Geology and zoning in the Steeple Rock district, New Mexico and Arizona

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Abstract — *The Steeple Rock district in New Mexico is a major epithermal gold-silver district that exhibits district zoning. Five types of ore deposits occur within the district:*

- *base-metal veins (with gold and silver) form the center of the district and occur along the Carlisle fault,*
- *gold-silver veins along northwest-trending faults and outward from the base-metal veins,*
- *copper-silver veins along the margins of the district,*
- *fluorite veins along the margins of the district, and*
- *manganese veins along the margins of the district.*

Areas of older acid-sulfate alteration occur throughout the district and also exhibit the following zoning: massive silica/chert zone (inner), silicified zone and clay zone (outer). This alteration overlies regional alkali-chloride (propylitic to argillic to sericitic) alteration. Synthesis of available data suggests the acid-sulfate alteration is related to a shallow, but older, epithermal hot-springs system. Subsequently, younger epithermal veins formed along faults.

Introduction

Systematic changes in the mineralogy, chemistry and/or physical and chemical conditions within a mining district are referred to as district zoning. These systematic changes reflect changes in evolving fluids with time and distance from the source. They provide excellent guides to ore deposits and enhance our understanding of the genesis of ore deposits. Zoning in epithermal districts is commonly difficult to interpret because the epithermal systems are dynamic and constantly changing. Overprinting of multiple epithermal (or geothermal) systems may also occur. The Steeple Rock district is an example of district zoning in an epithermal environment. The purpose of this paper is to describe the district zoning in the Steeple Rock district and to explain how district zoning can be used to enhance exploration and our understanding of the genesis of these deposits.

Location, production and exploration activity in the Steeple Rock district

The Steeple Rock mining district is located in the Summit Mountains of Grant County, NM, and Greenlee County, AZ (Fig. 1). The district derives its name from a prominent mountain peak (Steeple Rock) in the southern part of the area. Production of base and precious metals has occurred from fissure veins along faults.

Exploration began sometime around 1860, but production was not reported until 1880. An estimated $10 million worth of metals were produced from the district (in New Mexico) between 1880 and 1993. This includes approximately 151,000 ounces of gold, 3.4 million ounces of silver, 1.2 million pounds of copper, 5 million pounds of lead and 4 million pounds of zinc (Griggs and Wagner, 1966; McLemore, 1993). In addition, approximately 11,000 tons of fluorspar have been produced from the Mohawk, Powell, Leta Lynn and other mines (McAnulty, 1978; Richter and Lawrence, 1983; Hedlund, 1990b). In the Goat Camp Springs area, 2,000 tons of ore containing 74,500 pounds of manganese was produced, probably in the 1940s (Farnham et al., 1961). Two rock quarries were opened and mined for decorative and building stone.

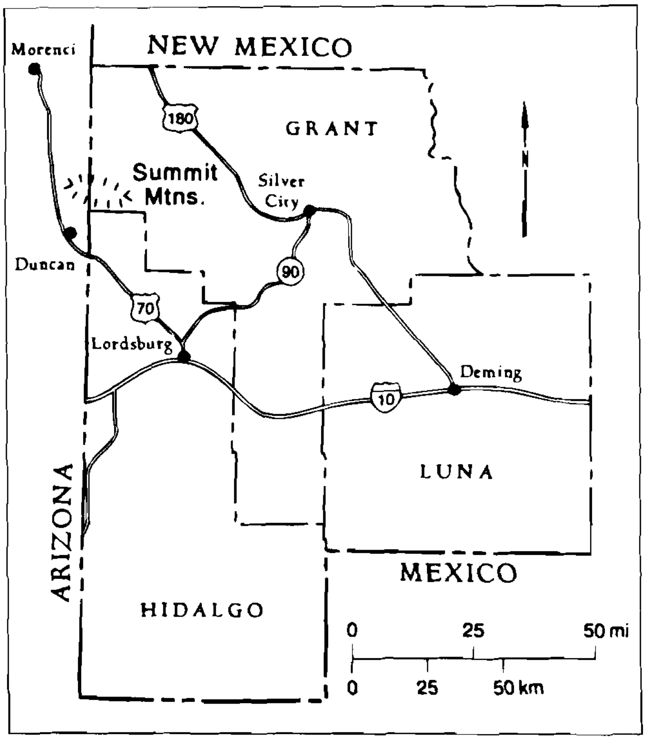

Figure 1—Location of the Steeple Rock district in the Summit Mountains, New Mexico and Arizona.

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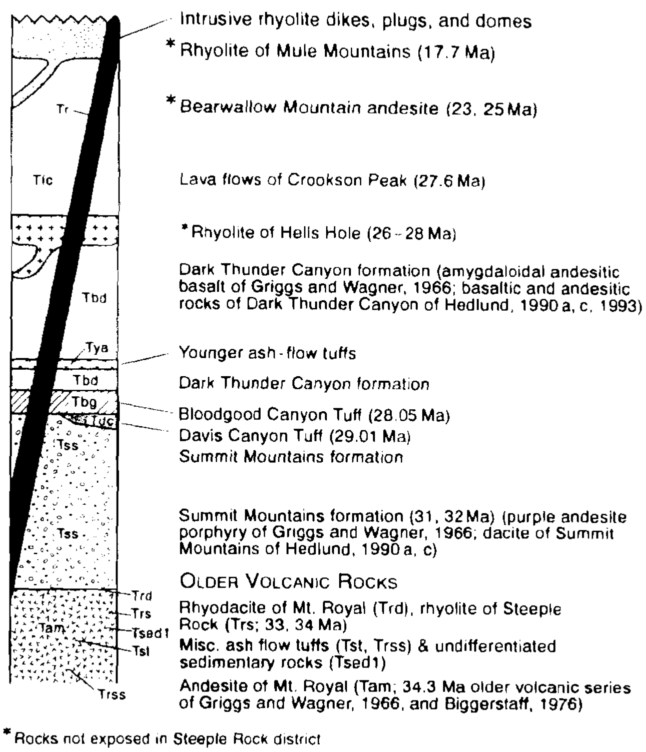


Figure 2—Generalized stratigraphy of the Summit Mountains (modified after Hedlund, 1990a, b, c, 1993; McLemore, 1993)

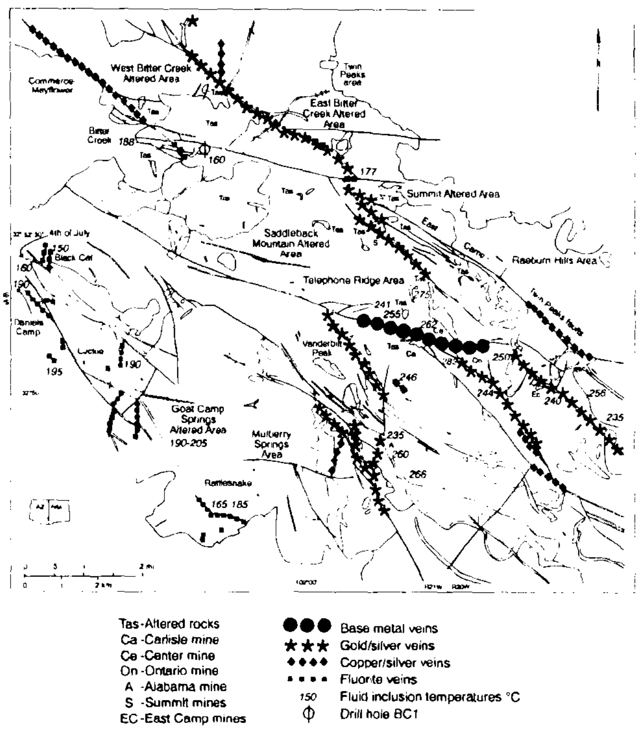


Figure 3—District zoning in the Steeple Rock mining district. Fluid inclusion temperatures from McLemore (1993).

In the 1970s through the 1990s, exploration for gold and silver intensified and resulted in additional exploration drilling and minor production, mainly for silica flux. In early 1994, only one mine, the Center mine owned by Mount Royal Mining Co., was being operated in the district. At least three different exploration programs are now under way at the Alabama, Carlisle and Summit mines. A discovery along the northwest-striking East Camp-Summit fault has been announced. The discovery reportedly contains 1.45 million tons of ore grading 0.18 oz/st gold and 10.3 oz/st silver (press release, May 1992).

Regional geologic setting

The Steeple Rock district occurs in a tectonically complex region. It lies on the southern edge of the Mogollon-Datil volcanic field (late Eocene-Oligocene), on the northern edge of the Burro uplift and near the intersection of the northwest-trending Texas and northeast-trending Morenci lineaments. Volcanic activity in the district occurred during mid-Tertiary extensional tectonics, but many of the regional faults have similar strikes as the older Laramide structures that were formed as a result of compressional tectonics. This suggests that reactivation of older crustal features may have occurred. This reactivation may have controlled volcanic and geothermal activity. Rocks exposed in the Steeple Rock district consist of a complex sequence of Oligocene to Miocene (34 to 27 Ma) andesitic, basaltic andesitic and dacitic lava interbedded with andesitic to dacitic tuffs, sandstones, volcanic breccias and rhyolite ash-flow tuffs that were subsequently intruded by rhyolite plugs, dikes and domes (Fig. 2, age: 33 and 28 to 17 Ma)(Hedlund, 1990a, 1990b and 1993; McLemore, 1993).

General description of fissure vein deposits

In the Steeple Rock district, the fissure vein deposits occur exclusively along faults and fractures within fault zones (Fig. 3). Some vein deposits occur along and cut across rhyolite dikes and plugs that are intruded along faults. In some places, later faults offset the vein deposits and rhyolite dikes (McLemore, 1993). The veins typically form prominent outcrops that bifurcate, are sinuous and pinch and swell along the strike. Complex vein textures, especially brecciation and rhythmic layering, are typically associated with high metal concentrations, although many complexly textured veins are barren of any mineralization.

Five types of vein deposits are distinguished on the basis of mineralogy and metal content:

- base-metal (silver-±gold),
- gold-silver (±base metals),
- copper-silver veins,
- fluorite veins, and
- manganese veins.

The extensive acid-sulfate alteration present in the Steeple Rock district offers exploration targets for a sixth type of deposit: high-sulfidation disseminated gold deposits (McLemore, 1993). The paragenesis of alteration and mineralization can be divided into six stages: premineralization, four mineralization stages (Stages 1, 2, 3 and 4) and postmineralization (Fig. 4). Additional information concerning paragenesis is in McLemore (1993).

The age of the vein deposits in the Steeple Rock district is problematical. Wahl (1983) reported a K-Ar age of 18 Ma on adularia from the East Camp vein. Veins cut the Bloodgood Canyon Tuff, as well as younger ash-flow tuffs, and are therefore younger than 27 Ma.

Base-metal veins

The base-metal veins in the Steeple Rock district occur

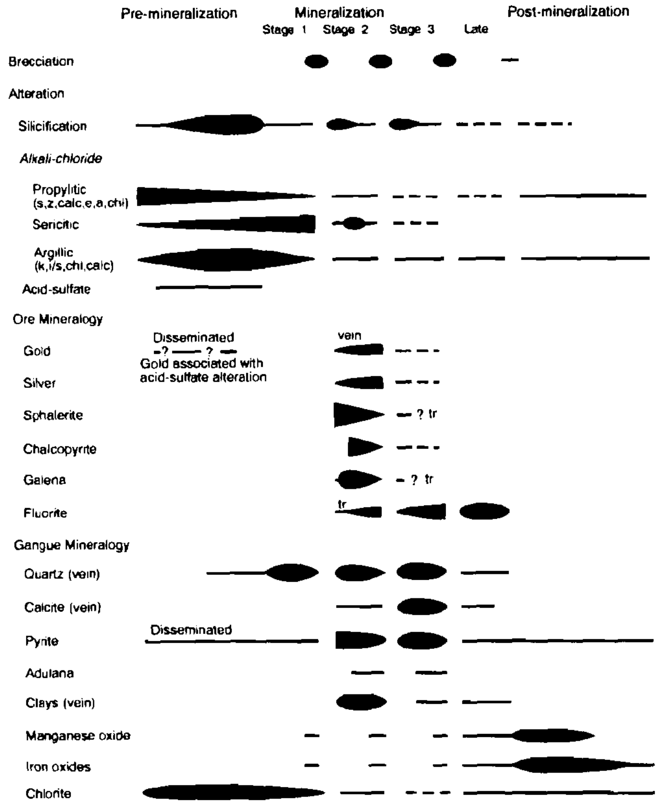


Figure 4—Simplified paragenetic sequence of events in the Steeple Rock district (from McLemore, 1993). s - sericite, z - zeolite, calc - calcite, 3 - epidote, a - adularia, chl - chlorite, i/s - illite/smectite, k - kaolinite.

exclusively along the Carlisle fault, from the Carlisle mine eastward to the Ontario mine (Fig. 3). These veins consist of 5% to 20% sulfides. The sulfides (galena, sphalerite and chalcopyrite) contain considerable silver (typically 1 to 12 oz/st) and gold (typically 0.1 to 0.4 oz/st, but as much as 5 oz/st). Local secondary sulfide and carbonate minerals occur with the sulfides in a gangue of quartz, pyrite, chlorite, illite/sericite, rare adularia and a few additional accessory minerals. Sulfide minerals vary in concentration throughout the fault zone. They occur in two or three ore shoots that are up to 4 m wide. The ore shoots appear to increase with depth and then decrease near the base of the mineralization (Griggs and Wagner, 1966; McLemore, 1993).

The ore occurs as:

- coarse-grained, massive sulfides (up to 20% base metals total) that occur locally with little quartz, and
- medium- to fine-grained sulfides disseminated throughout brecciated quartz veins and fault gouge.

Sulfides in the massive zone occur as streaks, irregular masses and veinlets with characteristic banded, rhythmic layering and brecciated textures. At least three periods of brecciation and cementation by silica have occurred. Sulfides occur in Stage 2 mineralization and locally in Stage 3 (Fig. 4). Lenses or zones of chlorite locally occur between bands of sulfides. Alteration is variable but typically silicification, chloritization and clay alteration are well developed along and between the veins. Acid-sulfate alteration occurs at the surface at the Carlisle and Ontario mines.

Gold-silver veins

The precious-metal veins in the Steeple Rock district consist of gold and silver with local, but minor, base-metal sulfides (<1%) (galena, sphalerite and chalcopyrite) disseminated in a gangue of quartz, pyrite, calcite, chlorite, illite/smectite, rare adularia, epidote and additional accessory minerals. These veins are predominantly quartz and quartz breccias that occur mainly along the northwest-striking faults (Fig. 3) but may occur along any fault trace. These veins are variable in size, rarely exceeding 30 m in width and are as much as several hundred meters long. The more important mines include the East Camp, Summit, Norman King, Laura, Jim Crow and Imperial. These veins grade locally along strike into the Carlisle base-metal veins, fluorite veins and copper-silver veins. Base-metal sulfides increase with depth in many of these deposits, with the total base metals rarely exceeding 1% to 3%. Gold and silver values are variable and are typically <1 oz/st gold and 12 oz/st silver (McLemore, 1993).

The best gold-silver values occur in complex veins that are banded, rhythmically layered and brecciated. At least three periods of brecciation and cementation by silica have occurred in many areas. Gold and silver occur in Stage 2 and locally in Stage 3 mineralization (Fig. 4). Lattice textures are locally common. A yellow to yellow-green staining of mottramite $(Cu,Zn)Pb(VO_4)(OH)$ or mimetite $Pb_5(AsO_4,PO_4)_3Cl$ is characteristic of higher values of gold and silver. Sulfides tend to occur in streaks or thin zones of disseminated sulfides giving the quartz a bluish or black tint. Distinction between mineralized veins and barren veins is difficult and confirmed only by chemical analyses.

Copper-silver veins

The copper-silver veins are characterized by secondary copper minerals (predominantly malachite and pseudomalachite) with detectable silver concentrations (typically <12 oz/st; McLemore, 1993) and rare gold concentrations. These veins are sporadically distributed throughout the district (Blue Bell, Delmire, Copper Basin, Commerce-Mayflower mines) and locally grade laterally and vertically into gold-silver or fluorite veins. The copper-silver veins have not been major producers of ore, although some deposits have yielded minor production of ore in the past.

The copper-silver veins are typically short and rarely exceed a few tens of meters in length. Malachite, pseudomalachite, azurite, chalcanthite, chalcocite, chrysocolla and other secondary copper minerals are prevalent along fractures and cracks within fault zones. The faults typically strike north, northwest and northeast. Gangue minerals include quartz, calcite and clay minerals and locally iron and manganese oxides. In contrast to the base-metal and gold-silver veins, the copper-silver veins are simple fissure-filling or fracture-coating deposits. Locally, the veins are zoned with quartz forming the outer portions and quartz, calcite and copper minerals forming the cores of the veins. The copper-silver veins exhibit locally one period of brecciation. Silicification of the wall rock is not as extensive as in the base-metal and gold-silver veins. Pyrite, malachite and chalcopyrite may occur disseminated throughout the silicified host rock for a distance of several meters from the veins.

Fluorite veins

The fluorite veins in the Steeple Rock district occur predominantly along the western edge of the district (Fig. 3;

Table 1—Summary of fluid inclusion analyses in quartz. *Quartz veins in acid-sulfate altered rocks. †See paragenesis in Fig. 4 (McLemore, 1993, section 6). prim - primary inclusion; sec - secondary inclusion. Location of mines in Fig. 3 and McLemore (1993).

Sample	No.	T_H avg	STD	No.	T_M ave	STD	T_H range	Type of	Ore
CARLISLE VEIN									
Ontario	14	253	50	16	1.7	0.7	150-310	prim, sec	stage 3
Ontario	8	283	21	7	1.9	1	255-310	prim	stage 2
182 (Sec. 2)	35	255	18	—	—	—	191-307	prim, sec	stage 3
400S (Carlisle)	4	262	27	4	0.8	1.5	237-288	prim, sec	stage 2
Center	22	282	29	21	2.1	1.0	227-327	prim, sec	stage 2
CARLISLE-CENTER DRILL CORE (USBM)									
H6-68.5A	24	265	19	24	1.9	0.4	238-306	prim, sec	stage 3
H6-76.8	4	250	5	7	1.7	0.8	245-257	prim, sec	stage 3
H6-196	68	283	21	51	1.9	0.5	244-344	prim, sec	stage 2
H11-34.2	9	242	13	—	—	—	255-270	prim, sec	stage 3
H11-331.2	87	270	17	76	2.6	0.7	234-315	prim, sec	stage 2
H9-497	3	232	13	2	2.3	0	218-243	prim, sec	stage 2
H9-501	27	266	16	21	2.4	0.6	241-313	prim, sec	stage 2
H14-259	44	269	25				237-331	prim, sec	stage 3
H14-315	42	267	26	15	1.4	0.4	234-324	prim, sec	stage 2
H14-344	42	247	18	8	0.9	0.6	197-288	prim, sec	stage 2
EAST CAMP-SUMMIT VEIN									
47 (East Camp)	16	239	9	—	—	—	223-254	prim, sec	stage 3
634 (Thanks.)	10	235	12	10	2.8	0.6	215-253	prim, sec	stage 2
McDon Upper	16	256	22	16	1.5	0.8	230-292	prim, sec	stage 2
SUMMIT DRILL CORE									
B91-17-992	1	214.9	—	1	1.4	—	—	sec	stage 2
ALABAMA-IMPERIAL									
231	18	249	10	—	—	—	229-264	prim, sec	stage 2
233	68	246	26	9	1	0.4	134-296	prim, sec	stage 2
310 (Imperial)	47	266	15	4	1.1	0.4	226-311	prim, sec	stage 2
434	3	235	0	—	—	—	235	prim, sec	stage 2
ALABAMA DRILL CORE									
Al-112.5	2	245	—	—	—	—	243-247	prim, sec	stage 2
A1-121	38	260	14	39	1.8	1.2	239.320	prim, sec	stage 2
Al-122	22	251	18	23	2.1	1.4	185-266	prim, sec	stage 2
OTHER									
148	58	244	17	—	—	—	194-321	prim, sec	stage 2,3
341*	3	275	83	—	—	—	190-357	prim, sec	alteration

Goat Camp Springs and Daniels Camp) and along Bitter Creek (Powell, Leta Lynn and Mohawk). These veins are typically simple fissure-fillings or fracture-coatings of colorless, green, blue and purple fluorite with minor quartz and calcite. In general, they occur along splays of major faults and along minor faults. They vary in width (as much as 3 m) and length (several tens of meters).

Manganese veins

Manganese oxides, typically psilomelane, occur as late-stage coatings along with other vein minerals throughout the Steeple Rock district. Locally, manganese oxides form thin veins and fracture-fillings that are up to 10 cm thick and several tens of meters long. The Black Cat deposit in the Foothills fault area is the single locality where manganese was mined and produced in the 1950s. This zone is up to 3 to 5 m wide. Fluorite is an accessory mineral and silicification is common.

High-sulfidation disseminated-gold deposits

Several areas of acid-sulfate alteration occur along or in the vicinity of mineralized faults (Fig. 3; McLemore, 1993). These areas consist of intensely altered and silicified host rocks (discussed in more detail below). Drill core and surface outcrops at Telephone Ridge, Raeburn Hill and Summit areas contain local concentrations of pyrite (as much as 5%) and high gold anomalies (as much as 20 ppm)(McLemore, 1993). These areas are similar in texture and composition to high-sulfidation, disseminated-gold deposits such as those found in Summitville, CO, (Rye et al., 1982) and may indicate similar deposits in the Steeple Rock district.

Fluid-inclusion studies

Fluid-inclusion studies provide data on the temperature, composition and pressure of the mineralizing and later fluids, and the studies provide data on the variation of these properties in space and time. Interpretation of fluid-inclusion data are discussed by Roedder and Bodner (1980), Roedder (1984), and Shepherd et al. (1985), and these techniques were applied in this study where appropriate.

Samples for fluid-inclusion microthermometric measurements were selected from vein quartz, fluorite veins and sphalerite disseminated in quartz veins from various parts of

Table 2—Summary of fluid inclusion analyses in sphalerite. All samples are stage 2 mineralization.

Sample	No.	TH avg	STD	No.	T_M ave	STD	T_H range	Type of inclusion
Center	8	306	12	8	1.1	1.2	288-340	prim, sec
Al.112.5 (Alabama)	1	265.1	—	1	2.8	—	—	prim
B91.17-992	18	190	56	7	1.3	0.8	116-284	prim, sec
(Summit)	1	281	—	—	—	—	278-284	prim
AVG	27	227	71	16	1.3	1	116-340	prim, sec

the district, including surface outcrops, underground workings and drill core. Doubly polished thick sections of vein material plus cleavage fragments of fluorite were analyzed using a Fluid Inc. adapted USGS heating/freezing system assembled on a Leitz microscope. Inclusions were identified as primary, pseudosecondary or secondary, in accordance with the criteria of Roedder (1984). Temperatures of homogenization (Th) and last-ice melting temperatures (Tm) were measured (Tables 1, 2 and 3). Duplicate measurements were run on all temperature analyses, and the difference between temperature readings of repeated measurements in the same inclusion typically was <0.5°C. Temperatures of homogenization are reported uncorrected for pressure and are presumably close to the formation temperature because the veins are epithermal. Methods are described in more detail by McLemore (1993).

Three types of fluid inclusions, i.e., liquid plus vapor, liquid-only and vapor-only, are found in quartz, fluorite and sphalerite in the district. No daughter minerals were found in any inclusions examined. The most abundant type of inclusions found are two-phase inclusions, i.e., liquid plus vapor. The vapor phase accounts for 5% to 30% of the total inclusion volume, using the visual estimation charts of Roedder (1984). The inclusions are suboval to irregular to prism shaped and range in size from <3 to 100 μm in diameter. Most inclusions are <15 μm in diameter. Many inclusions in fluorite retain a negative crystal shape. The liquid and vapor inclusions are typically suboval to irregular in shape and are <10 μm in diameter. Some vapor inclusions may actually be two-phase inclusions with a liquid phase of <15%. However, because of their small size, it is difficult to determine with any certainty if any liquid was present (Shepherd et al., 1985).

Primary inclusions occur as isolated inclusions, small clusters or planes of hundreds of inclusions along growth zones. Typically, inclusions along growth zones are <1 μm in diameter and not suited for microthermometric measurements. Secondary inclusions occur as planes of tens to thousands of inclusions of all sizes along healed fractures. Pseudosecondary inclusions occur as tens to hundreds of inclusions along healed fractures that terminate within the crystal, typically at growth zone boundaries and represent fluid trapped within fractures during the crystal growth (Roedder, 1984).

Fluid inclusions are common in quartz from the Steeple Rock district, although not all samples contain primary inclusions suitable for microthermometric measurements. Fluid inclusions are rare in sphalerite, especially where the sphalerite displays chalcopyrite disease (i.e., small solid mineral inclusions of chalcopyrite within larger sphalerite crystals). The sphalerites examined in this study typically are honey yellow to light brown in color. Dark-brown to black sphalerite is too opaque to allow examination of fluid inclusions. Most fluorite contains numerous secondary inclusions and lesser numbers of primary inclusions.

Only a few samples contained coexisting liquid-rich and vapor-rich inclusions, which were typically too small to be measured. Also it was difficult to determine if these inclusions were of the same fluids; most being secondary inclusions. If liquid-rich and vapor-rich inclusions from the same generation of fluids are present in a sample, this is interpreted

Table 3—Summary of fluid inclusion analyses in fluorite. All samples are late stage mineralization.

Sample	No.	T_H avg	STD	No.	T_M avg	STD	T_H range	Type of inclusion
Mohawk	53	177	39	9	0.9	0.7	148-222	sec
472 (Rattlesnake No. 2)	18	171	5	17	0.6	0.2	163-179.5	sec
473 (Rattlesnake No. 1)	28	176	5	—	—	—	165-185	sec, prim
510 (Ontario)	42	189	15	18	0.8	0.2	171.7-215	sec, prim
516 (Dean)	47	196	15	23	0.8	0.4	103-207	sec
518 (Dean)	12	164	24	12	0.9	0.1	156-239	sec
536 (Dean)	12	194	12	12	0.9	0.5	168-210	prim, sec
538 (Dean)	34	177	20	34	0.6	0.3	150-234	prim, sec
545 (Goat Camp Springs)	18	193	9	18	0.8	0.2	174.7-215	prim, sec
	9	203	8	9	0.5	0.5	195-215	prim
559 (Luckie No. 1)	7	187	8	—	—	—	175-195	sec, prim
Luckie No. 2	15	19	34	—	—	—	188.3-202	prim
Center (6th level)	7	142	33	—	—	—	105-178	sec, prim
1043 (Forbis)	18	196	4	19	0.1	0.3	191.5-210	prim
1041 (Forbis)	11	195	3	10	0.1	0.2	190-198.4	prim
Fourth of July	18	161	9	12	0.5	0.6	141-176	prim
Daniels Camp	25	187	2	7	0.2	0.1	185-190.8	prim
1057 (Black Cat)	8	150	5	2	0.2	0.3	140-155	prim
1003 (Leta Lynn)	15	188	19	8	0.3	0.2	159-229	prim
BCI-271	9	159	33	6	0.6	0.5	102-190	prim
AVG prim	210	181	18	141	0.5	0.4	103-234	prim
AVG sec	188	184	19	103	0.8	0.4	102-239	sec
AVG (all)	398	183	19	227	0.6	0.4	103-239	prim, sec

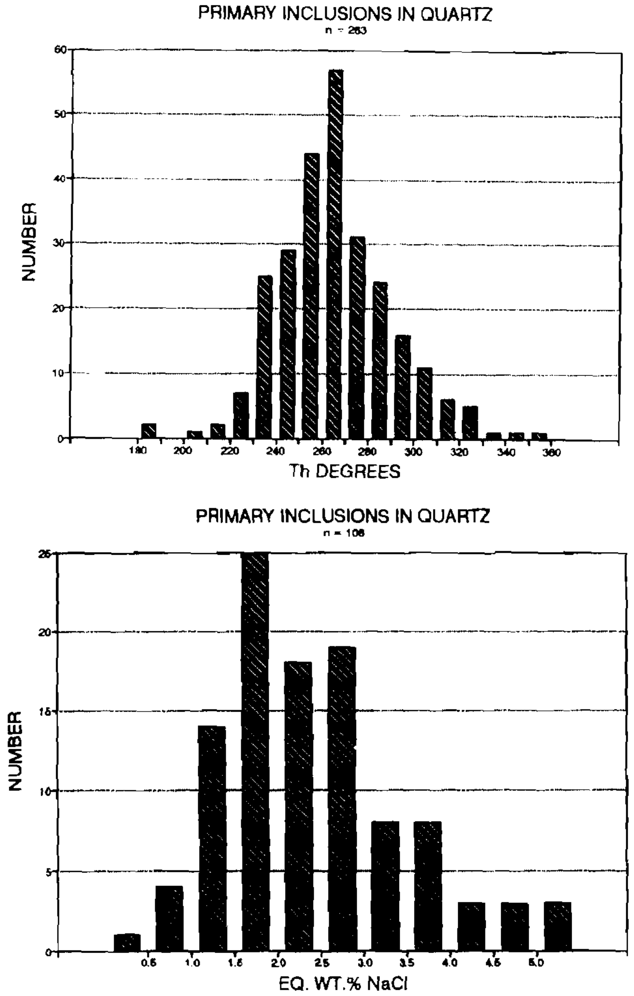


Figure 5—Histograms of temperatures of homogenization (Th) and salinities of fluid inclusions in quartz.

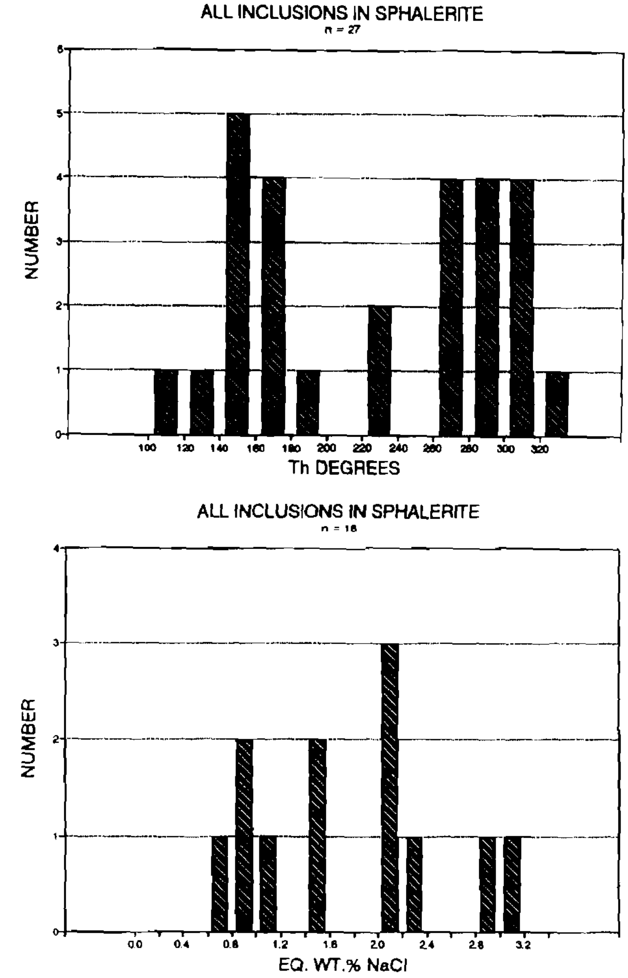


Figure 6—Histograms of temperatures of homogenization (Th) and salinities of fluid inclusions in sphalerite.

as evidence of boiling (Roedder, 1984; Shepherd et al., 1985). Fluid-inclusion evidence for boiling in the Steeple Rock samples examined is inconclusive.

Geochemical analyses of the gas and liquid composition of the inclusions are beyond the scope of this project. Ruff (1993) indicates that gas composition consists of H_2S, HS, O_2, CO_2, H_2, CH_4, N_2, Ar and He (Ruff and Norman, 1991; Ruff, 1993). These gases are found in other epithermal deposits and are suggestive of magmatic and meteoric sources (Ruff and Norman, 1991).

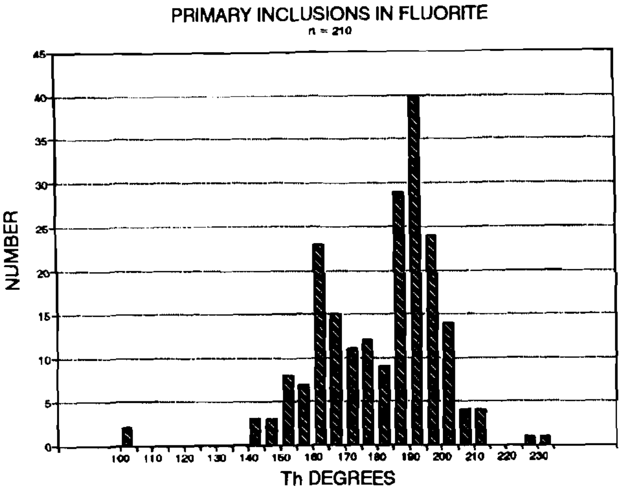
Quartz is the most common mineral in the veins and was deposited continuously before, during and after sulfide mineralization. Quartz that is associated with the sulfide minerals was found to contain fluid inclusions, and, therefore, it is assumed that microthermometric measurements of quartz associated with sulfide minerals represents similar temperatures and chemistries as the sulfide minerals. This assumption appears to be valid because fluid inclusions from quartz and sphalerite in the same samples had similar temperatures of homogenization (Tables 1 and 2)(McLemore, 1993). More than 700 primary and secondary inclusions in quartz were measured for this study (McLemore, 1993).

The highest temperatures of homogenization are in quartz samples taken from drill core of base-metal veins at the Carlisle and Center mines (Table 1). Temperature increases with depth (McLemore, 1993). Surface samples from the Carlisle fault typically contained fluid inclusions with temperatures of homogenization higher than elsewhere in the district. The next-highest samples were from quartz–precious-metal veins from the East Camp fault and in the Alabama-Imperial area. A normal distribution of temperature of homogenization of all samples exists (Fig. 5).

Sphalerite is the only ore mineral in the base-metal and gold-silver veins that contains visible fluid inclusions. Therefore, fluid inclusions in sphalerite are probably most representative of the ore-bearing fluids. Despite examining more than 25 polished sections, most sphalerites did not contain any primary fluid inclusions, and only 27 fluid inclusions in sphalerite from three sample sites were measured (Table 2).

Two distinct populations of fluid inclusions in sphalerite are identifiable (Table 2 and Fig. 6). The primary inclusions have an average temperature of homogenization of 285°C (range of 231.8 to 324.6°C) and an average salinity of 2.4 eq. wt.% NaCl (range of 2.1% to 3.0%). The fluid inclusions in the Center mine ore have the highest temperatures of homogenization (300 to 340°C)(Table 2).

Fluorite occurs in veins in the northern and western portions of the district and as late-stage mineralization in the Center mine. Almost 400 fluid inclusions were examined in polished sections and cleavage fragments of fluorite (Table 3). Two types of inclusions are identified in thin sections, i.e., primary and secondary (Table 3 and Fig. 7). The primary inclusions have an average temperature of homogenization of 181°C (range 103 to 239°C) and salinity of 0.5 eq. wt.% NaCl. The secondary inclusions have an average temperature of homogenization of 184°C (range 102 to 239°C) and a



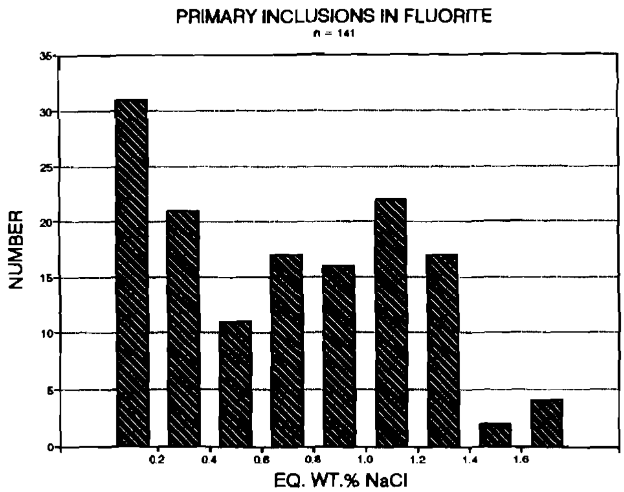


Figure 7—Histograms of temperatures of homogenization (Th) and salinities of fluid inclusions in fluorite.

salinity of 0.8 eq. wt.% NaCl. The temperatures of homogenization of primary inclusions forms a bimodal population (Fig. 7).

The highest temperature of homogenization come from fluorite in the Goat Camp Springs, Luckie and Forbis mines. The lowest temperatures are from the Center and Black Cat mines and from drill hole BC1 (Table 3).

Alteration

Alteration is a general term describing the mineralogic, textural and chemical changes in a rock that result from a change in the physical, thermal and chemical environment in the presence of water, steam or gas (Bates and Jackson, 1980; Henley and Ellis, 1983). Recognition of alteration zones and an understanding of their genesis are important in mineral exploration and in understanding the formation of ore deposits. Specific alteration types are associated with specific ore deposits. Furthermore, alteration halos surrounding ore deposits are typically more widespread and easier to recognize than some of the ore bodies themselves (Guilbert and Park, 1986).

Research by White (1955 and 1981) established the now recognized association between epithermal mineral deposits and modern, active geothermal systems. In modern geothermal systems, the alteration mineral assemblages reflect the composition of the prevailing fluid chemistry, and it is common to describe the alteration assemblage according to fluid chemistry (Browne, 1978; Reyes, 1990: Mitchell and Leach, 1991; Simmons et al., 1992). There are three end members of fluid compositions in modern geothermal systems:

- alkali-chloride waters,
- acid-sulfate waters, and
- bicarbonate waters.

Each type is characterized by specific mineral assemblages and other characteristics. Mixing of these end member fluids is common, and more than one type of fluid can be present (Browne, 1978). Geothermal systems are dynamic, constantly changing and rarely in equilibrium. Processes such as boiling, mixing and condensation constantly occur in the geothermal system, producing a wide range of overlapping mineral assemblages and associations. For the purposes of this study, the alteration types are classified according to the type of fluids, as indicated by the alteration mineralogy. This is because it is typically difficult to distinguish between the similar mineral assemblages of deuteric-, propylitic- and argillic-alteration types in epithermal deposits, especially in the Steeple Rock district. More details on the alteration are given by McLemore (1993), and only a summary is presented here.

The following two distinct types of alteration, as defined by mineralogy, occur in the Steeple Rock district:

- alkali-chloride (propylitic to argillic to sericitic to silicic), and
- acid-sulfate (advanced argillic).

At least three stages of alkali-chloride alteration affected the rocks (Fig. 4)(McLemore, 1993). The three stages are:

- regional premineralization,
- localized synmineralization, and
- regional postmineralization.

Alkali-chloride alteration is the most extensive and pervasive alteration type and is characterized by quartz, chlorite, pyrite and a variety of additional minerals, depending upon the host-rock composition, the permeability, the composition of the fluids, the temperature and the duration of the alteration process. Some of these additional minerals are temperature dependent (Elders et al., 1981; Reyes, 1990; Simmons et al., 1992). From the mineral assemblages, three zones are found in the Steeple Rock district: high-temperature assemblages (>200°C: epidote, illite, titanite, anhydrite), low-temperature assemblages (<200°C: smectite, illite/smectite, dolomite, kaolinite, and mordenite) and low- to intermediate-temperature assemblages (mixed chlorite/smectite, calcite, adularia, illite). Quartz, pyrite and chlorite are found in all three zones (McLemore, 1993). High-temperature assemblages are found at depth and adjacent to the epithermal veins in the district. Low-temperature assemblages are found distal to the epithermal veins (McLemore, 1993).

Several areas of acid-sulfate alteration that are superimposed and surrounded by alkali-chloride alteration have been mapped in the district (Fig. 3; McLemore, 1993). All of the larger acid-sulfate areas occur along the East Camp-Twin Peaks, Carlisle and Bitter Creek faults. The acid-sulfate altered areas are mineralogically, texturally and, probably, temperature zoned. They can be grouped into three types:

- clay zone (outermost zone, lowest temperatures),
- silicified zone, and
- massive silica/chert zone (innermost zone, highest temperatures).

The clay zone is characterized by fine-grained, sugary, vuggy, soft and friable textures. The silicified zone is characterized by fine- to medium-grained, massive to brecciated and vuggy textures. The clay and silicified zones are gradational and consist of kaolinite, quartz, hematite, pyrite and locally alunite, pyrophyllite, anatase, diaspore, illite/smectite, illite, jarosite and iron and manganese oxides. The quartz content increases from the clay zone to the silicified and massive silica/chert zones. The massive silica/chert zone is characterized by massive, locally brecciated, quartz and/or chert; no relict textures are preserved. Hydrothermal brecciation and hydrofracturing are common and suggestive of hydrothermal eruptions. The massive silica/chert zone consists of quartz with minor amounts of kaolinite, hematite, alunite, pyrophyllite, pyrite and anatase. Examination of drill core reveals that these acid-sulfate altered zones are repeated at different intervals and are separated by areas of alkali-chloride alteration.

Sulfur isotopic data and mineralogy suggest maximum temperatures of formation of 200 to 340°C (McLemore, 1993). Two areas are spatially associated with epithermal veins: Telephone Ridge area near the Carlisle and Center mines and Summit area near the Summit and Bank mines. Acid-sulfate alteration caps or overlies base-metal veins at the Carlisle and Ontario mines and overlies precious-metal veins at the Bank mine. Furthermore, the Goat Camp Springs area is associated with fluorite veins.

This acid-sulfate alteration overlies alkali-chloride alteration and locally mineralized veins. The drilling data, mineral assemblages and zonation suggest that the acid-sulfate altered areas may represent separate hydrothermal systems (i.e., hot springs and geysers) that are likely connected at depth (similar to modern geothermal fields such as at Yellowstone and New Zealand). These acid-sulfate altered areas may overlie undiscovered epithermal vein deposits similar to those found at the Carlisle mine.

District zoning

The base-metal vein deposits (>10% base metals) with significant gold and silver contents occur only along the Carlisle fault, between the Carlisle and Ontario mines and possibly westward into Section 2. This area represents the center of the district (Fig. 3). The highest temperature of homogenization in fluid inclusions came from sphalerites from deeper levels of the Center mine (Table 2; 288 to 325°C). Outward from the Carlisle-Center mines, gold-silver veins containing little or no base metals (<1%) occur along northwest- and north-trending faults. The gold-silver veins along the East Camp-Twin Peaks fault system are associated with bladed calcite or bladed quartz after calcite. These deposits are not spatially associated with any rhyolite intrusives, but the gold-silver deposits in the vicinity of Twin Peaks and Vanderbilt Peak in the western portion of the district are associated with rhyolite intrusives. Fluid-inclusion temperatures are slightly less than those at Carlisle and Center mines (Table 1). On the fringes or outer margins of the district, copper-silver veins locally grade into precious-metal veins. The outermost zone is represented by fluorite and manganese veins (Fig. 3). Late-stage fluorite was also deposited in local areas of base- and precious-metal deposits.

Two or more centers of fluorite mineralization can be interpreted from fluid-inclusion data from fluorite. The bimodal distribution of temperatures of homogenization (Fig. 7) is consistent with two centers of epithermal activity. The highest temperatures of homogenization are from fluorite mines and from prospects in the Goat Camp Springs area and the Forbis and Luckie mines (average 190 to 205°C, Fig. 7). Temperatures of homogenization decrease away from the Goat Camp Springs area: Rattlesnake mines average 165 to 185°C, Fourth of July mines average 155 to 170°C, and Daniels Camp mines average 190°C (Table 3 and Fig. 7). In the Bitter Creek area, temperatures of homogenization in fluorite from the Bitter Creek drill hole (BC1) are lower (160°C). These data suggest that a second center of fluorite mineralization may occur north of Bitter Creek. This temperature difference could also be accounted for by variations in lateral fluid flow and/or mixing.

These data, along with distribution of alteration, production and mineral assemblages, suggest at least three possibilities. The fluorite and manganese mineralization represents the outer margins of an epithermal system centered at the Carlisle-Center mines. Alternatively, the fluorite mineralization could represent the top of separate epithermal systems that grade into precious and base metals with depth. These separate epithermal fluorite systems may be barren of metal mineralization. A combination of these hypotheses is also possible.

Conclusions

Integration of geological, mineralogical and chemical data and district zoning indicates that the older alkali-chloride and acid-sulfate alteration probably represents a hot-springs geothermal system such as the Norris Geyser Basin in Yellowstone National Park. Locally, the acid-sulfate altered areas were faulted and perhaps covered by younger volcanic rocks (34 to 27 Ma). Epithermal vein mineralization associated with synmineralization alteration and rhyolite intrusives formed along faults (28 to 18 Ma) after the acid-sulfate alteration. The epithermal mineralization was centered at the Carlisle, Center and Ontario mines. Copper-silver, fluorite and manganese veins form the outer margins of the district. Locally, epithermal veins cut the acid-sulfate alteration, but, elsewhere in the district, acid-sulfate alteration caps epithermal veins. Acid-sulfate alteration and epithermal mineralization were subsequently affected by postmineralization alkali-chloride alteration.

The alteration and mineralization in the Steeple Rock district occurred in response to cyclic volcanic activity and subsequent development of local hydrothermal systems in areas of high heat flow (McLemore, 1993). The exact timing and duration of these events, based on a few age determinations and field relationships, are speculative. There is no evidence to support that these events were continuous; instead the alteration and mineralization were probably episodic, weaning and migrating from one locality to another, as suggested by field relationships, temperature distributions and age relationships (McLemore, 1993). Similar complex trends are observed in modern geothermal systems and other epithermal vein districts. The Steeple Rock district is one example of the early development of a geothermal system with both alkali-chloride and acid waters followed by younger epithermal mineralization.

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