Geology of the San Luis gold deposit, Costilla County, Colorado: an Example of Low-angle Normal Fault and Rift-related Mineralization in the Sangre de Cristo Range of Colorado

Robert G. Benson
Colorado School of Mines
Golden, Colorado 80401-1887

David M. Jones
Paradex Exploration
4901 East Sunrise, Suite 1808
Tucson, Arizona 85718

ABSTRACT

The San Luis deposit of Costilla County, Colorado, contained 11,021,000 tonnes (12,149,000 tons) of ore at 1.4 g/t (0.040 oz/st) gold in two minable zones. Gold mineralization is associated with silicification and quartz-sericite-pyrite hydrothermal alteration, localized in breccias in the lower-plate of a low-angle, normal/detachment fault zone. Gangue minerals include chlorite, specular hematite, chalcopyrite, chalcocite, and fluorite. Precambrian biotite-hornblende gneiss is the dominant rock type in the lower-plate of the detachment fault zone. Precambrian biotite-hornblende granitic gneiss is present in the upper plate of the detachment fault zone. Portions of the ore body are unconformably overlain by sedimentary rocks of the Tertiary Santa Fe Formation. The detachment-fault surface is commonly characterized by clay gouge of illitic to chloritic composition. Mineralization is mid-Tertiary in age and has a direct genetic relation to the emplacement of rhyolitic dikes and sills. The deposit formed during the early stages of extensional tectonism along the eastern edge of the present day Rio Grande rift. The deposit is similar to other mineralized areas of the Sangre de Cristo Mountains and is an excellent example of a rift and detachment-related gold deposit. Mining will be completed in 1997.

INTRODUCTION

Location

The San Luis deposit is located about 5 miles northeast of the town of San Luis in Costilla County, south-central Colorado, in the foothills of the Sangre de Cristo

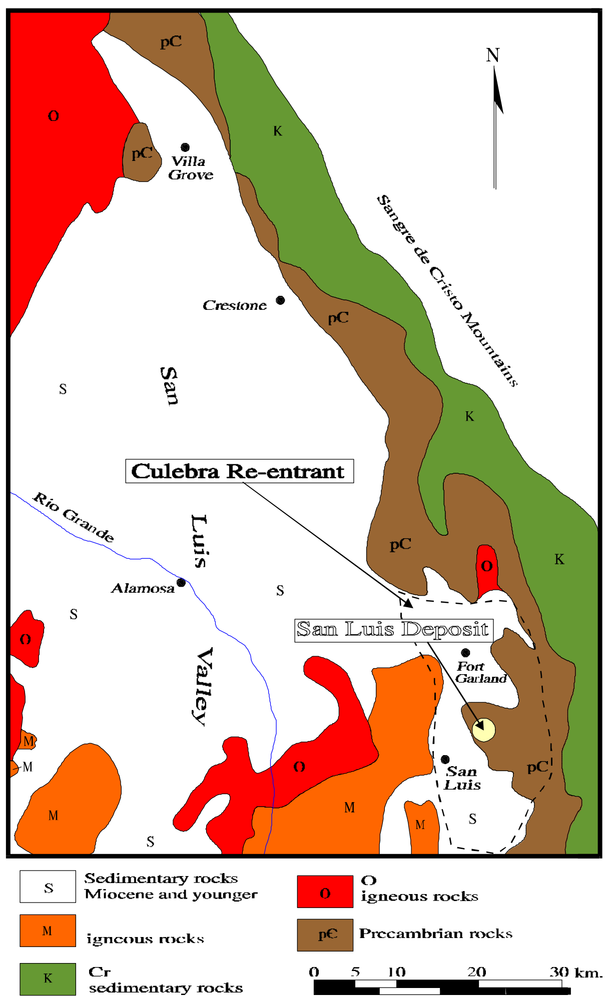

Figure 1. Location and geologic map of the San Luis Deposit area (modified from Keller, et al, 1984)

Mountains (Fig 1.). The deposit topography consists of gently- dipping southern to southwestern-facing slopes at elevations from 8200 ft. to over 9000 ft. The dominant vegetation is sagebrush, juniper, and piñon pine. Average rainfall at the mine site is 12" annually. The Rito Seco flows westward across the southern part of the deposit area.

North of the San Luis deposit adjacent to the west flank of the Sangre de Cristo Mountains are the towns of Fort Garland, Crestone, and Villa Grove, Colorado (Fig. 1). The large population center of Alamosa lies about 22 miles to the west. Historic mining districts and abandoned towns are also present along the western flank of the Sangre de Cristo Mountains north of the San Luis deposit (Ellis, et al., 1983; Johnson, et al., 1984; Scott, 1986; Ellis, 1988; Jones, 1991; Watkins, pers. comm.). The historic districts of Blanca, Liberty (Duncan), Crestone, and Orient (Villa Grove) represent some of the now-abandoned mining areas (Vanderwilt, 1947).

Historical activity and previous work

The San Luis deposit lies within the historical Sangre de Cristo land grant which was deeded by the Mexican government in 1844 to persons of purported Spanish ancestry (Simmons, 1979). After the 1848 Treaty of Guadalupe Hidalgo, the U.S. Congress formally recognized the grant as a private inholding in the newly established New Mexico Territory.

First knowledge of gold mineralization at San Luis probably dates back to the late 16th or early 17th century when Spanish expeditions from Mexico went in search of the mythical golden cities of Cibola. The first recorded mining activity started in 1890 near what was recently mined as known as the East Ore Zone. Lead and silver were the principal metals mined and the presence of galena accounts for the historical name of "El Plomo" for the San Luis deposit. A gold mill with an amalgamation circuit and later a cyanide circuit operated intermittently from 1897 through 1934. The mill-feed material mostly came from an open cut immediately south of the East Ore Zone (Fig. 2).

The area of the San Luis deposit was first described by Gunther (1905). Benson and Jones (1990; 1994) described the geology of the San Luis deposit during exploration, development, and production phases. Benson and Jones (1990; 1994) have proposed detachment-fault controls on mineralization at the San Luis deposit. Kaina (1993) has described some of the mineralogical, alteration, and geochemical characteristics of the San Luis deposit.

Mineralization and historical mining activity within the Sangre de Cristo Mountains were evaluated by Ellis, et al, (1983), as part of the Sangre de Cristo Wilderness study. The geology of the Sange de Cristo Mountains is described by Johnson, et al (1984) as part of the same study. The U. S. Geological Survey is presently mapping quadrangles between Mount Blanca and the San Luis Deposit (Wallace, pers. comm.). Kluth and Schaftenaar (1994) and Brister and Gries (1994) have recently addressed tectonic and basin development of the San Luis Valley.

The San Luis Deposit contained 11,021,500 tonnes (12,149,000 tons) of ore at 1.4 g/t (0.040 oz/st) of gold in two minable areas named the East Ore Zone and the West Ore Zone. The East Ore Zone contained 1,277,300 tonnes (1,408,000 tons) with a projected average grade of 1.68 g/t (.049 opt) of gold and lies in the extreme east portion of the mine property (Fig. 2). The West Ore Zone contained 9,744,000 tonnes (10,741, 000 tons) with a projected average grade of 1.34 g/t (.039 opt) of gold and lies in the central and western portion of the mine property (Fig. 2; Johnson, 1989).

GEOLOGIC SETTING

The San Luis deposit is located in the Sangre de Cristo Mountains. The Sangre de Cristo Mountains are a northerly trending chain of 12,000- to 14,000-foot peaks which extend over 340 km from Santa Fe, New Mexico to Salida, Colorado. The San Luis deposit lies between 8200 to 9000 ft. of elevation along the west slope of the range at the east edge of the San Luis basin (Fig. 1). The bulk of the Sangre de Cristo range in the deposit area consists of 1,800 Ma Proterozoic gneisses which have been intruded by 1,700 and 1,400 Ma granitic rocks (Tweto, 1979). The eastern half of the range consists dominantly of Paleozoic sedimentary rocks which were steeply upturned and folded during Laramide orogenic events. Near Crestone, Colorado, the Paleozoic rocks extend westward across range into the San Luis Valley for short distance (Fig. 1; Johnson, et al, 1984). The Sangre de Cristo Mountains form the eastern side of the Rio Grande Rift in the San Luis Valley area and the west-facing slope is where most known mineral occurrences are found. A complex series of rift-related faults are present along the west-facing slope of the Sangre de Cristo Mountains, including high-angle normal faults and low-angle detachment faults (Tweto, 1979, McCalpin, 1982; Brister and Gries, 1994; Jones and Benson, 1994; Kluth and Schaftenaar, 1994; Wallace, 1995). The present relative uplift of the range is inferred to have occurred during Neogene and Quaternary time (Tweto, 1979).

Synchronous with Neogene uplift of the Sangre de Cristo range was the development of the San Luis basin and deposition into it of poorly-sorted, high-energy sediments of the Miocene to Pliocene Santa Fe Formation and the Pliocene to Quaternary Alamosa Formation. The northerly trending San Luis basin extends over 240 km from Taos N.M. to Poncha Pass, Colo., and is an integral part of the Rio Grande rift system. Estimated depths of basin fill in the San Luis area are on the order of several thousand meters (Keller and others, 1984, Brister and Gries, 1994; Kluth and Schaftenaar, 1994).

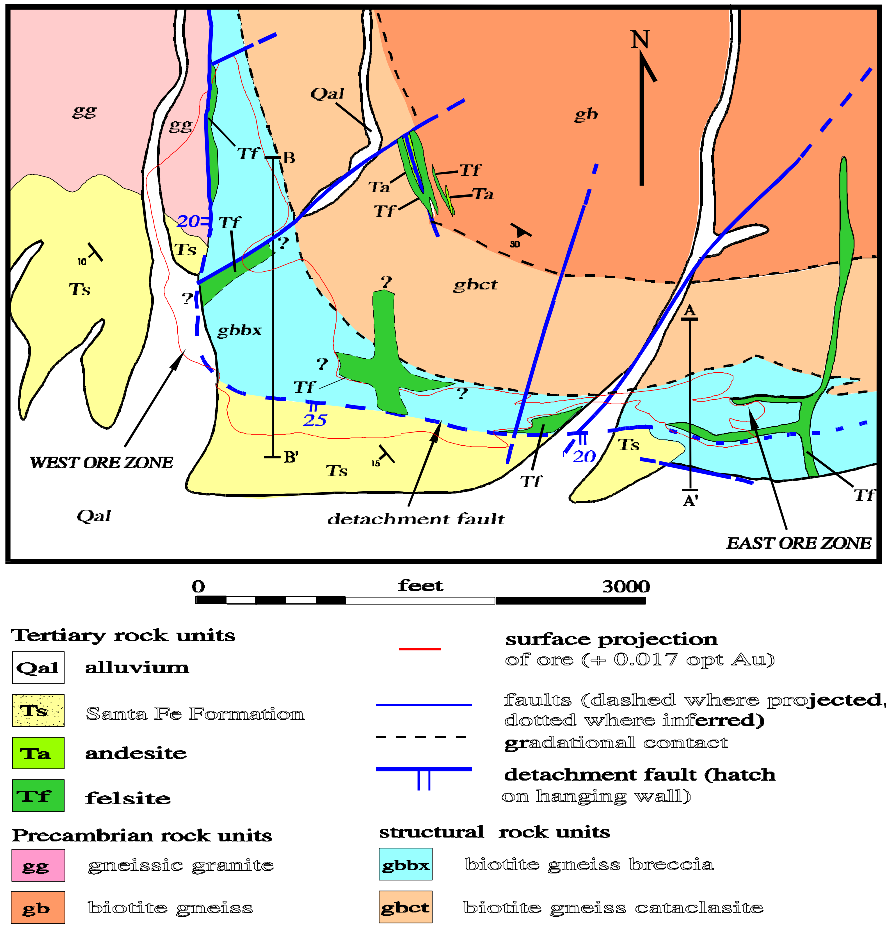

Figure 2. Generalized geology of the San Luis deposit area, based on mine mapping and Benson and Jones (1990, 1994). Tertiary and Precambrian rock units are grouped together. Structural rock unitas are derived from the Precambrian rock units. Fault clay is not shown here because the fault clay is typically less than 5 feet thick.

The San Luis deposit lies adjacent to a portion of the basin known as the Culebra reentrant (Fig. 1., Upson, 1939). Within the reentrant Santa Fe Formation is present and deeply eroded at elevations up to 10,000 ft. Elsewhere in the San Luis Valley basin, sediments of the Santa Fe lie at less than 8,000 ft elevation. It appears that the San Luis deposit lies within a portion of the Rio Grande rift where Tertiary sedimentary rocks are preserved at a higher structural level. Wallace (1995) has proposed a half-graben structural origin of the Culebra Re-entrant. Wallace (1995) also describes a complex mosaic of faulting within the Culebra Re-entrant.

No large Tertiary intrusions are exposed in the vicinity of the San Luis deposit. The nearest volumetrically significant intrusive centers are the 26-22 Ma Questa magmatic system to the south (Lipman and others, 1986), the 25-19 Ma Spanish Peaks system to the east (Tweto, 1979), and small sill-like intrusions near La Veta pass to the north. Oligocene andesitic lavas crop out in the study area southeast of Mount Blanca and north of the San Luis deposit (Tweto, 1979). Rhyolite and andesite (?) dikes and sills are present at San Luis but nowhere do these exceed 10's of meters in thickness.

GEOLOGY OF THE SAN LUIS DEPOSIT

Gold mineralization at San Luis occurs as tabular bodies within and below a low-angle detachment fault zone in cataclastically deformed Precambrian metamorphic rocks (Figs. 2, 3, 4). The major dislocation surface of the fault zone is preserved as unmineralized clay fault gouge which marks the upper extent of economic mineralization. Hangingwall to the fault zone are cataclastically deformed Precambrian metamorphic rocks and Tertiary-Quaternary sediments with minor interbedded volcanic flows. Higher gold grades in the deposit are closely associated with silicification and quartz-sericite-pyrite alterations that have destroyed the primary textures. Felsites are observed frequently within silicified areas adjacent to high-grade

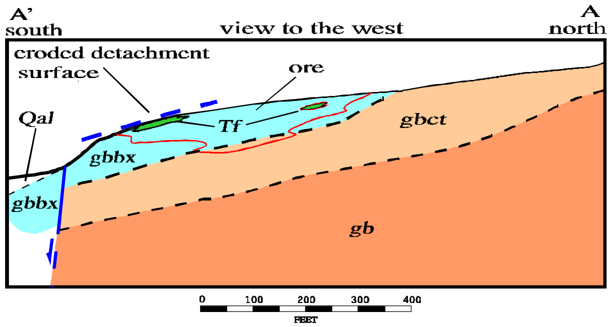

Figure 3. Generalized cross-section of the East Ore Zone, view to the west. Rock unit descriptions can be found on Figure 2.

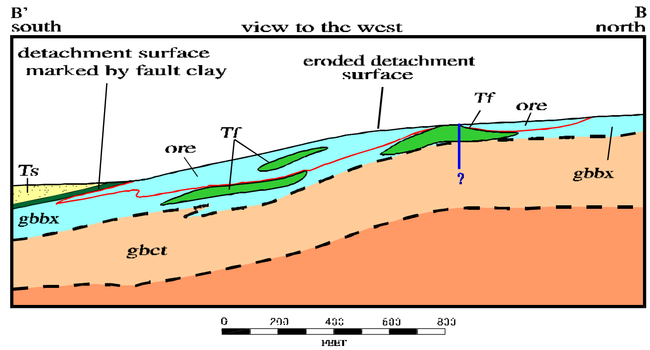

Figure 4. Generalized cross-section of the West Ore Zone, view to the west. Rock unit descriptions can be found on Figure 2. Fault clay is shown slightly larger for clarity, and is not shown in Figure 2.

gold mineralization. Peripheral areas are dominated by chlorite-carbonate and quartz-specular hematite alteration which carry low-grade to non-detectable gold values. Primary lithologies are discussed separately from structural or secondary lithologies.

Primary lithologies

Precambrian rocks

The dominant lithologies at San Luis are Proterozoic biotite gneiss and gneissic granite. Biotite gneiss is an 1800 Ma (Tweto, 1979) gray quartz-feldspar-biotite gneiss. Biotite gneiss is the dominant rock type below the detachment fault zone (Figs. 3, 4). Structurally deformed and hydrothermally altered biotite gneiss is the host to gold mineralization. A typical modal composition is 25 to 35% feldspar, 20 to 25% quartz, and 5 to 10% biotite. The remaining percentage consists of variable amounts of hornblende, chlorite, sericite, magnetite, and specular hematite. Chlorite and minor magnetite are more abundant closer to and within cataclastically deformed gneiss. Gneissic foliations vary from E-W, 15° to 30°S in the East Ore Zone, to N-S, 15 to 30°W in the northwestern part of the West Ore Zone. Foliations in the biotite gneiss appear to be sub-parallel to the orientation of the detachment fault up to 80m below the clay zone. In localized areas within cataclasticaly deformed biotite gneiss, foliations are disrupted and rotated.

Gneissic granite is a 1700 Ma (Tweto, 1979) greenish-gray to reddish-gray quartz-orthoclase granite. Gneissic granite occurs in the hangingwall of the detachment fault zone and crops out in the northwestern part of the West Ore Zone (Figs. 3, 4). Gneissic granite is deeply weathered where exposed. Gneissic granite does not host gold mineralization. A typical modal composition is 30 to 35% orthoclase and 25% quartz. The remainder of the rock consists of muscovite, biotite, amphibole, chlorite, clay, sericite and iron oxides. Locally extensive pegmatites of potassium feldspar and quartz crosscut and are locally concordant with foliation. Books of biotite weathering to chlorite are common along pegmatite contacts. Foliations are irregular and do not show a relationship to the detachment fault zone orientation. Diabase dikes and irregular masses occur within the gneissic granite. These equigranular and magnetite-rich intrusions are inferred to be Precambrian in age.

Tertiary igneous rocks

Two Tertiary igneous rock types of volumetric significance are present in the San Luis deposit area: felsite sills and dikes, and andesite dikes and flows. Felsite occurrences are far more common.

Felsite is an aphanitic to weakly porphyritic pale-green to gray intrusive rhyolite. Felsite is the igneous rock type associated with mineralization. Intrusive contacts are commonly flow laminated. Felsite is usually distinguished from altered biotite gneiss breccia by the presence of $\leq$2mm quartz and euhedral feldspar phenocrysts. Felsite can often be distinguished from associated silicified biotite gneiss breccia by more blocky and regular fracturing in the felsite.

Felsite sills and associated dikelets occur within the ore zones closely associated with mineralization. Sills are often difficult to distinguish from intense silicification and mineralization. Nowhere have felsites been observed cross-cutting the fault clay of the detachment surface.

Dikes trend north to north-northwest through the mine area. Dikes are typically pervasively sericitized, weakly to strongly silicified, and may contain trace fluorite and up to 1% disseminated pyrite. Dikes typically trend north-south and apparently crosscut all rock types below the detachment fault. Age dates on sericite concentrates from two felsites are 24.0 ± 1.0 Ma and 24.1 ± 1.0 Ma

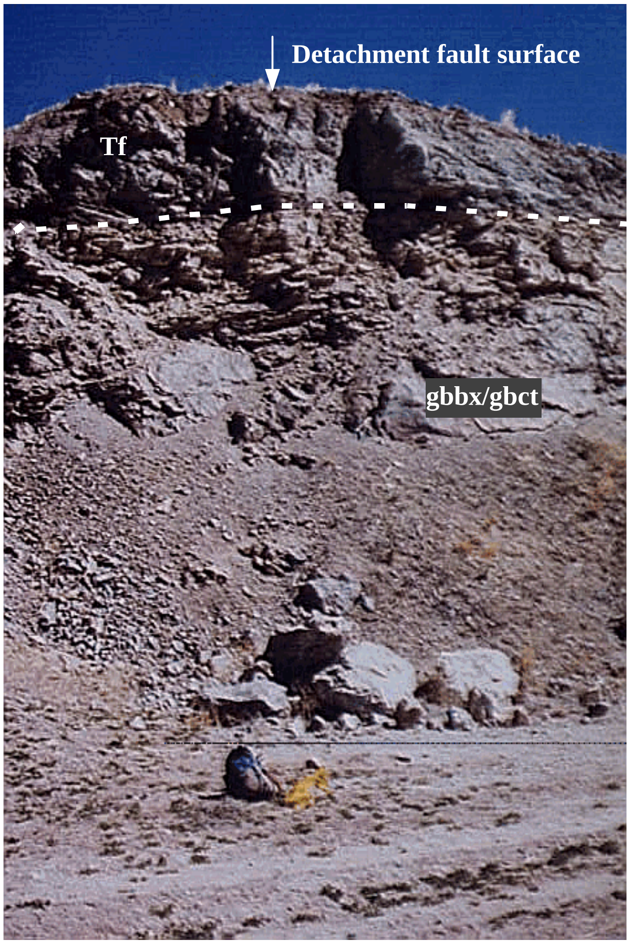

Figure 5. North -looking view of an outcrop of felsite sill above biotite gneiss breccia (gbbx) and biotite gneiss cataclasite (gbct). The contact is shown by the white dashed line. The top of the outcrop is a remnant of the detachment surface. Outcrop is about 30 ft. high, with pack in foreground for scale.

Figure 6. Example of Santa Fe Formation, showing poorly-sorted bedding and flat-lying beds. Outcrop is about 30 feet above fault clay in the detachment fault in the West Ore Zone. A six-inch scale lies at the tip of the arrow.

(K/Ar; Krueger Geochron Laboratories). The similar alteration of felsite and mineralized areas, and presence of felsite sills and dikelets directly within ore zones, strongly suggest a genetic relation of felsite to gold mineralization.

Andesite has been observed in flows and dikes. Andesite dikes contain pyroxene, plagioclase, biotite, hornblende, and magnetite. Dikes typically trend north-south and apparently crosscut all rock types below the detachment fault. Andesite dikes are not observed to crosscut the detachment fault surface. Andesite is believed to be younger than 24 Ma and is not associated with gold mineralization. Andesite flows occur in the southern part of the mine area, interbedded with Santa Fe Formation sediments, and are believed to be derived from the same source as the andesite dikes found north of the \west Ore zone.

Tertiary-Quaternary sedimentary rocks

Tertiary Santa Fe Formation at the San Luis deposit consists of a repetitive flat-lying sequence of silts, sands, gravels and cobble lenses. Santa Fe Formation unconformably overlies gneissic granite in the West Ore Zone. Santa Fe Formation unconformably overlies fault clay or biotite gneiss breccia in the East Ore Zone. Cobbles of gneissic granite are more abundant in the lower beds of the Santa Fe Formation.

Quaternary alluvium consists of channel-fill gravels and sands. A thin layer of alluvium is present over much of the deposit area, and is upwards of 20 ft. thick near the Rito Seco.

Structural lithologies

The detachment fault zone which hosts gold mineralization at San Luis is divided into three structural lithologic units: (1) fault clay, (2) biotite gneiss breccia, and (3) biotite gneiss cataclasite. Biotite gneiss breccia is the principal ore host, with lesser occurrences of ore in biotite gneiss cataclasite. The fault clay contains no mineralization.

Fault clay

A fault clay zone separates hangingwall gneissic granite from underlying biotite gneiss. Fault clay mostly separates lower plate biotite gneiss breccia from Santa Fe Formation. In general, fault clay thins to the north and east when present under Santa Fe Formation. Fault clay marks the detachment fault zone. The clay averages 2 meters in thickness and probably formed through extreme grain size reduction of mostly overlying gneissic granite and some underlying biotite gneiss breccia during displacement along the detachment fault. In lower parts of the fault clay, fragments of biotite gneiss breccia or cataclasite can be found. Upper contacts of the fault clay with overlying gneissic granite or Santa Fe Formation can be very irregular. In the western part of the deposit area where the detachment fault underlies the gneissic granite/Santa Fe Formation contact, fragments of Santa Fe Formation have been incorporated in the upper parts of the fault clay. Clay color ranges from gray to gray-green to pale reddish brown. Fault clay has an illitic to chloritic composition. Glanzman (pers. comm) suggested a 1-m illite composition in at least one sample of fault clay . Concordant gypsum veinlets are locally present in the fault clay. These veinlets are subparallel to the detachment surface.

Biotite gneiss breccia

Biotite gneiss breccia is the principal host to gold mineralization. The breccia consists of subangular to subrounded clasts ranging in size from <1 mm to 10's of mm, set in a fine-grained rock flour matrix. Clasts typically consist of quartz, with lesser amounts of feldspar. In thin section, strain textures are visible in quartz fragments. Biotite gneiss fragments and quartz-vein clasts are also present, but are less common. Clast size and abundance apparently decreases from the breccia-cataclasite contact up-section towards the fault clay zone. This is attributed to a general increase in the intensity of both structural deformation and alteration in this direction. Typically the breccia matrix is hydrothermally altered to an assemblage of quartz ± sericite ± pyrite (Romberger, written comm, 1989).

Biotite gneiss cataclasite

Biotite gneiss cataclasite consists of subangular to subrounded rock fragments in a weakly-foliated, fine-grained fragmented matrix. The fine-grained matrix generally constitutes of less than five volume percent of the rock. Fragments show little or no rotation or disaggregation. Foliations in the cataclasite are more irregular and less evident than foliations in deeper, less deformed biotite gneiss.

Faults

The principal structural feature of the San Luis Deposit is the detachment fault that separates gneissic granite from underlying biotite gneiss. In the southeast part of the West Ore Zone the detachment fault strikes east-west and dips 15° to 30° to the south (Figs. 2, 3). The fault changes to a more northerly strike, and dips 15° to 30° to the west in the northwest part of the West Ore Zone (Figs. 2, 4). The presence of brecciated, folded, and undisturbed quartz veins in outcrop indicates that faulting was at least in part syn-mineralization. Slickensided and distorted fracture and joint coatings of pyrite, and the presence of Santa Fe Formation in the fault clay also suggest syn-mineralization movement. Movement on the fault is inferred to be down-dip to the south and southwest. This is based upon interpretations of slickenside features, strikes and dips of hangingwall foliations, and asymmetrical folding in footwall rocks immediately below the detachment surface.

The deposit area is cross-cut by numerous northeast-southwest striking, steeply-dipping faults (Fig. 2). The East and West Ore Zones do not appear to have been significantly offset by post-mineralization fault movement. Mineralization in the West Ore Zone is partially cutoff on the north by a steeply-dipping, northeast-southwest striking fault. Mineralization in the East Ore Zone may be partially cutoff on the south by a steeply-dipping east-northeast striking fault. Faulting has had a local effect on ore body geometry. Inferred northerly-striking normal faults west of the deposit probably downdrop basement rocks and sediments to the west hundreds to thousands of meters and are likely rift-related.

Hydrothermal Alteration

Four alteration assemblages are identified at San Luis in footwall rocks: (1) silica replacements/veins, (2) quartz-sericite-pyrite replacements/veins, (3) chlorite-carbonate replacements/veins, and (4) quartz-specular hematite veins. The most intense alteration is silica replacement/veining which is commonly associated with high-grade gold mineralization immediately beneath the clay zone. Silicification typically grades into quartz-sericite-pyrite alteration. The least intense hydrothermal alteration is chlorite-carbonate replacement/ veining.

The overall hydrothermal alteration mineral distribution appears to be both lateral and downsection. The most intense silicification appears immediately below the fault clay that marks the detachment surface. Fault clay has not been silicified. Laterally and down-section, quartz-sericite-pyrite alteration becomes more intense. Further down-section and laterally, chlorite-carbonate alteration becomes the dominant alteration type. Specular hematite veins and replacements are frequently seen associated with quartz-sericite-pyrite alteration and are associated with chloritic alteration.

Silica replacements/veins (Silicification)

Silica replacement and veining occur as pervasive matrix replacement of biotite gneiss breccia. Breccia fragments show partial resorption in silicified areas in thin-section. Quartz veinlets and minor replacements occur locally in biotite gneiss cataclasite, but are weakly mineralized. Silica ranges in color from dark to light gray. Dark gray silica contains ≤3% fine-grained disseminated pyrite. Very high gold grades are associated with dark gray silicification. Silicification is most intense immediately below the fault clay in the West Ore Zone. Dark gray silicification grades laterally and downward into lighter gray silicification and quartz-sericite-pyrite alteration. Replacement silicification is commonly cross-cut by quartz-veinlets and felsite sills. Cross-cutting relations are inconsistent. The inconsistency of cross-cutting relations suggests a single hydrothermal event of numerous sub-events.

Quartz-sericite-pyrite replacements/veins

Quartz-sericite-pyrite alteration occurs as an intense gray-green matrix replacement of biotite gneiss breccia. Quartz veinlets commonly cross-cut the altered matrix. Pyrite associated with quartz-sericite-pyrite alteration is generally localized in clots and veinlets and is less commonly disseminated. Quartz-sericite-pyrite alteration grades upward into dark gray silicification and downward into chlorite-carbonate alteration. Quartz-sericite-pyrite alteration is distinquished from felsite by the absence of faint feldspar and quartz phenocrysts. Gold mineralization is associated with quartz-sericite-pyrite alteration but is not as intense as in the dark-gray silicification. Quartz-sericite-pyrite alteration crops out in the East Ore Zone.

Chlorite-carbonate veins

Chlorite-carbonate alteration is relatively widespread and includes an overall less intense alteration assemblage of chlorite ± carbonate ± magnetite ± clay ± pyrite. Chlorite commonly occurs as a foliation replacement in biotite gneiss cataclasite and biotite gneiss. Chlorite is commonly found as a joint and fracture coating throughout the deposit, but is the result of shearing. In thin section, primary quartz, microcline, and plagioclase are partially replaced by fine-grained clay, sericite, and carbonate, and biotite is replaced by chlorite ± magnetite (Romberger, written comm., 1989).

Specular hematite veins, replacements, and fracture coatings

Specular hematite veins, replacements, and fracture coatings may have formed early along the detachment fault zone. Specular hematite is abundant peripheral to the deposit but appears to have been overprinted by more intense silica-sericite events in the core of the deposit. Specular hematite may have been remobilized during hydrothermal alteration. Gold is not associated with specular hematite alteration.

Mineralization

Mineralization is present in hydrothermally altered zones in biotite gneiss breccia and to a very minor extent in biotite gneiss cataclasite. Gold mineralization correlates with silicification and sulfide content. The dominant sulfide present is pyrite, in three polymorphs, with minor occurrences of chalcopyrite, molybdenite, galena, and possible acanthite (Suthard, 1988). Chalcocite is present in locally high concentrations associated with quartz veins and veinlets. The average gold to silver ratio is 1:2.5. Specular hematite and chlorite are usually found in more weakly mineralized areas and are associated with less intense hydrothermal alteration. Fluorite is commonly present in narrow quartz-fluorite veinlets and in open-space fillings. Fluid inclusion studies (Kaina, 1993) suggest hydrothermal fluids ranging in temperature from 200 to 280°C and 0 to 12 eq. wt% NaCl were responsible for mineralization. Kaina (1993) also suggests mixing of magmatic and meteoroic water, based on N_2, He, and Ar gas analysis. Gold may have been transported as bisulfide complexes (Kaina, 1993).

Three forms of pyrite are present in mineralized zones. Two appear to have no consistent association with ore-grade gold mineralization. Euhedral, untarnished, relatively coarse-grained pyrite has little correlation with gold mineralization. Untarnished, poorly-twinned pyritohedrons also have little or no correlation with gold mineralization. Irregular fine-grained clots of tarnished pyrite appear to have the most consistent correlation with gold mineralization.

Ore microscopy studies of sulfide concentrates indicate the presence, in order of decreasing abundance, of pyrite, chalcopyrite, hematite, goethite, anatase, galena, molybdenite, covellite, gold, and pyrrhotite (Deakin and Lehman, 1988). Gold is present along fractures in pyrite grains, as small blebs within pyrite grains, and as discrete particles. Gold grain size ranges from 2 to 160 microns, averaging 20 microns.

Q-mode factor analysis was applied to multi-element whole rock data from 85 drill hole intercepts in the West Ore Zone (Jones, 1989). Gold mineralization factors suggest a correlation of gold with silver, lead, copper, molybdenum, and fluorine. These correlations indicate that gold deposition at San Luis was part of a polymetallic mineralizing event. Gold also correlates with both iron-rich and iron-poor factors reflecting an inconsistent association with pyrite.

East Ore Zone

The East Ore Zone strikes east-west and dips 15° to 25° to the south (Fig. 3). Ore was mostly confined to biotite gneiss breccia with minor mineralization occurring below in biotite gneiss cataclasite. The dominant alteration is intense quartz-sericite-pyrite alteration of biotite gneiss breccia. Silicification is intense but less so than in the West Ore Zone. Sulfides occur in clots and pods more than in disseminations. Breccia clast size generally decreases up section from the lower parts of the biotite gneiss breccia towards the fault clay zone. Biotite gneiss breccia zones range in thickness from 0 to 30 meters, averaging 15 meters. In the more intensely quartz-sericite altered breccias, clasts constitute less than 10% of the rock. The clay zone is present in irregular cappings throughout the East Ore Zone area, and is inferred to have capped the deposit prior to erosion. Asymmetrical folding immediately below the fault clay in hydrothermally-altered biotite gneiss breccia suggests normal movement along the low-angle fault. Numerous felsite sills and dikelets were exposed during mining. The felsite sills average 1 meter in thickness and generally show a close spatial relationship with mineralization. Felsite sills were often weakly mineralized. Felsite dikelets were also observed crosscutting mineralization at irregular intervals in the general area of felsite sills.

West Ore Zone

The strike and dip of the West Ore Zone is roughly conformable to that of the host fault breccia (Fig. 4). As the strike of the fault changes from nearly east-west in the southern portion of the West Ore Zone to north-south in the northern portion of the zone (Fig. 2) so does the strike of the ore zone. The West Ore Zone dips 15° to 30° degrees to the south in the southern portion of the zone and 15° to 30° degrees to the west in the northern portion of the zone. Breccia clasts are typically <1 cm and make up upwards of 15% of the rock volume. Breccia thickness ranges from 0 to 45 meters, averaging 30 meters. The hangingwall of the West Ore Zone is Santa Fe Formation and gneissic granite (Fig. 4). The thickness of the gneissic granite section decreases from north to south. Biotite gneiss breccia appears to decrease in thickness to the north along strike of the detachment fault.

The West Ore Zone is mostly confined to intensely silicified and sericitized biotite gneiss breccia. Biotite gneiss cataclasite contains minor ore occurrences. Pyrite content varies from trace to 5%. The highest gold grades of the deposit are within the West Ore Zone in dark gray, pyritic silicification directly below the fault clay zone. The most intense silicification of the deposit is within the West Ore Zone where primary breccia textures are overprinted and destroyed by silica replacement and veining. Felsite sill are found closely associated with ore in the West Ore Zone. Felsite sills are often mineralized. Felsite dikelets are also observed crosscutting mineralization at irregular intervals in the general area of felsite sills.

SIMILAR MINERALIZATION IN THE SANGRE DE CRISTO RANGE

Mineralization is known in the Sangre de Cristo Mountains north of the San Luis deposit (Fig 1; Ellis, et al., 1983; Johnson, et al., 1984; Scott, 1986; Ellis, 1988; Watkins, pers. comm.). Lexam Explorations (USA), Inc., has conducted extensive gold exploration work near Crestone, Colorado, and is presently developing an oil resource in the same area (Watkins, pers. comm.). The U. S. Geological Survey is presently mapping quadrangles between Mount Blanca and the San Luis Deposit (Wallace, pers. comm.). Similarities to the San Luis deposit are present in many of the mineralized areas of the Sangre de Cristo Mountains, but are undergoing further study.

The west side of the Sangre de Cristo Mountain Range is bounded by a complex series of rift-related faults, including high-angle normal faults (Tweto, 1979, Brister and Gries, 1994; Kluth and Schaftenaar, 1994; Wallace, 1995) and low-angle detachment faults (Jones and Benson, 1994). McCalpin (1982) mapped a low-angle normal fault in underground workings in the Wild Cherry Creek area north of Crestone. Balleweg (pers. comm) described possible low-angle structures that may have affected mineralization in the Orient Mine near Villa Grove, Colorado. Watkins (pers. comm) described features similar to the San Luis deposit near Crestone, Colorado. Detachment faulting is believed to be a significant control on mineralization on the western flank of the Sangre de Cristo Mountains (Jones and Benson, 1994). Low-angle breccia zones and associated lithologies, felsic intrusions, mineralization and hydrothermal alteration patterns similar to those found at the San Luis deposit are found through the mineralized parts of the Sangre de Cristo Mountains.

DISCUSSION

The San Luis deposit developed as part of a silicification/quartz-sericite-pyrite alteration event hosted by a low-angle detachment fault zone. Mineralization is polymetallic with gold deposition closely associated with silver, copper, and fluorine locally. Textural evidence clearly indicates that a major episode of faulting predated alteration and mineralization. A simple genetic model of the deposit can be derived from a discussion of the origin of the fault zone and the origin of the subsequent hydrothermal system. The genetic model may also provide insights on mineralization in the rift environment of the Sangre de Cristo Mountains. Areas of further work are discussed.

Origin of the fault zone

In Laramide time the area of the present day Sangre de Cristo range underwent strong compressional deformation which resulted in thrust faulting and attendant folding in Precambrian and Paleozoic stratigraphies (Tweto, 1979). More recent Neogene extensional normal faulting has dissected this Laramide uplift. On the basis of this geologic history, the fault zone at San Luis has most commonly been interpreted as a thrust fault. The most recent movement on the low-angle fault zone is considered to be normal. The evidence for movement is based on field observations within the deposit area.

Arguments for detachment-style faulting at the San Luis deposit are based upon local and regional observations. The most important of these arguments are: (1) the preservation of the fault clay zone at its contact with the Santa Fe Formation; (2) the location of the fault zone at the edge of Neogene depositional basins; (3) asymmetrical fold features in biotite gneiss breccia immediately below the fault clay, and (4) the evidence that faulting was in part synchronous with emplacement of felsite intrusions.

The fault clay zone always separates hangingwall gneissic granite from footwall biotite gneiss. In several core holes and in mining exposures, Precambrian hangingwall rocks are not present and the fault clay is in direct contact with Santa Fe Formation. If the Santa Fe Formation was deposited on an eroded Laramide thrust fault surface, the clay zone would have been rapidly removed long before sedimentation. Clay zone preservation could only occur if it were immediately buried by unconsolidated Santa Fe sediments upon removal of the overlying Precambrian plate. This constrains major movement of the upper plate as synchronous with development of Santa Fe depositional basins, a Neogene event.

The fault zone at San Luis marks the east edge of the San Luis basin. The proximity of this fault to the edge of the basin implies that it is a Neogene basin bounding structure as opposed to an eroded or reactivated Laramide thrust fault.

Asymmetrical folds are present in the biotite gneiss breccia below the fault clay that marks the detachment surface. The folds are slightly steeper on the downdip limbs, suggesting a normal shear-sense and displacement.

Emplacement of mid-Tertiary felsite sills and dikes at the east edge of the San Luis basin is apparently synchronous with low-angle faulting.

We believe that local and regional geologic evidence indicate a mid-Tertiary extensional detachment origin for the fault zone at San Luis. Alteration and mineralization overprinting on cataclastic textures indicate that ore deposition was post-faulting, but there is evidence for at least minor post-mineralization faulting as well. Post-mineralization movement is suggested by deformed pyrite and relatively unaltered fault clay immediately above intense hydrothermal alteration.

Origin of mineralization/alteration

The origin of the mineralizing fluids responsible for the San Luis deposit is not well understood at present. Age determinations (K/Ar) on sericite-altered felsite dikes at the deposit yield ~24 ± 1 Ma. Felsite intrusions are commonly associated directly with ore. These age dates, felsite spatial relations to ore, and the association of gold with base metals and fluorine, lead us to conclude that mineralization has a genetic relation to mid-Tertiary magmatism associated with rifting.

Genetic model

In the area of the San Luis deposit, low-angle detachment-style faulting developed in the middle Tertiary in response to an elevated geothermal gradient along the Rio Grande rift zone. Detachment faulting may have re-activated older thrust faults. Small-volume felsic magmas were emplaced at shallow crustal levels at this time. Magmatic metalliferous fluids intersected the low-angle fault zone at San Luis and precipitated sulfides in the relatively low-pressure, low-temperature environment of the breccias. Syn- and/or post-mineralization movement along the fault zone allowed for partial unroofing of the clay zone, which was immediately buried by unconsolidated Santa Fe sediments. Erosion of the Santa Fe Formation in the structurally elevated, "failed" portion of the rift basin allowed for partial exposure of the deposit.

Other areas of mineralization throughout the Sangre de Cristo Mountains show similar features to the San Luis deposit, but show some differences. As such, a San Luis genetic model cannot be directly applied to the Sangre de Cristo Mountains as a whole. However, the similarities observed in the field in many mineralized areas outside of San Luis strongly suggest a comparable genesis.

Further work

Further work to constrain the geology of the San Luis deposit and the similarities of other mineralized areas in the Sangre de Cristo Mountains is ongoing as part of the senior author's PhD thesis. Addition petrographic and geochemical studies are being done to evaluate the nature of the detachment fault zone at San Luis and the other areas mentioned previously. Additional age determinations are being done on felsite intrusions associated with mineralization. Additional mapping to complement previous work is also ongoing.

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