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4. The Quebrada Colorada vein: Geology, geochemistry, and genesis of bonanza-grade mineralisation at the El Peñón epithermal Au-Ag deposit, northern Chile

4.1 Introduction

The El Peñón Au-Ag deposit currently comprises six epithermal veins that are hosted by volcanic rocks in the Paleocene to early Eocene magmatic arc of northern Chile. Measured, indicated, and inferred resources for the El Peñón deposit are 8.4 million metric tonnes at 14 g/t Au and 234 g/t Ag, and ongoing exploration is adding to the resource. An important part of the resource is the bonanza-grade Quebrada Colorada vein that contains 1.4 million metric tonnes of ore at 31 g/t Au and 499 g/t Ag. Worldwide, epithermal deposits are notable for their Au-Ag contents, yet <1 percent are classed as bonanza deposits (>1 mt ore, >30g/t Au; Sillitoe, 1993; Sillitoe 2002; Sillitoe and Hedenquist, 2003). Detailed study of the geology and geochemistry of the Quebrada Colorada vein allows assessment of the controls on Au occurrence in a bonanza-grade epithermal Au-Ag deposit and processes responsible for its formation.

Mine and exploration geologists have generated abundant data from the Quebrada Colorada vein since the early 1990s, and especially since mining began in 2000. Thousands of Au and Ag assays are available for samples collected from the active mining face as drifting proceeded along strike, and these are typically available every 3-5 m along the strike of the vein where it has been mined. Hundreds of additional Au and Ag assays are available from drill intercepts of the vein. Detailed mapping of the vein, carried out at cm-scale using tape measure and precisely measured base stations, has been done throughout the course of mining by El Peñón mine geologists. As such, data are available relating Au and Ag contents to detailed measurement of the locations, widths, and orientations of the vein. Since ore grades (>5 g/t Au equivalent) are primarily contained in the vein and not adjacent wallrocks, grade-tonnage measurements of the ore body closely approximate that of the vein.
This study synthesises data generated during exploration and mining of the Quebrada Colorada vein. Building upon these data, Au occurrence is studied in detail with examination of its relationship to gangue mineralogy and textures. Knowledge about the composition of fluids and temperatures of formation come from fluid inclusion and oxygen isotope analyses of vein quartz. Detailed geochemistry of vein samples refines the knowledge of Au and Ag contents, allows comparison of Au and Ag contents to that of other trace elements, and allows estimates of the original mineralogical composition of the vein, since modified by pervasive supergene weathering down to ~400 m depth. Comparison of Au and quartz contents of the vein to mass fluxes in analogous modern geothermal environments, combined with $^{40}$Ar/$^{39}$Ar age determinations of vein adularia, allows consideration of the duration of time necessary to produce a bonanza-grade epithermal deposit. All these data together provide a framework for understanding the physical and chemical controls and genesis of bonanza-grade epithermal Au-Ag mineralisation.

4.2 Geologic Setting

El Peñón is located in the Central Depression of northern Chile, a physiographic province bounded to the west by the Coastal Cordillera and to the east by the Domeyko Cordillera (Fig. 4-1). The geology of the Central Depression is dominated by products of Late Cretaceous to early Eocene magmatic arcs that developed to the east of a Jurassic to Early Cretaceous magmatic arc following Middle Cretaceous orogeny (Coira et al., 1982; Boric et al., 1990; Davidson and Mpodozis, 1991). These rocks are part of a large volcanic suite, known as the Paleocene belt. It comprises basaltic to rhyolitic lavas and tuffs, subvolcanic porphyritic intrusions, and granitoid stocks that extend from southern Peru to central Chile and range in age from 72 to 40 Ma (Boric et al., 1990; Marinovic et al., 1995; SERNAGEOMIN, 2003; Fig. 4-1).
Figure 4-1. a. Map of Chile showing the location of the Paleocene belt and the El Peñón district. b. Map showing the location of epithermal and porphyry Cu deposits in the Paleocene belt of northern Chile and the boundary of Minera Meridian’s El Peñón property. Reported ages are from Puig et al. (1988), Camus (1990), Camus and Skewes (1991), Sillitoe (1991), and Singer et al. (2002). The darker gray shaded regions show outcrops of Late Cretaceous and early Tertiary volcanic and intrusive rocks that define the Paleocene belt of northern Chile (Marinovic et al., 1995; SERNAGEOMIN, 2003).
Epithermal Au-Ag mineralisation in the Paleocene belt occurs as veins, breccias, and disseminated deposits (El Peñón, Faride, El Soldado, Cachinal de la Sierra, and El Guanaco) that formed from two contrasting fluid types. Hydrothermal minerals (quartz, adularia, sericite/illite, chlorite, carbonate) associated with Paleocene to early Eocene deposits at Faride, El Soldado, and Cachinal de la Sierra (Fig. 4-1; Puig et al., 1988; Camus, 1990; Camus and Skewes, 1991; Sillitoe, 1991) reflect formation from near-neutral pH, reduced fluids. In contrast, hydrothermal minerals (quartz, alunite, kaolinite) associated with the early to middle Eocene El Guanaco deposit (Fig. 4-1; Camus, 1990; Sillitoe, 1991), as well as alteration associated with Late Cretaceous and Eocene intrusions, reflect formation from acidic pH, oxidised fluids. Hydrothermal alteration associated with each of these fluid types occur in the El Peñón district, but important Au-Ag mineralisation is only known to be associated with near-neutral pH, reduced fluid.

The geology of the El Peñón district comprises basaltic to rhyolitic, pyroclastic and flow units, subvolcanic rhyolites, and volcaniclastic breccias of Late Cretaceous to early Eocene age and of inferred Early Cretaceous age (Fig. 4-2; Zuluaga, 2004). Paleocene and early Eocene volcanic rocks host the El Peñón deposit. This stratigraphy consists of a lower sequence of volcanic breccia and andesitic to basaltic flows overlain by a sequence of rhyolitic to dacitic pyroclastic rocks (59.2 ± 1.6 Ma, K/Ar; Cornejo et al., 2003), dacitic to andesitic flows, and volcanic breccia. These rocks are intruded by, and the upper parts intercalated with, rhyolitic flows and domes (54-55 Ma, 40Ar/39Ar and U/Pb; Cornejo et al., 2003). The mostly flat-lying to gently east- and south-dipping volcanic rocks are intruded by minor andesitic dikes of likely early Eocene age that appear to be coeval with Au-Ag mineralisation at El Peñón mine (Robbins, 2000). Andesites south of the district have ages (50.5 ± 1.7 to 52.9 ± 1.8 Ma, K-Ar; Cornejo et al., 2003) that partly overlap the age of Au-Ag vein formation at El Peñón. The Paleocene and early Eocene volcanic rocks are locally intruded by 48.2 ± 1.3 Ma (K-Ar; Rojas, 1994) diorite that is exposed in the eastern and
Figure 4-2. Geologic map of the El Peñón district, as defined by the Minera Meridian property boundary (heavy outline), simplified from Zuluaga (2004). White areas are covered, except for some outside the property boundary where the geology is only partially mapped. At the El Peñón deposit north- and northeast-trending vein ore bodies are shown in black; andesite dikes are not resolvable there at this map scale.
southern parts of the district, locally in fault contact with Paleocene and early Eocene volcanic rocks (Zuluaga, 2004).

The dominant faults in the district controlled the margins of a graben containing Paleocene and early Eocene rocks. On the west side of the district, Falla Dominador trends north-northeast and places Early and Late Cretaceous volcanic rocks and Late Cretaceous intrusive rocks against Paleocene and early Eocene volcanic rocks (Fig. 4-2; Zuluaga, 2004). North-trending faults with up to hundreds of meters of displacement define the eastern margin of the graben and place Eocene intrusions against Paleocene and early Eocene rocks (Zuluaga, 2004). Throughout the district, faults displaying both normal and, less commonly, reverse displacements exhibit offsets of meters to tens of meters and trend north-south, northeast, or northwest (Zuluaga, 2004).

### 4.3 The El Peñón Deposit

Epithermal veins are hosted by rhyolite and dacite flows and minor pyroclastic and volcaniclastic rocks that are spatially associated with a rhyolite dome complex that extends for at least 3 km east-west and 6 km north-south (Fig. 4-3; Robbins, 2000). Six distinct veins host Au-Ag ore bodies, with the Quebrada Colorada, Quebrada Orito, and Discovery Wash veins currently in production. Additional veins are being discovered with ongoing exploration drilling, and some of these may eventually contribute to the resource.

The lowest part of the stratigraphy in the deposit area is a sequence of dacitic to andesitic flows with minor intercalations of volcaniclastic rocks that are probably equivalent to rocks exposed >1 km west and north of the mine area (Fig. 4-3). Overlying these rocks, the stratigraphy is dominated by a rhyolite flow-dome complex that comprises three sequences of rhyolite that are separated by dacite flows, pyroclastic rocks, and minor volcaniclastic rocks. Rhyolites from northwest of the deposit area have been dated at 54.4 ± 0.2 Ma and 55.4 ± 0.2 Ma (U/Pb; Cornejo et al., 2003) and 54.5 ± 0.6 Ma (Ar/Ar; Cornejo et al., 2003).
Figure 4-3. Mine area geology and location of the El Peñón ore bodies. The veins are shown as the surface projection of 5 g/t Au equivalent gradeshells.
Knowledge of vein mineralogy mainly comes from study of the Quebrada Colorada vein, and the mineralogy of other vein ore bodies (Quebrada Orito, Cerro Martillo, Discovery Wash) is generally the same. Veins are comprised of crustiform bands and hydrothermal breccias that contain quartz, adularia, quartz pseudomorphs of platy calcite (lattice textures), abundant Fe- and Mn oxyhydroxides, and, locally wallrock clasts. The dominant ore minerals are electrum, acanthite, and minor Ag-sulfosalts. Trace relict pyrite, chalcopyrite, and galena occur in oxidised veins, and they comprise, along with sphalerite, approximately 3% of veins in unoxidised drill intercepts below ~1500 m asl. In addition to pyrite and base metal sulfides, unoxidised veins contain up to 30% Ca-, Mn-, Fe-, and Mg-bearing carbonate minerals.

North-trending, steeply west- and east-dipping faults host the highest-grade Au-Ag-bearing veins, northeast-trending, moderately to steeply northwest-dipping faults host veins with generally lower Au-Ag grades, and northwest-trending, moderately to steeply southwest- and northeast-dipping faults host mostly barren quartz and calcite veins (Robbins, 2000). North-trending faults and veins are commonly cross cut by northeast- and northwest-trending faults and veins, but mutually cross-cutting relationships are also locally observed. Faults hosting vein ore bodies show vertical displacements of a few meters up to ~10 m, except at Cerro Martillo where stratigraphic offsets indicate vertical displacements up to 70 m. Vein ore bodies show slight variations in strike, dip, and dip direction along their strike lengths and vertical extents. The veins are continuous or occur as closely spaced or partially overlapping segments. The strike lengths of individual ore bodies range from <1 km at Cerro Martillo to 4 km at Quebrada Orito. The vertical extent of Au-Ag ore ranges from ~1365 to 1985 m asl, with individual ore shoots having maximum vertical extents mostly 350-450 m. Vein widths are variable, from decimeters to several meters, and the fault zone occupied by crushed vein material at Quebrada Orito also contains discrete hydrothermal breccias up to several meters in width. Veins are cut by later, west- to northwest-trending faults that are mostly steeply to shallowly northeast- or southwest-dipping. Displacements along later faults show both normal
and reverse offsets of mostly centimeters to a few meters, except at the northern end of the Quebrada Orito vein (Fig. 4-3) where reverse faults show displacements up to 50 m (B. Wulftange, pers comm., 2003).

Adularia from the Quebrada Colorada, Quebrada Orito, and Cerro Martillo veins range in age from $53.18 \pm 0.28$ Ma to $51.92 \pm 0.53$ Ma based upon $^{40}$Ar/$^{39}$Ar step-heating experiments presented in Chapter 3. The ages of the Quebrada Colorada and Cerro Martillo veins overlap, whereas the Quebrada Orito vein is at least 30,000 years younger at the 95% confidence level.

Hydrothermal alteration of host rocks is recognised in drill cores up to 1.5 km from vein ore bodies. Quartz, adularia, albite, illite, chlorite, smectite, calcite, and pyrite replace primary rock components, and quartz, adularia, calcite, and pyrite occur in mm-scale to, rarely, cm-scale veinlets. Generally, quartz and adularia dominate within meters of mineralised veins. Beyond this proximal zone, a hydrothermal mineral assemblage comprising variable amounts of quartz, feldspar, clay minerals, carbonate minerals, and pyrite is present (Warren et al., 2004). Though their mineralogy does not significantly or systematically vary, silicon and potassium contents of these rocks generally increase toward veins, often accompanied by decreasing sodium and calcium contents (see Chapter 5). Calcite, mixed-layer chlorite-smectite, and rare Ca-zeolites are most common hundreds of meters from mineralised veins. The absence of temperature-dependent clay mineral zoning is notable (Warren et al., 2004), since it is commonly observed surrounding epithermal Au-Ag deposits formed from near-neutral pH fluid (Lindgren, 1933; Buchanan, 1981; Heald et al., 1987; Izawa et al., 1990; White et al., 1995; Simpson et al., 2001) and in modern epithermal environments of geothermal systems (Browne and Ellis, 1970; Henley and Hedenquist, 1986; Simmons and Browne, 2000).
4.4 Methodology

Diverse datasets have been generated and compiled in order to characterise the geology and geochemistry of the Quebrada Colorada vein. Several scales of observation were undertaken during this study: kilometer-scale observations of the entire vein, 100-meter-scale observations of vein segments, 1- to 10-meter-scale observations at underground locations in the mine, centimeter- to decimeter-scale observations of hand samples, micron- to centimeter-scale observations of thin section, and micron-scale observations of individual mineral grains and fluid inclusions.

During field visits in 2001 and 2002, underground exposures were studied and vein samples collected from more than 50 localities in order to document vein mineralogy and textures (Appendix III). Of more than 200 hand samples examined, 106 were selected for transmitted and reflected light petrographic study to document Au occurrence and vein mineralogy and textures (Appendices IV and V). Duplicate offcuts of 87 of the 106 samples studied petrographically were analysed for major oxides and trace elements to compare with Au occurrence and to provide normative mineral compositions of the vein. Further details of the geochemistry of minerals forming the Quebrada Colorada vein were obtained from electron probe microanalyses (EPMA; Appendix VI) of ore minerals, carbonate minerals, and sphalerite. The composition, temperature, and pressure of hydrothermal fluid that formed the El Peñón deposit were determined from microthermometric measurements of fluid inclusions (49 doubly polished fluid inclusion plates) and δ18O analyses of 11 discrete quartz bands and hydrothermal breccias from 3 hand samples. Detailed vein maps and closely spaced (3 to 5 m) Au and Ag assay data generated by El Peñón mine geologists were compiled to compare vein geometry, strike, dip, and width to Au and Ag grades. Additional details regarding collection, processing, and interpretation of these datasets are provided in the relevant sections that follow.
4.5 Geology of the Quebrada Colorada vein

The Quebrada Colorada vein is deeply weathered and oxidised, which affects the compositions of both hypogene gangue and ore minerals. Vein textures and paragenetic relationships are partly obscured by the products of supergene weathering and also are modified by syn- and post-mineralisation faulting and hydrothermal brecciation. The majority of drill intercepts consist of RC drill chips. In addition to being uncommon, core samples are poorly preserved and incomplete due to splitting of samples for geochemical analyses. Since this study was carried out during active mining of the Quebrada Colorada vein, locations and duration of observations were constrained by necessary coordination with mining activities. Much of the information about the geology and detailed geochemistry of the vein therefore comes from large hand samples, up to 0.5 m long, that were collected from the underground workings during field visits in 2001 and 2002. Most of these samples were collected over a vertical extent of ~120 m (1643-1762 m asl). A few of the samples studied in detail are from unoxidised drill core intercepts located at ~1500 m asl. Most of the samples of this study are therefore representative of middle to upper levels of the ore body (total vertical extent 1377-1877 m asl), and well-preserved hypogene carbonate and sulfide minerals are known only from the lower part of the ore body. Figure 4-4 shows the longitudinal projection of the Quebrada Colorada 5 g/t Au equivalent gradeshell, plan view of the vein at mine level 1680-1682 m asl, geology of host rocks, and locations where observations of the vein were made and from which hand samples were collected for petrographic and geochemical analyses.

The vein generally trends north and mostly dips steeply to the west, though some parts, particularly the southern part, dip steeply to the east. It has a strike length of ~2 km, vertical extent of ~500 m (1377-1877 m asl), and varies in width from 0.5 m to 4.5 m. The vein rakes very shallowly to the south, as do the other vein ore bodies of the El Peñón deposit, likely owing to post-mineralisation tilting of the host volcanic stratigraphy to the south and
Figure 4-4. Longitudinal projection of the Quebrada Colorada 5 g/t Au equivalent gradeshell, host rock geology, and location of samples of this study (Y and Z coordinates from Table 4-6). There are numerous small “islands” within the gradeshell that are below the 5 g/t Au equivalent grade cut-off.
east. Taking this into account, the maximum, continuous vertical extent of the Quebrada Colorada ore body at any single location is ~350 m. Currently, mining provides access to >1.5 km of its strike length and ~200 m of its vertical extent.

Host rocks are dominantly rhyolite and dacite with minor rhyolitic tuff and volcaniclastic breccia (Fig. 4-4). Alteration is like that described above for all the veins of the El Penón deposit. Proximal quartz and adularia alteration consists of massive flooding and hydrothermal breccia with quartz and adularia matrix enclosing wallrock clasts. Veinlets and hydrothermal breccia seams (<10 cm) containing quartz and adularia locally extend from the vein into wallrocks. These offshoots locally reconnect with the main vein to form cymoid loops that envelop meter-scale wallrock horses/clasts. Locally, clay alteration, rather than quartz-adularia alteration, dominates wallrocks, particularly in tuff that hosts the uppermost part of the vein in the Carmin and Escarlata segments (>1740 m asl; Fig. 4-4). The vein has top, bottom, and along strike terminations that are located in all host rock types. Rheological contrasts between different host rock types do not appear to control the location of vein terminations, though veins are generally narrower and horse-tailing is more common where terminations occur in tuff, especially pervasively clay-altered tuff.

Knowledge about the periphery of the ore body is limited. During this study, there were few accessible mining levels near the top and bottom of the ore body, though the along strike terminations of vein segments were viewable at several locations and have been mapped in detail by mine geologists. There are few preserved drill core intercepts, and RC drill intercepts comprise only a few rock chips from mainly 1- to 2-m composite samples. Generally, the top, bottom, and along strike terminations of the ore body coincide with that of the vein. At most terminations the vein narrows before branching into splays and horsetails along strike. At some locations the vein pinches out and the host structure also terminates. This is most commonly the case for the top and along strike terminations, consistent with evidence for minimal vertical displacement of the host structure. At other locations the top of
the ore body, as observed in RC drill chips, is represented by mm-scale gray ± comb quartz veinlets. The bottom of the ore body is commonly characterised by brecciated vein and wallrocks that generally narrow downward to < 0.5 m wide, and the vein-hosting structure, represented by gouge and breccia, commonly extends beyond the lower termination of the gradeshell. In contrast, the bottom of the Quebrada Orito vein locally continues beyond the gradeshell (5 g/t Au equiv) and is up to 10 m wide (C. Robbins, pers. comm., 2004).

The Quebrada Colorada vein is comprised of four principal segments, from north to south, Magenta, Escarlata, Carmin, and Carmin Sur, and additional resources are being defined to the north and south along strike (Purpura and Bermellon segments, respectively; Fig. 4-4). Vein segments are defined by both continuity of the vein and continuity of ore grade (≥ 5 g/t Au equiv); the limits of ore bodies are generally defined by reduction in Au grade and vein widths below economic thresholds rather than breaks in continuity of the vein structure. The plan view map of the vein from the 1680-1682 mine level (Fig. 4-4) shows common vein segment orientations and relationships to one another. Further details of vein orientations and geometries and their relationship to Au and Ag occurrence are described below.

4.6 Vein structure and relationship to the distribution of Au and Ag

Grade control requires that numerous assays be obtained during active mining of the Quebrada Colorada vein so that the distribution of Au and Ag are known. Grade control data available through October 2003 for the Quebrada Colorada vein were converted to Au and Ag grade-thickness values, and then assigned a location at the midpoint of the composite sample array. Grade-thickness was calculated by multiplying Au concentration by the width of the sample and summing the products of each sample collected across the mining face at each grade control sample location (typically 5-8 samples at each location). These data were used to construct Figure 4-5 that shows the longitudinal projection of the 5 g/t Au equivalent
Meters asl

Au grade-thickness
- Maximum: 2046.16
- Minimum: 0.07
- Average: 61.8

Ag grade-thickness
- Maximum: 61267.9
- Minimum: 2.4
- Average: 1066.6

Ag/Au ratio
- Maximum: 427.3
- Minimum: 0.8
- Average: 24.2
Figure 4-5. Distribution of Au and Ag in the Quebrada Colorada vein. Shown are the longitudinal projection of the 5 g/t Au equivalent gradeshell, Au and Ag grade-thickness (parts per million-meters), and Ag/Au of part of the Quebrada Colorada vein. Compilation and processing of the gridded Au and Ag data are described in the text.
gradeshell, Au and Ag grade-thickness, and Ag/Au ratio. Gridded data were created using ArcMap8.2® software; values were assigned to 1-m² cells by applying a 10-m search radius and weighting the input values by the inverse of the distance squared from the centre of the cell. Detailed vein maps produced by El Peñón mine geologists provide additional information about the geometry and structure of the vein; some of these maps have been compiled, along with Au and Ag grade-thickness data, in order to compare vein geometry, structure, and Au and Ag grade-thickness (Figures 4-6, 4-7, and 4-8). Variations between the different vein segments are shown with reference to the 1680-1682 mining levels of the Magenta, Escarlata, Carmin, and Carmin Sur segments (Fig. 4-9). Vein width, dip, dip direction, and location of measurement were compiled from vein maps of 7 mine levels in the Carmin segment, 12 mine levels in the Escarlata segment, and 8 mine levels in the Magenta segment. Au and Ag grade-thickness data for each of these locations was extracted from the gridded data of Figure 4-5 using ArcMap8.2® software. The compiled structural data are compared with plots of width, dip, and dip direction versus Au and Ag grade thickness (Figure 4-10). Stereonet plots of the few structures for which kinematic information could be measured are shown in Figure 4-11.

The distribution of Au and Ag grade-thickness values show similar patterns (Fig. 4-5), partly related to their occurrence together in electrum (see below). Generally, values of Ag/Au are greater at depth and at the north and south ends of the Quebrada Colorada vein (Fig. 4-5). The Magenta segment in particular has notably higher Ag/Au values >30 throughout much of its along strike and vertical extent. Individual segments of the vein, i.e., Magenta, Escarlata, Carmin, and Carmin Sur, have highest Au and Ag grade-thickness values in their centres; outward from the centres along strike, and to some extent up and down dip, values typically decrease toward vein terminations (Figs. 4-5, 4-6, 4-7, and 4-8). Detailed plan maps of mining levels (Figs. 4-6, 4-7, and 4-8) show that the vein segments pinch out to the north and south along strike, vein widths mostly decrease above ~1700 m asl, and splays, bifurcations, and
Figure 4-6. Plan view maps of mining levels (approximate elevation, m asl) from the Magenta segment of the Quebrada Colorada vein showing the dip, width, geometry, Au and Ag grade-thickness values (parts per million-metres), and orientation of cross-cutting faults. Direction and length of arrows show the direction and magnitude of dip. Maps were produced by numerous El Peñón Mine geologists. Au and Ag grade-thickness data and calculations are described in the text. Faults are indicated with lines and tick marks that point toward the hanging wall.
Figure 4-7. Plan view maps of mining levels (approximate elevation, m asl) from the Escarlata segment of the Quebrada Colorada vein showing the dip, width, geometry, Au and Ag grade-thickness values (parts per million-metres), and orientation of cross-cutting faults. Direction and length of arrows show the direction and magnitude of dip. Maps were produced by numerous El Peñón Mine geologists. Au and Ag grade-thickness data and calculations are described in the text. Faults are indicated with lines and tick marks that point toward the hanging wall.
Figure 4-8. Plan view maps of mining levels (approximate elevation, m asl) from the Carmin segment of the Quebrada Colorada vein showing the dip, width, geometry, Au and Ag grade-thickness values (parts per million-metres), and orientation of cross-cutting faults. Direction and length of arrows show the direction and magnitude of dip. Maps were produced by numerous El Peñón Mine geologists. Au and Ag grade-thickness data and calculations are described in the text. Faults are indicated with lines and tick marks that point toward the hanging wall.
Figure 4-9. Mining levels 1680-1682 m asl in the Quebrada Colorada vein showing common relationships among the Magenta, Escarlata, Carmin, and Carmin Sur segments. The vein was mapped and dips measured by El Peñón Mine geologists. Au and Ag grade-thickness values were calculated as described in the text. Dip measurements are not available for the northern part of the Carmin segment.
discontinuities are generally more common near vein terminations, both along strike and up- and down-dip.

On the longitudinal projection (Fig. 4-5) parts of vein segments with high Au and Ag grade-thickness values have moderate to shallow apparent dips to the north and steep apparent dips to the north and south. These high grade-thickness values are parallel to the apparent dip of intersections of the dominantly north-trending Quebrada Colorada vein with crosscutting northwest- and northeast-trending faults that dip mostly to the north and less commonly to the south. Faults with these orientations locally offset the vein up to 1-2 m, and show both normal and reverse displacements (Figs. 4-6, 4-7, and 4-8; contacts migrate down-dip on the upthrown side of the fault). The aforementioned parallelism between apparent dip of fault intersections and parts of the vein with high grade-thickness values suggests that structural controls on vein grade-thickness are possibly related to the same stress regime as that responsible for forming mapped faults. This stress regime would have been dominant both during and after vein formation, since northeast- and northwest-trending faults locally offset the vein (Figs. 4-6, 4-7, and 4-8).

X-Y plots comparing Au grade-thickness, vein width, and vein dip direction provide information about the geometry of and the distribution of Au in the Quebrada Colorada vein. Data from the Carmin, Escarlata, and Magenta segments are considered separately, and the relationships described below are interpreted from X-Y plots that are shown in Figure 4-10. In the Carmin and Escarlata segments, plots of vein dip versus width show that steeper portions of the vein are generally wider; in the Magenta segment, such a relationship is less apparent. The three vein segments all show higher Au grade-thickness values in steeper parts of the vein, partly related to steeper veins generally being wider. Subtle trends in the data from the Escarlata and Magenta segments suggest that west- and east-dipping parts of the vein are narrower as strike direction bends further west of north (i.e., dip direction bends further south of west). Data from the dominantly north-trending Carmin segment show no correlation.
Figure 4-10. Plots comparing dip, width, dip direction (strike), and Au grade-thickness (Au GxT) in the Magenta, Escarlata, and Carmin segments of the Quebrada Colorada vein. Data were compiled from vein maps produced by El Peñón mine geologists and extracted from gridded Au grade-thickness values of Figure 4-5 using ArcMap8.2® software (see text).
between vein widths and dip direction (Fig. 4-10). Similarly subtle trends suggest that in west-dipping parts of all three vein segments, Au grade-thickness values decrease as the strike of the vein bends further west of north, partly relating to the aforementioned decrease in vein width as the strike of the vein bends further west of north. The same relationship is seen in east-dipping parts of the Escarlata and Magenta segments. East-dipping parts of the Carmin sector show the opposite relationship, with Au grade-thickness values decreasing as the strike of the vein bends further east of north. Except for east-dipping parts of the Carmin segment, decreasing Au grade-thickness values and vein widths as the strike of the vein bends to the west of north agree with these parts of the structure being “tighter” during vein formation. In all three segments the highest Au grade-thickness values occur in steeper parts of the vein that strike within 10° of north. Though there is a general trend of increasing Au grade-thickness values with increasing vein width, it is important to note that the highest Au grade-thickness values are not associated with the widest parts of the vein.

The sense of displacement along some faults is constrained by their orientations and mapped offsets of the vein where its orientation is known (i.e., Figs. 4-6, 4-7, and 4-8) or where stratigraphic offsets occur; however, only a few kinematic indicators were observed and measured during this study (Figure 4-11). Three slickensides were measured on faults hosting the Escarlata segment of the Quebrada Colorada vein; these faults trend further east of north than what is typical in other vein segments. One of the vein-hosting fault surfaces has slickensides indicating dominantly normal dip-slip displacement, with a small right-lateral slip component. The other two fault surfaces have slickensides that indicate dominantly strike-slip displacements, either left-lateral strike-slip displacement if the vertical component is normal or right-lateral strike-slip displacement if the vertical component is reverse. Slickensides, orientations, and vein offsets associated with crosscutting faults indicate several different senses of displacement. Northwest-trending faults that dip steeply to the northeast have normal displacements, based upon the associated offset of the vein, and show both left-
Figure 4-11. Lower hemisphere projection of fault planes and slickenside measured in the Quebrada Colorada mine workings. Faults are indicated by great circles and lineations by dots that correspond to the dip and plunge of fault surface striations. Three measurements are from the vein hosting structure; other measurements are from cross-cutting faults.
and right-lateral strike-slip components. Right-lateral oblique displacement characterises the northwest-trending and southwest-dipping fault. The west-northwest-trending, shallowly southwest-dipping reverse fault, based upon associated offset of the vein, has slickensides that indicate displacement with a right-lateral strike-slip component.

The relative timing of faults is constrained mainly where northwest- or northeast-trending faults are younger and crosscut vein-hosting faults. Elsewhere, mutually crosscutting relationships between northeast-trending faults and dominantly north-trending, vein-hosting faults are observed. At level 1643 of the Magenta segment (Fig. 4-6), a northeast-trending fault hosts vein and also crosscuts the main, north-trending, ore-hosting fault. Similar mutually crosscutting relationships also characterise the intersection of the Quebrada Colorada and Discovery Wash ore bodies (Fig. 4-3).

Displacements indicated by measurements of fault surface lineations from the vein-hosting structure and the geometries of vein segments, the Quebrada Colorada vein, and the El Peñón deposit (Figs. 4-3, 4-4, 4-6, 4-7, and 4-8) are most compatible with sense of movement corresponding to right-lateral oblique, dominantly dip-slip displacement during vein formation. Dip-slip displacement with a slight right-lateral oblique-slip component is compatible with the geometry of the Escarlata segment (Fig. 4-7), where widest parts of the vein generally occur in the north-northeast-trending part of the vein, between north- to north-northwest-trending parts. Depending on the exact orientation of the stress field, dip-slip displacement with a right-lateral oblique-slip component could have resulted in greater magnitudes of separation between the hanging wall and footwall in the north-northeast trending part of the Escarlata segment relative to the north- to north-northwest-trending parts. The geometry of the Quebrada Colorada vein as a whole is similarly compatible with a component of right-lateral oblique slip with the northeast-trending part of the Escarlata segment possibly forming a right-lateral extensional step-over between the dominantly north-trending Magenta and Carmin segments (Figs. 4-4, 4-9). At the deposit-scale a similarly
oriented right-lateral extensional step-over is represented by the northeast-trending Discovery Wash ore body located between the dominantly north-trending Quebrada Orito and Quebrada Colorado ore bodies, and vein ore bodies (Quebrada Orito, Quebrada Colorada, and Cerro Martillo) form a right-lateral en echelon array (Fig. 4-3). In contrast to the central part of the Escarlata segment, the widest parts of the Magenta and Carmin segments are north-trending and mostly coincide with the central parts of slightly convex-to-the-west segments, the sites most favourable for opening and vein filling along a structure dominated by dip-slip displacement (Newhouse, 1940; Figs. 4-6 and 4-8).

4.7 Gangue mineralogy and textures

The Quebrada Colorada vein originally contained gangue minerals consisting of crustiform bands and breccias of quartz, adularia, and carbonate minerals. Carbonate minerals are only preserved in drill intercepts below ~1500m asl; their former presence at higher levels is inferred from quartz and oxide pseudomorphs of platy calcite and bladed to acicular carbonate minerals (see below). Complex interleaved bands and breccia are related to variable fracture dilation during hydrothermal activity along the strike and dip of the vein and syn- and post-mineralisation faulting. Symmetrically banded deposits cannot be traced from the wallrock contacts to the centre of the vein, but they are recognisable locally, mostly at centimeter-scale. The combination of pervasive supergene weathering, complex vein filling, and syn- and post-mineralisation faulting and fracturing prevents determination of vein mineral paragenesis. This complexity is apparent at a wide range of scales from meters down to millimeters and varies both along strike and up and down dip.

Mapping of part of the 1652 level in the Magenta segment (Figure 4-12) illustrates typical along strike relationships between vein minerals, textures, and overprinting effects of supergene weathering. Banded deposits may be continuous and sub-parallel to the vein margins, locally convoluted, enveloping wallrock clasts/horses, or filling discrete lenses.
Figure 4-12. Map of part of the 1652 mine level in the Magenta segment of the Quebrada Colorada vein. Characteristics of vein filling minerals and the effects of syn- and post-mineralisation faulting, brecciation, and supergene weathering shown here are typical of much of the vein observed during this study. The location of samples collected for detailed study are shown along with the Au concentration of channel samples collected and analysed by mine staff. This map represents the most detailed and continuous observations that could be made underground; observations were made from the floor of the ~3 m high drift.
1. Coarse, white quartz filling elongate open space; similar discontinuous occurrences along vein margin; surrounded by bands of quartz, oxides, and white clay

2. White quartz-filled, elongate, irregular open space; similar to 1; appears massive with colloform textures visible locally; locally brecciated with oxide matrix; samples 1652-21A,B

3. Millimeter-scale bands of oxides and white clay; probably crosscut by 2; locally brecciated and chaotic; sample 1652-1

4. White quartz with abundant oxide fractures and staining; floods and brecciates silicified dacite wallrocks

5. Bands and breccia of white quartz extend into wallrocks

6. Dacite horses crosscut by white quartz veinlets and masses, locally crustiform; locally banded deposits enveloping the horse post-date veinlets in the horse

7. Irregular- to planar-banded quartz and oxides, similar to 4, appear to terminate at their contact with dacite horse

8. Continuation (?) of dacite horse veinlet(s) that pre-date horse formation

9. Irregular open space filled with quartz, oxides, and white clay; similar to 3 and 4; banding is better developed/preserved at the margins of this “zone”; comb and colloform textures are mostly obscured; hematite-rich part possibly cross cuts Mn-oxide-rich part

10. Quartz and clay-altered adularia bands with pervasive oxides; white quartz fills irregular, discontinuous open space within this “zone”, especially at the vein margin (to left) where it floods and cements brecciated wallrocks

11. Comb and colloform quartz; possible stringer off of 2

12. Millimeter- to cm-scale quartz bands; ~symmetrically filled open space with band width and crystal size increasing toward the centre; mostly sharp contact with wallrocks; pervasive oxides obscure textures; sample 1652-3

13. Massive white quartz and Mn-oxide breccia; locally extends into wallrocks

14. Chaotic bands of oxides, clay-altered adularia, and quartz; locally envelop clasts of dacite

15. String of brecciated dacite clasts that possibly formed a larger clast like that to the right

16. Millimeter-scale banding similar to 10; brecciated; obscured by pervasive oxides

17. Chaotic Fe-oxide and white clay bands; local and discontinuous

18. Coarse white quartz and adularia bands with pervasive Fe-oxide staining

19. Millimeter- to cm-scale quartz bands with pervasive Fe-oxide staining; appear to crosscut or were deposited within 20

20. Abundant oxides and minor white clay fill irregular open space; brecciated and chaotic

21. 10 cm wide interval of well preserved colloform banded quartz and oxides; locally incorporates small dacite clasts

22. Centimeter-scale banded quartz and oxides crosscuts banding/breccia similar to 14

23. Fractures filled with massive oxides

24. Slightly less chaotic equivalent to 20; possibly less affected by brecciation (?)

25.Probably equivalent to 2; well preserved mm- to cm-scale comb and colloform quartz with oxides accentuating banding

26. 1-3 cm wide white quartz veinlet in wallrocks

27. Oxide breccia enveloped by, or post-dating(?), banded deposits; crosscuts 28.

28. Open space filled with quartz, oxide, and white clay bands that are ~regular at the margins, passing inward to more chaotic (brecciated) and irregular bands; OR, cross-cutting breccia occupies the central part of the “zone”; Sample 1652-2B

29. Banded dark-coloured oxide and white clay

30. Textures obscured by oxides and clay, but probably similar to 25; vein becomes wider to the north, partly explained by wider chaotic/breccia zones; sample 1652-17A,B,C,D

31. White quartz and clay with green, supergene Cu minerals; probably crosscuts 24; sample 1652-4A,B,C,D,E

32. Similar to 31, but darker with more supergene Cu minerals and local cerrusite and/or anglesite; sample 1652-5
Relationships are commonly obscured by supergene weathering products and syn- and post-
mineralisation brecciation. Similar features characterise observed parts of the Quebrada
Coloradoa vein throughout its along strike and vertical extent. Figures 4-13, 4-14, 4-15a, 4-
15b, and 4-16 show examples of locations where sampling and observations were made and
provide further details of the complexity of relationships among vein filling minerals from the
Magenta, Escarleta, Carmin, and Carmin Sur segments, respectively. Hand samples collected
from these and other locations partly preserve successively deposited bands and provide
“snap-shots” of vein filling episodes. Figures 4-17, 4-18, and 4-19 show typical hand samples
that are characterised by diverse textures and complex relationships among the vein filling
phases. Figure 4-20 shows an atypical hand sample with well-preserved, successively banded
deposits; it is the best example of such banding studied. Observations from underground field
stations are given in Appendix III, preserved sequences of banded deposits are described in
Appendix IV, and occurrences of vein mineral textures are tabulated in Appendix V.

The gangue minerals and diverse range of textures, particularly of quartz, are
described below. The terminology used to describe vein textures follows that of Dong et al.
(1995). Most vein minerals and textures are found throughout the part of the vein that was
studied in detail. Except for hypogene carbonates and most sulfides that are restricted mainly
to levels below ~1550 m asl, there is no recognised zoning of minerals and textures (Fig. 4-
21).

4.7.1 Quartz

Quartz is the most abundant mineral and occurs throughout the vein as μm- to cm-
scale, anhedral to euhedral crystals that form crustiform bands and the matrix of hydrothermal
breccia. Colloform, comb, zonal, pseudoacicular, lattice (lattice-bladed), and massive textures
are observable in hand samples (Fig. 4-22). Colloform textures include spherical, cylindrical,
botryoidal, and mammilary varieties. Rarely, botryoidal textures grade into mm-scale moss
Figure 4-13. Composite picture of the active mining face at location MM734, Magenta segment, level 1702 showing the location of samples collected for detailed study. Numbers in the schematic map are Au assays (parts per million) from channel samples. Sample geochemical data are given in Tables 4-5, 4-6, and 4-8.
Figure 4-13 continued.

1 (0-50 cm): Banded quartz occurs with discrete mm-scale bands of Fe- and Mn-oxides. Approximately 50% of this interval is white quartz and adularia bands with minor Fe- and Mn-oxides, and the remaining 50% comprises earthy oxides, dominantly Fe- with lesser Mn-oxide. The eastern margin of this interval (5-10 cm) is coarse quartz with pervasive Mn-oxide along fractures and forming irregular masses.

2 (50-100 cm): Quartz with Mn-oxide and bright orange-red oxide forms cm-scale banding that envelopes clasts of quartz, adularia, and earthy hematite.

3 (100-150 cm; 734-155A,B): Banded quartz occurs with bands and irregular masses of Mn- and Fe-oxide. Locally, fine mm-scale colloform banding is visible. Coarse, late gypsum masses locally occur in vugs. Lozenge-shaped zones are filled with banded quartz. Intervals of bands and textures pinch and swell up- and down-dip and along strike.

4 (150-200 cm): This interval is like 3, but with an eastern margin (10-20 cm) of pervasive Fe-oxide.

5 (200-250 cm; 734-157): White quartz bands are interleaved with bands and masses of Fe-oxide.

6 (250-300 cm; FI-MM734-158): Fe-oxide bands envelop cm-scale clasts with quartz lattice texture. Clasts of colloform banded quartz look massive unless viewed on a clean surface.

7 (300-350 cm; 734-159): This interval is partly brecciated with local quartz lattice texture and white quartz and adularia bands enveloped in earthy, Fe-oxide.

8 (350-400 cm): Silicified dacite wallrocks contain abundant Fe-oxide fractures and cm-scale veinlets subparallel to the main vein.

9 (400-450 cm): Centimeter- and mm-scale white quartz and Fe- and Mn-oxide bands occur in discrete, closely spaced veinlets subparallel to the main vein. These veinlets probably merge up- and down-dip with the main vein so that wallrocks viewed here are horses along the margin of the vein.
Figure 4-14. Composite picture of the back at location MM560, Escarliata segment, level 1708 showing the location of samples collected for detailed study. Au and Ag assays of channel samples are not available at this location. Sample geochemical data are given in Tables 4-5, 4-6, and 4-8.
Figure 4-14 continued.

1: Silicified dacite wallrocks.

2: The eastern margin of the vein is generally light-coloured with variable red, yellow, and brown Fe-oxide and lesser Mn-oxide. Massive white to light gray quartz displays no readily apparent banding/texture. Abundant fractures dip 85-90° to the south. Irregular vugs are lined with quartz crystals and latest crystalline oxides and gypsum. Mn-oxide appears to vary along strike and is primarily fracture-controlled. This part of the vein is 50-90 cm wide and varies in width along strike due to an irregular margin with wall rock that locally incorporates wallrock clasts.

560-3: Inboard from 2. This part is 5-20 cm wide and has abundant hematite, lesser Mn-oxide, and yellow oxide or jarosite. A relatively continuous, 2 cm wide band of white to pink adularia appears to rim earthy Fe- and Mn-oxides and crustiform quartz bands, defining discontinuous, lozenge-shaped deposits that trend N10E. This part pinches and swells along strike. Very crude banding is displayed by <1 cm, white, clay-altered bands. Local hydrothermal breccia contains clear to gray quartz clasts. The west side of this part is characterised by preserved quartz and adularia banding with lesser oxides.

4: This part of the vein is 60-80 cm wide, comprised of yellow oxides, and located just to the east of the vein "centre." The eastern margin of this part is marked by 10 cm of brown to maroon oxides. This part contains brecciated quartz and adularia in a matrix of earthy yellow and red oxides with lesser white clay.

560-5: This part is located west of the vein "centre" and is 40-50 cm wide. Hematite and white clay accentuate bands of clear to gray quartz, white to pink feldspar, and form hematite-rich bands. Bands are a few millimeters to 2 cm wide. Hematite is earthy and friable, occurring with variable Mn-oxide. Some breccia textures and irregular-shaped open space are filled mostly with oxides.

560-6: This part contains abundant hematite with lesser Mn-oxide and white clay. Clear to gray comb and colloform quartz bands are 1-3 cm at macroscale but are comprised of 1-2 mm, alternating light and dark bands observable on clean/fresh surfaces. White to pink bands are probably adularia. Bands are generally continuous and slightly wavy. "Centre" portion contains abundant Mn- and yellow oxides forming the matrix of breccia containing banded quartz and adularia clasts.

7: The westernmost vein interval is similar to 6, but seems to be dominated by light-colored quartz with minor adularia. There is less hematite and more Mn-oxide than in 6. Locally, banding is continuous and sinuous but overall this part appears to be a chaotic hydrothermal breccia. Local, quartz lattice textures contain abundant Fe-oxide.

8: West side wallrock is silicified dacite.
Figure 4-15a. Composite picture of the back at location MM537-4, Carmin segment, level 1706 showing the location of samples collected for detailed study. Au and Ag assays of channel samples are not available at this location. Sample geochemical data are given in Tables 4-5, 4-6, and 4-8. Vein is ~1.5 m wide and strikes N10W. The east and west margins of the vein (537-1, 537-2A,B and 537-3A,B,C,D, respectively) are partly gradational into quartz-flooded and brecciated wallrocks. Vugs commonly contain euhedral quartz and Fe-oxides. The "centre" of the vein (537-5) is locally brecciated with euhedral quartz-lined cavities. Abundant earthy oxides obscure vein textures. Pervasive hematite, white clay, and breccia are related to a crosscutting structure, though the expression of the fault is very subtle in wallrocks. Lithic tuff wallrocks on the west contain Fe-oxides, white clay, and jarosite. Very poor viewing conditions limited observations at this locality.
Figure 4-15b. Composite picture of the back at location MM508, Carmin segment, level 1696 showing the location of samples collected for detailed study. Au and Ag assays of channel samples are not available at this location. Sample geochemical data are given in Tables 4-5, 4-6, and 4-8.

1: The east side of the vein contains abundant hematite and Mn-oxide. This part is crudely banded and gradational into brecciated and silicified wallrocks.

2: The "centre" of the vein contains bands that are locally accentuated by Mn-oxide and white clay. This part of the vein is mainly comprised of decimeter-scale, quartz-filled lenses with earthy, Fe-oxide centers. Local breccia contains abundant hematite.

3: The west side of the vein is crudely banded, but better preserved (visible) than on the east side. Fe-oxide and white clay locally accentuate banding. Rectangle shows location of large hand samples taken from this part of the vein.
Figure 4-16. Composite picture of the active mining face at location MM664+10, Carmin Sur segment, level 1640 showing the location of samples collected for detailed study. Sample geochemical data are given in Tables 4-5, 4-6, and 4-8. Numbers in the schematic map are Au assays (parts per million) from channel samples. This location is near the northern termination of the segment where the vein horsetails and ore grades (5 g/t Au equiv) are not maintained.
Figure 4-16 continued.

1: The hanging wall is comprised of flow-banded rhyolite with sheeted quartz veinlets. Quartz veins are white to gray ± amethystine and coarse (up to 1 cm), with variable Fe- oxyhydroxides, predominantly at the margins and in the "centre." Veinlets are generally parallel to main vein (ore zone).

2: A 15 cm wide quartz vein occurs in the hanging wall. Several (up to 1 cm) subparallel veinlets are like #1, but widen and merge with this vein. Between the 15 cm vein and the ore zone, four parallel sheeted veinlets up to 5 cm wide display mm-scale bands locally accentuated by Fe- and Mn-oxides. Flow-banded rhyolite clasts occur between the veinlets and are variably brecciated. Fe oxides compose earthy, friable zones which vary along strike and dip, generally occurring as lenses. Coarse (up to 1 cm) ± amethystine quartz occurs locally in the centre of veinlets.

3 (664-193): The west side of the main vein zone is partly gradational into brecciated, veined, and silicified flow-banded rhyolite wallrocks or forms a mostly planar contact with the wallrocks. This part of the vein consists of massive to crudely banded quartz, generally brecciated with abundant Fe- and Mn-oxides, jarosite, and white clay. Oxides and sulphates make the vein earthy and friable. Notable are distinctive orange-red oxides. Brown and yellow oxides locally form the matrix of breccia.

4 (FI-MM664-194): The centre portion of the vein contains mm- to cm-scale quartz bands. Oxides, jarosite, and clay are like that described in #3. Massive appearing centre part of the vein has more abundant oxides. Bands fill discrete lozenge-shaped zones, rather than forming planar, continuous bands. Lozenge is filled with successively deposited bands with local amethystine quartz at the margins, and a 'centre' with euhedral quartz and Fe-oxide-lined vugs.

5: The east side of vein is highly fractured and brecciated. Pervasive brown, orange, and pink oxides and lesser Mn-oxide locally form bands. Lattice textures occur at the eastern margin, directly inboard of ~10 cm of crustiform-colloform banded ± amethystine quartz with cm-scale vugs lined with euhedral quartz, Mn- and Fe-oxides, white clay, and flow-banded rhyolite clasts. Lozenges with high strike length:width ratios are composed of banded deposits (quartz and adularia) which coalesce to create a continuous "vein." Lattice textured part includes "clasts" of gray quartz that are generally massive with Fe-oxide-, white clay-, and jarosite-filled vugs. Lattice textures pinch out along strike and up dip.

6: Footwall is comprised of flow-banded rhyolite with Fe-oxide fractures, minor white clay, and trace quartz veinlets.
Figure 4-17. Map of vein textures and relative timing of vein filling minerals for a sample from the Magenta segment, mine level 1762. At least three vein filling episodes characterise this sample, with two of the episodes partly preserving earlier formed deposits as clasts in hydrothermal breccia.
Figure 4-17 continued.

I: Quartz with bladed oxides and vugs, later comb and zonal quartz. In thin section quartz locally replaces blades, exhibits ghost-sphere texture, and contains electrum and acanthite.

II: Comb and colloform quartz, colloform quartz with bladed oxides and vugs, oxide-rich colloform quartz locally with zonal quartz clasts, colloform quartz, oxide, and dark quartz matrix breccia with colloform quartz clasts. In thin section quartz locally exhibits ghost sphere texture, contains colloform inclusion trains, and exhibits feathery and flamboyant extinction indicating recrystallisation from primary chalcedony and/or amorphous silica. Fine-grained quartz and adularia with electrum and acanthite locally crosscut earlier formed quartz/amorphous silica and fill the centre of zone II.

IIb: Crosscutting clear to white comb quartz veinlet.

III: Zonal quartz clasts in fine-grained quartz with colloform cockade, later fine-grained quartz and adularia. In thin section fine-grained quartz locally exhibits ghost sphere and ghost blade textures and envelopes quartz and adularia clasts. Electrum and acanthite occur with fine-grained quartz, adularia, and oxide blades.

IIIb: Fine-grained quartz and adularia clasts locally supported by oxide-rich matrix.

Boxes show thin section sample locations (Tables 4-5, 4-6, 4-7, and 4-8).
Figure 4-18. Sample from the Escarlata segment, mine level 1663.

I-III: Coarse- and fine-grained adularia and quartz floods, envelopes, and deforms earlier formed mineralized bands. Quartz locally exhibits moss to ghost sphere texture and, with adularia, possible deformed lattice texture.

II-IIIb: Dark, fine-grained quartz with visible electrum and Ag-halides. Bands are discontinuous and irregular partly due to discrete depocenters rather than uniform deposition along a vein wall and owing to subsequent flooding by III.

IV: Vugs with comb and terminated quartz and adularia rhombs.

V: Millimeter-scale adularia.

VI: Fine-grained quartz with moss to ghost sphere textures and abundant oxides.

VII: Adularia forms lattice texture and interstices are filled with quartz, adularia, and electrum. Adularia rhombs and terminated quartz occur locally in vugs. Thin section shows feathery textures in quartz and curved quartz crystal boundaries. Possible preserved equivalent of I-III.

VIII: Fine-grained quartz with bladed oxides. Thin section shows saccharoidal and ghost sphere textures. Inclusion trains define colloform surfaces in some quartz. Trace relict chalcopyrite is partly converted to covellite.

Boxes show locations of thin section samples (Tables 4-5, 4-6, 4-7, and 4-8) and stars show locations of oxygen isotope samples (Tables 4-11 and 4-12).
Figure 4-19. Sample from location MM508, Carmin segment, mine level 1696 showing complex brecciated and interleaved crustiform deposits typical of the Quebrada Colorada vein. The relative timing of crustiform deposits and brecciation events cannot be resolved. Boxes indicate thin section sample locations (Tables 4-5, 4-6, 4-7, and 4-8) and stars show the locations of oxygen isotope samples (Tables 4-11 and 4-12).
Figure 4-20. Well preserved crustiform banded vein from the Carmin Sur segment, mine level 1682. Bands are dominantly comb and colloform quartz. Bands that contain isotope samples I-1682-2, I-1682-5, and I-1682-7 contain fine-grained adularia, and electrum is visible locally in the band containing sample I-1682-5. Boxes show locations of thin section samples (Tables 4-5, 4-6, 4-7, and 4-8) and stars show locations of oxygen isotope samples (Tables 4-11 and 4-12).
Figure 4-21. Longitudinal section of the Quebrada Colorada vein showing the distribution of vein minerals and textures. The outline of the 5 g/t Au equivalent gradeshell is shown for reference.
Figure 4-22. Diverse quartz textures from the Quebrada Colorada vein
Figure 4-22 continued. Diverse quartz textures from the Quebrada Colorada vein. Terminology follows that of Dong et al. (1995).

A. Colloform textures with botryoidal forms.

B. Lattice texture (top, left, and right), colloform texture with botryoidal forms, and later fine-grained comb amethyst.

C. Colloform, comb, and zonal quartz with oxide-rich bands, probably originally containing carbonate and/or sulfide minerals.

D. Well preserved comb and colloform quartz, including fine-grained bands with adularia and, locally, visible electrum.

E and F. Examples of hydrothermal breccias with oxide-rich matrix, possibly after carbonate minerals, and comb-colloform vein clasts.

G. Oxide-accented quartz lattice texture.

H. Bands of bladed and acicular oxides, probably after original carbonate minerals.

I. Pseudoacicular texture in quartz occurring with fine-grained adularia.

White bars = 1 centimeter
texture. Rare samples have colloform textures that include cylinders up to 1-2 cm long and <1 mm in diameter (Fig. 4-23). Lattice textures are formed by quartz replacement of millimeter-to centimeter-sized platy calcite crystals. Locally, colloform, comb, and lattice textures form cockade texture that envelops clasts of wallrock and vein. More commonly, hydrothermal breccia matrices are composed of massive, fine-grained quartz ± adularia. Breccia characteristics and occurrence vary from meter-scale, matrix supported, wallrock and vein clast breccias to more subtle, band-parallel incursions that locally crosscut earlier formed bands along discontinuous, sub-millimeter fractures. Locally, coarse ± amethystine quartz fills vugs. These represent the only occurrences of amethystine quartz, suggesting that it is generally late in the paragenetic sequence, although multiple events that formed amethyst quartz in vugs may have occurred over the time during which the Quebrada Colorada vein formed.

Microscopic scale textures observed in quartz include saccharoidal, moss, ghost-sphere, mosaic, feathery, and flamboyant. Saccharoidal, moss, and mosaic textures commonly grade into one another so that individual bands may display characteristics of one or more of these textures. Locally, trains of fluid inclusions and impurities in comb or coarsely crystalline (100s of μm to millimeters) and massive quartz define colloform surfaces.

4.7.2 Potassium feldspar

Adularia occurs as millimeter-scale bands of fine- to coarse-grained (100s of μm to millimeters), clear, white, or very light pink, commonly rhombic crystals. Very fine- and fine-grained adularia (10s of μm ) comprise up to 30 percent of bands and hydrothermal breccia matrix with very fine- and fine-grained quartz, locally occurring as rhombic crystals. It occurs throughout the vein (Fig. 4-21), and whole-rock geochemistry indicates at least trace amounts present in most samples (see below). Locally, adularia occurs with quartz replacing original platy calcite to form lattice textures. In unoxidised drill intercepts below ~1500 m asl,
Figure 4-23. Colloform texture with distinctive tubular forms. White bar = 1 centimeter.
adularia occurs in monomineralic bands adjacent to and in hydrothermal breccia matrix with quartz and carbonate minerals (Fig. 4-24a). The age of two adularia samples from Quebrada Colorado determined by $^{40}$Ar/$^{39}$Ar step-heating experiments are $52.85 \pm 0.37$ Ma and $52.95 \pm 0.40$ Ma (Chapter 3).

### 4.7.3 Carbonate minerals

Below ~1500 m asl, quartz- and adularia-bearing veins and hydrothermal breccias up to 0.5 m wide contain up to 30 percent calcite and Ca-, Mg-, Fe-, and Mn-bearing carbonates. Rhodochrosite, siderite, ankerite, and kutnahorite were identified by X-ray diffraction (XRD), and mixtures of these species are indicated by electron probe microanalyses (EPMA) of carbonate minerals from unoxidised drill intercepts (Table 4-1; Fig. 4-25; Appendix VI). Carbonate minerals are locally crustiform and display massive, acicular, bladed, and fanlike textures (Fig. 4-24a, b). Unoxidised veins and hydrothermal breccias containing carbonate commonly include <3 percent, and locally up to 10 percent, pyrite, chalcopyrite, galena, and sphalerite.

### 4.8 Ore minerals and related sulfides

The most important ore mineral is electrum that forms micron- to millimeter-sized (mostly <50 µm), subround to irregular grains, locally visible in hand samples (Figs. 4-18, 4-19, and 4-26). Electrum also occurs as <5 µm inclusions in acanthite. Au and Ag contents of electrum both vary from ~0 to ~100 wt percent. Average compositions are ~70 wt % Au and ~30 wt % Ag based upon EPMA analyses of 110 grains in 11 samples (Table 4-2; Appendix VI). Silver is also contained in acanthite and minor Ag-sulfosalt minerals. Acanthite grains are mostly <50-100 µm; they locally are visible in hand specimen and have diameters up to 2-3 mm. The composition of acanthite and sulfosalts is not well constrained because of the instability of Ag$_2$S under the electron beam and the generally poor polish of acanthite grains.