu Ore, Garnet Skarn	Carr Fork Mine[b]	600–270	1,240–300	2.4	0.057	ND	ND	0.02	0.4	—	—	42

Source: Data from The Anaconda Company: Atkinson and Einaudi (1978); Rubright and Hart (1967); Reid (1978).

NOTE: ND = no data; dash = no data on one of the elements in the ratio.

[a] Zn occurs sporadically; this value represents mean of Zn-rich ores.

[b] Grade of underground geological inventory.

TABLE 7.9

Main Stage Mineral Zoning in Deep Skarn at Carr Fork, Bingham, Utah

Distance From Bingham Stock (m)	Gangue	Garnet Color	Volume Fraction Garnet:Garnet + Diopside	Volume % Magnetite	Volume % Sulfides	Sulfide Associations	Volume Ratio Pyrite:Chalcopyrite
0–50	andradite-calcite-quartz-diopside	red-brown	0.7	1–2	1–2	chalcopyrite, minor chalcopyrite-bornite	0
50–100	andradite	red-brown	1.0	2–5	2–5	chalcopyrite-pyrite	0.2
100–300	andradite, diopside	red-brown, yellow in patches	0.9–0.8	5–10	15	chalcopyrite-pyrite	0.5–1.0
300–350	andradite, diopside	yellow, red in late veins	0.6	2	5	chalcopyrite-pyrite	5
350–400	wollastonite; veins, patches of garnet, diopside	yellow, yellow-green	highly variable	0	1	bornite-chalcopyrite-sphalerite, trace pyrite	0
400–600	wollastonite-diopside-quartz; wollastonite-calcite; marble	—	0	0	0.5	bornite, chalcopyrite, sphalerite, galena	0
>600	marble, limestone	—	—	0	trace	sphalerite, galena, pyrite	—

Source: Data from Atkinson and Einaudi (1978) and Einaudi (personal notes).

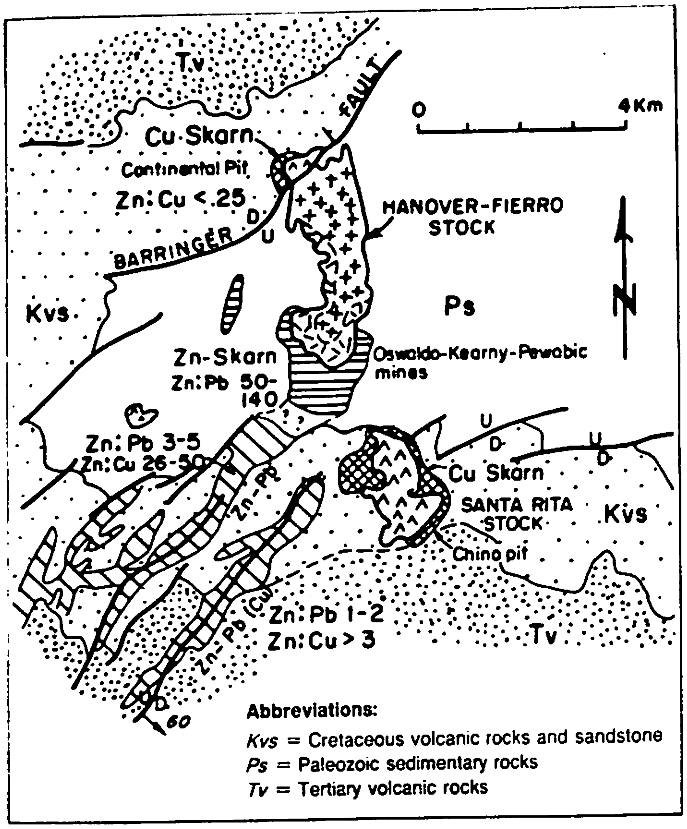


Figure 7.16. Generalized surface geology of the Central mining district, New Mexico, illustrating distribution of copper-bearing skarn (cross-hatched) in Paleozoic-carbonates at Chino pit (Santa Rita) and Continental pit, zinc-bearing skarn (horizontal ruling) near the southern lobe of Hanover-Fierro stock, and zinc-lead-(copper) veins (diagonal ruling) in a northeast-striking fault zone in the southwest portion of the district. Based on Jones and others (1967).

skarns. The relations between the contrasting environments of zinc- and copper-bearing skarn in the Central mining district remain an intriguing and unresolved question.

General Setting

The Oswaldo Formation of Pennsylvanian age, the principal host rock for Cu-bearing skarn in the district, consists of massive, non-dolomitic, cherty limestone, with thin shale partings and interbeds. The Syrena Formation, also Pennsylvanian in age, overlies the Oswaldo and consists of calcareous shale and interbedded impure limestone. The Santa Rita grandiorite and quartz monzonite porphyry stock and related dikes are elongated in a north-northwesterly direction parallel to the strike of bedding. Beds in the vicinity of the stock dip away from the stock at 20 to 40°.

Porphyry

Alteration-mineralization in the porphyry consists of an early potassium-silicate stage, which is best developed in the northern half of the stock, and a later stage of feldspar destructive alteration, which is, in part, superimposed on the potassium-silicate zone and appears to be structurally controlled by the western contact of the stock (Nielsen, 1968). The potassium-silicate stage is characterized by abundant quartz veining, secondary orthoclase and biotite, and a pyrite:chalcopyrite ratio of about 3. Total sulfides increase

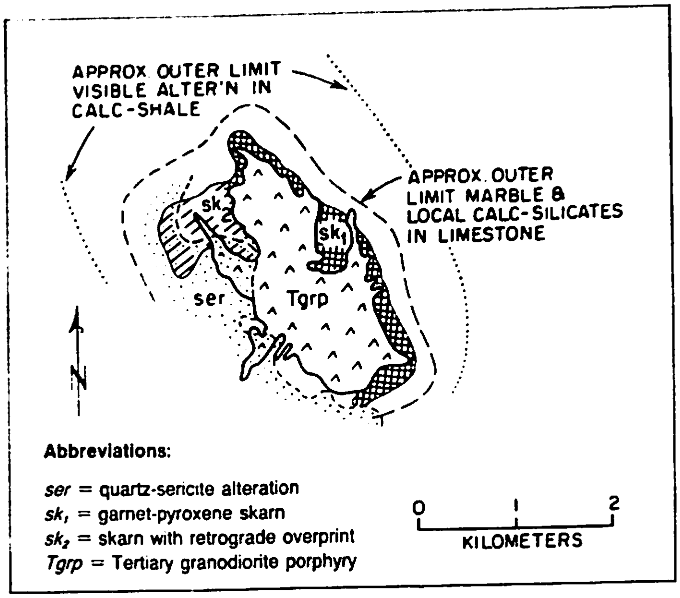


Figure 7.17. Sketch of the limits of alteration in limestone and calcareous shale and the distribution of the most intense sericitic alteration in igneous rocks at Santa Rita (Chino mine), Central mining district, New Mexico. The sketch illustrates the spatial relation between skarn and potassium-silicate alteration in stock on the east, and skarn destruction and sericitic alteration in stock on the west. Based on Nielsen (1970).

outwards from less than 1 weight percent in the core to 1 to 5 weight percent near the edge of the stock. The late stage consists of locally pervasive quartz-sericite alteration with 4 to 8 weight percent pyrite and a pyrite:chalcopyrite ratio of about 40. The hypogene grade is estimated to range from 0.1 to 0.3 percent Cu, with most of the potassium-silicate zone containing 0.1 percent Cu or less (Rose and Baltosser, 1966).

Sedimentary Rocks

The Oswaldo and Syrena Formations are intensely silicated or recrystallized within 60 to 900 m from the stock; hornfelses in calcareous shale extend outward an additional 600 m. Skarn considered to be ore grade (0.5–1% Cu?) occurs locally and erratically up to 600 m from the stock, although the most continuous areas of ore occur near the stock margins. The summary of zonal and paragenetic features that follows is based on Nielson (1970).

Hornfels. Recrystallization of calcareous shale is detected by X-ray analysis up to 2,400 m from the stock. Within 1,500 m, visible alteration consists of conversion to hornfelses containing quartz, calcite, actinolite, and plagioclase (Fig. 7.17). Fringing the ore zones closer to the stock, the hornfels takes on a mottled, greenish gray appearance and consists of epidote, quartz, actinolite, diopside, and albite, with minor garnet. Adjacent to potassium-silicate alteration in the stock, these hornfelses are cut by biotite-orthoclase veinlets; in the strong pyrite halo on the west margin of the stock, up to 10 percent pyrite occurs in veinlets with alteration envelopes containing variable mixtures of epidote, chlorite, montmorillonoids, calcite, siderite, and specular hematite.

Skarn. In the outmost zone of visible alteration, limestone beds contain thin reaction skarn at contacts with hornfelses (calcareous shales). Silication within relatively pure limestone beds is restricted to fractures of breccia zones; pale yellow-brown or green garnet veins with local sphalerite cut bleached marble. Closer to the stock massive, yellow-brown, garnet-diopside skarn, with interstitial magnetite and pyrite, replaces marble. Near the contact with porphyry, which contains potassium silicate alteration, magnetite (2–40%) and pyrite-chalcopyrite (4–18%) become more abundant as disseminations and cross-cutting veins in brown garnetite and in massive garnet-epidote-magnetite skarn. The pyrite:chalcopyrite ratio ranges from 1:1 to 10:1. Nielson (1970) concludes that this skarn assemblage (marked sk_1 on Figure 7.17) is synchronous with potassium-silicate alteration in the stock.

The early skarn assemblage is overprinted by hydrous silicates and carbonates near contacts with sericitized porphyry. Patches and veins of quartz-pyrite are bordered by a variety of late minerals, including actinolite, chlorite, montmorillonoids, epidote, siderite, pyrite and chalcopyrite. This type of alteration is associated with the highest grade of primary ore at Santa Rita and is particularly well developed at the northwest edge of the stock in the Lee Hill area (marked sk_2 on Figure 7.17). In this area, the skarn contains 20 to 75 percent magnetite and 10 to 25% total sulfides: the pyrite:chalcopyrite ratio is approximately 10:1 to 25:1.

THE CONTINENTAL MINE

A zone of secondary copper enrichment in Cretaceous sedimentary rocks was mined in the last century (1858 to 1861) at the Hanover Mountain mine, located on the north (down-thrown) side of the Barringer fault, near the northern lobe of the Hanover-Fierro stock (Spencer and Paige, 1935). From the turn of the century to approximately 1947, some 3 to 5 million tons of iron ore in skarn were mined from this same area at the Modoc, Republic, and Continental mines (Lindgren et al., 1910; Hernon, 1949). In 1947, interest shifted back to copper in the Continental mine area (see Fig. 7.16 for location), where significant mineralization in skarn had been discovered by surface diamond drilling (Forrester, 1972). Sporadic production ensued until 1962, when U.S. Smelting Refining and Mining Company substantiated a sufficient tonnage of copper ore to justify major development. The new Continental orebody, containing approximately 47 million tons of ore (W. T. Worthington, personal communication), was developed by open-pit and underground mining methods.

The following summary is based on discussions with W. T. Worthington, Chief Geologist at UV Industries' (formerly U. S. Smelting Refining and Mining Company) Continental mine, and on personal field notes.

Porphyry

The copper ore at the Continental mine occurs in skarn bordering the contact with the Hanover-Fierro stock. The igneous rock exposed in the east wall of the open pit consists largely of biotite quartz monzonite porphyry with a medium-grained aplitic groundmass. Chalcopyrite occurs almost exclusively in sparse pyritic quartz veins and veinlets which display sericitic alteration envelopes up to 0.3 m wide. Other quartz veinlets, generally lacking sulfides, but which are typical of potassium-silicate alteration, are encased in thin secondary biotite and magnetite alteration envelopes. Overall, the porphyry averages about 0.04 percent primary Cu, although some drill hole intercepts, up to 50 m in length, average as much as 0.1 percent Cu. Thus, the Hanover-Fierro porphyry exposed in the Continental pit has some characteristics of a weakly mineralized and altered porphyry copper pluton.

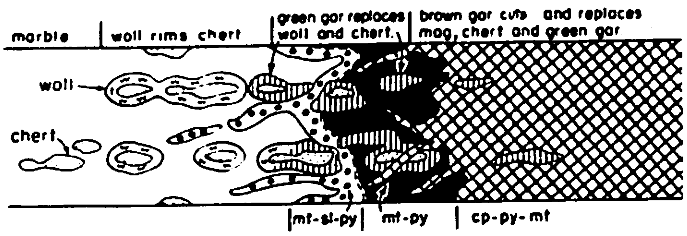
Sedimentary Rocks

Selective underground mining from the No. 3 Continental Shaft yields ore averaging approximately 2 percent Cu, 0.50 percent Zn, and 15 to 20% percent Fe as magnetite, largely from skarn in the Oswaldo formation. Open-pit copper ore in calcic skarn occurs dominantly in the Pennsylvanian Oswaldo Formation and the Mississippian Lake Valley Limestone. A minor portion of pit ore occurs in magnetite-rich magnesian skarn in the Montoya and El Paso dolomite of Ordovician age, which is separated from the upper Paleozoic strata by the Barringer fault. Open-pit ore averages approximately 0.85 percent Cu.

The Syrena formation overlying the Oswaldo skarn consists of flinty buff to green hornfels cut by a stockwork of thin pyrite veinlets with dark green alteration envelopes. Pale buff and red, massive garnet occurs as patches, veins, and veinlets. Magnetite is sparse to absent.

The Oswaldo skarn ore appears to be very similar to that exposed at the contact of the Santa Rita stock. On the outermost edge of silication, garnetite developed preferentially along the basal shale unit and overlying Syrena hornfels; locally garnetite at the marble contact is separated from marble by wollastonite and contains sphalerite, pyrite, and chalcopyrite. The main exposed ore-bearing skarn zone, some 200 m wide and extending along the stock contact approximately 1 km, consists of layers of dense, olive green, granular clinopyroxene (presumably salite) alternating with layers of red-brown garnet: the layering appears to be parallel to bedding, which dips 20 to 30° west. A lesser portion of the garnet occurs as irregular patches and crosscutting veins in the clinopyroxene. A large portion of the chalcopyrite, pyrite, magnetite, and hematite present in the skarn occur as disseminations in patches and veins of garnet, although garnet veins are cut by later quartz-chalcopyrite-pyrite veins. Within 30 m of the stock the grade drops to 0.15 percent Cu.

The skarn-marble contact in the Lake Valley Limestone is exposed in the south-central portion of the pit. A sketch of zoning and textures at the marble contact is presented in Figure 7.18. Beyond the skarn front, chert-nodules and lenses of white marble are rimmed with coarse wollastonite; the marble is cut by irregular, thick veins containing magnetite-pyrite or magnetite-sphalerite. Closer to the main skarn, wollastonite and most of the chert is replaced by pale green garnet and marble is replaced by massive magnetite with coarse patches of pyrite. Narrow pyrite-chalcopyrite veinlets with brown garnet envelopes cut green garnet and chert and appear to cut the massive magnetite. Veins and patches of brown garnet become more abundant toward the stock to the point where green garnet and chert become rare and the skarn consists of brown garnet, clinopyroxene, magnetite.



Abbreviations:

cp = chalcopyrite

gar = garnet

mt, mag = magnetite

py = pyrite

sl = sphalerite

w, woll = wollastonite

Figure 7.18. Sketch of zoning in calcic skarn of the Lake Valley Limestone at the Continental mine, Central mining district, New Mexico. Stock contact is toward the right. The scale is variable, on the order of tens of meters.

pyrite, and chalcopyrite in irregular, patchy, and complex vein textures.

The presence of green garnet in some magnetite-sphalerite veins suggests contemporaneity of these minerals. Also, in one magnetite-sphalerite vein that cut a wollastonite pod, the wollastonite was replaced by green garnet along the borders of the vein. These relations suggest that most of the sphalerite predated the formation of the main brown garnetite skarn and its associated chalcopyrite. However, the age relations between massive magnetite (lacking sphalerite) and brown garnet are ambiguous. Although brown garnet veins appear to cut massive magnetite, the magnetite may have preferentially replaced marble present between the brown garnet veins and green garnet pods.

THE SILVER BELL MINING DISTRICT

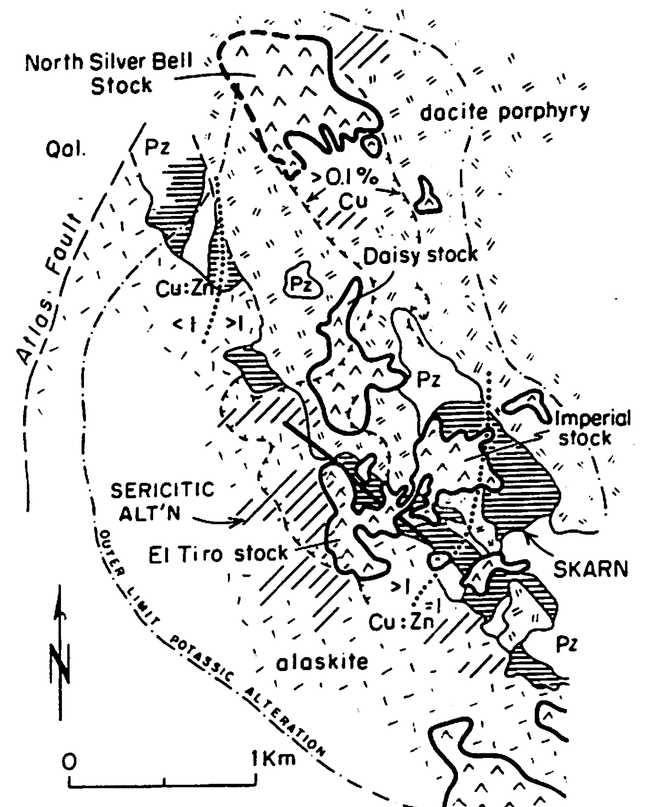
Mining activity in the Silver Bell mining district, located 56 km northwest of Tucson, was centered on local occurrences of copper-bearing skarn until 1930; after 1954, production largely came from supergene chalcocite ore in Laramide stocks, but during the 1970s hypogene copper ore in skarn was of increasing importance. The following summary is based on Stewart (1912), Richard and Courtright (1966), Graybeal (1982), and discussions with F. T. Graybeal and J. L. Galey of ASARCO Incorporated.

General Setting

According to Richard and Courtright (1966), a northwest-trending fault zone—which separates Paleozoic carbonate rocks on the northeast from Mesozoic arkosic sandstone on the southwest—served as the locus of magmatic activity in Laramide time. Emplacement of an elongate pluton of equigranular alaskite, (7 X 2 km in horizontal dimensions) and of later, sill-like bodies of dacite porphyry predated, by an unknown time interval, the intrusion of quartz monzonite porphyry stocks and the generation of the porphyry-skarn copper deposits. The porphyry stocks, which are irregular, steep-walled, and average 500 m in diameter, largely were emplaced along the northeast border of the alaskite batholith (Fig. 7.19). Graybeal (1982) has estimated that the Laramide surface was 1.8 km above the present surface.

Porphyry

The main zone of potassium-silicate alteration and mineralization is fairly symmetrical about a north-south line joining the El Tiro, Daisy, and North Silver Bell stocks (see Fig. 7.19). As described by Graybeal (1982), the highest grade of hypogene copper in igneous rocks (0.35% Cu) is associated with quartz-biotite-chalcopyrite ± pyrite veinlets in the central portion of the El Tiro stock. Copper grade decreases toward the outer portions of the stock and drops to less than 0.1 percent toward the east in the Imperial stock and surrounding dacite porphyry. Parallel changes in alteration-mineralization include the disappearance of veinlet biotite and an increase in the pyrite:chalcopyrite ratio from 1:2 to 4:1. Total sulfide content averages 2 volume percent. Bornite is rare and magnetite is absent. Beyond the outer edge of disseminated hydrothermal biotite, which defines the limit of potassium-silicate alteration (see Fig. 7.19), the pyrite:chalcopyrite ratio increases to 20:1 in the propylitic zone.



Abbreviations:

Pz = Paleozoic carbonate rocks

Qal = Quaternary alluvium

Figure 7.19. Generalized surface geology of the Silver Bell mining district, Arizona, illustrating distribution of skarn (horizontal ruling) in Paleozoic carbonates relative to the northwest-striking contact of alaskite and the north-trending zone of porphyry stocks, potassium-silicate alteration, and +0.1 percent hypogene Cu mineralization. Cu:Zn ratios in skarn (dotted lines) are broadly related to distnct-wide alteration patterns and not to individual stocks. El Tiro pit encompasses the southeastern portion of El Tiro and Imperial stocks and related skarn. Based on Richard and Courtright (1966) and Graybeal (1982).

Sericitic alteration generally is weakly developed at Silver Bell. Overall, the porphyry stocks contain 4 percent sericite as a weak, but pervasive, replacement of plagioclase. Locally intense sericitic alteration is restricted to the contact zone between alaskite and porphyry and is superimposed on potassium-silicate alteration as quartz-sericite ± pyrite envelopes on northeast-striking pyrite-quartz veins. In such areas, the pyrite content locally increases to 5 percent (Graybeal, 1982).

Skarn

In the mid-1970s mineralized skarn began to be an important source of copper ore in the eastern half of the El Tiro pit, where skarn and thin, interbedded hornfels extend a minimum of 330 m from the Imperial stock in the Abrigo and overlying Martin formations. The Escabrosa and Horquilla Limestones, exposed southeast of the El Tiro pit, are recrystallized but not extensively converted to skarn. On the basis of refractive index measurements, Buseck (1962) has suggested that garnet, the dominant silicate in calcic skarn, is pure andradite. Paragenetic relations determined by Stewart (1912) indicate the progressive formation of wollastonite, diopside, garnet-quartz, and calcite-quartz. The latter assemblage occurs as open-space fillings. Graybeal (1982) has indicated that chalcopyrite, pyrite, and magnetite occur in skarn as disseminations, replacing garnet, and in cross-cutting veinlets without alteration envelopes. Pyrite:chalcopyrite ratios increase from 2:1 near the stock to 5:1 at the outer marble contact; Zn:Cu ratios are close to 1:1 throughout. Local veins and patches of green garnet and wollastonite, accompanied by bornite-chalcopyrite-sphalerite, occur in marbleized limestone (Einaudi, 1978, personal notes). Garnet is absent from dolomitic members of the Martin Formation, where the dominant skarn association consists of serpentine, magnetite, chalcopyrite, and pyrite (J. L. Galey, 1978, personal communication).

The degree of skarn destruction in the Imperial stock area is relatively minor, in keeping with the dominance of potassium-silicate alteration and general lack of extensive hydrolytic alteration on the eastern side of the stocks. Skarn destruction is limited to veins and breccia dikes (up to 3 m wide), which consist of dense, purplish-black, jasperoidal silica containing garnet relics, finely and uniformly dispersed hematite, and veinlets and patches of chalcopyrite-quartz (Einaudi, 1978, personal notes). Silica-hematite replaces both skarn and marble, and is very similar to lesser occurrences at the Palo Verde mine.

Discussion

On a district scale, garnetite occurs in isolated blocks and patches of Paleozoic carbonate rocks engulfed by quartz monzonite porphyry along the northeast margin of the Alaskite batholith; this trend marks the position of Richard and Courtright's (1966) "major structure," and is located generally within the zone of potassium-silicate alteration as defined by Graybeal (1981). Garnetite occurs in carbonate rocks at contacts with alaskite, dacite porphyry, and quartz-monzonite porphyry, but is not continuous along all such contacts. The apparent lack of a systematic relationship between garnetite and igneous contacts suggests that: (1) some garnetite is metamorphic, dependent only on the presence of argillaceous limestone and a heat source; and (2) metasomatic skarns are related to fluids evolved from some, but not all, quartz monzonite porphyry stocks. The former possibility is supported by one analysis of garnet by Stewart (1912), which yielded grossularite and pyralspite contents (37.4 and 9.1 mole % respectively) not typical of porphyry-related ore skarns (Einaudi, 1982), and by evidence that extensive development of marble, wollastonite, and calc-silicate hornfels is related to the emplacement of dacite porphyry (S. L. Galey, 1978, personal communication; Graybeal, 1982). The latter possibility has been suggested by Graybeal (1982) with respect to the major area of mineralized garnetite located in the El Tiro-Imperial stock area. In this area the distribution of skarn and of Cu:Zn ratios appears related to the north-striking zone of >0.1 percent copper which passes through the El Tiro, Daisy, and North Silver Bell stocks (see Fig. 7.19). Graybeal has concluded that alteration-mineralization patterns were dominated by district-scale features, rather than by individual intrusive centers. Graybeal (1982) and Galey (1978, personal communication) have suggested that the development of ore-bearing andradite skarn and sulfide-actinolite veinlets in hornfels was broadly contemporaneous with potassium-silicate alteration in igneous rocks.

THE MORENCI DISTRICT

Ore deposits of the Morenci district are exclusively the result of supergene enrichment. The ores mined by underground methods in the years 1872 to 1932 consisted of high grade, exotic, oxide ores in limestone and supergene chalcocite ores in pyritic fissure veins. When open-pit mining commenced in 1942, lower-grade, disseminated, supergene chalcocite in porphyry was the sole source of copper (Moolick and Durek, 1966); it was still the only source in early 1981.

General Setting

Hypogene alteration-mineralization in the district is related to an intrusive complex consisting of a quartz monzonite porphyry stock intruded by a dike swarm of granite porphyry. The complex is exposed along a northeasterly trend for 16 km and varies in width between 1.5 and 6.5 km. Sedimentary strata exposed in the south-central portion of the district consist of a 300-m section of Paleozoic limestone, sandstone, and shale, overlain by sandstone and shale of Cretaceous age. The basal carbonate strata, of Late Cambrian to Late Ordovician age, include sandy limestone and dolomite of the El Paso Limestone and lower Montoya Group, which were included in the now-abandoned "Longfellow Limestone" of Lindgren (1905). These strata resemble the Abrigo in composition and bedding characteristics (Bryant, 1968); even the purest limestone beds contain significant quartz, dolomite, and argillaceous silt. According to Lindgren (1905) and Moolick and Durek (1966), the Longfellow is less susceptible to replacement by garnet skarn than the purer Modoc limestone (Lake Valley Formation), which occurs higher in the section, above an intervening unit of dark shale. The Modoc consists of gray limestone with lesser interbeds of sandstone and dolomite.

Porphyry

At the Morenci pit the quartz monzonite porphyry contains an elliptical enrichment blanket 1.5 km in diameter; Moolick and Durek (1966) have indicated that the protore below the enrichment blanket contains 3.5 to 8 percent pyrite —disseminated and in veinlets—in strongly sericitized porphyry. Minor sulfides include molybdenite, chalcopyrite, and sphalerite. Hypogene copper grade is 0.10 to 0.15 percent and zinc is present in concentrations only slightly less than copper. The pyrite:chalcopyrite ratio decreases to less than 1 at "considerable depth" (Moolick and Durek, 1966).

The description of altered rocks by Lindgren (1905), Reber (1916), and Moolick and Durek (1966) indicate that the Morenci porphyry exhibits moderately intense sericitic alteration at the surface, with pyrite-quartz-sericite largely restricted to envelopes on veinlets and larger pyrite-quartz fissures. The authors listed above all conclude that argillic alteration between sericitic selvages is largely supergene. There is no published evidence for the presence of advanced argillic alteration.

Sedimentary Rocks

In contrast with most porphyry-skarn deposits, the altered sedimentary rocks at Morenci appear to lack any large volumes of greater than 1 percent hypogene copper mineralization. According to Moolick and Durek (1966) high-grade ores mined in the period 1872 to 1932 consisted of two types: (1) irregular tabular bodies of oxide copper minerals in limestone or shale, which were the result of deposition from supergene fluids that leached copper from adjoining non-carbonate rocks (porphyry or skarn-hornfels); and (2) supergene chalcocite ore developed in quartz-sericite-pyrite fissure veins in non-carbonate rocks.

Alteration of calcareous strata at Morenci extends 500 to 600 m from the southern contact of the stock. In this zone abundant porphyry sills and dikes are propylitically altered and lack the strong sericitic alteration exhibited by the main body of the intrusive. Shale is altered to variable mixtures of quartz, kaolinite, amphibole, epidote, and pyrite. Limestone is replaced by calc-silicates up to 30 m from dike contacts. Except for epidote near porphyry, the Modoc skarns are dominated by honey brown to dark brown andradite (Lindgren, 1905). Chemical analyses of two samples from the Modoc horizon indicate a very low grossularite content (0.8 and 1.5% Al_2O_3). Wollastonite has not been reported to occur at garnet-marble contacts. Opaque minerals consist of disseminations and veinlets of magnetite, pyrite, chalcopyrite, and sphalerite; galena is rare. Magnetite locally is concentrated near porphyry or as replacement bodies in limestone. Calc-silicate rocks in the Longfellow Limestone contain more diopside and less garnet than the Modoc skarns (as would be expected, due to its higher dolomite content). Much of the garnet is greenish-brown in color and Moolick and Durek (1966) have suggested that it is aluminous. Calcite-diopside-tremolite hornfels, with disseminations and veinlets of magnetite, pyrite, and chalcopyrite occurs in the lower portion of the Longfellow Limestone in some areas; calcite-pyrite-magnetite veinlets are bordered by tremolite alteration envelopes (Lindgren, 1905). Local, small bodies of magnesian skarn, consisting of serpentine-magnetite, presumably replaced the more dolomitic members of the Longfellow Limestone.

THE ROBINSON MINING DISTRICT

The porphyry copper deposits of the Robinson mining district, also known as the Ruth or Ely district, produced over 255 million tons of 1.1 percent copper ore in the period 1908 to 1963. Some 20 percent of this production was from skarn in carbonate rocks and from hornfels in shale; after 1962, the proportion of skarn ore relative or porphyry ore increased. Thus, in the 1960s and 1970s Ely ranked as one of the major skarn ore districts in North America.

The major sources of geological data on the district include general reviews by Bauer and others (1964, 1966) and detailed studies of altered igneous rocks by Fournier (1967*a*, 1976*b*) and of altered sedimentary rocks by James (1976).

General Setting

According to Bauer and others (1964), a pre-intrusive thrust fault separates the Chainman Shale of Mississippian age from the overlying Ely Limestone of Pennsylvanian age from the Rib Hill Sandstone of Permian age. The fault zone apparently controlled the emplacement of irregular porphyry plugs and sill-like bodies in Mid-Cretaceous time. Post-ore faulting resulted in approximately 50 percent extension and accentuated the east-west trend of the zone of intrusion and mineralization (James, 1976). Faulting also preserved different structural elevations of the original mineralized column (Figs. 7.20 and 7.21); carbonate rocks at Ely display both typical skarn associated with biotite-orthoclase-altered porphyry, and massive silica-pyrite impregnation associated with intensely sericitized porphyry (James, 1976). Thus, Ely forms an important link between the classic porphyry-skarn environment of districts such as Bingham or Mission, and the massive limestone replacement ores at Bisbee.

Base and precious metal replacement deposits occur in a broad belt, 3 km wide, which extends 15 km westward from the town of Ely along the porphyry intrusive trend; production from these peripheral deposits amounted to less than 1 million tons of ore (Bauer et al., 1966).

Porphyry

Alteration-mineralization in igneous rocks is extremely variable, depending in part on level of exposure. Originally deep zones of quartz monzonite, exposed at the surface or intercepted in drill core, reveal fresh magmatic minerals; the adjacent limestone is recrystallized or metasomatically altered over widths of a few centimeters. Major portions of the stocks contain hypogene, ore-grade copper mineralization associated with biotite-orthoclase alteration; pyrite:chalcopyrite ratios average around 4:1 (Bauer et al., 1964) and bornite occurs locally with chalcopyrite. Such high pyrite:chalcopyrite ratios are not characteristic of potassic alteration in porphyry deposits, and at Ely they reflect a sulfidation

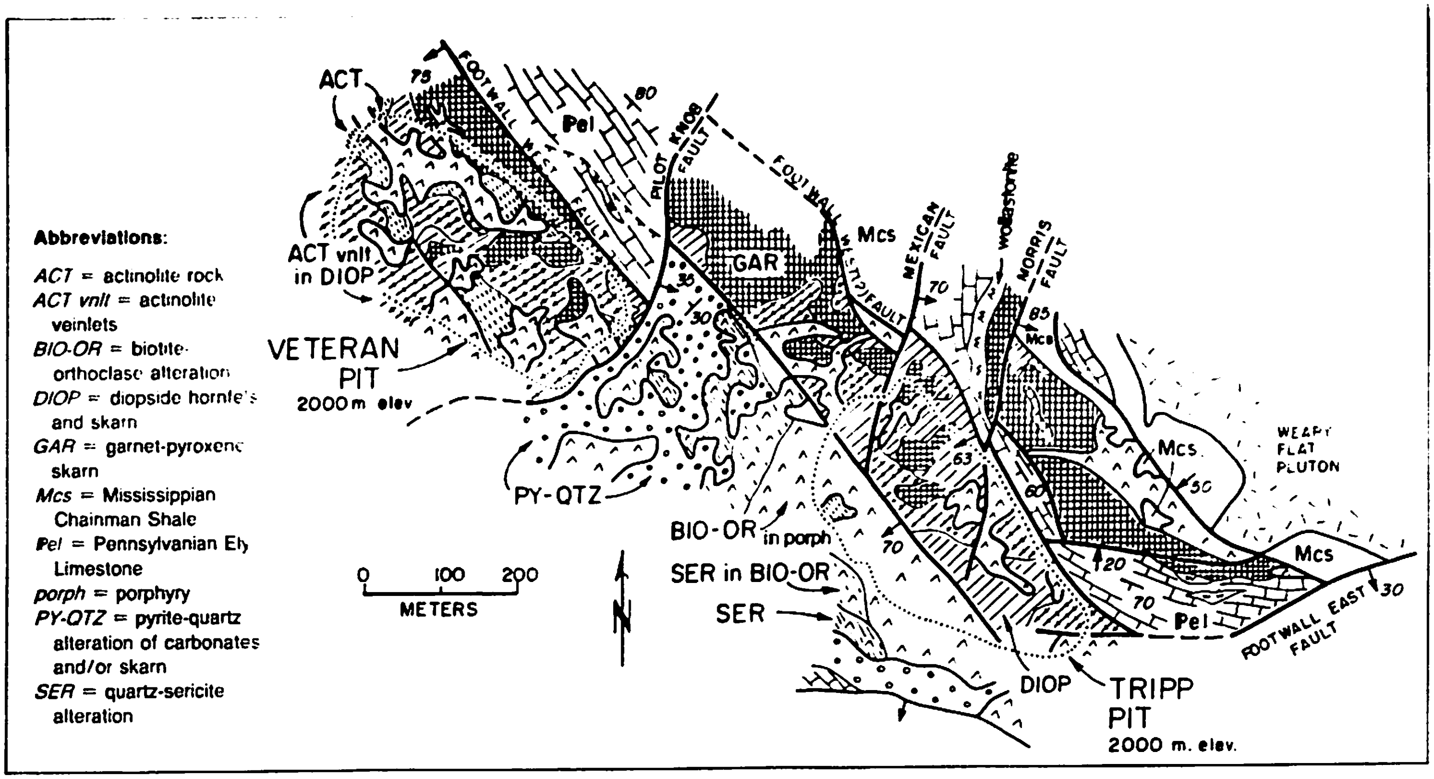


Figure 7.20. Surface geology in the area of the Tripp and Veteran pits in the Robinson (Ely) mining district, Nevada, illustrating the distribution of garnet-pyroxene skarn, diopside, and actinolite veinlet alteration relative to potassium-silicate alteration in porphyry; and the distribution of silica-pyrite alteration of limestone relative to sericitic alteration of porphyry. Redrawn from James (1972).

event accompanying the hydrolytic alteration of plagioclase to montmorillonite-sericite-kaolinite mixtures.

In the uppermost portions of open pits and in fault blocks which can be interpreted to have been originally at a high level relative to biotite-orthoclase alteration, the porphyry is intensely altered to a porous quartz-sericite-pyrite aggregate with subordinate (sub-ore grade) chalcopyrite. Areas of pervasive sericitic alteration grade into biotite-orthoclase alteration cut by quartz-sericite-pyrite veinlets.

Sedimentary Rocks

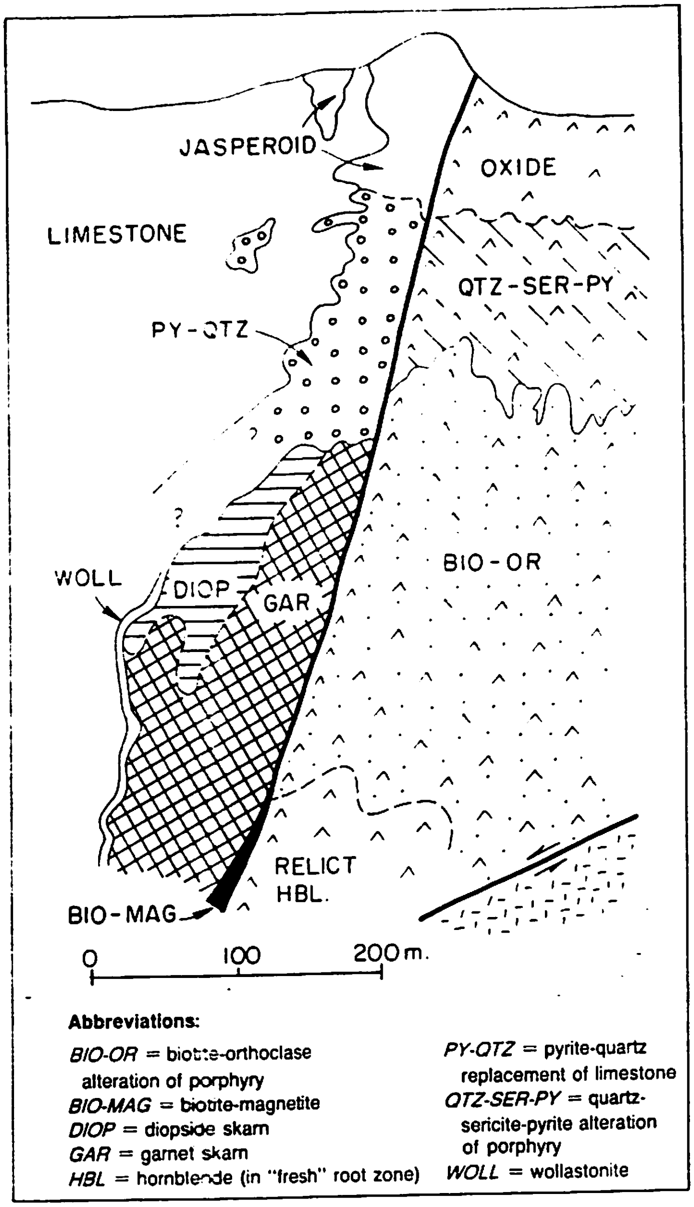
Two major alteration and mineralization styles occur in sedimentary rocks: calcic skarn and silica-pyrite.

Calcic Skarn. Limestone adjacent to biotite-orthoclase alteration displays a fairly typical skarn assemblage extending outward about 100 m (see Fig. 7.20). According to James (1976), garnet tends to occur near igneous contacts and gives way to garnet-pyroxene as the marble is approached. Red-brown garnet, associated with small amounts of interstitial quartz, calcite, and sulfides, generally contains greater than 90 mole percent andradite (James, 1976; Huang, 1976). A few fluid inclusions in garnet and in quartz-sulfide veinlets cutting garnet without alteration envelopes were studied by Huang (1976); homogenization temperatures ranged from 420 to 575°C. Diopsidic pyroxene, with generally less than 6 mole percent hedenbergite forms light green, fine-grained masses with interstitial quartz and local garnet veinlets.

The contact between skarn and marble locally is marked by a 5- to 10-m-thick zone of wollastonite-quartz with minor diopside, idocrase, and green garnet. Local zones within green garnets associated with wollastonite contain up to 50 mole percent grossularite (James, 1976). In many areas, wollastonite is absent, and skarn gives way to marble with local beds and masses of diopside-saponite-quartz-calcite, garnet-calcite-idocrase with minor fluorite, or pyrrhotite-magnetite-pyrite with local siderite. Small amounts of galena and sphalerite are common in the skarn-marble transition, but do not occur in economic concentrations. Beyond the skarn, bleaching and recrystallization, accompanied by local white clay, occur up to 300 m from known mineralized stocks.

The majority of copper mineralization in skarn is related to quartz-calcite-sulfide-magnetite veinlets concentrated within about 60 m of contacts with mineralization porphyry (Bauer et al., 1964; James, 1976). James (1976) has described the alteration selvages associated with these veinlets, which he has defined as the "clay-sulfide" stage, and has documented their dependence on original skarn mineralogy: in garnet rock, alteration envelopes are largely nontronite-calcite-quartz with lesser magnetite-calcite-quartz and actinolite; in diopside rock, envelopes are largely actinolite-calcite-quartz. The actinolite, which ranges from 17 to 31 mole percent ferroactinolite (James, 1976; Huang, 1976), locally replaces large volumes of diopside rock. In some areas, magnetite veinlets with talc-calcite-quartz alteration envelopes cut actinolite rock. At igneous contacts, actinolite skarn is replaced by phlogopite containing 15 to 33 mole percent annite.

James concludes that the "clay-sulfide" stage of alteration was synchronous with biotite-orthoclase alteration of igneous rocks. However, it is not clear whether actinolite and biotite alteration of diopsidic skarn and calcite-quartz-magnetite alteration of garnetite, which are included in the "clay-sulfide" stage, are synchronous with the formation of nontronite and ferro-saponite. A characteristic feature of many porphyry-related skarns is the presence of dark green actinolite alteration veinlets lacking brown, clay-altered diopside rock. Although this relation could be interpreted as the result of contemporaneous, zoned, actinolite-clay alteration of diopside, the common occurrence of identical actinolite veins in fresh diopside rock suggests that actinolite and clay alteration generally are not age-equivalent. The contemporaneity of actinolite alteration of diopside and biotitic alteration of the stock is convincingly illustrated in a sketch by James (1976, p. 502) of veinlet relations at skarn-stock contracts and is analogous to age relations observed at Bingham and Christmas. Clay alteration of diopside, with actinolite remaining stable, could then have occurred during the trend toward a hydrolytic base-leaching environment at lower temperatures, which resulted in sericitic-argillic alteration of plagioclase in the stock.



Abbreviations:

BIO-OR = biotite-orthoclase alteration of porphyry
BIO-MAG = biotite-magnetite
DIOP = diopside skarn
GAR = garnet skarn
HBL = hornblende (in "fresh" root zone)
PY-QTZ = pyrite-quartz replacement of limestone
QTZ-SER-PY = quartz-sericite-pyrite alteration of porphyry
WOLL = wollastonite

Figure 7.21. Schematic projection of mineral zoning in porphyry and limestone in a reconstructed (unfaulted) vertical cross section of the Robinson (Ely) mining district, Nevada. Redrawn from James (1976).

The above argument is supported to some extent by the geothermometric studies of Huang (1976). Huang found considerable variation in homogenization temperatures of fluid inclusions in quartz from clay-sulfide stage veinlets (with the majority falling in the range 275 to 475°C), and suggested that either boiling or appreciable temperature changes may have occurred. Ten samples, selected on the basis of internal consistency within a given sample, yielded temperatures of 315 to 445°C. Only 3 of the samples contained clay; the remainder contained quartz-calcite-sulfide-magnetite, with or without actinolite or biotite. Huang also attempted to define the temperature of the clay-sulfide stage by applying oxygen isotope fractionation factors to analyses of quartz-magnetite pairs. Although 9 determinations (355–465°C) fell in the general range of temperatures suggested by fluid inclusions in quartz of the clay-sulfide stage, 12 determinations were considerably higher (487–663°C) and fell in the range of temperatures determined from fluid inclusions of the main skarn stage. The implication is that: (1) veining of garnet-pyroxene skarn by quartz-sulfide-magnetite veinlets occurred over a broad range of temperatures and fluid compositions; (2) a significant amount of this veining occurred in the temperature range typically recorded by fluid inclusion studies of biotite-orthoclase alteration in porphyry systems and may well have been synchronous with such alteration; and (3) alteration of anhydrous calc-silicates along margins of these veinlets to calcite and/or actinolite-bearing quartz-magnetite-pyrite assemblages could have occurred during potassic alteration of the stock.

Silica-Pyrite. James (1976) has documented a close correlation of intense sericitic alteration of porphyry with massive quartz-pyrite replacement of limestone (see Fig. 7.20). One analysis of typical quartz-pyrite alteration yields, in weight percent: 28 percent quartz, 23 percent pyrite, and 48 percent calcite. Nontronite and siderite are present in minor amounts. In some cases, remnant sedimentary textures and patches of limestone indicate that quartz-pyrite replaced limestone; in other cases, it appears that quartz-pyrite replaced skarn. Relict skarn minerals, such as diopside, actinolite, and andradite, were noted near porphyry containing relict biotite-orthoclase alteration; these minerals suggest a transition to deeper skarn, although this transition was not directly observed.

THE MINERALIZED ZONE AT CANANEA

Cananea is located in north-central Sonora, 80 km by road from Bisbee, Arizona. The mineralized zone, 10 km long and 3.5 km wide, follows a northwesterly-striking belt of Laramide quartz porphyry stocks. Within this belt are located the mined-out, high-grade "plums" of the Capote and La Colorada breccia pipes and the immense tonnages of

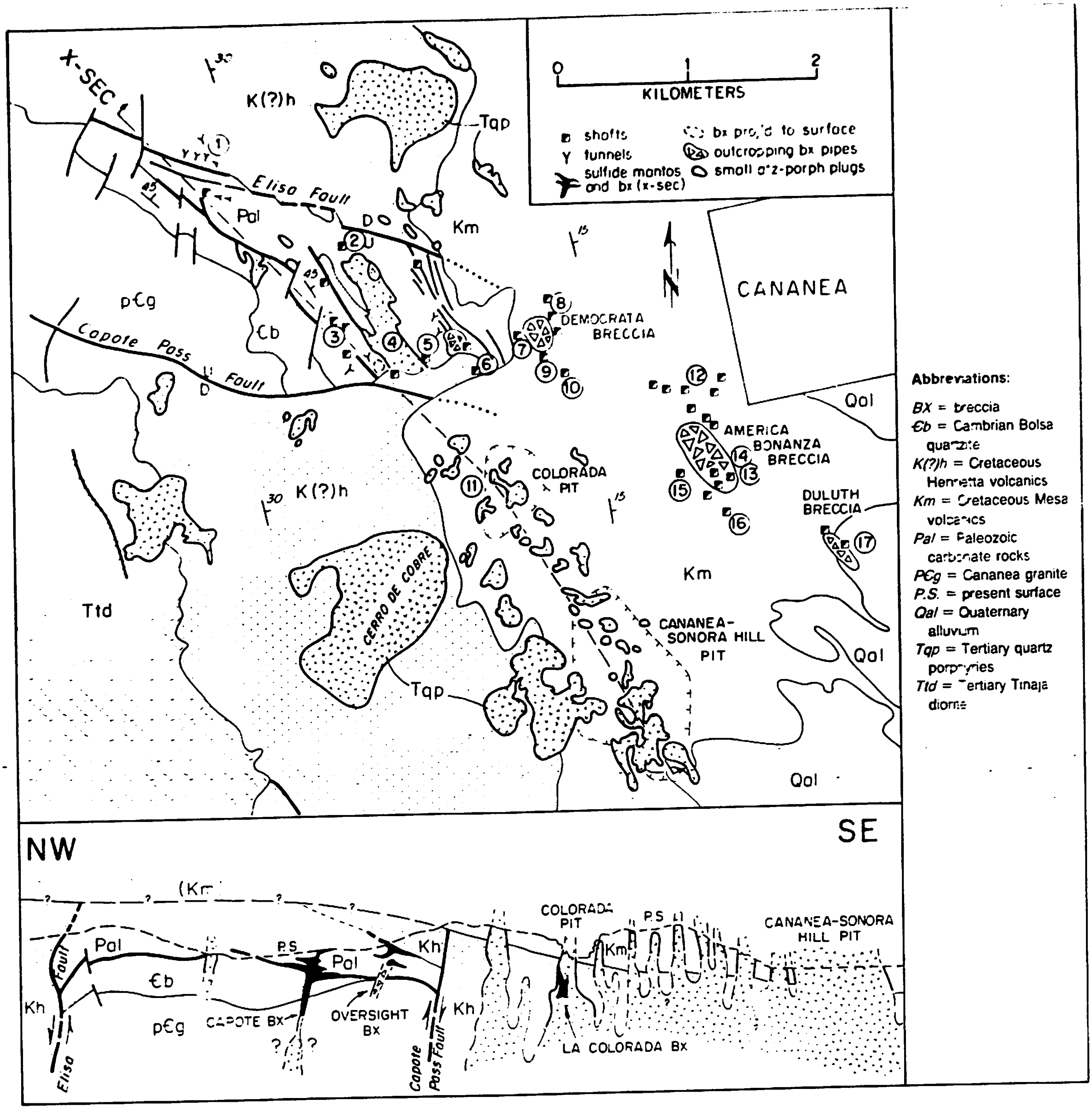


Figure 7.22. Generalized surface geology and cross section (looking northeast) of the Cananea mining district, Sonora, Mexico. The maps illustrate the location of: (1) supergene copper ores associated with the northwest-trending line of quartz porphyry plugs in Mesa volcanics at Colorada-Veta and Cananea-Sonora Hill pits; (2) ore breccia pipes in volcanic terrain at Duluth, America Bonanza, and Democrata; and (3) manto and breccia ores in Paleozoic carbonate rocks of Capote Basin horst. Mine locations: ① Elisa mine tunnels, ② Campana shaft, ③ Capote No. 2 shaft, ④ Capote No. 17 tunnel (Oversight), ⑤ Esperanza No. 1 shaft, ⑥ Veta Grande No. 5 shaft, ⑦ Democrata shaft, ⑧ Cobre Grande No. 5 shaft, ⑨ Kirk No. 9 shaft, ⑩ Kirk No. 10 shaft, ⑪ La Colorada shaft, ⑫ Cobre Grande shaft, ⑬ Cananea Central shaft, ⑭ Bonanza No. 1 shaft, ⑮ Bonanza No. 2 shaft, ⑯ Bonanza No. 3 shaft, ⑰ Cananea Duluth shaft. Based on Emmons (1910), Valentine (1936), and Velasco (1966).

disseminated ores that in 1981 were being mined at the Colorada-Veta and Cananea-Sonora pits. Twenty-year open-pit ore reserves in the latter area, published by Anaconda (Proxy Statement, 1976), were 213 million tons of 0.75 percent Cu; a substantially larger resource of approximately the same grade was estimated to exist beyond the reserves. Later figures indicated reserves of 1,500 million tons of 0.7 percent Cu (Maravilla, 1978).

General Setting

Pre-Laramide rocks exposed at Cananea include Precambrian granite, Paleozoic sedimentary rocks and Mesozoic(?) volcanic rocks. A 1,000-m-thick section of Paleozoic quartzite and limestone (see Fig. 7.2), which has been correlated with the Paleozoic section at Bisbee by Mulchay and Velasco (1954), is exposed in a west-northwest–trending horst, known as Capote Basin (Fig. 7.22). Here, the strata dip moderately to steeply northeast. North and south of the horst, the Paleozoic rocks are unconformably overlain by a minimum of 1,700 m of Mesozoic(?) tuffs and flows of dacitic to latitic composition which dip 30°ENE (Henrietta Formation of Valentine [1936]).

An older set of faults, which pre-dated the outpouring of Henrietta volcanics, are exposed in Capote Basin; they strike N45°W, and repeat the Paleozoic section to the northeast (e.g., Ricketts fault, Fig. 7.23). Younger faults (e.g., Capote Pass and Elisa faults, see Fig. 7.22) strike N20°W and dip vertically; these form the Capote Basin horst, and are post-Henrietta and pre-Laramide in age.

Laramide igneous activity, which extended from approximately 70 to 56 m.y. ago (Damon, 1965; Anderson and Silver, 1977), produced: (1) a complex series of equigranular diorite, granodiorite, and syenite plutons, which are largely exposed in the more deeply eroded terrains in the west-central portion of the range (e.g., Tinaja Diorite; see Fig. 7.22); (2) dominantly andesitic flows and tuffs of the Mesa Formation, which are preserved on the eastern range front, where they dip 15°ENE; and (3) a younger series of small quartz-porphyry stocks, plugs, and breccia pipes which are broadly contemporaneous with hydrothermal alteration-mineralization.

Emplacement of quartz porphyries was controlled on a district scale by the older, N45°W-striking faults, and this trend was especially marked by the belt of porphyry plugs extending through the Cananea–Sonora Hill and Colorado-Veta pits (see Fig. 7.22). On a local scale a set of north- to north-northeast-striking faults, with negligible displacement, and which are presumably of Laramide age, guided the emplacement of porphyries, breccias, and mineralization (Valentine, 1936).

Porphyry

Designation of the porphyries as quartz porphyries reflects their highly altered state; in fact, Schwartz (1947) had indicated that the Cananea porphyries represent the most completely sericitized rocks of the group of southwestern North American porphyry copper deposits he has studied. Work by Ochoa and Echavarri (1978) in the Colorado-Veta pit area suggests that the porphyries consist of at least four separate intrusive phases, ranging in composition from grandiorite to quartz monzonite.

Pervasive hypogene sericitic alteration of porphyry and andesitic wall rocks at the surface is centered on the belt of porphyry plugs. The presence of widespread hypogene alunite (Varela, 1972; Ochoa and Echavarri, 1978) suggests that advanced argillic alteration may be present in significant

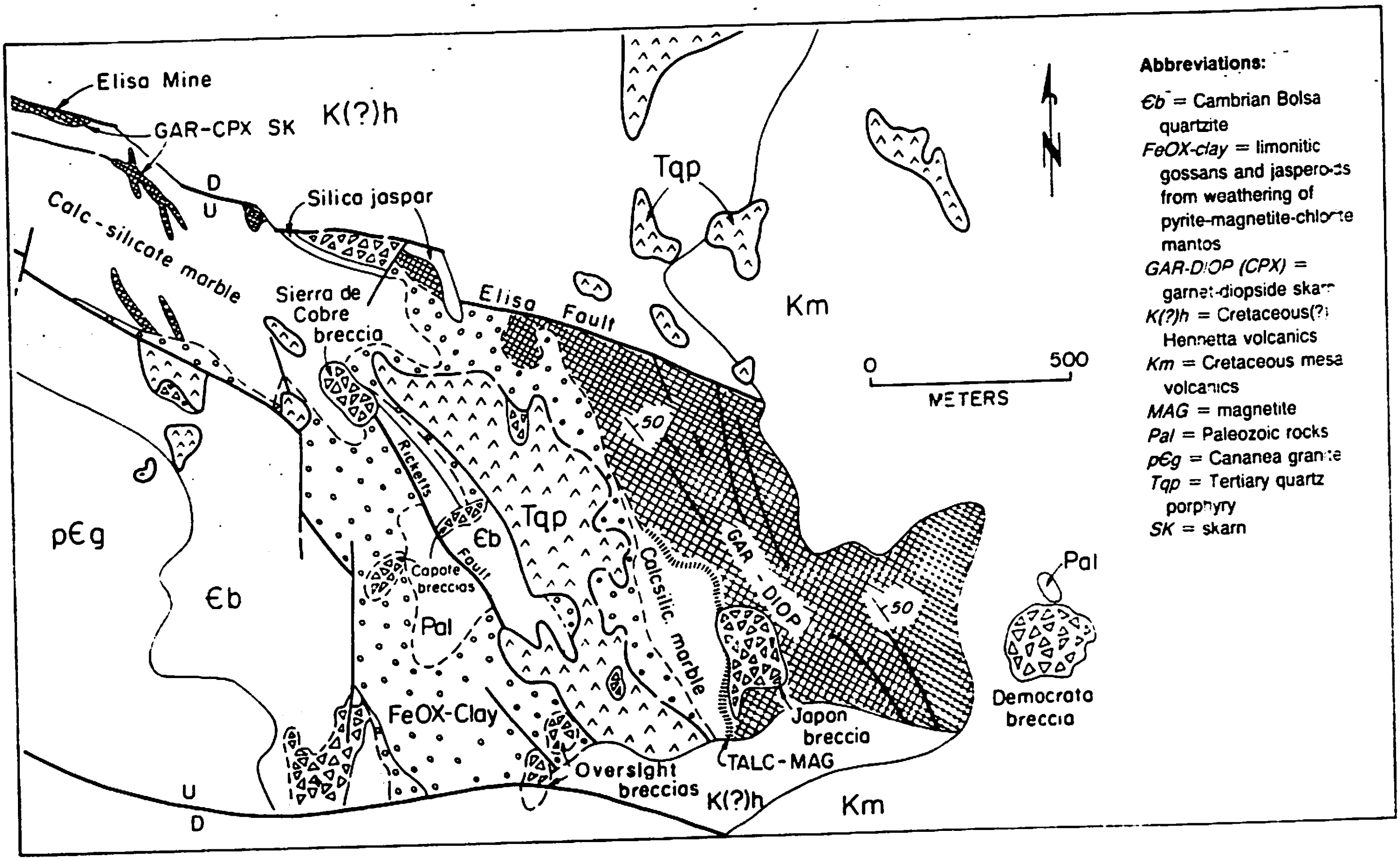


Figure 7.23. Preliminary geologic map of Capote Basin in the Cananea mining district, Sonora, Mexico, illustrating close spatial relation between pervasively sericitized porphyry, mineralized breccia pipes, and pyrite-magnetite-chlorite manto replacement bodies in carbonates. Skarn and calc-silicated marble appear as an earlier event. Based on L. D. Meinert (1977–1978, unpublished).

proportions within the broader sericitic zone, although replacement of sericite by kaolinite or pyrophyllite has not been reported. Quartz-sericite-pyrite alteration at the surface grades outward into propyllitic alteration at distances of approximately 250 m from porphyry contacts and diminishes in intensity with depth, so that at 500 m below the surface, the porphyries contain common fresh K-feldspar, biotite, negligible veining, and less than 1 percent sulfides—largely pyrite (Varela, 1972). Although the intensity of supergene chalcocite replacement renders it difficult to estimate the original content of chalcopyrite, it would appear that the majority of porphyries contained only trace amounts of hypogene copper-iron sulfides. Some porphyries, however, such as the Colorado quartz porphyry types described by Ochoa and Echavarri (1978), appear to have been the main sources of both chalcopyrite and molybdenite, and some deep drill holes have encountered significant intervals of copper-iron sulfide concentrations associated with an early (pre-sericite) generation of quartz veins and quartz breccias (R. Velasco, 1978, personal communication). The evidence suggests, however, that no broad zone of intense potassic alteration associated with disseminated copper mineralization with grades in excess of 0.2 percent Cu was ever formed at Cananea. Rather, copper was concentrated in structural openings —largely breccia pipes.

La Colorada Breccia

In 1926 La Colorada pipe was discovered; this extraordinary hypogene orebody was sacrificed at low copper prices to keep Anaconda in operation during the Great Depression. A series of papers by Perry (1933, 1935, and 1961) have summarized various aspects of La Colorada and other breccia pipe deposits at Cananea; sulfide paragenesis was studied by Kelley (1935). High-grade copper ore at La Colorada was enclosed in a pegmatitic quartz-phlogopite sheath located within a subsidence breccia near the apex of a quartz porphyry plug emplaced in volcanic rocks. During an early stage, a ring of massive molybdenite-chalcopyrite-bornite-chalcocite ore formed inside the quartz shell. Pyrite was concentrated peripherally and in overlying quartz veinlets during this early stage, and low-grade mineralization, consisting of quartz-chalcopyrite-molybdenite veinlets, extended downward at least 500 m below the ore pipe. A late stage is represented by the formation of pyrite-alunite veins containing luzonite, tennantite, covellite, sphalerite, and galena within the massive sulfide ring and by the formation of a brecciated core in the upper levels containing fragments of early sulfides altered to luzonite-tennantite and cemented by alunite and clays. A halo of silicification and sericitization, containing abundant alunite, extends 15 to 60 m outward into quartz porphyry on the bottom levels. Intense alkali-leaching alteration and sulfide mineralization do not extend above the top of the deposit, which was located 200 m below the pre-pit surface; the deposit at La Colorada had little surface expression, other than sporadic areas of slump breccia and quartz veinlets.

Thus, the sequential change from relatively low-sulfur assemblages, chalcopyrite-bornite-chalcocite and molybdenite-chalcopyrite-pyrite, to relatively high sulfur assemblages, containing luzonite and sphalerite, with parallel changes in gangue mineralogy from pegmatitic quartz-phlogopite to quartz-sericite-alunite, is especially well documented at La Colorada. Similar changes can be inferred for the quartz-porphyry belt as a whole.

Ores in Carbonate Rocks

The monumental treatment of Cananea geology by Emmons (1910) remains the best source of published data on the high-grade ores mined in Capote Basin during the turn of the century. The correlation of alteration-mineralization events in the volcanic terrain of the quartz-porphyry belt with events in the carbonate terrain of Capote Basin can be stated only in broad terms on the basis of published information. However, mapping by L. D. Meinert (1977–1978, personal communications) had yielded a sounder framework for such a correlation; some of his preliminary results are incorporated in Figure 7.23 and in the discussion which follows.

Emmons (1910) cast the ores occurring in carbonate rocks of Capote Basin into two general categories: (1) Skarn deposits, such as the Elisa and Puertecitos mines (see Fig. 7.22), in which bornite and chalcopyrite were the dominant copper-bearing sulfides, chalcocite enrichment locally was important, and hypogene grades averaged around 3 percent Cu; and (2) siliceous pyrite bodies in breccias or replacing limestone, such as the Capote, Oversight, Esperanza, and Veta Grande mines (Fig. 7.22), in which sphalerite locally was abundant, chalcopyrite occurred in small amounts, and supergene chalcocite enrichment was necessary to achieve ore grades. Perry (1933) has described the Capote orebody as a vertical breccia pipe cutting Precambrian granite and Cambrian quartzite at depth and grading into massive sulfide replacement bodies in limestone near the surface (see Fig. 7.22, cross section). The breccia, which extends over a known vertical interval of 350 m, contains mineralized angular fragments of porphyry and wall rock cemented by quartz, carbonates, pyrite, chalcopyrite, bornite, and chalcocite. The replacement ore, which occurs within 120 m of the surface, has been described by Emmons (1910) on one level as consisting of a supergene-enriched pyritic body, 100 m long and 50 m wide, containing 20 percent copper. Emmons has estimated that the copper grade of protore in the siliceous pyrite bodies of Capote Basin was less than 2 percent overall. Emmons concluded that these two deposit types represented successive periods of mineralization. He based this conclusion on the presence of transitional types, such as the Democrata, West Cobre Grande, and Kirk mines (see Fig. 7.22) in which early skarn, with minor bornite and sphalterite, was brecciated and cemented by quartz-pyrite, with minor chalcopyrite. In these ores he recognized the successively less important role of skarn formation and the increasing role of low-grade silica-pyrite mineralization.

On the district scale, according to Meinert, calcic skarn (Ad$_{65-100}$, Hd$_{10-30}$) was preceded by skarnoid (Ad$_{15-50}$, Hd$_{5-15}$), and both calc-silicate–forming events preceded the emplacement of quartz porphyry and breccias at the present level of exposure in Capote Basin. Skarn is restricted to the easternmost portion of the Basin, where it replaces Escabrosa Limestone (Puertecitos Formation of Mulchay and Velasco

[1954]), and does not occur as an envelope on the Capote quartz porphyry (see Fig. 7.23). Carbonate rocks in contact with quartz porphyry are recrystallized to marble and replaced by chlorite. The general area that includes porphyry and breccia pipes is a locus not of skarn, but of manto-type replacement bodies containing largely magnetite and pyrite, a lesser amount of chalcopyrite and specularite, and a gangue of calcite, quartz, and chlorite. Early skarnoid and hornfels are converted to epidote, chlorite, and clays. This type of alteration-mineralization extends in a discontinuous fashion for 3 km in thin-bedded, limestone-skarnoid-hornfels sequences of the Abrigo Formation (Esperanza Limestone of Mulchay and Velasco [1954]) from the deep levels of La Colorada mine on the southeast to the Elisa mine on the northwest (see Fig. 7.22). Weathering at the surface, particularly of the more pyritic zones, yields variable mixtures of iron-oxide, clays, and jasperoidal silica (shown as FeOX-Clay on Fig. 7.23).

The contemporaneity of manto replacement bodies in limestone, the destruction of skarnoid, and the deposition of pyrite-quartz in brecciated skarn with emplacement of quartz porphyry plugs and breccia pipes is suggested by Meinert's data. An intriguing unresolved question is the timing of skarn formation relative to older intrusive events.

THE BISBEE DEPOSIT

Within the group of deposits considered in this chapter, Bisbee fits at the end of the scale toward increasing sulfidation and hydrolytic alteration. The Sacramento stock, a complex of porphyries and intrusive breccias, was emplaced in Cambrian to Premain carbonate rocks (see Fig. 7.2). Hypogene ore containing greater than 3 percent Cu occurs in intrusive breccias and is associated with quartz-pyrite replacement bodies in limestone up to 2 km from the stock contact (Fig. 7.24).

Porphyry-Breccia Complex

Although large tonnages of low-grade, disseminated ore have been mined from intrusive rocks, this ore is exclusively supergene in origin. The primary mineralization-alteration bears little resemblance to the "typical" porphyry copper deposit. According to Bonillas and others (1917) and Bryant (1964, 1968), the primary ore consists largely of massive pyrite-bornite, with minor chalcopyrite, distributed erratically as isolated pods and lenses in highly silicified and sericitized intrusive breccias. The quartz porphyry is pervasively altered to a typical advanced argillic assemblage consisting of quartz-pyrophyllite-sericite with 15 to 18 percent pyrite and

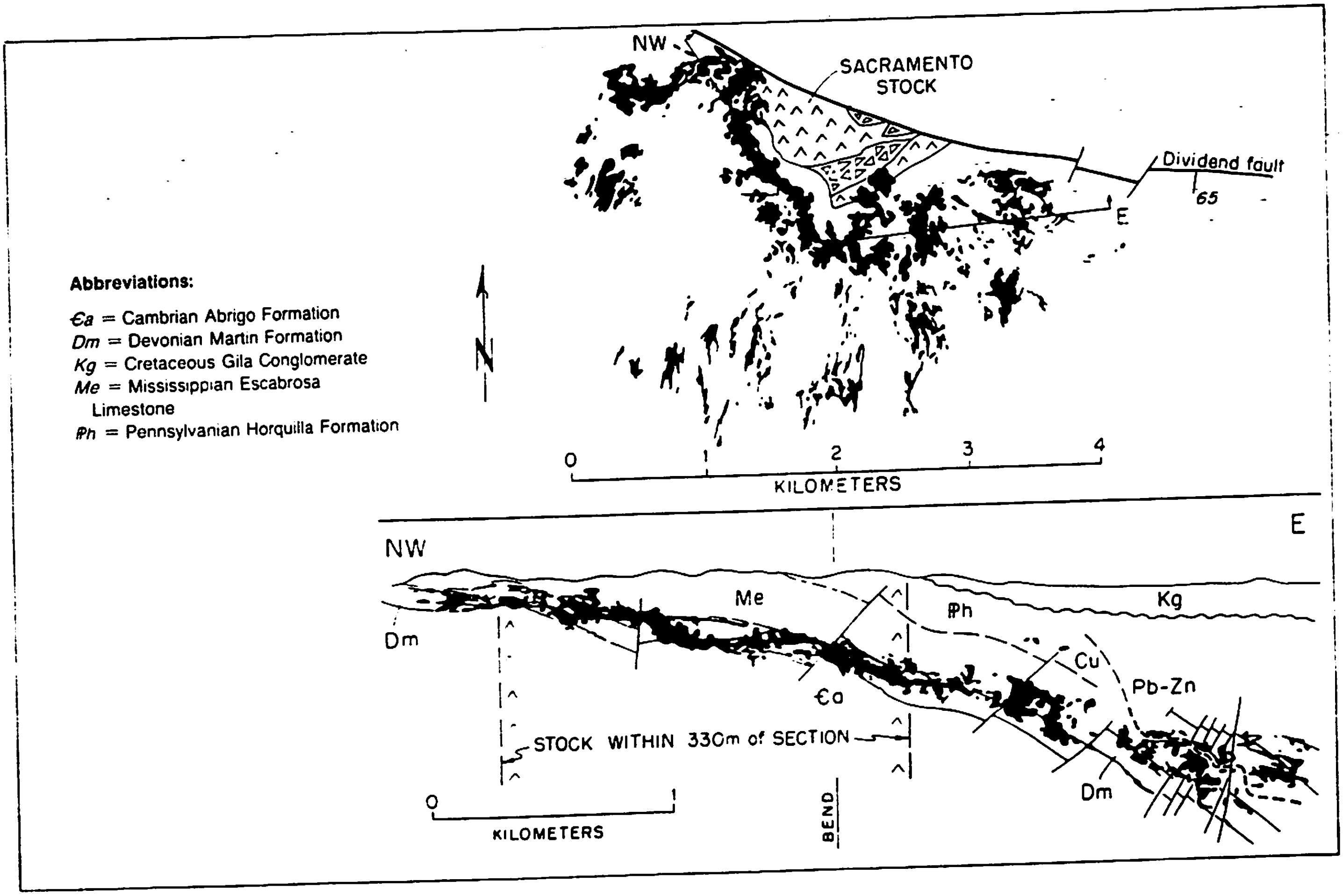


Figure 7.24. Projection of copper and lead-zinc stopes (black) in carbonate rocks to a horizontal plane (*top*) and vertical section (*bottom*) in the area of the Sacramento pit in the Bisbee mining district, Arizona. Only those stopes within 140 m of line of section (*top*) are projected onto vertical section (*bottom*). The figure illustrates the close spatial association of massive sulfide ores of copper in limestone (without skarn) with the porphyry-breccia complex of the Sacramento stock. Based on Bryant (1964).

accessory alunite, dickite, diaspore, and barite (Bryant, 1964). Local occurrences of pyrite-chalcopyrite veinlets with quartz-sericite-chlorite selvages in less-altered quartz-feldspar porphyry are reminiscent of sericitic alteration in the porphyry copper deposits, but there are no published accounts of potassium-silicate alteration.

It is conceivable that advanced argillic alteration destroyed the evidence of an earlier potassic stage. However, if the association of andradite-salite (± magnetite, chalcopyrite) skarn with potassium silicate alteration is accepted as the general case, then the apparent absence of skarn at Bisbee argues against the development of potassic alteration at the present level of exposure.

Sedimentary Rocks

According to Ransome (1904) calc-silicates occur as microscopic grains in greenish marble up to 350 m from the stock; the dominant silicates are tremolite and chlorite, with accessory grossularitic (?) garnet, diopside, and idocrase. These silicates are most prominent in the impure, shaly-sandy limestone of the Abrigo and Martin formations (Bonillas et al., 1917), and it is probable that they are entirely of metamorphic origin. The contact between the porphyry-breccia stock complex and relatively pure Escabrosa Limestone is characterized by only a narrow fringe of calc-silicates developed in marble. Locally up to 60 m from the stock, the marble is replaced by a granular aggregate of quartz-pyrite-calcite. The possibility that this zone represents the destruction of andradite skarn is not suggested by the published descriptions.

According to Trischka (1938) and Bryant (1964), the sulfide replacement bodies in limestone occur as pipe-like and ovoid masses, often associated with dikes and sills of porphyry or intrusive breccia, and are controlled by bedding and cross faults (see Fig. 7.24). The ores extend beyond the zone of contact silicates. The massive sulfide bodies are zoned from quartz-pyrite cores, which average less than 1 percent Cu, to intermediate pyrite-chalcopyrite ± bornite ore, to fringes of pyrite-sphalerite-galena. In some localities, specularite occurs between sulfides and limestone. Analyses of ore (Bonillas et al., 1917) indicate approximately 10–15 percent quartz, 15 percent copper-iron sulfides, and 50 percent pyrite. The ores in limestone at Bisbee, thus, are remarkably similar to the silica-pyrite zones at Ely and the manto ores at Cananea.

CONCLUSIONS

The data on ores in carbonate rocks associated with porphyry plutons indicate that, if the "noise" due to variability in original sedimentary lithologies, multiple intrusions, and early metamorphic events can be filtered out, the changes of alteration-mineralization with time can be correlated directly with events in the associated plutons. Table 7.10 summarizes these correlations.

Given a pluton displaying potassium-silicate alteration, the mineral associations in carbonate rocks can be predicted solely on the basis of original sedimentary lithology. Limestone develops andraditic garnet and diopsidic clinopyroxene with pyrite, chalcopyrite, and magnetite; outer zones may or may not contain wollastonite, but are consistently depleted in pyrite and enriched in bornite (without pyrite), sphalerite, pyrrhotite, and tennantite relative to garnet zones. Dolomite develops forsterite-serpentine-magnetite chalcopyrite skarn. Pyroxene hornfels is altered to actinolite and biotite along pyrite-chalcopyrite ± magnetite veinlets. The conclusion is

TABLE 7.10
Correlation of Generalized Stages of Skarn Evolution in Porphyry Copper Deposits

Temperature Range, °C	Intrusive Rocks	Sedimentary Rocks
900–700	Intrusion of melt	Some reaction with dolomite or, rarely, with limestone; no extensive skarn formed
700–500	Crystallization of pluton margins; emplacement of pre-skarn dikes	Metamorphism: decarbonation-dehydration reactions form light-colored silicates in impure carbonates: diopside forms in dolomitic siltstone; wollastonite (± diopside, grossularite, idocrase) in shaly limestone
600–400	Release of metasomatic fluid in partially solidified & fractured pluton; beginning of potassic alteration and disseminated chalcopyrite	Skarn formation proceeds outward along fissures, pre-skarn dikes, sedimentary contacts, permeable horizons: andradite-salite replaces wollastonite-diopside; magnetite replaces andradite near stock; interstitial sulfides. Actinolite-sulfide veinlets in fractured diopside hornfels
500–300	Continued potassic alteration; transition to sericitic. Disseminated and veinlet chalcopyrite-pyrite, molybdenite-pyrite	Ore deposition occurs before new skarn formation has ceased and continues during early skarn destruction: andradite → magnetite, quartz, pyrite, calcite, (actinolite); diopside → actinolite, calcite, quartz; early chalcopyrite remobilized into veins
350–200	Sericitic alteration accompanies influx of meteoric water; pyrite (± chalcopyrite) in veins. Local advanced argillic alteration	Retrograde alteration of skarn, during and after late stages of ore deposition, forms chlorite, montmorillonite, quartz, calcite, hematite, pyrite; peripheral sphalerite-galena-tennantite veins. Local silica-pyrite replacement bodies

Source: Based on Burt (1972, 1977), James (1976), Atkinson and Einaudi (1978).

NOTE: Emphasis is on calcic skarn.

that the physiochemical characteristics of hydrothermal fluids associated with potassium-silicate alteration in porphyry copper plutons were remarkably similar in the deposits considered.

Variability between porphyry-related skarn deposits largely involves the degree of retrograde alteration and is expressed in porphyry copper deposits in general by the degree of sericitic alteration (e.g., the "variation on a theme" of Gustafson and Hunt [1975]). Early stages of retrograde alteration of anhydrous skarn silicates probably are correlatable with the waning of potassic alteration and the beginning of sericitic; the dominant alteration products are quartz-magnetite (± pyrite, calcite) after andradite, and actinolite after salite. Sulfides are dominantly chalcopyrite with lesser pyrite. Later stages of retrograde alteration, correlated with main sericitic alteration in the pluton, involve increasing amounts of montmorillonoids (nontronite or ferrosaponite), chlorite, siderite, calcite, and hematite, accompanied by increasing pyrite and lesser chalcopyrite, tennantite, and sphalerite. The retrograde vent overprints the early skarn along zones of high permeability, which tend to occur along contacts with the pluton.

Skarns containing high-grade copper mineralization associated with unaltered garnet and pyroxene, such as Christmas and some portions of deep skarn at Carr Fork (Bingham) probably were mineralized prior to any retrograde alteration; in these cases, the better-grade zone tends to occur near the marble contact and a lower-grade garnet zone occurs near the stock. This spatial distribution may be the result of high temperatures near the stock, combined with the tendency for ferrous-clinopyroxene and/or calcite to be more abundant near marble. The latter could control the solubility of sulfides due to a decrease in f_{O_2} or an increase in pH, respectively (e.g., Crerar and Barnes, 1976).

Some deposits contain the highest grade of copper in skarn displaying relatively intense retrograde alteration at contacts with sericitized plutons, while less-altered anhydrous skarn farther out is only weakly mineralized. Examples include Ely and Chino (Santa Rita). These suggest that copper was introduced to the skarn, and not simply remobilized, during the retrograde stage. Possibly, some of this copper originated through leaching of early chalcopyrite in the stock by the relatively low pH fluids of the sericitic stage.

It is proposed that the presence of silica-pyrite bodies replacing limestone at contacts with porphyry plutons is *prima facie* evidence that the pluton never underwent potassium-silicate alteration at that level of exposure. The distribution in a given deposit of andradite skarn, as opposed to silica-pyrite, should enable the definition of the maximum upper extent of original potassium-silicate alteration in areas where this alteration has been overprinted and destroyed by sericitic alteration.

Bisbee and, to some extent, also Cananea differ in many regards from the generally accepted model of porphyry copper deposits. The term "porphyry copper deposit," when applied indiscriminantly to such deposits, masks the differences which are significant clues to variations in ore-forming processes. Table 7.11 and Figures 7.25 and 7.26 present a general classification of porphyry-related deposits; these stress the differences, rather than the obvious similarities, and are intended as a frame of reference with which to compare the deposits discussed in this chapter. The descriptive terms "disseminated" and "lode" are used with reference to the morphology and texture of ore occurrence (see Tables 7.11 and 7.12), but these reflect important differences in geological and geochemical environment, as discussed below. Both styles of sulfide occurrence may be present in a given deposit, but there is a tendency for most of the copper to be restricted to one or the other. Although no true endmember disseminated deposits may be identifiable, some possible endmember lode deposits are shown in Table 7.12 (last group listed under Deposit Examples). The latter, not classed as porphyry copper deposits, commonly are referred to as Cordilleran vein or lode deposits.

Five essential features serve to differentiate between lode mineralization and disseminated mineralization.

The development of major ore zones with intense silicification-sericitization or advanced argillic alteration, associated with pyrite-bornite-chalcocite and enargite, is the dominant feature of the copper zone of lode mineralization. In contrast, the characterizing feature of disseminated mineralization is the development of potassium-silicate alteration at the intermediate sulfidation-oxidation states implied by pyrite-chalcopyrite or chalcopyrite-bornite-magnetite. In both the lode copper and disseminated copper deposits, the trend of physiochemical evolution of the ore fluid with time at a given spot was the same: toward lower temperatures, higher sulfidation-oxidation states, and lower pH. However, the lode deposits reflect the extreme development of this trend, whereas the disseminated deposits show a pronounced development of the earlier stages.

Lateral zoning with distance from an igneous center is well established in the Peruvian lode deposits (see Table 7.12), where the sulfide assemblages record an outward decrease in sulfidation state (Petersen, 1970): enargite gives way to tennantite at approximately the point where pyrite-bornite gives way to pyrite-chalcopyrite and where sphalerite and then galena become abundant. These changes, which, if taken in conjunction with wall-rock alteration, imply an outward increase in pH, are especially pronounced in carbonate wall rocks. However, the same trend occurs in quartzo-feldspathic rocks, such as toward the western extremities of veins in the volcanic vent at Cerro de Pasco (Graton and Bowditch, 1936), near the periphery of the copper zone at Butte (Meyer et al., 1968), and toward the surface in the Magma vein (Hammer and Peterson, 1968). The zoning from core to fringe in the lode deposits is the reverse of the paragenetic sequence: high-sulfur sulfides generally replace low-sulfur sulfides (McKinstry, 1963), and sphalerite pre-dates the copper sulfides in the central copper zone (Meyer et al., 1968; Einaudi, 1977*b*). These data are consistent with outward expanding zones of alteration-mineralization. In contrast, the sulfide zonal pattern in disseminated deposits records an upward and outward increase in sulfidation state; chalcopyrite and chalcopyrite-pyrite give way to pyrite-bornite and minor sphalerite, and the zoning from core to fringe in this case parallels the paragenetic sequence from early to late (e.g., Gustafson and Hunt, 1975). These data are not consis-

TABLE 7.11
Generalized Characteristics of Endmember Types of Porphyry-Related Copper Deposits

LODE TYPE	DISSEMINATED TYPE
Igneous Rocks	
Small, isolated stocks and dikes of quartz monzonite porphyry	Small stocks and dikes of quartz monzonite porphyry in many cases associated with multiple, larger, equigranular intrusions
Intrusive breccias common and associated with ore	Pebble dikes and breccias less common and largely post-date ore
Post-ore porphyries absent	Post-ore porphyries common
Ore Textures and Grade	
Sulfides occur as massive, open space fillings in veins, breccias; replacement bodies	Sulfides are finely disseminated and in veinlets; peripheral veins
Irregular distribution of sulfides commonly leads to selective mining	Uniform distribution leads to bulk mining
10 million tons of 6% Cu, to 500 million tons of 2% Cu; no large tonnages of 0.5% Cu (except supergene or superimposed on disseminated stage)	100 to 2,000 million tons of 0.35 to 1.0% Cu; higher grades only in skarn
Molybdenum generally absent	Molybdenum generally present, average grade 0.015% Mo
Copper ores with 2 to 4 oz./ton silver; relatively low Cu:Ag	Average around 0.05 oz./ton silver; relatively high Cu:Ag
Contains major lead-zinc-silver ores in peripheral areas of both igneous and sedimentary rocks	Rarely contains major lead-zinc-silver ore; if present, only in limestone
Sulfides, General	
Enargite & bornite major ore minerals	Chalcopyrite major ore mineral
Pyrite abundant and generally early	Pyrite less abundant and generally late
Sphalerite ubiquitous in copper zone and precedes copper mineralization	Sphalerite rare in copper zone and post-dates copper mineralization
Tin-tungsten-bismuth minerals common, trace in central Cu-zone	Molybdenite common in central Cu zone and deeper
Lateral Zoning of Major Opaque Minerals	
Central: pyrite-digenite-enargite, with trace amounts of tin-tungsten-bismuth minerals	*Central:* bornite-chalcopyrite-magnetite, or pyrite-chalcopyrite, with molybdenite
Intermediate: pyrite-bornite-chalcopyrite-tennantite, with minor sphalerite	*Intermediate:* pyrite-chalcopyrite
Peripheral: pyrite-chalcopyrite-tennantite-sphalerite-galena, with minor hematite	*Peripheral:* pyrite, with minor chalcopyrite, tennantite, sphalerite, and galena; hematite or magnetite
Limestone: pyrite, bornite, chalcopyrite, tennantite, sphalerite, galena; minor magnetite or hematite	*Limestone:* pyrite-chalcopyrite-magnetite; minor sphalerite, tennantite, pyrrhotite
Major Gangue Minerals	
Quartz, pyrite, sericite, kaolinite, alunite, barite, carbonates	Feldspars, biotite, quartz, anhydrite, sericite
Lateral Zoning of Alteration Types	
Central: advanced argillic and silicification (pyrophyllite or kaolinite replaces sericite)	*Central:* potassic (biotite replaces hornblende; orthoclase replaces plagioclase)
Intermediate: sericitic (sericite replaces montmorillonite and orthoclase)	*Intermediate:* sericitic (sericite replaces feldspars)
Peripheral: well-developed intermediate argillic grades to propylitic (montmorillonite replaces plagioclase; chlorite replaces mafics)	*Peripheral:* intermediate argillic weak to absent; grades to propylitic
Limestone: massive quartz-pyrite bodies, breccias, mantos; contains siderite, calcite, specularite, magnetite, chlorite, clays	*Limestone:* zoned skarns with andradite-diopside; late actinolite, chlorite, clays, pyrite

NOTE: These characteristics refer to porphyry-related copper deposits which are associated with calc-alkaline magmatism in continental margin mobile belts of Mesozoic and younger age. Possible examples of a continuum between the two endmember types of deposits are listed in Table 7.12.

tent with outward expanding zones of alteration-mineralization; rather, the high-level sericitic zone expands onto the deeper potassic zone. Thus, downward and inward zoning accompanying meteoric water influx in the disseminated deposits mimics the outward zoning of the lode deposits and represents the embryonic development of the lode stage.

Lode deposits in igneous rocks are mined for copper, zinc, and often lead, silver, and manganese. The bulk of the ore minerals in igneous rocks are restricted to through-going vein systems or breccia pipes, are generally massive, and may be erratically distributed in ore shoots or pods. The morphology and texture of ore occurrence suggest that rapid deposition inhibited infiltration or diffusion of metals into wall rocks. These features of ore distribution are reflected in mining grades: selective underground mining in the copper zone of lode deposits characteristically yields ore grades of 2.5 to 5.5 percent Cu, with an average zinc content of nearly 1 percent and a silver content of 2 to 4 oz. per ton; bulk mining methods yield hypogene copper ores that range from 1.2 to 2.0 percent Cu. In contrast, disseminated deposits are mined for copper and molybdenum; silver is a by-product; and peripheral zones rarely contain significant lead-zinc mineralization unless they are rich in carbonate rocks. The ore minerals tend to be uniformly distributed in veinlets or as disseminations in porphyry; late porphyries and breccia pipes commonly are lower in grade. Copper ores rarely achieve grades that would support selective underground mining. The average hypogene copper grade in igneous rocks of 17 North and South American examples (from Lowell and Guilbert, 1970) is 0.44 percent Cu, and it rarely exceeds 1.0 percent.

Minor to trace amounts of bismuth sulfides (bismuthinite, wittichenite), tin sulfides (stannite, colusite), and tungsten minerals (wolframite, scheelite) occur in the copper zone of the lode deposits, but they are not reported from disseminated deposits. In many cases, the tin, tungsten, bismuth minerals are most abundant with enargite in the core of the copper zone: bismuthinite and wolframite occur with

TABLE 7.12
Continuum Between Lode-Type and Disseminated-Type Endmembers in Porphyry-Related Copper Deposits

Degree of Development Disseminated Stage	Degree of Development Lode Stage	Deposit Examples	Alteration in Limestone	Sources
Major, contains all known ore	Unknown (never formed, or removed by erosion)	Christmas, Arizona	Skarn	Koski & Cook, 1982; Perry, 1969
		Twin Buttes, Arizona	Skarn	Barter & Kelly, 1982
		Mission, Arizona	Skarn	Gale, 1965; Einaudi, 1974
		Bingham, Utah	Skarn	Atkinson & Einaudi, 1978
		Silver Bell, Arizona	Skarn	Richard & Courtright, 1966; Graybeal, 1982
		Santa Rita, New Mexico	Skarn	Nielsen, 1968, 1970
Major, highest grade (all of Cu and Mo introduced during this stage?)	Minor, lower grade (Cu leached during this stage?)	Ely, Nevada	Skarn, silica-pyrite	James, 1976
		Red Mountain, Arizona	Limestone absent	Corn, 1975
		El Salvador, Chile	Limestone absent	Gustafson & Hunt, 1975
Major, well-mineralized (all of Mo and most of Cu introduced during this stage?)	Major, highest grade (Cu leached from earlier stage and concentrated?)	Butte, Montana	Limestone absent	Meyer et al., 1968; Brimhall, 1979
		Chuquicamata, Chile	Limestone absent	Lopez, 1939; Perry, 1952
Local, minor, or absent (very minor Cu and Mo introduced?)	Major, highest grade (most of Cu introduced during this stage?)	Cananea, Mexico	Skarn?, silica-pyrite	Emmons, 1910; Kelley, 1935; Perry, 1961
		Morococha, Peru	Skarn, silica-pyrite	Barrentes, 1970; Petersen, 1965
		Bisbee, Arizona	Silica-pyrite	Bryant, 1964
Absent? (no Cu, no Mo)	Major (all of Cu introduced during this stage?)	Magma, Arizona	Silica-pyrite	Hammer & Peterson, 1965
		Cerro de Pasco, Peru	Silica-pyrite	Petersen, 1965; Einaudi, 1977*b*
		Yauricocha, Peru	Silica-pyrite	Petersen, 1965

NOTE Characteristics of disseminated stage and lode stage are summarized in Table 7.11.

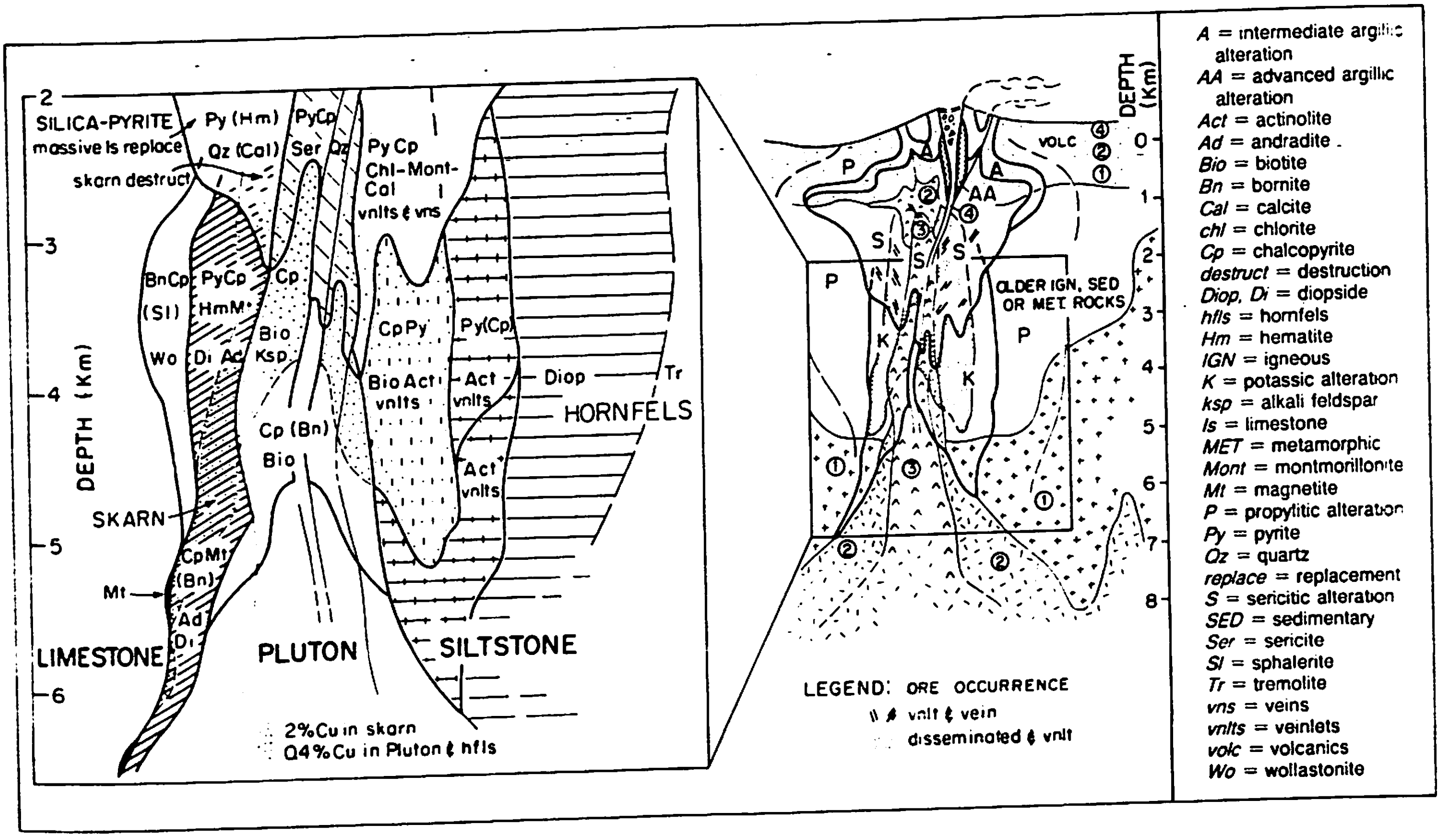


Figure 7.25. Schematic vertical sections of zonal patterns in an idealized disseminated-type porphyry-related copper deposit, in which the highest grade of ore is associated with potassic alteration. *Right:* general setting, with early to late intrusion sequence (circled numbers); main-stage alteration-mineralization is associated with intrusion number ③, which does not vent. Heavy lines enclose dominant alteration types, including a deep and central potassic, peripheral propylitic, and later sericitic. Advanced argillic alteration is restricted to a near-surface vent; argillic and propylitic alteration dominate in the volcanic edifice. Based on Lowell and Guilbert (1970), Sillitoe (1973), Gustafson and Hunt (1975), and Einaudi, Proffett, and others (in preparation). *Left:* equivalent zonal patterns in limestone and calcareous siltstone, mainly based on deposits at Christmas, Arizona, and in the Pima, Bingham, and Robinson mining districts.

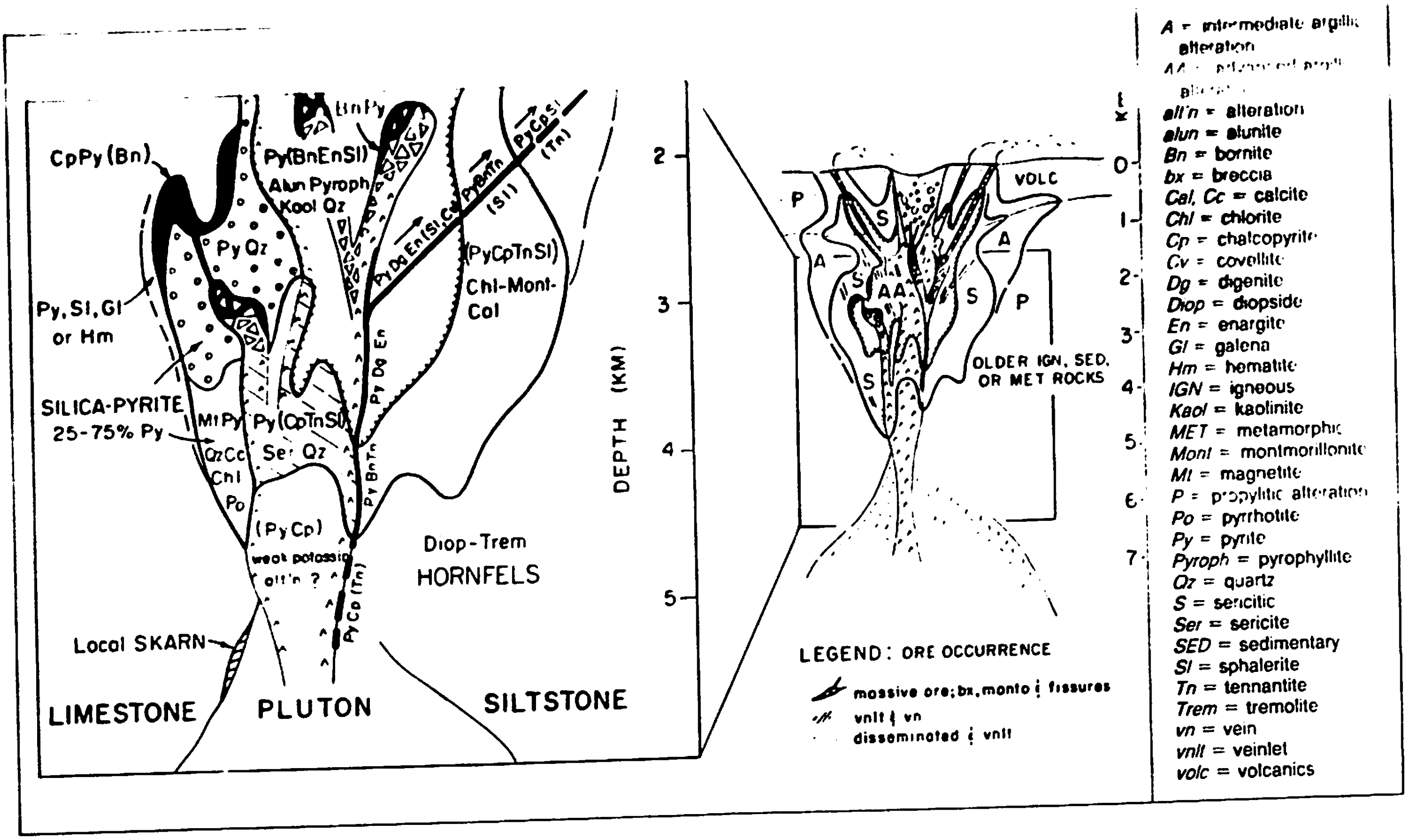


Figure 7.26. Schematic vertical sections of zonal patterns in an idealized lode-type porphyry-related copper deposit, in which the highest grade of ore consists of massive sulfide vein-fillings and mineralized breccias associated with silicification and advanced argillic alteration. *Right:* general setting, with heavy lines enclosing dominant alteration types (advanced argillic, with peripheral sericitic and intermediate argillic). Based on Graton and Bowditch (1936) and Meyer and others (1968). *Left:* equivalent zonal patterns in limestone and calcareous siltstone. Based on Hammer and Petersen (1967), Petersen (1965), and Einaudi (1977*b*).

enargite at Yauricocha (Petersen, 1965); stannite, wolframite and scheelite occur in the copper zone at Morococha (Petersen, 1965); colusite and wittichenite are rare constituents of copper ores at Magma (Hammer and Peterson, 1968); colusite and huebnerite are most abundant in the pyrite-covellite-digenite-enargite ores at Butte (John M. Proffett, Jr., 1974, personal communication); and wittichenite and scheelite are also known to occur in the copper zone (Meyer et al., 1968). At Cerro de Pasco, stannite, wolframite, and cassiterite occur in the early, low-sulfur, pyrrhotite stage of mineralization (Einaudi. 1977*b*).

The Limestone wall rocks of the lode deposits characteristically contain copper and lead-zinc ores associated with replacement pipes and mantos of passive pyrite-quartz, with local carbonates and specular hematite; calc-silicates are absent. Sulfide assemblages generally reflect a lower sulfidation state than those in associated igneous wall rocks, with pyrite-chalcopyrite-bornite present, rather than pyrite-bornite-chalcocite, and tennantite present, rather than enargite. Ore pipes and mantos are markedly zoned, with an early, barren pyrite-quartz stage or core zone, surrounded by copper and peripheral lead-zinc ores. In addition to the obvious analogies between Bisbee and Cerro de Pasco (Einaudi, 1977*b*), the zoning in silica-pyrite bodies at Bisbee is a remarkable duplication of zoning in the ore pipes in limestone at Morococha (Petersen, 1965), and also bears some resemblance to ore breccias in limestone at Yauricocha (Thomson, 1960, as summarized by Petersen, 1965) and mantos in limestone near the Magma vein (Hammer and Peterson, 1968).

The lack of ore-bearing skarns in limestone near contacts with leached igneous rocks in lode deposits is one of their most striking features and sets a sharp contrast with the disseminated deposits, where limestone wall rocks characteristically contain ore-bearing andradite-diopside skarns. Metasomatic replacement of limestone in the lode deposits apparently occurred at lower temperatures and/or higher sulfur fugacities than the andradite stability field. The relatively low pH of fluids associated with lode mineralization also effectively suppressed the formation of calc-silicates.

Factors which may control the degree of development of disseminated, as opposed to lode, mineralization in porphyry-related copper deposits have briefly been summarized by Gustafson and Hunt (1975) and Einaudi (1977*b*) and are implicit in the chemical model of Meyer and Hemley (1967). The major variables, as stated by Gustafson and Hunt, include: (1) geometries, time factors, and depth of emplacement of intrusions; (2) abundance of metals and volatiles evolved from the melt; and (3) degree of groundwater availability. The ultimate control may be the timing of groundwater influx.

If the influx is retarded due to deep emplacement, a prolonged period of intrusive activity, large size of intrusions, or relatively dry and impermeable wall rocks, then the mineralizing porphyry system cools slowly, and disseminated ore zones and skarn are favored. As the transition from alkali to hydrogen ion metasomatism occurs, due to decreasing pressure and temperature, accompanied and enhanced by the encroachment of groundwater, a stage of hypogene leaching begins. At Ely and El Salvador (Chile) overall depletion of copper may have occurred. At Butte, Brimhall (1979) has suggested that a new hydrothermal system, possibly largely meteoric in origin, was activated by heat supplied by late porphyry plugs. The lode stage, which post-dated the disseminated stage by several million years, initially leached chalcopyrite and resulted in whole-rock copper and iron depletion. This was followed by re-precipitation of copper as pyrite-bornite and pyrite-digenite-covellite in Main Stage veins. Chuquicamata (Chile) also may fit this model. At both Butte and Chuquicamata, the lode stage was superimposed directly onto the earlier stage of disseminated chalcopyrite and potassium-silicate alteration.

If the influx of groundwater occurs early—due to shallow porphyry emplacement, a limited period of intrusive activity, small size of intrusions, or relatively wet and permeable wall rocks—then the mineralizing porphyry cools rapidly, and lode-type deposits in igneous rocks and silica-pyrite replacement ores in limestone are favored. In this case, the lode stage may represent the first introduction of copper into the system. Deposits which may fit this end-member case include Cerro de Pasco (Peru), Yauricocha (Peru), and Magma (see Table 7.12). Bisbee and Cananea may represent deposits intermediate between Butte and Cerro de Pasco.

Alteration and mineralization in carbonate wall rocks of porphyry plutons are intimately tied to the environment of emplacement of the melt, to its subsequent cooling history and volatile evolution, and the geometries of hydrothermal convection. The type of alteration observed in carbonate rocks is an additional clue to unraveling these events. A goal of future research should be to place the above generalizations on a firmer base of field observation, analytical data, experimentation, and thermochemical computation.

ACKNOWLEDGMENTS

The thoughts expressed in this chapter represent the distillation of personal research, publication by authors cited in the text, and discussions with numerous colleagues. The last of these points is the most difficult to acknowledge, yet may be the most productive of ideas. In this regard, the mine geologists acknowledged in the section on individual deposits aided the author in acquiring the local context which could not be acquired by reading the literature. Colleagues who have had a significant influence on the author's thinking on porphyries and skarns include: W. W. Atkinson, Jr., R. C. Baker, D. M. Burt, L. B. Gustafson, and J. P. Hunt. The Anaconda Company, Anamax Mining Company, and U. V. Industries released useful data, and C. F. Barter, D. S. Cook, F. T. Graybeal, J. L. Kelly, R. A. Koski, and D. L. Norton supplied the author with early versions of the manuscripts for the chapters they contributed to this book. An all-day crash drafting session by graduate students at Stanford University saved the author from a great deal of embarassment. Finally, the encouragement and patience of S. R. Titley is gratefully acknowledged.

REFERENCES CITED

Anderson, T. H., and Silver, L. T., 1977, U-Pb isotope ages of granitic plutons near Cananea, Sonora: Econ. Geol., v. 72, p. 827–836.

Atkinson, W. W., Jr., and Einaudi, M. T., 1978, Skarn formation and mineralization in the contact aureole at Carr Fork, Bingham, Utah: Econ. Geol., v. 73, p. 1326–1365.

Barrentes, E. T., 1970, Geologia y estructura del yacimiento del proyecto de Morococha, *in* Geología de los yacimientos minerales operados por la Cerro de Pasco Corp., Primer Cong. Latino Americano de Geol., Lima, Peru: La Oroya, Peru, Cerro de Pasco Corp., p. 131–155.

Barter, C. F., and Kelly, J. L., 1982, Geology of the Twin Buttes mineral deposit, Pima Mining District, Pima County, Arizona, *in* Titley, S. R., ed., Advances in Geology of the Porphyry Copper Deposits, Southwestern North America: Tucson, Univ. Ariz. Press, Chapter 20.

Bauer, H. L., Jr.; Breitrich, R. A.; Cooper, J. J.; and Swinderman, J. N., 1964, Origin of the disseminated ore in metamorphosed sedimentary rocks, Robinson mining district, Nevada: AIME Trans., v. 229, p. 131–140.

Bauer, H. L., Jr.; Breitrich, R. A.; Cooper, J. J.; and Anderson, J. A., 1966, Porphyry copper deposits in the Robinson mining district, Nevada, *in* Titley, S. R., and Hicks, C. L., eds., Geology of the Porphyry Copper Deposits, Southwestern North America: Tucson, Univ. Ariz. Press, p. 233–244.

Bonillas, Y. S., Tenney, J. B., and Feuchere, L., 1917, Geology of the Warren mining district: AIME Trans., v. 55, p. 284–355.

Brimhall, G. H., Jr., 1979, Lithologic determination of mass transfer mechanisms of multiple-stage porphyry copper mineralization at Butte, Montana: Vein formation by hypogene leaching and enrichment of potassium-silicate protore: Econ. Geol., v. 74, p. 556–589.

Brant, D. G., 1964, Intrusive breccias and associated ore of Warren (Bisbee) mining district, Cochise County, Arizona: Unpub. Ph.D. thesis, Stanford Univ., 149 p.

———, 1968, Intrusive breccias associated with ore, Warren (Bisbee) mining district, Arizona: Econ. Geol., v. 63, p. 1–12.

Bryant, D. G., and Metz, H. E., 1966, Geology and ore deposits of the Warren mining district, *in* Titley, S. R., and Hicks, C. L., eds., Geology of the Porphyry Copper Deposits, Southwestern North America: Tucson, Univ. Ariz. Press, p. 189–204.

Burt, D. M., 1972, Mineralogy and geochemistry of Ca-Fe-Si skarn deposits: Unpub. Ph.D. Thesis, Harvard Univ., 256 p.

———, 1977, Mineralogy and petrology of skarn deposits: Rendiconti So. Ital. Mineral. Petrol., v. 33, p. 859–873.

Buseck, P. R., 1962, Contact metasomatic deposits at Concepción del Oro, Mexico; Tem Piute, Nevada; and Silver Bell, Arizona: Unpub. Ph.D. Thesis, Columbia Univ., N.Y.

Butler, W. C., 1971, Permian sedimentary environments in southeastern Arizona: Ariz. Geol. Soc. Digest, IX, p. 71–94.

Cooper, J. R., 1960, Some geologic features of the Pima mining district, Pima County, Arizona: U.S. Geol. Survey Bull. 1112-C, p. 63–103.

———, 1971, Mesozoic stratigraphy of the Sierrita Mountains, Pima County, Arizona: U.S. Geol. Survey Prof. Paper 658D. 42 p.

Corn, R. M., 1975, Alteration-mineralization zoning, Red Mountain, Arizona: Econ. Geol., v. 70, p. 1437–1447.

Damon, P. E., compiler, 1965, Correlation and chronology of ore deposits and volcanic rocks: U.S. Atomic Energy Comm. Contract AT(11-1)-689, Ann. Prog. Rept. COO-689-50: Tucson, Geochron. Labs., Univ. Ariz., p. A-II-3.

Eastlick, J. T., 1968, Geology of the Christmas mine and vicinity, Banner mining district, Arizona, *in* Ridge, J. D., ed., Ore Deposits of the United States, 1933-1967 (Graton-Sales vol.): AIME, New York, p. 1192–1210.

Einaudi, M. T., 1974, Skarn study, Palo Verde mine, Pima County, Arizona: unpublished report, The Anaconda Co., 44 p.

———, 1977*a*, Petrogenesis of copper-bearing skarn at the Mason Valley mine, Yerington district, Nevada: Econ. Geol., v. 72, p. 769–795.

———, 1977*b*. Environment of ore deposition at Cerro de Pasco, Peru: Econ. Geol., v. 72, p. 893–924.

———, 1982, General features and origin of skarns associated with porphyry copper plutons, southwestern North America, *in* Titley, S. R., ed., Advances in Geology of the Porphyry Copper Deposits, Southwestern North America: Tucson, Univ. Ariz. Press, Chapter 8.

Emmons, S. F., 1910, The Cananea mining district of Sonora, Mexico: Econ. Geol., v. 5, p. 312–256.

Forrester, J. D., 1972, Skarn formation and sulfide mineralization at the Continental mine, Fierro, New Mexico: Unpub. Ph.D. Diss., Cornell Univ., 205 p.

Fournier, R. O., 1967*a*, The porphyry copper deposit exposed in the Liberty open pit mine near Ely, Nevada: Part I, Syngenetic formation: Econ. Geol., v. 62, p. 57–81.

———, 1967*b*, The porphyry copper deposit exposed in the Liberty open pit mine near Ely Nevada: Part II, The formation of hydrothermal alteration zones: Econ. Geol., v. 62, p. 207–227.

Gale, R. E., 1965, The geology of the Mission copper mine, Pima mining district, Arizona: Unpub. Ph.D. Thesis, Stanford Univ., 162 p.

Gilluly, J.; Copper, J. R.; and Williams, J. S., 1954, Late Paleozoic stratigraphy of central Cochise county, Arizona: U.S. Geol. Survey Prof. Paper 266, 49 p.

Graton, L. C., and Bowditch, S., 1936, Alkaline and acid solutions in hypogene zoning at Cerro de Pasco: Econ. Geol., v. 31, p. 651–698.

Graybeal, F. T., 1982, Geology of the El Tiro area, Silver Bell mining district, Pima County, Arizona, *in* Titley, S. R., ed., Advances in Geology of the Porphyry Copper Deposits, Southwestern North America: Tucson, Univ. Ariz. Press, Chapter 24.

Greenwood, E.; Kottlowski, F. E.; and Thompson, S. III, 1977, Petroleum potential and stratigraphy of Pedregosa Basin: Comparison with Permian and Orogrande basins: Amer. Assoc. Pet. Geol. Bull., v. 61, p. 1448–1469.

Gustafson, L. B., and Hunt, J. P., 1975, The porphyry copper deposit at El Salvador, Chile: Econ. Geol., v. 70, p. 857–912.

Hallof, P. G., and Winniski, E., 1971, A geophysical case history of the Lakeshore ore body: Geophysics, v. 36, p. 1232–1249.

Hammer, D. F., and Peterson, D. W., 1968, Geology of the Magma mine area, Arizona, *in*, Ridge, J. D, ed., Ore Deposits of the United States, 1933–1967 (Graton-Sales vol.): AIME, New York, v. 2, p. 1282–1310.

Hansen, L. A., 1961, The stratigraphy of the Carr Fork mines, Bingham district, Utah: Utah Geol. Soc., Guidebook to the Geology of Utah, No. 16, p. 71–81.

Hayes, P. T., 1978, Cambrian and Ordovician rocks of southeastern Arizona and southwestern New Mexico: New Mexico Geol. Soc. Guidebook, 29th Field Conf., p. 165–173.

Hernon, R. M., 1949, Geology and ore deposits of Silver City region, New Mexico: West Texas Geol. Soc. Guidebook Field Trip 3.

Hernon, R. M., and Jones, W. R., 1968, Ore deposits of the Central Mining district New Mexico, *in* Ridge, J. D., ed., Ore Deposits of the United States, 1933–1967 (Graton-Sales vol.): AIME, New York, p. 1211–1238.

Himes, M. D., 1973, Mineralization and alteration at Pima mine—a complex porphyry copper deposit: AIME Trans., v. 254, p. 166–174.

Huang, Chi-I, 1976, An isotopic and petrologic study of the contact metamorphism and metasomatism related to copper deposits at Ely, Nevada: Unpub. Ph.D. Thesis, Penn. State Univ., 178 p.

Hunt, J. P., 1957, Rock alteration, mica, and clay minerals in certain areas in the United States and Lark mines, Bingham, Utah: Unpub. Ph.D. Thesis, Univ. Calif., Berkeley, 321 p.

Hunt, R. N., 1924, The ores in limestone at Bingham, Utah: AIME Trans., v. 70, p. 856–883.

Irvin, G. W., 1959, Pyrometasomatic deposits at San Xavier mine: Southern Arizona Guidebook II, Ariz. Geol. Soc. p. 195–197.

James, A. H., 1971, Hypothetical diagrams of several porphyry copper deposits: Econ. Geol., v. 66, p. 43–47.

James, L. P., 1972, Zoned hydrothermal alteration and ore deposits in sedimentary rocks near mineralized intrusions, Ely area, Nevada: Unpub. Ph.D. Thesis, Penn. State Univ., 241 p.

———, 1976, Zoned alteration in limestone at porphyry copper deposits, Ely, Nevada: Econ. Geol., v. 71, p. 488–512.

John, E. C., 1978, Mineral zones in the Utah Copper ore body: Econ. Geol., v. 73, p. 1250–1259.

Jones, W. R.; Hernon, R. M.; and Moore, S. L., 1967, General geology of Santa Rita quadrangle, Grant County, New Mexico: U.S. Geol. Survey Prof. Paper 555, 144 p.

Journeay, J. A., 1959, Pyrometasomatic deposits at Pima mine: Southern Arizona Guidebook II, Ariz. Geol. Soc., p. 198–199.

Kelley, V. C., 1935, Paragenesis of the Colorada copper sulfides, Cananea, Mexico: Econ. Geol., v. 30, p. 663–688.

Kinnison, J. E., 1966, The Mission copper deposit, Arizona, *in* Titley, S. R., and Hicks, C. L., eds., Geology of the Porphyry Copper Deposits, Southwestern North America: Tucson, Univ. Ariz. Press, p. 281–287.

Knopf, A., 1918, Geology and ore deposits of the Yerington district, Nevada: U.S. Geol. Survey Prof. Paper 114, 68 p.

Koski, R. A., 1978, Porphyry-type alteration and mineralization of igneous rocks at Christmas, Arizona: Unpub. Ph.D. Diss., Stanford Univ., 196 p.

Koski, R. A., and Cook, D. S., 1982, Geology of the Christmas porphyry copper deposit, Gila County, Arizona, *in* Titley, S. R., ed., Advances in Geology of the Porphyry Copper Deposits, Southwestern North America: Tucson, Univ. Ariz. Press, Chapter 17.

Lacy, W. C., 1959, Structure and ore deposits of the east side of the Sierrita Mountains, Arizona: Southern Arizona Guidebook II, Ariz. Geol. Soc., p. 185–192.

Langlois, J. D., 1978, Geology of the Cyprus Pima mine, Pima county, Arizona: Ariz. Geol. Soc. Digest, XI, p. 103–113.

Lanier, G.; John, E. C.; Swenson, A. J; and others, 1978, General geology of the Bingham mine, Bingham Canyon, Utah: Econ. Geol., v. 73, p. 1228–1241.

Lanier, G.; Raab, W. J.; Folsom, R. B; and Cone, S., 1978, Alteration of equigranular monzonite, Bingham mining district, Utah: Econ. Geol., v. 32, p. 1270–1286.

Lindgren, W. 1905, The copper deposits of the Clifton-Morenci district, Arizona: U.S. Geol. Survey Prof. Paper 43, 375 p.

Lindgren, W.; Graton, L. C.; and Gordon, C. H., 1910, The ore deposits of New Mexico: U.S. Geol. Survey Prof. Paper 68, 361 p.

Lopez, V. M., 1939, The primary mineralization at Chuquicamata, Chile, S. A.: Econ. Geol., v. 34, p. 674–711.

Lowell, J. D., and Guilbert, J. M., 1970, Lateral and vertical alteration-mineralization zoning in porphyry copper deposits: Econ. Geol., v. 65, p. 373–408.

MacKenzie, F. D., 1959, Pyrometasomatic deposits at the Mineral Hill and Daisy mines: Southern Arizona Guidebook II, Ariz. Geol. Soc., p. 193–194.

———, 1963, Geological interpretation of the Palo Verde Mine based upon diamond drill core: Ariz. Geol. Soc. Digest, VI, p. 41–48.

Maravilla, S., 1978, Minas en producción, minas en preparación y depósitos con reservas o menos conocidas en el Estado de Sonora: 1° Simposio Geol. Potencial Minero, Estado Sonora, Inst. Geol., U.N.A.M., Hermosillo, Sonora, Mexico, p. 85–87.

McKee, E. D., 1951, Sedimentary basins of Arizona and adjoining areas: Geol. Soc. Amer. Bull., v. 62, p. 481–506.

McKinstry, H., 1963, Mineral assemblages in sulfide ores: The system Cu-Fe-As-S: Econ. Geol., v. 58, p. 483–505.

Meyer, C., and Hemley, J. J., 1967, Wall rock alteration, *in* Barnes, H. L., ed., Geochemistry of Hydrothermal Ore Deposits: N.Y., Holt, Rinehart and Winston, p. 166–235.

Meyer, C.; Shea, E. P.; Goddard, C. C., Jr.; and Staff, 1968, Ore deposits at Butte, Montana, *in* Ridge, J. D., ed., Ore Deposits of the United States, 1933–1967 (Graton-Sales vol.): New York, AIME, p. 1373–1416.

Moolick, R. T., and Durek, J. J., 1966, The Morenci district, *in* Titley, S. R., and Hicks, C. L., eds., Geology of the Porphyry Copper Deposits, Southwestern North America: Tucson, Univ. Ariz. Press, p. 221–232.

Moore, W. J., 1978, Chemical characteristics of hydrothermal alteration at Bingham, Utah: Econ. Geol., v. 73, p. 1260–1269.

Moore, W. J., and Nash, J. T., 1974, Alteration and fluid inclusion studies of the porphyry copper ore body at Bingham, Utah: Econ. Geol., v. 69, p. 631–645.

Mulchay, R. B., and Velasco, J. R., 1954, Sedimentary rocks at Cananea, Sonora, Mexico, and tentative correlation with the sections at Bisbee and the Swisshelm Mountains, Arizona: AIME Trans., v. 199, p. 628–632.

Nielsen, R. L., 1968, Hypogene texture and mineral zoning in a copper-bearing granodiorite porphyry stock, Santa Rita, New Mexico: Econ. Geol., v. 63, p. 37–50.

———, 1970, Mineralization and alteration in calcareous rocks near the Santa Rita stock, New Mexico: New Mexico Geol. Soc. Guidebook 21st Field Conf., p. 133–139.

Ochoa, H., and Echavarri, A., 1978, Observaciones preliminares sobre la secuencia de las intrusiones hipabisales en el tajo Colorada-Veta del distrito minero de Cananea: Bol. Dpto. Geol. Uni-Son., v. 1, p. 57–60.

Parkinson, G., 1976, Cyprus develops moly-talc separation float: Eng. Mining Jour., May, 1976, p. 97.

Peirce, H. W., 1976, Elements of Paleozoic tectonics in Arizona: Ariz. Geol. Soc. Digest X, p. 37–57.

Perry, D. V., 1968, Genesis of the contact rocks at the Christmas mine, Gila county, Arizona: Unpub. Ph.D. Thesis, Univ. Ariz., 229 p.

———, 1969, Skarn genesis at the Christmas mine, Gila county, Arizona: Econ. Geol., v. 64, p. 255–270.

Perry, V. D., 1933, Applied geology at Cananea, Sonora, Mexico, *in* Ore deposits of the Western states (Lindgren vol.): New York, AIME, p. 701–709.

———, 1935, Copper deposits of the Cananea district, Sonora, Mexico, *in* Copper Resources of the World: Int. Geol. Cong., 16th, v. 1, p. 413–418.

———, 1952, Geology of the Chuquicamata ore body: Min. Eng. v. 4, p. 1166–1168.

———, 1961, The significance of mineralized breccia pipes: AIME Trans., v. 220, p. 216–226.

Petersen, Ulrich, 1965, Regional geology and major ore deposits of central Peru: Econ. Geol., v. 60, p. 407–476.

———, 1970, Metallogenic provinces in South America: Geol. Rundschau, v. 59, p. 834–897.

Peterson, N. P., and Swanson, R. W., 1956, Geology of the Christmas copper mine, Gila county, Arizona: U.S. Geol. Surv. Bull. 1027-H, p. 351–373.

Proffett, J. M., Jr., 1977, Cenozoic geology of the Yerington district, Nevada, and implications for the nature and origin of basin and range faulting: Bull. Geol. Soc. America, v. 88, p. 247–266.

Proffett, J. M., Jr., and Proffett, B. H., 1976, Stratigraphy of the tertiary ash-flow tuffs in the Yerington district, Nevada: Nev. Bur. Mines Geol., Rpt. 27, 28 p.

Ransome, F. L., 1904, Geology and ore deposits of the Bisbee quadrangle, Arizona: U.S. Geol. Survey, Prof. Paper 21, 168 p.

Reber, L. E., 1916, The mineralization of Clifton-Morenci: Econ. Geol., v. 11, p. 528–573.

Reid, J. E., 1978, Skarn alteration of the Commercial limestone, Carr Fork area, Bingham, Utah: Econ. Geol., v. 73, p. 1315–1325.

Richard, K., and Courtright, J. H., 1959, Some geologic features of the Mission copper deposit: Southern Arizona Guidebook II, Ariz. Geol. Soc., p. 201–204.

———, 1966, Structure and mineralization at Silver Bell, Arizona, *in* Titley, S. R., and Hicks, C. L., eds., Geology of the Porphyry Copper Deposits, Southwestern North America: Tucson, Univ. Ariz. Press, p. 157–164.

Roberts, R. J.; Crittenden, M. D., Jr.; Tooker, E. W.; Morris, H. T.; Hose, R. K.; and Cheney, T. M., 1965, Pennsylvanian and Permian basins in northwestern Utah, northwestern Nevada, and south-central Idaho: Am. Assoc. Pet. Geol. Bull., v. 49, p. 1926–1956.

Rose, A. W., and Baltosser, W. W., 1966, The porphyry copper deposit at Santa Rita, New Mexico, *in* Titley, S. R., and Hicks, C. L., eds., Geology of the Porphyry Copper Deposits, Southwestern North America: Tucson, Univ. Ariz. Press, p. 205–220

Ross, C. A., 1978, Late Pennsylvanian and Early Permian sedimentary rocks and tectonic setting of the Marathon Geosyncline: Permian Basin sec.: Soc. Econ. Paleont. Mineral., Pub. 78–17, p. 181–189.

Ross, C. P., 1925, Ore deposits of the Saddle Mountain and Banner mining districts, Arizona: U.S. Geol. Surv. Bull. 771, 72 p.

Rubright, R. D., and Hart, O. J., 1968, Non-porphyry ores of the Bingham district, Utah, *in* Ridge, J. D., ed., Ore Deposits of the United States, 1933–1967 (Graton-Sales vol.): New York, AIME, p. 886–908.

Schmitt, H. A., 1939, The Pewabic mine, New Mexico: Bull. Geol. Soc. America, v. 50, p. 777–818.

Schwartz, G. M., 1947, Hydrothermal alteration in the "porphyry copper" deposits: Econ. Geol., v. 42, p. 319–352.

Shafiqullah, M., and Langlois, J. D., 1978, The Pima mining district, Arizona—A geochronologic update: New Mex. Geol. Soc. Guidebook, 29th Field Conf., p. 321–327.

Sillitoe, R. H., 1973, Tops and bottoms of porphyry copper deposits: Econ. Geol., v. 68, p. 799–815.

South, D. L., 1972, Sulfide zoning at the Lakeshore copper deposit, Pinal county, Arizona: Unpub. M.S. Thesis, Univ. Ariz., 79 p.

Speed, R. C., 1978, Paleogeographic and plate tectonic evolution of the early Mesozoic marine province of the western Great Basin, *in* Howell, D. G., and McDougall, K. A., eds., Mesozoic paleogeography of the western United States: Pacific Coast Paleogeogr. Symp., Soc. Econ. Paleont. Mineral., v. 2, p. 253–270.

Stewart, C. A., 1912, The geology and ore deposits of the Silver Bell mining district, Arizona: AIME Bull., v. 65, p. 455–506.

Stoddard, Carl, and Carpenter, J. A., 1950, Mineral resources of Storey and Lyon counties, Nevada: Univ. Nev. Bull., Geol. Mining Ser., no. 49, 115 p.

Titley, S. R., 1976, Evidence for a Mesozoic linear tectonic pattern in southeastern Arizona: Ariz. Geol. Soc. Digest, X, p. 71–101.

Trischka, C., 1938, Bisbee district: Ariz. Bur. Mines Bull. 145, p. 32–41.

Valentine, W. G., 1936, Geology of the Cananea Mountains, Sonora, Mexico: Bull. Geol. Soc. America, v. 47, p. 53–86.

Varela, F. E., 1973, Tourmaline in the Cananea mining district, Sonora, Mexico: Unpub. M.S. Thesis, Univ. Calif. Berkeley, 79 p.

Velasco, J. R., 1966, Geology of the Cananea district, *in* Titley, S. R., and Hicks, C. L., eds., Geology of the Porphyry Copper Deposits, Southwestern North America: Tucson, Univ. Ariz. Press, p. 245–250.

Willden, Ronald, 1964, Geology of the Christmas quadrangle, Gila and Pinal counties, Arizona: U.S. Geol. Surv. Bull. 1161-E, p. 1–64.

Wilson, J. R., 1963, Geology of the Yerington mine: Min. Cong. Jour., v. 49, no. 6, p. 30–34.