Selected copper-bearing skarns and epizonal granitic intrusions in the southwestern United States

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Abstract: Although skarn composes a sizeable proportion of the altered and metallized parts of many epizonal systems, its implications for our understanding of porphyry copper genesis have been neglected. Skarns associated with porphyries apparently can form prior to, during, and after emplacement of related porphyritic granitic bodies. In the porphyry systems, alteration is extremely widespread, and fracture-controlled chemical changes may extend far beyond the skarn. Crystallization of garnet and pyroxene from nonboiling but saline fluids was followed in some skarns by deposition of subeconomic concentrations of copper and iron sulfides. Ore formed in these anhydrous skarns, however, only after repeated passage of Cu-bearing fluids, causing the subsequent, paragenetically complex crystallization of quartz and K-feldspar, amphibole, amphibole $\pm$ epidote, biotite $\pm$ amphibole, carbonate $\pm$ chlorite–white micas and sulfides. In one deposit the fluids became progressively saline as the skarns evolved and boiled during the late stages. In many districts, the hydrous mineral assemblages paragenetically overlap the final emplacement of the nearby granitic bodies as the fluid flow was periodically disrupted while the rocks opened and closed to the surface. In contrast to the epizonal porphyry coppers, deep-seated skarns, typified by the Pine Creek tungsten deposit in east-central California, show a horizontal extent of skarn limited closely to rock near the granite-carbonate contact. Metasomatic effects beyond the skarn are absent, and hypogene ore formed penecontemporaneously with the skarm minerals, in contrast to the porphyry coppers.

INTRODUCTION

The eastern rim of the Pacific Ocean, from the Aleutian Islands south through Peru and Chile, marks the site of a global metallogenic belt that comprises about 200 known important porphyry copper and porphyry molybdenum deposits (see S.C. Creasey, this volume). Relative to sea-floor spreading tectonics, this belt is on and parallel with the overriding continental side (Guilbert and Sumner, 1968; Guild, 1971, 1976; Sawkins, 1972; Sillitoe, 1972, 1975). The belt bulges eastward in the United States and reaches 1,200 km from the margin of the Pacific Ocean. Thus, the belt extends well into the continent and far beyond the Sierra Nevada and southern California batholiths of Mesozoic age. Although attempts have been made recently to explain the distribution of these deposits by theories not utlizing subducting lithospheres (Noble, 1970; Livingston, 1973; Lowell, 1974), most of the porphyry systems in the United States and Mexico, regardless of their underlying mode of origin, developed in an epizonal and subvolcanic environment (fig. 1). Reserves in currently known porphyry copper deposits in the southwestern United States and Mexico make up about 20 percent of the world total (Cox, et al., 1973), and include some of the largest commercial concentrations of copper known. Carbonate sedimentary rocks host, partly or entirely, many porphyry copper systems of various tonnages and grades (table 1) because of the diverse geologic environments in which the deposits occur. As a result, metallized skarn comprises a sizeable proportion of many of these systems, and because of its high concentrations of metals, skarn formed one of the first targets exploited by prospectors in the late 19th century and in the early 20th century. However, mass mining methods using open-pit techniques, pioneered in the early 1900's at the Bingham, Utah deposit (loc. 1, fig. 1), made the lower grade rocks
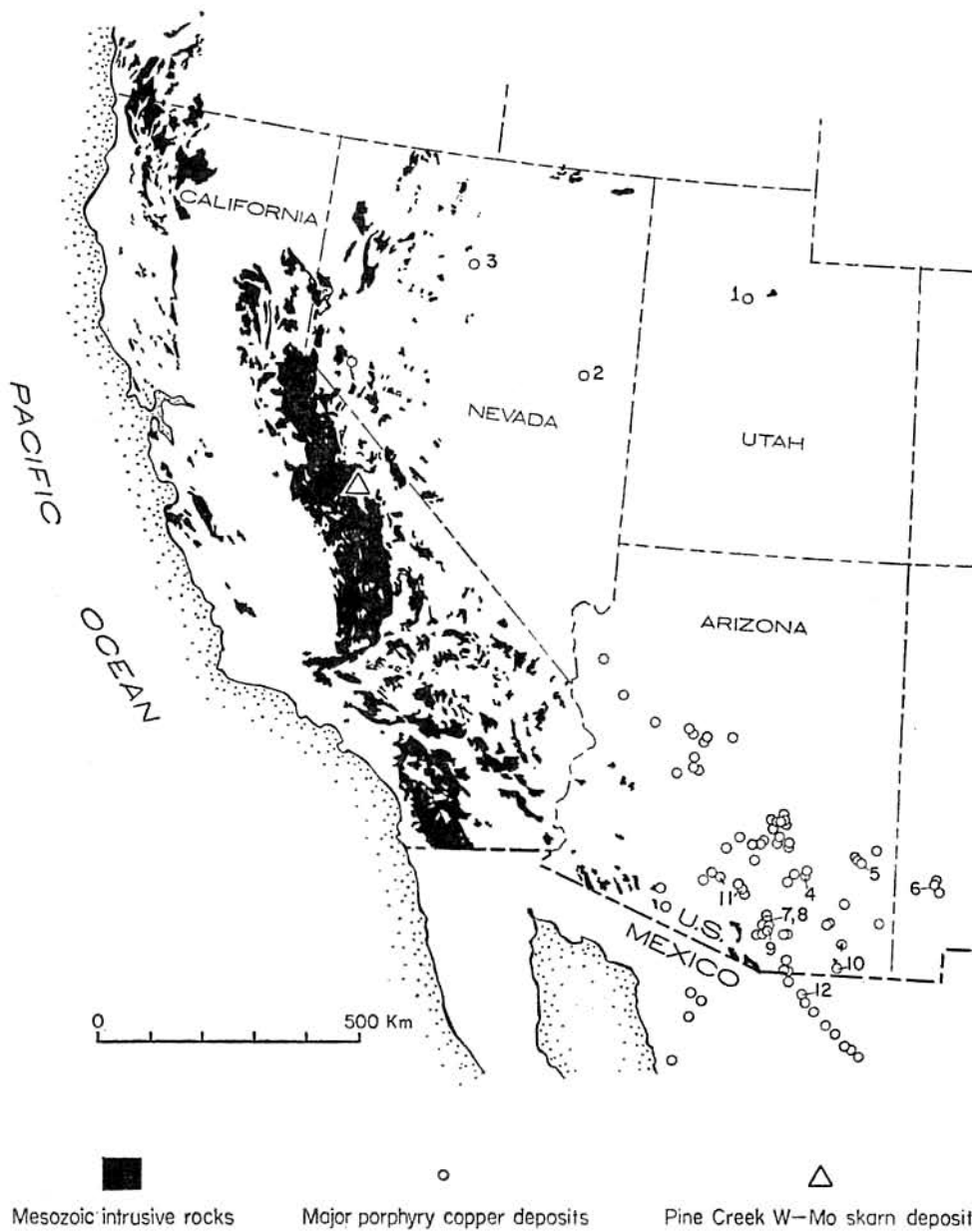
Fig. 1.   Distribution of Mesozoic intrusive rocks and the locations of major porphyry copper deposits in the Southwestern United States and northern Mexico. From Jerome and Cook (1967) and Lowell (1974). Numbered deposits keyed to table 1.

TABLE 1

PORPHYRY DEPOSITS IN THE UNITED STATES AND MEXICO, WHICH CONTAIN
SIGNIFICANT AMOUNTS OF COMMERCIAL METAL-BEARING SKARN

| Loc. no. (fig. 1)	Age		Reserves			Comments
	Million years	Reference	Size of ore body (million tonnes)	Grade (wt. percent) Cu	Year	
1	38	Moore and Lanphere (1971)	>1,000	0.75	1976	Production 1904–1975 >11 million tonnes Cu metal from disseminated Cu ore body (McCarter, 1975; Lowell and Guilbert, 1970)
2 Ely (Robinson)	109	McDowell and Kulp (1967)	200?	.8?	1975	Production 1908–1970 >2.7 million tonnes Cu metal (James, 1976)
3 Copper Canyon (Battle Mountain)	38	Theodore and others (1973)	8	.62	1975	Production 1967–1974 about 0.1 million tonnes Cu metal (T.G. Theodore and D.W. Blake, unpub. data; Morgan, 1975)
4 Christmas (Banner)	62	Creasey and Kistler (1962)	35	.6	1974	Production 1880–1972 about 0.05 million tonnes Cu metal (Eastlick, 1968; Beall, 1973)
5 Morenci-Metcalf	55–62	McDowell (1966)	1,200	.8	1975	Production 1942–1971 about 3.4 million tonnes Cu metal (Langton, 1972; Phelps Dodge Ann. Rept., 1974)
6 Chino (Santa Rita-Central)	63	Andersen (1968)	497	.78	1970	Production 1911–1962 about 2.4 million tonnes Cu metal (Rose and Baltosser, 1967)
7 Mission	59	Damon and Mauger (1966)	124	.68	1967	Production 1963–1973 about 0.5 million tonnes Cu metal (Metals Sourcebook, 1973)
8 Pima	56–60	Creasey and Kistler (1962)	265	.5	1972	Production 1952–1976 >100 million tonnes ore milled (Langlois, 1976)
9 Twin Buttes	58	Barter (1976)	447	.67	1973	Production 1970–1975 about 50 million tonnes sulfide ore milled (Kelly, 1976)
10 Bisbee (Warren)	163–178	Creasey and Kistler (1962)	None	—	1976	Total production from district (1885–1975) 4.4 million tonnes Cu metal (Bryant and Metz, 1967; Paydirt, 1975)
11 Silver Bell	63–67	Mauger et al. (1965)	<100	.75	1970	Production from district (1865–1966) about 0.2 million tonnes Cu metal (Richard and Courtwright, 1967; Lowell and Guilbert, 1970)
12 Cananea, Mexico	59	Livingston (1973)	1,000	<.4	1974	Production early 1700's–1976 about 3 million tonnes Cu metal (Velasco, 1967). Skarns are primarily Pb-Zn-bearing

Bingham — Loc. no. 1
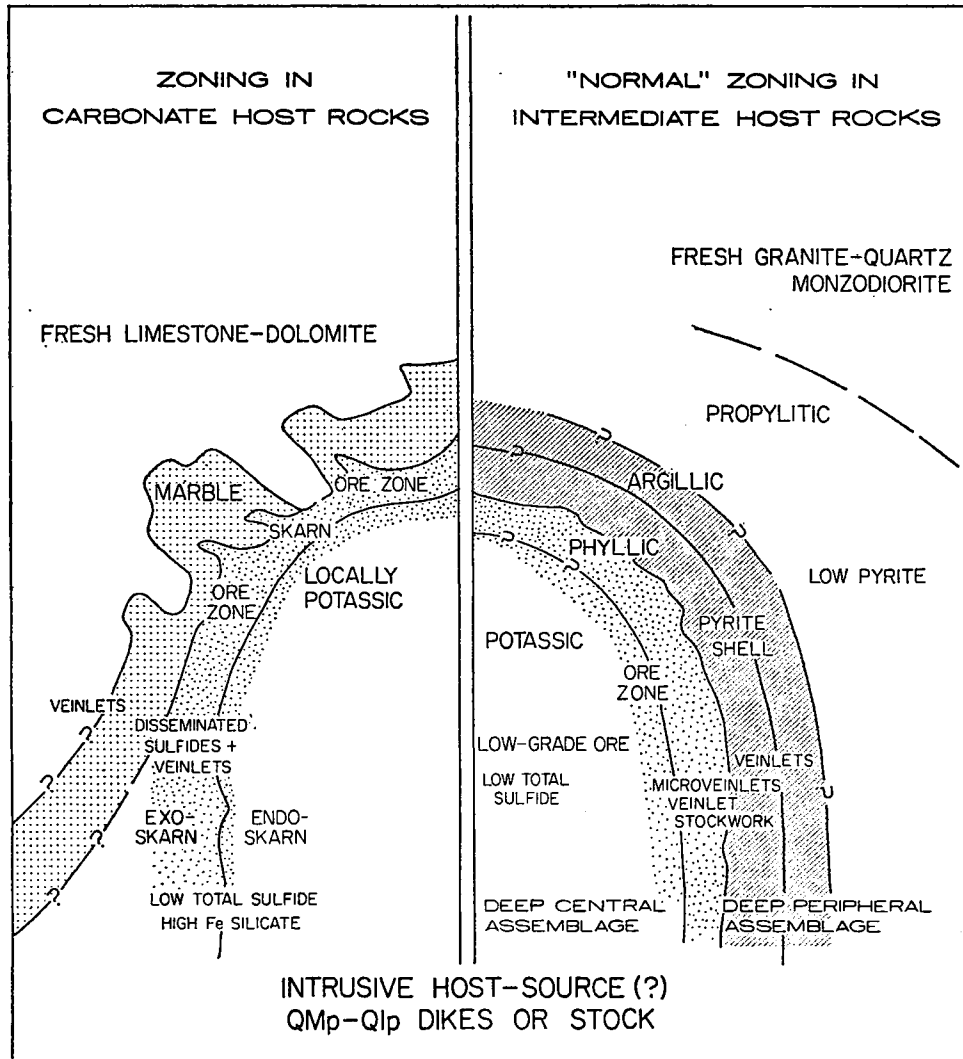
Fig. 2. Schematic comparison of alteration and mineralization in A, limestone-dolomite rocks; B, granite-granodiorite-quartz monzodiorite porphyritic intrusions (following the plutonic classification of Streckeisen et. al., 1973). Modified from Guilbert and Lowell (1974).

of the adjacent porphyritic intrusions economically viable. Since that time, the study of porphyry coppers has focussed on the geology of the intrusions. Nonetheless, skarn forms an important alteration facies (Titley, 1973) in every major porphyry system in which ore-forming fluids circulated through carbonate wallrock (fig. 2).

The purpose of this report is to point out the economic importance of skarn in porphyry systems and its substantial genetic implications. Skarns have become again economically attractive copper targets in the United States because of recent economic

conditions and because they generally contain copper and other metals in concentrations greater than the associated altered intrusions. This startling turn reflects partly the exorbitant amounts of energy required to mine and mill by conventional methods, rocks that have grades less than 0.2 weight percent copper (Page and Creasey, 1975).

ZONATION OF MINERALS IN SKARN AT BINGHAM, ELY, AND COPPER CANYON

Recently published descriptions of the porphyry systems at Bingham, Utah; Ely, Nevada; and Copper Canyon, Nevada (locs. 1–3, fig. 1); provide significant refinement of the mineral zoning pattern (fig. 2) developed in carbonate affected by a porphyry copper type of alteration and metallization.

The onset of metamorphism of sedimentary rocks in the Carr Fork area, the Anaconda Company's newly discovered skarn ore at Bingham, is marked by wide-
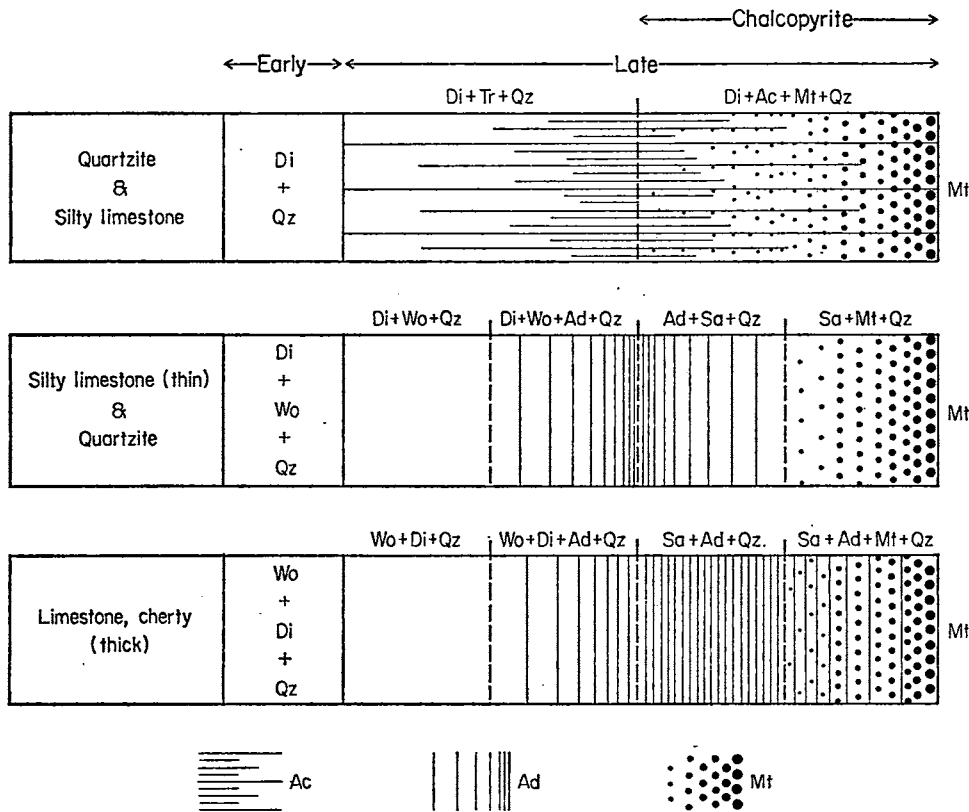

Fig. 3. Schematic sequence of mineral assemblages at the Bingham deposit (loc. 1, fig. 1) between wallrock (on left) and hypothetical magnetite rock (on right), which reflects the last deposition stage from metasomatic fluids. Widths of zones are schematic, and density of patterns implies relative changes in the amounts of iron-bearing minerals, Di, diopside; Tr, tremolite; Qz, quartz; Ac, actinolite; Mt, magnetite; Wo, wollastonite; Ad, andradite; Sa, salite. Modified from Einaudi (1975).
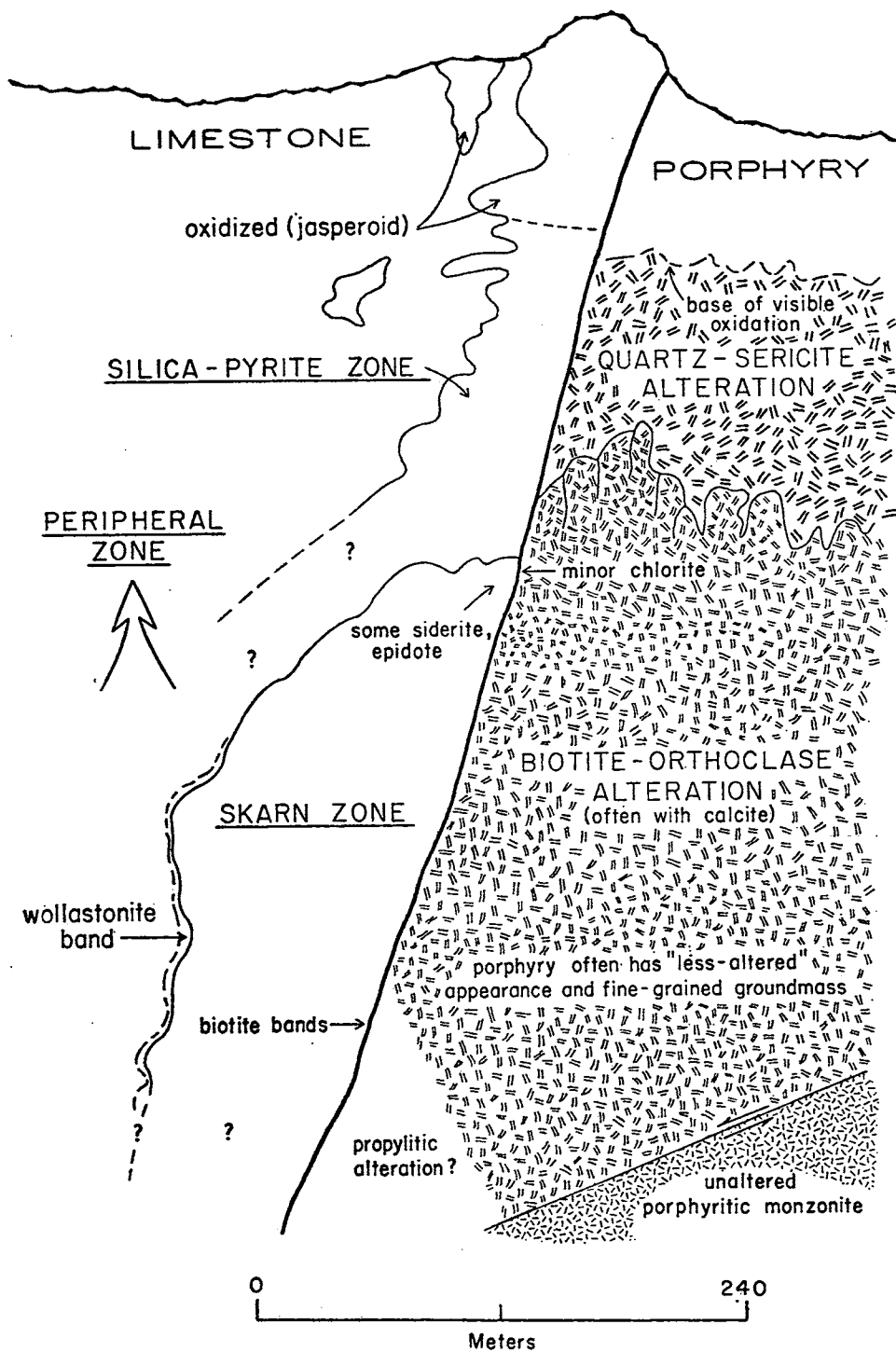
Fig. 4. Generalized cross section showing the geometry of alteration in limestone and porphyry at the Ely porphyry copper deposits (loc. 2, fig. 1). From James (1976).

spread Mg-contact metasomatism, which includes diopside-quartz and diopside-wollastonite-quartz assemblages (Atkinson, 1975; Einaudi, 1975); Fe-metasomatism apparently followed the Mg-metasomatism (fig. 3). Magnesian assemblages are replaced by successively more Fe-rich ones toward the porphyry; the compositional zones parallel the porphyry contact. In quartzite and silty limestone sequences, metamorphic assemblages contain hydrous silicates, tremolite and actinolite, whereas sequences that contained a high initial Ca/Mg ratio typically developed andradite + diopside, andradite +salite, and salite assemblages during the Fe-metasomatic stage of the skarn. The main ore mineral is chalcopyrite, which spatially coincides roughly with the distribution of andradite and actinolite (fig. 3). Early Mg-metasomatism has been reported at Twin Buttes also (loc. 9, fig. 1; Barter, 1976).

A comprehensive examination by James (1976) of silicate alteration assemblages in porphyry and adjacent limestone at the Ely porphyry copper deposits provides a correlation with depth between secondary mineral assemblages that developed in porphyry and in limestone (fig. 4). Wallrock limestone adjacent to secondary biotite-K-feldspar assemblages in porphyry or potassic assemblages of Creasey (1966) was replaced by skarn, which contains massive andradite-diopside assemblages. These secondary assemblages in the porphyry contain disseminated chalcopyrite. The bulk of the copper in the skarn, however, was deposited in pyrite-chalcopyrite veins which cut the andradite-diopside assemblages. The alteration envelopes around these veins contain actinolite-calcite-quartz-nontronite assemblages, which reflect a clay-sulfide stage (fig. 5) superposed on the early calc-silicates in skarn. At Ely, the mineral zones
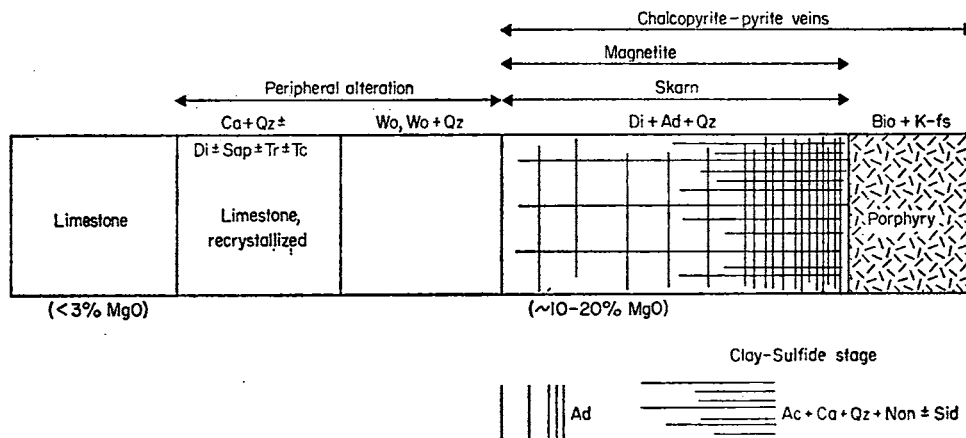

Fig. 5. Schematic geometric zonation of mineral assemblages around skarn at the Ely deposit (loc. 2, fig. 1) between limestone (on left) and porphyry (on right), which is altered to secondary biotite plus K-feldspar assemblages. Widths of zones are very schematic, and density of patterns implies relative changes in the amount of andradite (Ad), and clay sulfide stage. Abbreviations same as figure 3, and Ca, calcite; Sap, saponite; Tc, talc; Bio, secondary biotite; K-fs, secondary K-feldspar; Non, nontronite; and Sid, siderite. Modified from James (1976).

in the skarn generally parallel the porphyry contact, a relation resembling the zonal pattern at Bingham. Potassic-altered porphyry at Ely grades upward into porphyry affected by quartz-sericite alteration (fig. 4). This alteration is equivalent to the sericitic alteration of Creasey (1966) or the phyllic alteration of Lowell and Guilbert (1970), and occurs below the base of the oxide zone. Adjacent to quartz-serictei

altered porphyry, the limestone contains secondary calcite-pyrite-nontronite-quartz assemblages, which make up the silica-pyrite zone and formed penecontemporaneously with the quartz-sericite alteration in porphyry. Widespread entry of groundwater into the porphyry system probably accompanied development of the quartz-sericite alteration and silica-pyrite zone, which followed development of potassic assemblages in porphyry and skarn assemblages in limestone.

In one epizonal porphyry system, some skarn growth followed emplacement of the associated intrusion. For example, at the Christmas deposit (loc. 4, fig. 1), excellent textural evidence indicates that skarn-forming fluids penetrated slightly into the intrusive rock (Perry, 1969). The lateral zoning in endoskarn, which is up to several meters wide at this deposit, shows unaffected quartz monzodiorite replaced progressively by augite, augite-clay, grossular-augite, grossular-andradite, and grossular-andradite-diopside assemblages towards the pre-skarn intrusive contact. Skarn, which replaced carbonate wallrock adjacent to the endoskarn, probably formed at the same time as the endoskarn. In addition, this particular deposit apparently did not have an early stage of Mg-metasomatism. Mg-skarns are restricted to beds rich in dolomite.

Skarn hosts a significant percentage of the remaining Cu-Au-Ag ore in the Copper Canyon, Nevada, porphyry deposits (loc. 3, fig. 1), which belong to one of the smallest porphyry systems exploited successfully by industry in the United States
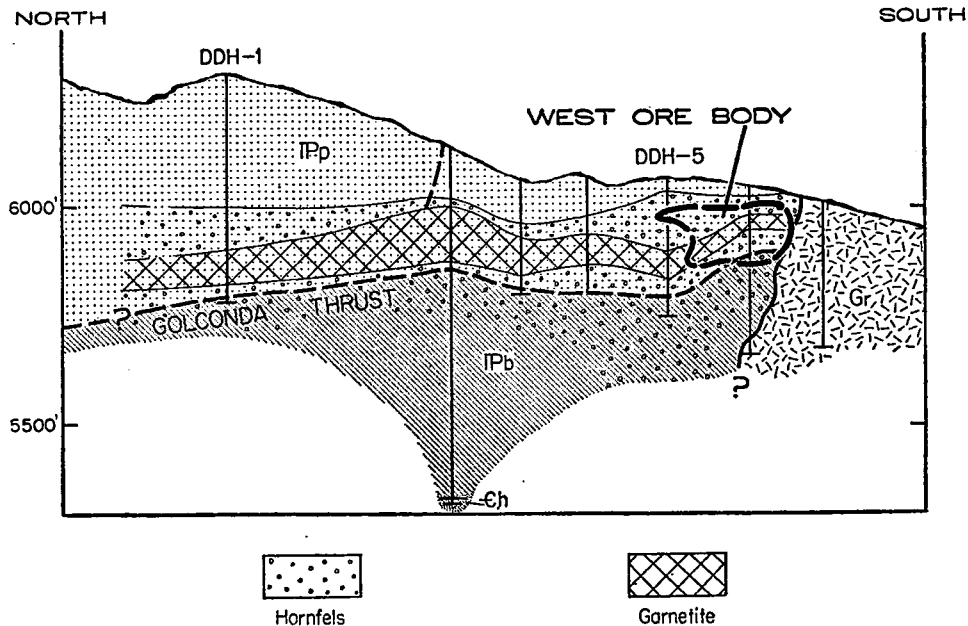

Fig. 6. Cross section through the Cu-Au-Ag skarn at Copper Canyon, Nevada (loc. 3, fig. 1) GR, granitic porphyry, potassic-altered; Pp, Pennsylvanian and Permian Pumpernickel Formation; Pb, Middle Pennsylvanian Battle Formation; Ch, Upper Cambrian Harmony Formation. Hornfels consists of diopside- and tremolite-actinolite-bearing assemblages, and garnetite consists of andradite-diopside assemblages. Rocks peripheral to hornfels and garnetite are altered to secondary mica-rich (mostly biotite) assemblages. From Theodore and Blake (1975B).

(Theodore and Blake, 1975A). Skarn replaces calcareous shale or argillite beds in Pennsylvanian and Permian rock just above the regionally extensive Golconda thrust (see Roberts, 1964); the nonsilicated and sulfide-free beds are unexposed and unavailable for study. A flat-lying tabular body of andradite-rich rock served as the locus for most metallization. Although the andradite-rich rock extends far beyond the economic concentrations of metals, at least 400 meters from a small, adjacent potassic altered porphyry (fig. 6), only that part within 180 meters of the porphyry contains economic concentrations of metals. Silicate zones in the skarn are symmetric about the adradite-rich rock or garnetite, and they include andradite-diopside, diopside-sphene-quartz, diopside-tremolite, tremolite-quartz, and biotite-K-feldspart$\pm$ tremolite assemblages (Theodore and Blake, 1975B). Because the calc-silicates are zoned mineralogically about the skarn at right angles to the porphyry, and because skarn does not occur in porous calcite-and hematite-rich conglomerate that butts up against the porphyry, the porphyry and (or) the present site of the porphyry ap-
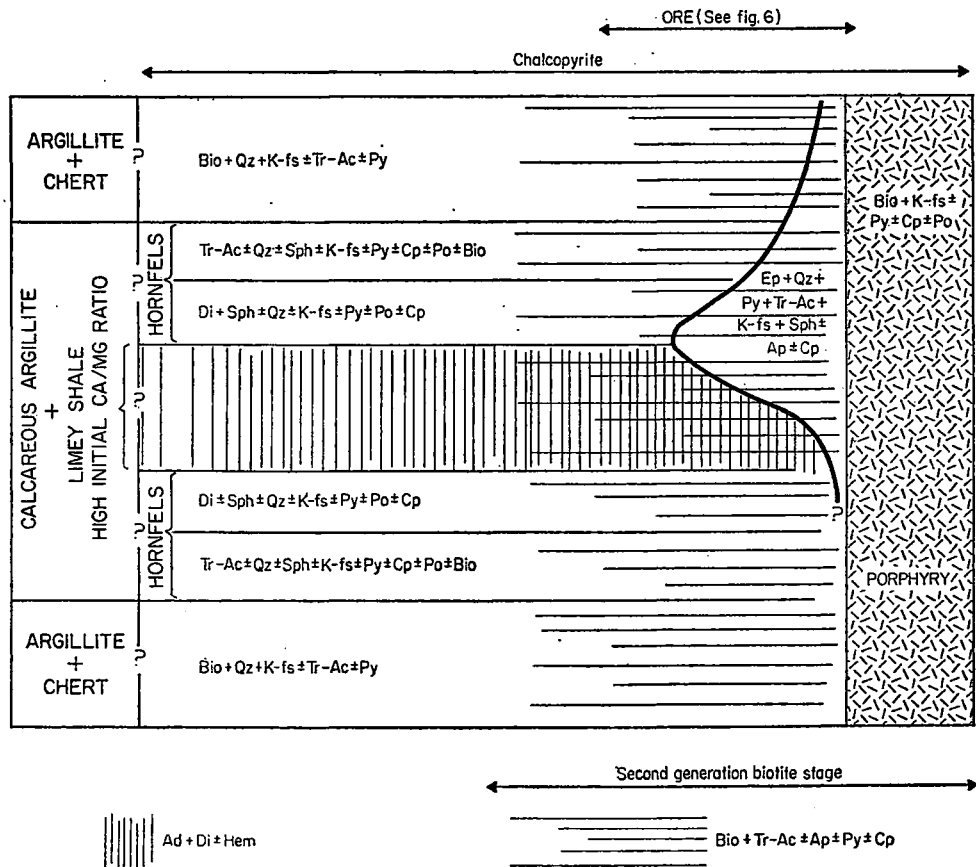

Fig. 7. Zonation of mineral assemblages at the Copper Canyon deposit (loc. 3, fig. 1). Widths of zones are schematic, and density of patterns implies relative changes in the amount of second generation biotite stage. Abbreviations same as figures 3 and 5, and Py, pyrite; Cp, chalcopyrite; Po, pyrrhotite; Sph, sphene; Ep, epidote; Ap, apatite; Hem, hematite. Modified from T.G. Theodore and D.W. Blake (unpub. data).

parently was not the locus from which the skarn-forming fluids emanated. Instead, it seems very likely that the early anhydrous stages, containing some sulfides, preceded final emplacement of the porphyry.

This relation, crystallization of skarn preceding the adjacent porphyry, distinguishes the skarn at Copper Canyon from those at Ely and Bingham. Utilizing the classification of Hosking (1973), the Cu-Au-Ag skarn at Copper Canyon would be similar genetically to his high-temperature metasomatic group. Other examples are the W-Bi-Mo skarn at Sandong, Korea (Yong, 1963), and the Zn-Pb-Cu skarn at Linchburg, New Mexico (Titley, 1961). In addition, the Copper Canyon ore deposits contain abundant pyrrhotite rather than pyrite, the predominant iron sulfide in almost all other porphyry districts in the United States. The Copper Canyon ore consists of pyrrhotite-pyrite-chalcopyrite, pyrrhotite-chalcopyrite, and pyrite-chalcopyrite sulfide assemblages as fracture fillings and replacements of early anhydrous calc-silicates in skarn. Close to the porphyry, however, andradite-rich rock containing postandradite pyrrhotite is replaced by epidote-pyrite assemblages, which are in turn cut by a second generation of hydrothermal biotite related probably to final emplacement of the porphyry. Figure 7 summarizes these paragenetic relations schematically.

Copper was deposited during both anhydrous—and hydrous-silicate mineral stages as the skarn evolved at Copper Canyon. Chalcopyrite is the predominant ore mineral, and subeconomic concentrations of chalcopyrite appear to have crystallized first in diopside-pyrrhotite-quartz-K-feldspar assemblages during final stages of diopside growth in the skarn. The bulk of the chalcopyrite was deposited subsequently during hydrous-silicate stages. Ore formed in the anhydrous skarn only after repeated passage through the skarn of Cu-bearing fluids, causing the paragenetically complex crystallization of secondary hydrous silicates and sulfides close to the porphyry (T.G. Theodore and D.W. Blake, unpub. data). The protracted paragenetic association of chalcopyrite in the skarn at Copper Canyon with minerals amenable to fluid-inclusion investigation permitted studies thereby of the physicochemical evolution of the copper-depositing fluit (s).

FLUID-INCLUSION STUDY OF SKARN AT COPPER CANYON

Previous fluid-inclusion studies by Nash (in Nash and Theodore, 1971; Theodore and Nash, 1973) and Batchelder (1976; Batchelder et al., 1976) were enlarged recently (T.G. Theodore and D.W. Blake, unpub. data) to include detailed investigations of inclusions in the skarn at Copper Canyon. Published fluid-inclusion studies of minerals from the geologic environment of skarn are relatively sparse, and studies of primary and (or) pseudosecondary fluid inclusions in andradite, one of the first silicates to crystallize near the onset of metallization at Copper Canyon, provided data bearing on the origins and evolutions of the fluid-rock system at Copper Canyon. Primary fluid inclusions are those that were trapped mostly along growth imperfections on the rim of a crystal during its formation, and primary pseudosecondary ones are those that are trapped by healing fractures formed in a crystal during its growth (Roedder, 1967; 1972).

The skarn and adjacent altered porphyry contain significant concentrations of three of the five recognized types of fluid inclusions (types I, II, and III of fig. 8) and very sparse occurrences of type IV (Nash and Theodore, 1971). Textural relations suggest that these liquid-rich inclusions reflect both primary and (or) pseudosecondary and secondary modes of origin relative to their host minerals. The repeated opening and rehealing of the rocks on a microscopic scale in a high-temperature hydrothermal

environment yield exceedingly complex and overlapping parageneses among populations of inclusions. This is especially true in quartz, less so in andradite (for additional descriptions of fluid inclusions in other porphyry-type districts see Roedder, 1971; Moore and Nash, 1974). At Copper Canyon, many liquid-rich inclusions in andradite
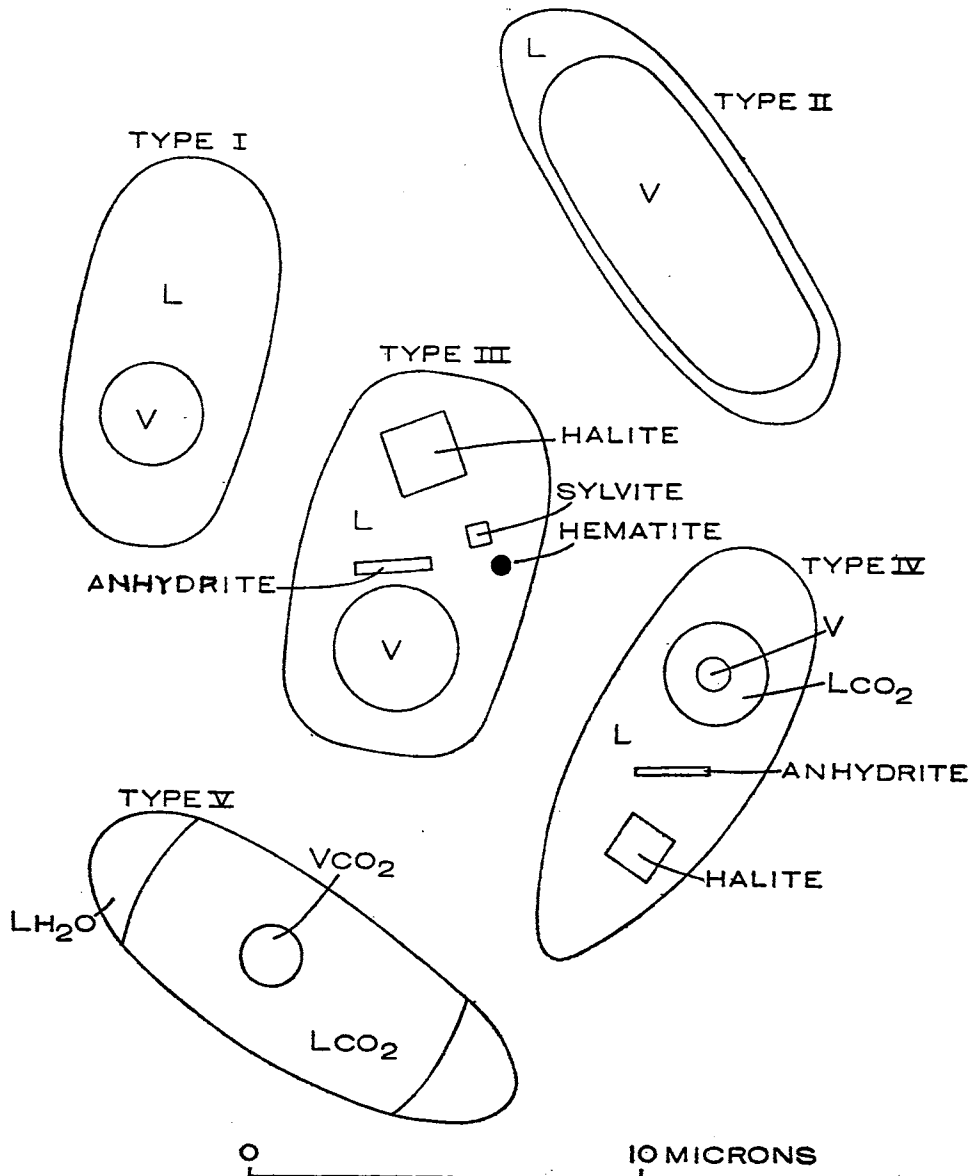

Fig. 8. Sketches of five types of fluid inclusions in and around the skarn at Copper Canyon, Nevada. Room temperature. L, mostly liquid H O; V, vapor; LCO ; VCO , vapor CO . From Batchelder (1976).

occur in three textural associations: (1) isolated, relatively large (30–40)μm angular inclusions in the core areas of crystals without visible traces of any related planar features; (2) local concentrations of angular inclusions generally oriented with their long dimensions at right angles to the andradite growth lines; and (3) swarms of small (<10μm), ovoid to ellipsoid inclusions with their long axes elongated parallel to the growth lines. Each of these three associations reflects trapping of fluid very close in time to the primary growth of the andradites, and these fluid inclusions show uniform proportions of their liquid and vapor phases, indicative of nonboiling conditions during growth of the andradites. Elsewhere, Tugarinov and Naumov (1969) also describe some inclusions that they judge to be primary which have their long dimensions oriented at right angles to growth lines in garnet. Textural relations at high magnification in andradite at Copper Canyon also suggest some superposed generations of inclusions and (or) sulfides. Some microfractures have been partly filled by anastomosing fingers of postandradite sulfides, chiefly pyrrhotite.

Although the early fluids were apparently unsaturated with respect to NaCl at 25 °C because of the absence of NaCl daughter minerals, they may be higly saline and may contain significant amounts of Ca and possibly Mg, which do not generally precipitate as daughter minerals. Inclusions made up of pure water (liquid plus vapor) cannot homogenize to liquid at temperatures above the critical point at 374 °C (Roedder, 1972). The proportion of liquid to vapor in liquid-rich inclusions that homogenize at high temperature (roughly 500° ± 50 °C) is fairly constant. They fill to liquid when heated. At several skarn deposits elsewhere, Sazonov (1962) and Sivoronov (1968) also determined that primary or pseudosecondary inclusions in garnets are of a liquid-plus-vapor variety (our type I) that fills to liquid in the temperature interval 450°–560 °C. All such fluids, including the ones at Copper Canyon, must be highly saline, at least 20 weight percent NaCl equivalent. Other experiments suggest that fluids associated with skarn development may be highly saline (Kiseleva, 1968; Vidale, 1969).

Moderate amounts of CO_2 in solution with the early fluids would produce significant effects. For a given temperature, CO_2 would cause effervescence or boiling to begin at a depth greater than if there were no CO_2 present because any CO_2 in the fluid would tend to increase the coefficient of thermal expansion of the trapped fluid (see Roedder, 1972, for a discussion of these phenomena). We infer, however, that partial presures of CO_2 in the early fluids at Copper Canyon were low because of the absence of liquid CO_2 from the early inclusions in andradite. Thus, the effects of CO_2 are probably not very large.

Deposition of quartz in the skarn was wide ranging both in time and space after early andradite and diopside had crystallized. Fluids circulated through the garnetite during the deposition of two generations of quartz, one a disseminated variety and the other, vein. The fluids in these two types of quartz seem to have differed both in chemistry and in the prevailing temperatures at which their inclusions homogenize. Textural relations suggest that crystallization of quartz disseminated through garnetite followed closely crystallization of the andradite and much of the diopside. This quartz typically occurs in minor amounts sprinkled throughout the garnetite as anhedral grains, locally intergrown with mattes of K–feldspar and some diopside and sulfides, mostly pyrrhotite. The quartz fills open spaces among previously crystallized, euhedral crystals of andradite and diopside. Heating tests of the fluid inclusions in disseminated quartz yield homogenization temperatures in the range 221°–315 °C for both liquid-rich type I and halite-bearing type III inclusions, the predominant varieties. In addition, the fluid-inclusion population in the quartz shows very wide ranging proportions

of liquid and vapor suggesting that the fluids were boiling. Thus, deposition of disseminated quartz and some of the first sulfides to precipitate in the skarn seems to have occurred at temperatures roughly 200 °C less than the temperatures associated with the onset of the crystallization of andradite. In addition, the chemistry of the fluids seems to have changed: it appears to show higher concentrations of Na during disseminated quartz stage, and possibly higher overall salinities, than during the andradite stage. Approximate salinities of the type III inclusions in disseminated quartz, measured from the solution temperatures of halite daughter minerals, are in the range 32–43 weight percent NaCl equivalent. A major unknown, however, is the concentration of Ca in the fluids during crystallization of andradite in the skarn.

Some of the continued changes in the physical and chemical environment of the skarn are reflected by fluids associated with quartz-pyrrhotite-epidote veins containing minor K–feldspar and tremolite, which cut garnetite. Abundant swarms of type I, II, and III inclusions with extremely complex and overlapping interrelations among planar alinements of inclusions typify the quartz of these veins. Very wide ranging homogenization temperatures and phase proportions for type I and II inclusions, from 327° to 470 °C and from 300° to 500 °C, respectively, typify these inclusions. Type II inclusions, the gas-rich ones, homogenize in most cases to vapor, but a few homogenize to liquid. The halide-bearing type III inclusions homogenize to liquid at somewhat lower temperatures, 263°–308 °C The liquid-rich (type I) inclusions, whose liquid-vapor proportions are fairly constant within the small volumes of polished chips, homogenize to liquid at temperatures of about 400° to 420 °C. From this we infer that the fluids associated with the deposition of some postandradite quartz in veins were boiling at approximately these temperatures. These homogenization-temperature data also suggest possible local influx of hot low-density fluids circulating through the skarn as some veins were opening after part of the disseminated quartz had already crystallized in the skarn.

The pressure during mineralization can, under certain conditions, be estimated from fluid-inclusion relations by making appropriate assumptions and by referring to some experimentally studied systems. The primary fluid-inclusion populations of the mica (largely biotite), the tremolite-actinolite, and the diopside rocks around the garnetite contain abundant textural evidence for boiling. Phase proportions in the fluid inclusions of these rocks vary widely; liquid-rich and gas-rich inclusions are abundant. We found that type I inclusions with the most uniform vapor-liquid proportions in very small volumes of quartz-rich rock typically fill to liquid somewhere in the 360° to 400 °C range. This relation was found both in the widespread mineral zones that surround the skarn and also in narrow veins that cut the skarn. However, the P–T position of the boiling or two-phase (gas-plus-liquid) curve for the system $NaCl–H_2O$ significantly varies with composition (Haas, 1971). The overall salinity for these early fluids at Copper Canyon is probably about 20 weight percent NaCl equivalent, although we have no direct measurements of their salinities because of optical limitations on the freezing stage. In a hydrostatic system open to the surface, a fluid of such a composition will boil at 360 °C anywhere from the surface to a depth of about 1.9 km (153 bars); at 400 °C, to a depth of about 3.3 km (182 bars). These depths are based on the calculations of Haas (1971), and in part on an extrapolation of his data. However, his calculations assume no throttling points along a vertical column of brine or suspended vapor bubbles along the column. Nonetheless, the shallow depths of formation for the ore that one would infer from these data are consistent with our geologic reconstruction of the cover rocks at the time of mineralization (see Nash and Theodore, 1971; Theodore and Blake, 1975A).

TABLE 2

SUMMARY RANGES OF HOMOGENIZATION TEMPERATURES
MEASURED FOR THE DIFFERENT TYPES OF INCLUSIONS IN
AND NEAR THE SKARN AT COPPER CANYON, NEVADA
(Gar, garnetite; Di, diopside rock; Ta, tremolite-actinolite rock; Mic,
secondary-mica-rich rock; Por, altered porphyry)

Fluid–inclusion type	Relative abundance	Host rock	Age relative to host mineral	Range of filling temp. (°C)
I-[1]	Common	Gar	S;PPS-[2]	161–565
		Di	PPS	337–510
		Ta	PPS	202–412
		Mic	S;PPS	202–515
		Por	S;PPS	240–490
II	do	Ta	PPS	332–503
		Mic	S;PPS	317–530
		Por	S;PPS	337–590
III	do	Gar	PPS	219–337
		Di	S;PPS	215–425
		Ta	PPS	205–400
		Mic	S;PPS	208–396
		Por	S;PPS	186–317
IV	Rare	Por	S	345

[1]/I, liquid rich; II, gas rich; III, halide bearing with low gas volumes; IV, same as type III but also with optically recognizable liquid CO_2 at 25°C.

[2]/S, secondary; PPS, primary-pseudosecondary.

The primary-pseudosecondary type I inclusions in andradite from the garnetite clearly contrast with inclusions in all other rocks at Copper Canyon. The fluids associated with the crystallization of andradite apparently were not boiling; many compose fairly uniform proportions of their liquid and gas phases, and they fill to liquid when heated to very high temperatures of about $500° \pm 50°C$ (table 2). Such supercritical fluids must have been highly saline (Roedder, 1972). However, there must have been sufficient pressure on the fluid to retard physical separation of a vapor phase during growth of the andradite. If these fluids can be referred properly to the system $NaCl$–H_2O, then a vapor pressure of about 380 bars, close to lithostatic for Copper Canyon (Nash and Theodore, 1971), could be maintained at 500°C (Sourirajan and Kennedy, 1962). From their experimental work, we would also infer that such a fluid must have had a salinity of about 20 weight percent $NaCl$ equivalent. Most important, however, the fluid-inclusion data seem to suggest that pressure in the skarn may have approached lithostatic during its early period of crystallization. Figure 9 summarizes the mineral and fluid parageneses around the skarn at Copper Canyon.

EPIZONAL AND BATHOLITHIC SKARNS

Comparison of skarn ore in the epizonal environment of the porphyry coppers and in the deep-seated batholithic environment provides added insight into the characteristics of fluid flow during skarn development. The Pine Creek deposit (fig. 1), which is a W-Mo skarn near the east edge of the Mesozoic Sierra Nevada batholith
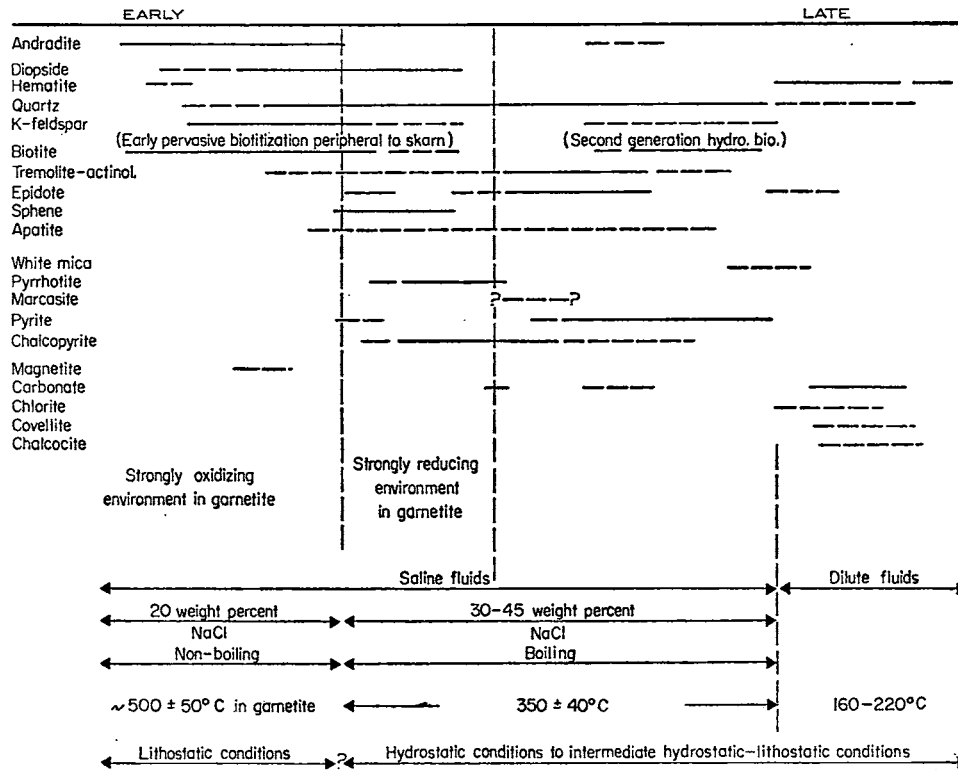
Fig. 9. Paragenetic relations among minerals and fluids in and around the skarn at Copper Canyon.

(Bateman, 1965), is currently the largest producer of tungsten (scheelite) in the United States. This deposit will serve as a representative of the deep-seated class of skarn deposits. As shown in a cross section through the North ore body (fig. 10), one of the major ore bodies at Pine Creek, commercial concentrations of scheelite are disseminated through quartz-poor garnet-pyroxene zones of the skarn. Another general type of scheelite-bearing ore shoot occurs in rock which includes abnormally high amounts of quartz (Bateman, 1965). Metasomatic effects in the upper Paleozoic marble adjacent to skarn at Pine Creek are absent, and the horizontal extent of skarn is limited closely to rock near the contact. The relatively restricted extent of deep-seated skarn bodies becomes especially apparent when they are compared with the epizonal skarns of porphyry coppers described above. The most massive development of skarn ore in the North ore body occurs under an "overhanging lip" of the adjacent granite (fig.10). This relation suggests that the granite adjacent to the skarn acted as a structural trap for skarn-forming fluids as they moved primarily up along the contact towards the surface (Bateman, 1965). Thus, the granite must have been emplaced before the skarn was formed. Because channelways for fluid circulation are provided by a myriad of premineral structures in the epizonal environment, skarn-forming fluids potentially may range much more widely from their sources than in the batholithic environment. In many epizonal porphyry copper deposits, skarn commonly extends far beyond the economic boundaries of hypogene ore (figs. 3, 5, 6), although some large deposits, which are sec-
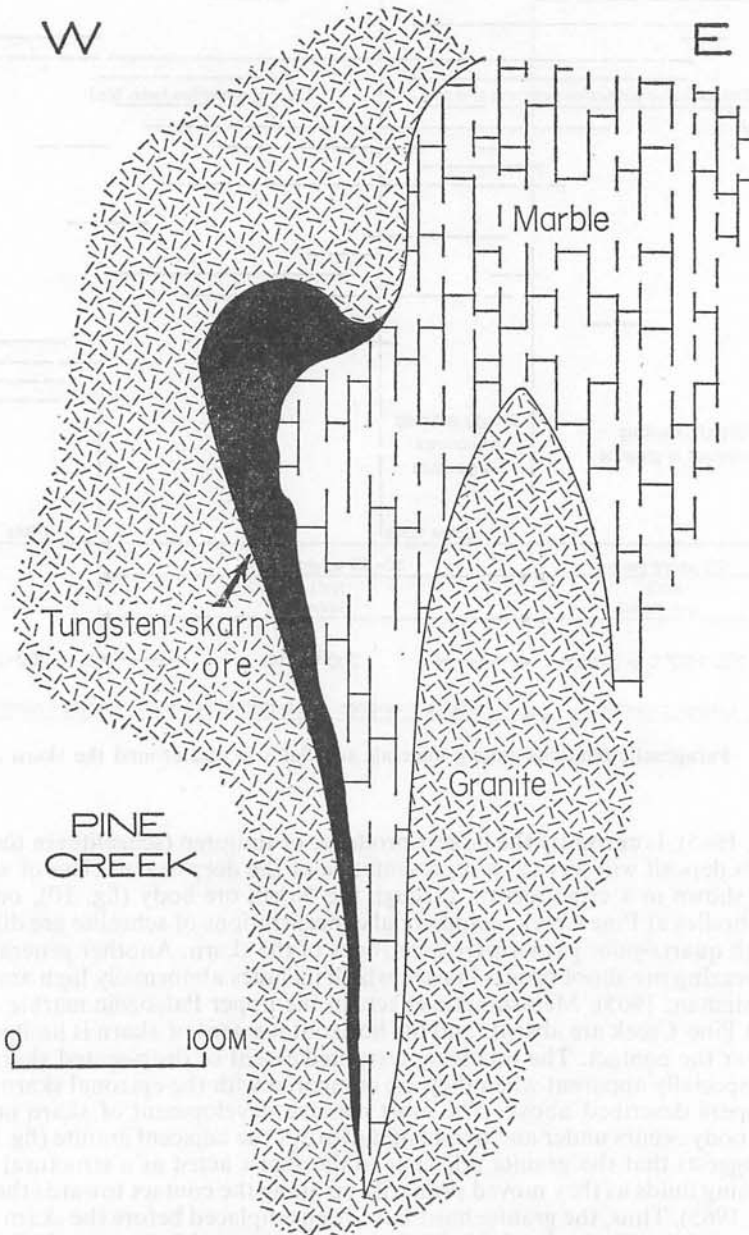
Fig. 10. East-west schematic cross section through the North ore body Pine Creek W-Mo skarn deposit. GR, granite. Modified from Bateman (1965).,

ondarily enriched, commonly contain commercial enrichment blankets across the entire mineralized system in both porphyry and wallrock. Ore generally extends laterally no farther than skarn in the batholithic environment. Last, the apparent easy mobility of tungsten during hypogene processes, which has been documented by the removal of scheelite from skarn during subsequent silication (Bateman, 1965, p. 129–130), suggests that many skarns in porphyry copper districts may have been impoverished in tungsten by the repeated passage of hypogene fluids through these rocks as the systems evolved.

SUMMARY

This review of recently published investigations concerning petrogenesis of skarn suggests that their study may provide significant data which help elucidate the P–T–X of fluids in epizonal systems during transition from a magmatic regime to a hypogene hydrothermal one. Although relations among the associated porphyries, skarn, and ore are typically complex and vary significantly in detail from deposit to deposit, some generalizations may now be made which refine previously published models (fig. 2) of skarn development. One conclusion, which seems to emerge from relations documented in several porphyry deposits, is that alteration of carbonate to skarn laterally may range widely, and skarn usually extends far beyond the economic limits of hypogene ore. Abundant premineral structures in the epizonal environment provide channelways readily accessible to the circulation of skarn-forming fluids. In several deposits, additive Fe-metasomatism has been preceded by widespread Mg-metasomatism and the mineral zones formed primarily by infiltration phenomena. In others, skarn seems to have formed by a combination of infiltration and diffusion phenomena as carbonates reacted with surrounding silicates to yield skarn. There is good evidence that postmagmatic fluids, which produced potassic alteration assemblages (secondary biotite-and K–feldspar-rich ones) in the porphyries, commonly react with carbonates to yield andradite-diopside-bearing skarn. Finally, detailed paragenetic studies coupled with fluid-inclusion studies at one of the porphyry deposits suggest that saline non-boiling fluids were initially involved in the crystallization of the anhydrous silicate minerals in skarn, and that the fluids became highly saline and were boiling as the skarn evolved through its sulfide and hydrous silicate stages. Fluid-inclusion studies are needed in skarns at many more porphyry deposits before additional generalizations are made.

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