LA CARIDAD PORPHYRY CU-MO DEPOSIT: A PORPHYRY-EPITHERMAL TRANSITION IN THE SOUTHWEST NORTH AMERICA PORPHYRY COPPER PROVINCE.

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RESUMEN
La Caridad porphyry copper-molybdenum deposit, located in northern Mexico, is the largest copper producer in Mexico (~150,000 tons of Cu in 2001). Regionally, the deposit is located in an untilted and upright block. It is associated with the emplacement of a Tertiary quartz-monzonitic stock and hosted by Laramide plutonic and volcanic rocks. Molybdenite Re-Os ages associated to potassic and phyllic alterations suggest that the mineralization took place in a short period of time. Main stages of alteration and mineralization comprise an early episode with K-silicate veins with orthoclase-quartz-anhydrite-biotite in the intrusive complex and pervasive biotitization of andesites-diorites, with a zone of propylitic alteration around this biotitic zone. Early alteration includes weak mineralization of magnetite-chalcopyrite-molybdenite-sphalerite-pyrite. A second hydrothermal mineralization event is represented by quartz veins associated with pyrite-sericite-chlorite. Tourmaline occurs as acicular radiating crystals intergrown with sericite-pyrite-quartz. This alteration type is associated with the main mineralization event of chalcopyrite-pyrite and lesser molybdenite. Lead-zinc-silver mineralization was emplaced peripherally during the final stages. High-sulfidation mineralization in the mine is represented by quartz-tennantite-chalcopyrite-pyrite-quartz-sericite veinlets. La Caridad Antigua, located 3 km east of la Caridad deposit, contains advanced argillic alteration that locally hosts high-sulfidation epithermal Cu-Ag-Au mineralization. The spatial-temporal association suggest a genetic link.

INTRODUCTION
Spatial and temporal links between epithermal and porphyry copper deposits have been documented in many areas in the Circum-Pacific ring (Lepanto, Philippines, Arribas et al, 1995, Hedenquist et al 1998; Nevados del Famatina and La Mejicana, Argentina, Losada-Calderon and McPhail, 1996; Maricunga Belt, Chile, Muntean and Eunaudi, 2001). In the Southwest North America region with its more than 50 porphyry copper deposits (Wilkins and Heidrick, 1995) the transition between porphyry-epithermal ore deposits in this region has seldom documented. Here we present a description of La Caridad porphyry Cu-Mo and preliminary data suggesting that La Caridad porphyry copper-molybdenum deposit and La Caridad Antigua, a high-sulfidation epithermal system, are related.

La Caridad porphyry Cu-Mo deposit is one of the two Mexican world-class copper-molybdenum deposits and is the most productive Cu deposit in Mexico (~150,000 ton Cu/y). La Caridad is located in northeastern Sonora, Mexico, 240 kilometers southeast of Tucson (Fig. 1). Reserves in 2001 were ~4 million tons of Cu and 250,000 tons of Mo (internal report). The deposit was...
discovered in 1967 in a program of the Mexican Government in conjunction with the United Nations and began production in 1978. The geology and history of its discovery and development have been outlined by Coolbaugh (1979) and Seagart et al. (1974).

La Caridad mine is the only world-class porphyry copper deposit in the Nacozari mining district, the other minor deposits in the district are Florida-Barrigon (90 million tons with 0.30% Cu and 0.15% Mo), Los Alisos, El Batamote (4.4 million tons 0.36% Cu) and Pilares (Breccia pipe 80 million tons with 0.70 % Cu).

Figure 1.- Localization of La Caridad porphyry copper deposit within the state of Sonora, Mexico. Also shown are other porphyry copper deposits in the region.

REGIONAL GEOLOGY
The geology of northeastern Sonora is essentially an extension of the geology of southern Arizona (North America Terrane). The area is dominated by north-trending mountain ranges consisting of strongly deformed greenschist-grade volcanic and sedimentary rocks of 1.7 Ga (Anderson et al., 1980) that are intruded by granites emplaced at 1.4 and 1.1 Ga (Anderson and Schmidt, 1983). Overlying these units are Late Proterozoic and Paleozoic miogeoclinal rocks, succeeding by volcanic and plutonic rocks of Mesozoic and Cenozoic age. Elongate, north-trending plutons of Laramide age intrude the Mesozoic volcanic sequence. The intervening valleys are filled with Tertiary conglomerates and Quaternary gravels.

The Nacozari mining district lies in the northwestern portion of the Sierra Madre Occidental physiographic province (Raisz, 1959). The Sierra Madre Occidental physiography in this area consists of typical Basin and Range structures, with general faulting oriented NW as a response an old northwestern-oriented structural fabric parallel to the former continental margin, which became rejuvenated during Laramide time (Titley, 1976). The Nacozari mining district is cut by two regional structures that divide the district in three blocks. La Caridad and Pilares mines are located in the central block that is acting as a horst, and the west and the east blocks are grabens.
The Pilares normal fault crops out 7 km from La Caridad deposit; the structure has an orientation of N40°W dipping S72°W. The La Caridad postmineral normal fault is located at the northeast side of the ore body and has a general orientation of N45°W dipping N45°E.

The Nacozari district is characterized mainly by extrusive rocks; consisting of a thick series of andesitic to latitic flows and ignimbrites of Laramide age. The geology from a structural point of view, can be divided in three blocks:

- **West Block**: This block is dominated by a sequence of dacitic to andesitic flows, volcanic breccias and basaltic dikes (fig. 2). El Batamote and Florida-Barrigon porphyry copper deposits are located in this block. Locally, a partially metamorphosed sedimentary sequence composed of limestones and sandstones from the Upper Paleozoic, located in the Copper Queen and La Cobriza ranges.

- **Central Block**: This area is dominated by pseudostratigraphic ignimbrites, andesitic, rhyolitic and latitic flows (Fig. 2). Reyna and Mayboca (1986) proposed a stratigraphic column of the following informal units, from older to younger: 1) Esperanza rhyolitic ignimbrite, 2) Lithic ignimbrite Paulina, 3) Rosario andesite, and 4) Pilares latite. These rocks are intruded by diorite, granodiorite and quartz monzonite porphyry at La Caridad mine area. La Caridad porphyry copper deposit, Pilares and the Santo Domingo breccia pipe (Cu-W) are located in this block.

*Figure 2.- Simplified regional geologic map of the Nacozari mining district*
East Block: This block is characterized by premineral and postmineral rocks separated by an erosional unconformity. The premineral rocks are andesites and rhyolitic ignimbrites which are intruded by a quartz monzonite porphyry (mineral phase). These rocks are overlain by an ferruginous fanglomerate that represents the first phase of postmineral rocks. In the northern area the fanglomerate is covered by El Globo rhyolite (24 Ma, Livingston, 1973). La Caridad Antigua, a high sulfidation epithermal deposit, is located in this block (Fig. 2).

Many of the deposits of the southwestern North-America porphyry copper province (e.g. San Manuel-Kalamazoo, Ajo, Cananea) have been significantly faulted, extended and rotated during Oligocene and Miocene time. The magnitude of rotation varies from moderate (30° to 60°) to severe (60° to 90°) (Wilkins and Heidrick, 1995). However, the central block of the Nacozari mining district has been drilled vertically for more than 800 m in the contact between the vertical breccia Pilares and the host rock, suggesting that the central block is upright and untilted.

**DEPOSIT GEOLOGY**

Plutonic and volcanic rocks compose the mineralized rock suite of La Caridad porphyry copper deposit. Approximately 90 percent of the mineralization is contained in the quartz monzonite porphyry and hydrothermal breccia. Other igneous and volcanic rocks associated with the deposit are andesites, diorites, granodiorites, aplites and porphyry dikes. The mine scale geologic map is shown in Figure 3.

Units are described in order of deposition or emplacement. The Oldest rock in the area are andesites, which form the host rock for the deposit. These rocks are intruded by diorite dikes that range from fine to coarse grain. Petrographically, the diorite porphyry, has a hypidiomorphic-granular texture and is composed of 40 to 60 % of euhedral plagioclase phenocryst (An 40-45), clots of biotite (20-30%), quartz (15-20%) and K-feldspar (2-3%). Locally there are breccia of diorite and andesite. These rocks are located in the southwest and west part of the deposit.

The granodiorite occupies most of the east part of the deposit, plagioclase (An 32-36) appears as euhedral to subehedral crystals (35 –45%) that range in size from 0.5 to 5 mm. This rock is composed of euhedral K-feldspar phenocrysts (20-25 %), quartz (20-25%) and subehedral biotite (7-10%). Accessory minerals include apatite, rutile, sphene, zircon.

The quartz monzonite porphyry consists of crowded porphyry with 50 % of phenocrysts. The sizes of the phenocrysts normally range from 1 to 5 mm, locally can reaching 15 mm. The relative abundance minerals in this rock is plagioclase 30-35%, micropertithic, twinned K-feldspar phenocryst 5-10%, quartz eyes 5-10% and biotite 5-10%. Accessory minerals include apatite, rutile, sphene, and zircon. Quartz monzonite porphyry is the productive rock in the deposit; and intrudes the contact between the granodiorite and the diorite-andesite.

Irregular bodies termed pegmatite (Reyna y Mayboca, 1986) occur in the central and peripheral portions of La Caridad deposits. These bodies consist mostly of coarse-grained interlocking biotite crystals with massive quartz and minor K-feldspar.

Barren Tan porphyry dikes intruded the rocks mentioned above. This unit is a crowded porphyry with an average phenocryst content of 15-20% vol. (quartz eyes and plagioclase). Narrow aplitic dikes 20-120 cm wide are located in the central part of the deposit.
Large bodies of siliceous hydrothermal breccia are located around and in the quartz monzonite porphyry. The breccia is monolithic to polimictic depending to the adjacent rocks, and is related to the intrusion of the porphyry complex. The high-grade mineralization is hosted in these rocks.

Although, the La Caridad geology and the intrusive lithologic units have been studied and established before, it is still debated whether if the quartz monzonite porphyry is the product of multiple intrusions (Reyna and Mayboca, 1986, Contla, 2002, Pers. Comm.) or a single intrusion (Seagart et al, 1974, Echevarri, 1971, 1973, Berchenbritter, 1976). Field observation indicates no cross cutting relations between the intrusive units suggested by Reyna y Mayboca (1986).

Figure 3.- Geological map of La Caridad mine area, plan view at 1290m level.

STRUCTURE
More than 500 faults were analyzed in La Caridad Pit at benches 1380 and 1305. These data exhibit two dominant trends: a N31°E/68°NW and a N26°W, 70°SW (Fig. 4). The NE system is less abundant that the NW orientations. These trends are the same prominent directions as those reported for Laramide stocks throughout Arizona (Rehrig and Heidrick, 1972; Heidrick and Titley, 1982). Fracture density varies from 0.2 to 0.4/cm on the upper benches, to 0.2 to 0.3/cm on the lower benches (Esquivias-Flores, 1998).

ALTERATION AND MINERALIZATION
The main stages of alteration and mineralization comprise an early episode that is represented by K silicate veins with orthoclase-quartz-anhydrite-biotite in the intrusive complex and a pervasive
biotization of andesites and diorites, with propylitic assemblages around this biotitic zone. This early alteration includes weak mineralization consisting of magnetite, chalcopyrite, molybdenite, sphalerite and pyrite. This episode was followed by the emplacement of hydrothermal breccia at the contact between the andesite-porphyry and porphyry-granodiorite.

A second hydrothermal mineralization event is represented by quartz veins associated with pyrite, sericite and chlorite, and also occurs as pervasive replacements. Tourmaline occurs as acicular radiating crystals intergrown with sericite, pyrite and quartz. This event generated the main mineralization, with mineralization of chalcopyrite, pyrite and lesser molybdenite.

A High sulfidation event that represent the latest alteration stages and the collapse of the system, affected the central part of the pit and is represented by quartz-tennantite-chalcopyrite-pyrite-sericite veinlets. Lead-zinc-silver mineralization was emplaced as peripheral veins during the final stages.

Irregular bodies termed pegmatites and veinlets containing coarse molybdenite and pyrite with minor chalcopyrite cut all the hydrothermal alteration zones. Supergene mineralization, which has been mined out, was present as a blanket of about 2 km in diameter with an average thickness of approximately 50 m and ranging from 10 to 230 m (Seagart et al., 1974).

AGES
Available radiometric ages of major intrusive rocks are shown in figure 5. The K-Ar ages for this deposit range from 53.5 to 55 Ma (Livingston, 1973, 1974; Damon 1968, Damon et al., 1983). K-Ar dating shows significant discrepancies with respect to the observed field relationships. Field mapping indicates the following sequence of intrusion: andesite, diorite, granodiorite, quartz monzonite porphyry, pegmatite bodies, tan porphyry, aplites, however, K-Ar dates suggest that the host diorite (49.8± 1.2 Ma) is younger than the quartz monzonite porphyry (53.1± 0.8 Ma).
and the pegmatite (55.2 to 50.4 Ma), both of which are observed to cut the quartz diorite porphyry in the field. These discrepancies are possibly the result of resetting of the radiometric clock by a later thermal event (e.g. intrusion of pegmatites and or quartz monzonite porphyry).

La Caridad Antigua
La Caridad Antigua is located 3 km east of La Caridad ore body in the hanging wall of La Caridad Fault, and was described by Wandke (1925). This deposit was mined at the beginning of the past century (1907-1916) and is hosted in latites and rhyolites that are intruded by a small quartz monzonite porphyry. This deposit has an acid-sulfate epithermal mineral association that includes pyrophyllite, kaolinite, sericite, alunite, quartz and barite as alteration minerals and a variety of sulfides that include chalcopyrite, pyrite, enargite, bornite and tennantite. The quartz monzonite porphyry intrusion generated a massive silicic alteration that extends for more than 100 m laterally away from the deposit.
La Caridad Antigua is believed to represent the high level portion of a porphyry copper system with a gap between both deposit of ~2-3 km. Given the relatively short period of hydrothermal activity (53.6 ± 0.3 Ma, Re-Os in molybdenite in K and phyllic alteration), the identical ages for the host rocks and mineralization, and the intimate spatial association, it is highly improbable that the two deposits are independent and unrelated. It is more likely that the two deposits were formed from a single magmatic-hydrothermal system that evolved from porphyry Cu-Mo deposit at depth to high sulphidation epithermal at shallow levels.

CONCLUSIONS

La Caridad porphyry copper deposit is located at the contact between diorite-andesites and the granodiorite, which controlled the location of the quartz monzonite porphyry, the mineralization and the alteration.

Similar Re-Os mineralization ages obtained from the potassic and phyllic alteration zones suggests a single and short period of mineralization

La Caridad porphyry copper is located in an un tilted block and exhibits two dominant trends: a N31°E/68° NW and a N26°W/ 70° SW, similar to those reported in other North America porphyry deposits.

The mayor introduction of copper mineralization occurred during phyllic alteration event.

Field relationships, structures and radiometric ages support the general hypothesis of a spatial and temporal link between La Caridad porphyry Cu-Mo deposit and La Caridad Antigua high sulphidation epithermal system. This spatial and temporal link between these two deposits has not been previously described in the North American porphyry copper province.
ACKNOWLEDGEMENTS

We are most grateful to Grupo Mexico for allowing access to the mine operations and logistics and to the Arizona Geological Society for generous financial support. In particular, we would like to thank to Ing. Remigio Martinez, Ing. Narcizo Javier Olvera, Ing. Jose Contla, Ing. Marco Figueroa, Sergio Castro, Dr. John Chesley and Dr Chris Eastoe for their help and for interesting discussions.

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