Porphyry Copper Deposits of the American Cordillera

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ABSTRACT

Porphyry copper deposits in the American southwest comprise a distinctive and important metal resource. Their exploration and exploitation during the past hundred years was accompanied by significant advances in geological knowledge and development of increasingly efficient mining and extraction methods. Cause and effect are indistinguishable because the necessity for increasing mining efficiency resulted in enhancement of extractive methods and because geological study of the ores resulted in recognition of broadly applicable geological and exploration concepts. The early view of linear tectonic-based regional controls was supplanted by integration of concepts of plate movements. Early views of the environment of formation of hydrothermal ores have been given rigor or modified by the results of studies based on modern methods of analysis and application of sophisticated chemical principles. Deposits have been sites of basic studies of hydrothermal systems, the results of which have been applicable across a wide spectrum of ore deposits. Most importantly, information and methods developed in the study of ores and their mining have served as bases from which the search for deposits in many regions of earth has proceeded successfully during the past half century.

INTRODUCTION

The American Southwest, comprising the southwestern half of Arizona and contiguous parts of New Mexico and Mexico (“the region”) is the site of an extraordinary endowment of porphyry copper deposits. Most deposits are in southeastern Arizona where historic and recent copper production amounts to about two-thirds of newly mined copper in the United States. Significant quantities of by-product molybdenum, silver, gold, and platinum are also produced.

This paper presents a brief history of the technological evolution of southwest porphyry copper deposits as bulk low-grade deposits and the evolution of knowledge of their settings, habits, and genesis over the past century. This summary sets forth important parameters that may be contrasted and compared with other porphyry systems in other regions. The writer has selected significant characteristics described in an extensive literature developed during the past half century to serve as fundamental points from which to consider the environment and processes of formation of porphyry copper deposits as viewed in the 1990s.

Background

Following Daniel Jackling’s innovations in mass filtration at Bingham, Utah, during early years of the century, mines in the southwest gradually evolved from high-grade, mostly underground operations to bulk low-grade, mostly open-pit operations. These districts and mines included Miami, Inspiration, Ray, Chino, Morenci, and Bisbee. Under the impetus of material requirements for prosecution of the war, the search for copper ores by 1942 had focused almost solely on discovery of new disseminated orebodies and resulted in identification of 25 porphyry copper deposits by 1980. Among the first recognized as having porphyry copper potential by mid-century were the disseminated ores at Silver Bell, described by Richard and Courtright (1954). Much of the early history of these deposits has been recorded from economic and engineering perspectives by Parsons (1933, 1957).

In the early 1990s mining was proceeding at a dozen deposits in Arizona that had survived the economic downturn of the 1980s: Twin Buttes, Sierrita- Esperanza, San Xavier-Mission, San Manuel-Kalamazoo, Ray, Morenci, Pinto Valley and Inspiration, and Bagdad. Leaching of copper was taking place at Mineral Park, Lake Shore, and Silver Bell. Chino and Tyrone were operating in New Mexico, and Cananea and La Caridad were producing copper in Mexico. At this writing, ten more deposits have been explored but are undeveloped or unmined.

The porphyry copper deposits of the region have been not only sites of recovery of significant mineral wealth but also sites of detailed and extensive studies of process geology and development of mining and beneficiation technology. Geological studies of mining districts of the southwest reported mostly by geologists of the U.S. Geological Survey during the early part of the century developed a basis of regional stratigraphy and structural geology that is used to this day with only minor modifications. Basic concepts of ore occurrence and classification developed from studies of ores at Bisbee, Ray, Miami, and Morenci have been refined continuously since the beginning of the century with heightened study during the decades of the 60s, 70s, and 80s. Mines and districts of the region have been sites of development and testing of newly widely used exploration technology that includes both geophysical (Brant, 1966) and geochemical (Bloom, 1966; Chaffee, 1982a, 1982b) methods. Arizona deposits have been sites of development of innovative technology in mineral extraction during the past half century and have served as field laboratories for development of methods and machinery.

Production and Grade

A tabulation of grade and tonnage of porphyry copper ores of the region has been published by Gilmour (1982) and summarized by Titley and Anthony (1989) and Titley (1994). Reserves in 1989 have been listed by Beard (1989). Production figures summarized for 45 porphyry copper deposits in the United States by Titley and Beane (1981) are 15.8 billion tons of copper ore production and reserves with a weighted copper grade of 0.68 percent. Fourteen deposits that reported molybdenum had a weighted grade of 0.0325 percent molybdenum.

Literature and the Growth of Knowledge

Literature of the first half of the century dealt largely with
field observations and descriptions of known deposits. Much of this was in Monographs and Professional Papers of the U.S. Geological Survey, as Transactions of the American Institute of Mining and Metallurgical Engineering, and in serial publications such as Economic Geology. Viewed from the perspective of the evolution of ideas, papers of the 1940s were the first important reports treating alteration, mineral zoning, rock descriptions, and regional settings of these large systems. Collections of current reports focusing on the region and treating both deposits and topical information have been published by Titley and Hicks (1986) and Titeley (1982a). Papers treating general properties of the deposits of the region as contrasted with deposits of other areas have been published by Jerome and Cook (1967), Lowell (1974), Hollister (1978), Titeley and Beane (1981), and Titeley (1992, 1994). Comparable treatment of porphyry deposits in western Canada has been published by Sutherland Brown (1976).

A surge of scientific interest has been marked by a comparable increase in the flux of papers treating different properties of porphyry copper systems. This increase began in the early 1960s, and the numbers of publications reached a peak during the late 1970s and early 1980s. The period was witness to application of increasingly widely available techniques of measurement and applications and testing of theory. Many concepts of hydrothermal ore genesis were refined. Porphyry systems were studied as examples of epigranular intrusion-centered ores systems, of the evolution of hydrothermal processes in time and space, of the evolution of petrogenetic systems, of metal and alteration zoning, and of supergene enrichment and weathering processes. Many fundamental and now widely accepted notions of hydrothermal ore formation evolved from these studies.

GENERAL GEOLOGICAL HABITS AND GENESIS

Porphyry copper ores are phenomena of island arcs such as the western Pacific, of cratons in continental margin settings such as the western United States and contiguous Mexico, and of accreted, constructed continental margin settings such as western Canada. The character and complexity of deposits in these different settings vary in petrological and metallogenic detail, but notwithstanding such contrasts the deposits of all these regions share important features. The apparent association of ores with subaerial andesitic volcanic activity and the affinity of ores with felsic intrusive porphyry centers link porphyry copper deposits with specific geologic settings which have undergone the effects of plate convergence, most commonly along continental margins and island arcs.

Tectonic Settings and Geologic History

The history of modern knowledge and ideas concerning the regional association of ores with crust commences with Butler (1933), who noted the distribution of porphyry districts in a belt around the Colorado Plateaus. Under the influence of work by Billingsley and Locke (1935, 1941) and Mayo (1958), studies of the fabric of continents during the next two decades led to ideas of lineament control of ore districts. These workers showed districts to be localized at intersections of major regional structures or associated with major tectonic belts. Harrison Schmitt (1966) studied the location of porphyry districts from a global perspective and associated ore districts with major lineaments and zones of rifting. Even at this early time Schmitt invoked potential continental drift as a mechanism to explain continuation and offset of his major structures and proposed effects related to the influence of the East Pacific Rise. Using large numbers of potassium-argon radiometric dates, Jerome and Cook (1967) carried the notion of occurrence of districts in belts to a degree of sophistication and examined porphyry associations with characteristics of crustal geology. The idea that regional structures control the location of porphyry copper districts has withstood the advent of more recent notions concerning the evolutionary history of continental margins based on plate motions. Conflicting ideas of the importance of flaws in the crustal fabric of North America to district localization have been expressed by Lowell (1974) and Sillitoe (1975).

Areal and Structural Geology

Porphyry deposits of the region lie above the North American craton in Arizona, New Mexico, and contiguous Mexico. The geology of this region has been described in relevant parts by various workers including Anderson (1966, 1968) and Titeley (1981, 1982b, 1992). The craton basement of the region comprises Proterozoic sedimentary and volcanic rocks at varying levels of metamorphism and batholithic scale plutons representative of at least three episodes of Proterozoic igneous activity. Most of the region's porphyry copper systems lie within or above a 1.68 to 1.72 Ga basement dominated by clastic metasedimentary rocks and included plutons; three deposits in northwestern Arizona lie within a possibly older (ca. 1.8 Ga) basement of metavolcanic rocks and older plutons. Figures 1A and 1B show the distribution of deposits and generalized basement ages of the region.

The Proterozoic basement is overlain by 2 to 4 kilometers of Phanerozoic cover consisting of Paleozoic platform strata and a variable thickness of Mesozoic clastic and volcanic rocks. In many districts mineralized basement is exposed in intrusive contact with porphyry intrusions and in fault contact with Phanerozoic strata, suggesting the existence of a still unresolved episode of Mesozoic tectonism that may have occurred in the Jurassic. Pre-Laramide Mesozoic rocks are represented by intrusions, by basin strata in the central part of the region, and by mixed volcanic and clastic strata in southern Arizona and contiguous Sonora, Mexico.

Courtright (1958) and Richard and Courtright (1960) were the first workers to report observations on volcanic rock successions that established the Laramide interval as manifesting a distinct geological style in contrast with that of the older Mesozoic. The Laramide interval is a 25 m.y. span of time marked by both volcanic and intrusive igneous activity. The interval followed a period of 90 m.y. of igneous quiescence and was succeeded by a further 25 m.y. period of similar quiescence in the region. Laramide lithologies of the region are dominated by igneous rocks ranging from extrusive flows and pyroclastic successions to intrusive batholiths, stocks, and dike-sill swarms. Magmas were emplaced in the shallow crust, and their first manifestation appears to have been development of andesitic stratovolcanoes. Remnants of subaerial flows are widely exposed through the region (fig. 2). The volcanic rocks are commonly altered or miner-
Figure 1A. Generalized basement ages in Arizona and California as suggested from neodymium isotope and corresponding $T_{DM}$ data of Bennett and DePaolo (1987) and Lang (1991), and in Mexico by Anderson and Silver (1981) based on radiometric ages of Proterozoic plutons and the inferred presence of the Mohave-Sonora Megashear (m-s). Although the terrane boundaries are generally real, their specific definition on the ground is general and unspecific in most instances because of paucity of appropriate outcrop. In Arizona, boundaries are modified from Bennett and DePaolo (1987) and Chamberlain and Bowring (1990).
became rejuvenated during Laramide time (Titley, 1976). Stock emplacement have remained elusive except at Bagdad, which demonstrates the importance of an old northwest-oriented structural fabric parallel to the former continental margin which has been summarized by Schmitt (1966). More recent work concerning the structural style of the Laramide has been summarized by Davis (1979) has demonstrated a Laramide structural zona by Davis (1979). The widespread association of porphyry systems with these igneous suites coupled with observations of petrologic associations in island arcs and Andean-like margins has led to a general notion that the porphyry systems have evolved in the subvolcanic intrusive roots of andesitic stratovolcanoes. However, the evidence of evolution in such settings has not been successfully interfaced with interpretations of the existence of Laramide calderas in the region (Lipman and Sawyer, 1985).

Since Laramide time, oxidation, leaching, and episodes of erosion interrupted by younger episodes of volcanic activity and Basin and Range uplift have modified the original character of ores. Intermittent uplift and erosion have presently exposed porphyry deposits of the region at levels believed to be a few kilometers beneath their original tops. Many modern ideas of the structural setting of the porphyry deposits had their roots in the application of lineament tectonics summarized by Schmit (1966). More recent work concerning the structural style of the Laramide has been summarized by Krantz (1989). Mapping and interpretation in southeastern Arizona by Davis (1979) has demonstrated a Laramide structural style dominated by basement-cored uplift. This interpretation demonstrates the importance of an old northwest-oriented structural fabric parallel to the former continental margin which became rejuvenated during Laramide time (Tittley, 1976). Despite this and other work, however, the structural controls of stock emplacement have remained elusive except at Bagdad, where Anderson and others (1955) mapped the intrusion center at the intersection of two orthogonal Laramide fault sets.

**Time and Plate Tectonics**

A link between porphyry ore genesis and tectonic events related to plate convergence was first suggested for the region by Sillitoe (1972, 1975). Two principal episodes of porphyry copper deposit formation are recognized in the region, one of Jurassic age as represented by the replacement and breccia complex at Bisbee and another of Late Cretaceous to Early Tertiary (Laramide) age as represented by more than 40 mineralized centers in the region. Both the Jurassic and Laramide events represent short-lived episodes of near-normal convergence of the North American and Pacific Plates (Coney, 1978). The extensive dating of ore deposits in this region summarized in Reynolds and others (1985) leaves little doubt of the temporal correlation of ores with high rates of normal plate convergence during the Laramide. Moreover, Laramide stress directions inferred from plate convergence geometries are mimicked in fracture and dike patterns seen in Laramide intrusion centers (Heidrick and Tittley, 1982). However, precise understanding of all elements of plate convergence phenomena that led to formation of the deposits of southwestern North America remains elusive.

The restoration of Baja California to a pre-rift fit along the Mexican mainland reveals that belts of deposits grossly parallel the old continental margin (fig. 4), but the inference of a craton setting for deposits of coastal Mexico is subjective (Tittley, 1992). Deposits of Arizona and contiguous Mexico represent ores of 58 to 65 Ma age, while those in a subparallel belt west of the volcanic cover of the Sierra Madre Occidental in Mexico are generally of about 55 Ma age (Damon and others, 1983).

Deposits of Mesozoic and younger age in the western hemisphere are along the western continental margin, while North American porphyry copper deposits of Paleozoic age are in parts of the old convergent margin now deeply eroded or hidden in the deformed parts of the Appalachian orogen along the eastern continental margin. The dense array of districts and deposits of the southwestern United States together with Cananea and La Caridad in Sonora have been considered a separate porphyry copper population. Concentration of study on this population by many workers including Noble (1970, 1976) has resulted in a provincial view of the cluster of deposits in the so-called “copper quadrilateral” and precluded a broader regional perspective and geologic synthesis. Data do exist: Sillitoe (1976) published results of a study of porphyry copper systems of Mexico, Coney and Campa (1987) have developed a regional view of Mexican geology based upon terrane analysis, and Anderson and Silver (1981) have presented results of a study of basement ages and distribution in northern Mexico. Based on these works a regional overview of porphyry copper distribution that extends beyond the border region of the United States and Mexico is shown in figure 4. In this figure the Gulf of California has been closed to approximate the inferred Laramide configuration of the continental margin. Basement ages and relationships as determined or suggested from the work of Anderson and Silver (1981) in Mexico and by Bennett and DePaolo (1987) in the contiguous United States are integrated with the terranes of northern Mexico to suggest a configuration of basement and tectonics at the time of Laramide ore formation.
Igneous Petrology

Porphyry copper deposits and genetically comparable intrusion-centered deposits of molybdenum and tin are conventionally viewed as results of late stage events in the emplacement and cooling of felsic magmas that produce porphyritic rocks at shallow (less than 5 kilometers) depths during a volcanic cycle. That granite-associated ores may evolve in caldera rather than isolated volcanic systems and that some porphyry-related ores may have evolved as results of diatreme genesis are commonly recognized exceptions to this generalization: diatreme association may be represented at Ok Tedi in the New Guinea Highlands (about 1 Ma in age), which lacks associated volcanic strata. Notwithstanding such exceptions, the presence of closely contemporaneous andesitic volcanic strata with many systems in both cratons and island arcs lends credence to the conventional model. Rapid rise of magmas and their rapid cooling in a shallow environment is believed to result in porphyritic textures and profound thermal disequilibrium, which in turn results in the cracking of very large (cubic kilometers) volumes of wall rock conducive to the convective cooling processes that result in hydrothermal fluid flow (Burnham, 1981; Burnham and Ohmoto, 1980; Norton, 1979, 1982). Thus the petrology of igneous rocks and their cooling history is important to the understanding of porphyry copper systems. The focus of mineralization on centers of porphyry intrusion indicates a close genetic tie with cooling processes of magmas in the shallow crust, the effects of flow of hydrothermal solutions are temporally and spatially associated with certain plutons. Moreover, certain metal assemblages appear to be linked with specific igneous suites, which are also commonly regionally constrained.

Petrogenic studies treated the petrology of rock descent and differentiation and the questions of magma source, evolution, and ascent. Results of both of these approaches have been productive during the past several decades in advancing knowledge of how porphyry-centered metal systems evolve. No unanimous view among workers has yet developed, but there exists substantial field, experimental, and theoretical bases on which study continues to progress. Stringham (1966) summarized much petrographic data and outlined igneous associations in some copper districts. The first overview of petrologic compositional trends of Arizona deposits was offered by Creasey (1977) in a series of variation diagrams treating rocks from Ray. Cornwall (1982) further detailed chemical petrology at Ray, favoring a model

Figure 2. Map of southeastern Arizona, southwestern New Mexico, and northern Sonora showing distribution of Laramide porphyry copper deposits and outcrops of Laramide volcanic and volcaniclastic rocks. That these rocks and Laramide porphyry ores were regionally coextensive was recognized in the 1960s.
EXPLANATION

Tertiary volcanic and sedimentary strata
Laramide Copper Flat q.monz.
Warm Springs q.monz.
andesite

Paleozoic sedimentary strata
Precambrian rocks
Dikes and veins
Faults

Figure 3. Geologic map modified and adapted from Dunn (1982) of the Copper Flat porphyry system at Hillsboro, New Mexico. The copper deposit is centered on the Copper Flat Quartz Monzonite, interpreted here as a subvolcanic intrusion emplaced within a succession of subaerial andesite flows and breccias. In its present configuration it is faulted down against Paleozoic strata to the north, south, and west. This style of occurrence, protected since the Laramide by faulting of the complex, is hypothesized from data elsewhere (fig. 2) as manifesting the dominant geological style of porphyry copper environments of Laramide deposits in the region.
Figure 4. Map of southwestern United States and adjoining northwestern Mexico incorporating details of figure 1A and 1B, terrane designations of Mexico, and porphyry copper and other selected ore deposit types of the region from Titley (1992). The Gulf of California has been closed juxtaposing Baja California and the present northwestern coast of Mexico. The terranes of Mexico from Coney and Campa (1987) are as follows: CHIH, Chihuahua; COA, Coahuila; CTZ, Cortez; CA in northern Sonora is Caborca; SMO, Sierra Madre Occidental; G, Guerrero and m/s is the Mohave Sonora megashear of Anderson and Silver (1981). In the United States, CA is California, AZ is Arizona, and NM is New Mexico; v/s is approximate boundary between volcanic- and sediment-dominant Proterozoic basements of Arizona and contiguous Sonora. Patterned area of northwestern Arizona and the Caborca terranes hypothesized as common and older than the patterned terrane of Arizona and adjoining New Mexico; open pattern of California is partially Mohave terrane.
Figure 5. Plot of Initial strontium ratios (1Sr*) vs. epsilon neodymium for Laramide intrusions of Arizona compared with values for other igneous rocks of Chile, Mexico and western Pacific Island arcs. The data for porphyry systems reveal changing sources and compositions of rocks of the Laramide igneous complexes and linear paths of evolution that commence with andesite with a significant mantle component and evolve to more evolved crustal progenitors. The andesite envelope encloses those initial compositions seen in 5 porphyry centers of Arizona. Lines of evolution are shown with distinctive coding for each, abbreviated as: TMST, Tombstone; SIER, Sierrita; RAY, Ray; BGD, Bagdad; DJ Diamond Joe; CB, Copper Basin, and CHR, Christmas. PNG is Papua New Guinea. Data from Anthony and Titley (1988) and Lang (1991).
that implies magmas and solutions from a probable source in the mantle. Igneous evolution of systems in the region commenced with outpouring of andesite dacite volcanic materials followed by emplacement of intrusions which evolved to progressively more felsic phases. Sharp contacts and striking compositional contrasts in the intrusive suites of the region are the rule and have been interpreted as representing emplacement of successive magmatic phases rather than in situ differentiation of single magmatic progenitors.

Compositions of igneous rock series associated with deposits have been reported from Sierrita (Anthony and Titley, 1988a, 1988b), Christmas (Koski and Cook, 1982), Ajo (Wadsworth, 1968), and numerous additional Laramide districts (Lang, 1991). In terms of long accepted rock names, evolutionary trends of intrusions of the Laramide districts run from quartz diorite through granodiorite to a preponderance of porphyries of quartz monzonite. This range corresponds roughly within the L.U.G.S. (Streckheisen, 1973) nomenclature of monzodiorite through granodiorite to granite.

Burnham (1967, 1979) has traced magmatic evolution of porphyry deposit related systems through the stage of formation of hydrothermal fluids by in situ differentiation. The role of water is addressed in detail because of its importance to magmatic processes and ground preparation through stages of solidification of igneous carapaces and their subsequent rapture as the pressure of confined volatiles increases during magma cooling. This results in the jointing of rocks, typically creating a stockwork. Wyllie (1981) reported studies of the origin of calc-alkaline melts in a subduction-related environment. Farmer and DePaolo (1983, 1984) have attributed the source of many Great Basin magmas including those related to porphyry metal systems to the crust. Anthony and Titley (1988a, 1988b) and Lang (1991) have reported results of studies of the evolution of major and trace element chemistry and neodymium and strontium isotopes in Laramide igneous suites of the region that reveal apparent deep crustal sources of porphyry magma progenitors to the mineralization. A plot of neodymium-strontium data is shown in figure 5, where Laramide suites are compared with island arc and Chilean intrusions and with the mid-Tertiary volcanic episode of the Sierra Madre Occidental of Mexico. One significant property of the Laramide intrusive centers in the Arizona region is that their isotopic properties reveal continuous evolution and change from magmas of perhaps 50 percent mantle component to magmas dominated by crustal components. The youngest intrusions are most evolved, and Anthony and Titley (1988a, 1988b) have interpreted a lower crustal amphibolite magma source on the basis of rare earth element patterns. An additional property of the intrusive suites is their evolution along specific trend lines as revealed by the isotopic habits in figure 5; changes in rock isotopic compositions are transitional, indicating gradually evolving magmas rather than abrupt contributions of different magmas from changing sources. Chemical and isotopic analyses of these rocks reveal that no single rock may be considered as representative of a porphyry copper intrusion and that interpretations of magma genesis and evolution must be premised upon the composite signature of the suite as a whole. Petrogenic interpretations of porphyries must be made in the context of the properties of magma suites rather than the properties of single samples of igneous rocks.

The Style of Alteration and Mineralization

The style of hydrothermal modification in deposits has been described in general terms by Titley (1982c). The most common habit of porphyry copper mineralization is as hydrothermally altered, copper-mineralized stockworks. The stockworks comprise tens of cubic kilometers of fractured rock many tens of square kilometers in area either centered on porphyry intrusion cores or (more commonly) distributed asymmetrically across intrusion wall-rock contacts. Vertical exposures and measurements of paleopressures suggest mineralization and alteration originally extended over many kilometers vertically; most Laramide deposits of Arizona are exposed at a weathered level 1 to 3 kilometers below the original surface. The deposits ubiquitously reveal zoning of metals and alteration in patterns and cross-cutting habits that indicate a complex sequence of origin. Significant mineralization and the more commonly recognized alteration types are restricted to relatively small volumes in the hearts of stockworks. Where altered fractures of the stockworks have been mapped as at Sierrita (fig. 6) (Haynes and Titley, 1980; Titley and others, 1986), Silver Bell (Kanbergs, 1980; Norris, 1981), and Red Mountain (Kistner, 1984), mineralized centers defined by copper grades are revealed to be located in a few cubic kilometers of volume of closely spaced (centimeter) joints within a larger volume of less abundant fractures composing the stockwork.

The mineralogical, chemical, and physical conditions of alteration have been subjects of significant interest during the last half-century. The habits and environment of alteration have been important both in the search for ore and in the advancement of important elements of hydrothermal theory. Significant data on alteration including specific information treating porphyry metal systems have been published by many authors. Papers of the 1940s were among the first to describe the physical habits of alteration of deposits in Arizona. Much of this was the work of Peterson and others (1946) at Castle Dome and Anderson (1950) at Bagdad. Nearly 30 years of intense study of the chemistry of the alteration process in the region, much of it receiving impetus from the classic work of Sales and Meyer at Butte (1948), developed a fundamental base of knowledge of hydrothermal processes. By the early 1960s a generalized view of the essential nature of alteration had been developed and many of the habits of alteration of porphyry systems had been elucidated by Jerome (1966). Fundamental mineral associations and specifications of alteration stages had been outlined by Creasey (1966), and Beane and Titley (1981) outlined the alteration mineral chemistry in porphyry systems.

The minerals of alteration suites differ fundamentally with differences in their host rocks. Host rocks are varied, and their proximity to intrusions is controlled solely by geological coincidence. Porphyry copper deposits commonly manifest varied styles and compositions of alteration influenced in the main by the contrasts between and among mafic, carbonate, and potassium silicate dominated hosts: Conversion of volumes of rock to garnetite is a phenomenon seen in carbonate rather than potassium-aluminum silicate host rocks, while conversion of volumes of rock to orthoclase is a phenomenon seen in potassium-aluminum silicate rather than carbonate host rocks. These seemingly simple contrasts form an important basis for consideration of the
origin of fluids and alteration components as well as metal and sulfur. Details of these contrasting alteration types have been reported by Einaudi (1982a, 1982b) for carbonate rocks and by Beane (1982) for felsic igneous rocks. Important features of alteration in these contrasting wall rocks are enumerated below.

**Alteration of Potassium-Aluminum Silicate Rocks**

1. Alteration associated with porphyry copper deposits in non-carbonate hosts occurs in the fractured rocks of stockworks centered on porphyry plutons.

2. The metallogenic effects of hydrothermal processes are the deposition of sulfide minerals in large rock volumes. Sulfide composition commonly ranges from 3 to 8 volume percent pyrite and chalcopyrite with ore minerals changing in specific alteration episodes from chalcopyrite-dominant to pyrite-dominant.

3. Alteration and most economic mineralization are controlled by the fractures of the stockwork, which are the permeable channels of the system. Some specific kinds of alteration at specific times may be pervasive and result in wholesale conversion of one rock composition to another by metasomatic processes. Alteration of veinlet walls is also pervasive but is restricted to domains of mesh-like distribution along narrow (centimeter) alteration selvages.

4. Alteration and mineralization are episodic and chemically sequential, and much of the alteration seen is thermally retrograde. Chemical changes as manifested by mineralogy generally reveal an (Titley, 1994) early, locally pervasive, anhydrous alteration followed by fracture-localized alteration that becomes dominated by a progressive shift to cooler solutions and stabilization of hydrous silicate minerals.

5. Copper minerals and minerals of other economically important metals occupy their own specific positions in the paragenetic succession and altered rock volume as parts of the hydrothermal zoning.

6. Episodic and sequential development of alteration minerals attends episodes of fracturing. Each fracture generation is altered in the same way at the same time. The net effect of this process is overprinting of rock volumes by discretely and uniquely altered fracture sets, each of which is different from the others.

7. Host rock compositional variations in calcium, sodium, potassium, magnesium, and iron result in the development of contrasting alteration mineralogies in single alteration stages.

8. Quartz diorite and granodiorite, chlorite, quartz, sericite, and pyrite are equilibrium minerals of the "phyllic" stage and epidote and orthoclase are equilibrium minerals of the "potassic" stage. In granites, orthoclase and sericite are equilibrium minerals in an early stage that lacks definitive characteristics of any formally recognized stage.

9. The effects of overprinting render the definition of "alteration zones" difficult and commonly equivocal even when the effects of contrasting wall rock are considered. Inclusion of carbonate host rocks further heightens the difficulties in correlation of alteration stages.

**Alteration of Carbonate Rocks**

1. Alteration of carbonate host rocks produces exoskarns and broad aureoles of metasomatized and recrystallized carbonate rocks of hydrothermal origin. Stockwork control is signifi-
cant in some systems where early alteration was pervasive and formed brittle rocks that fractured during succeeding events.

2. Calc-silicate and hydrous magnesium-silicate minerals dominate the alteration mineralogy in carbonate host rocks. Potassium-silicate minerals are uncommon or absent in carbonate rocks but may be present in clay or clastic-bearing strata within the sedimentary succession.

3. Calc-silicate alteration is closely controlled by original stratigraphic composition. Unlike potassium-silicate-host rocks in which there may be little compositional change within large rock volumes, carbonate rocks are commonly part of sedimentary successions which may change sharply from bed to bed and result in distinctive differences in alteration: Diopside in original dolostones and grossularite in calcareous mudstones may form at the same time and represent the same level or intensity of alteration.

4. These stratigraphically controlled contrasts in alteration mineralogy are not easily correlated in space with the zoned alteration stages assigned to alteration in potassium-silicate-host rocks.

5. The temporal distribution of alteration mineralogy and styles in carbonate-hosts of the porphyry systems resembles the evolutionary style of alteration in potassium-silicate rocks. Generally early calc-silicate alteration is anhydrous and pervasive and is followed by hydrous alteration minerals in veins and veinlets.

6. In a chemical and mineralogical sense, skarn-altered parts of porphyry copper systems contain a lower overall sulfide content and a correspondingly higher chalcopyrite-to-pyrite ratio than is common in potassium-silicate wall rocks.

**Mafic Rocks**

1. Amphibolites, basalt, diabase, and hornblende diorite are wall rocks of a few porphyry copper systems. All alter in much the same way: Biotite which replaces hornblende, is the dominant pervasive alteration product.

2. Mineralization is associated mostly with quartz veins of biotitized masses, and vein selvages may contain minor amounts of orthoclase locally.

**Supergene Alteration**

1. With only few exceptions development and mining of the major porphyry copper deposits of the region commenced in supergene-enriched copper sulfide. The weathering processes that formed the enriched ores also altered rocks of the original mineral assemblage. This process and its results have been recognized for more than a century and were first reported in detail for porphyry copper deposits at Morenci by Lindgren (1905).

2. The chemical process stems from the weathering of pyrite, which produces acid necessary to the formation of silica, clays, sulfates, and oxides in a horizontally layered body of oxidized rock and leached capping included within and overlaying a zone of economic copper enrichment.

3. Alteration products are those of the acid-oxidizing environment and mimic to a significant degree the hypogene advanced argillic alteration of the shallow, near surface hydrothermal environment. Intermittent study of these processes and products has resulted in a general view of capping formation that may be applied to analysis of outcrops (Anderson, 1982).

**THE PROCESS OF PORPHYRY COPPER FORMATION**

A porphyry copper deposit represents the result of dynamic, episodic geologic events related to magma cooling; Gustafson (1978) has summarized important aspects of the process. Porphyry copper formation commences with emplacement of rapidly rising magma at shallow depth in the crust. The magma column may be many kilometers high, but rapid cooling in its upper portions develops a hardened carapace with porphyry texture that confines volatiles. Volatile pressure increases beneath the carapace released when it exceeds the strength of the chilled carapace and the lithologic load (Burnham, 1979), resulting in extensive fracturing of the porphyry and its overlying cap and walls. Episode fracturing results in diminishing areas of fractured rock, with the abundance of fractures increasing as the system collapses progressively closer to the porphyry center or thermal heart of the system.

At an early stage of fracturing and volatile release water carrying other volatiles, metal, and sulfur flows upward from the still-cooling magma. As cooling deepens in the magma, repetitive failure takes place. Gradually water from wall rocks is entrained into the fracture system, and the pluton cools rapidly by convection. This convection process involves great volumes of water and results in development of alteration and precipitation of metals. Young alteration assemblages of veins overprint older vein alteration types. The process has been modeled by Norton (1979, 1982), and the chemical processes have been modeled by Helgeson (1970). Field evidence from mapping of alteration sequences and temperature determinations on fluid inclusions indicate that predictable changes in alteration mineralogy take place under falling temperatures as the system cools. The chemical conditions in the convection cells range from reducing at depth to oxidizing and acid near the surface where meteoric water is involved. The process of repetitive fracturing appears to be enhanced by "case-hardening" of the stockwork at each stage of fractures is altered.

**MAPPING AND MODELS**

The 1970s and 1980s were times of great interest in ore deposit models. Models as shown and defined by a variety of workers in various ways purport to show some common features through which a class or some properties of a class of deposits can be described. As such they range from single diagrams that show the general features of deposits to groups of diagrams that attempt to show stages in evolution of dynamic hydrothermal systems. Much of the interest in models of the porphyry systems stemmed from publication of the Lowell and Guibert (1970) diagrams depicting features of lateral and vertical zoning of these systems, apparently adapted from the zoning shown by Lowell (1968) at Kalamazoo.

A number of variants in the model for porphyry copper deposits were proposed by Sutherland Brown (1976), who drew from the examples in western Canada. Hollister (1978) suggested models based upon composition of associated porphyries. A useful descriptive model was developed by McMillan
La ramide volcanics
Paleozoic limestone

Figure 7. Geologic map of the orebody and host lithologies at Christmas, Arizona, after Koski and Cook (1982) and Einaudi (1982a). The intrusion is in contact with Paleozoic carbonates in its western half and with Laramide andesite on its eastern half; the disseminated copper orebody occurs with skarn in the limestone block in the west. Alteration affects both of the contrasting lithologies and represents overprinting of K-silicate alteration minerals on an early biotite-stable alteration in the andesite. The shaded outer boundary in andesite is the outer limit of biotite as both replacement of hornblende of the andesite and as scattered biotite veinlets. The map shows in an elegant way the habits of alteration of many ore systems in the southwest.

ROCKS
Laramide stocks, dikes
Laramide volcanics
Paleozoic limestone

Figure shows a geological profile that is characteristic of regions where Paleozoic platform carbonate successions overly craton and have been importantly involved in alteration and mineralizing processes in plutonic environments.

PERPECTIVE

The high rate of discovery of copper ores in the region during the last half century is a manifestation of three major developments: (1) an increasingly enhanced understanding of the nature of the deposits, (2) development and refinement of exploration technology from outcrop interpretation to geophysical methods, and (3) increasingly efficient mining and processing methods.

Research into the formation of porphyry copper deposits has been significant, and published work reveals a deep insight into processes of ore formation. Modeling of fluid flow to incorporate the changing chemistry along hydrothermal paths represents a significant advance in understanding hydrothermal process geology and geochemistry and demonstrates that changes in alteration chemistry attend the process (Helgeson, 1970; Norton, 1979, 1982). Important questions involving the link between ore-forming processes and environments remain, however. The answers to these questions will significantly advance our understanding of these systems and our knowledge of the nature of metallogenic regions.
Questions concerning the crustal controls for the localization of these ore deposits and the reasons for their extraordinary abundance in the region remain. Further, the question of the source of both primary and accessory metals in these systems has yet to be solved. Plate-tectonic theory and reconstructions are consistent with interpretations of localized crustal stress, but linear distributions of deposits in belts paralleling the old continental margin resurrect older notions of linear crustal controls. Contrasts in alteration mineralogy as functions of crustal lithologies and data suggesting a crustal provenance for both magmas and precious metals in these ores (Anthony and Titley, 1988b) are consistent with interpretations of localized crustal stress, but linear distributions of deposits in belts paralleling the old continental margin resurrect older notions of linear crustal controls. Contrasts in alteration mineralogy as functions of crustal lithologies and data suggesting a crustal provenance for both magmas and precious metals in these ores (Anthony and Titley, 1988b) leave open important questions of the extent of crustal influences. If it is held that metals are contained in and transported with magmas, logic requires that the crust be the site of the penultimate metal province.

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REFERENCES


