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Regional geology and ore-deposit styles of the trans-border region, southwestern North America

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ABSTRACT

Nearly a century of independent geological work in Arizona and adjoining Mexico resulted in a seam in the recognized geological architecture and in the mineralization style and distribution at the border. However, through the latter part of the 20th century, workers, driven in great part by economic-resource considerations, have enhanced the understanding of the geological framework in both directions with synergistic results.

The ore deposits of Arizona represent a sampling of resource potential that serves as a basis for defining expectations for enhanced discovery rates in contiguous Mexico. The assessment presented here is premised on the habits of occurrence of the Arizona ores. For the most part, these deposits occur in terranes that reveal distinctive formational ages, metal compositions, and lithologies, which identify and otherwise constrain the components for search of comparable ores in adjacent crustal blocks.

Three basic geological and metallogenic properties are integrated here to identify the diagnostic features of ore genesis across the region. These properties comprise: (a) the type and age of basement as identified by tectono-stratigraphic and geochemical studies; (b) consideration of a major structural discontinuity, the Mojave-Sonora megashear, which adds a regional structural component to the study and search for ore deposits; and (c) integration of points (a) and (b) with the tectono-magmatic events over time that are superimposed across terranes and that have added an age component to differing cycles of rock and ore formation.

Mineralization episodes are far more diverse than can be completely documented in this study. The important ones considered here are mainly those of the Paleoproterozoic, the Jurassic, the Cretaceous-Tertiary (Laramide), and the Tertiary. Examples are the volcanogenic massive sulfide (VMS) ores hosted in the 1.8-Ga volcanic province of central Arizona; the Nevadan-age (Jurassic) massive sulfide replacement and porphyry ores at Bisbee; the Laramide porphyries and skarns; the Cenozoic high-temperature, carbonate-hosted base- and precious-metal ores; the mid- and late Tertiary precious metal ores such as caldera-related epithermal veins; and the Tertiary and Quaternary weathering products that have resulted in the evolution of significant economic oxidized copper.

The potential for increased discovery and development of ores in the trans-border region is real and substantial. Lower Proterozoic gneisses of limited areal extent in western Sonora may host VMS or sedimentary exhalative (SEDEX) mineralization. Jurassic porphyry and massive sulfide replacement ores could be found in previously unidentified Jurassic outcrops or be buried in basins that resulted from tectonics related to the Mojave-Sonora megashear (MSM). Laramide porphyry and skarn deposits will

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continue to be found in Arizona and Sonora, but targets may be variably rotated and dismembered by Basin and Range faulting and/or buried under younger cover. More potential for orogenic gold deposits exists in those areas that exhibit the deeper erosional levels and an association to crustal-scale structures such as the MSM. The exploration potential for Cenozoic, high-temperature, carbonate-hosted replacement ores remains high, notwithstanding the challenges presented by the subdued surface expressions of alteration and weathering. Mid- and late-Tertiary ore types including precious-metal veins remain targets of interest. Lastly, the discovery rate for enriched ores and exotic copper and supergene zinc ores across the border region should improve where the geologic section and structural history are well studied and correlated.

INTRODUCTION

The realities of a contrast in the observed density of identified districts and the distribution of ore deposits across the border region between the United States and Mexico appear to be evident from the work presented here. Likewise, this contrast exists on a comparison of existing geological maps and data and the quality of integration of geologic features between the two regions. Questions arise from these disparities concerning whether they are geologically real (in frequency of occurrence of comparable ores and resource distribution), or whether they are an artifact of reporting, political attitudes and regulations, or indeed a reflection of the density of exploration efforts and financing as they evolved and changed over three centuries of activity. We propose that components of all of these issues may be involved and that the potential for increased discovery and development of ores in the trans-border region is real and substantial.

This paper focuses on geological and mining aspects and addresses the nature of the ores and ore districts based on their distribution in space and time. The basis of our comparisons is established on the premise of the association of specific ore styles with specific rock assemblages of specific ages and distinct crustal affinities. Comparison of time-rock slices across the border regions is achieved from a newly integrated GIS (Geographic Information System) geologic correlation database (compiled and adapted with permission from Chernoff et al., in prep.). The comparison of ore time and style is extracted from map information of mines and districts in Arizona from Keith et al. (1983). Their work is based upon ages of ore deposits and rock sequences related to some 260 districts, including more than 5000 named mines or claim groups.

REGIONAL GEOLOGICAL CHARACTERISTICS AND CONTRASTS

The geology of the two regions (Arizona in the USA and the states of Baja California, Sonora, and Chihuahua in Mexico) are compared separately at various scales and bases. However, the generalized time-unit map of Figure 1 (adapted from Chernoff et al., in prep.) provides a consistent geologic base across the border region. This map reveals the three important geological styles present in Arizona, which are separated by generally northwest-trending borders. The Colorado Plateaus compose the northeastern third of the state and comprise generally flat-lying Mesozoic and upper Paleozoic strata at elevations of about 6000 ft (2 km). These sedimentary rocks are bordered to the southwest by sections of juxtaposed Proterozoic and lower Paleozoic rocks of the Central Mountain Province (Transition Zone).

The contact of Plateau and Central Mountain rocks is not generally faulted, but reflects past uplift and erosional removal of Paleozoic strata from the Central Mountain area followed by tectonic lowering of the Central Mountain rocks so that elevations generally decrease southwestward away from the Plateau. The transition zone is adjacent to the Basin and Range Province whose elevations gradually lower to near sea level in the southwestern corner of Arizona. The mountain ranges of the Basin and Range province represent faulted and folded strata of Proterozoic, Paleozoic, Mesozoic, and Cenozoic ages. Within the Basin and Range province of Arizona, planimeter measurements reveal that only about 25% of the surface exposes pre-Pleistocene rocks. All of these time-units in Arizona are underlain by Proterozoic basement. 1.7-1.8-Ga, greenstone-dominated successions in the Yavapai Province of northwestern Arizona contrast with the 1.6-1.7-Ga, clastic-dominated successions in southeastern Arizona.

An important aspect of the geology the Basin and Range is that the lower (older) parts of the geological column gradually deepen to the south and are ultimately covered by thickening volcanic strata, alluvial deposits, and soils. This has resulted in the burial of many older ores located in this province. In conterminous Mexico, these same "ore rocks" of Arizona are also largely buried beneath Miocene and younger cover. The reader is referred to Zürcher (2002) for an in-depth account of the regional geology of northwestern Mexico. The geology across the border into northwestern Mexico is represented by scattered outcrops of Proterozoic basement in the North American and Caborca terranes (Campa and Coney, 1983). Various interpretations and revisions of this terrane discrimination have been proposed, but resolution of basement boundaries on the basis of contrasting tectono-stratigraphic units is well accepted (Fig. 2).

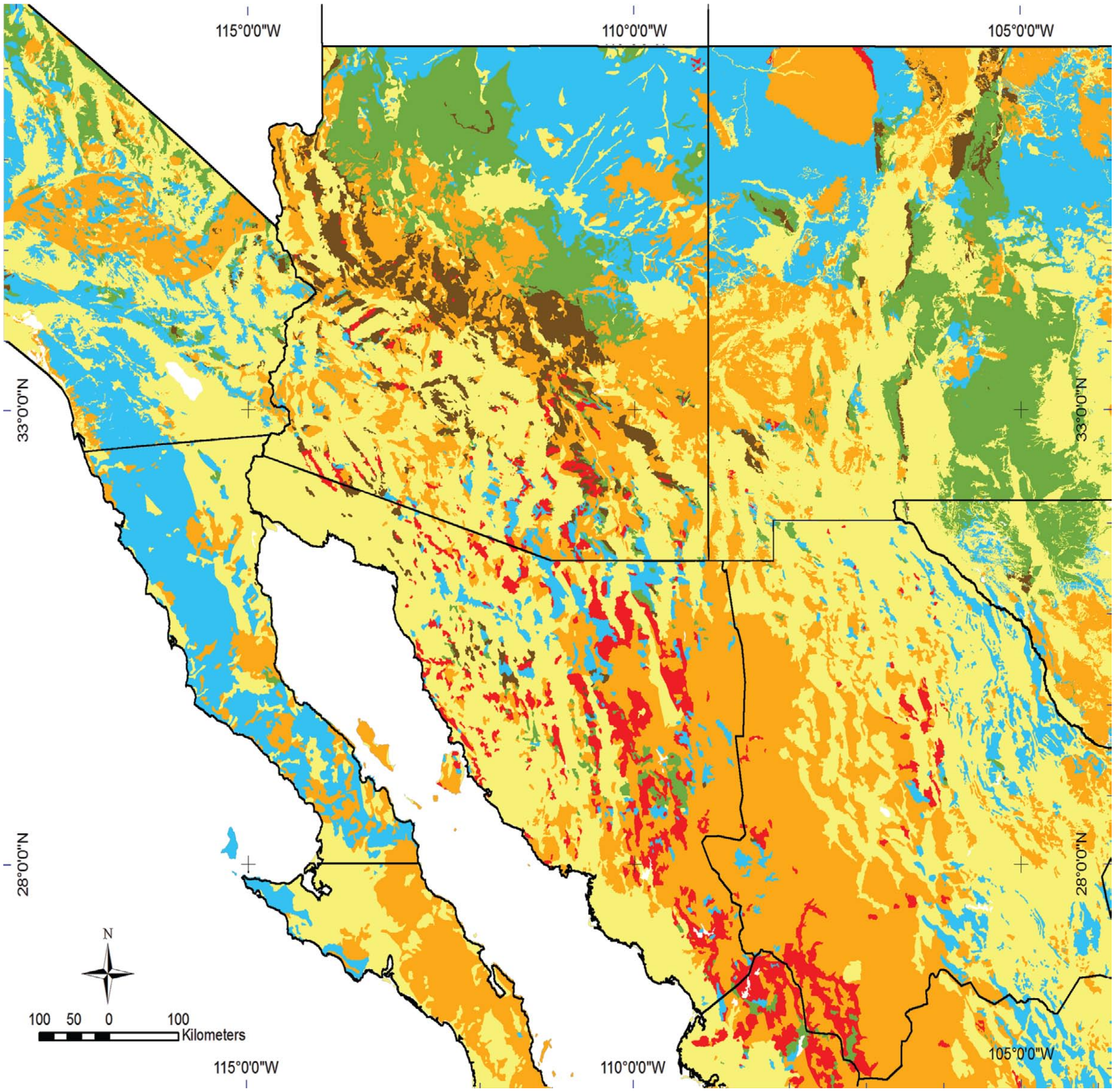

Figure 1. GIS geological time-unit map of a portion of the USA – Mexico border region (compiled and adapted from Chernoff et al., in prep.). Brown = Proterozoic; Green = Paleozoic; Blue = Mesozoic; Red = Cretaceous-Tertiary; Orange = Tertiary; Yellow = Quaternary.

The oldest rocks dated in the Caborca terrane are amphibolite grade volcanosedimentary rocks dated at 1.7-1.8 Ga, whereas the oldest units identified in the adjacent North American or Chihuahua terrane are metasedimentary formed from 1.6 to1.7 Ga (Anderson and Silver, 1981). Notwithstanding the marked contrast in exposure level and metamorphic grade, Precambrian basement in the Caborca terrane would appear to be similar to that in the Yavapai province of northwestern Arizona. Similarly, Precambrian basement in the Chihuahua terrane correlates well with Proterozoic rocks in southeastern Arizona. As in northern Arizona, Paleozoic sedimentary rocks are more widely exposed over the Caborca and Cortez terranes, rather than over the Proterozoic Mazatzal (Pinal Schist) basement of southeastern Arizona (Fig. 2), where they are overlain by younger strata. Upper Paleozoic exposures become more widespread to the east in New Mexico. This time-related style of off lap and on lap of rock systems persists across the Phanerozoic geological column and is in part related to the many uplift and associated erosional episodes that the region has experienced over time.

Similarly, Triassic and Lower Jurassic sedimentary and vocaniclastic rocks predominate in the Colorado Plateau, adjacent New Mexico, and Caborca terrane, but less so over the Mazatzal Province in southeastern Arizona and Sonora. Rocks of the Middle to Upper Jurassic volcanic arc transect Proterozoic basement of the Yavapai, Mazatzal, Chihuahua, and Caborca terranes from California and southwestern Arizona across the border into Mexico. The Paleozoic and lower to middle Mesozoic strata are overlain by Lower Cretaceous, dominantly clastic strata that are widespread in

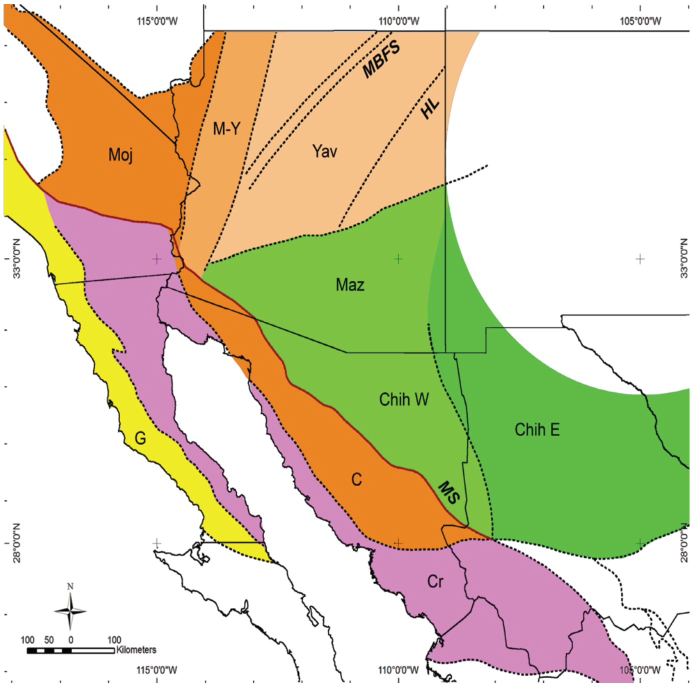

Figure 2. GIS tectono-stratigraphic terrane map of Mexico (after Campa and Coney, 1983) with Precambrian basement boundaries (after Wooden and Miller, 1990) and salient magnetic trends in Arizona (after Sauck and Sumner, 1971). Chih E = Proterozoic Eastern Chihuahua Terrane; Chih W = Proterozoic Western Chihuahua Terrane; Cr = cratonic-accreted composite Cortez Terrane; G = accreted Mesozoic Guerrero Terrane; Maz = Proterozoic Mazatzal Province; Moj = Proterozoic Mojave Province; M-Y = Proterozoic Mojave-Yavapai transition; Yav = Proterozoic Yavapai Province; MS = Mojave-Sonora Megashear; MBFS = Mesa Butte fault system; HL = Holbrook line.

Chihuahua and southeastern Arizona and are believed to be related to the opening of the Gulf of Mexico. These strata in turn are overlain by Upper Cretaceous continental sedimentary units in northern Sonora and southernmost Arizona, as well as in northern New Mexico. The dominantly sedimentary Cretaceous rocks in the mainland overlie cratonic basement, whereas Cretaceous sedimentary, metamorphic, and igneous rocks in western Baja California Norte and California are related to the accreted Guerrero island arc terrane.

Rocks associated with the Laramide continental arc transect all older basement types across the western United States and Mexico. Domains with significantly more plutonic rather than volcanic strata are exposed in the relatively more exhumed regions of southern and northwestern Sonora, as well as western Arizona.

Laramide rocks are largely covered by middle- to late-Tertiary volcaniclastic successions across the Sierra Madre Occidental (SMO) province. These Oligocene-Miocene continental arc strata are in turn overlain on the western side of the SMO and Baja California Sur by alkalic-dominated igneous rocks related to the opening of the Gulf of Cortez, which began around 12 Ma.

A portion of the Magnetic Anomaly Map of North America covering the border region (Bankey et al., 2002) is shown on Figure 3. The superimposed Precambrian province boundaries are demarcated well by magnetic highs in Arizona, where Precambrian basement is present at shallower levels in the crust. In northwestern Mexico, where Precambrian exposures are far more limited and deeply buried, the correspondence of magnetic anomalies and Proterozoic basement boundaries is not as obvious. However, what is evident is the marked "boxwork" magnetic fabric, which mimics the pattern of Phanerozoic sedimentary basins as blue troughs, and, most prominently, the batholiths of Baja California as a red ridge.

The Mojave-Sonora megashear

The Mojave-Sonora megashear is a component of northern Mexico's geological architecture that has displaced pre-Upper Jurassic depositional features along a discontinuity that points to a left-lateral transcurrent fault with approximately 800 km of displacement. Silver and Anderson (1974) and Anderson and Silver (1979, 2005) recognized and proposed this geological discontinuity on the basis of contrasts in U-Pb ages of intrusions into different terranes or basements that were juxtaposed along a fault exposed in the Mojave Desert, where a 5-km wide zone of mylonite separates Triassic granitoids and Precambrian gneisses from Jurassic volcanic and clastic rocks. Their finding is compatible with the accepted Late Jurassic east- to east-southeast-directed Farallon plate motion (i.e., Engebretson et al., 1985)

Figure 4 shows the relationship of basement ages, with the Sonora-Mojave megashear marking the boundary between the Caborca block (ca. 1.7-1.8 Ga) and the Chihuahua or North American block (ca. 1.7-1.6 Ga).

The exact location of the Sonora-Mojave megashear in Mexico is difficult to establish because the area was affected by subsequent westward-directed overthrusting during the Laramide, which resulted in imbrication of Cretaceous, Jurassic, and Precambrian rocks into stacks that overlie and conceal much of the strike length of the megashear, and the same region also was affected by crustal extension (e.g., Stewart et al., 1998). Vigorous debate remains on many aspects of this feature (Anderson et al., 2005). However, geologic evidence such as the Lower Cretaceous alluvium-filled extensional basins of the Glance Conglomerate, which would have formed during and after the time of development of the Megashear (Anderson and Nourse, 2005), certainly indicate the presence of a related and important regional-scale structural event. Notwithstanding the ongoing debate concerning many of the geological aspects of the megashear (Anderson et al., 2005; Bassett and Busby, 2005), its degree of relevance to first-order and second-order controls on the formation and distribution of ores in northern Mexico should be considered.

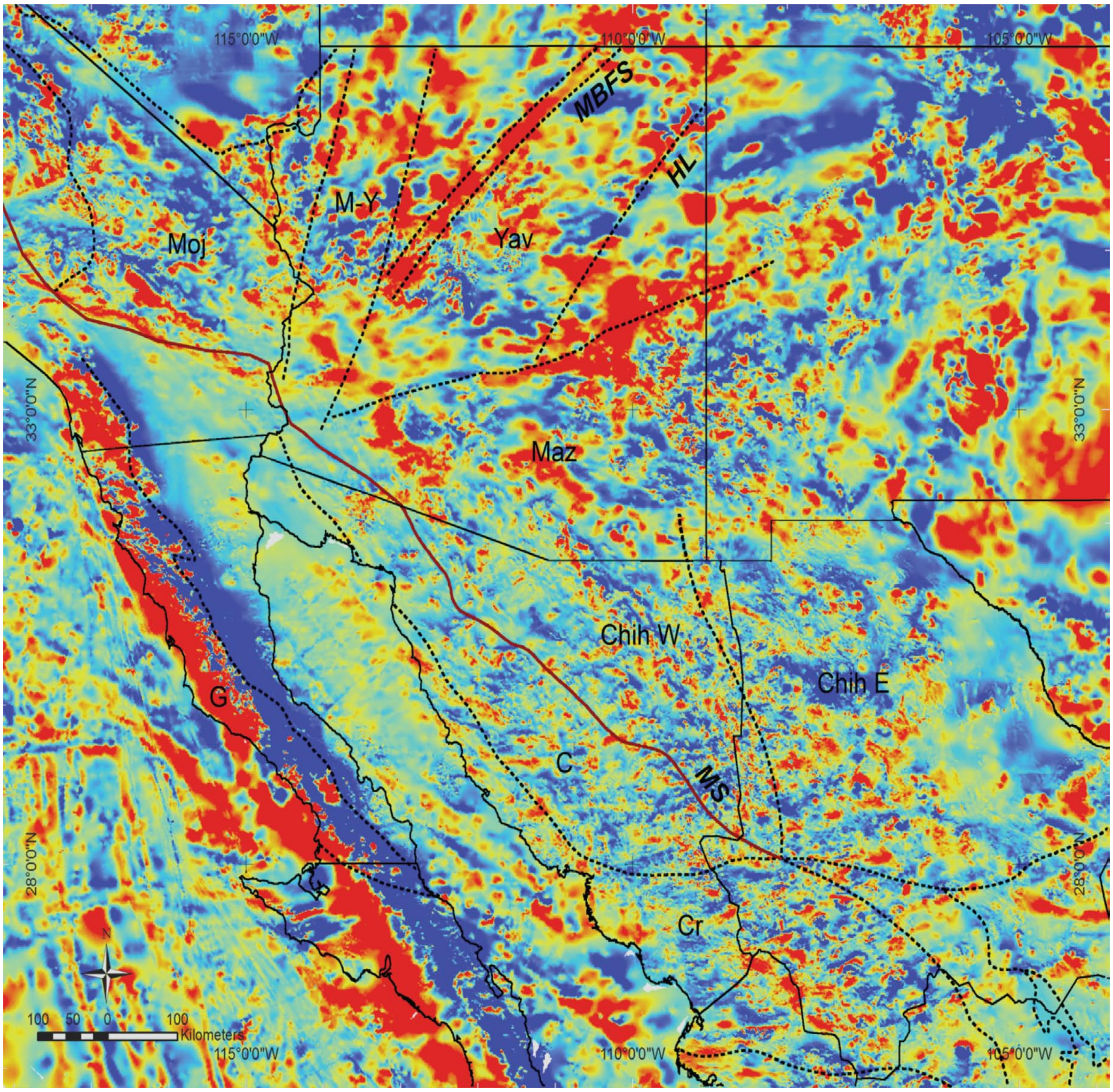

Figure 3. USA – Mexico border region section of the Magnetic Anomaly Map of North America (Bankey et al., 2002). The dotted black lines mark terrane boundaries (see Figure 2), which closely trace magnetic anomalies. The Mesa Butte fault system (MBFS) and Holbrook line (HL) boundaries are based on the Residual Aeromagnetic Anomaly Map of Arizona after Sauck and Sumner (1971) and Sumner (1989).

SPACE, TIME, AND ORES OF THE TRANS-BORDER REGIONS

The widely recognized phenomenon of association of ores and ore-deposit styles with specific rocks or rock groups has been incorporated into notions of the metallogenesis of southwestern North America (Burnham, 1958; Wisser, 1960; Ruiz, 1986; Silberman et al., 1988; Titley, 1991, 1992, 2001). The observations and discussions presented here are based on the premise that the consanguinity revealed in certain ores and rocks of Arizona, California, and New Mexico, in conjunction with their tectonic histories, should reveal regions of resource potential in certain rocks in parts of adjacent Mexico. The grouping of some index rocks of Arizona is shown in Figure 5 and their relevance to ores is considered in the following paragraphs.

The relevant elements of the geological architecture of Arizona are also visible and accessible in northern Mexico. As in Arizona, these ore-related terranes are variably affected by subsequent extension and/or burial (Stewart et al., 1998) and thus are not exposed over large areas. The tectonic episodes associated with deposition of the ore-related rocks resulted in the evolution of a broad spectrum of metallization and ore styles across the region. A listing of most of the important styles is shown in Table 1. The contrasting levels of exposure of both Precambrian and Phanerozoic ores have influenced the constraints on style and classification of epigenetic ores, because the entire original vertical and lateral zoning is commonly not visible. This is especially the case with vein- and intrusion-

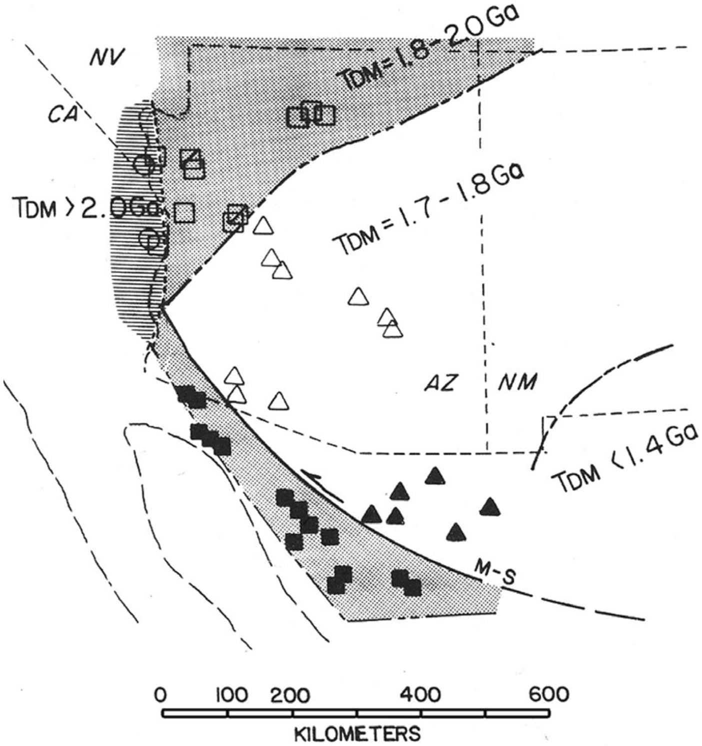

Figure 4. Map of basement ages (Titley, 1995b) based upon TDM data in the United States (Bennett and DePaolo, 1987; DePaolo and Farmer, 1984) and U-Pb dates in Mexico (Anderson and Silver, 1981; Anderson et al., 2005). Open squares = 1.8-2.0 Ga TDM ages; Open triangles = 1.7-1.8 Ga TDM ages; Solid squares = 1.8 Ga U-Pb ages; Solid triangles= 1.7 Ga U-Pb ages; M-S, Mojave-Sonora Megashear. The basement boundary in northwestern Arizona is from Chamberlain and Bowring (1990).

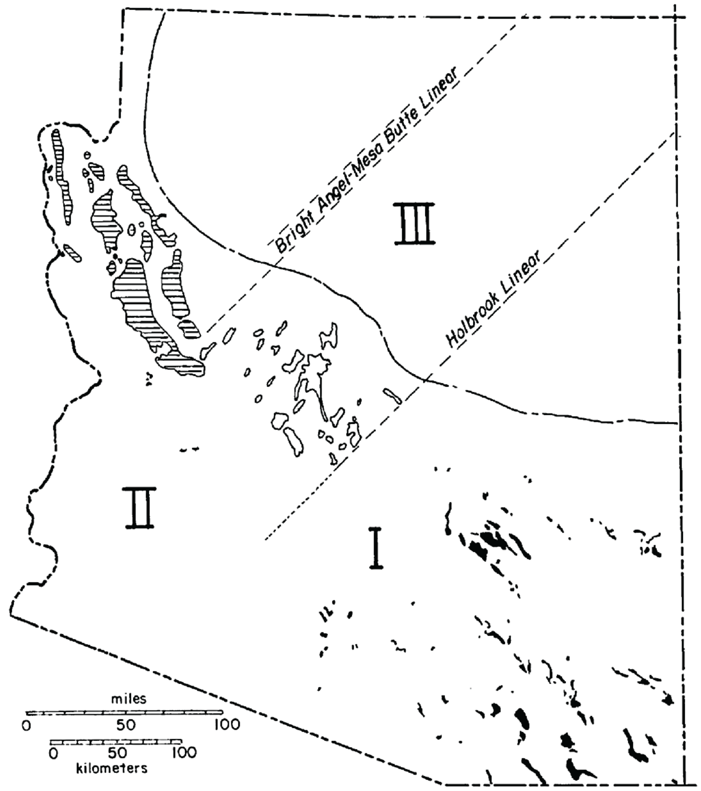

Figure 5. Map of relevant outcrop distributions over contrasting basement rocks in Arizona (from Titley, 1987). Domain I shows outcrop patterns of Paleozoic strata that are floored by ca 1.65-1.7 Ga argillites; Domain II is floored on its southeast margin by ca. 1.75-1.8 Ga greenstones, and to the northwest by probable 1.8-2.0 Ga metamorphic strata. Mesozoic strata mostly overlie Domain III. Northeast-trending boundaries represent the Mesa Butte and Holbrook lines derived from the Residual Aeromagnetic Anomaly Map of Arizona (Sauck and Sumner, 1971; Sumner, 1989).

related systems where we view and can only classify these zoned ores on the basis of the characteristics that are exposed. The extension of such classifications into other regions such as northern Mexico must be kept in mind before relationships and similarities to ore types can be compared across the border.

Both Proterozoic and Phanerozoic episodes of stratabound mineralization are episodic and related to tectonic cycles (Titley, 1993). For the most part, districts in Arizona (which may contain several separate ore deposits) are centered upon or related to intrusions and/or volcanic activity. In districts of Laramide or older age in Arizona and New Mexico, the effects of deep weathering and supergene enrichment, or post-ore tectonic disassembly of primary mineralization, are significant (Cook, 1994; Cook and Porter, 2005). The metal budgets in certain Proterozoic (and also Phanerozoic) ores appear to result not only from tectonic effects, but also from differences in the composition of the host rock. These ore styles are summarized in Table 2.

TABLE 1. Overview of Time and Style of Arizona Ore Deposits

PRECAMBRIAN ORES	PHANEROZOIC ORES
Volcanogenic Massive Sulfides	**Uranium Ore Pipes**
Syn-Sedimentary Exhalative Ores	Sandstone Uranium Ores
Banded Iron Formations	**Porphyry Systems**
Layered Mafic Intrusions	**Base-Metal Skarns**
REE? Metallization of Intrusions	**High-T Carbonate Replacement Ores**
Granite-Related Sn and W	**Epithermal Base- and Precious-Metal Veins**
Gold Veins	**Supergene Oxidation and Enrichment Ores**
	Placer Ores

TABLE 2. Principal metallogenic epochs across Arizona and contiguous regions

METALLOGENIC EPOCH	ORE STYLES
Proterozoic (ca.1.78-1.82 Ga)	**Volcanogenic**, SEDEX, and banded iron formation ores
Proterozoic (1.74, 1.71, 1.6, 1.4, 1.1 Ga)	Contact and **vein Au**, W, U, Fe, (Sn?) ores and LMI(?) metallization
Mesozoic (240, 200, 185, 150 Ma)	**Intrusion-centered**, caldera(?)-related base and precious metal, and **U pipe** ores
Laramide (80-45 Ma)	**Intrusion-centered**, **base- and precious-metal replacement**, and vein ores (Cu, Au, Mo, W)
Mid-Tertiary (35-15 Ma)	**Zn-Pb-Ag replacement and precious-metal vein ores**
Basin and Range tectonism?	Detachment-related base- and precious-metal mineralization
Pliocene and Quaternary	**Oxidized base-metal ores related to weathering and epeirogenic uplift** and placer gold

PRECAMBRIAN ROCKS AND METALLIZATION

Comparison of the Precambrian district map (Titley, 1987) of Figure 6a with the Precambrian outcrop map of Figure 5 illustrates how Precambrian mineralization in Arizona is controlled by host-rock composition. The new GIS compilation in Figure 6b shows that Early Proterozoic volcanic (orange) and plutonic (red) protoliths crop out beyond the domain that lies between the Holbrook line and the Mesa Butte fault system, where most Precambrian mineral districts are located. However, outside of this domain, Early Proterozoic igneous and potentially also their metamorphic time-unit equivalents (most of the outcrops colored lavender in Figure 6c) are not known to host significant Precambrian mineralization. Thus, host rock composition does appear to have a fundamental effect on metal endowment.

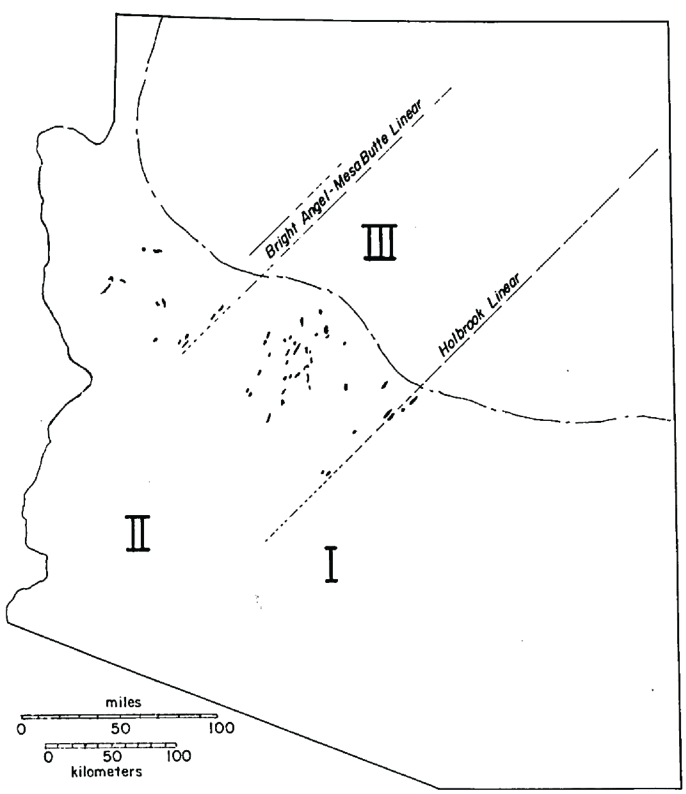

Figure 6a. Map of Precambrian mineral districts in Arizona (Titley 1987, adapted from Keith et al., 1983). Note the absence of Precambrian districts southeast of the Holbrook line.

The Precambrian ores in the Yavapai province in central Arizona have been described and discussed by Donnelly and Hahn (1981) and Lindberg (1989) largely in the Jerome area, and by Conway el al. (1986) to the west in the Bagdad area. The dominant economically important ore deposits are those of volcanogenic massive sulfide ores (VMS; Franklin et al., 1981) at Jerome and environs, and VMS or sedimentary exhalative ores (SEDEX) at Bagdad (Conway et al., 1986). The ages of these ores of ca. ~1.7 Ga place them within a coeval worldwide family of similar stratabound, volcanogenic, and sediment-hosted base- and precious-metal deposits (Titley, 1993).

Both VMS and SEDEX ores are parts of Proterozoic volcanic successions and in both areas, the ore controls are, generally, stratigraphic (Anderson, 1968a). These petrological controls on VMS ores and their importance stem from characteristics recognized in the Miocene of Japan (Horikoshi, 1960) and the Archean of Canada (Spence and de Rosen-Spence, 1975), where mineralization concentrates on tops of felsic volcanic rocks in successions of alternating felsic and mafic compositions. The greenstones (Anderson and Silver, 1981) hosting the Arizona Proterozoic massive ores across the belt of Yavapai strata have been separated and assigned different nomenclature at Bagdad and Jerome, for example, but the general ages and cyclical changes in composition of ore-related successions are mostly the same. The stratabound and stratiform SEDEX ores at Bagdad occur in a strongly faulted and overturned section of these rocks.

The Proterozoic rocks at the western edge of the central mountains of Arizona, shown separately in Figure 5, reveal a greater degree of metamorphism, to amphibolite and granulite facies, than those of the Bagdad-Jerome interval. Nonetheless, they retain a metallogenic signature and host rock petrochemistry closely similar to that of the Bagdad and Jerome areas, for example in the Hualapai Mountains (Lindberg, 1989). In all of the recognized occurrences of VMS ores, iron cherts form a widespread cap on the systems. The chemistry and the stratigraphy of these rocks have been described by Anderson

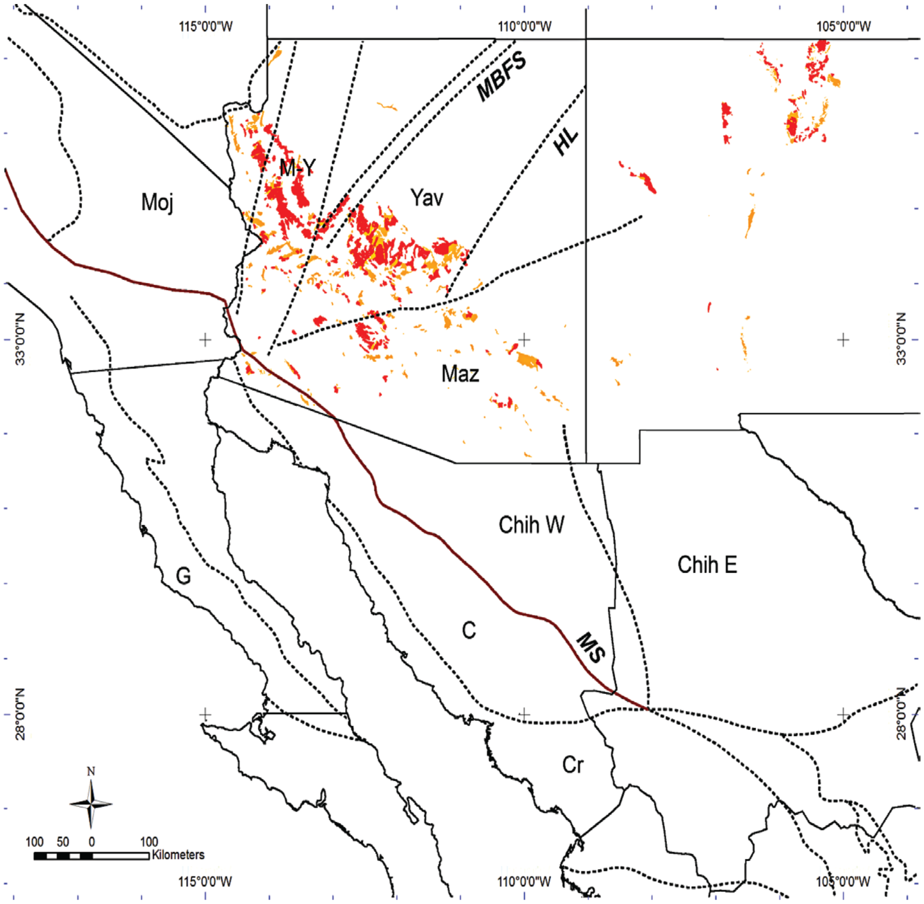

Figure 6b. GIS map of Early Proterozoic intrusive (red) and volcanic (yellow) rocks of the USA – Mexico border region (compiled and adapted from Chernoff et al., in prep.) with superimposed tectonic boundaries (see Figure 2). Note outcrops of similar rocks that lie outside the Yavapai and Mojave-Yavapai domains.

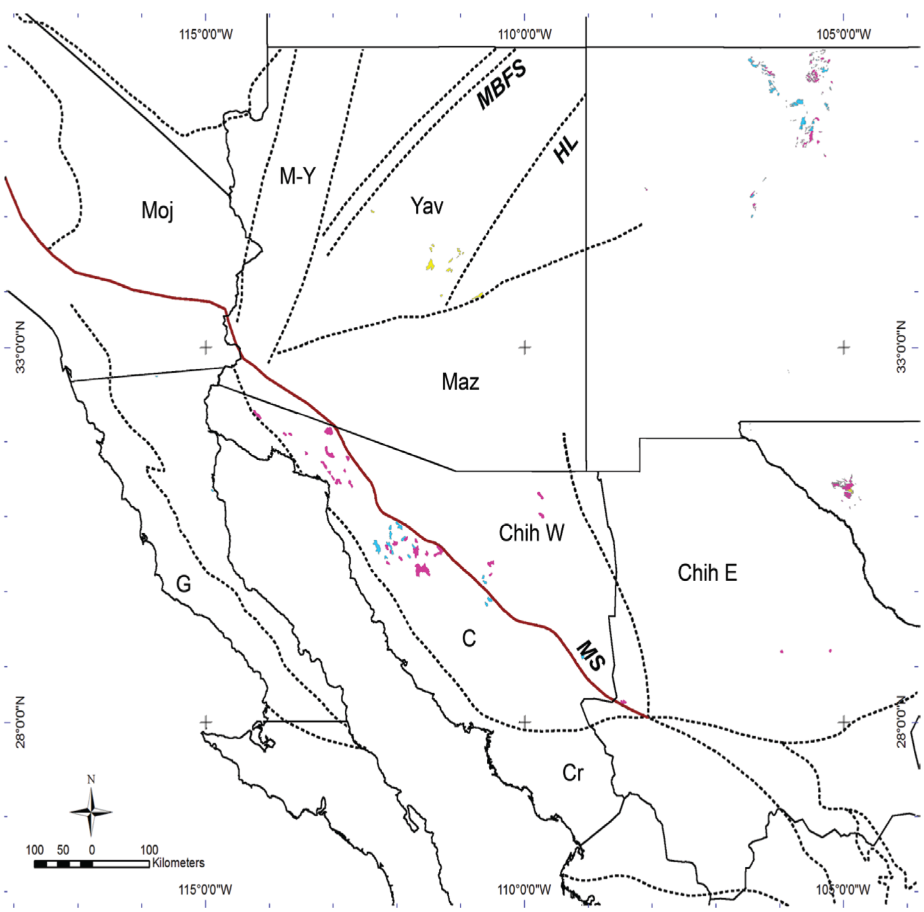

Figure 6c. GIS map of Proterozoic metamorphic (lavender), marine (blue) and continental (yellow) sedimentary rocks of the USA – Mexico border region (compiled and adapted from Chernoff et al., in prep.). Most metamorphic outcrops are of Early Proterozoic age. Rocks in Arizona are Apache Group strata of ca 1.2 Ga.

(1968b). The extension of metamorphic and potentially time-equivalent rocks into northern Mexico is shown in Figure 6c, where they lie in the Caborca block on the southwestern side of the megashear. The terrane displacement is consistent with interpretations of the presence of rocks of the Yavapai Group into this part of Mexico (Nourse et al., 2005).

Implications

Whereas the exposures of these rocks in northwestern Sonora are limited in area and extent, the gneisses (amphibolite/granulite) still merit study to seek lithologic indicators that may be preserved, such as the gold-bearing iron formations that attend the centers of mineralization of VMS and SEDEX ores in central Arizona. Included in such assessments are the added possibilities, exemplified in central Arizona, of gold-quartz veins and tungsten ores.

Shown also in Figure 6b are exposures of sedimentary strata of Late Proterozoic age. In the Caborca region, these rocks include latest Precambrian units that do not correlate temporally with the Apache Group in central Arizona (i.e., Livingston and Damon, 1968). Notwithstanding the contrasts, their potential similarities may reveal comparative histories of formation. The metallogenesis of the Arizona Apache Group has been described by Wrucke et al. (1986) and includes modest-sized deposits of asbestos, ironstone, and uranium.

Both lower and upper Paleozoic successions in the border region are almost exclusively sedimentary, indicating that Paleozoic orogenic events identified elsewhere in North America did not affect or are not well preserved in Arizona or northern Mexico. As a result, significant mineralization of this age has not been identified.

MESOZOIC ROCKS AND METALLIZATION

Suites of mid-Mesozoic intrusive and volcanic rocks occur in the southwestern part of Arizona in a belt that transects the international boundary. The age ranges of these strata extend from ca. 150 to 185 Ma. They comprise, at the levels currently exposed, caldera-related silicic to andesitic subaerial volcanic rocks and local alkaline igneous suites. Intrusive rocks are commonly present but their relation to volcanic units is speculative in many instances. The Jurassic suites are part of a convergent tectonic setting, illustrated in Figure 7 (from Dickinson, 1989). The Upper Jurassic Mojave-Sonora megashear is shown truncating this mid-Jurassic arc.

Volcanic rocks of this event are widespread in the ranges of southernmost Arizona. Figure 8 shows the base-metal districts associated with Jurassic rocks in Arizona, where they are commonly associated with weak mineralization in, apparently, deeply weathered systems. Anomalous amounts of molybdenite and tungsten are also known to occur in related intrusions.

However, the important exception in Arizona is the ore system preserved at Bisbee (Figure 9), which illustrates the ore potential of rocks in this magmatic belt. At present, conclusive evidence for the age of Bisbee remains uncertain. The published K-Ar dates (Anderson, 1968b) of 163 Ma at Bisbee

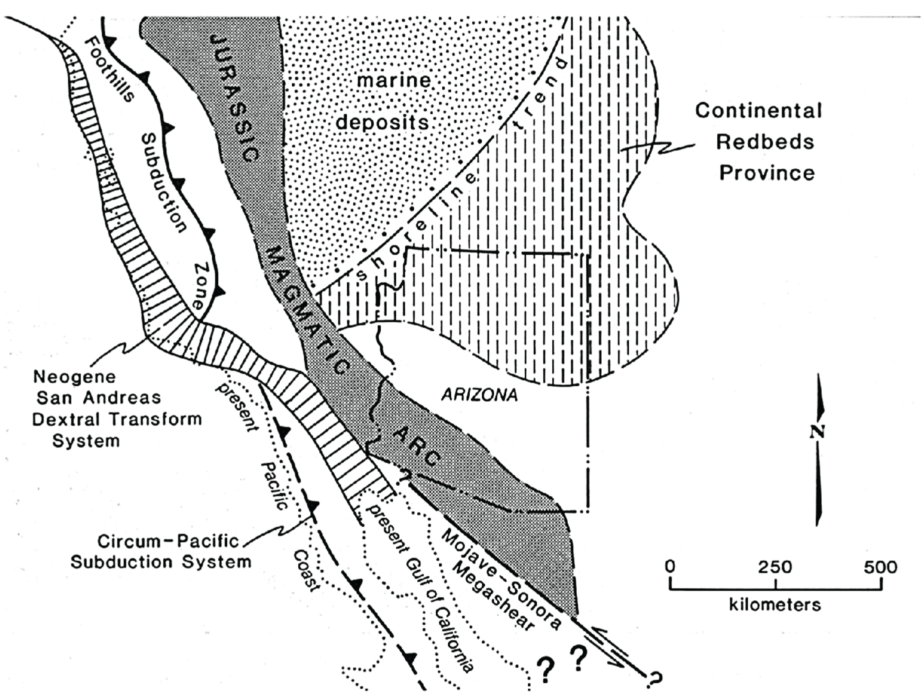

Figure 7. The Jurassic magmatic arc of Dickinson (1989); see also Coney (1978). Exposed intrusions and volcanic rocks of this arc straddle the international border (compare with Figure 10).

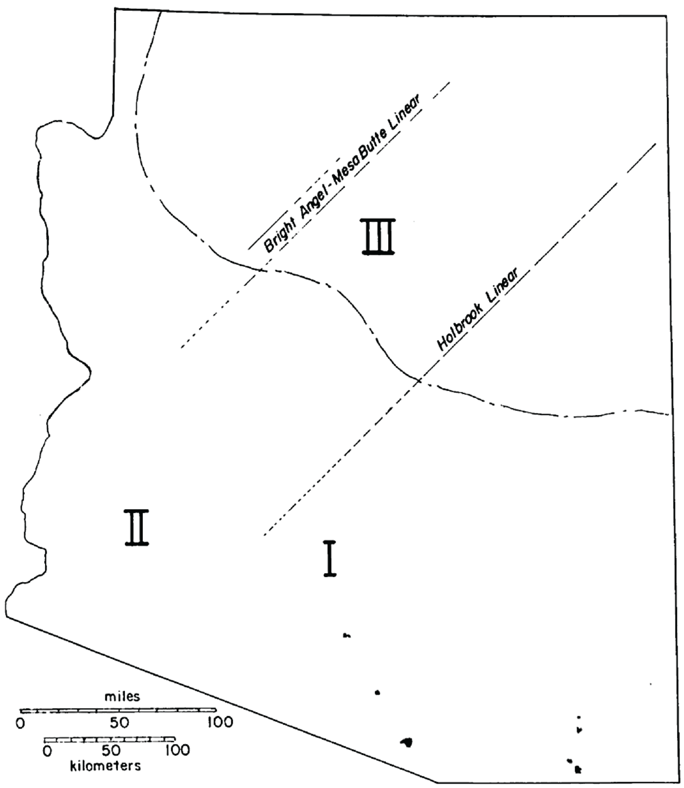

Figure 8. Map of Jurassic base-metal districts in Arizona (after Keith et al., 1983).

correspond with fragments of oxidized ores found within the Glance Conglomerate (Lower Cretaceous?) for which, in turn, an age of 165 Ma has been inferred (Busby et al., 2005). More recent U-Pb ages on igneous rocks indicate an age of approximately 200 Ma for Bisbee, as well as for some rocks of the Courtland-Gleason district (Lang et al., 2001). Notwithstanding the deeply buried and complex relationships and uncertain ages of igneous rocks associated to this deposit, age relations still place it comfortably within the belt of Jurassic igneous activity.

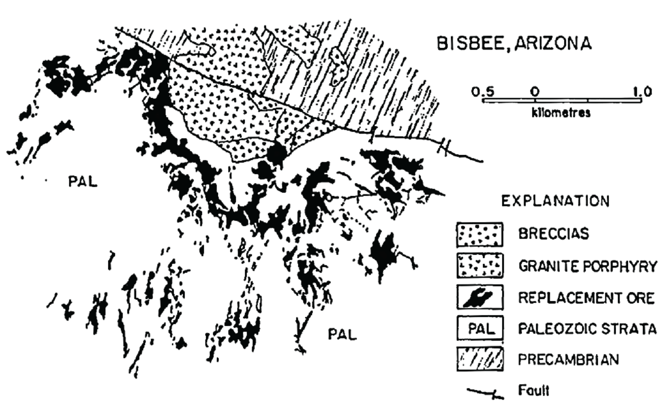

Figure 9. Map of the rocks and ores at Bisbee (after Bryant, 1966).

Implications

The ores of Bisbee (Bryant, 1966) are "world class" and represented metal production valued at more than US$1,000,000,000 by 1948. Bisbee, which was covered by Glance Conglomerate and exposed only as an accident of erosion of canyon fill, is a massive sulfide carbonate-hosted replacement associated with a high-level porphyry copper center that exhibits high-sulfidation characteristics based on mineralogy. The presence of post-ore cover by the basal conglomerates of the Glance Conglomerate, which appear to have been deposited in separate extensional basins related to the megashear (Bassett and Busby, 2005), suggests that the megashear evolved at about the time of emplacement of the intrusions and ores at Bisbee. The distribution and genesis of the Glance Conglomerate thus lends to a target concept that involves identification of extensional basins within the Jurassic magmatic arc. The placement of these basins with the aid of magnetic data (i.e., Figure 3), for example, could potentially be used as an exploration guide not only in Arizona but in northern Mexico as well.

The map of Jurassic igneous rocks shown in Figure 10 depicts the areal extent of these rocks in Arizona and Sonora. Jurassic rocks in Baja California are part of a potentially independent island arc and host the 165 Ma El Arco porphyry system (Valencia et al., 2006). Notwithstanding that many exploration groups have unsuccessfully sought another Bisbee in mid-Mesozoic mining districts of southeastern Arizona, it is our view that there exists significant potential that should be critically considered within this block of crust in both Sonora and Arizona, particularly as previously miss- or un-identified Jurassic outcrops continue to be located.

CENOZOIC ROCKS AND METALLIZATION

Included in the discussions of the Cenozoic are ores of the Laramide of Arizona and Mexico, even though the ages of ores of the region span an interval from within the Upper Cretaceous (ca. 80 Ma) to the lower Tertiary (Eocene, ca. 45 Ma). These age ranges have been widely discussed and there remain some controversies, but they do document temporal constraints of kinds of tectonic and intrusive activity in North America.

Mid- and late-Cenozoic rocks are dominant across southern and southwestern Arizona and contiguous Mexico, where they constitute the much of the outcrop. Volcanic lithologies are pervasive and often associated with small plutons. Mid- and late-Cenozoic ores constitute the best exposed mineralization and manifest a great variety of evolutionary styles. The search for these ores involves challenges of recognition of outcrop as well as application of remote methods to explore beneath cover. These varied ores are considered here in temporal, lithologic-orogenic, and deposit-type contexts.

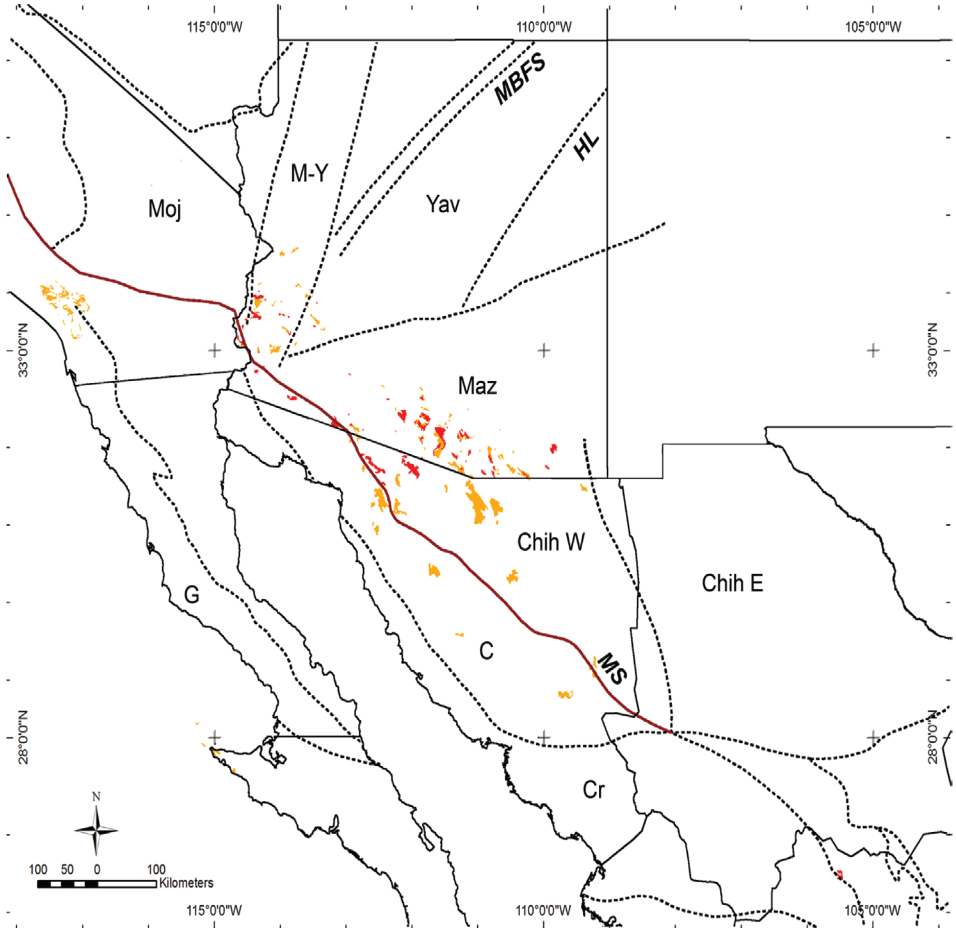

Figure 10. GIS map of Jurassic igneous rocks of the USA – Mexico border region (compiled and adapted from Chernoff et al., in prep.). Intrusive = red; volcanic = orange. The bold line is the Mojave-Sonora Megashear.

Laramide rocks and ores

Laramide rocks and associated ores are widespread across the trans-border region and have composed the basis of extraordinary mineral wealth (Titley, 1982; Barton et al., 1995). Porphyry and skarn are the dominant epigenetic ore styles related to both intrusive energetics as well as metamorphic processes, but mineralization occurs as complex base- and precious-metal veins as well. The Laramide orogenic event, as considered here, is bracketed in the time between 80 and 45 Ma ago and was a time of extensive regional volcanism with an attendant rise in crustal heat. Widespread volcanic rocks and intrusions emplaced around 65 Ma ago coincide with changes in age, thickness, and density of the lithosphere being subducted beneath the western margin of the North American plate (Engebretson et al., 1985).

A map of Laramide districts of Arizona is shown in Figure 11. The map reveals a larger concentration of districts in Domain I where the Proterozoic basement is largely composed of siliciclastic rocks. Districts are sparser in Domain II where the effects of Laramide events overprint older mineralization episodes and appear to be more eroded or else covered by younger rocks. Figure 12 shows the GIS map of Laramide rocks in the larger trans-border region.

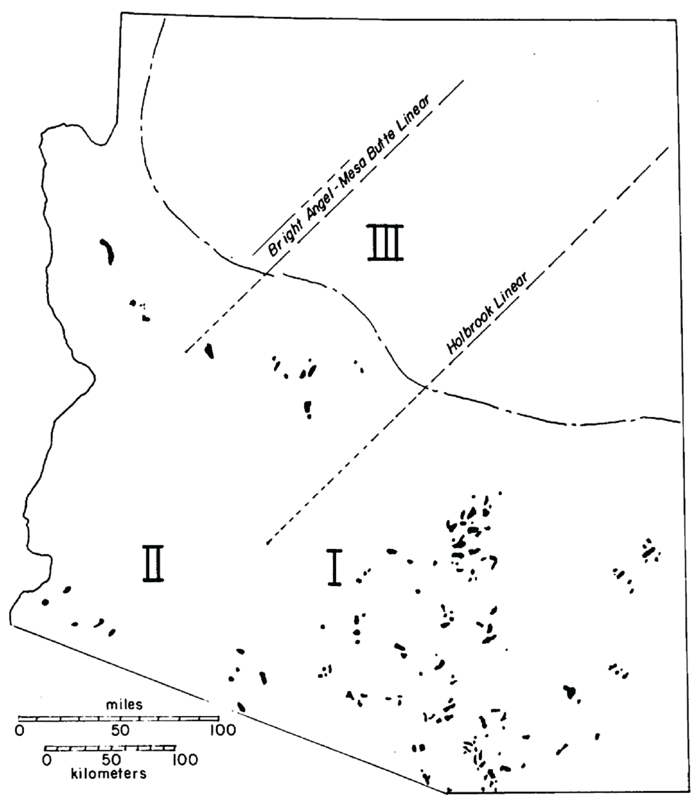

Figure 11. Map of Laramide mineral districts of Arizona (Titley 1987, adapted from Keith et al., 1983).

The Laramide styles of mineralization are dominated by the presence of igneous centers, as well as structural-tectonic features that may be related to the dynamics of the east-northeast-oriented subduction of the Farallon (Pacific) plate. Tertiary erosion has removed as much as 2-3 km from the original tops of many Laramide systems, but nonetheless, some remain deeply buried as a result of complex Basin and Range faulting (Staude and Barton, 2001). The widespread exposures in Arizona have led to intensive studies, and there is a wealth of knowledge reported in more than a half-century of publications, of a number of the ores that have served as worldwide examples of intrusion-centered mineralization. The reader is referred to Titley and Anthony (1989), who have published an overview of the Laramide ores and rocks in Arizona that has drawn heavily on field-based studies as well as the published literature.

The correspondence of ores with rock types in southeastern Arizona and contiguous Mexico is significant. Figure 13 shows an interpretative reconstruction of the pre-15 Ma configuration of Baja California and the Mexican mainland together with the distribution of Laramide-aged porphyry copper deposits in Arizona and in Mexico as reported by Sillitoe (1976). The deposits shown in Figure 13 as open circles are related to porphyry intrusions. Other mineralization styles shown include younger base- and precious-metal veins, complex replacement ores in both marine sedimentary and epiclastic volcanic rocks, as well as carbonate replacement ores. These are discussed in subsequent sections.

Deposits of "orogenic gold" shown in Figure 14 are interpreted to have originated from deep metamorphism and possible dehydration of Proterozoic rocks (Goldfarb et al., 2005). They have been recognized in the relatively exhumed northwestern portion of Sonora and contiguous Arizona and California. In Mexico, available radiometric dates for these deposits record synchroniety of orogenesis and mineralization within a Laramide age range of 45-67 Ma (Iriondo et al., 2005; Quintanar Ruiz, 2008). Across the border in the United States, ages of similar deposits remain to be adequately constrained. Some gold occurrences in Arizona with "orogenic" characteristics could be Tertiary in age and related to detachment faults.

Implications for Laramide ores

One important attribute of Figure 13 is the distribution of terranes in Mexico and the apparent contrast in the densities of porphyry mineralization. Particularly noticeable is the relative absence of exposures of porphyry-style mineralization

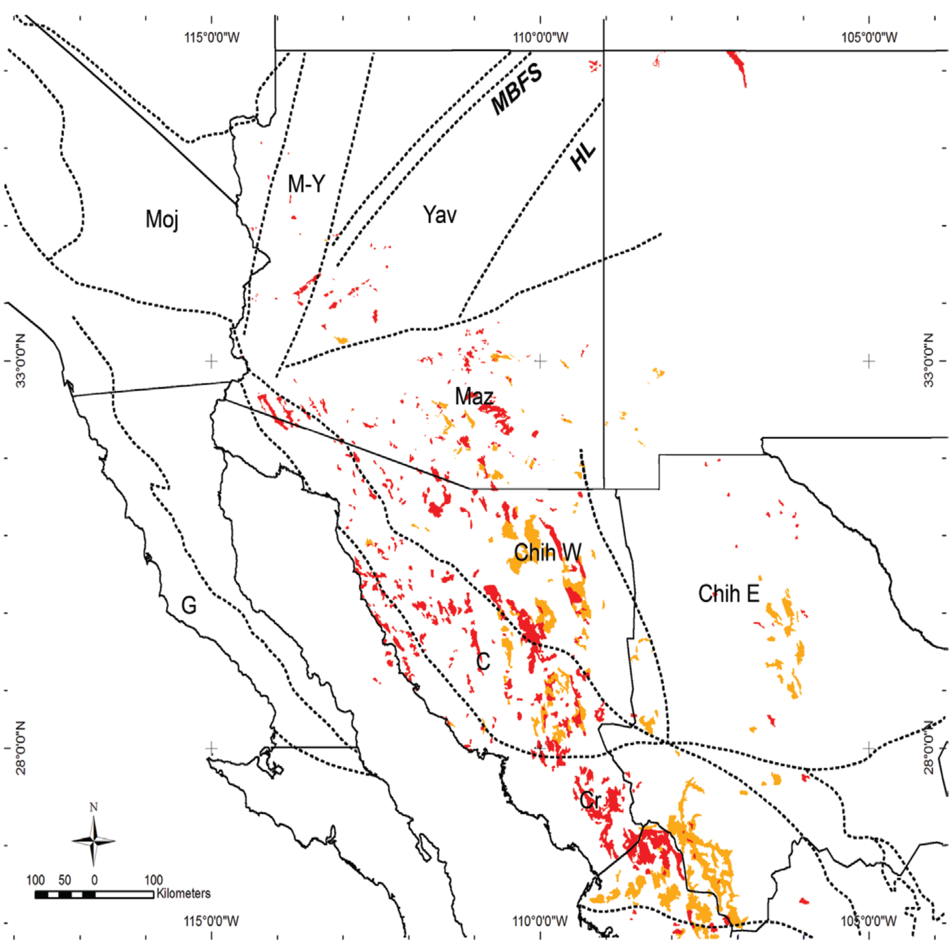

Figure 12. GIS map of Laramide igneous rocks of the USA – Mexico border region (compiled and adapted from Chernoff et al., in preparation). Intrusive = red; volcanic = orange.

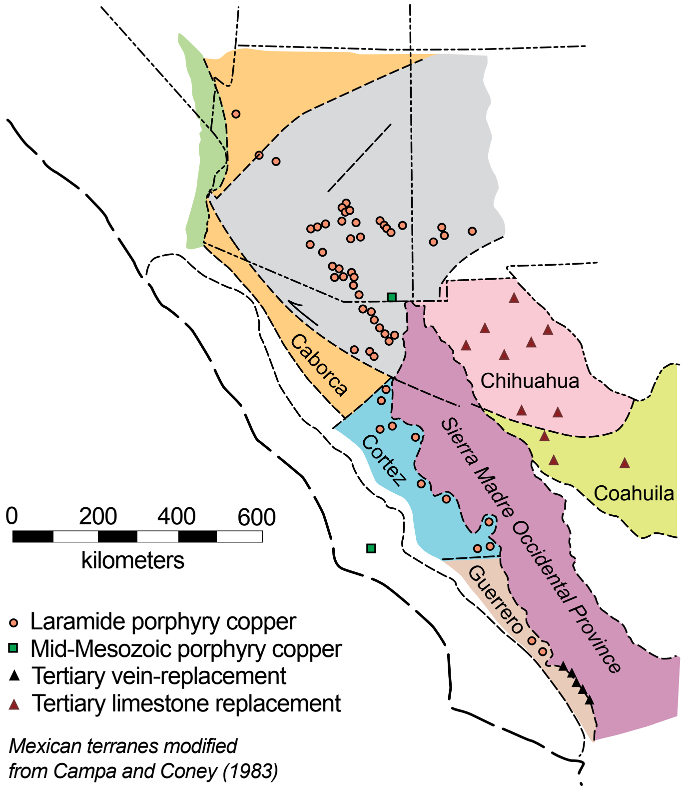

Figure 13. Distribution of deposit styles of different ages in the USA – Mexico border region. The map closes the Gulf of Cortez to hypothesized Laramide time by restoring Baja California to its pre-opening configuration. G = Guerrero Terrane; CTZ = Cortez Terrane; CA = Caborca Terrane; CHIH = Chihuahua Terrane (North American Terrane); COA = Coahuila Terrane; SMO = Sierra Madre Occidental province. Porphyry ores (open circles) of the Laramide arc transect the Guerrero, Cortez, and North American terranes. Mid-Tertiary high-temperature carbonate replacement ores (open triangles) occur chiefly in the North American cratonic terranes. Mid-Tertiary veins (black triangles) of the Sierra Madre Occidental province are well preserved in the Guerrero terrane.

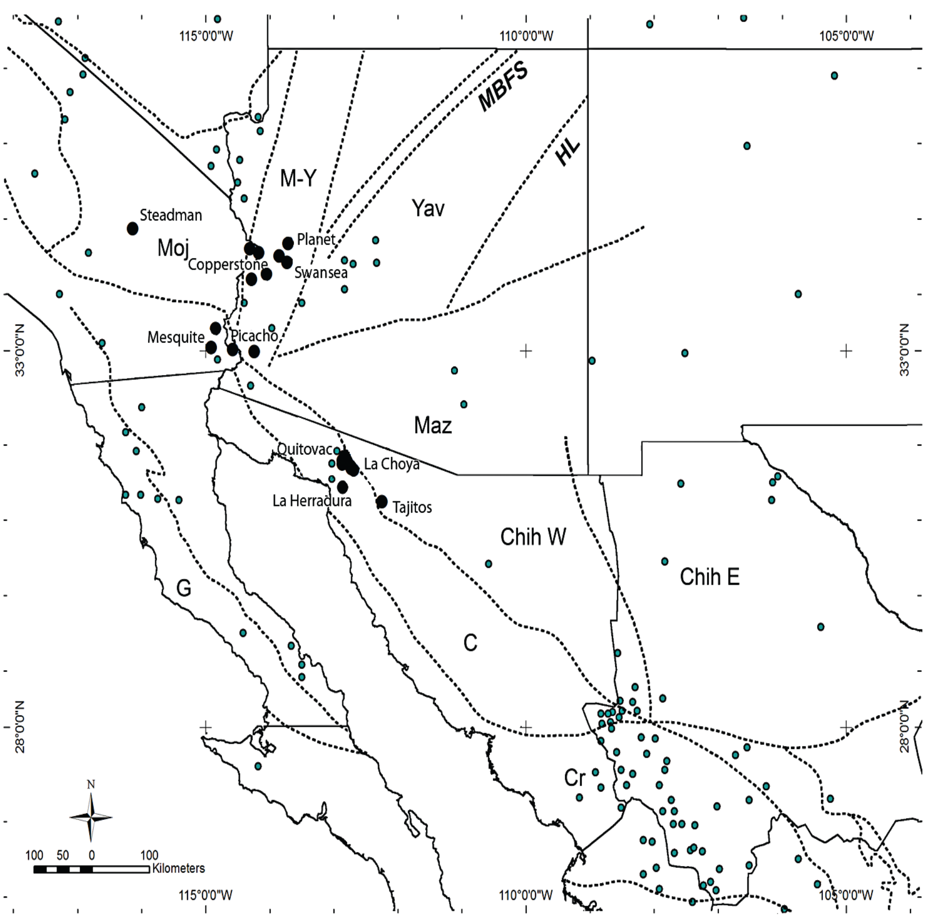

Figure 14. GIS map of orogenic gold districts (large black circles) and gold occurrences (small gray circles) compiled from Lee et al. (1987). Albeit younger, orogenic gold deposits of northwestern Sonora and contiguous California occur in rocks that are spatially associated with the Jurassic Mojave-Sonora Megashear.

in the more deeply exhumed regions of western Arizona and the Caborca terrane of Mexico. Furthermore, large porphyry systems identified to date in Mexico are basically restricted to the Nacozari (Valencia et al., 2008) and Cananea (Valentine, 1936; Velasco, 1966) districts. New deposits will undoubtedly be found along this trend, but they may be variably rotated, dismembered, and buried under cover, such as were the cases of Kalamazoo (Lowell, 1968), and the newly-discovered world-class Resolution deposit (Manske and Paul, 2002) in central Arizona.

Orogenic gold deposits, some of which are considered to be related to deep metamorphism associated with a subducting Pacific plate in the Laramide, occur in the Caborca terrane, and in the Yavapai and Mojave provinces of Arizona and California. They appear to be absent in the Mazatzal province of southeastern Arizona and eastern Sonora. This may be a direct consequence of basement composition. In Arizona, Titley (2001) provided persuasive evidence with silver-gold ratios from production figures. The 17.5 Ag/Au ratio mimics the Holbrook line between the Yavapai and Mazatzal Proterozoic provinces. Furthermore, the more important mines are located about the Mojave-Sonora megashear, which probably provided exceptional structural ground preparation. These combined factors suggest potential for more orogenic gold deposits in western Sonora and Arizona, particularly in those areas that exhibit the deeper erosional levels.

Temporal and spatial transition of ore styles: The high-temperature, carbonate replacement ores

The porphyry systems shown in Figure 13 are distinctly Laramide in age. Younger intrusions are present across the region and manifest the same distinctive alteration characteristics of porphyry systems. However, none is known to attain the size and mineral endowment of some of the Laramide ores. Figure 15 shows the Laramide and mid-Tertiary high-temperature, massive-sulfide carbonate-replacement ores in the border region. The nature and contrasting characteristics of these ores have been reviewed by Megaw et al. (1988) and Titley (1995a). A commonality between them is that all are emplaced in miogeoclinal carbonate-dominated strata. The deposits of Arizona are mostly of Laramide age and associated with porphyry copper-dominant metal assemblages, whereas many of those in Mexico are of Oligocene age, lead-zinc-silver dominant, and related to caldera activity. The contrasting metal associations that changed with time are the result of the evolving tectonic setting and associated intrusion compositions (Barton et al., 1995).

Implications for high-temperature, carbonate-hosted replacement ores

Many of these high–temperature, carbonate replacement deposits have higher copper contents in their deeper parts.

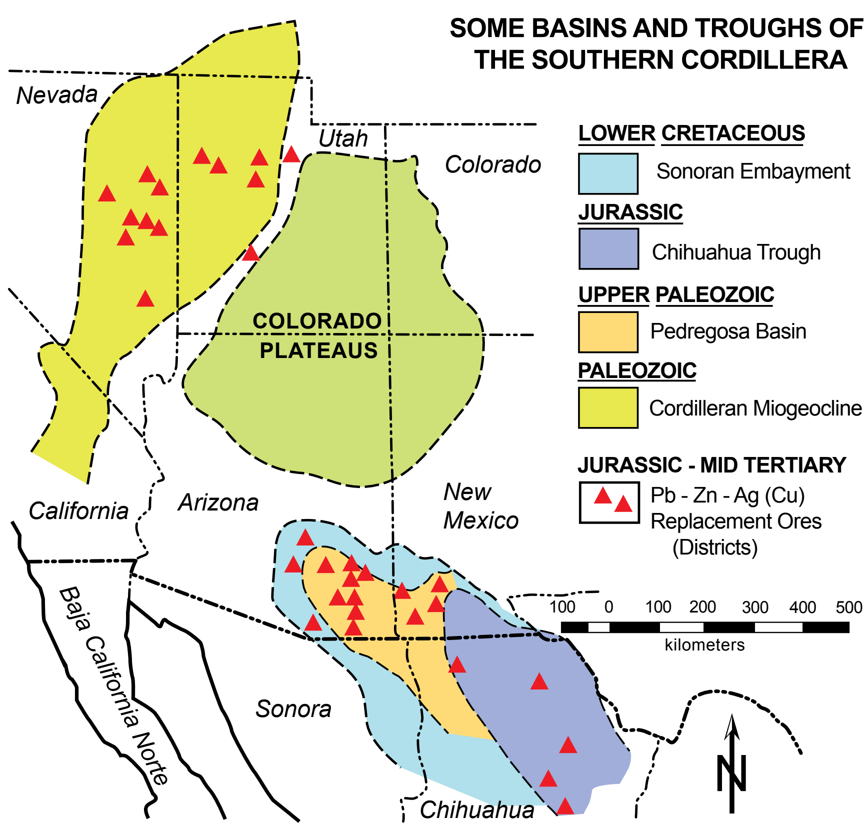

Figure 15. Map of carbonate replacement ores of the USA – Mexico border region and the Great Basin (adapted from Titley, 1995a, and Greenwood et al., 1977).

One can ponder on what these systems would have looked like if they had intruded quartz-feldspathic rocks instead of carbonate rocks. Assuming an equivalent Cu grade of 1.5% in the 100-Mt San Martin-Sabinas (Cu)-Zn-Pb-Ag replacement deposit in Zacatecas, for example, the comparable porphyry deposit could have potentially contained on the order of 300 Mt at a hypogene grade of 0.5% Cu. The exploration potential for these systems remains high, notwithstanding the challenges presented by the often highly subdued expressions of alteration and weathering about these orebodies.

Epithermal hypogene ores of the mid- and late Tertiary

Middle and upper Tertiary hypogene ores have been summarized by Spencer and Welty (1989) for Arizona and by Ruiz (1986) for Mexico. A map of mineral districts of Arizona is shown in Figure 16. Comparison of the distribution of these districts with those of older ages in Arizona and Mexico reveals the extent of overprinting of ore types and districts in the region. Thus, it is reasonable to propose that the dominant volcanic hosts and related ores can be superimposed upon older deposits across the trans-border region.

The work on the middle Tertiary districts of Arizona described by Spencer and Welty (1989) outlines properties of four major contrasting styles of ores, all of which reflect characteristics of the epithermal environment. The ores occur in approximately 180 districts and are represented metallogenetically by relative gold-rich, silver-rich (Titley 1987), base metal-rich, and complex ores locally associated with tungsten and fluorite. The styles of these occurrences range from veins to carbonate replacement bodies of, with few exceptions, modest size, which may also be associated with small intrusive plugs and dikes. The preponderance of districts occur in Oligocene through Pliocene volcanic rocks, although the dominant age of volcanic hosts is on the order of 20 Ma, based on dating of numerous related small stocks and dikes. This largely Miocene volcanic succession assumes greater importance as exposures in the southern part of Arizona thicken and become more widespread into Mexico. A map of the distribution of middle to upper Tertiary volcanic units is shown in Figure 17. Many of the epithermal vein districts in Mexico (e.g., Figure 13) occur in the heart of the Sierra Madre Occidental province. Perhaps not by chance, the majority of gold-rich veins occur over the island arc Guerrero and composite Cortez terranes, and not the North American or Chihuahua terranes, where silver-rich veins are more common.

Basin and Range extension and ore deposits

The middle Tertiary of this region was a time of tectonic extension, one major result of which was the dismembering, and/or burial or exposure of older ore deposits (Barton et al., 1995; Staude and Barton, 2001). This history has led to significant field research in identifying the primary configuration of ore bodies as well as a search for missing mineralized

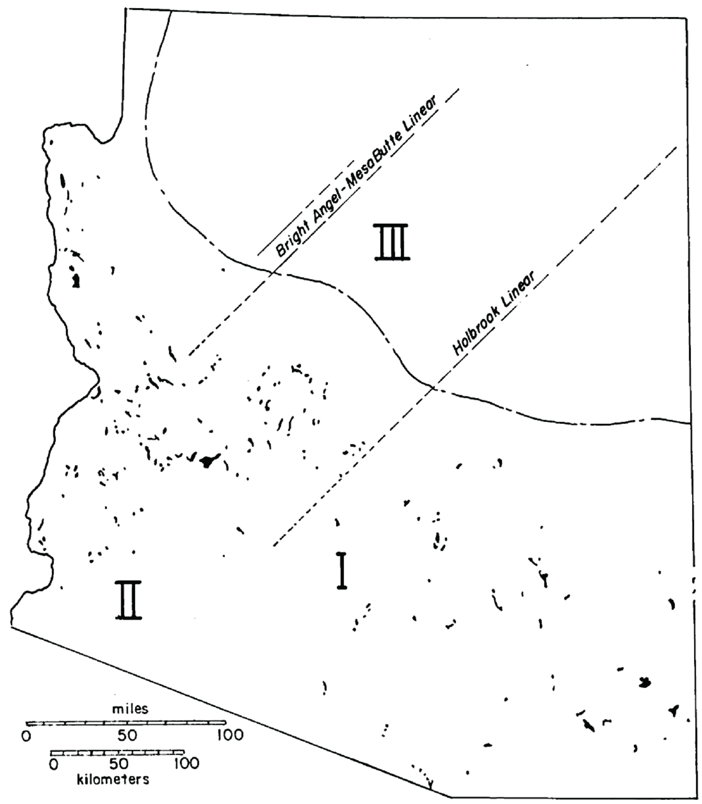

Figure 16. Map of mid-Tertiary and younger mining districts of Arizona (Titley 1987, adapted from Keith et al., 1983). Comparison of locations and density of these districts with those shown in Figure 6a and Figure 11 reveal the habit of temporal overprinting of ore deposits in Arizona.

blocks along low-angle faults. In the first instance, the discovery of the Pima mine in Arizona (a porphyry system) in 1952 (Heinrichs, 2000) represents a break with geological traditions in opening the search for buried ores. In the second instance, the finding of Kalamazoo in 1966 as a significant piece of the San Manuel orebody (Lowell, 1968) along the down-dropped side of a fault initiated much research and exploration activity (e.g., Wilkins and Heidrick, 1995).

Supergene ores of the middle and late Tertiary

Processes involving meteoric water take place in the zone of oxidation, across the zone of leaching, and in the zone of precipitation. These processes dissolve pyrite and other primary sulfides and precipitate iron oxides and chalcocite about the existing water table, as well as copper-bearing oxides down the hydrologic gradient (Titley and Marozas, 1995). Furthermore, supergene blankets are known to readjust and "recycle" as they are affected by individual faulting events (Enders, 2000). In many porphyry environments, secondary enrichment of hypogene mineralization has played a fundamental role in making the mineral deposit economic.

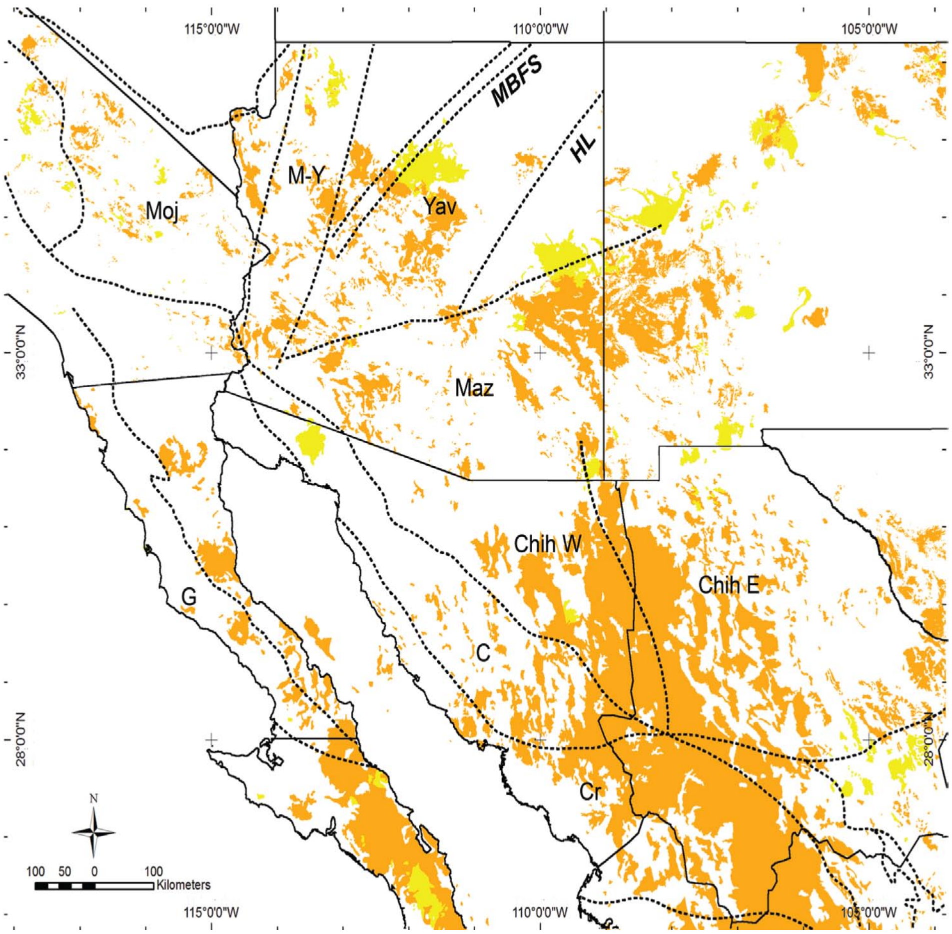

Figure 17. GIS map of Late Tertiary and Quaternary volcanic rocks of the USA – Mexico border region (compiled and adapted from Chernoff et al., in prep.). Late Tertiary = orange; Quaternary = yellow. Not shown because of their limited outcrop size are intrusive time-equivalents.

Across Arizona and New Mexico there is regional stratigraphic commonality of age dates of alunite and illite from supergene weathered and enriched copper systems that reveal a relation to regional epeirogenic uplift events (Cook, 1994). $^{40}Ar/^{39}Ar$ dates point to four tectonic episodes across the Tertiary geologic section shown in Figure 18. These episodes correspond to cycles of enrichment observed in outcrop.

Both old and new technology has been the means of making mines out of these supergene copper systems across the trans-border region. Solvent extraction/electrowinning (SX/EW) technology, which is in widespread use today, evolved in the 1980s and created the chemical means to concentrate copper in a solution that could ultimately be produced across low electric potentials. Together with favorable metal prices and economics, SX/EW technology has widened the search for oxidized ore bodies that resulted from weathering of hypogene ores. Beyond the extraction of copper from ores with concentrations of less than one kilogram per tonne (0.1%), a growing recognition of the importance of the weathering cycle has generated enhanced interest in the extraction of many other metals or minerals from their occurrence in weathered systems.

Implications for middle to late Tertiary ores

The sites of exposures of the more complete volcanic sections present favorable targets to explore for ores. The search should be enhanced by detailed structural and lithological information that may be applied to form a basis for understanding zonation at the local scale, as well as comparative metallogenesis at regional scale.

A search of high-level strata is also merited because of the potential for supergene ores. Whereas the search for favorable units (on the basis of alunite ages) has expanded in Arizona, more attention to various basin units and their ages is merited across the trans-border region. Good potential remains for discovery of enriched ores and exotic copper around porphyry districts across the border region. In-situ leaching technologies that are coming of age should further augment this economic potential.

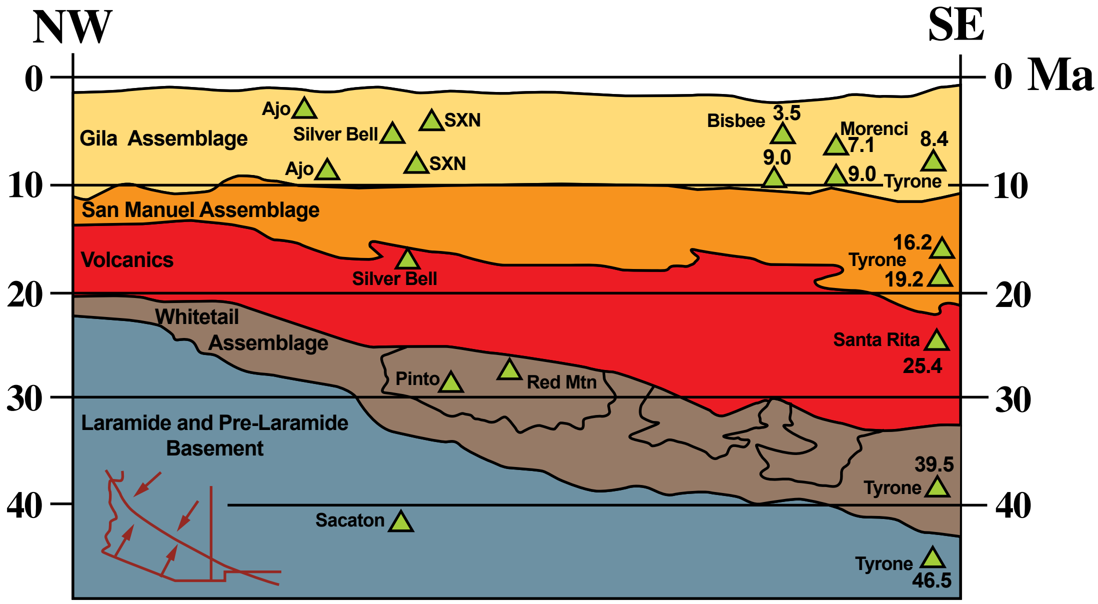

Figure 18. Tertiary geological section along a traverse across southeast Arizona with $^{40}Ar/^{39}Ar$ age dates of alunite and illite from supergene-enrichment deposits. Dates point to 4 episodes of enrichment consistent with observed regional epeirogenic uplift and volcanism events. The geological section is from Scarborough (1989) and the dates are from Cook (1994).

EFFECTS OF QUATERNARY OVERBURDEN ON THE DISTRIBUTION OF OLDER ORES

To gain an appreciation of how important the effects of cover are across the border region, a GIS map of Quaternary overburden is shown in Figure 19. About 65% of the area is overlain by Quaternary deposits. Furthermore, it is worth noting that this percentage appears to be considerably higher in northern Mexico, where much of the remaining area is also overlain by middle to late Tertiary cover (see Figure 17). When compared to southeastern Arizona, one can ponder, for instance, whether the greater thickness of post-ore cover may be responsible for the lesser numbers of large Laramide porphyry deposits found to date in northern Mexico (i.e., Staude and Barton, 2001).

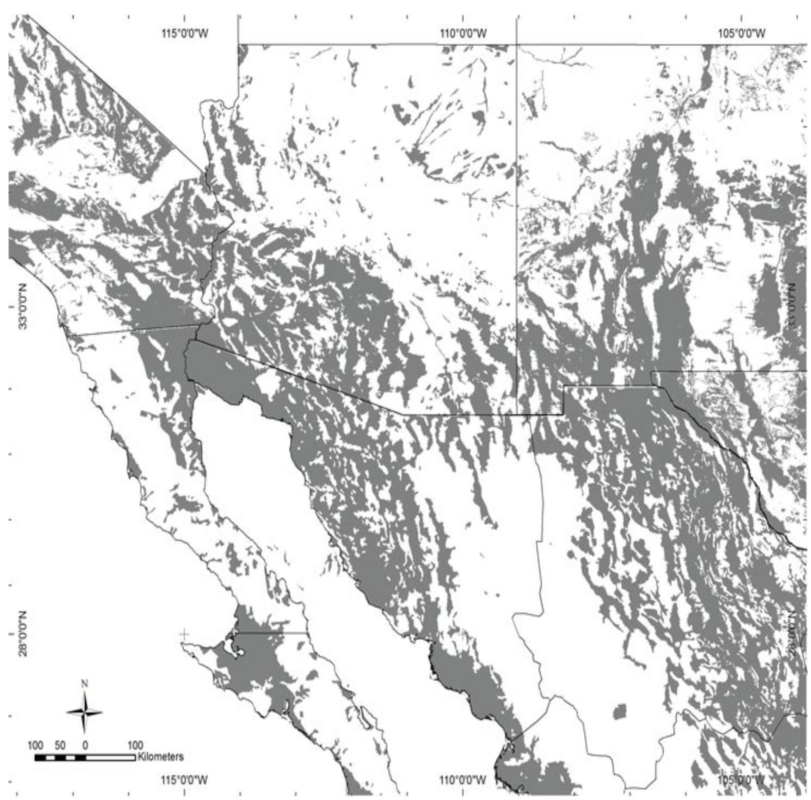

Figure 19. GIS map of Quaternary sedimentary cover of the USA – Mexico border region (compiled and adapted from Chernoff et al., in prep.). Overburden represents 65% of the area. Note that southeast Arizona (where numerous important Laramide porphyry deposits have been found) shows less cover than adjacent northern Mexico (see also Late Tertiary volcanic cover map of Figure 17).

CONCLUSIONS

The superposition of geologic events is an important fact that should always be kept in mind during exploration efforts in the border region. Besides careful follow-up of color, geochemical, and/or geophysical anomalies with geologic field work, some of the conventional geologic tools that have continued to prove successful include:

1) Extrapolation of mineral-occurrence styles in given types of hosts to areas with similar rocks.

2) Identification of areas with the least thicknesses of cover or overburden over favorable ground.

3) Mapping of lithology, alteration, and mineralization to recognize the level of exposure, orientation, potential size, as well as the relative age relationships that constrain not only the time but the timing of mineralization with respect to local and regional tectonic events.

4) Recognition of ores within the same mining district that are unrelated in time and style, by combining gangue- and metal-zoning studies with radiogenic dating.

5) Detection of the effects of post-mineral faulting that can potentially rotate and dismember an orebody or parts thereof, by carrying out required structural studies.

6) And yes, the gold pan!

Pursuing the points above could prove fruitful in both Mexico and Arizona for new discoveries of:

1) VMS ores around confirmed Early Proterozoic outcrops.

2) Porphyry ores associated with known and yet to be identified Jurassic rocks that may be covered by Glance Conglomerate or younger rocks.

3) Laramide porphyry and associated skarn ores that may be buried under Tertiary and/or Quaternary overburden. These may also be rotated and dismembered if located within high-extension corridors in the Basin and Range province.

4) Orogenic gold deposits in highly exhumed and structurally favorable areas.

5) Middle Tertiary, high-temperature, replacement ores associated to small stocks and dikes emplaced in carbonate-dominated hosts.

6) Epithermal vein ores in areas of modest erosion since deposition of the host rock.

7) Enriched and exotic copper ores in porphyry districts where geologic units exhibiting adequate compositional contrasts and histories are preserved.

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