ABSTRACT

Intrusion-related copper-bearing ore deposits in Mexico span a wide range of deposit types and geological settings and formed from the mid-Mesozoic through the Holocene. These deposits include world-class copper porphyry and skarn deposits as well as a continuum of similar skarn, porphyry, vein, and replacement deposits that contain variable quantities of molybdenum, zinc, silver, lead, iron, gold, tungsten, tin, fluorine, and beryllium. Based on a new compilation, this paper reviews data on the full spectrum of intrusion-related deposits, concentrating on copper-rich systems, and attempts to place them in a generalized geological and petrological context.

In Mexico, intrusion-related mineral deposits are primarily Mesozoic to middle Tertiary in age. Three broad periods are prominent in the mineralization record: the late Mesozoic, the Laramide, and the middle Tertiary. Jurassic to Late Cretaceous calc-alkaline batholiths with sparse volcanic rocks occur along the Pacific margin mainly on eugeoclinal crust, although locally on continental crust (for example, in Sonora). Latest Cretaceous to Early Tertiary ('Laramide') calc-alkaline batholith, subvolcanic, and volcanic centers occur in an overlapping but somewhat more easterly band that extends with diminished intensity and somewhat younger ages into the Sierra Madre Oriental. Mid-Tertiary volcanism and local intrusive centers are widely developed, with the greatest abundance of calc-alkaline felsic volcanics in the Sierra Madre Occidental and more mafic middle to late Tertiary arc volcanics in the Sierra Madre del Sur in southern Mexico and as a fringe of alkaline volcanic and subvolcanic centers in northeastern Mexico.

Over 600 copper-rich intrusion-related systems can be inferred from the literature; about 100 can be documented with some confidence. Copper-rich deposits occur with both intermediate (dioritic) and felsic (granodioritic) intrusive centers and show a corresponding variety of associated metals and alteration types. Styles include porphyry-type disseminated or stockwork mineralization, skarn, breccia pipes, and pegmatites. Multiple styles commonly occur in the same district. Porphyry copper deposits are best developed in association with the Laramide intrusive centers of northern Mexico and the mid-Tertiary intrusions in southern Mexico. Other intrusion-related deposit types occur within the same magmatic framework, but they have different temporal and spatial correlations related to their igneous composition and exposure level.

The continuum of intrusion-related mineralization in Mexico can be divided by geological associations, metal contents, and styles of alteration. Although more than 1,500 intrusion-associated mineral deposits are known, the scarcity of data requires a simplified approach focusing on major districts. We distinguish the following overlapping groups of deposits based on their metal contents and igneous compositions: (1) porphyry or skarn Cu-(Mo-Zn) associated with intermediate to felsic granitoids, (2) porphyry or skarn Cu-(Au-Fe) associated with intermediate intrusions, (3) greisen, skarn, or pegmatite W-(Mo) associated with intermediate to felsic granitoids, (4) replacement or skarn Zn-Pb-Ag-(Cu-F) deposits associated with felsic intrusions, (5) volcanic-hosted vein Ag-Au-Zn-F-Sn) deposits associated with hypabyssal felsic intrusions, (6) vein ± replacement Ag-Au-Cu-Zn-Pb) deposits associated with intermediate stocks, (7) volcanic-hosted Au-Ag-(Cu) systems, (8) rhyolite-related F(-Sn-Be) deposits, (9) diorite-related Fe(Au-Cu) skarns, and (9) rhyolite-related Fe deposits.

Some inferences can be drawn from examination of these patterns:
- Igneous compositions vary in time and space in Mexico, but multiple compositions commonly were emplaced at different times in the same region. Temporal variations (as in Sonora) are as important as differences in province (as between Sonora and southern Mexico).
- Alteration and metal differences between alkaline and subalkaline, felsic and mafic magma suites can be partly rationalized from equilibria among igneous minerals (for example, in terms of $a\text{Al}_2\text{O}_3$ vs $a\text{CaO}$ vs $a\text{SiO}_2$), fluid chloride and sulfur contents, and magmatic metal contents which reflect province and process.
- Exposure and preservation filter observed Mexican metallogeny. Erosion of the Mesozoic arc superstructure in the west leaves mainly tungsten-skarns, burial of the Laramide arc in central Mexico interrupts porphyry copper patterns, and minimal exhumation of mid-Tertiary intrusive centers preserves distal vein or replacement systems.
- The superimposed metallogenic patterns in Mexico have parallels with metallogenic patterns in the western United States in terms of the effects of preservation, process, and province. Future work should focus on increasing the basic geological data on mineral deposits and igneous rocks. Geochronology, petrology, and geochemistry would help better define the temporal, spatial, and compositional interrelationships between tectonism, magmatism, and mineralization.
INTRODUCTION

Overview

Copper mining began in Mexico over 400 years ago, and development of porphyry copper deposit mining began nearly 100 years ago (Barrett, 1987). High-grade underground mines and large-scale open-pit mines have helped make Mexico one of the larger copper producers in the world, providing approximately 8 percent of annual world copper production (Cardenas-Vargas, 1993), mostly from two mines, Cananea and La Caridad. The porphyry copper deposits of Mexico range from the economically insignificant and/or unexplored to the world-class deposits exploited in the Cananea and Nacozari Districts of Sonora. Copper-dominated deposits vary considerably among themselves and can be considered part of a larger continuum of intrusion-related ore deposits of Mexico and southwestern North America. In this paper the term “porphyry copper systems” is broadly applied to large intrusion- and volcanic-hosted copper-dominated deposits. As such it may include districts where the predominate mineralization may be in the form of skarns or breccia pipes but the intrusive phases nevertheless show porphyry-like alteration. Such systems share many characteristics with other intrusion-related mineral deposits.

The varied geological settings and prolonged magmatic history of Mexico present an opportunity to examine a wide spectrum of intrusion-related mineralization. Here we summarize the types and distribution of intrusion-related mineralization in Mexico with an emphasis on porphyry copper-type systems. We refer the reader interested in other types of Mexican igneous-related mineralization to reviews of volcanogenic massive sulfide deposits (for example, Miranda-Gasca, 1994) and epithermal deposits (for example, Buchanan, 1981). We first review characteristics of Mexican copper deposits and then compare them to other types of Mexican metallic ore deposits in order to provide an updated synthesis of their distribution and geology. We briefly consider the importance of factors such as exposure and preservation, igneous compositions, and geographic distribution in controlling the types and distribution of mineralization in order to draw attention to patterns within and between metallogenic groups. Our synthesis is based primarily on better known districts for which a range of geological and geochemical data are available, but where possible we have incorporated new data from current or previously unpublished research.

Previous Work

Interest in Mexican porphyry copper occurrences goes back to the turn of the century, when the first detailed descriptions of copper mineralization in the Cananea and Rio Yaqui areas appeared in the mining literature (Ordoñez, 1905; Weed, 1902). Published work on porphyry copper systems during the first half of this century evolved from short site descriptions (Pearce, 1910; Richard, 1904; Russell, 1908; Southworth, 1905) to more detailed summaries of both districts and porphyry copper areas (Emmons, 1910; Mishler, 1920; Valentine, 1936). Since 1950 a variety of deposit and district-scale studies have been published along with a number of reviews and syntheses of existing information. Notable among these are syntheses that show distribution and metallogenic characteristics (Salas, 1975), porphyry-style mineralization and alteration (Sillitoe, 1976), possible relation to subduction zone tectonics (Clark and others, 1982), and geochronology (Damon and others, 1983). In these summaries fewer than thirty deposits are identified as porphyry copper systems. Published alteration maps or detailed geochemistry or petrology are available for only a few districts. Sillitoe (1976) and Damon and others (1983) compiled data on some deposits, and we summarize data for additional deposits here. Only the two producing Sonoran districts are described in more than a few papers in the international literature. Considerable information exists in theses and in private and government files, and we have attempted to augment published data with unpublished information where possible. One of the largest unpublished data sources, the files of the Consejo de Recursos Minerales, is beginning to be published in the form of state summaries of ore deposits (for example, Cardenas-Vargas, 1992, 1993). These summaries provide a valuable geologic and mineralization framework to interpret the distribution of metallic occurrences and extent of mineralization at the district scale.

We have compiled data on over 7,000 metallic districts and igneous centers in Mexico. This data set summarizes reported lithologic, mineralization, and timing information. Data on intrusion-hosted and associated ore systems are useful in expanding present understanding of porphyry and related systems in Mexico. Our work deepens and broadens the earlier compilations of Gonzalez-Reyna (1944; 1956b), which showed about 300 copper-bearing districts.

Considerable private and government exploration in the 1960's focused on exploration for porphyry copper deposits. One of the most successful campaigns resulted in the discovery of the La Caridad porphyry deposit in the Nacozari District, Sonora. Saegart and others, 1974) and the location of several prospects in the Nogales region (Tio Flaco, El Correo, Planchas de Plata). These discoveries were the consequence of a joint Federal District of Mexico project, porphyry-copper exploration program that ran from 1964 through about 1974. During the same general period industry exploration identified numerous copper skarn, breccia, and porphyry deposits throughout Mexico. For example, Anaconda geologists located more than 15 districts of these types in central Mexico, including most Guerrero. The Anaconda geologists did not publish their findings, but their unpublished reports, which are in the collections of the University of Wyoming, provide basic information about alteration styles and host rocks.

GEOLOGICAL FRAMEWORK

The distribution of intrusion-related mineralization in Mexico reflects the timing and spatial distribution of magmatism as well as the post-magmatic geological history. The general geological and tectonic framework of Mexico has recently been interpreted by Sedlock and others (1993). Their summary builds upon plate tectonic and terrane studies by Coney (1983) and Campa and Coney (1983). Coney (1989) and De Cserna (1990) provide excellent tectonic syntheses. Lopez-Ramos (1974), and books published during the 1956 International Geological Con-
Triassic volcanic rocks are mainly mafic in composition. They are predominantly basaltic to intermediate volcanics with some arc-related intrusive centers from Sonora and Baja California to Chiapas (fig. 2). Near the coast, Jurassic rocks belong to a hornblende-central Mexico (Damon and others, 1983). Sparse mafic rocks gabbroic to tonalitic intrusions (Cardenas-Vargas, 1992). Inland, Mexico, but significant hydrothermal alteration and limited porphyry-type mineralization occurs in Triassic rocks in the Guerrero, Mixteca, and like terranes (Campa and Coney, 1983; Sedlock and others, 1993).

Intrusive rocks are present in some porphyry copper districts such as Cananea (Meinert, 1982; Bushnell, 1988). Copper mineralization has not been described with these rocks, but some iron skarns with minor copper in Baja California and perhaps southern Mexico may be related to Jurassic diorites. These Jurassic suites match comparable Jurassic rocks which commonly have extensive hydrothermal alteration and some copper mineralization in the western United States (Barton and others, 1988; Riggs and Haxel, 1990; Saleeby and Busby-Spera, 1992) from the Bisbee and Courtland-Gleeson Districts in southern Arizona northwestward into eastern California and Nevada (Battles, 1990; Tosdal and others, 1989).

Cretaceous and Cenozoic magmatism are responsible for virtually all igneous-related mineralization in Mexico. After a Late Jurassic lull, vigorous magmatism renewed in western Mexico where it continued through much of the Cretaceous before expanding eastward during the Laramide Orogeny (about 80 to 40 Ma). This produced the metaluminous diorite-tonalite suites of the early and mid-Cretaceous Peninsular Range and Sinaloa Batholiths of Baja California, Sinaloa, and southern Sonora (Gastil and Krummenacher, 1981; Henry, 1975). The Sinaloa Batholith, much like the Sonora Batholith, is a composite batholith with plutonism spanning a range of compositions (granite to gabbro) and age (50 to 102 Ma). These batholiths correlate with the well known Peninsular Range and Sierra Nevada Batholiths of California. These composite intrusive complexes are typically equigranular and have associated metasedimentary and sparse metavolcanic rocks. Cretaceous volcanic rocks of pre-Laramide age (older than 80 Ma) are common in only a few areas of central and southern Baja California and northeast of Mazatlán, Sinaloa. Farther south, time-equivalent monzodioritic to granodioritic intrusions are abundant in Cretaceous limestone-intermediate volcanic sequences of the Guerrero terrane (states of Nayarit through Guerrero).

Igneous Distribution and Compositional Trends

Mexico has a complex magmatic history that dates back at least to the mid-Proterozoic and continues at present. Magmas intrude all parts of the Mexican crust but are best exposed in the western half of the country. Economic deposits are largely restricted to late Mesozoic and Cenozoic igneous centers related to plate convergence along the Pacific margin.

Pre-Jurassic magmatism is widely developed in Mexico. Proterozoic granite suites in southwestern Mexico continue the mid-Proterozoic belts of the southwestern United States (Anderson and Silver, 1977). Paleozoic intrusions are rare with the exception of equigranular granitoids of Permian age (Torres-Vargas and others, 1994). These are widely distributed in eastern through southern Mexico and are apparently related to proto-Atlantic convergence in eastern Mexico. The Permian rocks lack significant mineralization or coeval volcanic rocks. Sparse Triassic volcanic rocks are mainly mafic in composition. They are known in western Baja California (Gastil and others, 1975), in the rift-related late Triassic Barranca group in Sonora (Stewart and Roldán, 1991), and in various parts of the Zacatecas Formation of central and southern Mexico (Sedlock and others, 1993). Mineralization associated with these rocks is not evident in Mexico, but significant hydrothermal alteration and limited porphyry-type copper mineralization occurs in Triassic rocks in the southwestern United States (Battles, 1990; Seedorff, 1991).

Jurassic igneous rocks are well dated in only a few areas but are inferred to be common from northwestern to south-central Mexico (Damon and others, 1983). Sparse mafic rocks occur with rift-related sedimentary rocks along the Gulf of Mexico coast, and a few tonalitic intrusions occur inland in Veracruz (Ortega and others, 1992). Most Jurassic rocks lie in arc-related intrusive centers from Sonora and Baja California to Chiapas (fig. 2). Near the Pacific coast, Jurassic igneous rocks are predominantly basaltic to intermediate volcanics with some gabbroic to tonalitic intrusions (Cardenas-Vargas, 1992). Inland, from Sonora to Guerrero, Jurassic rocks belong to a hornblende-bearing monzodiorite-quartz monzonite-granite suite and locally have associated andesitic volcanic rocks. Jurassic volcanic and
Beginning at about 80 Ma, magmatism spread across much of northern Mexico. Laramide magmatism began in western Sonora and southern Baja California (fig. 3; McDowell and Claibough, 1979). By Eocene time magmas were being emplaced across the breadth of northern Mexico from central Sonora and Sinaloa into eastern Chihuahua, San Luis Potosi, and Zacatecas (Aguirre Díaz and McDowell, 1991). The dioritic to granodioritic Sonoran Batholith and sparse exposures of similar intrusive rocks to the south represent the first phase of this expansion (Rangin, 1986). Volcanic rocks are sparse to absent and intrusions are generally pre- and early Laramide in western Sonora, Baja California, and western Sinaloa (Gastil and others, 1981; Henry, 1975). Farther south, magmatism apparently expanded only moderately to the east, remaining within a few hundred kilometers of the Pacific coast.

Hydrothermally altered andesitic volcanic rocks are abundantly preserved along much of the Laramide arc, particularly in the eastern half (fig. 3). These rocks constitute the lower volcanic complex of the Sierra Madre Occidental and adjoining areas (McDowell and Keizer, 1977). They are partly covered by voluminous mid-Tertiary volcanic rocks of the Sierra Madre Occidental ignimbrite province. To the south Laramide volcanic rocks are widespread but largely covered by younger volcanic rocks (Ortega and others, 1992). The scarcity of volcanic rocks in the west may be due to erosion, whereas the more complete early Tertiary sections in the east suggest that few of the late Laramide intrusions vented. From this evidence and abundant Laramide dates in south-central Mexico it appears that the early Tertiary magmatism formed a rather wide and largely continuous arc somewhat inboard of the Pacific margin. For the most part Laramide igneous centers are intermediate in composition with subordinate felsic rocks. Hornblende-(pyroxene- and biotite-) bearing quartz diorites and granodiorites are the most common intrusive rocks; altered andesites and local dacites comprise the majority of the coeval volcanic lithologies. Late rhyolites and quartz-feldspar porphyries are common in many intrusive centers as in the Cananea District. Volcanic-poor regions of central Sonora commonly contain strongly peraluminous monzogranitic intrusions of Laramide to mid-Tertiary age (Roldán, 1991). These two-mica granitoids broadly correlate in age and composition with intrusive rocks of the Eocene Wilderness Suite of southern Arizona (Keith and others, 1980), and in a more general sense the magmatism of northwest Mexico has close parallels in the southwestern United States (Coney and Reynolds, 1977; Miller and Barton, 1990).

Oligocene to early Miocene magmatism extended from the voluminous ignimbrite-dominated volcanism of the Sierra Madre Occidental to sparser and relatively volcanic-poor intrusive cen-
Intrusion-related mineralization can be classified by metal contents, associated igneous compositions, alteration types, and structural styles. Table 1 gives our classification based on these characteristics. Specific information has been compiled on igneous centers to the east. South of the trans-Mexican volcanic zone, mid-Tertiary and younger magmas in the Sierra Madre del Sur form a composite arc of mainly intermediate compositions (Moran-Zenteno, 1990). In the Sierra Madre Occidental, ignimbrites from multiple centers coalesce to form a nearly continuous volcanic pile from southern Arizona to the trans-Mexican volcanic belt (fig. 4). This sequence is variably disrupted by Tertiary extension (Henry and Aranda-Gomez, 1992). The lower volcanic series of the Sierra Madre Occidental is regionally propylitized and hosts innumerable epithermal vein-type deposits (Wisser, 1966). Felsic porphyritic intrusions have been documented in a few areas in the Sierra Madre Occidental, and many felsic porphyries of a variety of compositional types are known to the east (Megaw and others, 1988). The less abundant central and eastern igneous suites range from metaluminous rhyolites, felsites, and biotite granites, including some topaz rhyolites in the central and eastern parts of the country (Ruiz, 1985), to peralkaline quartz-saturated to undersaturated rocks that mainly occur in the northeast (McAnulty and others, 1963). The latter intrusive suites are distinctively felsic and typically have characteristic associated element suites.

In overview, Mexico has a complex geological history that produced and variably preserved igneous rocks of a wide variety of compositions. Pre-Cretaceous suites are either plutonic or marine volcanic and have little associated mineralization. Cretaceous through early Tertiary rocks show a progression in composition and space with time, beginning with deeper exposures of mainly intermediate composition rocks in the west and progressing to a more shallowly exposed intermediate-felsic suite in the main Laramide arc. This suite contains the majority of porphyry copper and molybdenum-tungsten occurrences in the northern half of the country. Iron-rich systems are predominantly with the older and western rocks of Jurassic and younger age except for volcanic-related felsic systems along the eastern fringe of the Sierra Madre Occidental. Igneous centers of mid-Tertiary to Pliocene age also have abundant associated mineralization. In the Sierra Madre del Sur epithermal deposits and many copper occurrences occur with intermediate composition volcano-plutonic complexes, whereas in the north volcanic-hosted epithermal and carbonate-hosted replacement deposits occur with predominantly felsic centers.

Types of Intrusion-Related Mineralization

Intrusion-related mineralization can be classified by metal contents, associated igneous compositions, alteration types, and structural styles. Table 1 gives our classification based on these characteristics. Specific information has been compiled on igne-
ous rocks, country rocks, mineralization, alteration, tonnage and grade of metals, references, and additional comments for about 50 districts (table 2). These districts are shown in figure 5 along with the generalized distribution of igneous rocks. As with igneous-related deposits worldwide, there is a considerable variety within classes and many alternative classification schemes might be used. Most Mexican deposits are associated with intermediate to felsic subalkaline rocks, but a few are associated with peraluminous or peralkaline rocks. Later in this paper we interpret these systematic relationships in terms of compositional, preservational, and provincial controls.

Mexican copper systems can be divided into hornblende-biotite granodiorite-granite-related (equivalent to quartz monzonite-type) and pyroxene-hornblende diorite-granodiorite-related types (equivalent to diorite-type). Iron replacement and skarn deposits with accessory gold and copper are associated with dioritic to syenitic intrusions and apparently represent a more mafic type of hydrothermal system, but it is also possible that they may represent the deeper equivalents of diorite-type systems just as molybdenum- and tungsten-bearing skarn or greisen systems may be the deeper equivalents of the quartz-monzonite type. Shallow portions of intermediate to felsic porphyry-type systems may be represented by gold-silver (copper-zinc-lead) districts of the Batopilas (quartz diorite, andesite) and Mulatos (dacite, rhyolite) types (table 1). In strongly felsic igneous systems, porphyry-type mineralization (for example, molybdenum-rich) has not been described in Mexico, however the zinc-lead-silver-fluorine suite associated with hypabyssal intrusions (for example, Bolanos) and deeper stocks (for example, San Martin) reflect a similar variation in style with depth. As noted below, the relationships between porphyry mineralization and various other kinds of ore deposits is tantalizing but not established (Sillitoe, 1973).

In the following sections we discuss the characteristics of these groupings of deposits with an emphasis on igneous compositions and characteristics of mineralization. These relationships are summarized using a simple classification of igneous rocks and oxygen and sulfur fugacity (fig. 6). These diagrams provide a consistent framework to compare deposits, although in most cases rock types and mineral assemblages are evaluated on the basis of rather sketchy information.

**COPPER-RICH PORPHYRY AND SKARN MINERALIZATION**

We have identified over 600 mining districts in Mexico associated with igneous rocks that have copper as a major commodity. Of these, more than 100 are sufficiently well described...
Table I. Generalized characteristics of intrusion-related mineralization

<table>
<thead>
<tr>
<th>Deposit Type / [example]</th>
<th>Associated Igneous Rocks (IUGS)</th>
<th>Mineralization &amp; Alteration</th>
<th>Time-space distribution (see also fig. 5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu(-Mo-Zn) Cananea, SON</td>
<td>bi-hbl-mt granodiorite to bi monzogranite porphyry</td>
<td>stockwork Cu w/ Kf-qz-ser-py; Zn skarn</td>
<td>Laramide, minor pre-Laramide &amp; Tertiary; inboard western</td>
</tr>
<tr>
<td>Cu(-Au-Fe) El Arco, BC</td>
<td>px-hbl-qtz diorite to bi-hbl granodiorite porphyry</td>
<td>stockwork Cu w/ bi-Kf-mt/ chl-py-ser; ± Fe skarn</td>
<td>pre-Laramide &amp; Tertiary (SW Mexico); outboard western</td>
</tr>
<tr>
<td>Mo(-Cu-W) San Nicolas, SON</td>
<td>bi granodiorite to bi granite</td>
<td>stockwork pegmatitic Mo w/ Kf-qtz-mu-py</td>
<td>Laramide; inboard western</td>
</tr>
<tr>
<td>[Cumobabi, SON]</td>
<td>porphyry</td>
<td>W(-Mo) skarns, pegmatite &amp; greisen (mu-qtz) W(-Mo)</td>
<td>pre-Laramide &amp; Laramide; western</td>
</tr>
<tr>
<td>W(-Mo) San Nicolas, SON</td>
<td>bi-hbl granodiorite to mu-bi granite</td>
<td>Zn-Pb-Ag(-Cu) skarn &amp; replacement; ± stockwork qtz</td>
<td>Tertiary, minor Laramide; north-central</td>
</tr>
<tr>
<td>Zn-Pb-Ag(-Cu-F-Sn) San Martin, ZAC</td>
<td>bi granodiorite to bi rhyolite porphyry</td>
<td>Ag-Au(-Zn-Pb-Cu-F) veins in volcanic rocks; central Cu-Sn in rhyolitic plugs</td>
<td>Tertiary; central</td>
</tr>
<tr>
<td>Ag-Au(-Zn-F-Sn) Bolaños, JAL</td>
<td>(bi) rhyolite</td>
<td>Ag-Au(-Zn-Pb-Zn) qtz-carb vein &amp; replacement; ± stockwork Cu Au(-Cu-Ag) advanced argillic &amp; sericitic zones</td>
<td>pre-Laramide &amp; Tertiary; inboard western &amp; north-central</td>
</tr>
<tr>
<td>Ag-Au(-Cu-Zn-Pb) Batopilas, CHI</td>
<td>px-hbl qtz diorite to bi granodiorite porphyry</td>
<td>carbonat replacement fl-qtz±Be, (± igneous Sn, Mo, topaz)</td>
<td>Tertiary; inboard western</td>
</tr>
<tr>
<td>[Mulatos, SON]</td>
<td>bi-mt-hbl dacite to bi rhyolite</td>
<td>Fe ± Cu skarn w/ Na- (±K-) silicate alteration</td>
<td>pre-Laramide and Laramide; outboard western</td>
</tr>
<tr>
<td>Fe(-Be-Sn-Mo) Aguachile, COA</td>
<td>rich syenite or bi qtz latite to (bi-) alkali rhyolite</td>
<td>massive hmat after mt (volcanic?) w/ Na-pyroxene to Qz-clay-apat</td>
<td>Tertiary; north-central</td>
</tr>
<tr>
<td>Fe(-REE) Cerro de Mercado, DUR</td>
<td>px-bi-hbl diorite to (bi) qtz monzonite</td>
<td>W(-Mo) skarn (dior-syen) (dior-gr) (grd-gr) (dgr) (rhyolit)</td>
<td>Fe(-REE) (rhyolite)</td>
</tr>
<tr>
<td>[Cerro de Mercado, DUR]</td>
<td>px-mt qtz latite to hbl-mt rhyolite</td>
<td>Cu(-Mo-Zn) (dior-syen) (grd-gr)</td>
<td>Laramide, minor pre-Laramide &amp; Tertiary (SW Mexico); outboard western</td>
</tr>
</tbody>
</table>

*Abbreviations consistent with table 2.

Figure 5. Generalized distribution of Mesozoic and Cenozoic magmatism and the intrusion-related ore deposits described in table 2.
to fit into the broad category of porphyry copper and closely related deposits (fig. 7; table 3). Common features of these districts include enrichment in copper, a close association in space and presumably in time with magmatism, and extensive hydrothermal alteration. The styles of mineralization may be broadly divided into disseminated, breccia pipe, and skarn (figs. 5 and 7). In many cases, two or three of these types occur within the same district. Associated metals include combinations of molybdenum, gold, silver, tungsten, zinc, and lead. Hydrolytic alteration of quartzofeldspathic rocks is the most common type of alteration, but alkali-exchange alteration, skarn, and various hypogene and supergene clay alteration types are also widespread. Mineralization occurs with dioritic to granodioritic intrusions which most commonly take the form of composite stocks with one or more strongly porphyritic phases.

Metals

Although variable but economically significant concentrations of molybdenum, silver, gold, tungsten, and zinc are present in some deposits, copper is the dominant metal in these systems. Grades are poorly known for most districts (table 2). Distinctions between supergene and hypogene grades are rarely made. It is evident that the higher copper grades in large tonnage deposits are supergene (Sillitoe, 1976), yet moderate tonnages of high hypogene grades (greater than 2 percent copper) are common in breccia pipes and skarns as in the Cananea District (fig. 8; table 2). Although many copper occurrences lack reported molybdenum or gold, Mexican porphyry copper deposits broadly fall into two types: molybdenum-bearing and gold-bearing. Molybdenum-enriched copper deposits contain subordinate zinc, silver, and tungsten. Gold may be present but is generally in low concentrations (less than 0.2 grams per tonne). Molybdenum-bearing deposits are most common in northwestern Mexico. These systems, which include districts like Cananea, are large and have both disseminated and breccia pipe type mineralization. Metals in these systems zone outward to base metals, commonly zinc-copper skarns (fig. 8). Gold-bearing copper deposits are less common. The best described example is El Arco in Baja California which contains over 0.3 gram gold per tonne but lacks other metals (table 2). Gold-bearing copper deposits generally contain greater than 0.2 gram gold per tonne with minor molybdenum and other metals.

Supergene enrichment is best developed in northern Mexico (Sillitoe, 1976) and is a factor in governing the economics of porphyry copper district production (Titley, 1982). This distribution may be a consequence of climatological, chronological, and petrological factors. The older mineralization of northern Mexico may be more extensively enriched because (1) the arid environment is better suited for producing enrichment than are the humid, tropical climates of southern Mexico; (2) post-Laramide stable and extensional environments in the north provided a setting for extensive weathering, enrichment, and preservation (perhaps in several cycles) that was lacking in the south; and (3) the more felsic systems of the north contain more extensive hydrolytic alteration with abundant pyrite and thus may have been better progenitors for supergene chalcocite. For example, the Cananea District contains very large hypogene and supergene copper resources, but most production comes from thick chalcocite blankets developed in areas of overlap.

Figure 6. Compositional framework for comparison of deposits. A. Simplified IUGS diagram showing the names used in this paper. B. Limiting sulfidation-oxidation assemblages for classifying higher-temperature (~450°C) and lower-temperature (~300°C) alteration mineral assemblages.
<table>
<thead>
<tr>
<th>District</th>
<th>Igneous rocks / Age</th>
<th>Country rocks / Age</th>
<th>Mineralization / Alteration</th>
<th>Metals / Grade / Tonnage</th>
<th>Comments</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aguaclla, Coah</td>
<td>Rhy phy ring dikes (0.8km²) + Rieb-qtz-micro syenite plag (0.36km²) + Analcite diabase dikes (Teschenite) / all Tmio-plio</td>
<td></td>
<td>Replacement mantos, br and chneys: CaF₂(1)-CaF₂(2)-Bertrandite-CaF₂(3) Zoning: Be concentrations highest near rhy contact Alteration mints.: bannite, powellite, adularia, kaolinite, gypsum</td>
<td>Resources: Aguachile deposit: 17Mt (700x700x130m) @ 81.6%CaF₂; 12%CaCO₃; 5% SiO₂; 0.1% Be Cuatro Palmas Body: 0.8Mt (100x100x30m) @ 70%CaF₂; 18%CaCO₃; 5% SiO₂ Tr.Y,Mo,Mn,Ti,V,Zr</td>
<td>Structure: The central part of the Aguachile Dome subsided along a ring fault about 1.6km in diameter forming a cauldron. This fault was the locus of a rhy phy ring dikes w/ a brecciated inner contact localizing the fluorap deposits. The dome is affected by strong N50E post-mineral faults. Presently inactive</td>
<td>Griffiths and Coolly, 1974 McAnulty and others, 1963</td>
</tr>
<tr>
<td>Batopilas, Chih</td>
<td>2 separate intrusive systems: Satevo-Tabonas aug dix phy, aug-bits-tnt microqtn dix (51 Ma), and bi gd.</td>
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<tr>
<td>Bernejai, Gro</td>
<td>Bi-gd phy dikes (50km²), associated to skarn + late qtz monzonites (ass. to veins) Teg</td>
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<tr>
<td>Bismark, Chih</td>
<td>Bi qtz mon-gd phy stock and late rhy phy / 42.51.11Ma (K-Ar)</td>
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<tr>
<td>Bolanos, Jal</td>
<td>Sn-bearing sanidine-kspar ry domes / 22Ma, intr. breccias (+ diorite plugs)</td>
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<tr>
<td>Cananea, Son</td>
<td>Bi-hbl Cuitaca Grid (100 km²/ 6415 Ma (U-Pb, zircon), Tinaja Diorite, &amp; mafic dikes</td>
<td>Cananea granite, C Bolivia epize, C Atacalto, D Martin Iletst, E Escab. Iletst, IP Horquilla, Iletst, chert, IP P Naco Iletst, T-J Elenita, Iletst, felsic volcanics, J(?) El Torre syenite, K Marquita mafic volcs. &amp; Mesa interm., volcanics, M tep cgl.</td>
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<tr>
<td>Bi-hbl qtz-monz phy plogs (20 km²)/ 58.212 Ma (K-Ar, bi., Colorado); 52.82±3 Ma (K-Ar, ser., Teocalli)</td>
<td>Skarn, manto, bpx pipes + disseminated; Skarn: J-gross-diop+calcic 2Jas- diop+biotoff (after chert); plbg-mt-py-crep-sph-ga (after dol);joh-calcite; 2Jmaph-py-cpy (30 Ma) Bx pipes: RCl-qtz-chl-sser-ser py-mpt-ft-ph-mt-ft-ph-ga, chl-calc, daft, cpy, tps-mantos (after Is)</td>
<td>Supergene enrichment very important</td>
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<tr>
<td>Cerro de Mercado, Digo</td>
<td>Aguila mafic-gr. alk. m- bbl rhy tuff (&gt;200 km²)/ 30.4 Ma</td>
<td>Leona fine-gr. alk. m-bbl domes ruffa/ 30.7 Ma</td>
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<tr>
<td>Mercado Iron Mbr. (7 petrol. facies)</td>
<td>Tinaja bi-hbl rhy tuff 30.3 Ma</td>
<td>Total reserves: 1.9Gt @ 0.7%Cu (typ = 0.47), 0.02% Mo, 0.1 g/t Au, and significant Ag, Au, minor Pb in replacement ores.</td>
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<td>Concepcion del Oro, Zac</td>
<td>Bi-bbl mt-d &amp; tonalite (10 km²)/ 40±1.2 Ma (K-Ar on br) + kser-bi alaskite dikes</td>
<td>Kg Js; tep andes dike (48.52 Ma)</td>
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<td>Tepich Regr sta (31.8 Ma), Tepich Post Carpintero Tunal, Sta.Maria, GaravitoTapia, S hill, Membres, and Subaldo Fms silic. tuffs (28.3 Ma)</td>
<td>Total prod: 2.3 Mt Cu &amp; 0.036 Mt Zn in skarn</td>
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<tr>
<td>Cosalí, Sin</td>
<td>Bi-bbl gd (100km²)/ 57.2±1.2 Ma (K-Ar on br)</td>
<td>Leona fine-gr. alk. m-bbl domes ruffa/ 30.7 Ma</td>
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<tr>
<td>Hbl-mt dio, dacite phy dikes &amp; stocks/ Tep &amp; Bi-epize (5km²) &amp; alkali gr (7km²)/Te</td>
<td>Kg Js (Tataiaka-Cupido Fms), Kmzd 2 ± chert (Cuesta Curra Fm), Kg Js, ch (Caracol Fm), M tep adewhy</td>
<td>Total reserves: 2.0 M@ 28.5°C, 1.6 g/t Au</td>
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<tr>
<td>Cuatro Hermanos, Son</td>
<td>Gd phy with peripheral bpx pipes/ K-3 Tep</td>
<td>Kg Js (Izones)</td>
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</tr>
<tr>
<td>Cucomari, Son</td>
<td>Qut-bht mpy ph (63.1 ±17X1 km²) accessory msp-tap</td>
<td>Kg Js; tep calc alkaliandes flows (200 mm thick) overlain by dac flows (75 mm) with porphyritic qtz-rich rhy capes. Voles may be coeval with intrusive complex</td>
<td></td>
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</tr>
</tbody>
</table>

### Production (to 1979):
- Skarn: 150,000 t Cu
- Braceloa 7622 t Cu & 2200 t Mo
- Dip 35,190 t Cu & 0.02 Mt Mo

### Structure:
- 1Juranic N60-80°W
- Elsia, Capote, and Tinaja high angle faults out El Torre, Elsia, and Henrietta Fms but not overlying rocks. 2Jteg basic dikes-qtz mont pipes intrud along N540°E and N60-80°W trends. 3J15° Northeast tilting of Mesa Fm and 8x pipes during B&K? Active mine

### Notes:
- Two caldera episodes
- Tabular ore bodies and large bor areas with magnetic matrix. Structures control much of mineralization
- Shat down

### Authors:
- Lyons, 1988b
- McDowell and Kelzer, 1977
- Authors, unpublished data

### References:
- Meinert, 1982
- Bushnell, 1988
- Wodzicki, 1992
- Zürcher, unpublished data

### Location:
- Zurcher, Wodzicki, 1992
- Authors, unpublished data

### Table 2. Description of selected intrusion-related districts (continued).
Table 2. Description of selected intrusion-related districts (continued).

| El Arco, BCN | Hbl monz-diorite phy (1 km³), qtz-monz phy stock (3 km³)²|107 Ma | Post-ore diabase dikes | K marine ss, sh, calcareous silts, sh | Khl +andes massive flows with interbedded volcanoclastic s and silts | Chalcopyrite blanket over pyrrhotite stock w/ minor molybdenite. Silicic core? metasomatic + pyrite halo. Qz-Kspar+py-mt-cpy-mo veins w/ halo of qz-chl epidote-epi-cc. Elevated geochron anomalies in Cu, Mo, Au (stream sedis, vols, and ocotillo plants) extends 2 km from deposits | 660Mt of 0.6% Cu and 0.3% Ag. Small Au pods <80m wide have >0.4 g/t Au. Cu enriched in cap upper 60 m then 20 m transition, 250m tabular subhorizontal cpy ore body, partly open at depth w/ 2% cpy hypogean grades consistent | Supergene low grade metamorphosis assoc with southern edge of Baja Peninsula Batholith. K-Ar dates vary from 114 to 101 Ma with youngers ones on ser. Half of deposit covered by alluvium Presently inactive | Bartholomew, 1974 | Echavarri and Rangin, 1978 | Silva, 1983 |
| El Realito, Gto | Gr plugs & Rhyodacite Bx | 30 Ma | K-Ar | PC, T, and Z metamorphosed sh, K is-sh (Doctor - Pita Fms) | Tremad jetambrites + volcanoclastic | Chalcopyrite (Replacement + kast filling @ 180-220°C): Fb-cpy, cpy, cpy Alteration: kool = FeOx in vols. | 3.3 Mt @ 8% CaP² | Lithocap: contact between K is and Te vols | Structure: N75E;0°; pre-min. NW, SE faulting; NW-SE folding; bx | Ordonez, 1986 |
| El Triunfo, BCS | Hbl-(bi) diorite (>9km²) | Kl | Bi-(bh) granodiorite (4 km³) | Bx | Uncertain association of these or other intrusions to mineralization | Veins/Qtz-As-tetra-sphathenite-chl with minor sph-gm-lasmonite act-py. Extinct Ag camp noted for large As alteration halos. Spotty stawkw py-qtz veins may systems may be local porphyry system but relation to Ag-Appe veins uncertain | Old vein mining camp, historic production >200,000 oz Au, >4 M oz Ag from high grade qte-chl-cpy veins | Structurally control Ag veins strike NE and NW with banneca ore shoots at flexures and structure intersections | Consejo de Recursos Minerales, unpublished reports | Meencha, 1985 | Staude, unpublished data |
| Fresnillo, Zac. | Qtz monz. gis, ph, & qte trachite phy dikes (very limited outcrops)³|32 Ma | Uncertain association of these or other intrusions to mineralization | Kg,nol (Valdocoars) | Cuera Santa Manuel and chunneys(1 + Santo Niño veins(2): 1) Heavy sulfide (proximal, early): gp-sph- cpy-py-Ag sulfosalts 2) Light sulfide (distal, late): py-asp-sph- gm-yes-py-asp-chl-sph-tetrahargill-ster-mats-proustite-(po-7)-polys | Production: 10k wt: 1.6t Au; 0.7Mt Ph; 0.9Mt Zn; 74k Cu | Cu-Mo-Sn-(Au), abundant Hg prospects in area | Sante Niño(N75E): Three structural zones identified, all related to oblique deformation and dextral strike-slip. Pinching and swelling toward W, cymoid loops in Central part, and step en-echelon toward E Cuera Santa(N70W) Many veins, including Santo Niño pinch out before reaching surface Presently active | MacDonald and others, 1986 | Gennel and others, 1988 | Simmons and others, 1988 | Rulaca and Thompson, 1988 | Albinsion, 1988 | Simmons, 1991 | Authors, unpublished data |
| Guadalupe, SLP | Tourno-musc-moly granite; numerous aplite and pegmatite dikes | Kg ls, shaly marl, limy sh, fossiliferous is broadly warped | Tabular, lenticular and pipe-like skarns and replacement vns of py, aspy, gn, sph, cpy, mo, sph, gold, acant, tetrah, polybasite, mal, azur, chry | Alt is mantled is and skarn of ad, qte, veseu, ep, diop, danber, axinite, toorn, ffr, cc, barie | Cu-Mo-Sn-Au, abundant Hg prospects in area | Cu-Mo-Sn-Au (Au), abundant Hg prospects in area | Mineralization related to F-rich moly granite. Hg deposits present zoned outward from skarn with asby, gpy, sulp, dol, bar, ffr Massive sulfide skarns, mattress fluorite pods, cpy, and open cpy veins occur in and along contact with granite intrusions Presently inactive | Wittich, 1972 | Wittich and Ragotrzy, 1921 | Foshag and Fries, 1942 |
| Guazapares, Chih | Bi dacite and rhyodacite, possibly minor dacite stocks (Oligo7x4 km³), overlying fresh bi rhy tuffs | Kg ls which is not exposed in the mine area | Disseminated auriferous py in strongly silicified alluvite-pyrophy-kool dazite vols. Minor sph, gn, tetrahstens, trace cpy in post advanced arg veins. Prevalent advanced arg alt. over deeper qz- py-Ais-Ahs (Cu-Mo-Mc) structurally controlled mineralization | Dissemin•5Mt @ 80 g/t Au, 0.8g/t Ag (large resource below advanced arg cap) Vein: base metal >3Mt @ 220 g/t Au, 3% Zn, 2% Pb. Ag-Au ge vees =1Mt of 3 g/t Au, 200 g/t Ag | Possible domal intrusive centers may be capping portion of porphyry-related system. Exploration stage | | Gonzalez Reyna, 1956a | Staude, unpublished data | Porphyry Copper and Other Intrusion-Related Mineralization in Mexico | 497 |
### Table 2. Description of selected intrusion-related districts (continued).

<table>
<thead>
<tr>
<th>District</th>
<th>Description</th>
<th>Age (Ma)</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inguarón, Mich</strong></td>
<td>8 intrusive quartz monzodiorite pipes (0.3 km²) 0.8 Mt (K-Ar) 0.65 ± 0.356% Fe (estimated)</td>
<td>2.3 ± 0.2 &amp; 4.3 ± 0.3</td>
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<tr>
<td></td>
<td>Qz + Fe + plagioclase + magnetite + hematite</td>
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<tr>
<td></td>
<td>Injection brecia 7 Mt @ 1.0% Cu; 0.02-0.04% WO₃</td>
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<tr>
<td><strong>La Perla, Chih</strong></td>
<td>Hbl-cpx-opx-san ilmenite calcalkine high K, andesitic-rhyolite sequence (29-30 Ma)</td>
<td>2.2 ± 0.1</td>
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<td></td>
<td>Fe-ore hosted in vitrophyte of porphyritic rhyolitic flow</td>
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<td></td>
<td>Specularite, marlite, minor</td>
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<td></td>
<td>Massive ore in volcanic layer: 47 Mt @ 67% Fe (est. 1961)</td>
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<tr>
<td><strong>La Verde, Mich</strong></td>
<td>Hbl-qz-diorite phyl stock/33.4 ± 3.7 Mt (K-Ar on hbl) bi-qz fumaral stock + collapse brecia</td>
<td>2.1 ± 0.1</td>
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<td></td>
<td>Qtz-accent pegmatite (albite)</td>
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<td></td>
<td>Collapse brecia 7 Mt @ 0.7% Cu and cobalt occurrence</td>
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<tr>
<td><strong>La Cuevas, SLP</strong></td>
<td>High K, calc-alkaline rhyolite breccia 2.95 ± 0.3 Mt (K-Ar) 0.32 ± 0.01% Fe</td>
<td>2.0 ± 0.1</td>
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<td></td>
<td>Qz + Fe + plagioclase + magnetite + hematite</td>
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<tr>
<td></td>
<td>Massive ore repl. (60%) and open space breccia 45% (100); CaF₂ ± 0.04% WO₃</td>
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<tr>
<td></td>
<td>Zoning: qz incr. toward the rhyolite breccia, cr incr. toward the ls</td>
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<td>Alteration (Rhy bx): kaol of Kspar + silica.</td>
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<td>Grade: 76% CaF₂ Tonnage: 80 Mt</td>
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<td></td>
<td>Mineral: contact between ls and rhyolite breccia</td>
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<tr>
<td></td>
<td>Tonnage: 60% 330-700 °C 0% argsilicate and other</td>
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<tr>
<td></td>
<td>Mineral: contact between ls and rhyolite breccia</td>
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<tr>
<td></td>
<td>Massive ore: 67 Mt @ 61.5% total Fe</td>
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<td></td>
<td>Structure: E-W faults, minor struct., breccia</td>
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<td></td>
<td>Deposit morphology: roof pendant</td>
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<td></td>
<td>Re-evaluation underway</td>
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<tr>
<td><strong>Las Salinas, Gro</strong></td>
<td>Qtz monzodiorite phyl stock/62.8 ± 4.5 Mt (K-Ar on hbl) intrusive brecia</td>
<td>2.0 ± 0.1</td>
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<td></td>
<td>Paleoz吵ic intercalation</td>
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<td></td>
<td>Dissemin. + stockwork: Specularitic quartz-serpentinite-propyl: chalcopy</td>
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<td>Grade and Tonnage: 7</td>
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<tr>
<td><strong>Las Truchas, Mich.</strong></td>
<td>Augite-bll-bi diorite + qz diorite + qz (490 km²)</td>
<td>1.9 ± 0.1</td>
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<td></td>
<td>Kgls + Te + Mg + Fe + plagioclase + magnetite + hematite</td>
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<tr>
<td></td>
<td>Massive ore: 67 Mt @ 61.5% total Fe</td>
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<td>Structure: E-W faults, minor struct., breccia</td>
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<td>Deposit morphology: roof pendant</td>
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<td>Re-evaluation underway</td>
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<td></td>
<td>Also known as Copper King</td>
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<tr>
<td><strong>Los Reyes, Chih</strong></td>
<td>Equigran bi-gdgr (3km²), 36.6 ± 0.8 (K-Ar on bi 7)</td>
<td>2.0 ± 0.1</td>
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<td>+ andesite porphyry dikes + swarms</td>
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<td>Kg Benexides sh</td>
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<td>Cu min. in structures cutting skarn inactive at present</td>
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<td>0.5 Mt @ 3% Cu, 7 g Ag from skarn (2-18 Mt reserve of 2% Cu)</td>
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<tr>
<td>District</td>
<td>Intrusion-related Deposits</td>
<td>Description</td>
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<tr>
<td>Malpica, Sin</td>
<td>Hbl-bi-mt-sph</td>
<td>Qz diorite, augite-hbl diorite</td>
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<tr>
<td></td>
<td></td>
<td>Graded gr. tuff, bi-mt of qz, pHv, py, Hbl, ser, and Fe-oxides.</td>
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<td>Veins of varying assemblages with qz-sl, Kspar-phl-qtz-ep,</td>
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<td>Cu-Bi-Sn-As reservoirs.</td>
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<td>Low grade bulk mineralization with qz-tk kv, Cu-Au &amp; Ag.</td>
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<tr>
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<td></td>
<td>Grades up to 35 g/t Au and 1200 g/t Ag in veins.</td>
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</tbody>
</table>
|              |                | Resources: 2Mt @ 0.89% oxide Cu, 0.4% Au & 0.7% mixed Cu, 3Mt @ 0.2% mixed Cu (1Mo).

| Nacozari District, Son | Florida-Barrion: Qz-monz: py. (5 km²) | Veins of varying assemblages with qz-sl, Kspar-phl-qtz-ep, Cu-Bi-Sn-As reservoirs. |
|                       |                               | Low grade bulk mineralization with qz-tk kv, Cu-Au & Ag. |
|                       |                               | Grades up to 35 g/t Au and 1200 g/t Ag in veins. |
|                       |                               | Resources: 2Mt @ 0.89% oxide Cu, 0.4% Au & 0.7% mixed Cu, 3Mt @ 0.2% mixed Cu (1Mo).

| Naica, Chih       | High-silica rhy dikes and sills | Endoskarn: 1) albite and potassic alteration; 2) Bi-veins. |
|                  |                              | Resources: 21Mt @ 0.9% Cu remaining. |

| Peña Colorada, Col. | Augite-hbl diorite (>100 km²) | Calc-silicate alteration: |
|                    |                               | Potassic alteration: 2) Kspar-phl-qtz-ep-cc. |
|                    |                               | Endoskarn present, but mostly exoskarn. |

|                  |                               | Low grade bulk mineralization with qz-tk kv, Cu-Au & Ag. |
|                  |                               | Grades up to 35 g/t Au and 1200 g/t Ag in veins. |
|                  |                               | Resources: 2Mt @ 0.89% oxide Cu, 0.4% Au & 0.7% mixed Cu, 3Mt @ 0.2% mixed Cu (1Mo).

|                  |                               | Low grade bulk mineralization with qz-tk kv, Cu-Au & Ag. |
|                  |                               | Grades up to 35 g/t Au and 1200 g/t Ag in veins. |
|                  |                               | Resources: 2Mt @ 0.89% oxide Cu, 0.4% Au & 0.7% mixed Cu, 3Mt @ 0.2% mixed Cu (1Mo).
<table>
<thead>
<tr>
<th>District</th>
<th>Description of Selected Intrusion-Related Districts (continued).</th>
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<tbody>
<tr>
<td><strong>Frias de las Casas, Son</strong></td>
<td>Bi-qtz moly porphyry, &gt;3 km long, resorbed qtz, fels (3 km²) (K-Ar) teg.</td>
</tr>
<tr>
<td></td>
<td>Mz or Pz meta-clastic sediments of greenstone facies, K-facies, impure l and s.g. quartz diorite (part of Sonora-Sinaloa batholith)</td>
</tr>
<tr>
<td></td>
<td>Hydrous, grades consistently 0.1-0.15% Cu with supergene overall grades of 0.45% Cu in chalcocite ore. Tonnage is being expanded by current drilling (AZCO, 1993)</td>
</tr>
<tr>
<td></td>
<td>Metamorphic grade may predominate mineralization and may be associated with the Laramide age Sonora-Sinaloa batholith. Pre-feasibility stage</td>
</tr>
<tr>
<td><strong>Providence, Zac</strong></td>
<td>Hbl-biqtz moly (6 km²) / 4022 Ma (K-Ar) and related qtz porphyry dikes</td>
</tr>
<tr>
<td></td>
<td>Jl, ls (Zunaga Fin)</td>
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<tr>
<td></td>
<td>Ore: py-sph-cpy-ge-py-cq-cq-Ag</td>
</tr>
<tr>
<td></td>
<td>Resources: Zn: 0.5Mt @ 0.5%</td>
</tr>
<tr>
<td></td>
<td>Structure: N10W to N15E radial fracture system. N30E &amp; N75E (normal to strata) are important ore controls at depth. NSSW bedding planes control min. at shallow levels. Status: mined out</td>
</tr>
<tr>
<td><strong>Real de Castillo (Sierra Juarez), BCN</strong></td>
<td>Hbl-biqtnu granodiorite (140 km²) / K</td>
</tr>
<tr>
<td></td>
<td>PzJ, metaased, graphite marbles, bi-musc-chQtch, slate</td>
</tr>
<tr>
<td></td>
<td>Stockwork veins with chl-ser-ksp, quartz veins with chl-ser-ksp, sparse Au in veins.</td>
</tr>
<tr>
<td></td>
<td>Mostly mined out although large, poorly defined low grade resource still present and no recent exploration drilling undertaken. Marble and diorite make best sch host where pegmatite dikes are close. Mines are areas of aggregations of small prospect pits. Ore was hand cobbled</td>
</tr>
<tr>
<td><strong>San Antonio de la Huerta, Son</strong></td>
<td>Microdiorite (andes porphyritic 7-2 km², 51.4, 21.4, dacite porphyry, minor gd)</td>
</tr>
<tr>
<td></td>
<td>O or T-J shallow marine sh, s.s. Is-T-J argillites, metaarkose, and rhyolite</td>
</tr>
<tr>
<td></td>
<td>Laramide Sonora batholith exposed N, S, and W</td>
</tr>
<tr>
<td></td>
<td>Mineralized stockworks are nickel mineralization and may be</td>
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<tr>
<td><strong>San Fernando, BCN</strong></td>
<td>Hbl-(ts) diorite (40 km²) / K</td>
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<tr>
<td></td>
<td>PzJ, meta-igneous, K-facies flakes, metagneiss, and biotite</td>
</tr>
<tr>
<td></td>
<td>Stockwork veins with chl-ser-ksp, quartz veins with chl-ser-ksp, sparse Au in veins.</td>
</tr>
<tr>
<td></td>
<td>Small drilled areas intersected chalc, but no published Cu or Fe reserves</td>
</tr>
<tr>
<td><strong>San Francisco del Oro, Chih</strong></td>
<td>Rhy flows/dikes/whole rock (25.3x15.3 km²) (K-Ar) and related qtz porphyry dikes</td>
</tr>
<tr>
<td></td>
<td>Jl, K-facies calcite, chalcedonic quartz diorite, 32.8x0.5Ma (K-Ar)</td>
</tr>
<tr>
<td></td>
<td>Veins: Stage 1 (2-2m env. of mass sulf (as-chl-ser-qtz-acis); gnsph-py-cpy-scheelite)</td>
</tr>
<tr>
<td></td>
<td>Production 1650-1988: 13x10³ Ag</td>
</tr>
<tr>
<td></td>
<td>Mineralization control: where bedding displays chaotic folding and slumping</td>
</tr>
<tr>
<td></td>
<td>Structures: NS and NW shear zones Zoning (increasing from S to N): Pb/Zn, Ag, Pb, Zn, Ag, Au. Presently active</td>
</tr>
</tbody>
</table>

**Metamorphic grade may predominate mineralization and may be associated with the Laramide age Sonora-Sinaloa batholith. Pre-feasibility stage.**

**Structure: N10W to N15E radial fracture system. N30E & N75E (normal to strata) are important ore controls at depth. NSSW bedding planes control min. at shallow levels. Status: mined out.**

**Mostly mined out although large, poorly defined low grade resource still present and no recent exploration drilling undertaken.**

**Small drilled areas intersected chalc, but no published Cu or Fe reserves.**

**Mineralization control: where bedding displays chaotic folding and slumping.**

**Metamorphic grade may predominate mineralization and may be associated with the Laramide age Sonora-Sinaloa batholith. Pre-feasibility stage.**

**Structure: N10W to N15E radial fracture system. N30E & N75E (normal to strata) are important ore controls at depth. NSSW bedding planes control min. at shallow levels. Status: mined out.**

**Mostly mined out although large, poorly defined low grade resource still present and no recent exploration drilling undertaken.**

**Small drilled areas intersected chalc, but no published Cu or Fe reserves.**

**Mineralization control: where bedding displays chaotic folding and slumping.**
<table>
<thead>
<tr>
<th>Location</th>
<th>Deposit Type</th>
<th>Geologic Setting</th>
<th>Mineralization</th>
<th>Relevance</th>
</tr>
</thead>
</table>
| San Isidro, Mich | Gd batholith | 32.5±0.7 Ma       | Breccia filling & Stockwork: Propylite: chl-qz-tour-cpy-pb-sph-gr
Exotic: maclahite | Grade: 0.4% Cu (one pipe) |
| San Martin, Zac  | Bi-bi qz monz | Bi-cpx grade (4km²) + phy phases | Skarn: gd-sacc qz-gr-ferralite-vesuvianite-scap-ep-qz-tem-ls
Ore mine: gn-ar-py-pb-cys-sph- 
              tetrah-Ag-granite-stib-jiang | Reserves: 30.5 Mt @ 1.0% Cu;  
5.0% Zn; 0.5% Pt; 150 g/t Ag;
0.3-0.7 g/t Au |
| San Nicolas, Son | Bi gd equigranular | Bi-cpx grade & phy dikes and small intrusions | 3 types of ore bodies: Gt, ep, qz, calcite skarn with minor fl, py, cpy, powellite
Powellite: In vs. qz, feldspar, mica, chl, sht, cu-tungstate, wolframite, mo, py, cpy, chalcocite
Granite: Qz-ch-cpx vns
Alteration of greisen and hydrolytic halo >4 km² | Prod 1916-1945 90,000 t @
0.7-2% (ave -1.5%) WO³ |
| San Pedro, Chih  | Te porphyritic monz or gd stock | 1 Mt chimney: produced & reserves @
7% Pb, 7% Zn, 1.5% Cu, 219 g/t Ag, Au up to
6 g/tp, and Mo traces. | The andes is possibly early Te age and is altered locally
mineralized | Presently in production. |
| Santa Eulalia, Chih | Pre-mineral qz monz stock | 3.75±0.75±0.3 Ma (K-Ar) | East Camp mineralization: gsd skarn to massive and disseminated sulfides, chalcocite, manto, and proximal intrusive bds.
Local stockwork near contact | Production: (E and W) @
5.0% Zn; 0.5% Pb; 150 g/t Ag; 2.0 g/t Au |
| Santa Fe, Chih   | Gd dolerite (diabase) | 37.8±5.7±5.2 Ma (K-Ar) | Pre K7 intrusive complex poorly exposed
Elliptical skarn halo with boninite, tetrah, bournonite, cpy, gn, py, enargite, 
lineusite, sericite. Gold in skarn matrix of qz-cc-gt-woll (paragenesis unclear)
Also greisen min | Cs-Au-Ag in wollastonite halo around small dike stock
Disseminated metal and wollastonite potential | Reserves: 10,000 t @
600 g/t Ag; 2.47% Cu at the
Santa Fe mine.
Disseminated metal and wollastonite potential | Ls intruded by diabase and granite, mineralization appears related to mafic cupolas |
| Santo Tomas, Sin | Qtz monzphy split | 57.2±1.2 Ma (K-Ar bi) | Stockwork + dissemination:
Potassic: qz-ksp-bi-tour-py-cpy (hn)-ep
Propylite: chl-ep-py
Other: calc-silicate, chalcocite blanket
Talus cemented by mal-chrysocolla | 250 Mt @ 0.45-0.52°Cu
10 Mt oxide
14 Mt @ 0.74% Cu superfine blanket |
| Susqui Verde, Son | Bi-cq monz-tonalite phy | Bi±qz phenos and making up at least 2 distinctive phases/ 58.8
bbl, 56.4 bbl | System is >2 km (E-W) x 1.5 km (N-S) with alteration well developed in vols to E and S but not as well in batholith to N.
Bi and kspar in bbl, adcs, and batholith with approx 1% total sulfides, QSP well
developed and overprinting potassic with hypogene grades up to 0.3% Cu | Hypogene grade in potassic alt rock 0.1-0.15% Cu. Cu enriched by supergene processes along 2 km E-W zone
400 wide zone of chalcocite and oxides (0.3-0.5% Cu) |
| San Martin, Zac  | Bi-bi qz monz w/bbi | 42.±1Ma Rhy psh sh | Pb-Ag veins above Zn-Cu skarn show strong zoning
Presently active | Olivares, 1991 |
| San Nicolas, Son | Bi gd equigranular | 49±1.2 Bi cr & qz phy dikes and small intrusions | Extensive alteration areas in region with cpy and mo veils associating with nearby porphyry intrusions.
W veins may be a large resource which has not been worked for 50 yrs. | Weise and Canedaus, 1985 |
| San Pedro, Chih  | Te porphyritic monz or gd stock | 1.5±0.7 Te skarn to near dike contact | The andes is possibly early Te age and is altered locally
mineralized | Dimmorth, 1999 |
| Santa Eulalia, Chih | Pre-mineral qz monz stock | 3.75±0.75±0.3 Ma (K-Ar) | East Camp: massive sulfide chimneys, manto, and proximal intrusive bds.
Local stockwork near contact | Production: (E and W) @
5.0% Zn; 0.5% Pb; 150 g/t Ag; 2.0 g/t Au |
| Santa Fe, Chih   | Gd dolerite (diabase) | 37.8±5.7±5.2 Ma (K-Ar) | Pre K7 intrusive complex poorly exposed
Elliptical skarn halo with boninite, tetrah, bournonite, cpy, gn, py, enargite, 
lineusite, sericite. Gold in skarn matrix of qz-cc-gt-woll (paragenesis unclear)
Also greisen min | Cs-Au-Ag in wollastonite halo around small dike stock
Disseminated metal and wollastonite potential | Reserves: 10,000 t @
600 g/t Ag; 2.47% Cu at the
Santa Fe mine.
Disseminated metal and wollastonite potential | Ls intruded by diabase and granite, mineralization appears related to mafic cupolas |
| Santo Tomas, Sin | Qtz monzphy split | 57.2±1.2 Ma (K-Ar bi) | Stockwork + dissemination:
Potassic: qz-ksp-bi-tour-py-cpy (hn)-ep
Propylite: chl-ep-py
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Talus cemented by mal-chrysocolla | 250 Mt @ 0.45-0.52°Cu
10 Mt oxide
14 Mt @ 0.74% Cu superfine blanket |
| Susqui Verde, Son | Bi-cq monz-tonalite phy | Bi±qz phenos and making up at least 2 distinctive phases/ 58.8
bbl, 56.4 bbl | System is >2 km (E-W) x 1.5 km (N-S) with alteration well developed in vols to E and S but not as well in batholith to N.
Bi and kspar in bbl, adcs, and batholith with approx 1% total sulfides, QSP well
developed and overprinting potassic with hypogene grades up to 0.3% Cu | Hypogene grade in potassic alt rock 0.1-0.15% Cu. Cu enriched by supergene processes along 2 km E-W zone
400 wide zone of chalcocite and oxides (0.3-0.5% Cu) | Economic mineralization strongly controlled by E-W structures which influence superfine fluid flow |

**POREX: COPPER AND OTHER INTRUSION-RELATED MINERALIZATION IN MEXICO**

**Damon and others, 1981**

**Sillitoe, 1976**

**Rubin and Kyle, 1988**

**Authors, unpublished data**

**Weise and Canedaus, 1985**

**Sillitoe, unpublished data**

**Stauda, unpublished data**

**Gonzalez Reyna, 1985b, a**

**Megaw and others, 1988**

**Megaw, unpublished data**

**Dilmore, 1999**

**Hewitt, 1943**

**Megaw, 1990**

**Sala, 1975**

**McCarthy, 1896**

**Perequera and others, 1977**

**Pantoja, 1991**

**Damon and others, 1981**

**Sillitoe, 1976**

**Bustamante, 1985**

**Drier, personal communication, 1993**

**Damon and others, 1983**
<table>
<thead>
<tr>
<th>District</th>
<th>Intrusive Province</th>
<th>Intrusion Type</th>
<th>Age (Ma)</th>
<th>Description</th>
<th>Mineralization</th>
<th>Other Geologic Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tameapa, Sin</td>
<td>Bi-hbl-qtz monz. + qtz monz. phy</td>
<td>52.9±1.1</td>
<td>Diorite</td>
<td></td>
<td></td>
<td>N65E norm. faults</td>
</tr>
<tr>
<td>Tolimán, Chis</td>
<td>Hbl qtz-monz. phy (&gt;1 km²) (5.6 Ma², Pb-alpha age)</td>
<td>33.4±1.7</td>
<td></td>
<td>Stockwork + bks:</td>
<td>Porphyry Cu arsenic w/ Central American strike slip faulting and southern Mexico collisional arc</td>
<td></td>
</tr>
<tr>
<td>Tumbiscatío, Mich</td>
<td>Diorite + pegmatite dikes/ 7 Ma &amp; Andesite dikes » Bowls? 2 Ma</td>
<td></td>
<td></td>
<td>Stockwork:</td>
<td>Porphyry Cu arsenic w/ Central American strike slip faulting and southern Mexico collisional arc</td>
<td></td>
</tr>
<tr>
<td>Velardeña, Dgo</td>
<td>Bi-qtz-latite phy (5/km²) 33.1±1.8</td>
<td>200±(6±5)</td>
<td>23.2±1.2</td>
<td></td>
<td></td>
<td>Presently inactive</td>
</tr>
<tr>
<td>Verde Grande, Son</td>
<td>Hbl qtz-monz. bi-hbl gd (Late K?) (&gt;4 km²), no phy exposed; late post-mineral mafic dikes</td>
<td>200±(6±5)</td>
<td>23.2±1.2</td>
<td></td>
<td></td>
<td>Presently inactive</td>
</tr>
<tr>
<td>Zimapán, Hgo</td>
<td>Concordia augite qtz monz-monz dikes (6km long±30 m wide) 38.7±0.8 Ma</td>
<td>19.6±1.2</td>
<td>18.9±1.2</td>
<td></td>
<td></td>
<td>Presently inactive</td>
</tr>
</tbody>
</table>

**Abbreviations from Barton and others (1991b) and Kretz (1983).**
porphyry copper deposits are associated with a range of intermediate to felsic magmas. These deposits can be broadly related to both the relatively felsic quartz monzonite (granite)-type systems and the dioritic or alkaline-type systems (Hollister, 1978). Sparse petrographic data in most districts makes it difficult to evaluate the igneous characteristics associated with copper-bearing systems. Nevertheless, deposits of both types are apparently common; indeed, there may be a broader spectrum than this simple two-fold classification indicates. This is one of the reasons that we chose to compare a variety of other igneous-related systems, many of which contain copper, to the more restricted class of porphyry copper deposits.

Felsic-dominated systems typically belong to composite, generally long-lived igneous centers. The characteristic suite of metals is copper with lesser molybdenum and zinc, here designated Cu(-Mo-Zn). Early magmatic activity is generally intermediate (andesitic or quartz dioritic) in composition. This is superseded by voluminous variably porphyritic granodioritic to quartz monzonitic phases and their volcanic equivalents (fig. 9a). More often than not, copper mineralization is most closely associated with strongly porphyritic quartz-feldspar rocks (fig. 8). Minor igneous minerals typically include biotite and hornblende with accessory magnetite and sphene. Related volcanic rocks are typically prominent within the districts and may or may not serve as hosts for mineralization. The most prominent examples are in Sonora, but representatives occur throughout Mexico (Inguañan, table 2, fig. 9a). These moderately felsic systems closely resemble the Laramide porphyry centers of Arizona and New Mexico (Titley, 1982).

Dioritic rather than highly alkaline rocks characterize a more mafic group of porphyry copper systems. Associated metals are ill-known, but gold, iron (in the form of hydrothermal magnetite), and molybdenum are commonly reported. We designate this deposit type as Cu(-Fe-Au). Typical intrusive complexes contain early diorite or gabbro and evolve to porphyritic phases of tonalitic to granodioritic compositions. Associated volcanic rocks are andesitic and may lack the dacitic to quartz latitic phases seen with the Cu(-Mo-Zn) suite. For example, La Verde,
Table 3. Intrusion-hosted copper districts in Mexico.

<table>
<thead>
<tr>
<th>Map#</th>
<th>District</th>
<th>State</th>
<th>Map#</th>
<th>District</th>
<th>State</th>
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<tr>
<td>1</td>
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<td>Mi Madre</td>
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<td>Las Trojes-San Jose del Llano</td>
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Porphyry Copper and Other Intrusion-Related Mineralization in Mexico

Cananea, Sonora

Porphyry Copper, and Other Intrusion-Related Mineralization in Mexico

Michoacan, consists of tonalitic and quartz dioritic porphyries which intrude a quartz dioritic batholith having coeval andesitic volcanics (Coochey and Eckman, 1978; fig. 10, table 2). Hornblende, clinopyroxene, and magnetite with or without sphene are typically present in these rocks. Where described, compositional trends are distinctively plagioclase-dominated (fig. 11a). More highly alkaline rocks may be present but have not been documented in the literature. Plutonic systems that may be analogous, such as some Fe-Cu-Au skarn systems, do have reported syenite and monzonites (Peña Colorada, table 2). Strongly alkaline igneous rocks such as are present with British Columbia alkaline copper systems are apparently absent. Strongly alkaline centers in central and eastern Mexico are associated with other types of mineralization (mostly fluorine-rich) and are discussed below.

A common feature of many districts of both compositional types is well developed magmatic evolution with copper mineralization restricted to later, more felsic phases. It is unclear from the available evidence in most districts whether there are multiple hypogene mineralizing events. In a few areas such as Cananea it is clear that multiple stocks were involved in mineralization at the level of observation. Copper-rich skarn systems (Verde Grande, Sonora, table 2, fig. 5) and some copper-bearing epithermal systems (Mulatos, Sonora, table 2, fig. 5) associated with intermediate to felsic volcanic or plutonic systems may be systems that did not generate porphyry deposits or they may be the tops, bottoms, or sides of such systems.

Hydrothermal Characteristics

The types, distribution, and timing of hydrothermal alteration in porphyry copper systems in Mexico are typical of such systems worldwide, but few details are available for most Mexican districts (table 2). Alkaline, hydrolytic, propylitic, and skarn

Figure 8. Simplified geological map of the Cananea, Sonora Cu(-Mo-Zn) district. Compiled and simplified from Valentine (1936), Meinert (1982), Bushnell (1988), and W.A. Wodzicki (unpublished mapping).

Figure 9. Igneous compositions and conditions of mineralization for selected Cu(-Mo-Zn) deposits. See table 2 for details and sources.

Figure 10. Simplified geological map of the La Verde, Michoacan porphyry copper deposit. Modified from Coochey and Eckman (1978).
alteration are all well-known; styles and abundances vary with the nature of the igneous and host rocks. Hydrolytic alteration, particularly sericitic alteration, predominates in most districts. Clay-dominated alteration types (supergene and hypogene) are widely distributed as well as extensive propylitic alteration in volcanic rocks. Skarns, typically garnet-rich (andradite?), are common where carbonate hosts are present but account for a relatively small portion of the overall alteration in the larger districts. Conversely, many small copper-bearing skarns occur with intrusions bearing little or no described alteration.

Alkaline alteration is commonly recognized and typically consists of vein-controlled secondary potassium-feldspar and biotite. Sulfide-bearing pegmatitic biotite-potassium-feldspar-bearing dikes and veins are prominent in a number of molybdenum-rich districts (Cananea, Cumobabi, Nacozari; table 2). Potassic alteration assemblages are typically present in stockwork zones in the central and deeper portions of systems. In the pegmatitic occurrences, potassic and hydrolytic assemblages may be telescoped into narrow intervals (the La Colorado and Maria deposits, Perry, 1961; Wodzicki and Barton, 1991).

Chalcopyrite is widespread in potassic assemblages with lesser pyrite and magnetite and uncommon bornite and pyrrhotite. In the Cu-Mo-Zn systems, chalcopyrite with or without magnetite and relatively magnesium-rich biotite in the potassic assemblages indicate modestly high sulfidation states (fig. 9b). In contrast, the early magnetite-rich, bornite- and pyrrhotite-bearing assemblages in deposits such as La Verde are consistent with less sulfidizing conditions in the Cu-Fe-Au (dioritic) systems (fig. 11b). In terms of timing, potassic alteration is widely overprinted by hydrolytic assemblages. It may also grade outward into extensive weak propylitic alteration of volcanic and plutonic sequences. Igenous minerals in propylitized rocks are variably converted to chlorite, epidote, sericite, calcite, and pyrite in very extensive (commonly greater than 10 square kilometers), ill-defined zones (figs. 8, 10). Sodium-rich alkaline alteration like that observed in some other porphyry copper systems (Carten, 1986) has apparently not been described in Mexico, but it is present in some iron-rich skarns (table 2) and might be expected in some of the diorite porphyry systems.

Skarn assemblages are typically garnet-rich with carbonate-hematite-quartz-pyrite retrograde assemblages. Silica-pyrite rock is prominent at Cananea and may be present elsewhere (Einaudi, 1982a). Copper skarns are widespread in limestone-bearing districts with intrusion-hosted mineralization (fig. 7). Like many of the polymetallic systems discussed below, many copper-rich skarn systems lack significant mineralization in the igneous rocks. In some districts porphyry style alteration may be present, as in the Concepcion del Oro District where andradite garnet-chalcopyrite-pyrite skarns line the contact with a granodioritic stock with closely-spaced gold-bearing quartz-sericite-pyrite (-chalcopyrite) veins (table 2). Although many copper skarns likely formed synchronously with intrusion-hosted mineralization (Einaudi, 1982b), it has been argued that some such skarns are diachronous and perhaps older than such mineralization (Meinert, 1982).

Among the hydrolytic alteration types, sericitic alteration is by far most abundant and is reported in virtually all described districts. It is typically expressed as quartz-sericite-pyrite veins with sericite-rich envelopes which destroy all feldspars. Sericitic alteration can be gradational with greisen or potassium-feldspar-stable veins, particularly in more felsic systems as in many Arizona porphyry copper systems (Titley and Beane, 1981; compare Cananea, Cumobabi, Santa Ana in table 2). In intermediate and especially in mafic host rocks chlorite and lesser epidote become key minerals in the hydrolytic assemblages. Chlorite-epidote-quartz assemblages with or without sericite, hematite, and pyrite as at La Verde (Coochey and Eckman, 1978; fig. 10) apparently are the mafic analogous of the more common quartz-sericite-pyrite assemblages of more felsic systems (Seedorff, 1991). Advanced argillic assemblages are reported in only a few Cu-Mo-Zn districts (table 2). Areas of exposed hydrolytic alteration commonly exceed several square kilometers and, like potassic alteration, usually grade outward into weaker alteration types (figs. 8, 10). A complication in understanding the distribution of hydrolytic alteration in Mexican porphyry systems is the distribution of supergene clays and alunite. These minerals should constitute a significant component of the leached caps and large supergene ore bodies, but they are virtually undocumented in the published literature.

The oxidation and sulfidation states of the hydrolytic assemblages parallel the conditions estimated for higher-temperature assemblages (figs. 9c, 11c). Opaque minerals in hydrolytic assemblages are predominately pyrite and chalcopyrite. Hypogene hematite is present in some of the more mafic systems, apparently in place of pyrite. Pyrite-to-chalcopyrite ratios typically increase with time and distance from mineralization centers. A few districts locally contain high sulfidation state assemblages (enargite and bornite-pyrite) typically associated with advanced argillic minerals.

**Distribution**

Porphyry deposits in northern Mexico are associated primarily with Laramide magmatism in the western third of the country (fig. 7). Older porphyry systems associated with Jurassic and Cretaceous arcs (El Arco) are sparse and may be the consequence of erosional exposure as is observed in the western
United States (Barton and others, 1988, p. 142-144). Younger porphyry copper deposits are common primarily south of the trans-Mexican volcanic belt from Michoacan to Chiapas. They are associated with mid- to late-Tertiary arc volcanic centers related to the central American trench (Damon and others, 1983). Very few regional or district descriptions have been published for these southern deposits.

Baja California and southern Sinaloa contain a number of porphyry systems associated with the mid- to Late Cretaceous batholiths. El Arco and related occurrences in Baja California and southern Sinaloa are related to weakly porphyritic phases of Cretaceous batholiths (older than 90 Ma) which generally lack coeval volcanic rocks. Laramide centers in southwestern Mexico, particularly in northern Sonora (Cananea, Nacozari), contain the largest of the Mexican porphyry copper deposits. These are associated with 65 to 50 Ma weakly to strongly porphyritic intermediate to felsic intrusions with abundant coeval volcanic rocks. These deposits contain only modest gold but significant molybdenum compared to the older and more westerly occurrences. Breccia pipes are abundant, and hydrolytic alteration is particularly voluminous. West of a region of metamorphic core complexes in western Sonora slightly older intrusions (80-60 Ma) and related volcanic rocks host widely dispersed chalcopyrite-quartz-pyrite vein-controlled mineralization and have small but locally rich copper skarns. Breccia pipes are rare with these deposits. South of this area similar deposits occur in sparse Laramide (“older”) volcanic rocks exposed in windows through the Sierra Madre Occidental volcanic province in Sinaloa. East of the Sierra Madre Occidental in Chihuahua, Durango, and Zacatecas, sparsely late Laramide (Eocene) intermediate composition volcano-intrusive centers have copper mineralization (Concepcion del Oro, Nazas; fig. 7). Some of these occurrences have copper skarns and base-metal replacement ores in Cretaceous carbonates; none of them are reported to contain significant volumes of economic grades in the igneous rocks.

South of the trans-Mexican arc in Jalisco, Cretaceous (?) batholithic rocks contain minor copper occurrences broadly similar to those of Baja California. In contrast, to the southeast in Guerrero and Michoacan more abundant porphyry copper mineralization is present in younger Laramide to mid-Tertiary volcano-intrusive complexes. Like the deposits of northern Sonora, these deposits are associated with breccia pipes and numerous small copper skarns, but comparable large igneous-hosted deposits have not been reported. Rock types and associated metals are generally not documented, although available information suggests that both Cu(-Fe-Au) (diorite-type) and Cu(-Mo-Zn) (granodiorite-type) are present (fig. 5, table 2). The youngest porphyry province of Mexico extends from eastern Oaxaca southeast through Chiapas into Central America along the Neogene arc.

**Synopsis**

As elsewhere in the world, porphyry copper and closely related deposits in Mexico share key features but differ in substantive ways. Copper enrichment, association with shallow parts of calc-alkaline intrusive centers, and extensive wall rock alteration are universal. Metal contents, style and extent of alteration and mineralization, and associated igneous rocks vary consider-ably. Of these features, only copper enrichment (of primary or secondary origin) and possibly magmatic compositions distinguish Mexican porphyry copper deposits from a wide-range of analogous systems variably enriched in iron, base and precious metals, and lithophile elements.

**OTHER IGNEOUS-RELATED MINERALIZATION**

Sharing a link with intrusions, other Mexican deposit types pose an interesting comparison with the copper-dominated deposits reviewed above. These types include:

1. greisen, skarn, and pegmatite W(-Mo) deposits associated with intermediate to felsic granitoids,
2. replacement and vein Zn-Pb-Ag(-Cu) deposits associated with felsic intrusions,
3. volcano-hosted vein Ag-Au(-Zn-F-Sn) deposits associated with felsic intrusions,
4. vein and replacement Ag-Au(-Cu-Zn-Pb) deposits associated with intermediate stocks,
5. volcano-hosted Au-Ag(-Cu) systems,
6. rhyolite-related F(-Sn-Be) deposits,
7. diorite-related Fe(-Au-Cu) skarns, and
8. rhyolite-related Fe deposits.

The patterns in these deposits help elucidate the overall intrusion-related metallogeny of Mexico. They provide insight into possible controls on igneous-related mineralization. In this section, we describe the mineralization and igneous characteristic of each type. In the concluding section, we summarize the patterns and discuss possible reasons for systematic similarities and differences.

**Greisen and Skarn W(-Mo) Deposits**

Tungsten- and molybdenum-rich skarns, greisens, and pegmatitic deposits in northwestern Mexico occur with Cretaceous to early Tertiary biotite-bearing granitoids (Mead and others, 1988). We designate these Mo(-Cu-W) occurrences. Greisen (coarse-grained muscovite and quartz with accessory minerals) and pegmatite mineralization occurs with Laramide biotite-rich granodiorite to granitic intrusions in Sonora; more mafic phases may be present but are volumetrically minor (fig. 12a). Greisen alteration is common in the intrusions and often post-dates a pegmatic stage (quartz + alkali-feldspar + biotite + muscovite). This alteration style closely resembles and may be transitional with pegmatic mineralization in some of the copper-rich breccia pipes (as in the Cananea and Nacozari Districts, table 2). Significant molybdenum production has come from a few greisen and pegmatite districts exemplified by the Cumobabi molybdenum-copper-tungsten district in Sonora (table 2). At Cumobabi, variably sheeted stockworks of coarse-grained quartz, feldspar, biotite, muscovite, and tourmaline contain molybdenite, scheelite, and chalcopyrite. Early veins contain common alkali feldspar, whereas later veins generally lack feldspar and contain abundant muscovite and moderate pyrite. High-salinity, high-temperature fluid inclusions and close association with late felsic phases indicate a strong link to magmatic processes. Conditions of mineralization (fig. 12b, c) resemble those in the Cu(-Mo-Zn) porphyry systems with moderately sulfidizing conditions and variation from feldspar-stable to moderately acid
assemblages, but the Mo(-Cu-W) systems have a more lithophile-element-rich metal suite and a distinctively pegmatitic character.

Small tungsten skarns are widespread in carbonate-bearing screens of the Peninsular Range, Sonora, and Sinaloa Batholiths (Fries and Schmitter, 1945; Menchaca, 1985). These deposits contain primarily tungsten and molybdenum with minor copper; we designate them W-Mo(-Cu). Associated intrusions are generally little altered, equigranular, and composite; they may be hornblende-bearing or peraluminous. Although rocks as mafic as diorites or gabbros are described, all of these complexes apparently have felsic variants (Fries and Schmitter, 1945; Gastil and others, 1975) which we infer to be related to skarn formation as in the Real de Castillo District (table 2, fig. 13a). Sparse scheelite-bearing greisen veins are the most common igneous-hosted alteration in Baja California. Calcite skarns contain grossularitic garnet-wollastonite-epidote with scheelite and minor copper-gold-bearing quartz veins. In the San Nicolas District (table 2), calcic W-Mo(-Cu) skarns are associated with more intensely altered (quartz-muscovite and potassium-feldspar-quartz-biotite veins) molybdenum-bearing Laramide stocks. Less than 100,000 tons of tungsten ore was produced from skarn-dominated mineralization in the San Nicolas District. Inferred conditions of formation are relatively high temperature, moderate pressures, and moderate sulfidation state (fig. 13b).

**Sediment-Hosted Zn-Pb-Ag(-Cu) Deposits Associated with Felsic Intrusions**

High-temperature sediment-hosted deposits of northern and central Mexico are dominated by zinc, lead, and silver with accessory copper, tungsten, molybdenum, and gold; they are designated as Zn-Pb-Ag(-Cu) deposits. They show a characteristic association with evolved felsic igneous rocks (Naica, San Francisco del Oro, Santa Eulalia, San Martín, and Velardeña Districts; fig. 5, table 2; Megaw and others, 1988). These deposits are mid-Tertiary in age (45 to 25 Ma), and they overlap with an analogous but more copper-rich suite of base-metal silver deposits associated with somewhat less felsic rocks of mid-Tertiary and older age (Providencia, Concepcion del Oro, Cosala, Zimapan, Fresnillo; see table 2). Ores in most districts are carbonate-hosted manto and chimney deposits, but veins are dominant where clastic or volcanic rocks are the host as at San Francisco del Oro. Base-metal sulfides occur in paragenetically and spatially zoned pyrrhotite-pyrite-carbonate-quartz-fluorite replacements. Iron-poor metamorphic and iron-rich metasomatic calcilicates are typically abundant near the intrusions, where they comprise complex zinc-dominated polymetallic skarns (Einaudi and others, 1981; Megaw and others, 1988). Metal zoning is typically well developed from distal silver and manganese with minor lead through a zinc-lead-silver zone to proximal zinc-rich mineralization with minor copper, silver, tungsten, molybdenum, and gold. The San Martin District illustrates many of the these features (fig. 14). It contains a large zinc-rich copper- and tungsten-bearing skarn on the flank of a partly altered composite stock; lower-temperature silver-rich lead-zinc assemblages are superimposed on and external to the zinc skarn.

Associated igneous rocks include ubiquitous highly felsic dikes and sills, which may or may not be sparsely porphyritic (fig. 15a). Where the rocks are exposed, as in the Velardeña and San Martin Districts (fig. 14), porphyritic to equigranular biotite-(pyroxene) quartz monzonite and monzogranite are the major phases. Alteration in the igneous rocks has not been extensively studied but seems to consist of local endoskarn and modestly developed sulfide-poor potassium-feldspar- and muscovite-fluorite-bearing quartz vein assemblages. At San Martin two vein sets can be observed in the felsites that are spatially associated with the skarns: an early discontinuous stockwork of sulfide-poor irregular quartz veins and younger through-going quartz-pyrite veins with hydrolytic and endoskarn envelopes. Timing relationships between the felsites, hydrothermal alteration, and main phases of the stocks are uncertain (Rubin and Kyle, 1988). Connection to igneous events is demonstrated by these relationships at San Martin and by the direct connection between igneous breccias and chimney formation at Santa Eulalia.

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**Figure 12. Igneous compositions and conditions of mineralization for the Cumobabi, Sonora Mo(-Cu-W) District.** See table 2 for details and sources.

**Figure 13. Igneous compositions and conditions of mineralization for selected W(-Mo) skarn and greisen deposits.** See table 2 for details and sources.
porphyry, rhyolite porphyry, carbonate & clastic rocks, and metamorphic aureole.

**Figure 14.** Simplified geology of the San Martin, Zacatecas Zn-Cu-Pb-Ag deposit. Simplified from Rubin and Kyle (1988).

(Miranda and Megaw, 1986). Petrological and geochemical studies are consistent with involvement of igneous as well as sedimentary components in ore formation (Megaw and others, 1988). Hydrothermal conditions vary systematically from early, moderately reduced and low-sulfidation state (though sulfide-rich) assemblages to later, moderately oxidized and sulfidized assemblages (fig. 15b, c). In contrast to the copper systems, alteration in the intrusions is weakly developed and much poorer in total sulfide and relative volume of hydrolytic alteration.

**Figure 15.** Igneous compositions and conditions of mineralization for polymetallic replacement and skarn deposits associated with felsic intrusions. See table 2 for details and sources.

Volcanic-Hosted Ag-Au(-Zn-F-Sn) Deposits Associated with Felsic Intrusions

Some volcanic-hosted vein districts bear an obvious if problematic relationship to rhyolitic hypabyssal intrusions. These are epithermal systems in that metals occur in quartz-carbonate veins and related stockworks. They have small volumes of vein-controlled hydrolytic (mainly sericitic) alteration and somewhat more extensive retrograde hydration and carbonation ("propylitic") alteration. Metals are dominated by silver and zinc with lesser...
gold, lead, copper, and tin; they are designated as Ag-Au(-Zn-F-Sn) deposits. Fluorite is an important gangue mineral in veins. The Bolaños District (Lyons, 1988a; table 2, fig. 16) is perhaps the clearest example. At Bolaños, faults contain ore bodies that are symmetrically zoned around the Tepec dome, a porphyritic hypabyssal to volcanic rhyolite body. Central parts of the system contain copper, tin, and silver mineralization including cassiterite-hematite veins in the Tepec dome; silver and base metals constitute the principal ore zone away from the center. Moderate salinity fluids, pronounced zoning around the Tepec dome, and geological evidence consistent with mineralization broadly coeval with the Tepec intrusion led Lyons (1988a) to conclude that the Bolaños system had a close connection to magmatism. Similar relationships are postulated in the Guanajuato District on the basis of field and petrographic studies (Megaw, personal observation, 1994; Zantop, personal communication, 1994). As in a number of other silver-rich epithermal systems in central Mexico, associated igneous rocks in both districts are felsic (fig. 17a) and commonly show significant fluorine and tin enrichments. Conditions of formation for the vein systems are not well constrained, but mineral assemblages suggest that they are only modestly sulfidized and are strongly oxidized only near the surface, where boiling or mixing may be important (fig. 17c). In this respect as in their general element enrichments and associated igneous rocks they resemble the felsic-associated polymetallic replacement systems described above.

Vein-Dominated Ag-Au(-Cu-Pb-Zn) Deposits Associated with Intermediate Intrusions

A number of large vein-type precious-metal and base-metal districts are associated with intrusive centers of intermediate composition. Although these are primarily silver producers with silver-gold ratios greater than 100, gold grades commonly exceed 1 gram per tonne. These districts are Laramide (Batopilas, Cosala) and mid-Tertiary (Fresnillo) and have produced much silver with significant gold and base-metals from veins, replacements, and skarns (table 2). We designate them Ag-Au(-Cu-Pb-Zn) deposits. Although they are similar to many epithermal districts, these districts differ (perhaps due to level of exposure) in having abundant base metals, an inconspicuous elevation control on grades, and a close relationship with intrusive intrusions (compare Buchanan, 1981). These districts are zoned from silver-rich peripheries to higher base-metal and gold contents near to the intrusions (fig. 18). Copper-gold mineralization occurs in intrusion-hosted stockworks or skarns in the Batopilas and Cosala Districts. Associated intrusive rocks are mainly intermediate in composition (hornblende quartz diorites to biotite-hornblende quartz monzonites, fig. 19a).

In the Batopilas District (fig. 18) two stocks contain disseminated copper mineralization associated with extensive sericitic alteration (Wilkerson and others, 1988; Bagby, 1979). The productive portion of the Batopilas District is strongly zoned and bears only a general relationship to the two intrusive centers. High silver-gold ratio, low sulfidation-state assemblages grade to lower silver-gold ratio, more sulfidized assemblages. Alteration in the volcanic host rocks is mainly chlorite-dominated with some sericite. The intermediate composition of the host rocks may lead to the relative abundance of magnesian hydrolytic assemblages as a more mafic equivalent of sericitic alteration in felsic host rocks. At Fresnillo, Cretaceous volcanoclastic and carbonate rocks are intruded by mid-Tertiary stocks and dikes of intermediate composition. These units host predominantly quartz vein mineralization, but there has been significant production from zinc-lead-silver replacement bodies with minor copper and gold near igneous contacts. High-temperature assemblages indicate relatively low sulfidation states with system evolution to lower temperature assemblages of low to moderate sulfidation and oxidation states (fig. 19b, c). At Batopilas, for example, hypogene native silver is one of the most important ore minerals.

Volcanic-Hosted Au-Ag(-Cu) Deposits

Volcanic-hosted acid-sulfate systems occur in a number of areas in the Sierra Madre Occidental, where they appear to be...
related to hypabyssal intermediate to felsic intrusive centers. These systems exhibit the high sulfidation states and advanced argillic alteration characteristic of this deposit type worldwide (Heald and others, 1987). Although they are incompletely explored, they appear to have relatively high gold-to-silver ratios (generally greater than 1:10), minor copper, and little zinc or lead. We designate these systems Au-Ag(-Cu) deposits. Large volumes of advanced argillic alteration suggest a relationship to magmatic fluids such as has been proposed elsewhere (Heald and others, 1987), but at present there is no confirming evidence. While alteration is commonly fracture-controlled, gold is dispersed in significant volumes of strongly acid-altered, highly silicified host rocks. In contrast, most volcanic-hosted epithermal systems in northern and central Mexico involve largely vein-controlled alteration of the adularia-sericite type. Where studied, these latter systems appear to have formed from dilute meteoric fluids, possibly in shallow boiling zones with no more than a small magmatic component.

Relatively little is known of the volcanic-hosted acid gold-silver districts, the best studied example of which is the Mulatos District in eastern Sonora. In the Mulatos region an Oligocene dacite to rhyodacite ignimbrite sequence contains dacitic domes and dikes which appear to be closely associated with mineralization centers (Staude, unpublished data; fig. 20). Several strongly silicified, advanced argillic (pyrophyllite-kaolinite-alunite-quartz) zones host disseminated Au-Ag(-Cu) mineralization which averages more than 1 gram gold per tonne. The highest grades (greater than 10 grams per tonne) are along quartz-pyrite-enargite-barite veins. Areas of advanced argillic alteration up to 1 kilometer across are embedded within larger zones of up to 10 square kilometers of montmorillonite±chlorite±kaolinite alteration (Staude, unpublished data). Elsewhere in the Sierra Madre Occidental advanced argillic alteration occurs in precious metal districts which are associated with hypabyssal intermediate to felsic intrusions, but surprisingly few such districts have been documented in the literature (fig. 21a). In some, such as the Guazapares District (table 2), advanced argillic alteration containing disseminated gold and silver is spatially associated with vein-type silver-base metal mineralization. Although the advanced argillic alteration in some of these systems may represent a deeper source of oxidized highly acidic and possibly magmatic fluids, some systems such as Guazapares may instead represent acid caps generated by boiling over more typical sericite-adularia-type vein systems. High-temperature mineral assemblages are absent at the surface in these districts but have been found by drilling. Compared to hydrothermal exposures in other systems that are closer to stocks or deeper, Au-Ag(-Cu) systems are relatively low temperature and formed under exceptionally sulfidized and oxidized conditions (fig. 21b, c).

**Rhyolite-Related F(-Sn-Be-Mo) Deposits**

Evolved felsic volcanic centers of the Sierra Madre Oriental and surrounding areas in northeastern and central Mexico have abundant associated fluorite and lesser but occasionally significant amounts of other metals; these are designated F(-Sn-Be-Mo) districts. These shallow intrusive centers and superjacent volcanic edifices are typically metaluminous but may be peralkaline, particularly in Coahuila and Nuevo Leon. Topaz rhyolites form an important part of this suite (Ruiz, 1985) and are broadly continuous with the fluorine-rich silicic rocks of the Rio Grande rift region and west Texas in the United States. These...
high-silica and fluorine-rich igneous rocks are broadly similar to the felsites associated with sediment-hosted Zn-Pb-Ag(-Cu-F) deposits, but the intermediate composition igneous rocks associated with these deposits tend to be strongly alkaline and include local peralkaline and undersaturated varieties (fig. 22a).

Mineral resources are dominated by fluorite (hundreds of occurrences) with lesser amounts of beryllium, tin, and antimony. Zinc, molybdenum, silver, and lead may be associated. These rocks resemble alkaline rhyolites of west Texas, New Mexico, and Colorado that have associated Climax-type porphyry molybdenum deposits (Cave Peak, Texas; Questa, New Mexico; Climax and Henderson, Colorado). Recognized deposits are mainly lower-temperature fluorite-rich replacements (Las Cuevas, San Luis Potosi; Aguachile, Coahuila; fig. 22a, table 2), and small occurrences of wood tin (gas phase cassiterite) are common. Sulfides are rare in these shallow systems. High-temperature alteration includes topaz-bearing assemblages, whereas lower temperature alteration is generally clay (commonly kaolinite)-quartz. Clearly fluorine-rich skarn-type occurrences, such as Guadalcazar and Charcas, San Luis Potosi, may represent transitions to alkaline fluorine-rich replacement deposits. In contrast to the typical felsite-associated Zn-Pb-Ag(-Cu-F) replacement and vein systems, sulfides tend to be sparse except in late assemblages. Consequently the conditions of formation of these deposits are somewhat more oxidized and less sulfidized than those of the Zn-Pb-Ag(-Cu-F) deposits (compare fig. 22b, c with figs. 15b, c, 17c).

**Diorite-Related Fe(-Au-Cu) Deposits**

Small to moderate sized iron-oxide-rich and variably gold- and copper-bearing skarn and replacement deposits, designated Fe(-Au-Cu), are widespread in southern and westernmost Mexico where they are associated with stocks of intermediate composition (hornblende-pyroxene diorites to monzonites). Field relationships are consistent with most of these deposits being Mesozoic in age. In northwestern Mexico they may be as old as Jurassic, whereas in southern Mexico most are likely to be Cretaceous. Proximal magnetite-(hematite) skarns are developed in carbonate and andesitic rocks in western Baja California and from Guerrero to Chiapas. Minor pyrite and chalcopyrite are present, typically late in the paragenesis. Gold is present in some of these systems such as Bermejal and Nukay. The Bermejal deposit is reported to contain 18 million tonnes of resource at 1 part per million gold (Page, 1993; De la Garza, 1994).

**Peña Colorada, Colima**

Figure 22. Igneous compositions and conditions of mineralization for selected fluorine-rich hydrothermal systems associated with felsic magmatic centers. See table 2 for details and sources.

Figure 23. Simplified geology of the Peña Colorada iron deposit, Colima. Simplified from unpublished mapping of L. Zürcher and Peña Colorada staff.

Figure 24. Igneous compositions and conditions of mineralization for Fe(-Cu-Au) skarns. See table 2 for details and sources.
Magnetite-(hematite) bodies occur at Peña Colorada with extensive oxidized garnet (andradite)-pyroxene skarn and a later chlorite-epidote-pyrite-chalcopyrite-talc overprint which may be associated with hematitization (fig. 23). Late potassium-feldspar-biotite-quartz-apatite assemblages cut the skarn at both Peña Colorada and Las Truchas. Alteration in the diorite intrusive rocks is described as endoskarn, but the distribution and relationship to intrusive phases are not well known. Geochemical studies at Peña Colorada (Zürcher, unpublished) indicate that intrusive components dominated skarn formation, but the ultimate source of the fluids is yet to be resolved. These systems occur with igneous suites of intermediate composition and of poorly known oxidation state and alkalinity (fig. 24a). Available mineralogical information suggests that the systems have relatively low sulfidation and oxidation states in their high-temperature (main) stages and evolve to modestly sulfide-rich, oxidized assemblages during late retrograde skarn formation (fig. 24b, c).

Rhyolite-Related Fe Deposits

Iron-oxide ore bodies are associated with a number of mid-Tertiary felsic volcanic centers east of the Sierra Madre Occidental in north-central Mexico. Significant production has come from the Cerro de Mercado, La Perla, and Hercules deposits in Durango and Chihuahua (table 2, fig. 5). These deposits are characterized by massive hematite-magnetite bodies that are broadly conformable with coeval (?) latitic to rhyolitic volcanic rocks. Hydrothermal alteration is variably developed and consists of common hydrolytic (clay-dominated) alteration with silicification and calc-silicate alteration to various extents. Sulfides are sparse and late in the paragenesis and non-ferrous metals appear to be absent, but apatite, sulfates, and fluorite can be common.

The Cerro de Mercado deposit (fig. 25) is the largest of these systems and is associated with the Chupaderos caldera complex near the city of Durango. This deposit has been described in detail by Lyons (1975, 1988b), Felix (1978), and Labarthe and others (1988). The iron oxide-rich bodies of this deposit are largely conformable with their enclosing volcanic pile and appear to be localized near an intracaldera vent. This area also centers extensive hydrothermal alteration of volcanic rocks consisting of pyroxene-rich replacement (loosely termed “skarn”) and laterally extensive silicification and clay alteration. The conformable nature of the deposit and its association with iron-rich volcanic rocks led Lyons (1988b) and some others to conclude that the main mass of the iron-oxide body represented an oxide-rich magma with superimposed hydrothermal and gas-phase alteration. In contrast, Felix (1978) and Labarthe and others (1988) felt that the ores were hydrothermal and had largely replaced particular units of the volcanic series. Rare-earth elements are strongly concentrated in the late hydrothermal apatites associated with silicification and topaz rhyolite in the same caldera complex has minor wood tin mineralization. The La Perla and Hercules deposits are less intensively studied but share the same enigmatic origin. Apatite is sparse at La Perla but fluorite and sulfates are abundant. These systems are very shallow and are associated with latitic to rhyolitic volcanic and hypabyssal intrusive centers (fig. 26a). Mineralization is relatively oxidized and sulfur-poor with evidence for abundant sulfate and strong late-stage hypogene oxidation (fig. 26b, c).

Figure 25. Simplified geology of the Cerro de Mercado iron deposit, Durango. Simplified from Lyons (1988b).

METALLOGENIC PATTERNS AND POSSIBLE CONTROLS

The characteristics of porphyry copper and other intrusion-related mineralization in Mexico exhibit many systematic patterns. In this section we outline the general patterns that emerge when comparing the particular deposit types. Metal and alteration types bear systematic relationships to igneous compositions, host rocks, and depth and broad patterns are apparent in
the temporal and spatial distribution as has been noted by others (for example, Clark and others, 1982).

We also present some general relationships that appear to be helpful in understanding these patterns. Likely controls on the characteristics of igneous-related mineralization can be grouped according to (1) the nature of the processes involved (mobilization, transport, and deposition of materials), (2) the exposure and preservation of appropriate crustal levels, and (3) the influence of varying lithospheric provinces on the compositions of ore-forming systems. Each of these is almost certainly important in the metallogeny of Mexico, but the relative importance of each is not clear.

Compositional Correlations: Igneous and Hydrothermal

Magmatic and hydrothermal compositions are broadly correlated. This is illustrated in figure 27, which summarizes the compositional ranges for igneous rocks associated with the various metal suites presented above. The salient aspect of this diagram is the general change in metal suites from siderophile- and chalcophile-element dominated suites associated with mafic to intermediate rocks to the chalcophile- to lithophile-element dominated suites associated with the more felsic rocks. This compositional correlation has been long appreciated (e.g., Lindgren, 1933; Mitchell and Garson, 1981) and has been extensively promoted on the basis of empirical correlations (for example, Keith, 1986; Keith and Wilt, 1986). Metaluminous and oxidized systems appear to be broadly base-metal rich. Strongly alkaline (notably, low CaO) systems appear to be dominated by fluorine and other lithophile elements, and strongly peraluminous systems typically have lithophile elements with significant base metals. Subtler distinctions can be made on the basis of variables such as alkalinity and oxidation state, but the general controls on these features remain enigmatic. The paucity of a good mineralogical and chemical data for Mexico currently precludes detailed analysis.

Complementary to the metal-igneous compositional correlation is the correlation between hydrothermal mineral associations, their total and relative abundances, and the chemical conditions that they represent. These relationships are summarized in table 1 and figure 28. Virtually all systems appear to show a strong tendency towards more oxidized and sulfidized assemblages with time. Within this general trend further distinction is evident between alkaline and mafic systems compared to felsic metaluminous and peraluminous systems. The former are dominated by iron-oxides with relatively minor base metals, whereas the latter have considerably more sulfide-rich assemblages and base metals.

The types of hydrothermal alteration and their relative abundance also change systematically with igneous rocks and metal suites. In aluminous host rocks (mainly igneous), alkaline and hydrolytic alteration show considerable variation (see for example, Barton and others, 1991b). In carbonate host rocks, skarn and replacement mineralization are likewise variable (Einaudi and others, 1981). Alkaline alteration (common potassic, rare sodic) is found in virtually all types of systems (table 1) but is quite variably developed: Potassic alteration is best developed in deeper exposures and intermediate to felsic rock types, while sodic alteration is apparently restricted to some dioritic and alkaline systems such as Peña Colorada and Cerro de Mecado (table 2). Hydrolytic alteration including greisen, sericite, chlorite, and advanced argillic types is more variable and typically more voluminous in most systems than alkaline alteration. In subalkaline felsic systems (as opposed to mafic or alkaline systems) muscovite or sericite typically makes up a greater fraction of the overall alteration. For example, in strongly peraluminous suites muscovite-rich greisen-type assemblages may comprise virtually the only alteration type (see Barton, 1987), whereas in peralkaline systems hydrolytic alteration may be effectively absent at as at Aguachile (table 2). Carbonate-hosted alteration (table 2) follows the worldwide patterns outlined by Einaudi and others (1981). Oxidized skarns (andradite ± magnetite rich) predominate with copper and iron systems, whereas more pyroxene-rich reduced or manganese-rich skarns are more common with zinc-lead-silver and tungsten-molybdenum systems. Replacement bodies yield analogous patterns. Fluorite is prominent in replacements related to alkaline intrusions and is the dominant mineral in some deposits such as Aguachile.
Chemical Interpretation of Igneous-Hydrothermal Correlations

The pronounced correlations between igneous compositions and hydrothermal features point to a widespread control of hydrothermal systems by related igneous rocks or magmas. It is widely accepted that magmatic fluids are important in the formation of intrusion-related ore deposits but compositional correlations alone do not require this mechanism. Geochemical evidence for involvement of other fluids in intrusion-related mineralization abounds (for example, Guilbert and Park, 1986). Equilibration of other fluids circulating through intrusive and volcanic rocks could well provide many of the characteristics that distinguish particular deposit types. For example, intrusion-related volcanic-hosted iron-oxide-apatite deposits in Nevada (which have many similarities to the iron-oxide deposits of central Mexico) formed by circulation of evaporitic brines through mafic and felsic intrusions, leading to analogous though quite different alteration assemblages and element enrichments in the mafic and felsic hosts (Barton and others, 1991c; Johnson and others, 1993).

Igneous compositions could exert a basic control on the nature of related hydrothermal systems through some combination of original element enrichments and chemical equilibria. Original elemental enrichments are demonstrably important in some environments such as in ultramafic suites (Guilbert and Park, 1986). Systematics of regional metallogenic patterns also suggest control from crustal and igneous enrichments (for example, Titley, 1991; Mitchell and Garson, 1981). It is equally evident, however, that other process-related (i.e., chemical) controls are involved as is illustrated by the common close proximity of dramatically different metal and alteration suites (see, for example, fig. 5; see also Barton, 1990). Many compositional controls have been advocated: alkalinity, oxidation state, alumina saturation, and halogen ratios to name a few. One approach to synthesizing compositional controls on fluids equilibrated with igneous rocks is shown in figure 29. In this figure the chemical potentials of lime (CaO) and alumina (Al₂O₃) are used to quantify relationships among quartz-bearing igneous mineral assemblages, alkalinity, alumina saturation, and fluid compositions. These relationships are briefly outlined here; the thermodynamic concepts are discussed elsewhere for purely igneous problems (for example, Carmichael and others, 1974). Oxide components can be related to igneous minerals by the following types of reactions:

\[
\begin{align*}
\text{(1a)} & \quad [\text{Al}_2\text{O}_3] + \text{KAlSi}_3\text{O}_8 + \text{H}_2\text{O} = \text{KAl}_2[\text{AlSi}_3\text{O}_8\text{(OH)}] \\
\text{(1b)} & \quad [\text{Al}_2\text{O}_3] + 2\text{NaFeSi}_2\text{O}_6 + 2\text{SiO}_2 = 2\text{NaAlSi}_3\text{O}_8 + \text{Fe}_2\text{O}_3 \\
\text{(1c)} & \quad \text{CaO} + \text{MgSiO}_3 + \text{SiO}_2 = \text{CaMg}[\text{Si}_2\text{O}_5] \\
\text{(1d)} & \quad \text{CaO} + [\text{Al}_2\text{O}_3] + 2\text{SiO}_2 = \text{CaAl}_2[\text{Si}_2\text{O}_5]
\end{align*}
\]

The first two reactions illustrate restrictions on alumina saturation: two-mica granites are limited by (1a) and peralkaline systems are limited by (1b). Reaction (1c) gives one of several limits on the distribution of tholeiitic (orthopyroxene present) rocks. Plagioclase is ubiquitous, but its composition across the diagram is given by reaction (1d). Simplified representation of each of these reactions is shown in figure 29a, with corresponding rock and metal types illustrated in figure 29b. Complementary fluid-bearing reactions are:

\[
\begin{align*}
\text{(2a)} & \quad 3\text{[CaO]} + 3\text{FeTiO}_3 + 3\text{SiO}_2 + 1/2\text{O}_2 = 3\text{CaTiSiO}_4 + \text{Fe}_2\text{O}_3 \\
\text{(2b)} & \quad \text{[CaO]} + 2\text{HF} = \text{CaF}_2 + \text{H}_2\text{O} \\
\text{(2c)} & \quad [\text{Al}_2\text{O}_3] + 2\text{Na}^+ + 6\text{SiO}_2 + \text{H}_2\text{O} = 2\text{NaAlSi}_3\text{O}_8 + 2\text{H}^+ \\
\end{align*}
\]

The first reaction (2a) illustrates that the important redox boundary between ilmenite-bearing and titanite-magnetite-bearing rocks is a function of the activity of CaO in addition to the oxidation state. Lime-rich rocks will form titane under more reduced conditions than will lime-poor rocks. The second reaction (2b) illustrates the importance of CaO activity to the mobility and enrichment of fluorine in hydrothermal systems (Barton, 1987). Fluorine mobility is suppressed in all but alkali-rich rocks, but there are no constraints imposed by the Al₂O₃ activity. This rationalizes the strong hydrothermal enrichment of fluorine in multiple types of peraluminous–peralkaline-associated Mexican ore deposits (table 2).

The third reaction (2c) represents a fundamental mineralogical control on fluid acidity. Reaction 2c indicates that for a constant activity of sodium ion (that is, for fluids of approximately constant salinity) a pH decrease of one unit will occur for every two unit increase in activity of alumina. As a result, peralkaline rocks are about 2 pH units more alkaline than corresponding peraluminous rocks (fig. 29a). Acidity, in turn, has a profound effect on the mobility of most metals because of reactions such as:

\[
\begin{align*}
\text{(3a)} & \quad \text{Zn}^2+ + \text{H}^+ = \text{Zn}^++ \text{H}_2\text{S} \\
\text{(3b)} & \quad \text{Zn}^2+ + [\text{Al}_2\text{O}_3] + 2\text{Na}^+ + 6\text{SiO}_2 + \text{H}_2\text{O} = 2\text{NaAlSi}_3\text{O}_8 + \text{Zn}^++ \text{H}_2\text{S} \\
\end{align*}
\]

Consequently, if other things are equal, most metals will become substantially more soluble with increasing activity of alumina (that is, in metaluminous and peraluminous rocks). These relationships help explain the abundance of base metals associated with peraluminous and modestly calcic metaluminous systems and the virtual absence of metals associated with peralkaline systems (fig. 29b). Furthermore, this relationship predicts the observed increase in the abundance and proportion of hydrolytic alteration in felsic metaluminous and peraluminous systems. In greisen-type alteration, which is characteristically associated with peraluminous igneous rocks, secondary white micas form in virtually all assemblages.

Mineralogical reactions act in concert with other important factors in controlling fluid acidity, oxidation state, and sulfidation state. Higher chlorine contents usually make solutions more reactive and better transporting agents. Fluid sulfur contents contribute to acidity through hydrolysis of magmatic SO₂ (Burnham and Ohimoto, 1980):

\[
\text{SO}_2 + 4\text{H}_2\text{O} \rightarrow 3\text{HSO}_4^- + 3\text{H}^+ + \text{H}_2\text{S} \quad \text{(decreasing temperature)}
\]

Another result is that high total oxidized sulfur content produces relatively high sulfidation states consistent with the following reactions:
SO$_2$ + 2H$_2$S = 2H$_2$O + 1.5S$_2$  
(5a)

HSO$_4^-$ + H$^+$ + 3H$_2$S = 4H$_2$O + 2S$_2$  
(5b)

These reactions explain the voluminous pyrite-rich hydrolytic alteration present in sulfur-rich intermediate to felsic systems such as Cu(-Mo-Zn) and Au-Ag(-Cu) deposits (fig. 28) and complement the alumina activity effect which can produce dominant acid alteration without necessarily having the highly sulfidized (or oxidized) assemblages encountered in some W (-Mo-Cu) systems.

The nearly universal trend of lower to higher oxidation and sulfidation states with time (fig. 28) follows from the behavior of reactions (5a, b) and (6a, b).

SO$_2$ + H$_2$O = H$_2$S + 1.5O$_2$  
(6a)

HSO$_4^-$ + H$^+$ = H$_2$S + 2O$_2$  
(6b)

With decreasing temperature, these fluid reactions interact with mineral reactions in such a way as to produce more oxygen- and sulfur-rich mineral assemblages (see Burnham and Ohmoto, 1980). Consequently, reduced and sulfur-poor assemblages containing magnetite, pyrrhotite, iron-silicates, and iron-rich sphalerite are typically superseded by oxidized and sulfur-rich assemblages containing hematite, pyrite, and iron-poor sphalerite. This explanation is not unique because similar oxidation paths can result from other mechanisms such as mixing with surface waters or sulfate-bearing connate fluids (see, for example, Megaw and others, 1988).

**Time-Space Correlations: Metals, Depth and Style**

Many factors beyond chemical controls influence the style and distribution of mineralization. Alteration types and metal contents vary with exposure level and depth of emplacement. The filters of preservation and exposure complicate the identification and interpretation of patterns in space that reflect differences in crustal composition.

Relative depths of exposure and emplacement range widely. A qualitative assignment of exposure levels and compositions for the deposits listed in table 2 is shown in figure 30a. This is based primarily on the textures and metamorphic grade of intrusive and host rocks and to a lesser extent on quantitative estimates from petrology, fluid inclusions, and stratigraphy. A rough distribution of metals is given in figure 30b. As is true worldwide, shallow systems in Mexico are dominated by moderate to low temperature vein and replacement mineralization with widely varying degrees of wall-rock alteration. Alteration is prominent in some sulfur-rich precious metal systems such as Mulatos and sparse in sulfur-poor systems such as Bolaños. Skarn and porphyry-like systems of many varieties develop at deeper crustal levels. The deepest systems are characterized by equigranular intrusive rocks, sparse igneous-hosted alteration, skarns, and regional metamorphism and probably represent both the bottoms of productive systems and various levels of unproductive systems. Although there are good reasons to think that some systems such as some porphyry copper and acid-sulfate

**lime-alumina activities in quartz-saturated igneous rocks**

![Diagram A](image1)

**generalized metal and rock types**

![Diagram B](image2)

**Figure 29.** Activity of lime (CaO) versus activity of alumina (Al$_2$O$_3$) diagrams appropriate to igneous-related mineralization. Calculated at 600°C using thermodynamic data from Helgeson and others (1978). A. Some limiting reactions involving solids and(or) fluids. B. Generalized distribution of major rock and metal types. See text for discussion.
PORPHYRY COPPER AND OTHER INTRUSION-RELATED MINERALIZATION IN MEXICO

Figure 30. Generalized composition-depth relationships among selected districts from table 2. This is not meant to imply that most districts are stacked. Depths of mineralization likely differ between districts. See text for discussion. A. Schematic distribution. B. Generalized metal distributions (same coordinates as in A).
gold systems may be stacked, it seems unlikely that most are stacked. Instead, economic mineralization may form at substantially different and restricted levels in the upper crust depending on the nature of the magma (water content, volume, and emplacement mechanism) and the host (reactivity, permeability, and readiness of deformation).

The general spatial distribution of igneous-related ore deposits in Mexico described above has been extensively treated by other investigators (Clark and others, 1982; Damon and others, 1983; Salas, 1975). This distribution is marked by a first order change from siderophile-element enriched ore suites in the west through chalcophile to lithophile element suites in the east. Because this corresponds to the eastward progression of the locus of magmatism from the Mesozoic through the mid-Tertiary, these characteristics also correlate with age. There is also a broadly comparable change from relatively felsic systems in northern and central Mexico to predominantly intermediate systems in southern Mexico. In addition to these regional changes, many regions show multiple mineralizing events of different types. For example, in northwestern Mexico (particularly Sonora) over 1,000 volcanic- and intrusive-associated occurrences range from Fe(-Cu-Au) skarns to Cu-(Mo-Zn) porphyries and skarns to Pb-Zn-Ag(-Cu-W) replacements to Au-Ag(-Cu) epithermal systems (Staude, 1994). Such temporal variations are as important as differences in province among northwestern, eastern, and southern Mexico.

The distribution of intrusion-related copper deposits shown in figure 31 illustrates the relationship between magmatism, mineralization, and level of exposure. Most deposits, and particularly those of Laramide age, are concentrated somewhat inland in western Mexico. To the east only scattered copper occurrences and no major deposits are described. Most Laramide copper deposits occur along a broad trend that corresponds to a belt of subequal exposures of Laramide volcanic and intrusive rocks (fig. 31; see also fig. 3). The central and southern portions of this trend are partly buried by the mid-Tertiary ignimbrites of the Sierra Madre Occidental. In western Sonora as in southern Mexico many Laramide intrusive systems are fairly deeply eroded, exposing equigranular stocks with little or no volcanic rock. Corresponding mineralization typically consists of small copper skarns with little alteration in associated igneous rocks. In Sonora these deeper exposures correspond to the region that underwent the greatest mid-Tertiary extension (Staude, unpublished data, 1994; Anderson and others, 1993; Stewart and Roldán, 1994). East of the Sierra Madre Occidental, Laramide stocks and volcanic rocks are sparse and copper mineralization has been noted in only a few centers. Older batholithic complexes in Baja California and Sinaloa lack significant copper mineralization except in the few regions where coeval volcanic rocks are preserved as near El Arco. Younger copper systems are known in southern Mexico where volcano-plutonic complexes have been moderately dissected, but the occurrence of por-

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**Preservation & Exposure**

- **Intrusion-related Cu district**
- **Mid-Tertiary volcanics**
- **Extrusive**
- **Intrusive**

Figure 31. Distribution of intrusion-related copper deposits compared to the distribution of volcanic and intrusive rocks. The middle Tertiary volcanic rocks are shown in light gray to emphasize their role as cover. The older igneous rocks have different timing relationships in different regions (see figs. 2-4 for details).
phry-type mineralization is problematic to the north along the less-dissected mid-Tertiary volcanic province of the Sierra Madre Occidental.

Provincial patterns in other intrusion-related deposit types are analogous to the copper-rich systems. For example, silver-rich "belts" in the Sierra Madre Occidental and areas to the east (Clark and others, 1982) largely correspond to regions of more abundant felsic magmatism and favorable host rocks: Volcanic rocks host vein-type silver-gold-lead-zinc deposits in the Sierra Madre Occidental and carbonate rocks host the replacement and skarn Zn-Pb-Ag-(Cu-F) deposits of the Mesa Central and Sierra Madre Oriental. In some districts such as San Francisco del Oro and Fresnillo, vein and replacement mineralization formed in contrasting host rocks as parts of single events (Grant and Ruiz, 1988; MacDonald and others, 1986). The tungsten province of Sonora and Baja California (Mead and others, 1988) corresponds to areas of continental basement, granitic magmatism, and relatively deep exposures.

Time-Space Controls: Preservation and Crustal Province

The depth of emplacement of intrusions and the depth of formation of related hydrothermal systems strongly impacts the energy and mass transfer processes that form ores as well as geological preservation-exposure potential. Level of exposure due to erosion, tectonic denudation, and burial subsequent to mineralization governs our knowledge of existing systems and our ability to infer the distribution of systems in the past. Depth is important primarily because pressure controls the nature of second boiling; the distribution coefficients of metals and ligands between melts, minerals, and fluids; the available thermo-mechanical energy; and the availability of external fluids (Barton and others, 1991b, see figure 27, p. 817; Burnham and Ohmoto, 1980; Hemley and others, 1992). There are two consequences: Different levels of emplacement will generate fluids with widely varying capacities to transport metals and generate wall-rock alteration, and different levels of exposure can reveal substantially different parts of the same types of systems. It seems likely that the distinctions between the major districts illustrated in this paper are the result of differing levels of economic mineralization in the former case and stacked systems in the latter. In addition, the abundance of deposits of all types should correlate with the abundance of magmatism. For example, the porphyry copper provinces of Sonora-Sinaloa and southern Mexico may represent the centers of their respective arcs, regions where the largest volumes of compositionally appropriate magmas were generated.

The metallogenic changes that take place from west to east in Mexico have been interpreted as a consequence of variable subduction angle (Clark and others, 1982) and differences in crustal composition (Camp and Coney, 1983). Although both factors may be significant, the superposition of different intrusion-related deposit types in the same region as in Sonora demonstrates that process controls, probably chemical, are important (compare Barton, 1990). Porphyry copper provinces extend across terrane boundaries, as from the Precambrian cratonic region of northern Sonora to the eugeoclinal terranes to the south and west (compare figs. 1 and 5). In roughly the same regions of the Sierra Madre Oriental, Tertiary intrusive systems include both copper-rich deposits associated with intermediate stocks and fluorine-dominated deposits associated with highly felsic stocks like Concepcion del Oro and Gualdaazar. Analogous juxtapositions elsewhere include dioritic and granodioritic porphyry systems such as La Verde and Ingúrain in Michoacan and porphyry copper and silver-base metal-tin-fluorine systems such as Malpica and Bolaños in the central Guerrero terrane.

Metallogenic patterns reflect the multiple factors involved in creating, exposing, and preserving intrusion-related deposits. Models based on only one or a few parameters are unlikely to fully explain the wide variations in the compositions, timing, and distribution of intrusion-related mineralization in Mexico. Lithospheric compositions provide a largely time-independent framework that fixes potential contributions to magmas and metal inventories as well as potential host rocks. Transient characteristics are also important in governing the compositions and evolution of magmatic and hydrothermal systems. These characteristics include thermal regimes state of stress, and availability of external fluids. Magma compositions are thus a function of many factors including an uncertain subduction contribution and the composition, thermal budget, and state of stress of the lithosphere (see, for example, Wilson, 1989). During emplacement, the compositions of external fluids and host rock influence chemical reactions and the state of stress and thermal structure influence permeability and fluid paths. Lastly, preservation and exposure limit our ability to interpret ancient and modern distributions because we can observe only the uppermost modern crust. Resolving magmatic and upper crustal controls from the broader effects of provincial controls is a continuing challenge that requires better definition of the temporal, spatial, and compositional interrelationships between tectonism, magmatism, and mineralization.

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