Questa Rock Pile Weathering and Stability Project

GEOLOGIC SETTING AND MINING HISTORY OF THE QUESTA MINE, TAOS COUNTY, NEW MEXICO

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May 18, 2009

New Mexico Bureau of Geology and Mineral Resources

Open-file Report OF-515

Molycorp Task 1.2.2, B1.1

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INTRODUCTION AND PURPOSE

The Chevron Mining Inc. (formerly Molycorp, Inc.) Questa molybdenum mine is located on the western slope of the Taos Range of the Sangre de Cristo Mountains of the Southern Rocky Mountains near the edge of the Rio Grande rift in north-central New Mexico (Fig. 1). It is on N.M. Highway 38, between Questa and Red River. The mine is on southward facing slopes and is bounded on the south by Red River (elevation of approximately 7500 ft) and on the north by the mountain divides (elevation approximately 10,750 ft) (Fig. 2). The geology and mining history of the area is complex and is summarized in this report from Carpenter (1968), Clark (1968), Reed et al. (1983), Lipman (1988), Meyer and Leonardson (1990), Czamanske et al. (1990), Roberts et al. (1990), Ludington et al. (2005) and others as cited. Lithologies likewise are diverse, ranging from metamorphic rocks to volcanic rocks to granites to shales, limestones, and sandstones.

The purpose of this report is to summarize the geologic setting and mining history in the Questa-Red River area in order to provide a framework for the Questa Rock Pile Weathering and Stability Project (QRPWASP) with emphasis on interpretations from recent references. Descriptions of the various lithologies, including photographs, mineralogy, and chemical analyses are presented in a separate lithologic atlas (McLemore et al., 2009).

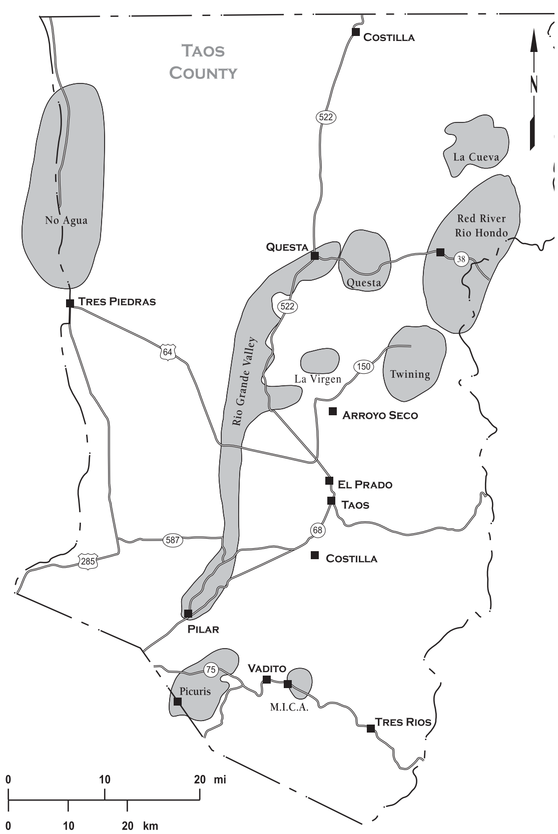

FIGURE 1. Location of the Questa and other mining districts in Taos County (McLemore and Mullen, 2004).

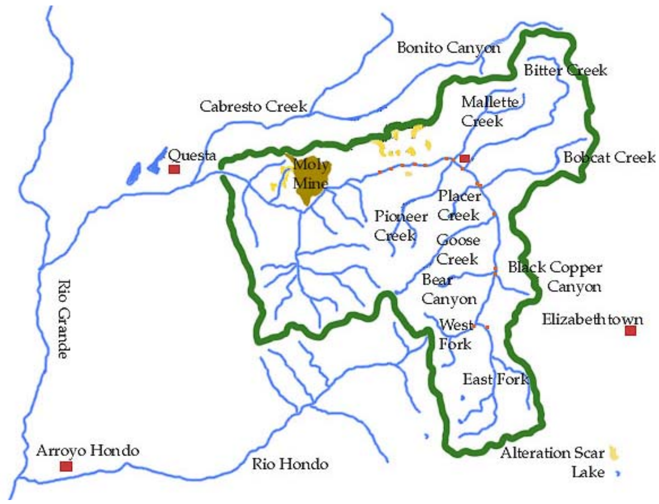

FIGURE 2. Location of the Questa mine within the Red River basin. Heavy green line delineates the upper Red River watershed.

Vegetation within the area includes Douglas Fir, Engelman spruce, Ponderosa pine, Gambel oak, mountain brome, kinnikkinnik, aspen, Kentucky bluegrass, Arizona fescue, and whortleberry (Hagan, 2001). Along the valley floor, the alpine to sub-alpine community gives way to a meadow or riparian corridor including willow, narrowleaf cottonwood, various grasses, and shrubs, including wild rose, Rocky Mountain clematis, scotch broom, and squawberry. The steeper, rockier north slope of the canyon favors fir and spruce, while the south slope of the canyon shows more aspen, narrowleaf cottonwood, and other undergrowth.

CLIMATE

The climate at the Questa mine is semi-arid, with cold snowy winters and moderate warm summers with monsoons during July and August. Summer rains often cause mudslides and flash floods that have blocked the highway at times. The Red River drainage receives an average of 20.6 inches of precipitation per year, concentrated mostly in July and August (Table 1; Hagan, 2001; Western Regional Climate Center, 2007). The record maximum winter snowfall for New Mexico is 483.0 inches in 1911-12 at the Anchor mine near Red River and the record maximum 1-day snowfall for New Mexico is 36.0 inches on March 12, 1978 at Red River (Western Regional Climate Center, 2007). The record maximum annual precipitation in New Mexico is 62.45 inches in 1941 at White Tail (near Cloudcroft) and the record maximum 24-hour precipitation is 11.28 inches on May 18-19, 1955 at Lake Maloya (near Ruidoso; Western Regional Climate Center, 2007). The average annual pan evaporation rate for Eagle Nest (southwest of Red River) is 42.96 inches as measured from 1937 to 2005, with most of the evaporation occurring from April through October (Western Regional Climate Center, 2007). Eagle Nest, Cloudcroft, and Lake Maloya are in mountainous areas similar to the Questa mine.

The differences in relief between the Questa rock piles result in large variations in temperature and precipitation each rock pile is subjected to. Climatic data from primary weather stations at the Questa mine show some of these differences due to elevation changes. Table 2 is a statistical summary of climatic data from these stations (Golder Associates, Inc., 2005). Temperature extremes tend to be lower for stations at higher elevations than those at lower elevations, but the precipitation data demonstrate much stronger differences between stations at different elevations. Daily temperatures typically range between 30 and –30˚C over the course of a year, but the values increased with decrease in elevation. When aggregated on a monthly basis, daily lows are more variable, as represented by the data range for each month, during the colder months (December – April) than the warmer months. Inspection of the monthly rainfall and snowfall data reveals that median and maximum monthly precipitation increased with increase in elevation (Talbot and Burian, 2007). Topographic effects lead to more precipitation on windward slopes and concentrated storms in the mountain valleys.

TABLE 1. Monthly climatic summaries from 1/1/1915 to 4/30/2007 for Red River, NM (from Western Regional Climate Center, 2007). min=minimum, max=maximum, temp=temperature, prec=precipitation.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average max temp (°F)	36.6	39.2	44.3	53.6	62.6	72.7	76.0	73.6	68.7	58.5	45.0	37.6	55.7
Average min temp (°F)	4.6	8.2	14.8	22.2	28.9	35.3	41.0	40.3	33.7	25.2	14.3	6.3	22.9
Average total prec (inches)	1.09	1.19	1.81	1.79	1.72	1.28	2.90	3.14	1.70	1.55	1.32	1.15	20.65
Average total snowfall (inches)	20.7	21.5	29.9	21.8	7.3	0.1	0	0	0.5	8.3	18.4	19.2	147.8

TABLE 2. Summary climate statistics for the primary weather stations at the Questa mine (more details in Golder Associates Inc., 2005).

Monitoring Period	Station, elevation	Average Daily Temp °F	Average Daily Relative Humidity (%)	Average Daily Wind Speed (m/s)	Total Daily Net Radiation (Mj/m2)	Cumulative Precipitation (inches)	Cumulative Potential Evaporation (inches)
8/7/00-7/23/01	TP-4 9250 ft	42.46	50.5	3.77	6.69	14.39	46.86
	TP-5 9800 ft	40.14	52.9	3.01	5.16	14.65	36.31
	TP-6/7 8735 ft	43.69	51.1	2.34	7.07	17.85	49.71
7/24/01-7/24/02	TP-4 9250 ft	44.49	43.0	3.87	7.57	11.63	55.52
	TP-5 9800 ft	42.64	44.7	3.27	6.23	9.53	45.68
	TP-6/7 8735 ft	45.75	43.7	2.41	7.53	13.20	55.28
	Mobile near TP-4 9250 ft	43.85	43.7	4.11	5.32	NA	38.73
7/25/02-7/24-03	TP-4 9250 ft	43.94	46.8	3.71	6.41	12.98	46.81
	TP-5 9800 ft	41.95	48.5	2.93	6.50	12.92	47.44
	TP-6/7 8735 ft	45.17	47.1	2.20	8.13	14.79	59.45
7/25/03-7/24/04	TP-4 9250 ft	43.91	46.6	3.82	7.28	14.97	53.36
	TP-5 9800 ft	41.57	48.6	2.34	7.38	15.78	54.17
	TP-6/7 8735 ft	45.15	46.8	2.34	7.38	15.78	54.17
	Mobile near ST-3 9075 ft	42.40	51.5	2.69	5.86	NA	42.94

GEOLOGIC AND TECTONIC HISTORY

The Questa-Red River area, like much of the Rio Grande rift in New Mexico and Colorado has experienced multiple geologic and tectonic events that resulted in the geology we see today (Fig. 3a-c, Table 3). The regional geology of the Questa-Red River area can be roughly divided into five general tectonic periods: Proterozoic, Paleozoic ancestral Rocky Mountains, Laramide orogeny, Rio Grande rift volcanism (including the Questa caldera), and recent Rio Grande rift fill.

TABLE 3. Summary of geologic history of the Questa area (Bauer et al., 2004; Ludington et al., 2005; Samuels, 2008; Zimmerer, 2008).

Approximate age	Event	Event
2 Ma-present	Pediment and stream deposits	
4.5 Ma-present	Beginning of alteration of scars	
2.34-5.88 Ma	Taos Plateau volcanic field	
1-16.4 Ma	Santa Fe Group	Miocene lavas
5 Ma to present	Slow extension, basin subsidence	
18.6-5 Ma	Rapid extension of Rio Grande rift	
16.5-22.9	Postcaldera magmatism, southern margin	
24.7-22 Ma	Resurgent plutonism, postcaldera volcanism, southern caldera margin plutonism and molybdenum mineralization (Latir Peak volcanic field)	Slow extension of Rio Grande rift
25.2 Ma	Amalia Tuff (Questa caldera collapse)	peralkaline rhyolite dikes
25.2-28.3 Ma	Precaldera volcanism (Latir Peak volcanic field)	sedimentary rocks
28.5-33.7 Ma	Early regional extension Rio Grande rift	Transition from crustal shortening to extension
33.7-65 Ma	Laramide orogeny	
1610-1752 Ma	Precambrian rocks	

The Proterozoic basement rocks consist of supracrustal rocks of metamorphosed sedimentary, volcanic, and volcaniclastic origins intruded by a variety of plutonic rocks, which range in composition from mafic to felsic that were emplaced during four tectonic periods: (1) crustal assembly during the Mazatzal orogeny, 1800-1600 Ma (Karlstrom and Bowring, 1988, 1993; Karlstrom et al., 1990, 2004), (2) Late Proterozoic granitic plutonism, 1480-1350 Ma (Karlstrom and Bowring, 1988; 1993; Adams and Keller, 1996; Karlstrom et al., 1997, 2001, 2004; Karlstrom and Humphreys, 1998), (3) pre-Grenville extension and formation of continental margin at 1350-1200 Ma (Pittenger et al., 1994; Adams and Keller, 1994, 1996; Karlstrom et al., 1997; Karlstrom and Humphreys, 1998; Barnes et al., 1999, Karlstrom et al., 2004), (4) 1200-1080 Ma period of mafic, volcanic, and A-type granitic intrusions in New Mexico, Texas, and Arizona, coincident with the Grenville orogeny and perhaps extension (Adams and Keller, 1996; Smith et al., 1997; Shannon et al., 1997; Mosher, 1998; Barnes et al., 1999; Reese et al., 2000; Bickford et al., 2000). The Proterozoic rocks have been subjected to amphibolite-grade regional metamorphism resulting in conspicuous foliation. Proterozoic events left an underlying structural fabric that has controlled structural and magmatic events ever since (Graugh and Keller, 2004a; CD-ROM working group, 2002; Karlstrom et al., 2004). Northeast, north-south, and northwest structures are attributed to Proterozoic foliation and shear zones (Karlstrom and Humphreys, 1998).

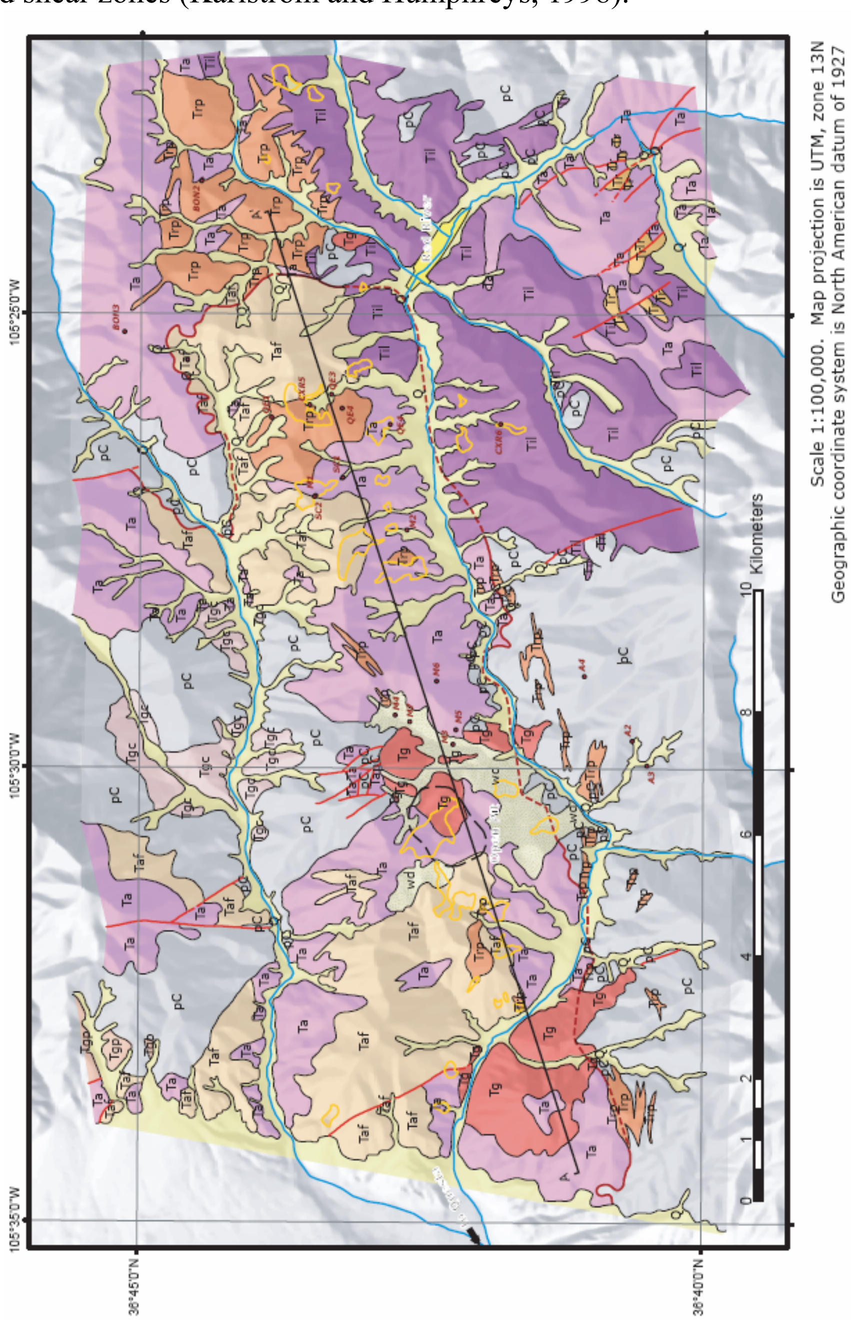

FIGURE 3a. Simplified geologic map of the southern portion of the Questa Caldera in the vicinity of Red River, New Mexico from Ludington et al. (2005) modified from Lipman and Reed (1989). The individual rock types shown are a starting point for

conceptualizing what might be significant units or domains in the study area. Lithologies are described in more detail in the lithologic atlas (McLemore et al., 2009). Note that the areas impacted by hydrothermal alteration (alteration scars) are outlined in orange. Key in Figure 3b and cross section A-A' in Figure 3c.

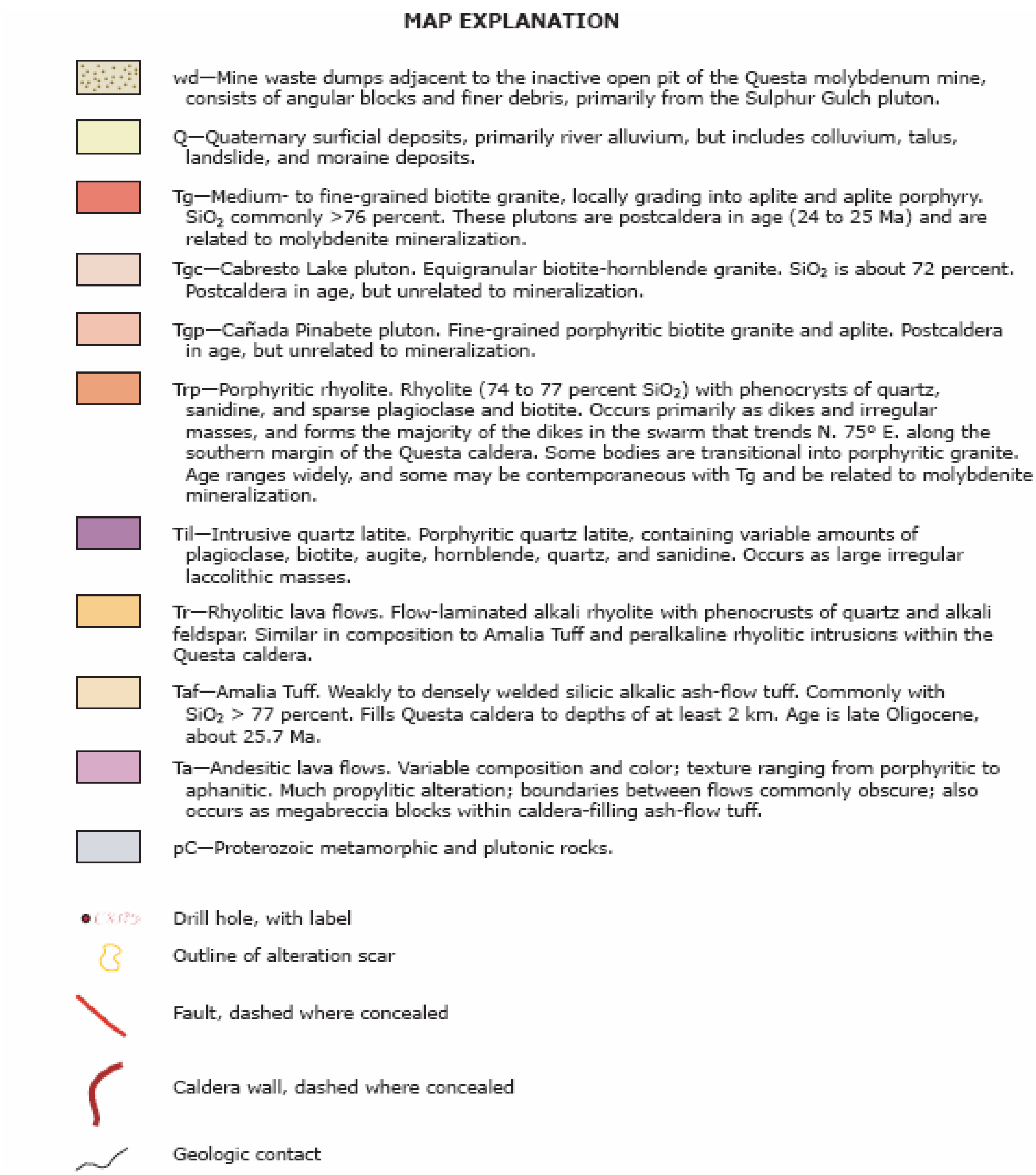

FIGURE 3b. Key to geologic map in Figure 3a, from Ludington et al. (2005) modified from Lipman and Reed (1989).

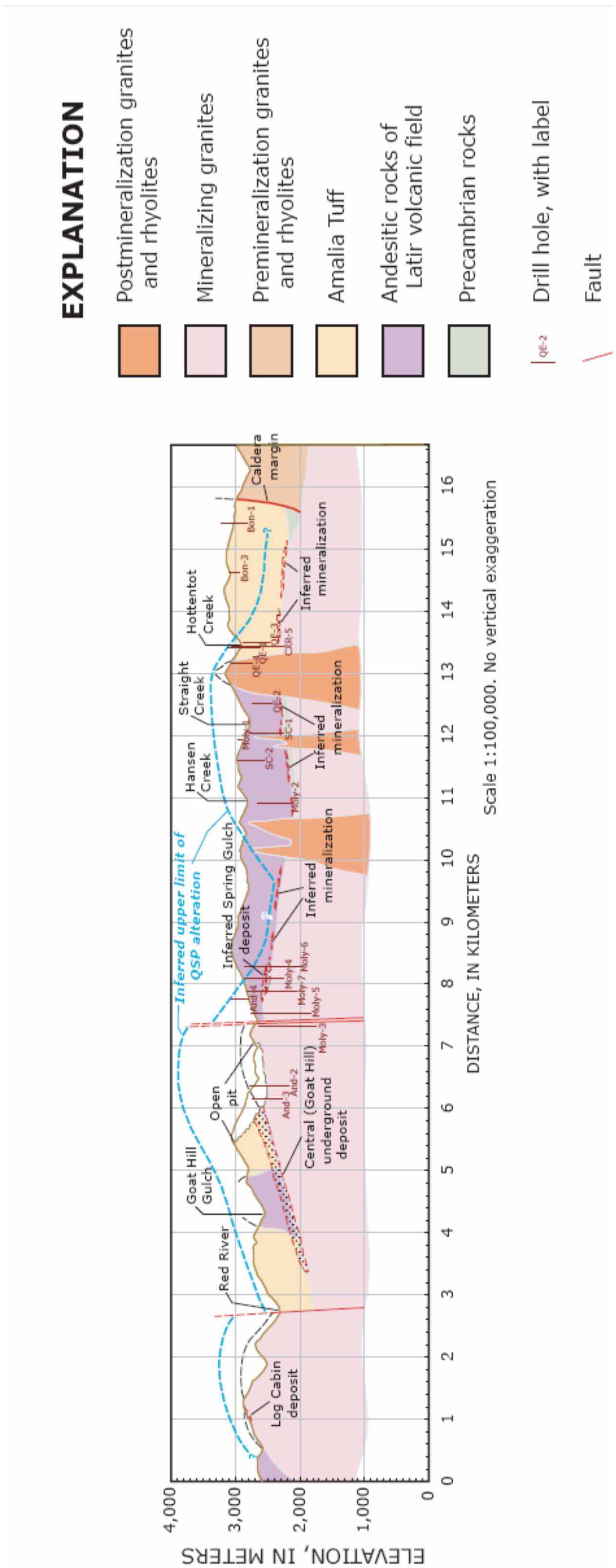

FIGURE 3c. Cross section along line A-A' in Figure 3a, from Ludington et al. (2005) modified from Lipman and Reed (1989).

Paleozoic period of basin formation and uplift as part of the Ancestral Rocky Mountains resulted in the Uncompahgre-San Luis highlands and Sangre de Cristo uplift in the Tusas and Sangre de Crsito Mountains. Paleozoic rocks belong mostly to the clastic units of the Pennsylvanian Magdalena Group, although in local areas the Mississippian Espiritu Santo and Terrero Formations are exposed as erosional outliers (Lipman and Reed, 1989; Baltz and Myers, 1999; Bauer and Kelson, 2004a).

Crustal shortening related to subduction of the Farllon plate elevated the Sangre de Cristo Mountains again during the Laramide orogeny as well as the San Luis uplift, west of the Sangre de Cristo Mountains. The Laramide orogeny resulted in a series of thrust and high-angle reverse faults that were reactivated Paleozoic structures (Baltz and Myers, 1999; Chapin and Cather, 1994; Cather, 2004).

The most important group of rocks in the Red River drainage are Rio Grande rift-related volcanic rocks. These rocks include those associated with the Latir volcanic field, which covers approximately 1200 sq km and consists of a series of Miocene (18.6-28 Ma) mildly alkaline extrusive rocks, ranging in composition from basaltic and quartz-latitic flows to welded ash-flow sheets of high-silica alkaline rhyolite (Amalia Tuff) that erupted from the Questa caldera 25.7 Ma ago. These rocks are approximately 2 km thick at the mine. Subsequently, several granitic intrusions and subvolcanic porphyries intruded the Latir volcanics. These post-caldera intrusions are derived from a large buried batholith and are the apparent sources of the molybdenum deposits. The silicic rocks of the caldera cycle are alkaline (some are peralkaline) and are enriched in Y, Zr, and rare earth elements (REE). Younger mineralization-related intrusions are calc-alkaline, high in fluorine and silica, and strongly depleted in Y, Zr, and heavy REE, similar to the source rocks of other Climax-type molybdenite deposits (Dillet and Czamanske, 1987; Johnson et al., 1989; Ludington et al., 2005; McLemore et al., 2009). Other intrusions in the area are similar to the composition of the volcanic rocks, and vary from mafic to felsic composition (Lipman and Reed, 1989; Czamanske et al., 1990). These intrusions range in age from 25 to 18 Ma (Zimmerer, 2008). The Questa mine is on the southern flank of the Questa caldera and Latir volcanic field. Most of the volcanic and intrusive rocks are fractured as a result of multiple intrusions and tectonic events.

Only the southern margin of the Questa caldera is apparent in the aeromagnetic data, but most of the caldera is apparent in the gravity data, where it corresponds to a gravity low that approximately follows the Red River valley (Grauch and Keller, 2004b). This gravity low has been attributed to a large batholith underlying the Questa caldera that could be the source of the intrusive rocks in the Questa-Red River area (Lipman, 1983). The Questa batholith is a narrow, 10 km-wide, zone trending north-south (Cordell et al., 1985). A series of north-west trending aeromagnetic highs are attributed to granitic intrusions along the southern Latir volcanic field. The western margin of the Questa caldera is truncated by a north-south, rift-related Sangre de Cristo fault (Grauch and Keller, 2004a). It is unknown if the Questa caldera continued beneath the Taos graben west of the mountain range.

To the west of the Red River valley, normal faults of the Rio Grande rift down-drop the western side of the Latir volcanic field, forming the San Luis basin. This basin has been subsequently filled with a series of colluvial gravels (the Santa Fe Group) interlayered with basalts of the Taos and No Agua volcanic fields.

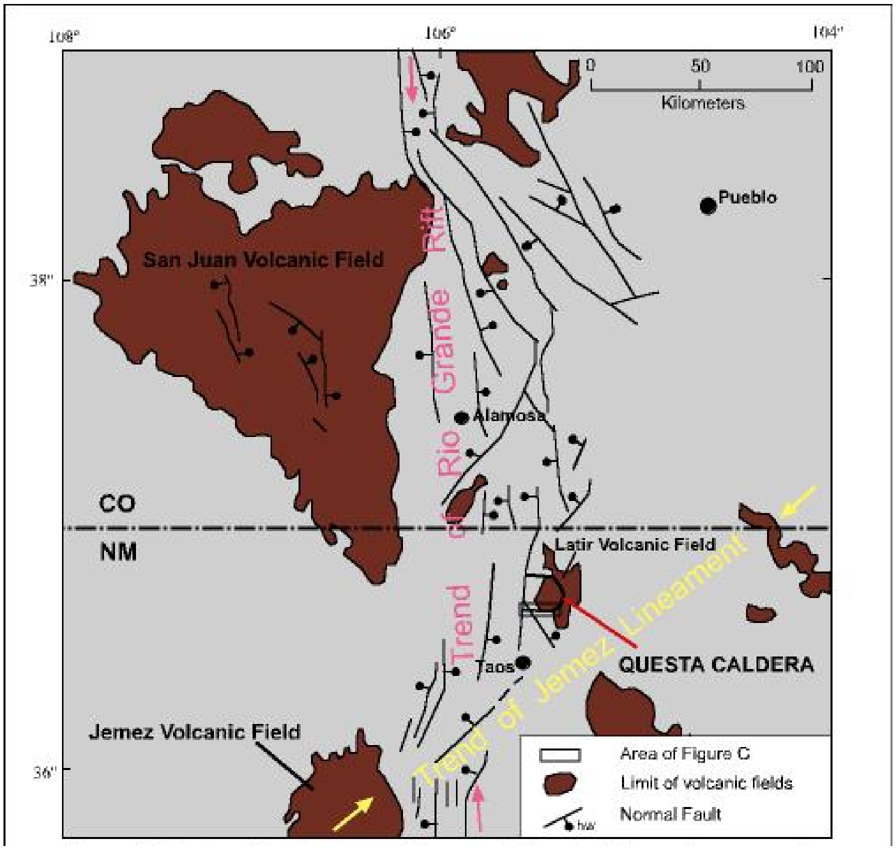

FIGURE 4. Tectonic geologic setting of the Questa-Red River area (modified from Meyer and Leonardson, 1990; Meyer and Foland, 1991).

Structural Setting

The rocks in the Red River-Questa area exhibit brittle deformation as a result of past tectonic events, especially the Questa caldera and Rio Grande rifting. The Questa caldera-margin fault zone is well exposed in the Red River valley and the Questa mine is along that margin (Fig. 3). Caine (2006) performed detailed structural analysis of the Red River-Questa area and found that the entire area is jointed with a few distinctive patterns: orthogonal, oblique orthogonal, and conjugate joint sets. Joint intensity (the number of joints measured per unit line length) is high to extreme. Three types of fault zones are present: partially silicified, low- and high-angle faults with well-developed damage zones and clay-rich cores, and high-angle, unsilicified open faults. Complex, stockwork and other vein networks cut the host rocks in the mine area.

San Luis basin

The Rio Grande rift consists of many north-south, topographic and structural basins that are separated by northeast-trending zones that accommodate the opposing sense of tilting; the largest of which is the San Luis basin (Chapin and Cather, 1994; Bauer and Kelson, 2004a). These basins are half-grabens that are tilted to the east or west and have a relatively active north-striking fault system along one border. The San Luis half-graben tilts to the east, whereas the Espanola basin to the south tilts to the west. The San Luis basin is bordered on the east by the Sangre de Cristo Mountains and on the west by the Tusas and San Juan Mountains. The Sangre de Cristo fault is the major fault system between the Sangre de Cristo Mountains and the San Luis basin. The Taos plateau consisting of Pliocene basaltic rocks forms the southern boundary of the San Luis Basin. New estimates of the minimum average extension rate in the San Luis basin ranges from 102 to 83 m/m.y. during the last 3 m.y. (Bauer and Kelson, 2004b). During the Pleistocene, the San Luis basin was a closed basin, receiving water from the San Juan and Sangre de Cristo drainages.

Red River

The headwaters of the Red River, a perennial river, are on Wheeler Peak, south of the town of Red River. The river flows northward through the town of Red River, turns westward and flows into the Rio Grande (Fig. 2). Discharge from the Red River measured near Questa varies between 21 m^3/s during spring runoff and <0.07 m^3/s during winter freeze, while averaging somewhat less than 1.5 m^3/s year around (Allen et al., 1999).

The fluvial terraces in Red River valley are weakly imbricated and cross-stratified. Sediments are poorly to moderately well sorted, medium to thickly bedded, gray sandy gravel and gravelly sand. The gravel clasts are subangular to well rounded. Loess units less than 1.5 m in thickness commonly overlie the fluvial sands and gravel. The mouth of Red River consists of a thin volcanic section (Servietta Formation of the Taos volcanic field?) that overlies a thick gravel pile (Lama Formation?) that probably represents the ancestral Red River alluvial fan. Red River actually formed the headwaters of the Rio Grande prior to mid-Pleisotocene (Wells et al., 1987). The ancestral Red River emptied into a large lake, Sunshine Valley that fed into drainages of the ancestral Rio Grande. The lake probably drained southward by middle Pleistocene (Machette, 2003). Capture of the drainage north of Red River by the Rio Grande is uncertain, but may be related to progressive head cutting, perhaps 0.3-2 Ma ago (Wells et al., 1987; Bauer, 2008).

Glaciation

The southernmost extent of North American Quaternary alpine glaciation occurred in New Mexico repeatedly during the Pleistocene and Holocene, or about 150-250 ka to 18-20 ka (Ray and Smith, 1940; Pazzaglia and Hawley, 2004). However, very little has been published on the glaciation of the Red River valley. Cirques and moraines are visible on the northeastern slopes of the mountains south of the Questa mine (Fig. 5). A study of glacial features in the southern Sangre de Cristo Mountains by Wells (1987) suggests that microclimate effects and bedrock features play important roles in the formation of glaciers. Glaciers did not develop on western slopes in the Sangre de Cristo Mountains, because of exposure to afternoon sun and prevailing westerly winds, which enhance snow and ice ablation. Well developed fractures in bedrock lithologies enhanced the formation and preservation of glaciers. Thus the smaller source areas resulted in less glacial sediment and outwash.

FIGURE 5. Cirques and moraines on the northeastern slopes of the mountains south of the Questa mine.

MINING HISTORY

Although there are various accounts of Spanish mining gold from the Red River area prior to 1680 (Lindgren et al., 1910; Pearson, 1986), the earliest claims in the area were staked in 1826, with production reportedly beginning in 1871 in the Red River district (McLemore and Mullen, 2004). Mines belonging to the Red River, Questa, and northern part of Twining mining districts are within the Red River drainage basin (Fig. 1). Early mining operations in the area, with the exception of the Questa mine, produced gold, silver, copper, and lead, but soon closed because of low grade and small tonnage.

Questa district

Molybdenum was discovered in the Questa district along the Red River about 1914 (Schilling, 1960, 1990). The soft black to steel blue mineral was first misidentified as graphite, and the bright-yellow molybdenum veins and jarosite altered outcrops were misidentified as sulfur (hence the name Sulphur Gulch). By 1918, the R and S Molybdenum Mining Company correctly identified the ore as molybdenite and began underground mining of high-grade veins. The ore was hauled several miles by horse and mule drawn wagons to the June Bug mill, which was the relocated gold mill from Elizabethtown. In 1919, R and S Molybdenum Mining Company was reorganized as the Molybdenum Corporation of America in 1921, which eventually became Molycorp, Inc. (now Chevron Mining Inc.). In 1923, Molycorp built a processing mill, which was one of the first flotation mills in North America. The mill has since been rebuilt several times.

Underground mining of high-grade vein ore was from 1919 to 1958, with a production of 0.375 million tons of >4% MoS_2 (Schilling, 1960, 1990; Ross et al., 2002; McLemore and Mullen, 2004). Exploration continued from 1953 to 1964, when open-pit mining commenced. The current mill was built in 1964. The company mined some 81 million tons of ore from their open pit at a grade of 0.191% MoS_2 between 1965 until 1982. In 1975, Molycorp and their partner, Kennecott, discovered several deeper deposits in the Southwest and Northeast ore zones. Kennocott sold their interest to Union Oil Company of California (UNOCAL) in 1977. Underground block caving of ore commenced in 1982. Molycorp continued mining through 1986, when poor market conditions caused the temporary shutdown of the mine until 1989. Mining operations again were placed on standby in 1992 and resumed in 1995 and continue to this day. Production from the Goat Hill orebody from 1983 to 2000 amounted to 21.11 million tons of 0.31% MoS_2. Current production is from the adjacent D-orebody since 2001 with a grade of 0.338% MoS_2. In early April 2005, Chevron-Texaco announced purchase of UNOCAL, including Molycorp, Inc. and in October 2007, Molycorp, Inc. officially became Chevron Mining Inc.

Current ore grade ranges between 0.3 and 0.5% Mo. Reserves and resources (Bruce Walker, Molycorp, personal communication, 11/99) at Questa are as follows:

Proven reserves	16,344,898 tons of 0.343% MoS_2 at a cutoff grade 0.25% MoS_2
Probable	47,198,409 tons of 0.315% MoS_2
Possible	3,223,000 tons of 0.369% MoS_2.

When proven and probable reserves are considered the mine life is 25-35 years, and when resources are included the mine life is 50-80 years.

Potential mineralized bodies have been delineated to the west of the Questa mine in the Log Cabin deposit (on the upper contact of the Bear Canyon stock; Daniel, 1967), and east of the Questa mine in the Spring Gulch deposit (Fig. 6). Some exploration drilling was done in most of the alteration scars to the east of the mine, with the majority of the drilling in the Hottentot area (Loucks et al., 1977). Molybdenite veins were encountered, but no deposits of sufficiently high grade to be considered economic were found.

Red River-Rio Hondo district

Six deposit types are found within the Red River-Rio Hondo district, upstream of the Questa district: placer gold, volcanic epithermal veins, alunite-argillic alteration, porphyry molybdenum, and Precambrian vein and replacement deposits. The production from the district mostly has come from the volcanic epithermal veins and placer gold deposits. Major exploration and development didn't occur until 1867, when the Waterbury Watch Company of Connecticut began development at the Anaconda group. By 1897, Red River had a population of 2000, but the mines never yielded large amounts of gold or other metals (Lindgren et al., 1910; Roberts et al., 1990; McLemore and Mullen, 2004). Exploration and development, with little mining, continued into the 1980s. There are several reasons why mining was not profitable, including poor milling practices, bad management, lack of sufficient capital, high operating costs, isolation of the district and low grades.

Metals deposits in the Red River-Rio Hondo district are found as fault-controlled quartz-cemented breccia zones and banded, massive or vuggy quartz veins that are characteristic of volcanic epithermal vein deposits. Gold, pyrite, molybdenite, sphalerite, galena, bornite, chalcocite, malachite, azurite, fluorite, chalcopyrite, pyrargyrite, and argentite are found in the breccia zones and veins.

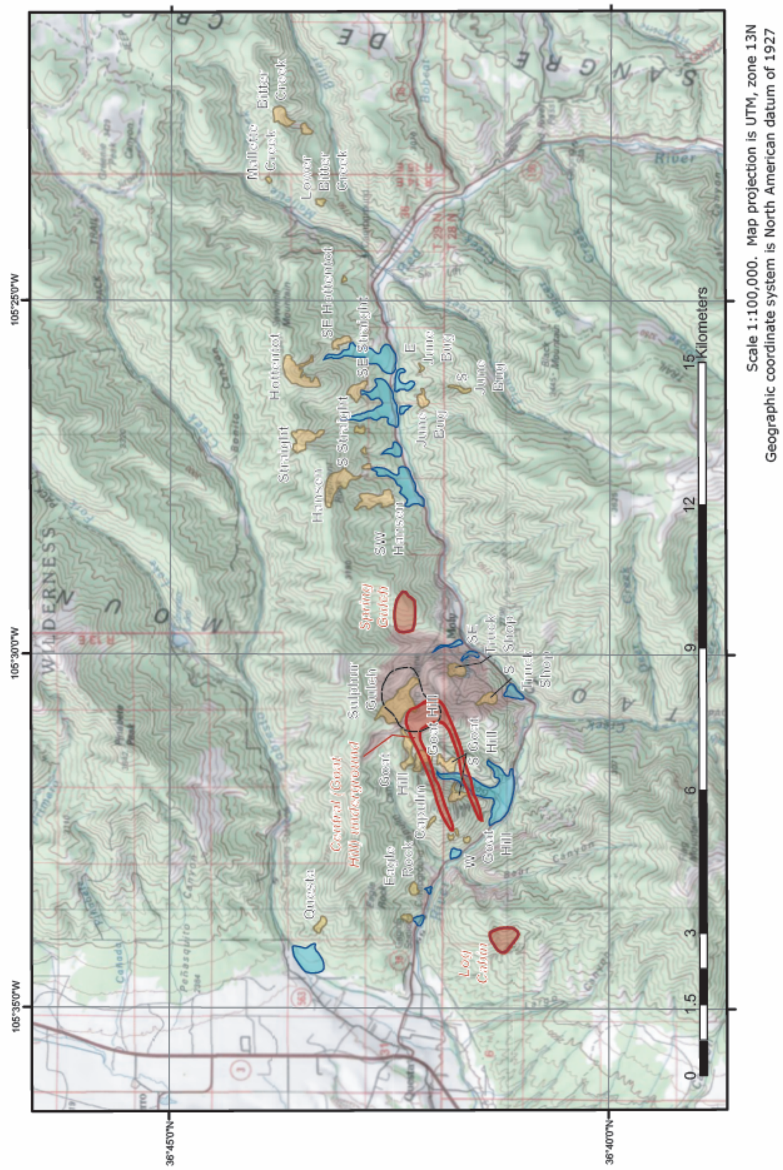

FIGURE 6. Topographic map of the Red River valley showing alteration scars (yellow), debris fans (light blue), ore bodies (red), and the Questa mine (black) (from Ludington et al., 2005).

Other deposits are found in the district. Placer gold deposits are found in Red River and local drainages of Red River. Quartz-molybdenite veins associated with Tertiary porphyritic granitic intrusions in the Bobcat, Mallette, and Bitter Creek area indicate the possibility of concealed porphyry molybdenum deposits (Schilling, 1960). Local areas of pyrite-bearing hydrothermal and acid weathering, locally known as alteration scars, are associated with both the Red River-Rio Hondo and Questa districts in Red River valley, where alunite is found. Alunite is a potential source of aluminum. Quartz veins of unknown age are found in Precambrian rocks that contain small amounts of gold, silver, copper, and other metals.

Twining District

Mining in the Twining district began around 1869 (Park and McKinlay, 1948). Shear zones in the metamorphic Precambrian rocks (metavolcanics and metasediments) and quartz veins, act as hosts for the ore minerals. Common minerals present within the quartz vein zones are tourmaline, epidote, pyrite, galena, chalcopyrite, and malachite. Gold, bornite, chalcocite, hematite, magnetite, azurite, and fluorite are some of the other minerals found in the district. The major mine in the Twining district was the Frazer. It was a copper mine that was worked before the turn of the century by local prospectors. However, the amount of copper extracted from the Fraser mine is not known (Park and McKinlay, 1948).

MINERALIZATION AND ALTERATION AT QUESTA

Formation of Questa Molybdenum Deposit

The Questa deposit is a Climax-type porphyry molybdenum (±tungsten) deposit, which is a large, low-grade (0.1–0.2% Mo) deposit that contains disseminated and stockwork veinlets of molybdenum sulfides and is associated with silica- and fluorine-rich porphyritic granitic intrusions (Fig. 7). The deposits formed from hydrothermal fluids that evolved in part from the granitic magmas (Johnson et al., 1990; Cline, 1991; Cline and Vanko, 1995; Klemm et al., 2008). All of the mining has been from a horseshoe-shaped system of ore bodies between Goat Hill and Sulphur Gulch, including 1) the original underground mine mined during 1919-1958, 2) the open pit mined during 1965-1983, 3) the Goathill ore body mined by block-caving underground during 1983-2000 4) the D-ore body, mined by block-caving during 1983-2000, and 5) remaining reserves, also mined by block caving that are now being developed and mined (Schilling, 1960, 1990; Carpenter, 1968; Molling, 1989; Ross et al., 2002; Ludington et al., 2005; Rowe, 2005; Klemm et al., 2008).

The deposits consist of thin veinlets, fracture coatings, breccia zones, and disseminations in granitic host rock and ore minerals include molybdenite, powellite, scheelite, beryl, helvite, bismuthinite, and wolframite. Quartz, sericite, fluorite, and pyrite are common gangue minerals. Two geochemical subclasses of porphyry molybdenum deposits are recognized, low-fluorine quartz monzonite and high-fluorine Climax type; the Questa deposit is a Climax type (Westra and Keith, 1981; Mutschler et al., 1981; White, 1981; Cox and Singer, 1986; Klemm et al., 2008). Three morphological forms of porphyry molybdenum deposits are found (Fig. 8; Guilbert and Park, 1986; Ross et al., 2002; Rowe, 2005): horizontal breccia body and veins (i.e., Questa), vertical breccia pipe and veins (i.e., Victorio Mountains, New Mexico), and stockwork veins without any breccia (i.e., Henderson, Colorado). The Climax form is further modeled into alteration zones as shown in Figure 6. The deposits are similar in form to the porphyry copper deposits, but are younger (35-25 Ma) and exhibit only minor supergene alteration. Three separate ore bodies form the Questa deposit, from west to east: Log Cabin, Central, and Spring Gulch. The Central ore body is the horseshoe shaped deposit consisting of the Southeast and Northeast ore zones and has been the site of historic and recent mining. Molybdenum is used in steel alloys and molybdenite, the most common molybdenum mineral, is used as a lubricant.

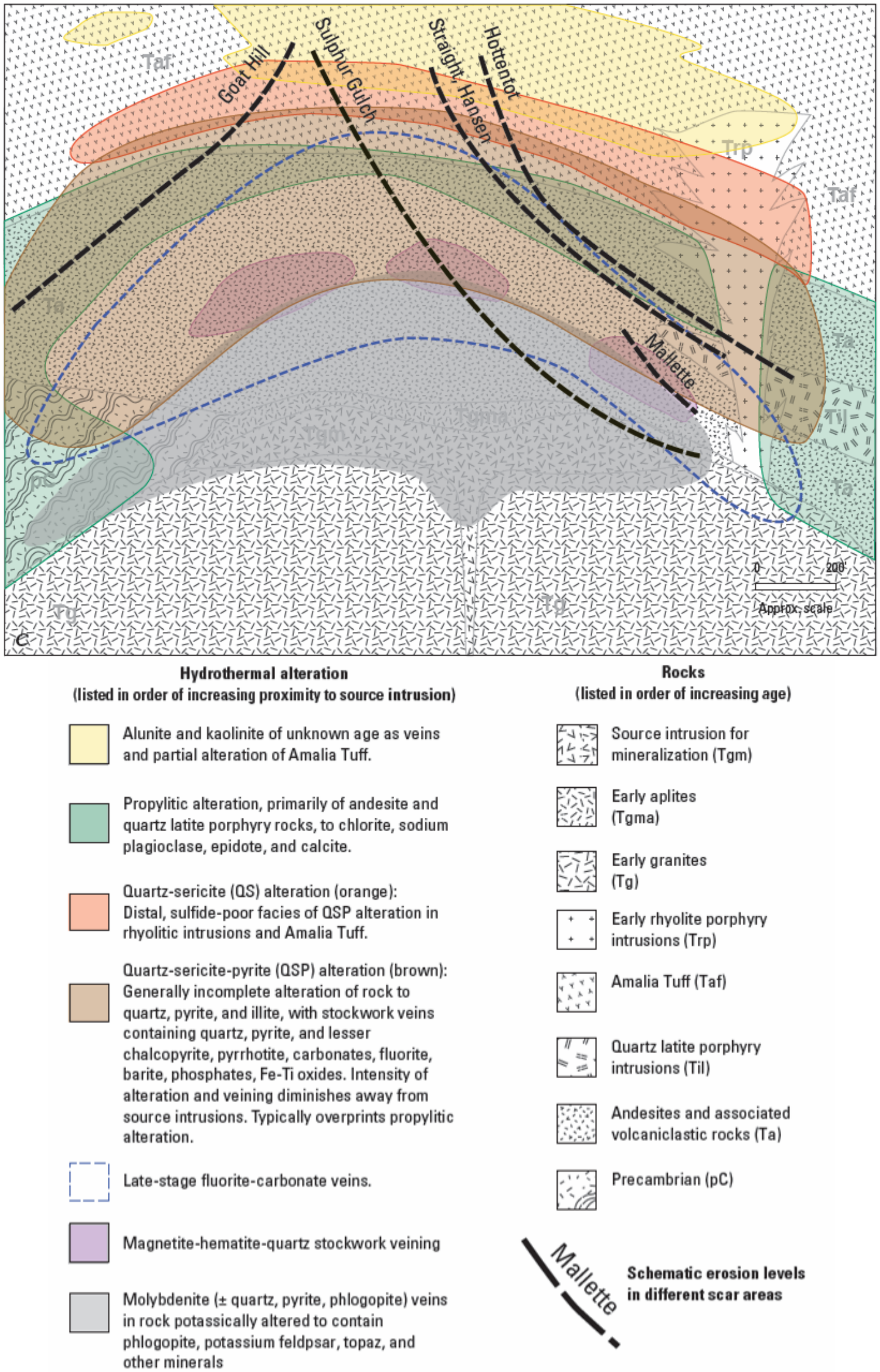

FIGURE 7. Cross section showing schematic spatial distributions of lithologies, alteration assemblages, and alteration scars in the Red River valley (taken from Ludington et al., 2005, which is modified from Martineau et al., 1977).

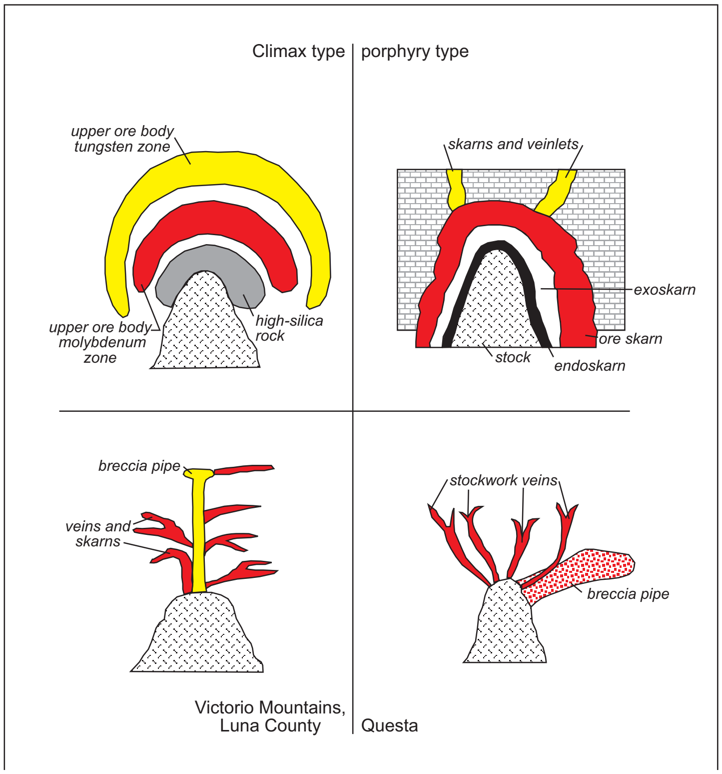

FIGURE 8. Schematic sketch of forms of porphyry molybdenum deposits that are dependent upon the amount of fluid in the source magma, overpressures, host rock permeability, and other physical/chemical characteristics (modified in part from Ross et al., 2002; Guilbert and Park, 1986).

Alteration associated with the Questa deposit

Six general types of hydrothermal alteration assemblages are found in the Red River-Rio Hondo, Questa, and Twining districts (Fig. 6; Martineau et al., 1977; Molling, 1989; Meyer, 1991):

- early and late propylitic (consisting of chlorite, calcite, pyrite, albite, epidote)
- argillic (consisting of chlorite, calcite, epidote, quartz, pyrite)
- potassic (consisting of replacement by K-feldspar and potassium-bearing micas, with fluorite, quartz, and molybdenite)
- quartz-sericite-pyrite (QSP), also is called phyllic, sericitic and silicic (QSP)
- silicification (replacement by quartz)
- post-mineral carbonate-fluorite and magnetite-hematite veining (locally with anhydrite).

Pyrite occurs as fine disseminated crystals in the host-rock matrix and as stockwork veins up to 6 inches thick. Younger epithermal quartz veins cut these altered rocks and locally, fragments of the altered rocks are present in the mineralized veins. The alteration mineral assemblage consists of essential chlorite (producing a green color), quartz, and pyrite and a variety of additional minerals depending upon original host rock lithology, temperature, and composition of the fluids, including calcite, epidote, zeolites, adularia, sericite/illite, smectite, etc. Silicification is the most extensive alteration adjacent to and along mineralized veins in the districts. Locally, chloritization, argillization, and sericitization form a halo surrounding mineralized faults. Epidote is present within this halo and indicates temperatures of formation >200°C. These altered zones consist of illite, kaolinite, chlorite, quartz, and iron oxides. More detailed descriptions of alteration assemblages are in McLemore et al. (2009).

ALTERATION SCARS

More than 20 naturally forming "alteration scars," are found along the mountain ridges of Red River between the towns of Questa and Red River (Fig. 6, 9). Public and scientific interest in these scars has increased during the last decade because of sporadic but destructive mudslides or debris flows that emanate from the scar areas during wet periods (Meyer and Leonardson, 1990). In addition, water quality degradation of the Red River by the input of acid, sulfur, and other elements from surface and ground water derived from the alteration scars has been documented by recent environmental studies (Allen et al. 1999; Shaw et al., 2003; Briggs et al., 2003; Lovetere et al., 2004; Maest et al., 2004; Ludington et al., 2005; Nordstrom et al., 2005; Naus et al., 2005; Kimball et al., 2006; Nordstrom, 2007). These alteration scars are particularly important to the QRPWASP, because they have the potential to provide a possible analog to past weathering and aid in the understanding of the future weathering processes of the Questa rock piles. Recent dates indicates their formation began approximately 1.5 Ma ago, possibly as a result of down cutting of the Red River and Rio Grande (Samuels, 2008).

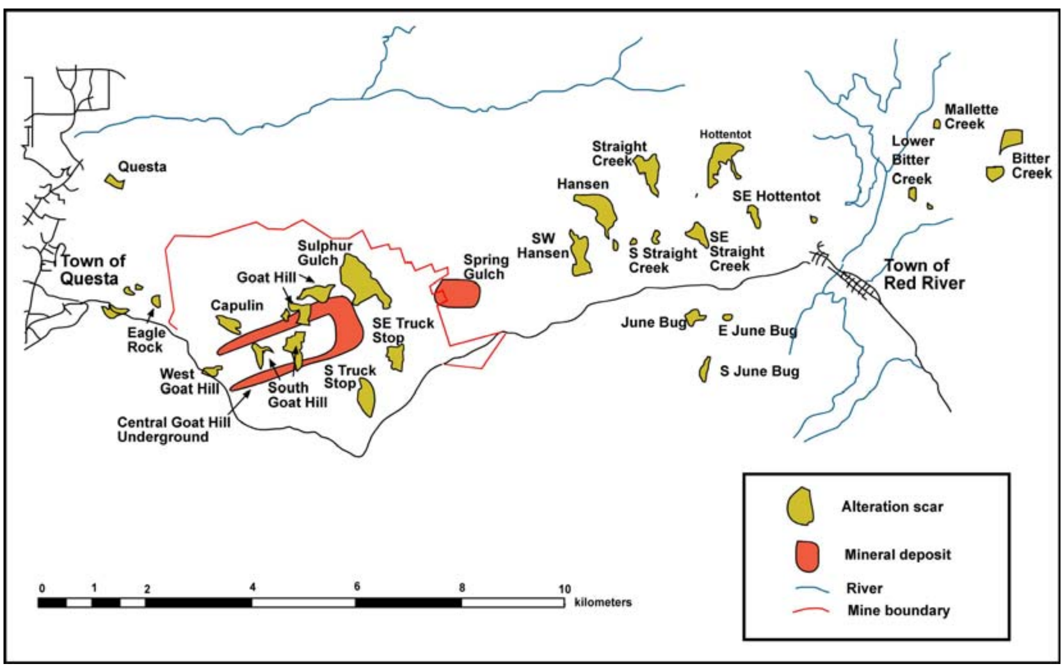

FIGURE 9. Map showing the alteration scars and mineral deposits of the Red River area. Alteration scar names from Meyer and Leonardson (1990).

Alteration scars are natural, colorful (red to yellow to orange to brown), unstable weathering landforms that are characterized by steep slopes (greater than 25 degrees), moderate to high pyrite content (typically greater than 3%), little or no vegetation, and extensively fractured bedrock. The scars are variable in size ranging from 1 to more than 100 acres. Two basic types exist based on their location; the higher elevation scars are called the divide scars and the lower elevation scars are called inner valley scars (Meyer and Leonardson, 1990). The older divide scars are larger with larger drainage areas compared to younger inner valley scars. Explorationists were first attracted to the Questa-Red River area, because these scars are similar to alteration halos associated with porphyry copper and molybdenum deposits elsewhere (Fig. 7; Cox and Singer, 1986; Mutschler et al., 1981). The distribution of the alteration scars appears to closely follow molybdenum and pyrite mineralization patterns in the area. However, the relative amounts of hypogene or supergene alteration that can contribute to scar formation is yet undetermined. Many scars are located on south-facing slopes, which tend to have lower vegetation density and snow cover in winter. Erosion of the alteration scars and rapid transport from the source areas forms large apron-like debris fan deposits at the base of the scars. Perched ferricrete breccias, locally in multiple zones are found along the margins of and within many scars. Ludington et al. (2005) estimated alteration scar erosion levels and found that the erosionally highest divide scars are Straight, Hanson, and Hottentott, which is supported by sulfur isotope data (Lueth et al., 2005; Campbell and Lueth, 2008; Samuels, 2008). The divide scars are older than the inner valley scars with age dates of 4.45±0.70 Ma. The lowest elevation, inner valley scars are younger with age dates of 0.31±0.23 Ma (Graf, 2008; Samuels, 2008; Samuels et al., 2008). The average incision rate of the scars as determined from isotopic studies is 77 m/m.y. (Samuels, 2008; Samuels et al., 2008).

Most alteration scars are composed of andesite overlain by Amalia Tuff or intruded by granitic intrusions, although other rock types also are found in some scars. The Amalia Tuff (rhyolite) forms the upper portions of most scars, especially those found high on the valley margins. The more competent rhyolite forms near-vertical spires, or hoodoos, at ridgelines, and is underlain by the weaker andesite and together form a badlands topography of erosion, rockfalls, slumping, landslides, and local down-slope creep of unstable ground.

Preliminary analyses of Airborne Visible-Infrared Imaging Spectrometer (AVIRIS) data indicate that the scars are characterized by abundant jarosite, kaolinite, and locally gypsum, surrounded by a halo of goethite (Livo and Clark, 2002). These secondary minerals are found in addition to common mineral phases, typical of the hypogene quartz-sericite-pyrite (QSP) altered andesite and rhyolite. Within a scar, a progression of grain-size reduction is apparent (Ludington et al., 2005; Graf, 2008). The relative sizes of clasts within the profile become smaller and the abundance of clay-size material increases progressing upward in the profile, similar in character to soil horizons. Secondary mineralogies (mainly sulfates) typically cement this material during dry periods resulting in a hard surface. With prolonged wetting, this finer material becomes soft and fails readily.

The high erosion rates on the bare slopes of the scars lead to denudation that continuously exposes additional pyrite-bearing outcrops. Pyrite when exposed to water and air, oxidizes and forms sulfuric acid (acid drainage or AD), which then dissolves other minerals in the rock forming soluble sulfate, oxide, and hydroxide minerals. The dissolved constituents form acid drainage that mixes with surface and ground water and ultimately enters Red River. Paste pH of soils in the alteration scars averages 2.5, and have high paste conductivities (greater than 1000 μS/cm), and sulfate concentrations that ranges from 1 to 11.5 percent (Shaw et al., 2003; Robertson GeoConsultants, Inc., 2000a, 2000b, 2001; data from this study). Leach extractions of samples from the alteration scars show elevated concentrations of S, Cu, F, Bi, Sn, Mn, K, and Th (Robertson GeoConsultants, Inc., 2000a, 2000b, Shaw et al., 2003). There does not appear to be any chemical distinctions between the various scars (Robertson GeoConsultants, Inc., 2000a, 2000b, Shaw et al., 2003; Briggs et al., 2003), which suggests that they were formed from similar rocks by similar processes.

The debris fan deposits consist of varying mixtures of interbedded fluvial, alluvial, and mudflow deposits. The buildup of these deposits in Red River reduces the river flow and results in the formation of meadows upstream of the constrictions (Meyer and Leonardson, 1990). The town of Red River, the mill, and Fawn Lakes are built upon these meadowlands.

SUMMARY

The geology and mining history of the Questa-Red River is complex and a result of multiple tectonic events. Lithologies likewise are diverse, ranging from metamorphic rocks to volcanic rocks to granites to shales, limestones, and sandstones. Three types of fault zones are present: partially silicified, low- and high-angle faults with well-developed damage zones and clay-rich cores, and high-angle, unsilicified open faults. Complex, stockwork and other vein networks cut the host rocks in the mine area. The differences in relief between the rock piles result in large variations in temperature and precipitation each rock pile is subjected to. Molybdenum was discovered in the Questa district along Red River about 1914. After a period of underground mining of high-grade vein ore from 1919 to 1958, open pit mining commenced in 1964 and continued through 1983. Underground block caving began in 1982 and continues today. The Questa deposit is a Climax-type porphyry molybdenum (±tungsten) deposit, which is a large, low-grade (0.1–0.2% Mo) deposit that contains disseminated and stockwork veinlets of molybdenum sulfides and is associated with silica- and fluorine-rich porphyritic granitic intrusions. The deposits formed from hydrothermal fluids that evolved in part from the granitic magmas. Six general types of hydrothermal alteration assemblages are found in the Red River-Rio Hondo, Questa, and Twining districts: early and late propylitic, argillic, potassic, quartz-sericite-pyrite, silicification and post-mineral carbonate-fluorite and magnetite-hematite veining. More than 20 naturally forming “alteration scars,” are found along the mountain ridges of Red River between the towns of Questa and Red River and offer a potential analog to long-term weathering in the Questa rock piles.

ACKNOWLEDGEMENTS

This project was funded by Chevron Mining Inc. (formerly Molycorp, Inc.) and the New Mexico Bureau of Geology and Mineral Resources (NMBGMR), a division of New Mexico Institute of Mining and Technology. Kelly Donahue, Amada Rowe, Meghan Jackson, and Mike Breeze assisted with this report. Bruce Walker reviewed earlier versions of this manuscript and his comments are appreciated. This work is part of ongoing research on the mineral resources in New Mexico at NMBGMR, Peter Scholle, Director and State Geologist.

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