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CHARACTERISTICS OF GOLD DEPOSITS IN NORTHERN SONORA, MEXICO: A PRELIMINARY REPORT

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Geologic Framework of Northern Sonora

The geology of northwestern Mexico is complex and is similar in many respects to that of southeastern California and southern Arizona. The region (Fig. 1), typical of the southern basin-and-range physiographic province of which it is a part, is characterized by elongate, northwest-trending ranges separated by wide alluvial valleys. Basement rocks in the area include Precambrian gneisses, metamorphosed andesites, and granites. These rocks are overlain by younger Proterozoic quartzites and limestones, Paleozoic and Mesozoic carbonate rocks, and Mesozoic volcanic, clastic, and carbonate sedimentary rocks. Mesozoic plutonic rocks and Tertiary extrusive and intrusive rocks related to volcanic activity of the Sierra Madre Occidental are widely distributed. Broad areas are underlain by plutonic and associated volcanic rocks of the Sonora-Sinaloa batholith of Cretaceous to early Tertiary (Laramide) age. The outcrop areas of the plutonic rocks are smaller in northwestern Sonora, west of Magdalena de Kino where many of the gold deposits are concentrated, than they are farther to the east and south (Fig. 2).

The most common structural features are northwest-trending range front faults and numerous low-angle shear zones related to thrust or detachment faults. The Mojave-Sonora megashear defined by Silver and Anderson (1974) and discussed in detail by Anderson and Silver (1979) is a principal regional feature that passes near Quitovac, Caborca, and just south of San Francisco (Figs. 2 and 3). The megashear is a wide zone separating Precambrian basement rocks of slightly different age. The megashear is occupied by a Jurassic magmatic arc composed of volcanic, sedimentary, and plutonic rocks. The volcanic units within the zone are strongly deformed along low-angle thrust faults; the associated sedimentary rocks have been tightly folded. The southwestern boundary of the megashear appears to be a major fault which juxtaposes the Precambrian basement against the Jurassic magmatic terrane (Anderson and Silver, 1979). The nature of movement along the shear is uncertain, but Anderson and Silver (1979) suggest that as much as 800 km of left-lateral movement occurred along it after Middle Jurassic time. Earlier movement is possible. Many of the gold prospects in Sonora occur within or adjacent to the southwestern boundary of the megashear in Precambrian, Mesozoic, and Tertiary rocks.

Mineral Deposits

The most important metal product of Sonora is copper, mostly from porphyry deposits. The large deposit at Cananea contains 1.5 billion tons of ore (Roldan-Quintana, 1979). Amorphous graphite deposits and W skarns are the next most important mineral deposits. Production of Ag, Mo, Pb, Zn, and Au is significant but of lesser value. Important barite deposits occur, and fluorite and U have been produced (Roldan-Quintana, 1979; Ruiz, 1986). The northeastern Sonora Cu, Mo, W province represents an extension of the porphyry copper province of the southwestern United States. Northwestern Sonora contains mines and prospects of Au, Sb, Pb, Zn, Ag, and Mn. In the region of Caborca and north, mines and prospects of Au and Ag are mostly inactive (Roldan-Quintana, 1979), but there has been a recent increase in exploration activity for Au deposits of the Picacho (disseminated gold deposits spatially associated with low-angle structures) and Carlin (disseminated gold deposits hosted by silty, carbonaceous, carbonate sedimentary rocks and their associated jasperoids and breccias) types by both Mexican- and American-based companies. A small deposit of the Carlin type is being mined east of Magdalena de Kino, and many other prospective areas for this type of deposit are being examined in the same region (Skillings,

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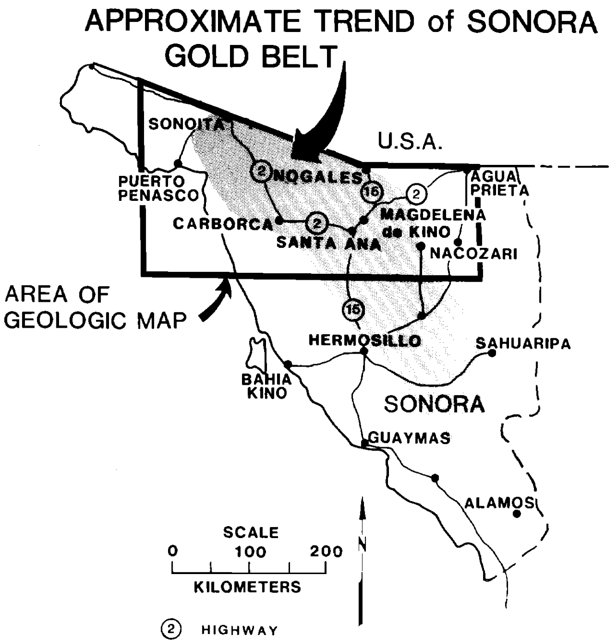

FIG. 1. Approximate trend of Sonora gold belt, from data compiled by J. M. Staude (writ. commun., 1987).

1987). A recent compilation of mineral deposit types in Sonora from the literature (J. M. Staude, writ. commun., 1987) suggests a belt of gold deposits trending approximately southeast from Sonoita (Fig. 1). A similar but much more diffuse trend of Au- and Au-Ag-bearing quartz vein deposits is evident in figures 21 and 31 of Perez-Segura (1985). Clark et al. (1982) define a belt of Au-Ag deposits, mostly fissure veins in the Sierra Madre Occidental to the east of the map area (Fig. 2), which is separate from and partly parallels the belt in Figure 1.

The characteristic types of gold deposits in northern Sonora have been delineated only by reconnaissance field investigations of the authors. Additional detailed field investigations doubtlessly will refine this suggested classification.

Four main environments of lode gold deposits are present in Sonora:

1. Epithermal veins and breccias: Hosted in volcanic rock, the veins can have strike lengths of several hundred meters. The breccias are related to volcanic domes. The deposits are characterized by elevated contents of Ag, As, moderate Sb, and Cu, Pb, Zn, and Mo. Examples are Tajitos (veins) and Cerro Colorado and Magallanes (breccias related to domes).

2. Discontinuous quartz veins: Generally thin, centimeter to meter-wide, discontinuous veins of limited strike length occur in volcanic, carbonate, and clastic sedimentary and metamorphic host rocks. They have, in addition to Au, low to moderate Ag contents, variable but generally low As, and variable but generally low to moderate base metals. Examples are the area east of Altar north of Highway 2 and parts of Banco de Oro.

3. Structurally controlled Au: Graubard (1984) used this term for Au mineralization along or spatially associated with low-angle shears and faults related to thrusting or detachment faulting. In part, these are the Picacho-type deposits referred to by Ruiz (1986). Gold occurs in breccias, quartz veins, and quartz vein stockworks along the low-angle structures, along high-angle splays, or in the hanging wall or footwall of the structures. Host rocks include Precambrian gneisses and granites, Paleozoic and Mesozoic clastic sedimentary and volcanic rocks, Mesozoic granitic rocks, and Tertiary volcanic rocks.

The structurally controlled category probably includes several deposit types. Distinctions can be made on the basis of the types of lithologies involved, the physical nature of the low-angle structures, and the spatial relations of gold mineralization and its characteristics (e.g., stockwork veining, breccias, quartz veins, etc.). Geochemical differences are present also, but the one common characteristic is the spatial association of gold mineralization to low-angle structures. Many deposits of this general category occur in western Arizona and southeastern California (Wilkenson and Wendt, 1986). Further work will be necessary to categorize completely their different varieties in Sonora.

The geochemistry of these prospects is quite variable. Gold is usually associated with elevated contents of Ag, Pb, Zn, Cu, along with Ba, and frequently high Mn. In general, Pb is greater than Zn or Cu, but Cu-dominated examples occur. Many of the prospects have elevated As, but Sb is more variable. Boron is strongly anomalous in a few prospects. Gold is most frequently associated with high Pb and As. Examples are Quitovac, La Cienega, Lluvia de Oro, San Francisco Mine at Llano, La Choya, part of Banco de Oro, Las Laminas, and La Herradura (Fig. 2).

4. Carbonate sedimentary-hosted disseminated Au: These deposits are Carlin-type systems. Au mineralization is in carbonaceous, silty, carbonate rocks and associated jasperoids and breccias. The environment of parts of northern Sonora is generally similar to the Great Basin in Nevada where most of these deposits occur. In the area east of Magdalena de Kino, in a Cretaceous (?) carbonate sequence, Minera Zapata, a 49 percent-owned subsidiary of Phelps Dodge, has discovered significant gold mineralization at the Amelia prospect. An announcement of a reserve of 3 million tons at a grade of 2 g/ton heap leachable was recently made (Skillings, 1987). The prospect is being mined at present by Cia. Minera Minas Neuvas. Minera Zapata is evaluating many other prospects of this type in the area.

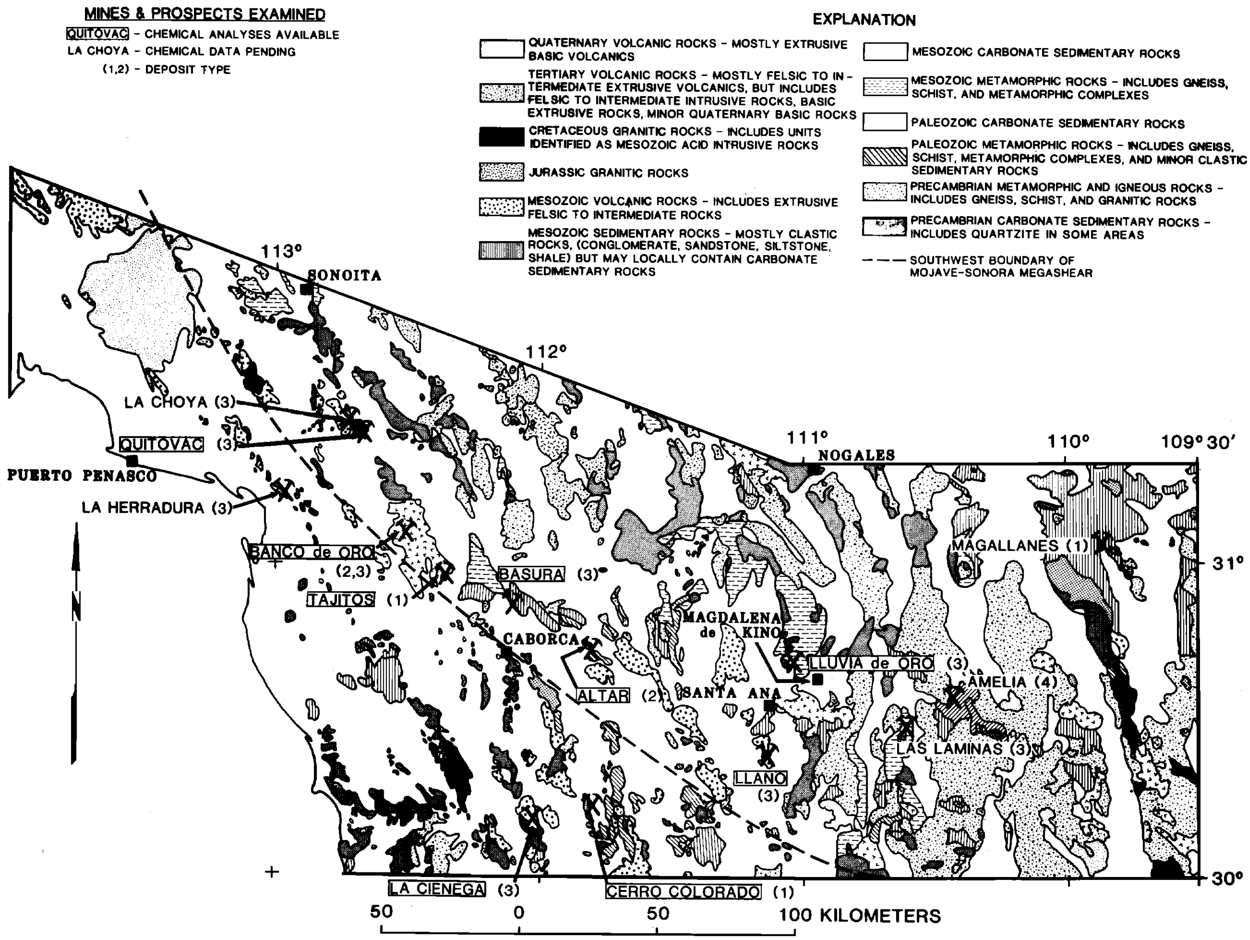

FIG. 2. Geologic map of part of northern Sonora, Mexico, modified from Carta Geologica Tijuana, 1:1,000,000 (1980). Deposit types: (1) = epithermal veins and breccias; (2) = discontinuous quartz veins; (3) = structurally controlled Au; (4) = carbonate sedimentary-hosted disseminated Au.

Descriptions of Individual Prospects

Fifteen mines and prospects or prospective areas were visited and sampled during field investigations in 1984, 1985, and 1987. The prospects are located by the mine symbol in Figure 2. Their host lithologies and nature of mineralization are summarized from our field and petrographic studies. Figure 2 is generalized from the Carta Geologica Tijuana (1980), published by the Direccion General del Territorio Nacional at a scale of 1:1,000,000. Geologic maps at a scale of 1:250,000 are also available for the following areas: Carta Geologica Caborca (1982), Carta Geologica Cananea (1982), and Carta Geologica Puerto Penasco (1982). The actual lithologies at the prospects do not always agree with those indicated by the maps of either scale, which themselves are, in some areas, inconsistent.

Geochemical data and petrographic analyses are presently available for ten of the prospects and analyses are in progress for the other five. In addition, X-ray fluorescence and instrumental neutron activation analyses for major and selected minor and trace elements and fluid inclusion and stable isotope analyses are in process for the first ten areas. Analytical data for gold-bearing samples from each of the prospective areas are organized by deposit type in Table 1. The data for Amelia are still incomplete, but enough are available to characterize it. Analyses of gold-bearing ore samples from the Mesquite, Picacho, and Cargo Muchacho deposits in Imperial County, California, broadly categorized as structurally controlled Au deposits are similar to several of the Sonoran prospects and deposits examined and are listed in Table 2 for comparative purposes. Prospects of each type are described below, and their geochemistry is discussed in the following section.

Epithermal veins and breccias

Tajitos: Tajitos is located approximately 35 km northwest of Caborca, just west of Highway 2 (Fig.

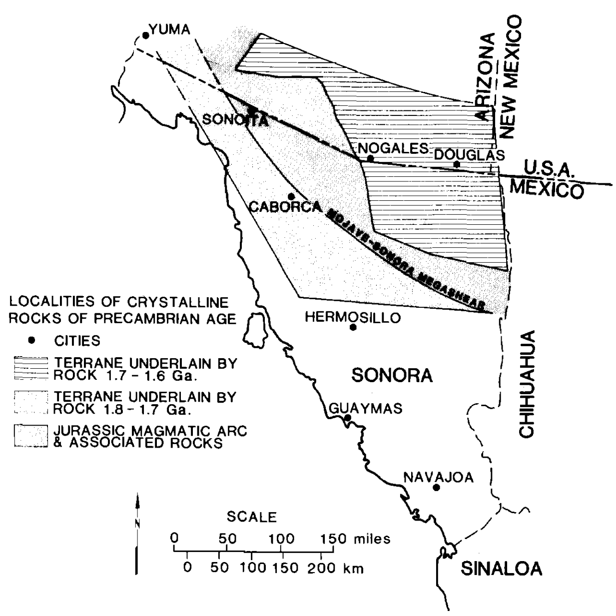

FIG. 3. Map of Sonora and adjacent parts of Mexico and the southwestern United States showing the location of the Mojave-Sonora megashear, modified from Anderson and Silver (1979).

2). Ten northwest-trending quartz veins are hosted in metamorphosed Jurassic sandstones and rhyolite. The veins are 1 to 3 m wide and contain gold-bearing ore shoots for 20 to 200 m along strike. The vein quartz is fractured and contains sericite along the fractures. Hematite-matrix quartz breccias occur along the vein margins. Finely disseminated pyrite and traces of malachite are associated with the gold.

Cerro Colorado: This rhyolite dome, approximately 60 km south-southeast of Caborca (Fig. 2), intrudes Precambrian gneisses and Paleozoic limestones. Gold mineralization in breccias on the periphery of the dome is associated with pyrite, hematite, and minor copper oxides. The rocks are strongly sericitized and silicified and contain hematite as fracture coatings, irregular veinlets, and the matrix to the breccias. The dome has prominent northeast- and northwest-trending fractures. Prior to 1920, 100,000 tons of ore were mined from the oxidized part of the peripheral breccia on the southern margin of the dome. Narrow high-grade veins in the limestones adjacent to the dome contain cerussite, gold, and silver and are presently being mined by gambusinos (prospectors).

Magallanes: Another rhyolite dome, approximately 30 km south of Douglas (Fig. 2), intrudes Cretaceous siltstones and sandstones and Paleozoic carbonate sedimentary rocks. Structurally controlled breccias contain gold associated in part with considerable fluorite. Analytical results from samples collected in 1987 are pending.

Discontinuous quartz veins

This intermediate category of gold-bearing quartz veins is unlike both the epithermal veins and breccias and the structurally controlled Au categories.

Banco de Oro: In parts of the Banco de Oro area farther north in the same range as Tajitos (approx 50 km northwest of Caborca, Fig. 2), quartz veins occur in a variety of lithologies including cherts and sandstones, rhyolite porphyries, biotite gneisses of Jurassic age, and Cretaceous granite. The quartz veins are coarse grained, fractured to brecciated, and contain limonite and hematite, some after pyrite, and frequently a boxwork iron oxide texture. Most of the host rocks are sericitized, some adularized. Several of these steeply dipping veins with gold ore shoots 0.5 to 5 m in width have been mined. The host rocks are intruded by plutons of diorite and small bodies of pyroxenite and are overlain by rhyolite ash-flow tuffs. The claim block of Compania Unidos will be described in the "structurally controlled Au" section. In general, the veins and host rocks in this area have disappointingly low gold contents (Table 1).

Altar: Just east of Altar, north of Highway 2 (Fig. 2), discontinuous quartz veins are hosted in silty argillites and sandstones of Paleozoic or Jurassic age. The quartz veins are both steep and crosscutting or occur along bedding or foliation which dips at low angles. The veins are coarse grained, fractured, and brecciated in places and are healed by later, finer grained quartz. Fractures in the quartz contain hematite.

Structurally controlled Au

Most of the prospects examined in Sonora belong in this category including Quitovac, the Compania Unidos claim block of Banco de Oro, Basura, La Cienega, Lluvia de Oro, and Llano. Other prospects of this category are shown in Figure 2, but no geochemical data are currently available for them.

Quitovac: This area is in the low range of hills west of Highway 2 approximately 90 km northwest of Caborca (Fig. 2). Gold mineralization occurs along a low-angle shear zone which separates Mesozoic hanging-wall phyllites and footwall sandstones. The shear zone, up to 20 m wide, contains a stockwork of quartz veinlets. Parts of the zone contain 0.5 to 2.5 g/ton of Au associated with Fe and Pb oxides. A sample of unoxidized vein quartz from the dumps contained galena, chalcopyrite, and pyrite intergrown with coarse-grained quartz. The veins are brecciated and healed, and the wall rocks show intense sericitic alteration and limonite and hematite staining.

Compania Unidos: The Compania Unidos claims are part of the Banco de Oro prospective area described earlier. Shear zones 2 to 6 m wide contain 3

TABLE 1. Geochemistry of Gold-Bearing Samples from Prospects in Northern Sonora (in ppm)

Sample no.	Lithology	Au[1] (0.001)	Ag[1] (0.05)	Hg[2] (0.02)	As[1] (1)	Sb[1] (1)	Cu[1] (1)	Pb[1] (1)	Zn[1] (1)	Mo[1] (0.5)	Mn[4] (10)	B[4] (10)	Ba[4] (20)	Sr[4] (100)
Epithermal veins and breccias														
Tajitos														
M3A	Brecciated quartz vein	1.4[3]	15[4]	0.6	180[3]	2[3]	5[4]	1,000[4]	55[3]	50[4]	10	50	20	N
Cerro Colorado														
M4C	Silicified, brecciated rhyolite	1.6[3]	5[4]	0.04	5[3]	N[3]	30[4]	200[4]	50[3]	5[4]	150	100	1,000	100
M4D	Silicified, brecciated rhyolite	4.7[3]	10[4]	0.02	50[3]	10[3]	70[4]	700[4]	190[3]	7[4]	50	70	150	L
Discontinuous quartz veins														
Banco de Oro—several areas														
85-2A	Limonitic stained chert	0.13	0.3	0.04	25	3	221	16	42	9	500	30	500	500
2C	Biotite gneiss	0.02	1.4	N	2	2	55	47	125	20	700	1,500	1,000	500
2D(2)	Brecciated hematitic quartz vein	0.19	1.3	N	1	2	12	78	7	11	100	10	20	L
Altar														
85-5A	Brecciated hematatic quartz vein	2.7	1.8	0.12	2	L	24	14	18	5	100	10	N	N
Structually controlled Au														
Quitovac														
M2A	Muscovite, chlorite gneiss with quartz veins	0.9[3]	N[4]	0.04	N[3]	N[3]	20[4]	150	L[3]	N[4]	100	20	500	100
M2C	Brecciated quartz vein with galena, pyrite	3.3[3]	100[4]	6.2	10[3]	22[3]	1,000[4]	20,000	10[3]	150[4]	10	15	N	100
Banco de Oro, Unidas claims														
85-2E	Brecciated quartz vein, hematite	11	3.5	0.02	4	4	14	121	L	18	50	20	N	N
85-2E(1)	Brecciated rhyolite	0.28	1.6	0.02	L	2	6	21	8	3	100	20	500	100
Basura														
85-3B	Brecciated silicified argillite with sulfides	6.6	3.4	N	32	2	28	21	26	5	70	30	700	L
85-3B(1)	Limonitic quartz vein	3.3	1.6	0.12	11	2	14	8	17	6	50	10	200	L
La Cienega														
M5C	Quartz-feldspar gneiss with quartz veins	0.45[3]	1.5[4]	0.06	5[3]	N[3]	50[4]	1,500[4]	220[3]	N[4]	500	20	1,000	100
Lluvia de Oro														
85/1-103	Brecciated hematitic sandstone	1.5	0.4	0.02	173	11	2,133	227	379	4	10,000	200	700	200
85/1-130	Silicified hematitic granite	1.9	0.6	0.02	10	2	738	5	16	7	100	50	200	L
Llano														
85-6A	Quartz vein with tourmaline	47	10	0.04	L	1	12	27	7	8	200	3,000	300	100
85-6A(2)	Sericitic granite with quartz veins	0.8	0.5	0.01	L	2	8	4	7	2	500	30	500	100
Carbonate sedimentary-hosted disseminated Au														
Amelia prospect														
Sg-3	Silicified hematitic breccia with jarosite	15[4]	7[4]		700[4]	300[4]	20[4]	70[4]	L[4]	5[4]	700	20	300	L
Sg-4	Brecciated, silicified silty limestone	20[4]	7[4]		1,000[4]	150[4]	20[4]	30[4]	N[4]	10[4]	20	50	200	300

[1] Analyses by acid dissolution and multielement inductively coupled plasma procedure by GSI, Inc.; numbers in parentheses are lower limit of detection

[2] Analyses by instrumental method (McNerny et al., 1972; Vaughn and McCarthy (1964); numbers in parentheses are lower limit of detection

[3] Analyses by atomic absorption flame methods (O'Leary and Meier, 1984; Veits, 1978); limits of detection: Au (0.05), As (5), Sb (2), Zn (5)

[4] Analyses by direct current arc spectrography (Grimes and Marranzino, 1968); lower limit of detection in parentheses for Mn, B, Ba, and Sr; where done, for Cu (5), Pb (10), Mo (5), Ag (0.5), Zn (200)

N = not detected at limit of determination indicated, L = detected but below limit of determination

TABLE 2. Geochemistry of Gold-Bearing Samples from Brecciated Gneiss-Hosted Deposits in Southeastern California (in ppm)

Sample no.	Lithology	Au	Ag	Hg[1]	As	Sb	CU	Pb	Zn	Mo	Mn[2]	B[2]	Ba[2]	Sr[2]
Mesquite														
M-7	Fractured, oxidized biotite gneiss with pegmatitic quartz veins	8.5[3]	5[2]	0.04	450[2]	2[3]	10[2]	70[2]	35[3]	10[2]	500	10	1,500	200
85-M27	Brecciated limonitic hornblende gneiss with thin, drusy quartz vein	36[4]	7.3[4]	0.02	140[4]	4[4]	320[4]	7[4]	58[4]	12	500	100	1,000	200
Picacho														
P4	Limonite-stained silicified breccia, along detachment	5.2[4]	0.2[4]	0.14	111[4]	18[4]	14[4]	4[4]	33[4]	5	2,000	20	2,000	200
P4A	Brecciated, silicified pegmatite, hematitic	6.9[4]	1.1[4]	0.70	201[4]	52[4]	11[4]	11[4]	33[4]	2	200	20	1,500	200
Cargo Muchacho														
CM3	Brecciated quartz vein-American Girl canyon	4.8[3]	N[3]	1.5	L[3]	N[3]	100[2]	50[2]	120[3]	N[2]	200	10	50	L
CM9B	Brecciated quartz vein-Madre y Padre mine	19[3]	0.1[3]	0.34	L[3]	6[3]	50[2]	200[2]	240[3]	N[2]	500	50	200	200
CM11	Sheared, partly silicified granite, Colorado mine	4.4[3]	L[3]	L(0.02)	L[3]	N[3]	50[2]	100[2]	230[3]	10[2]	1,500	20	200	200

[1] Hg by instrumental method as in Table 1
[2] Analyses by direct current arc spectrography as in Table 1, same limits of detection
[3] Analyses by atomic absorption flame methods, as in Table 1; Ag lower limit of detection (.05)
[4] GSI analyses limits as in Table 1

to 4 g/ton of Au in strongly brecciated, hematite-stained quartz veins. The shear zones separate lower plate andesite and volcaniclastic rocks from upper plate rhyolite porphyry. The wall rocks are sericitically altered, with propylitic alteration farther from the shear zone. One sample of vein quartz contained 11 g/ton Au (Table 1). Gold-bearing placer deposits occur near the lode deposit.

Basura: This prospect is in the southern part of Sierra la Gloria about 20 km north of Caborca (Fig. 2). The range is a sequence of thrust slices of schistose clastic sedimentary rocks and metamorphosed felsic volcanic rocks of Jurassic age (Corona, 1979). Steeply dipping quartz veins in these rocks locally carry gold. In the southern part of the area, sampled in this study, a gently dipping zone of quartz veinlets 5 to 8 m in width locally contains Au. The host rocks are siliceous argillites and sandstones. In the zone of quartz veinlets, the host rocks are silicified and contain sericite and sulfide-bearing silica-matrix breccias. A sample of the breccia contained 7 g/ton Au (Table 1).

La Cienega: The Cienega claim block (Fig. 2) is in a large area of gold and scheelite placer deposits. The area is underlain by Precambrian andesite and rhyolite volcanic rocks, metamorphosed to mafic and felsic gneisses. Steeply dipping Precambrian quartzites and limestones are thrust over the gneisses. Irregular quartz veins, centimeters to meters in width, occur in intensely fractured gneisses below the thrust. Some of these veins have been mined for Au and Ag, and there are many prospect pits. The host rocks have undergone variable amounts of sericitization and some chloritization in the vicinity of the widespread quartz veins. Vein quartz is medium to coarse grained, fractured, and hematite stained. The rocks and quartz veins sampled have little gold; the highest grade was 0.5 g/ton Au (Table 1) in quartz-feldspar gneisses with thin (cm scale) quartz veins. The placer deposits were mined from small shafts collared in alluvium or colluvium and sunk to the bedrock surface where concentrations of plate and wire gold were found.

Lluvia de Oro: This prospect is in the Sierra Jojoba about 30 km north of Magdelena de Kino (Fig. 2). Multiple flat gold- and copper-bearing quartz veins have been mined over 1- to 3-m widths in an area 1 by 2 km. The host rocks are schists produced by metamorphism of a sequence of limestone, shale, and sandstone of Mesozoic (?) age. The veins are in a series of closely spaced thrust faults. Granitic sills or dikes occur along the structures. The host rocks are brecciated, fractured, and intensely oxidized with large amounts of hematite and limonite. Alteration is largely sericitic. The quartz veins along some of the structures are coarse grained and dismembered. All samples from Lluvia de Oro contained approximately 1 g/ton or more Au and were remarkably consistent compared to other areas visited.

San Francisco: This mine is at Estacion Llano, about 20 km south of Santa Ana (Fig. 2). Steeply dipping tourmaline-bearing quartz veins and veinlets in sericitically altered Precambrian granite occur in a 300- by 300-m area. Old mining operations reported 15 g/ton of gold to 60 m depth along one of the stronger structures (D. A. Giles, unpub. data, 1986). The prospect overlies a low-angle structure that hosts a large quartz vein. Several pits and trenches near the old mine expose intense sericitic alteration and fracturing in granitic rock. A tourmaline-bearing quartz vein in one of the pits had 46 g/ton Au; altered granite with thin quartz-tourmaline veins contained about 1 g/ton.

Carbonate sedimentary-hosted disseminated Au

Amelia: The Amelia deposit is approximately 50 km east of Magdalena de Kino (Fig. 2). The host rocks are a strongly folded sequence of Cretaceous (?) limestones which have been affected by several periods of deformation. Ignimbrites overlie the carbonate rocks. No diorite dikes have been found in the immediate area. Mineralization is localized in the upper part of a silty, sandy limestone or calcareous sandstone which underlies a relatively massive, carbonaceous limestone. Steep faults cut the rock units and offset their contacts. There is much brecciation, fracturing, and silicification at the intersections of the faults with lithologic contacts. Limonite and hematite replace sulfides, and jarosite is present on fractures. Gold contents of silicified breccias at the fault-contact intersections had 15 to 20 ppm Au, based on preliminary analyses. Many other prospects of this type in the area are currently being evaluated.

Geochemistry of the Gold Deposits and Prospects

Epithermal veins and breccias

Samples from Tajitos and Cerro Colorado have significant Au (up to 4.7 ppm) and moderately high Ag (up to 15 ppm) contents with a Au/Ag less than 0.5. The arsenic content is moderately high (up to 180 ppm) and the Sb content somewhat irregular, though generally higher at Cerro Colorado than at Tajitos. The Hg content is low in both prospects (less than 1 ppm), as is generally true of the Sonoran gold deposits examined. The Pb content is strongly anomalous (up to 1,000 ppm), and Pb > Zn > Cu. The Mo content is elevated at Tajitos (50 ppm). Gold appears to be associated with Ag, Pb, and As, and base metals are present in moderately elevated amounts.

The geochemistry of gold-bearing epithermal vein and breccia deposits worldwide varies so much that meaningful comparison among systems is difficult. A characteristic suite of trace elements including Au, Ag, As, Sb, Hg, Pb, Zn, and Cu is usually present in epithermal deposits regardless of their location (Berger and Eimon, 1983). Other elements, such as Mo, Te, Tl, B, and W, are frequently present, but the concentrations vary tremendously and there is little consistency in the assemblage even within a deposit (Silberman and Berger, 1985). The two Sonoran deposits are by no means unique in their geochemistry. The association of gold with fluorite, as at Magallanes, usually indicates association with alkalic igneous rocks in the western United States volcanic-hosted systems. Incomplete preliminary analyses of Magallanes samples show elevated Nb and Y contents—other indications of alkalic affinity.

Discontinuous quartz veins

The gold content of the discontinuous quartz veins was generally less than 0.2 ppm (Table 1). Many of the samples of brecciated, oxidized wall rocks had higher gold content than the veins. The quartz vein at Altar had the highest Au content (2.7 ppm) and the highest Hg content (0.12 ppm). Arsenic content was low to moderate (1-25 ppm) and the Au/Ag ratio varied from 0.01 to 1.5. Base metal content was moderately elevated but showed no consistent pattern (Table 1). The Mo content of Au-bearing veins in the Banco de Oro area is moderately elevated (9-20 ppm) and contents of up to 270 ppm occurred in veins that were not gold bearing. Occasional high B content (up to 1,500 ppm) in other samples from Banco de Oro appear unrelated to Au. The geochemical signature of these veins is not consistent, and metal contents are generally low to moderate.

Structurally controlled Au

The geochemistry of the structurally controlled Au deposits is variable. The quartz veins within these deposits usually contain the highest grades of Au. The Au is usually associated with Ag, but the Au/Ag ratio varies significantly from prospect to prospect. In many of the deposits it is greater than one, usually greater than 2 in the U.S. deposits (Tables 1 and 2), but at Quitovac and La Cienega it is less than 0.1. The Cu, Pb, and Zn contents are usually high (Cu and Pb can be as high as 2,000 or 20,000 ppm, respectively; Zn can be as high as about 400 ppm) with Pb > Cu, and >Zn. Cu-dominated examples occur at Lluvia de Oro in Sonora, and at some of the U.S. deposits, notably Copper Stone and parts of the deposits in the Cargo Muchacho Mountains. The Mo content is strongly elevated in some prospects and low to absent at others (Tables 1 and 2). The Lluvia de Oro prospect has considerable Mn (up to 10,000 ppm), and notably high B (200 ppm). The arsenic content can be high (200 ppm) in some of the prospects and nearly absent in others, but where present, it does tend to be associated with Au. In summary, the geochemistry of the structurally controlled gold systems in Sonora is variable, but it can generally be categorized as containing Au and Ag—with Au/Ag generally > 1 with the exception of Quitovac and Cienega, moderate to strongly elevated Pb, Cu, and Zn, and the frequent association of other elements—including As, Mn, and B with occasional Sb (Table 1). The gold appears most often associated with Ag and Pb, often As, and occasionally Cu.

Silberman et al. (1987) noted that many of the gneiss-hosted or structurally controlled (as defined in this paper) Au prospects of Sonora are broadly similar to many of the Au deposits being mined at present in southeastern California. Many of these California deposits are associated with low-angle structures, although specific settings and host rocks vary in detail as they do in Sonora. Descriptions of the important California mines can be found in Wilkenson and Wendt (1986) and Drobeck et al. (1986), including the Mesquite (the largest), Picacho, American Girl, and Madre y Padre mines. Geochemical data for several of these deposits are listed in Table 2. Sample CM11, from the Colorado prospect in sheared granite in the northern part of the Cargo Muchacho Mountains, contains anomalous W, in addition to the elements listed in Table 2 (M. L. Silberman, unpub. data, 1985). The samples listed in Table 2 are high-grade gold-bearing material; the average grade of these deposits is on the order of 1 to 3 g/ton.

The arsenic content is high (up to 450 ppm) at Mesquite and Picacho; the Sb content is moderately high (up to 50 ppm) at Picacho but not so at Mesquite. The Cargo Muchacho Mountains deposits are notably low in As and Sb. Base metals are quite variable—in Mesquite and Picacho they are generally below about 50 to 100 ppm each. Zn is usually greater than Cu and Pb, although occasionally Cu is above 300 ppm. In the deposits of the Cargo Muchacho Mountains, in contrast, Cu, Pb, and Zn are usually above 50 to 100 ppm (Table 2).

Only three of the many areas of mineralization in the Cargo Muchacho Mountains are included in Table 2. The geochemical signatures of gold-rich rock are different in each of these areas. For example, at American Girl, Cu tends to be higher than Zn and Pb, whereas at Madre y Padre, Zn exceeds Cu and Pb when the total sample suite is considered (M. L. Silberman, unpub. data, 1985).

The California and Sonora prospects and deposits of this type both show considerable geochemical variability. Oxidation in all of them is severe. The characteristic intense fracturing and brecciation has allowed intimate contact of oxygenated meteoric ground waters to the rocks, enhancing the effects of weathering. The extensive development of limonite and hematite suggests that the host rocks were pyritic. The process of oxidation was significant in making the U. S. deposits economically viable. Heap leaching can be utilized to recover the gold in these basically low-grade systems. The geochemistry of these systems may have been severely modified by the weathering process. Although more definitive geochemical comparisons might be possible if unoxidized material was available, it is usually the oxidized zone that is examined in exploration applications. Although limited in extent, the geochemical data presently available from these systems demonstrate their variability of trace element association. Gold appears to be the best indicator element for geochemical exploration, but detailed studies may show that individual deposits have specific patterns of geochemical zoning that could prove useful for delineating zones of mineralization as was found in some of the carefully sampled volcanic-hosted epithermal systems in the western United States (Silberman and Berger, 1985).

Carbonate sedimentary-hosted disseminated Au

The geologic environment of parts of northern Sonora and Chihuahua is generally similar to that of the Great Basin of the western United States, where most of these deposits are currently being mined. The prospect at Amelia is of this type. Only emission spectrographic data on samples from Amelia are available. The gold content is strongly elevated and the Ag content is moderately elevated, with the Au/Ag > 2. The arsenic and Sb contents are both high, Cu and Pb contents relatively low, and the Ba content moderately elevated. No analyses are available yet for Hg, or for Zn at levels below 200 ppm. The trace element suite present, Au, Ag, As, Sb, and Ba, is similar to that which characterizes this class of deposit (Bagby and Berger, 1985). The silicification, host-rock composition, and geochemistry suggest that Amelia is a variety of the Carlin-type deposits.

Conclusions

The complex geology of northern Sonora has a variety of environments suitable for gold mineralization. Three of these, the volcanic-epithermal vein and breccia systems, the structurally controlled gold environment, and the carbonate-hosted disseminated gold systems are the current focus of considerable exploration activity. Large areas have broadly favorable geology for these types of deposits, but they are poorly known in detail.

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