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VOLCANIC-EPITHERMAL DEPOSITS IN THE MOGOLLON-DATIL VOLCANIC FIELD, WEST-CENTRAL NEW MEXICO

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Abstract—Most volcanic-epithermal precious-metal deposits in New Mexico are restricted to Oligocene to Miocene volcanic rocks and to areas immediately adjacent to volcanic centers in the Mogollon-Datil volcanic field in west-central New Mexico. These deposits occur in areas of complex regional and local structures that appear to control emplacement of magmas and subsequent flow of hydrothermal fluids. Although the mechanism of ground preparation varies, most districts occur along the ring-fracture zones of calderas, in the vicinity of rhyolitic domes, and/or along faults associated with regional crustal lineaments. Two types of volcanic-epithermal deposits occur in the Mogollon-Datil volcanic field. Most deposits are of the low-sulfidation (quartz-adularia) class and formed by multiple cycles of low salinity (<5 eq. wt.% NaCl), slightly acidic to neutral pH fluids, at temperatures between 150° and 300°C, at relatively shallow depths (<1500 m) and low pressures (<150 bars). The mineral deposits at Alum Mountain are high-sulfidation (acid-sulfate) deposits. In addition, acid-sulfate alteration similar to that found in high-sulfidation deposits is present in several districts and may indicate that additional high-sulfidation precious-metal deposits may occur in these areas as well. Limited geologic and geochemical data are consistent with formation of acid-sulfate alteration by acidic fluids at temperatures below 340°C at relatively shallow depths (<1.5 km) in a magmatic-hydrothermal environment. The acid-sulfate alteration characteristic of the high-sulfidation deposits appears to be restricted to 27-33 Ma in the Mogollon-Datil volcanic field, whereas the low-sulfidation, volcanic-epithermal vein deposits are younger than 27 Ma. The economic resource potential for low-sulfidation, volcanic-epithermal vein deposits in many districts is good because many favorable structures have not been adequately explored. Also, there is good potential for the discovery of high-sulfidation precious-metal deposits in areas of acid-sulfate alteration.

INTRODUCTION

Epithermal deposits have been recognized as an important class of mineral deposits for many years. Some of the largest gold and silver deposits in the world are epithermal deposits, including the "bonanza" gold deposits of the Comstock Lode (286 tons contained gold) and Sleeper (83.6 tons contained gold) deposits in Nevada; Cripple Creek, Colorado (830.5 tons contained gold); and El Indio, Chile (154 tons contained gold; Sillitoe, 1993). Lindgren (1922, 1933) defined the term "epithermal" to include a broad range of deposits that formed by ascending waters at shallow to moderate depths (<1500 m), low to moderate temperatures (100-200°C), and which are typically associated with intrusive and/or volcanic rocks. From fluid inclusion and isotopic data, it is now generally accepted that epithermal deposits were formed at slightly higher temperatures (50-300°C) and relatively low pressures (few hundred bars). Not all epithermal deposits occur in igneous rocks; for example, the McLaughlin deposit in California is hosted in mafic and ultramafic metamorphic and sedimentary rocks (Lehrman, 1986). Many Carlin-type deposits appear to be epithermal and are found in sedimentary rocks (Bagby and Berger, 1985; Berger and Henley, 1989).

Most precious-metal epithermal deposits in New Mexico are restricted to volcanic rocks and areas immediately adjacent to volcanic fields and are called volcanic-epithermal deposits (North and McLemore, 1986, 1988). The majority of the volcanic-epithermal deposits in New Mexico are precious-metal deposits, hosted by Oligocene to Miocene volcanic and intrusive rocks, located within the Mogollon-Datil volcanic field in west-central New Mexico (Table 1, Fig. 1; North and McLemore, 1986, 1988). Not all epithermal deposits consist of precious metals. The Taylor Creek tin deposit in Sierra County is an epithermal deposit without any precious metals (Eggleston and Norman, 1986). Some fluorite and manganese deposits are also epithermal deposits but do not contain any precious metals (such as the Bishops Cap fluorite and Rincon manganese deposits in Doña Ana County; Dunham, 1935).

This paper compares and contrasts geologic, mineralogic and geochemical characteristics of volcanic-epithermal deposits in the Mogollon-Datil volcanic field and offers some theories concerning structural controls, genesis and resource potential of these deposits. The deposits in the Mogollon-Datil volcanic field are briefly described in Table 2 and located in Figure 2. Production is in Table 3. This work is part of ongoing studies of mineral deposits in New Mexico and includes updates and revisions of prior work by North (1983) and North and McLemore (1986, 1988).

TYPES OF VOLCANIC-EPITHERMAL DEPOSITS

An important advance in knowledge of epithermal-mineral deposits was Hayba et al's. (1985) two-fold classification (adularia-sericite and acid-sulfate) of volcanic-hosted epithermal deposits based on mineralogy and associated alteration. In order to define both classes according to mineralogy, Berger and Henley (1989) refined this classification to adularia-sericite (illite) and alunite-kaolinite (±pyrophyllite). Earlier models referred to these deposits as quartz-adularia and quartz-alunite (Cox and Singer, 1986, model #25). However, one problem with applying these classifications in the field is that some of the minerals, such as alunite, diaspore and adularia, are too fine grained to be identified easily (Berger and Henley, 1989). Thus White and Hedenquist (1990) refined this classification even further to low-sulfidation and high-sulfidation deposits (Table 4). Bonham (1988) added alkalic-related, epithermal precious-metal deposits to this scheme. The alkalic-related epithermal deposits in New Mexico are included with the Great Plains Margin deposits (North and McLemore, 1986, 1988).

Most volcanic-epithermal deposits in New Mexico, including those in the Mogollon-Datil volcanic field, are of the low-sulfidation (quartz-adularia) class (Tables 1, 2, 4). The mineral deposits at Alum Mountain (#20) are high-sulfidation deposits based on the alteration mineral assemblage. In addition, acid-sulfate alteration is present in several districts (Tables 1, 2) and if these areas are formed by magmatic-hydrothermal fluids they may contain high-sulfidation precious-metal deposits.

LOW-SULFIDATION DEPOSITS

Most of the largest gold and silver districts in New Mexico are low-sulfidation, volcanic-epithermal deposits in the Mogollon-Datil volcanic field (Tables 1, 3; North and McLemore, 1986). However, none of the precious-metal deposits in New Mexico are considered giant (>220 tons of contained gold) or bonanza (>33 tons of gold in ore grading 1 oz/ton gold) deposits as defined by Sillitoe (1993). Nearly 600,000 oz of gold and 26.6 million oz of silver have been produced from volcanic-epithermal districts in the Mogollon-Datil volcanic province (Table 3). Both the Mogollon and Steeple Rock (#2) districts

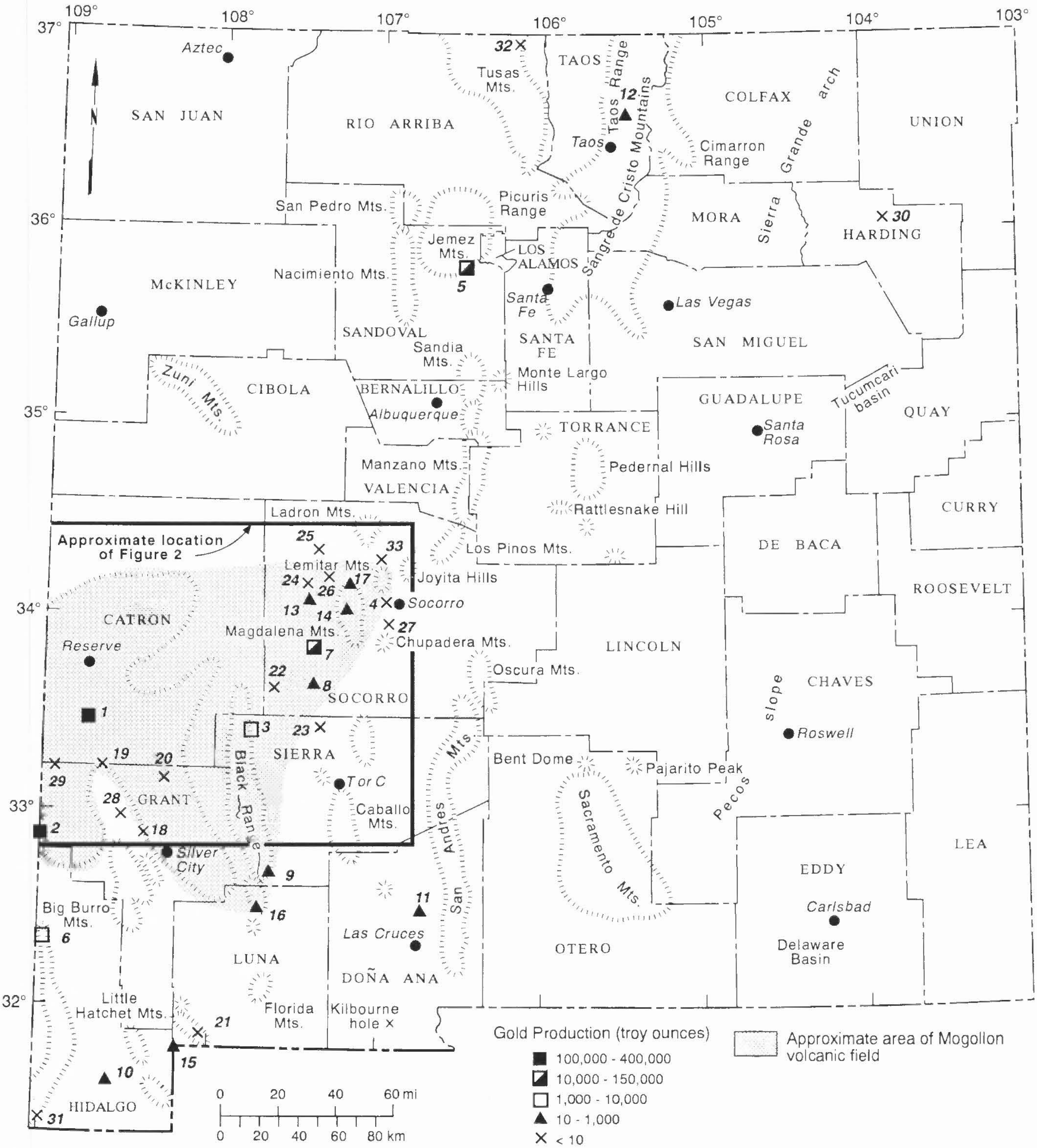

FIGURE 1. Volcanic-epithermal deposits in New Mexico, showing estimated gold production in troy ounces. Numbers refer to Tables 1 and 2. Modified from North and McLemore (1986, 1988), McIntosh et al. (1992a, b), and New Mexico Geological Society (1982).

rank in the top ten of gold-producing districts in the state. The Mogollon district (#1) has produced more silver than any other district in New Mexico. In addition, 5.8 million lbs of copper, 7.5 million lbs of lead, and 4 million lbs of zinc have also been produced from these deposits. Locally, barite, fluorite, manganese, clay, tellurium and tin have been produced from some districts as well (Table 2). In recent years, production from the Mogollon and Steeple Rock districts has been for use as silica flux.

Most volcanic-epithermal deposits in the Mogollon-Datil volcanic province contain predominantly silver with lesser amounts of gold, unlike giant and bonanza gold deposits elsewhere in the world (Fig. 3; Sillitoe, 1993). Grades vary, but typically deposits contain 0.15-0.20 oz/ton gold and 7-10 oz/ton silver (Table 5). The Rosedale district (#7) is one of the few volcanic-epithermal districts in the state that contains predominantly gold with low silver. The Socorro Peak district (#4) contains predominantly silver with little gold (Lasky, 1932). Most volcanic-epithermal deposits in New Mexico contain minor amounts of base metals, although base-metal content typically increases with depth

Map number (Fig. 1)	District	County	Gold (oz)	Silver (oz)
1.	Mogollon*	Catron	365,000	>20,000,000
2.	Steeple Rock*,‡	Grant	151,000	3,400,000
3.	Chloride*	Sierra	9,000	2,000,000
4.	Socorro Peak*	Socorro	--	750,000
5.	Cochiti‡	Sandoval	42,000	210,000
6.	Kimball	Hidalgo	1,500	400,000
7.	Rosedale*	Socorro	28,000	10,000
8.	San Jose*,‡	Socorro	<1,000	13,000
9.	Macho	Sierra	100	20,000
10.	Gillespie	Hidalgo	5	16,000
11.	Doña Ana Mountains	Doña Ana	100	5,000
12.	Red River‡	Taos	65	1,103
13.	Cat Mountain*	Socorro	53	1,302
14.	Hop Canyon*	Socorro	82	1,137
15.	Fremont	Hidalgo	10	10,000
16.	Old Hadley	Luna	150	533
17.	North Magdalena*	Socorro	35	149
18.	Cora Miller*	Grant	W	W
19.	Wilcox*,‡	Catron	some	17
20.	Alum Mountain*,‡	Grant	1	21
21.	Carrizalillo	Luna	some	some
22.	Taylor*	Socorro	--	some
23.	Goldsboro*	Sierra	some	some
24.	Council Rock*	Socorro	--	some
25.	Abbe Spring*	Socorro	--	some
26.	Bear Mountains*	Socorro	--	--
27.	Luis Lopez*	Socorro	--	--
28.	Gila Fluorspar*,‡	Grant	--	--
29.	San Francisco*	Grant	--	--
30.	Bueyeros	Harding	--	--
31.	Silver Tip	Hidalgo	--	--
32.	Cruces Basin	Rio Arriba	--	--
33.	San Lorenzo*	Socorro	--	--

TABLE 1. Volcanic-epithermal precious-metal deposits in New Mexico. *Deposits in Mogollon-Datil volcanic field. All deposits are low-sulfidation deposits (see Table 4) except for Alum Mountain (#20) which is of the high-sulfidation class. Alteration in some districts, designated by ‡, indicate that high-sulfidation deposits may occur in these districts.

in many districts (Table 2). The Steeple Rock district has yielded more lead and zinc than any other volcanic-epithermal district in New Mexico (Table 3). The Carlisle and Center mines in the Steeple Rock district contain significant base metals together with silver and gold; these veins consist of 5-20% sulfides as galena, sphalerite, chalcopyrite and pyrite (McLemore, 1993).

Nearly all volcanic-epithermal deposits in the Mogollon-Datil volcanic field are hosted by Oligocene to Miocene volcanic and intrusive rocks (Table 2). Epithermal veins are hosted locally by Paleozoic and Mesozoic sedimentary rocks in a few districts, such as Chloride (#3), Cat Mountain (#13) and Abbe Spring (#25), but these districts are near Oligocene-Miocene volcanic centers. Most low-sulfidation, volcanic-epithermal veins are Oligocene or younger in age and are significantly younger than the host rocks (Fig. 4, Table 2). In districts where age determinations and/or stratigraphic and structural relationships can be used to date mineralization, mineralization is typically 5-15 Ma younger than the host rocks (Table 2).

The low-sulfidation, volcanic-epithermal vein deposits are similar with respect to vein emplacement, mineralogy, chemistry, alteration and textures (Table 2). They are structurally controlled and fill open spaces along faults, fractures, and locally bedding planes. The veins commonly form prominent outcrops and are bifurcating, sinuous and pinch and swell along strike. Complex vein textures, especially brecciation, banded layering and cementation by quartz, are common to most districts and locally are associated with higher concentrations of metals (Buchanan, 1981;McLemore, 1993). Gangue minerals generally include quartz, calcite, sericite, pyrite, chlorite, iron and manganese oxides, and locally fluorite, barite and adularia. Gold and silver occur as native species, electrum, various silver minerals, and as solid inclusions within pyrite or galena. Base-metal sulfides, predominantly galena, sphalerite, chalcopyrite and pyrite, are found in most districts in at least trace amounts. Silicification and argillic, propylitic, sericitic and chloritic alteration are common in most districts. Older acid-sulfate alteration is also found in a few districts (Tables 1, 2); these areas are discussed separately in this report. Textures, fluid inclusion data and isotopic data indicate that boiling occurred in most districts (Table 2). Zoning of metals varies through a district. In some districts (e.g., Steeple Rock), base-metal content increases and calcite decreases with increasing depth. In the Mogollon district, copper and lead are more abundant in the northwestern and northern portions of the district, whereas silver and gold are predominant elsewhere (Ferguson, 1927; Kamilli, 1993). Geologic, geochemical and mineralogic data indicate that mineralization occurred in multiple pulses and was produced from low salinity (<5 eq. wt.% NaCl), slightly acidic to neutral pH fluids, at temperatures between 150° and 300°C, at relatively shallow depths (<1500 m) and low pressures (<150 bars; Buchanan, 1981; Kent, 1983; Eggleston et al., 1983; Forureu, 1984; Harrison, 1990; McLemore, 1993; Kamilli, 1994).

Volcanic-epithermal deposits occur in areas of complex regional and local structures that appear to control emplacement of magmas and subsequent flow of hydrothermal fluids. Many districts occur along or near the ring-fracture zone of calderas (i.e. Mogollon; Fig. 2; Table 2), but not all calderas are mineralized (Rytuba, 1981). A few individual volcanic-epithermal deposits occur in the vicinity of rhyolitic domes (i.e. Chloride; Harrison, 1988, 1990). Regional crustal lineaments appear to control mineralized faults in other volcanic-epithermal districts (i.e. the

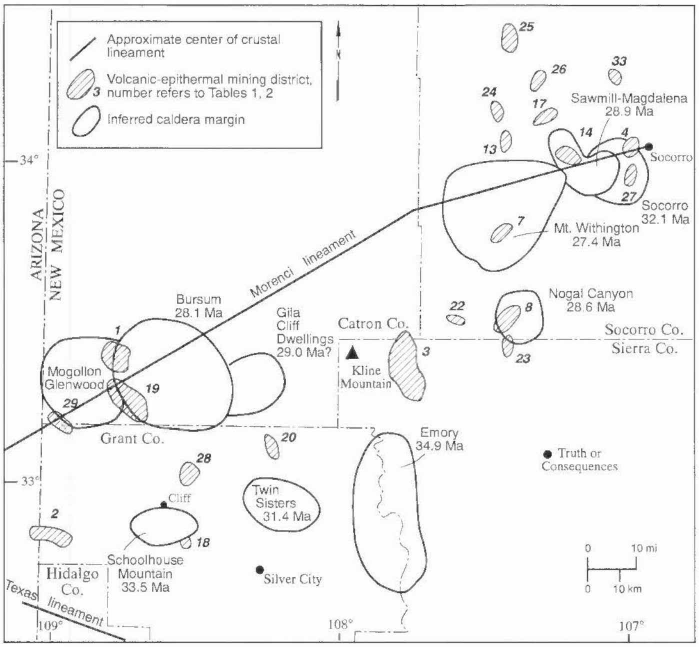

FIGURE 2. Volcanic-epithermal districts in the Mogollon-Datil volcanic field, west-central New Mexico. Numbers refer to Tables 1 and 2 and to text. Modified from McIntosh et al. (1992a, b) and Ratté (1989).

Texas lineament near Steeple Rock, Figs. 1, 2; McLemore, 1993). Although the mechanism of ground preparation varies from district to district, local faulting, fracturing and brecciation of the host rocks are critical in forming volcanic-epithermal vein deposits.

HIGH-SULFIDATION DEPOSITS

Only one deposit in New Mexico is classified as a high-sulfidation deposit, Alum Mountain (#20). Alum Mountain consists of intensely altered lava flows and pyroclastic and volcaniclastic rocks that are cut by rhyolite and quartz monzonite dikes and sills (Ratté et al., 1979). Alteration minerals include quartz, opal, clays, alunite, halotrichite and alunogen (Hayes, 1907; Ratté et al., 1979). Disseminated veinlets, thin stockwork veins and disseminations of quartz and calcite contain precious metals (Ratté et al., 1979) and were mined for gold and silver in 1945 (USBM Mineral Yearbooks). Drilling results are not known. However, areas of intense acid-sulfate alteration are found elsewhere in the Mogollon-Datil volcanic field, which may have potential for additional undiscovered high-sulfidation deposits.

High-sulfidation epithermal deposits are characterized by areas of acid-sulfate alteration. Acid-sulfate alteration, a subclass of advanced-argillic alteration, is spatially associated with many types of mineral deposits, including volcanic-epithermal deposits. Acid-sulfate alteration is characterized by the mineral assemblage containing quartz, kaolinite, alunite, and locally pyrite and pyrophyllite, and forms as a result of base leaching by acidic fluids containing H_2SO_4. Original textures and mineralogy are commonly destroyed by this process. Recognition and understanding the genesis of acid-sulfate alteration are important in mineral exploration and the understanding of the formation of mineral deposits, because specific alteration types are associated with specific mineral deposit types.

Four types of environments can produce acid-sulfate alteration in an epithermal system (Rye et al., 1992): (1) atmospheric oxidation of sulfides (supergene); (2) atmospheric oxidation at the water table in a steam-heated environment (steam-heated); (3) disproportionation of magmatic sulfur to H_2S and H_2SO_4 (magmatic-hydrothermal); and (4) magmatic steam produced by rapid release of fluids from a magma (magmatic-steam). Specific types of mineral deposits are associated locally with each type of acid-sulfate alteration (Rye et al., 1992). Supergene acid-sulfate alteration may overlie a sulfide zone containing precious metals or it may overprint older sulfide mineralization. Steam-heated acid-sulfate alteration also may overlie sulfide mineralization. Gold mineralization occurs within acid-sulfate altered areas in a magmatic-hydrothermal environment. Magmatic-steam environments may overlie porphyry mineralization or are adjacent to low-sulfidation deposits.

Acid-sulfate alteration occurs in several volcanic-epithermal districts in the Mogollon-Datil volcanic field (Tables 1, 2): Steeple Rock, San Jose, Wilcox, Alum Mountain, and Gila Fluorspar. Acid-sulfate alteration also occurs at Kline Mountain near the Taylor Creek epithermal tin deposit in northwestern Sierra County (A, Fig. 2; Hall, 1978; Eggleston and Norman, 1986; Eggleston, 1987). Most areas of acid-sulfate alteration in the Mogollon-Datil volcanic field have been examined only briefly and the genesis of the alteration is not well established. Areas of acid-sulfate alteration occur in the vicinity of porphyry copper deposits at Chino and Tyrone. Stable-isotopic data on alunite from the Chino porphyry-copper deposit confirm a supergene origin (Field, 1966; Rye et al., 1992). K/Ar age determinations on alunite from the Tyrone porphyry-copper deposit indicate an age of 19.5 Ma, and other geologic data confirm a supergene origin for acid-sulfate alteration at Tyrone (Cook, 1993).

Several areas of acid-sulfate alteration in the Steeple Rock district were studied extensively by McLemore (1993). Three of these altered areas occur adjacent to younger low-sulfidation, epithermal-vein deposits, whereas other areas are in the vicinity of vein deposits. The acid-sulfate altered areas are mineralogically, chemically, texturally and probably temperature zoned, including a clay zone (outermost, lowest temperature), silicified zone (intermediate), and silica/chert zone (innermost, highest temperature). Alunite occurs in all three zones but enargite has not been identified from the district (McLemore, 1993). Some areas contain anomalously high gold assays. The acid-sulfate alteration grades outward to argillic and then to prophylitic alteration. The acid-sulfate alteration is of a similar age as the host rocks, as indicated by a K/Ar age determination on quartz-alunite whole rock from Saddleback Mountain (at Steeple Rock) of 31.3±1.1 Ma (Marvin et al., 1987, #175; Hedlund, 1993). The host andesite of Summit Mountain (at Steeple Rock) is dated as 31.3±2.2 Ma (K/Ar on hornblende, Hedlund, 1993). Some areas of acid-sulfate alteration in the Steeple Rock district are as young as 27 Ma, as determined from stratigraphic relationships (McLemore, 1993). Limited stable-isotopic data from Bitter Creek in the northern part of the Steeple Rock district (Field, 1966), together with mineral and chemical zonations, preserved textures, multiple horizons, stratigraphic relationships and age determinations (McLemore, 1993), are consistent with a magmatic-hydrothermal origin by acidic fluids at temperatures less than 340°C in a relatively shallow environment (<1.5 km) as defined by Rye et al. (1992). The acidic fluids are produced by disproportionation of magmatic sulfur with decreasing temperature as the fluids rose toward the surface. Gold is commonly carried in these magmatic-hydrothermal fluids and gold assays in acid-sulfate altered areas indicate good potential for undiscovered high-sulfidation gold deposits (Table 4; McLemore, 1993). The epithermal veins are younger than the acid-sulfate alteration, as shown by crosscutting relationships, stratigraphic position and age determinations (McLemore, 1993).

Elsewhere in the Mogollon-Datil volcanic field, known areas of acid-sulfate alteration have not been studied in the same detail as in the Steeple Rock district. However, evidence (such as gold assays and similar ages of the alteration and host rocks) suggests some of these areas may have been formed in a magmatic-hydrothermal environment (Table 4; White and Hedenquist, 1990; Rye et al., 1992). Anomalous gold and silver assays were reported in altered rocks at Alum Mountain (up to 0.28 oz/ton Au and 0.36 oz/ton Ag; Ratté et al., 1979, #528) and in the Gila Fluorspar district (0.02 oz/ton Au and 0.22 oz/ton Ag; Ratté et al., 1979, #476). Recent work by McOwen (1993) suggests that the quartz-sericite/illite-pyrite alteration in the Gila Fluorspar district is older than the regional chloritic (or argillic) alteration. The quartz-sericite/illite-pyrite alteration was produced by acidic, sulfur-rich fluids but alunite and kaolinite have not been found. K/Ar age determinations

TABLE 2. Descriptions of volcanic-epithermal deposits in the Mogollon-Datil volcanic field, New Mexico. [1]Names and ages of formations updated from most recent reference and Osburn and Chapin (1983).[2]Interpretations from cited references and/or this author. [3]Includes element associations identified by Laughlin (1985) from NURE data. [4]From fluid inclusion data. *Indicates districts examined by the author.

Map no.	District	Host rocks[1]	Mineralization Age	Mineralization Style (Table 4)	Commodities produced (present) (Table 3)[3]	Predominant mineralogy of veins	Structural setting	Alteration	Evidence of boiling[2]	Temperature range °C[4]	Salinities eq. wt.% NaCl[4]	Comments	Selected references
1	Mogollon* (Coney)	Oligocene andesite flows, ash-flow tuffs, and rhyolite intrusives (33-23 Ma)	Miocene 16-18 Ma on adularia (Marvin et al., 1987, #78; Kamilli, 1994)	low sulfidation; quartz-calcite veins, hydrothermal brecciation, stockworks	Au,Ag,Cu,Pb, Zn,U (Ba,Mn,F)	quartz, calcite, chlorite, adularia, pyrite, electrum, fluorite, galena, sphalerite, bornite, chalcopyrite, gold,	along normal faults associated with the Bursum caldera, veins trend N60W 75-85N, N10E 70S	argillic, silicification, chloritization, sericitic, propylitic	very fine-grained quartz, fluid inclusion evidence, ore shoots with flat bottoms, loss of CO_2, bladed calcite	150-300	< 5	copper and lead are more abundant in the north	Jones (1904), Ferguson (1927), Buchanan (1981), Kent (1983), Bornhorst et al. (1984), Wolfe (1985), Marvin et al. (1987), Kamilli (1993, 1994), Ratté (1981), Bornhorst and Kent (1985), Avery (1988)
2	Steeple Rock* (Carlisle, Duncan, Twin Peaks, Hells Hole)	Summit Mt. and Dark Thunder Canyon Fm (31-28 Ma; Oligocene)	Miocene veins 28-18 Ma; acid sulfate alteration 27-31 Ma (McLemore, 1993)	low sulfidation veins, high sulfidation alteration older than veins; quartz veins, hydrothermal brecciation	Au,Ag,Cu,Pb, Zn,Mn,F (Mo, alunite, clay)	quartz, calcite, pyrite, fluorite, galena, sphalerite, chalcopyrite, malachite, gold, silver, Mn and Fe oxides, sericite, alunite, jarosite, chlorite, epidote	on northern flank of Texas lineament, normal faults trend NE to E-W with steep dips to the W or S	older acid-sulfate grading laterally to argillic alteration; silicification, chloritization and propylitic adjacent to veins	very fine-grained quartz, loss of CO_2, bladed calcite and quartz pseudomorphs, hydrothermal brecciation	240-325	< 5	base-metals increase with depth, central zone of base metals with gold-silver grading to gold-silver to outermost zone of fluorite-manganese, quartz veins grade vertically upward to calcite veins, excellent potential for additional deposits in Hells Hole area	Griggs and Wagner (1966), Biggerstaff (1974), Hedlund (1990, 1993), McLemore and Clark (1993), McLemore (1993), Ratté et al. (1982a)
3	Chloride (Apache No. 1, Phillipsburg, Grafton, Black Range)	Rubio Peak Formation (Eocene-Oligocene), Magdalena Group (Pennsylvanian)	Miocene 25-27 Ma on adularia (Harrison, 1988, 1990; Behr, 1988)	low sulfidation; local jasperoids	Au,Ag,Cu,Pb, Zn,Sn (F,Mo,Ba)	quartz, bornite, sphalerite, galena, chalcocite, chalcopyrite, pyrite, calcite, adularia, epidote, sericite, fluorite, barite	southern part centered around Chloride Creek dome, northern veins trend N-S	propylitic, silicification, potassic, sericitic, argillic	very fine-grained quartz, hydrothermal brecciation, fluid inclusion evidence, gas analyses	220-300	< 5 (Behr, 1988; Neal and Larson, 1986)	gold-copper veins toward the north grading southward to older silver-lead-zinc veins	Harley (1934), Maxwell and Heyl (1976, 1980), Willard (1973), Freeman and Harrison (1984) Harrison (1986, 1988, 1990), Lovering and Heyl (1989), Neal and Larson (1986), Behr (1988)
4	Socorro Peak*	Socorro Peak Rhyolite 12-7 Ma, Popotosa Formation	Miocene 10-12 Ma (Chamberlin, 1980)	low sulfidation; silver veins	Ag,Pb (Au, Ba,F,W,V, As,Br)	quartz, barite, clay, silver, malachite, calcite, Mn-Fe oxides, galena, fluorite, chlorapyrite, argentite	faults associated with Socorro caldera, veins strike N20W to N15E and N60-70E with steep dips	silicification, argillic, regional potassic alteration	hydrothermal brecciation	—	—	best ore associated with abundant fluorite, grades range up to 20 oz/ton Ag and 0.25 oz/ton Au (Lasky, 1932), areas of silicification may be older than 10-12 Ma veins	Lasky (1932), North (1983), Chamberlin (1980), Moats and Queen (1981)
7	Rosedale*	South Canyon Tuff 26.7 Ma, Lemitar Tuff 28.4 Ma	Miocene(?)	low sulfidation veins, hydrothermal brecciation	Au,Ag (U,Cu,Mn)	quartz, gold, Mn oxides, Fe oxides, fluorite chlorite	associated with Mt. Withington caldera ring-fracture zone, veins strike N20W 80E	argillic, silicification adjacent to veins	very fine-grained quartz, hydrothermal brecciation	—	—	veins 3-5 ft wide, grades up to 0.5 oz/ton Au, minor placer deposits	Jones (1904), Lasky (1932), Lindgren et al. (1910), North (1983), Ferguson (1990), Neubert (1983), Johnson (1972)
8	San Jose*	Spears Formation 33-39 Ma, Vicks Peak Tuff 28.6 Ma	Oligocene to Miocene(?) veins, acid-sulfate alteration less than 28.6 Ma	low sulfidation veins, hydrothermal brecciation, high sulfidation alteration	Au,Ag,Cu Pb (Mo)	quartz, gold, chlorargyrite, silver, malachite, stephanite(?), pyrite, adularia, sericite, cerargyrite, chlorite, alunite	associated with Nogal Canyon caldera ring-fracture zone, veins strike N10-30E	acid-sulfate alteration grading laterally to argillic and phyllic alteration; silicification near veins	bladed calcite and pseudomorphs of quartz, hydrothermal brecciation	—	—	veins 1-5 ft wide, central zone of acid-sulfate alteratin consists of massive silica cap	Lasky (1932), Lindgren et al. (1910), North (1983), Forurea (1984)
13	Cat Mountain*	Spears Formation 33-34 Ma, Abo Formation (Permian), Rock House Canyon Tuff	Oligocene to Miocene(?)	low sulfidation, veins, brecciation	Au,Ag,Cu (U,F,Ba,W)	quartz, barite, fluorite, calcite, pyrite, galena, malachite, cerussite, wulfenite, gold, chalcopyrite	associated with Morenci lineament veins strike N50-60E, 80-90NW and N30W, north of Mt. Withington caldera	silicification, argillic, propylitic, pyritic	—	180-230	< 5	veins converge at depth, veins cut basaltic dikes, widths up to 8 ft, lead isotope data confirms an epithermal origin (modern leads)	Jones (1904), Wilkinson (1976), North (1983), Lasky (1932), Slawson and Austin (1962)
14	Hop Canyon (Hope Canyon)	Hells Mesa Tuff 32.1 Ma, Sawmill Canyon Formation 31-29 Ma, Lemitar Tuff 28.4 Ma	Oligocene to Miocene(?)	low sulfidation veins	Cu,Ag,Au, Pb (Ba,Zn)	quartz, gold, copper sulfides and carbonates	associated with Sawmill Canyon-Magdalena caldera, veins strike N30W N20E, N10W, 70SE	silicification, argillic	—	—	—	—	Lindgren et al. (1910), Lasky (1932), Allen (1979), North (1983)
17	North Magdalena (Pueblo, Silver Hill, St. Viciente)	La Jara Peak Basaltic Andesite 24-31 Ma	Oligocene to Miocene(?)	low sulfidation veins	Cu,Ag,Au,Pb (V,Zn,Ba)	quartz, calcite, copper minerals, galena, argentite sphalerite, barite, anglesite, hematite	associated with Socorro transverse shear zone, veins trend N70W to N35E, 60-90° dips north Sawmill Canyon-Magdalena caldera	silicification, argillic, propylitic, hematization	—	—	—	lead and vanadium high toward the east (Pueblo) and copper high westward (Silver Hill), veins up to 6 ft wide	North (1983), Lasky (1932) Simon (1973)
18	Cora Miller	Tertiary rhyolite, ash-flow tuff	Miocene to Oligocene(?)	low sulfidation veins	Au,Ag,Cu,Pb (Mn)	quartz, gold, malachite	veins strike N70-75E, associated with Schoolhouse Mountain caldera ring-fracture zone	silicification, argillic	—	—	—	1-5 ft wide vein	Gillerman (1964), Lindgren et al. (1910), Richter and Lawrence (1983)
19	Wilcox*	Oligocene andesite and rhyolite intrusives	Miocene veins Oligocene acid-sulfate alteration 31-33 Ma (Marvin et al., 1987, #53)	low sulfidation veins, older high sulfidation alteration	Cu,Au,Ag,Te, F, (Pb, Zn, Mo, Cd)	quartz, alunite, kaolinite, pyrite, chlorite, calcite, fluorite	veins associated with Bursum caldera ring-fracture zone	acid-sulfate, silicification, chloritization, argillic, sericitic, propylitic	hydrothermal brecciation	150-210	< 5	5 tons of tellurium ore produced	Arnold (1974), Ratté et al. (1979), Ratté and Stotelmeyer (1984), Marvin et al. (1987), Bornhorst et al. (1984)

Map no.	District	Host rocks[1]	Mineralization Age	Mineralization Style (Table 4)	Commodities produced (present) (Table 3)[3]	Predominant mineralogy of veins	Structural setting	Alteration	Evidence of boiling[2]	Temperature range °C[4]	Salinities eq. wt.% NaCl[4]	Comments	Selected references
20	Alum Mountain (Gila River, Alunogen Copperas Creek)	volcanic complex of Alum Mountain 30 Ma (Ratté et al., 1979)	Oligocene acid-sulfate alteration 30 Ma (Ratté et al., 1979; Marvin et al., 1987, #98, 99)	high sulfidation disseminated and thin veins and stockwork veins	Au,Ag, alum (Cu,Pb,Zn, clay, Ga)	quartz, alum, alunogen, pyrite, gold, kaolinite, calcite, clay, sericite	veins associated with altered rhyolite domes, veins strike N50W, district is between Gila Cliff Dwellings and Twin Sisters calderas	acid-sulfate silicification	hydrothermal brecciation	—	—	one assay of 0.28 oz/ton Au, 0.36 oz/ton Ag (Ratté et al., 1979, #528)	Ratté and Gaskill (1975), Ratté et al. (1979), Ratté and Stotelmeyer (1984), Marvin et al. (1987), Hayes (1907)
22	Taylor (Ojo Caliente #2)	Tertiary rhyolite and andesite	Late Tertiary	low sulfidation veins	Cu,Pb,Ag (Au,Mn)	quartz, cerusite, chrysocolla, malachite, Mn and Fe oxides	veins strike N65-70E dip 75-80NW	silicification, propylitic	—	—	—	mineralized zone up to 15 ft wide	Hillard (1969), Lasky (1932), North (1983), Griffitts and Alminas (1968)
23	Goldsboro (Goldsborough, Aragon Hill, Monticello)	Tertiary rhyolite intrusive and andesite flows	Oligocene to Miocene(?)	low sulfidation veins	Au,Ag (Sn, V)	quartz, fluorite, gold, pyrite, limonite	veins strike N10-15W 68-80SW	silicification	—	—	—	veins are 3-10 ft wide	Lasky (1932), Lovering and Heyl (1989), Harley (1934)
24	Council Rock* (Iron Mountain, Ten Mile)	Spears Formation 33-39 Ma, Hells Mesa Tuff 32.1 Ma	Oligocene to Miocene(?)	low sulfidation veins	Pb,Ag,Fe,Au, (Mn,Ba,F,Cu, U,Zn)	quartz, magnetite, barite, calcite, siderite, hematite, trace galena, Mn oxides, cerussite, gold, chlorargyrite	veins trend N10W to N45W and N30E to N60E	propylitic, argillic, pyritic, silicification	—	—	—	mines at intersections of veins forming pipe veins, veins are 2-5 ft wide, lead stable isotope data, confirms an epithermal origin (modern leads)	Lasky (1932), Chamberlin (1974), Jones (1904), North (1983), Slawson and Austin (1962)
25	Alhbe Spring* (Springhill?)	faults cutting Baca and Chinle Formations and Dakota Sandstone	Late Tertiary	low sulfidation veins	Cu,Pb,Ag, (Ba,Zn)	chalcocite, quartz, clay, malachite, barite, bornite		argillic, silicification	—	—	—	—	Mayerson (1979), North (1983), Chapin et al. (1979)
26	Bear Mountains	La Jara Peak Basaltic Andesite 24-31 Ma	Oligocene to Miocene(?)	low sulfidation veins	(Cu,Ag,Sb,Zn)	quartz, pyrite hematite, calcite, chrysocolla	associated with Hells Mesa fault	argillic, silicification	—	—	—	veins up to 1 ft wide, assay reported by North (1985)—no Au, 0.75 oz/ton Ag	North (1985)
27	Luis Lopez*	Lemitar Tuff, South Canyon Tuff, Hells Mesa Tuff, 32.1 Ma, basaltic andesite	Miocene-Pliocene as young as 3-7 Ma (Eggleston et al., 1983)	low sulfidation Mn veins	Mn (Au,Ag,Zn, W,Pb)	Mn oxides, calcite, quartz	associated with Socorro caldera and Rio Grande rift structures, veins strike N15W to N30W with steep dips	regional potassic alteration with minor silicification adjacent to veins	fluid inclusion evidence, gas analyses	150-375	< 1	veins fill vertical fractures, suggesting mineralization may be younger than 10-12 Ma (C. Chapin, personal commun., 1/24/94), oxidized epithermal system	Hewitt (1964), Norman et al. (1983), Eggleston et al. (1983), North and McLemore (1987)
28	Gila Fluorspar* (Brock Canyon)	Oligocene andesite flows and rhyolite intrusive	veins are Miocene, acid-sulfate alteration is older (Ratté et al., 1979; McOwen, 1993)	low sulfidation veins, high sulfidation alteration older than the low sulfidation veins	F (Au,Ag,U, Cu,Pb,Zn,Mo)	fluorite, quartz, Mn and Fe oxides, kaolinite, calcite, barite, epidote, chlorite, pyrite	normal faults strike N45E with steep dips, district is between Bursum and Schoolhouse Mountain calderas	acid-sulfate(?) and sericitic alteration with pyritization and silicification surrounds a core of argillic, propylitic and chloritic alteration	hydrothermal brecciation	—	—	—	Ratté et al. (1979), Gillerman (1964), Ratté and Stotelmeyer (1984), Rothrock et al. (1946), Backer (1974), McOwen (1993)
29	San Francisco*	Oligocene rhyolite and andesite flows and intrusives	Oligocene to Miocene(?)	low sulfidation veins	(Au,Ag,Cu, Mo,Sb,Mn)	quartz, calcite	veins associated with Mogollon caldera ring-fracture zone	argillic, silicification adjacent to veins	—	—	—	anomalous values as high as 5000 ppm Mo, 100 ppm Ag, 4 ppm Au, 500 ppm Cu, 100 ppm Sb, placer gold deposits reported	Ratté et al. (1982b), U.S. Geological Survey et al. (1969)
33	San Lorenzo* (Jerome)	Oligocene volcanic rocks	Oligocene to Miocene(?)	low sulfidation veins	Cu,Ag (U,Au)	malachite, chrysocolla, quartz, alunite, kaolinite, tridymite	north of Socorro caldera and in Rio Grande rift zone	argillic, silicification adjacent to veins	—	—	—	dump samples assay as high as 1.8 oz/ton Ag (North, 1983)	North (1983), Lasky (1932)
ACID-SULFATE ALTERED AREA (base and precious metals unknown)													
A	Kline Mountain	Oligocene volcanics	Oligocene 28.4 Ma (Eggleston and Norman, 1986)	high sulfidation alteration	clay (alunite)	quartz, alunite, kaolinite, tridymite	rhyolitic dome complex	silicification forms innermost and uppermost zone within acid-sulfate alteration	—	—	—	no precious or base metals indicated at surface, near Taylor Creek tin deposit, central zone of massive silica cap	Hall (1978), Eggleston and Norman (1986), Eggleston (1987)

on alunite and altered whole rock in the Wilcox district (33.8±1.2 Ma and 32.0±1.7 Ma; Marvin et al., 1987, #53) are essentially the same age as the host rocks. The alteration at Alum Mountain, dated as 30 Ma (K/Ar on feldspar and biotite, Marvin et al., 1987, #98, 99), is also of a similar age as the host rock. The acid-sulfate alteration at Kline Mountain, near the Taylor Creek tin deposit, is 28.4±1.2 Ma (K/Ar on alunite; Eggleston, 1987), similar to that of the host rock. The acid-sulfate alteration in the San Jose district occurs in the Vicks Peak Tuff, which is 28.6 Ma (McIntosh et al., 1992a). Reconnaissance examination by the author of acid-sulfate altered areas in some districts suggests chemical and mineralogical zonations may exist similar to those found in the Steeple Rock district. These limited data and observations are consistent, but not necessarily conclusive, with a magmatic-hydrothermal origin for these areas of acid-sulfate alteration.

The acid-sulfate alteration found in volcanic-epithermal districts in the Mogollon-Datil volcanic field appear to be restricted in time to 27-33 Ma (Table 2, Fig. 4). In addition, acid-sulfate alteration is typically older than the precious- and base-metal epithermal veins in these districts (Fig. 4), as indicated by crosscutting relationships and limited age determinations. All acid-sulfate altered areas should be examined in more detail to determine the origin of the acid-sulfate alteration and the resource potential for high-sulfidation gold and silver deposits.

TABLE 3. Estimated production of volcanic epithermal deposits in the Mogollon-Datil volcanic field (USBM Mineral Yearbooks).

Map No. District	Year of discovery	Periods of production	Ore (short tons)	Copper (pounds)	Gold (ounces)	Silver (ounces)	Lead (pounds)	Zinc (pounds)	Comments	Additional references
1 Mogollon	1875	1902-1969	--	1,500,000	365,000	>20,000,000	1,200,000	some	1879-1957 over $24 million	Ferguson (1927), Anderson (1957), Jones (1965), North and McLemore (1986)
2 Steeple Rock	1860	1880-1991	365,000	1,200,000	151,000	3,400,000	5,000,000	4,000,000	Over $10 million produced	Griggs and Wagner (1966), Anderson (1957), McLemore (1993)
3 Chloride	1879	1934-1988	--	3,060,000	10,000	2,340,000	1,300,000	some	1880-1988 about $20 million produced	Harrison (1986, 1990)
4 Socorro Peak	1867	1867-1900	--	--	--	750,000	Some	--	<$1 million produced	North (1983)
7 Rosedale	1882	1882-1981	<100,000	--	27,000	10,000	--	--	Minor placer gold reported	North (1983), Johnson (1972), North and McLemore (1986)
8 San Jose	1900 1946	Prior to	5,000	250	900	13,000	100	--	--	North (1983), Neubert (1983)
13 Cat Mountain	1870	?	--	some	<100	1,300	--	--	--	North (1983)
14 Hop Canyon	1880	1913-1941	500	7,000	<100	1,100	200	--	--	Loughlin and Koshman (1942), North (1983)
17 N. Magdalena	1863	Prior to 1957	<500	some	35	<200	1,400	--	--	North (1983)
18 Cora Miller	1880	1940-1941	--	some	some	some	some	--	--	Gillerman (1964)
19 Wilcox	1879	1941	2	some	some	19	--	--	Additional ore produced about 1900	Jones (1904)
20 Alum Mountain		1893	1945	3	--	1	21	--	--	--
22 Taylor		?	--	some	--	some	some	--	--	North (1983)
23 Goldsboro		?	--	--	some	some	--	--	--	
24 Council Rock	1881	1880s	--	--	--	some	some	--	--	Jones (1904)
25 Abbe Spring	Prior to 1904	?	--	some	--	some	--	--	--	
26 Bear Mountain			None	--	--	--	--	--	--	-- --
27 Luis Lopez		None	--	--	--	--	--	--	Mn production	--
28 Gila Fluorspar	1880	None	--	--	--	--	--	--	--	
29 San Francisco		None	--	--	--	--	--	--	--	--
33 San Lorenzo	1901	None	--	--	--	--	--	--	--	
TOTAL PRODUCTION	--	--	--	5,767,250	554,135	26,515,640	7,501,700	--	--	

SUMMARY

Low-sulfidation, volcanic-epithermal vein deposits carrying precious metals are widespread in the Mogollon-Datil volcanic province. Mineralization is controlled by complex regional and local structures and proximity to centers of volcanic activity. Geologic and geochemical data suggest that mineralization occurred in multiple pulses in a shallow hydrothermal environment from both meteoric and magmatic fluids.

High-sulfidation (acid-sulfate), volcanic-epithermal vein deposits carrying precious metals are found only at Alum Mountain, although areas of acid-sulfate alteration are present in several areas. These areas of acid-sulfate alteration appear to be restricted in time to 27-33 Ma and are older than the low-sulfidation, volcanic-epithermal vein deposits. Geologic and geochemical data suggest that these altered areas are formed by acidic fluids in a shallow environment. Limited data (sulfur isotope data, mineral and chemical zonations, presence of pyrophyllite, gold assays) are consistent with a magmatic-hydrothermal origin, which is capable of carrying precious metals to form high-sulfidation deposits.

RESOURCE POTENTIAL

The potential for additional low-sulfidation, volcanic-epithermal vein deposits in most districts is good, because many favorable structures have not been adequately explored. Most districts have been examined only along known mineralized structures. Audio-magnetotelluric resistivity profiles, character of the veins, and probable offset by the Queen fault in the Mogollon district suggest that the area east of the Queen fault may contain significant mineral deposits (Kamilli, 1993, 1994). Two areas in the Steeple Rock district have been drilled and mineralization was encountered. Queenstake Resources Ltd. delineated 155,535 tons of ore averaging 0.11 oz/ton Au and 3.45 oz/ton Ag at the Jim Crow-Imperial mines (unpublished Queenstake Resources press release, 4/2/87; McLemore, 1993). Biron Bay Resources, Ltd. announced the discovery of a deposit containing 1.45 million tons of ore grading 0.179 oz/ton Au and 10.26 oz/ton Ag along the Summit vein (Petroleum and Mining Review, May 1992, p. 2; McLemore, 1993).

TABLE 4. Characteristics distinguishing the low-sulfidation (adularia-sericite) and high-sulfidation (alunite-kaolinite) deposits (from Hayba et al., 1985; Cox and Singer, 1986; Heald et al., 1987; Berger and Henley, 1989; White and Hedenquist, 1990).

	HIGH SULFIDATION (Alunite-kaolinite; acid-sulfate)	LOW SULFIDATION (Adularia-sericite)
Structural Setting	intrusive centers	structurally complex
Host rocks	rhyodacite common, acid to intermediate volcanics	various acid to intermediate volcanic and intrusive rocks
Timing of ore and host	typically similar ages of the host and ore	variable
Ore mineralogy	Higher sulfide mineral assemblage Enargite, pyrite, gold, electrum, base-metal sulfides including covellite no selenides Mn minerals rare Bismuthinite	Lower sulfide mineral assemblage Argentite, tetrahedrite, tennantite, silver, gold, base-metal sulfides selenides Mn minerals common No bismuthinite
Alteration/gangue mineralogy	Chlorite rare Chalcedony and adularia absent unless overprinting, abundant alunite and pyrophyllite	Chlorite present Chalcedony common, adularia, minor alunite and pyrophyllite
Production	Gold, silver, and copper	Gold, silver, variable base metals
Alteration	Extensive propylitic with advanced argillic to argillic with hypogene alunite and kaolinite, but no adularia	Extensive propylitic with sericitic to argillic with supergene alunite and some kaolinite and abundant adularia
Localizing controls	any faults or fracture zones related to volcanic centers	major regional faults or subvolcanics
General character of fluids	low to high salinity meteoric with magmatic waters pH acid from magmatic HCL and H_2S oxidized to reduced Total S typically high Base-metal content low to high	low salinity meteoric waters dominant pH near neutral reduced Total S low Base metal content variable

Areas of acid-sulfate alteration have been examined for the potential for porphyry-copper deposits without much success. At least three areas of acid-sulfate alteration in the Steeple Rock district were studied by companies for the potential of high-sulfidation epithermal deposits. Although intercepts containing gold assays were encountered, no reserves were developed (McLemore, 1993). Other areas of acid-sulfate alteration in the Mogollon-Datil volcanic province should be examined to determine the origin of acid-sulfate alteration and the potential for high-sulfidation precious-metal deposits. Acid-sulfate alteration in some cases is also found above porphyry copper and/or molybdenum deposits.

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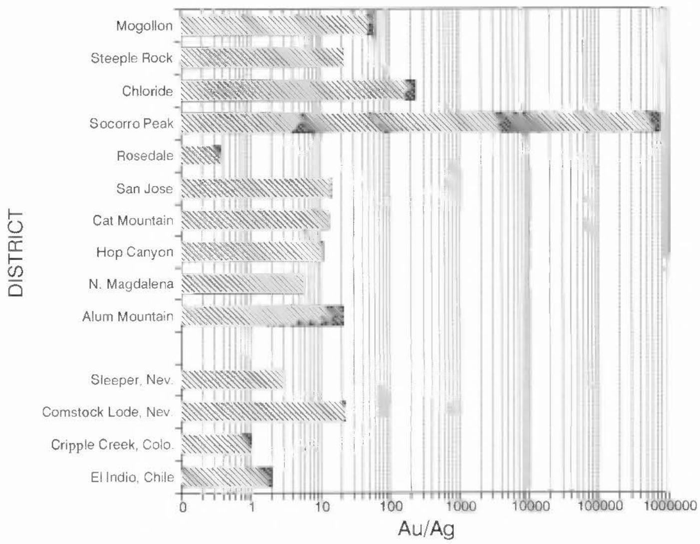

FIGURE 3. Approximate Ag/Au ratios for volcanic-epithermal deposits in New Mexico based on production (Table 3). Ag/Au ratios for Sleeper, Comstock Lode, Cripple Creek and El Indio deposits are from Sillitoe (1993).

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TABLE 5. Grade and tonnage from production of selected volcanic-epithermal deposits in the Mogollon-Datil volcanic field in New Mexico. *Estimated reserves of the St. Cloud mine as of 1982.

Map no.	District (period of production)	Ore (short tons)	Grade Au (oz/ton)	Ag (oz/ton)	Cu %	Pb %	Zn %	Source
1	Mogollon (1904-1925)	1,388,506	0.20	9.5	--	--	--	Ferguson (1927)
2	Steeple Rock (1904-1959)	199,095	0.19	7.7	0.3	1.3	1.1	Griggs and Wagner (1966)
3	Chloride* (1982)	375,217	0.04	8.9	1.4	1.0	1.3	Freeman and Harrison (1984)
7	Rosedale	81,828	0.16	0.12				North (1983)
8	San Jose	4,701	0.19	2.7	--	--	--	North (1983)

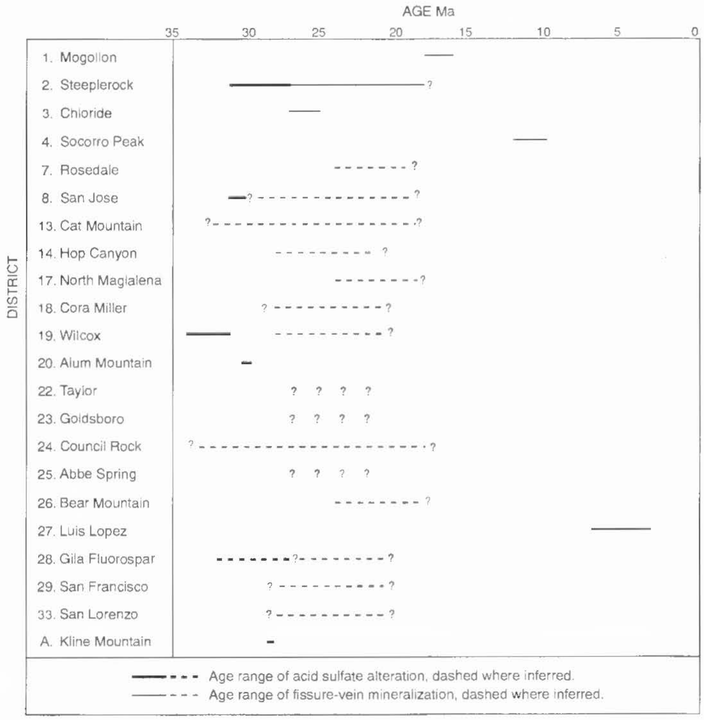

FIGURE 4. High-low graph showing age ranges of acid-sulfate alteration and mineralization in volcanic-epithermal districts in the Mogollon-Datil volcanic field. Dashed lines are inferred age ranges from stratigraphic data (Table 2). ? indicates age range may be greater or less than shown.

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Plains of San Agustin from Point of Rocks Canyon at the northwest base of the San Mateo Mountains, New Mexico. View is N75°W. From left to right, landmarks on the skyline include Horse Mountain, Mangas Mountain, Little Alegres Mountain, Alegres Mountain (bilevel), Sugarloaf Mountain, and Crosby Mountains. Alegres Mountain, elev. 3118 m, is the highest point on the Mogollon slope of west-central New Mexico. Horse Mountain is a dissected dacitic to rhyolitic volcano of late Miocene age. All the other landmarks are capped by Bearwallow Mountain Andesite of late Oligocene age. Flat-topped hills in middle ground, to left of center, define an intrabasin horst capped by an Oligocene ignimbrite of the Mogollon Group. C-N playa is at the floor of the basin below the flat-topped hills. Rocks in foreground are pink welded ash-flow tuff which underlies low hill northwest of Highway 52. Camera station is in SE ¼ sec. 16, T4S, R8W. Altitude about 2230 m. Wayne Lambert photograph No. 93L81. August 15, 1993, 3:58 p.m. MDT.