Magmatic activity and mineralization along the Capitan, Santa Rita, and Morenci lineaments in the Chupadera Mesa area, central New Mexico

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MAGMATIC ACTIVITY AND MINERALIZATION ALONG THE CAPITAN, SANTA RITA, AND MORENCI LINEAMENTS IN THE CHUPADERA MESA AREA, CENTRAL NEW MEXICO

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ABSTRACT—The Capitan, Santa Rita, and Morenci lineaments are regional crustal structures that focused magmatic activity and mineralization across central New Mexico, especially in the Chupadera Mesa area. The diversity of igneous rocks and mineral deposits in this region suggests highly fractionated and differentiated magmas. The existing K/Ar and $^{40}Ar/^{39}Ar$ ages indicates magmatic activity occurred during multiple pulses, rather than one single event. The easternmost intrusion along the Capitan lineament is the 27.9 Ma Railroad and Camino del Diablo dikes, whereas the Springerville volcanic field could define the western limit. The Lincoln County porphyry belt (LCPB) is a N-S belt of Tertiary porphyritic calc-alkaline to alkaline rocks that were emplaced in at least two pulses: 32-38 Ma and 26-30 Ma and are associated with Au-Ag-Te veins, REE-Th-U veins, Fe (±Au) skarns, and porphyry Mo deposits. The 28.8 Ma Capitan pluton forms the eastern part of the LCPB and is the largest Tertiary intrusion in New Mexico. The zoned Capitan pluton is associated with Fe skarns and REE-Th-U-Au vein deposits. East of Socorro several small deposits of Cu-Ag-U (±Fe, Au) vein and Rio Grande rift (RGR) barite-fluorite-galena deposits are found along faults; they are not directly associated with igneous activity and could represent migration of mineralizing fluids along rift structures. $^{40}Ar/^{39}Ar$ ages and field relationships suggest that RGR deposits formed during the last 10 Ma coincident with the later stages of rifting in central New Mexico, locally near the intersection with regional lineaments and other structures. Most of the available ages of igneous activity are K/Ar dates; detailed, high precision geochronology will be required to fully understand the temporal relationships between regional magmatic activity and mineralization.

INTRODUCTION

A lineament is an extensive regional linear feature that is believed to reflect crustal structure (Neuendorf et al., 2005). The relationship between mineral deposits and lineaments has been debated for many decades (Mayo, 1958; van Alstine, 1976; Gilluly, 1976; Walshe et al., 1999; Hildenbrand et al., 2000), even though some of the largest metal deposits in western United States occur at the intersection of lineaments (i.e. Bingham porphyry copper deposit, Utah, La Caridad-Mineral Park belt, Arizona, Hildenbrand et al., 2000). Ultimately, the relationship between mineral deposits and lineaments depends upon understanding the geologic processes that control the lineament and the processes that control or affect the distribution and formation of mineral deposits. Since many mineral deposits are spatially, if not genetically, related to magmatic activity and lineaments tend to control the distribution of magmatic activity, then it is likely that lineaments are related to some mineral deposits and can aid in exploration for new deposits. Preliminary examination of the coincidence of mining districts in New Mexico with major lineaments (Fig. 1) shows little correlation, except locally. There are as many districts that are not along lineaments as there are that lie along lineaments. However, it is likely that the processes that controlled magmatic activity along these lineaments also controlled mineralization and could be areas of future mineral exploration.

In New Mexico, much research has been focused on the magmatic, structural, and mineralization association along the Jemez lineament (Fig. 1; Mayo, 1958; Aldrich and Laughlin, 1984; Sims et al., 2002; Cather et al., 2006; Chamberlin, 2007), but not much has been published on the lineaments south of the Jemez lineament, including the Capitan, Santa Rita, and Morenci lineaments. The Chupadera Mesa area in central New Mexico is transected by the Capitan, Santa Rita, and Morenci lineaments. The diversity of igneous rocks and mineral deposits along these lineaments suggest highly fractionated and differentiated magmas (Allen and McLemore, 1991; Allen and Foord, 1991), but there is little precise, detailed geochronology of the igneous rocks. The existing K/Ar and few $^{40}Ar/^{39}Ar$ ages suggest that magmatic activity occurred during multiple pulses, rather than as one single event. Several different types of mineral deposits and numerous mining districts are found along these lineaments, but only a few districts have been significant producers of minerals in the Chupadera Mesa area (Fig. 2; Tables 1, 2). Evolving knowledge of the formation of mineral deposits and the recognition of new deposit types provides new information that suggests that additional deposits could occur in the Chupadera Mesa area. This should encourage new exploration for these deposit types in the subsurface of the Chupadera Mesa area.

The purposes of this paper are to 1) describe the Capitan, Santa Rita, and Morenci lineaments in the Chupadera Mesa area, 2) describe the magmatic activity and mineral resources along these lineaments, 3) present some hypotheses on the origins of the mineral deposits, and 4) discuss the relationship of the Capitan, Santa Rita, and Morenci lineaments with magmatic activity and mineralization in central New Mexico.

DATA SETS AND METHODS OF STUDY

The New Mexico Bureau of Geology and Mineral Resources has collected published and unpublished data on mines and mining districts in New Mexico and has converted much of that data into an Access database called the New Mexico Mines Database (McLemore et al., 2005a, b). This database was entered into ARCMAP along with other data sets, including the New Mexico geologic map (New Mexico Bureau of Geology and Mineral Resources, 2003), landsat map, geochronology database, and

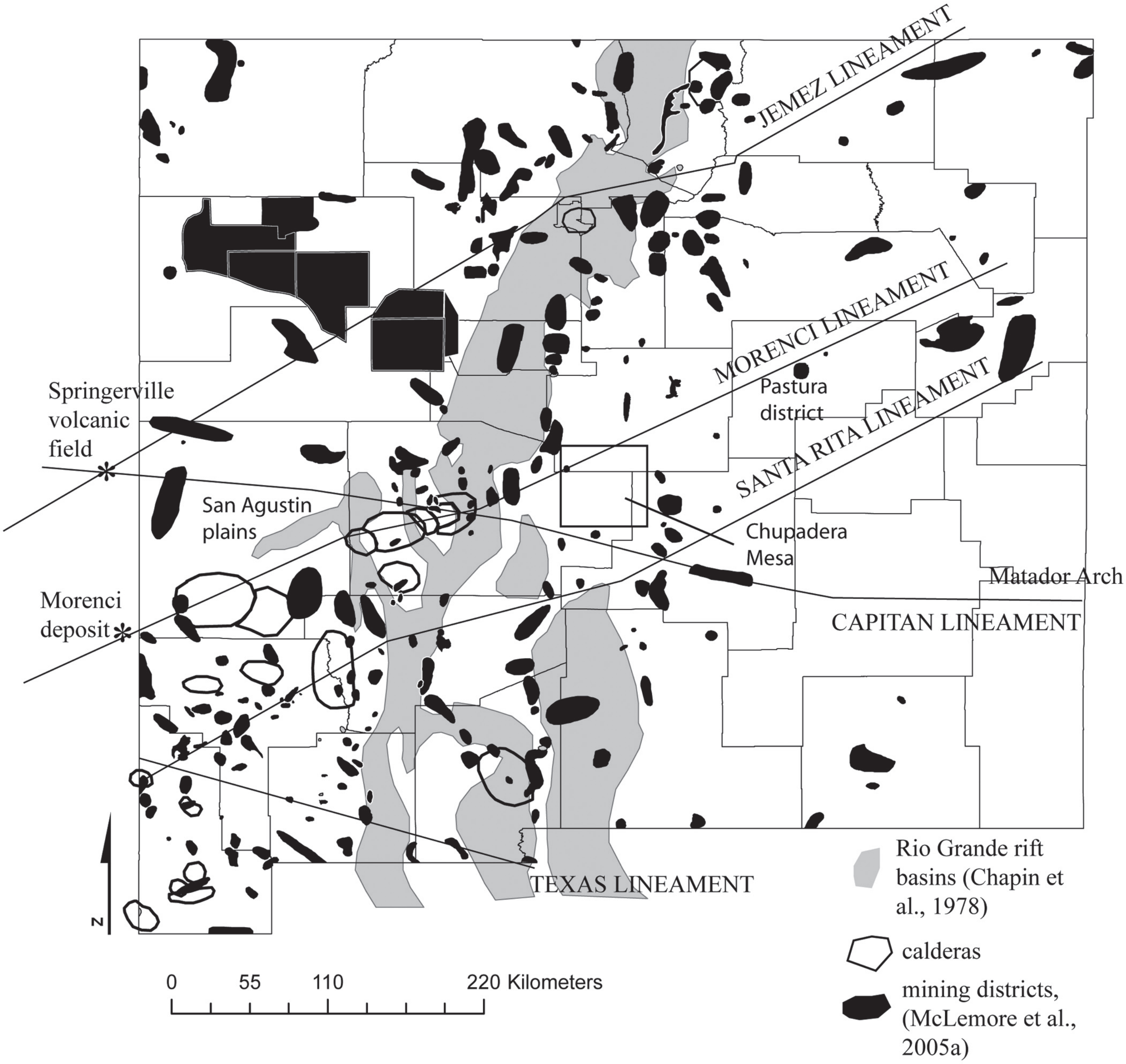

FIGURE 1. Lineaments, calderas, and mining districts in New Mexico (Chapin et al., 1978, 2004; McLemore, 2001; Sims et al., 2002; McLemore et al., 2005a).

aeromagnetic anomaly maps (Kucks et al., 2001). ARCMAP allowed the integration of these datasets and aided in producing Figures 1 and 2, along with the extensive literature cited in this paper.

DESCRIPTION AND REGIONAL STRUCTURAL SETTING OF THE CAPITAN, SANTA RITA, AND MORENCI LINEAMENTS

Chapin et al. (1978) delineated three lineaments that cut across the Chupadera Mesa area; the Capitan, Santa Rita and Morenci lineaments. These lineaments are regional crustal features that are defined by magmatic activity and structural features. Numerous mining districts with several different types of deposits lie along these lineaments (Figs. 1, 2). These lineaments are actually zones several km wide.

The Capitan lineament, first defined by Kelley and Thompson (1964) is defined by the alignment of E-W to ESE trending dikes, the Capitan stock and E-W trending faults and other structures (Fig. 1, 2). The easternmost extent of the Capitan lineament is the Paleozoic Matador Arch (Kelley and Thompson, 1964; Kelley, 1971; Ewing, 1990) in eastern New Mexico and west Texas and the east-west trending Railroad and Camino del Diablo dikes near Roswell (Fig. 1, 2). The Red River and Roosevelt uplifts (Paleo-

TABLE 1. Major mineral deposits in the Chupadera Mesa area, central New Mexico (after North and McLemore, 1986, 1988; Cox and Singer, 1986; McLemore and Chenoweth, 1989; McLemore, 2001).

NMBGMR Classification	USGS Classification (USGS Model Number)	Commodities	Perceived Age
Great Plains Margin (alkaline-related) (1) polymetallic, epithermal to mesothermal veins (2) gold-bearing breccia pipes and quartz veins (3) porphyry Cu-Mo-Au (4) Cu, Pb/Zn, and/or Au skarns or carbonate-hosted replacement deposits (5) Fe skarns and replacement bodies (6) placer gold (7) Th-REE-fluorite and Nb epithermal veins, breccias, and carbonatites	Copper porphyry, polymetallic veins, copper skarns, iron skarns, placer gold (17, 22c, 18a,b, 18d, 39a)	Au, Ag, Cu, Pb, Zn, Mn, F, Ba, Te	47–25 Ma
Sedimentary iron deposits	Oolitic iron (34f)	Fe	Cambrian–Ordovian
Replacement iron	Iron skarn (18d)	Fe	Cretaceous–Miocene
Sedimentary-copper deposits	Sediment-hosted copper (30b)	Cu, Ag, Pb, Zn, U, V	Penn–Permian, Triassic
Sandstone uranium deposits	Sandstone uranium (30c)	U, V, Se, Mo	Penn–Permian, Triassic, Jurassic, Cretaceous, Eocene, Miocene
Cu-Ag-U (±Fe, Au) vein deposits	Polymetallic veins (22c)	Cu, Ag, U	Miocene–Pliocene
Rio Grande Rift barite-fluorite-galena (formerly sedimentary-hydrothermal)	Fluorite and barite veins, polymetallic replacement (IM26b, c, 27e, 19a)	Ba, F, Pb, Ag, U	12–8 Ma, maybe as young as 700,000

zoic) in west Texas also lie along the Capitan lineament (Ewing, 1990; Cather, 1991). Other evidence for the Capitan lineament includes the basaltic craters of the Carrizozo lava flows, Capitan fold belt, the termination of the Pedernal arch, and the E-W-trending Jones Camp dike (Fig. 2). The Rio Grande rift could have offset or even terminated the Capitan lineament, since west of the Rio Grande, the Capitan lineament is not as well defined. If the Capitan lineament continues west of the Rio Grande rift, it could be defined by the Springerville volcanic field, a 3000 sq km basaltic volcanic field consisting of thoelitic to hawaiite basalts dated at 1-8 Ma (K/Ar dates, Condit and Connor, 1996). The Rio Grande rift north of the intersection with the Capitan and Morenci lineaments is basically one graben, but south of the intersection with the Capitan and Morenci lineaments, the Rio Grande rift divides into two or more grabens. In western New Mexico, the Capitan lineament could be defined by the edge of a magnetic high on the magnetic map of New Mexico (Kucks et al., 2001).

The Morenci lineament is defined by alignment of structural features, stratovolcanoes, and the Morenci intrusive-porphyry copper complex in Arizona (Chapin et al., 1978). Sanford and Lin (1998) called this the Socorro fracture zone, which is also defined by recent earthquake swarms. The Morenci porphyry copper deposit is one of the largest porphyry copper deposits in the United States (Long et al., 2000). Several calderas, including Socorro (32 Ma), Sawmill Canyon (28.7 Ma), Magdalena (28 Ma), Mt. Whittington (24.3 Ma), and Bursum calderas (28.1 Ma), are aligned along the Morenci lineament (Fig. 1; McIntosh et al., 1992). The NE-trending dikes in the Chupadera Mesa area in Socorro and Torrance Counties (Fig. 2) are along the Morenci lineament. The San Agustin plains parallels the Morenci lineament (Fig. 2). The Morenci lineament is not well defined east of the Rio Grande.

The Santa Rita lineament is defined by the alignment of structural features and several Laramide intrusive-porphyry copper complexes (Chapin et al., 1978; McLemore, 2008). The Santa Rita porphyry deposit is the largest porphyry copper deposit in New Mexico and one of the largest in the United States (Long et al., 2000; McLemore, 2008). In the Salinas Peak area (no. 203, Fig. 2), several rhyolite dikes and sills have intruded the sedimentary rocks and could be associated with the Santa Rita lineament (Fig. 2); the only other area of major igneous activity in the San Andres-Organ Mountains is in the Organ Mountains (33.3 Ma, recalculated from McLemore et al., 1995 using the new decay constant), which is the tilted core of the Organ caldera. The area between the Jemez and Santa Rita lineaments is defined as the New Mexico structural zone by Sims et al. (2002) and is the locus of many of the major metal-producing districts in New Mexico and Arizona (Fig. 1; McLemore et al., 2005a).

The Capitan, Santa Rita, and Morenci lineaments are intersected by several prominent N-S structural features; the most important of which is the Rio Grande rift. The Pedernal arch also intersects the Capitan lineament in Lincoln County and, along with the Capitan lineament, localized magmatic and volcanic activity in the Lincoln County Porphyry Belt (LCPB; Kelley and Thompson, 1964; Kelley, 1971; Allen and Foord, 1991). The NE-

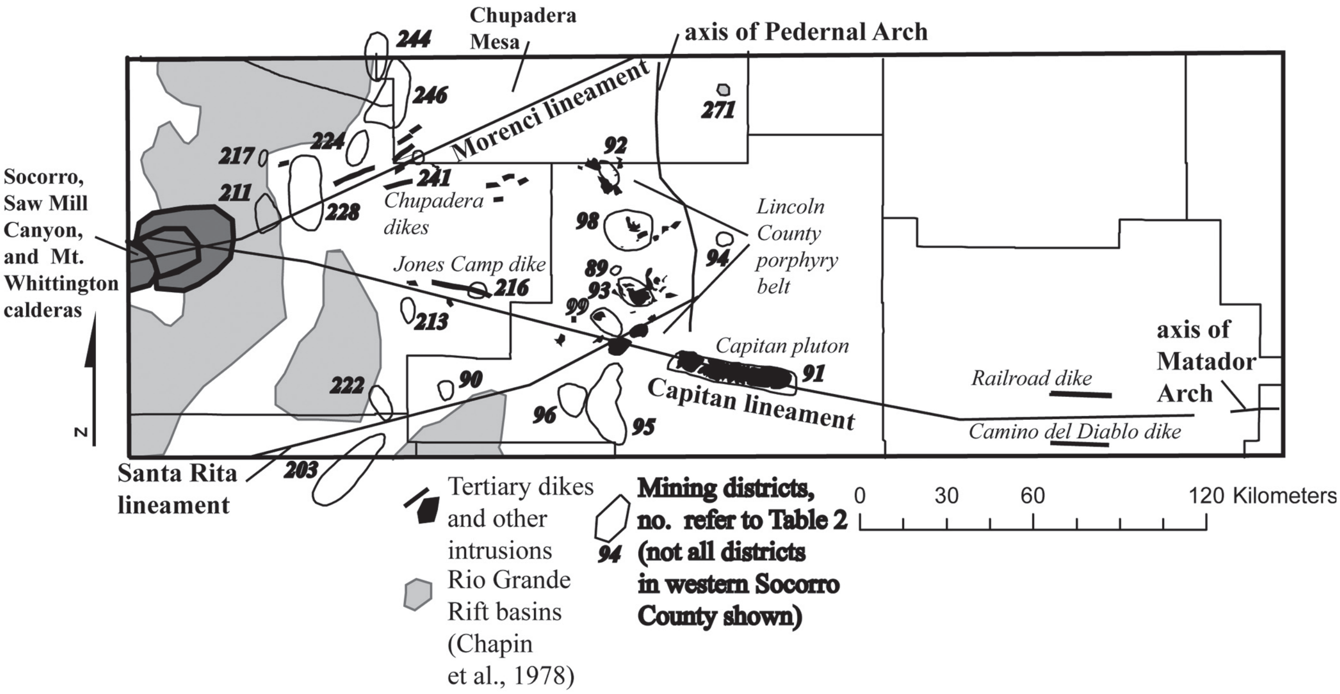

FIGURE 2. Magmatic activity and mineral deposits along the Capitan, Santa Rita, and Morenci lineaments in the Chupadera Mesa area, central New Mexico. Refer to Table 2 to reference the numbers representing the mining districts. .

trending Jemez, Morenci and Santa Rita lineaments also intersect the Capitan lineament (Fig. 1; Mayo, 1958; Chapin et al., 1978).

MAGMATIC ACTIVITY ALONG THE CAPITAN, SANTA RITA, AND MORENCI LINEAMENTS IN THE CHUPADERA MESA AREA

Magmatic activity along the Capitan, Santa Rita, and Morenci lineaments in the Chupadera Mesa occurred between 38 Ma and 25 Ma (Fig. 3). The easternmost intrusion along the Capitan lineament is the 27.9 Ma Railroad and Camino del Diablo dikes. Most of the magmatic activity was focused in the LCPB where the E-W to ESE trending Capitan lineament intersects the N-S trending Pedernal Arch (Allen and McLemore, 1991). K-Ar and sparse $^{40}Ar/^{39}Ar$ dating suggests the LCPB likely represents two stages of magmatism, an early alkaline belt emplaced along a N-S trend (Pedernal uplift) between 38 and 32 Ma and a younger bimodal suite emplaced along an E-W trend between 30 and 25 Ma (Fig. 2; Allen and Foord, 1991). In the LCPB, the intrusive rocks are associated with Au-Ag-Te veins, REE-Th-U veins, Fe (±Au) skarns, and porphyry Mo deposits (Allen and Foord, 1991). Three compositionally complex stocks intrude the Sierra Blanca volcanics (36.5-38.2 Ma): Bonito Lake (26.6 Ma), Three Rivers (36.36 Ma), and Rialto (31.4 Ma; Allen and Foord, 1991). The southernmost intrusion in the LCPB is the Black Mountain stock. $^{40}Ar/^{39}Ar$ analyses indicate magmatism at 37.8 Ma and 34.6 Ma. K-Ar analyses suggest magmatism could have continued until 32.6 Ma. The northernmost intrusions along the LCPB are located in the Tecolote Hills and Gallinas Mountains. There are no known ages of these intrusions.

The largest intrusion on the Capitan lineament is the compositionally and texturally zoned Capitan pluton, which also is the largest exposure of a mid-Tertiary intrusion in New Mexico (Allen and McLemore., 1991). The best estimate of the age of the pluton is 28.8 Ma, based on $^{40}Ar/^{39}Ar$ dating of adularia that is associated with emplacement of the pluton (Dunbar et al., 1996). The E-W trend of the Capitan pluton reflects the influence the Capitan lineament had on controlling its emplacement. The Capitan pluton is associated with Fe skarns and REE-Th-U-Au vein deposits.

The western limit of mid-Tertiary magmatism along the Capitan lineament in the Chupadera Mesa area is defined by the calderas located in the Socorro-Magdalena region (Fig. 1). The caldera cluster aligns along the Morenci lineament near the projected intersection with Capitan lineament. The Socorro, Sawmill Canyon, Hardy Ridge (Magdalena), Mt. Withington, and Beartrap calderas formed during the eruption of the Hells Mesa Tuff at 32.2 Ma, La Jencia Tuff at 28.9 Ma, Lemitar Tuff at 28.2 Ma, South Canyon Tuff at 27.6 Ma, and Turkey Springs Tuff at 24.5 Ma, respectively (McIntosh et al., 1992; Chapin et al, 2004; ages recalculated using the new standard).

The unmineralized Carrizozo lava flow (2.8-4.3 cu km of basaltic lava dated 5200 ± 700 yrs, ^{36}Cl; Dunbar, 1999) is perhaps the most well-known and noticeable feature on the Capitan lineament. Though the Carrizozo lava flow is located on the lineament, genetically it is unrelated to the mid-Tertiary magmatic activity.

The NE-SW trending Chupadera Mesa dike (southern Torrance Co) is 30.2 Ma and lies along the Morenci lineament (Aldrich et al., 1986). Additional NE-SW dike swarms are found throughout

TABLE 2. Mining districts in the Chupadera Mesa area, central New Mexico. Names of districts are after File and Northrop (1966) wherever practical, but many former districts have been combined and new districts added. Estimated value of production is in original cumulative dollars and includes all commodities in the district. Production data modified from Lindgren et al. (1910), Anderson (1957), U.S. Geological Survey (1927-1990) and U.S. Bureau of Mines (1902-1927), and New Mexico State Inspector of Mines Annual Reports. The district number refers to the New Mexico Mines Database district number (McLemore et al., 2005a).

District no.	District	Types of deposits	Years of Production	Estimated Cumulative Production	Reference
DIS271	Duran	GPM-iron replacement		none	Kelley (1971), McLemore (1984)
DIS092	Gallinas	GPM-REE-Th- U veins, sedimentary copper, placer gold	1909-1955	$261,000	Perhac (1970), Griswold (1959), McLemore (1991)
DIS098	Tecolote Hills	GPM	1915-1919	$24,000	Rawson (1957), Allen and Foord (1991), Korzeb and Kness (1992)
DIS094	Macho	sedimentary iron	1930	$1000	Kelley (1951), McLemore (1991)
DIS089	Ancho	sedimentary	1902-1922	$10,000	McLemore (1991)
DIS093	Jicarilla	GPM, placer gold	1850-1957	$165,000	Seagerstrom and Ryberg (1974), McLemore (1991), Griswold (1959)
DIS099	White Oaks	GPM, placer gold	1850-1953	$3,100,000	Thompson (1991), Ronkos (1991), Griswold (1959)
DIS091	Capitan Mountains	GPM-REE-Th-U veins, Fe skarn	1960-2000	$500,000	Allen and McLemore (1991), Campbell et al. (1995), McLemore and Phillips (1991), Phillips (1990)
DIS096	Schelerville	GPM		$10,000	Griswold (1959), Korzeb and Kness (1992)
DIS095	Nogal-Bonito	GPM, placer gold	1865-1942	$300,000	Thompson (1968, 1991), Allen and Foord (1991), Aldrich et al. (1986), Korzeb and Kness (1992)
DIS132	Three Rivers (Apache No. 1, White Mtn)	replacement iron	1911-1943	$160	McLemore (1991)
DIS090	Estey	sedimentary copper, sandstone uranium	1900-1910	$10,000	McLemore (1991)
DIS222	Mockingbird Gap	Cu-Ag-U (±Fe, Au) vein, RGR, Precambrian vein and replacements	1934-1941	$4000	McLemore (1994)
DIS203	Salinas Peak (Good Fortune Creek, Bearden Canyon, Bear Den)	RGR	1935-1948	<$5000	
DIS213	Hansonburg	RGR	1872-1957	$1,700,000	Putnam (1980), Norman et al. (1985)
DIS216	Jones Camp	iron replacement	1942-1943	$1000	Aldrich et al. (1986, #312), Gibbons (1981), Chamberlin (2009)
DIS241	Chupadera Mesa	iron replacement		$1000	Aldrich et al. (1986, #322), McLemore (1984)
DIS224	Rayo	sedimentary-copper	1900	$1000	
DIS246	Scholle	Precambrian vein and replacements, sandstone uranium, sedimentary-copper	1915-1961	$300,000	McLemore (1984)
DIS244	Manzano Mountains	Precambrian vein and replacements, volcanic-epithermal vein, sedimentary-copper, volcanic massive sulfide		None	McLemore (1984)
DIS217	Joyita Hills	Cu-Ag-U (±Fe, Au) vein, sandstone uranium, volcanic epithermal vein, RGR	1915	$1000	North and McLemore (1986)
DIS228	Socorro	Cu-Ag-U (±Fe, Au) vein, sandstone uranium	1955-1963	$70,000	McLemore (1983)
DIS211	Chupadero	Precambrian vein and replacements, sedimentary copper, RGR		$1000	

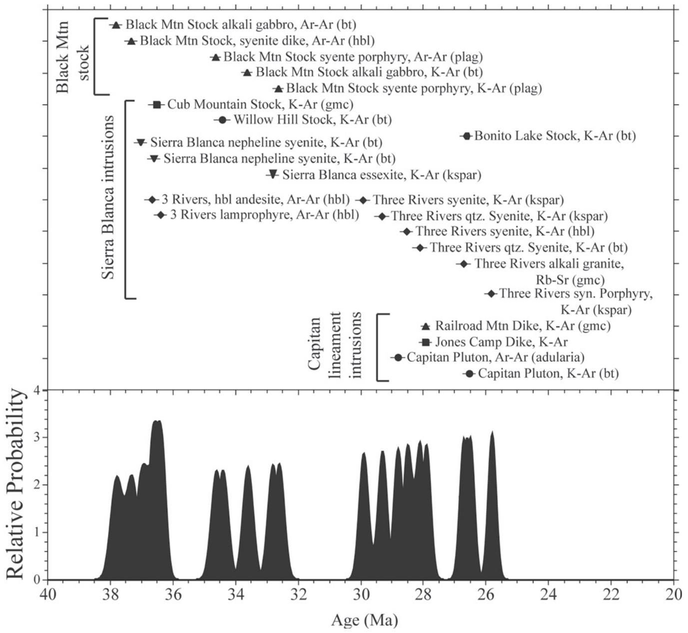

FIGURE 3. Ideogram of K/Ar, Rb/Sr, and Ar^{40}/Ar^{39} ages of igneous rocks in the Chupadera Mesa area. $^{40}Ar/^{39}Ar$ ages have been recalculated using the new decay constant. References are cited in the text.

the Chupadera Mesa area (Fig. 2). The only magmatic activity along the Santa Rita lineament in the Chupadera Mesa area are dikes and sills at Salinas Peak (Fig. 2).

DESCRIPTIONS AND ORIGIN OF MINERAL DEPOSITS ALONG THE CAPITAN, SANTA RITA, AND MORENCI LINEAMENTS IN THE CHUPADERA MESA AREA

Introduction

Types of mineral deposits in the Chupadera Mesa area are listed in Table 1. Known mining districts in the Chupadera Mesa area are briefly described in Table 2 and located in Figure 2. Tables 2 and 3 summarize the production from those districts. The following section briefly describes the major types of deposits found in the Chupadera Mesa and their relationship to the lineaments. More details on the specific geology of the Chupadera Mesa and surrounding area are in Wilpolt et al. (1946), Kelley and Thompson (1964), McLemore (1984), cited references in Table 1, and elsewhere in this guidebook.

Great Plains Margin Deposits (alkaline-related)

Some of the state's largest gold deposits occur along a N-S belt roughly coinciding with the Great Plains physiographic margin with the Basin and Range (Rio Grande rift) and Rocky Mountains physiographic province (McLemore, 1991). These deposits have similar characteristics that, when compared with their tectonic setting, define a class of mineral deposits referred to as Great Plains Margin (GPM) deposits by North and McLemore (1986, 1988) and McLemore (1996, 2001). Alternative classifications by other workers include alkalic-Au or alkaline-igneous-related-Au deposits (Fulp and Woodward, 1991; Thompson, 1991; Mutschler et al., 1985, 1991; Richards, 1995), porphyry Au deposits, and Rocky Mountain Au province.

Alkaline to subalkaline igneous rocks are found in all districts in the LCPB, but mineralization is locally associated with silica-saturated (monzonite) or oversaturated (quartz monzonite) rocks (Segerstrom and Ryberg, 1974; McLemore and Phillips, 1991; Thompson, 1991). The veins have high Au/base metal ratios and typically low Ag/Au ratios (McLemore, 1996) in contrast with other high Ag/Au deposits in western New Mexico (McLemore, 2001). The GPM deposits consist of seven associated deposit types: (1) polymetallic, epithermal to mesothermal veins, (2) breccia pipes and quartz veins, (3) porphyry Cu-Mo-Au, (4) Cu, Pb/Zn, and/or Au skarns or carbonate-hosted replacement deposits, (5) Fe skarns and replacement bodies, (6) placer Au, and (7) Th-REE-fluorite epithermal veins, breccias, and carbonatites.

The GPM deposits in New Mexico coincide with a belt of alkaline igneous rocks and eastward lithospheric thickening, which follows the tectonic boundary from Texas to Colorado between the tectonically stable Great Plains and tectonically active Rocky Mountains and Basin and Range Provinces. The lithosphere of the Basin and Range and Southern Rocky Mountains is thinner, has a higher heat flow, and is more permeable and fractured than the lithosphere of the Great Plains (Eaton, 1980; Prodehl and Lipman, 1989). This belt of alkaline-igneous rocks occurs along this boundary and continues northward into

TABLE 3. Estimated base and precious metal production from the mineral deposits in Chupadera Mesa area, central New Mexico. W - Production withheld. Production data modified from Lindgren et al. (1910), Anderson (1957), U.S. Geological Survey (1927-1990) and U.S. Bureau of Mines (1902-1927), and New Mexico State Inspector of Mines Annual Reports.

District (period of production)	Copper (pounds)	Gold (troy ounces)	Silver (troy ounces)	Lead (pounds)	Zinc (pounds)
Gallinas (1909-1953)	385,418	6.58	23,723	1,726,738	17,344
Jicarilla (1850-1957)	4,201,474	7347 (lode) 8,000 (placer)	37,531	2665	none
Nogal (1865-1942)	W	15,000	20,000	W	W
Schelerville	W	minor	small	W	none
White Oaks (1850-1951)	450	162,500 (lode) 1000 (placer)	1044	12,200	none

Canada and southward into Mexico (Clark et al., 1982; Clark, 1989; Mutschler et al., 1991). The diversity of igneous rocks and associated mineral deposits within this belt (McLemore, 1996) suggests that the boundary between the Great Plains and Rocky Mountains and Basin and Range provinces is a region of highly fractionated and differentiated magmas (Thompson, 1991; Allen and Foord, 1991). Low initial $^{87}Sr/^{86}Sr$ ratios suggest intrusive rocks associated with GPM deposits are derived from upper mantle to lower crustal sources (McLemore, 1996). It has not been proved that these mineral deposits are genetically related to the igneous rocks; however, it is likely that they are. Supporting evidence for a magmatic origin includes: 1) fluid inclusion, stable isotope, and age data from the Capitan quartz veins (Phillips, 1990; Phillips et al., 1991; Campbell et al., 1995; Dunbar et al., 1996), 2) nature of stockwork molybdenum deposits at Sierra Blanca (Thompson, 1968, 1983), 3) close spatial association with igneous rocks (Table 2), 4) presence of skarn deposits along the contacts of igneous rocks (Table 2), and 5) similarity to other deposits at Cripple Creek, Colorado and elsewhere where a magmatic origin is favored (Thompson et al., 1985; Porter and Ripley, 1985; Thompson, 1992; Maynard et al., 1989, 1990). It is likely that the co-occurrence of Au, Cu, Fe, Mo, F, W, and other elements is the result of several complex magmatic fractionation and differentiation events and tectonic subenvironments, which overlap near the Great Plains Margin. The association of lineaments and other major structures with igneous rocks and mineral deposits in New Mexico suggests that near vertical deep-seated fracture systems probably channeled the magmas and resulting fluids. Once the magmas and fluids reached shallow levels, local structures and wall rock compositions determined the final character and distribution of intrusions and mineralization.

Evidence suggests that complex, multiple intrusions are needed to generate the fluids necessary to produce GPM mineral deposits. The more productive districts, such as Nogal and White Oaks occur in areas of complex magmatism that lasted for more than 5 Ma and resulted in intrusions of different ages. Many of these areas have older calc-alkaline rocks followed by younger alkaline rocks (Table 2; Allen and Foord, 1991). In areas such as the Capitan Mountains where intrusive activity occurred in less than 5 Ma, only localized minor Au, Ag, and REE occurrences are found (McLemore and Phillips, 1991). Additional age determinations are required to confirm these observations, especially in the Gallinas, Sierra Blanca, and Tecolote districts.

Iron was produced intermittently from several districts in the Chupadera Mesa area. The Capitan iron deposit is estimated to contain 1-3 million tons of ore averaging 45-48% Fe (Kelley, 1949; McLemore and Phillips, 1991). Iron is found in the Jones Camp, Gallinas and Tecolote districts (Table 2). The Blackington and Harris iron deposits in the Chupadera district were mined between 1964 and 1975; approximately 100 tons of Fe ore worth $125 were produced (McLemore, 1984). The iron deposits are small, of intermediate grade, and are found adjacent to Tertiary dikes in Yeso sedimentary rocks as replacement bodies. The largest bodies are only 30 m long and 2 m wide and assayed 39.6% to 47% total Fe and trace amounts of Au (Table 4; McLemore, 1984). Small iron deposits are found in Permian Yeso sandstones near Duran adjacent to a Tertiary sill. A sample assayed 47.94% total Fe (Table 4; McLemore, 1984).

Sedimentary copper deposits

Sedimentary copper deposits are found in sandstones of the lower member of the Permian Abo, upper member of the Bursum, and the Mesita Blanca Sandstone Member of the Yeso Formations in the Scholle, Rayo, and Estey districts in the Chupadera Mesa area, but are not associated with any magmatic activity. Copper is the primary mineral and is associated with U, V, Ag, Pb, and trace amounts of Au in several stratabound horizons in bleached sandstones and siltstones. Approximately $700 worth of radium also was produced from the Scholle district in 1916 (McLemore, 1984). Copper and other minerals are found as disseminations within bleached arkoses, along bedding planes and fractures at or near sandstone-shale, sandstone-siltstone, and sandstone-limestone contacts, and as replacements of wood and other organic materials. The sedimentary copper deposits at Abo, Rayo, and Estey are typical sandstone-hosted deposits, and were likely formed during the Permain or perhaps are much younger than the host Permian rocks (La Point, 1979; McLemore, 1983). Oxidizing waters could have leached metals from 1) Proterozoic rocks enriched in these metals, 2) Proterozoic base-metal deposits, and 3) clay minerals and detrital grains within the red-bed sequences (La Point, 1976, 1979, 1989; Brown, 1984). Sources for chloride and carbonate needed to form soluble cuprous-chloride or cuprous-carbonate and other metal complexes (Rose, 1976) occur in older Paleozoic evaporite and carbonate sequences. Additional descriptions of these deposits are in LaPoint (1976, 1979, 1989) and McLemore (1983, 1984).

Rio Grande rift (RGR) and Cu-Ag-U (±Fe, Au) vein deposits

The Rio Grande rift is a dynamic system known to have elevated heat flow and circulating warm waters (Reiter et al., 1978; Witcher, 1989). Although, the Cu-Ag-U (±Fe, Au) vein and Rio Grande rift barite-galena-fluorite (RGR) deposits have been clas-

TABLE 4. Chemical analyses of iron samples from the Chupadera and Duran districts, Chupadera Mesa. T83-5-Chupadera mine, T83-6-Geoslim pit, T83-15, 16, 17-Garner mine.

Sample	Fe total %	Au ppm	Mn %	SiO2 %	P2O5 %	CaO %	TiO2 %	Cu ppm	Zn ppm	Co ppm	Ni ppm	Cr ppm
T83-5	39.6	0.7	0.12	1.70	0.33	24.59	0.20	345	20	257	76	17
T83-6	47.0	0.7	0.03	1.75	0.19	19.22	0.24	560	20	109	138	13
T83-16	14.5	Trace		83.84		0.56	0.21	50	55			
T83-17	12.0	Trace		85.13		1.26	0.27	56	11			
T83-15	47.94	Trace		47.62		0.21	0.69	82	198			

sified and described as separate classes, there are many similarities between these deposits that suggest that they have a similar origin. These two deposit types differ in their primary mineralogy and metal associations. The Cu-Ag-U (±Fe, Au) vein deposits contain predominantly Cu minerals with some Ag and locally U, but only trace amounts of barite, galena, and fluorite associated with them; whereas the RGR deposits contain predominantly barite and fluorite with some galena, Ag, and locally small amounts of Cu, but little or no U. Both types of deposits appear to be Miocene-Pliocene in age and are open-space fillings by low temperature, moderate salinity fluids found along or near local faults (Böhlke et al., 1992; McLemore et al., 1998; Lueth et al., 1998, 2005; McLemore, 1999; Hill et al., 2000; Partey, 2004, Partey et al., 2009).

RGR deposits, formerly called sedimentary-hydrothermal barite-fluorite-galena deposits or Mississippi-Valley type (MVT) deposits, are found within the Rio Grande rift in central New Mexico (McLemore et al., 1998) and are characterized by a unique regional geologic setting, simple mineralogy dominated by fluorite and/or barite, low temperature of formation (<200-250°C), deposition as open-space fillings with little or no replacement of host rocks, common paragenetic sequence, and no obvious direct association with any magmatic or volcanic activity. These deposits occur along faults, fractures, contact zones, unconformities, shear zones, bedding planes, and solution cavities in diverse Precambrian, Paleozoic, and Tertiary rocks. Age determinations and field relationships suggest that RGR deposits formed during the last 10 Ma coincident with the later stages of rifting in central New Mexico (McLemore et al., 1998; Lueth et al., 1998, 2005).

One of the most significant of the Cu-Ag-U (±Fe, Au) vein deposits is the Jeter mine, where 58,562 pounds of U_3O_8 at grade of 0.33% was produced (McLemore, 1983). Uranium (primarily coffinite with local paraschoepite, meta-autunite, meta-torbinite, soddyite) and copper (malachite, azurite) minerals are found along a 500 ft section of the low angle Jeter fault between Proterozoic granite and Tertiary sedimentary and volcanic rocks (Collins and Nye, 1957: Chamberlin et al., 1982). The fault zone is highly bleached and kaolinized granite. The mineralization is younger than the Jeter fault, which separates the Miocene Popotosa Formation from the Proterozoic granite. There are additional Cu-Ag-U (±Fe, Au) vein deposits of probable Miocene age in New Mexico. Veins at the La Bajada mine (Santa Fe County) are along faults and appear to be controlled by the distribution of organic material (Haji-Vassiliou and Kerr, 1972) or carbonaceous mudstone (Collins and Nye, 1957). Uranium, vanadium, copper, and silver were produced from La Bajada (McLemore, 1999). Deposits in the Bent district, previously classified incorrectly as sedimentary copper deposits (Lindgren et al., 1910; McLemore, 1991, 2001), have reported production of 560,000 lbs Cu and 1189 oz Ag. The Virginia deposit at Bent was as much as 45 ft thick, within 10-30 ft of the surface, and contained 2.5-45% Cu, 0.07-4 oz/ton Ag, and 0.01-0.02 oz/ton Au (Lindgren et al., 1910; NMBMMR file data). The ore occurs as 1) lenses and veins in upper Proterozoic diorite, 2) ore stringers and veinlets in diorite and Cambrian Bliss Sandstone, 3) veins and tabular, replacement deposits in the sandstone associated with glauconite, and 4) placer Cu deposits in the adjacent arroyo (Bauer and Lozinsky, 1991; McLemore, 1991).

Uranium is found in several types of deposits in the Chupadero district in central Socorro County. Uranium occurs along fractures and joints in weathered and altered Proterozoic Tajo granite (Fig. 2), where six outliers of granite are exposed along two NW-trending fault blocks. Fluorite, barite and U minerals are found along these faults and fractures within the granite. Uranium concentrations as high as 0.019% U_3O_8 have been found (McLemore, 1983). Four additional small Cu-Ag-U (±Fe, Au) vein deposits are found along faults within the Rio Grande rift (Lucky Don-Little Davie, Aqua Torres, Maria No. 1) on the edge of the Chupadera Mesa and total production from them has amounted to 4688 pounds of U_3O_8. The mineralized zones are discontinuous and found in silicified and recrystallized limestones and sandstones along the faults.

It is suggested that both the RGR and Cu-Ag-U (±Fe, Au) vein deposits were formed from meteoric waters by similar processes (Bohlke et al., 1992; Hill et al., 2000; Lueth et al., 2005; Partey et al., 2009). Furthermore, Lueth et al. (2005) and Partey et al. (2009) have shown that the HF in RGR deposits is magmatic-derived, thereby linking the RGR deposits to magmatic processes. The difference in mineralogy and metal associations can be explained by local variations in the geochemical dissolution and precipitation history and sources of the elements. During the Miocene-Pliocene, meteoric waters within the Tertiary and older sediments of the rift evolved chemically as they became warmer with depth due to burial and/or basin compaction, by dissolving rock constituents to produce waters of varying salinities and metal concentrations. As these warm brines interacted with Precambrian basement rocks, Jurassic and Cretaceous sediments, Tertiary volcanic rocks, and sediments derived from these sources, the fluids mobilized U, Cu, Ag, Fe, and other metals. As the rift developed, favorable discharge zones such as faults and along contacts of dikes and intrusions, many controlled by the regional lineaments, allowed the mineralizing fluids to migrate up along fractures and faults. Circulation of these warm waters would be along faults, fractures, contact zones, and other permeable zones within the basin. Once the deposit was emplaced, oxidation, dissolution, and downward re-precipitation and enrichment of the deposit occurred as the groundwater level dropped in the area.

Potential source rocks are abundant in the subsurface. Sulfur could have been derived from lacustrine evaporite deposits, pyrite-rich black shales, or other sulfur-bearing units in the subsurface (Hill et al., 2000; Lueth et al., 2005; Partey et al., 2009). Fluorine is derived from magmatic sources (Partey, 2004; Partey et al., 2009). Uranium could have been derived from uranium-bearing Cretaceous and Jurassic sedimentary rocks. Copper, silver, and other metals could have been derived from sedimentary copper deposits, Proterozoic metal deposits, or Paleozoic, Jurassic, Cretaceous, or Proterozoic crystalline rocks enriched in these metals. Lead, Sr and Nd isotope data suggest that the galena and fluorite was derived from the Proterozoic granites (Slawson and Austin, 1962; Beane, 1974; Ewing, 1979; Partey, 2004).

SIMILARITY TO IRON OXIDE-CU-AU (IOCG) DEPOSITS (OLYMPIC DAM DEPOSITS)

The Olympic Dam deposit in Australia, a Fe oxide-Cu-Au ±U (IOCG) deposit, is one of the largest Cu-U deposits in the world and is reported to contain a measured resource of 650 million tons (Mt) of 500 g/t U_3O_8 (425 ppm U), 1.5% Cu, and 0.5 g/t Au with a total resource estimated to be approximately 3.8 billion tons of 400 g/t U_3O_8 (339 ppm U), 1.1% Cu, and 0.5 g/t Au (Hitzman and Valenta, 2005). Many mineral deposits in the world are being re-examined for the potential for this class of deposit and some of the minor deposits along the Capitan, Santa Rita, and Morenci lineaments in the Chupadera Mesa area are suggestive of undiscovered IOCG deposits, because they have similar structural features and metal associations. IOCG deposits are found in continental rift setting and appear to be controlled by regional lineaments. IOCG deposits contain essential Ti-poor magnetite and/or hematite and most are associated with saline hydrothermal fluids, calcalkaline to subalkaline to alkaline A-type igneous rocks, low sulfur contents, and enrichment in REE, Cu, Au, Ag, and U (Barton et al., 2000).

The various mineral deposits found along these lineaments in the Chupadera Mesa area have similar metal associations as IOCG deposits. Barton and Johnson (1996) presents evidence that sulfate deposits are found in known areas of Fe oxide deposits and that they actually control mineralization, not the magmas. Permian evaporate sedimentary deposits are common in central New Mexico and RGR deposits (some with U). Replacement textures, zoned alteration patterns (Fe-, Na-, and K-metasomatism), and alteration-associated veins, of a hydrothermal origin are common. The origin of IOCG deposits is uncertain, and seems to range from magmatic to non-magmatic types (Hunt et al., 2007); the various mineral deposits in the Chupadera Mesa area range from deposits associated with the alkaline intrusions in the LCPB and the dikes in the Chupadera Mesa area to RGR and Cu-Ag-U (±Fe, Au) vein deposits, which are not directly associated with igneous activity.

MINERAL RESOURCE POTENTIAL

It is unlikely that any of the deposits in the Chupadera Mesa area will be mined in the near future because of small tonnage and low grades of deposits found at the surface, except for some Au vein deposits in the LCPB (especially in the White Oaks and Sierra Blanca districts). Unpublished magnetic surveys suggest the presence of large iron skarn and carbonate-replacement deposits in limestones in the subsurface surrounding the Capitan Mountains. However, there is no immediate market for iron deposits in New Mexico, which could change as the supply of iron in the world changes and the price increases. The Capitan deposits contain small amounts of Au, U, REE, and perhaps other metals, but not in economic concentrations that could be recovered by current known technologies. It is possible that additional deposits will be found in the Chupadera Mesa area as exploration continues in this area.

CONCLUDING REMARKS

Structural, stratigraphic and magmatic evidence suggests that the Capitan, Santa Rita, and Morenci lineaments have been a crustal feature that has focused structural activity since at least late Paleozoic times and have focused magmatic activity since about 38 Ma. Known igneous activity occurred in three pulses, an early, alkaline pulse at 38-36 Ma, a second pulse of late, bimodal mafic and granitic plutons at 30-26 Ma (Allen and Foord, 1991), and the youngest recent event, the Carrizozo lava flows at 5200 ± 700 yrs (Dunbar, 1999). Additional age determinations of igneous rocks along these features are required to fully understand the temporal relationships. Numerous mineral deposits occur along and in the vicinity of these lineaments, especially at the intersections with other regional structural features, and further suggest the leakage of hydrothermal fluids along faults associated with the Rio Grande rift and the Capitan, Morenci, and Santa Rita lineaments forming RGR deposits and Cu-Ag-U (±Fe, Au) vein deposits. The GPM vein deposits, noted for their Au abundance (even in the Fe skarn and replacement deposits) are associated with the igneous stocks and dikes in the LCPB and dikes of the Chupadera Mesa area.

Lineaments have played a role in localizing magmatic activity and, locally, mineralizing fluids; however, many volcanic and magmatic events and mining districts in New Mexico are not found along lineaments (Fig. 1). Many factors, such as surface topography, development of rift structural architecture, erosion and tectonic elimination of aquitards, unroofing of carbonate aquifers by karst formation, climate, rates of extension, basin sedimentation, subsidence, compaction, over pressuring, and crustal magmatism, have all played roles in the location, types, and intensity of mineral deposit evolution at any particular site. As a result, deposits of different ages, size, temperature of formation, and accessory mineralogy are a common feature of the deposits found along and near the Capitan, Santa Rita and Morenci lineaments, especially in the Chupadera Mesa area. Lineaments, especially where they intersect other structural features could be viable exploration targets.

Our understanding of mineral deposits has evolved over the years and new deposit types and better understanding of the geologic and chemical processes involved in forming mineral deposits has result in new interpretations and, hopefully, the discovery of new deposits. As central New Mexico has evolved through the Cenozoic, the nature of heat redistribution by ground-water advection also has been dynamic and resulted in the movement of fluids along these regional lineaments and other regional structural features that ultimately form various mineral deposits found in this area. The association of Fe oxides, Cu, U and other metals with these lineaments in the Chupadera Mesa area suggests that mineralizing fluids along with magmas have leaked along the lineaments and possibly could indicate additional, perhaps larger deposits, even Fe oxide-Cu-Au ±U (IOCG) deposits in the subsurface.

FUTURE WORK

One of the most important future research activities is the precise dating of the volcanic and plutonic rocks along the Capitan, Santa Rita, and Morenci lineaments to fully understand the temporal relationships and to better delineate the timing of igneous activity and associated mineralization and alteration. Better integration of the regional magnetic and gravity data also is required to identify areas where more local geophysical surveys are needed. Some areas need detailed geologic mapping to determine if the local structures also are related to the lineaments and to establish the framework for interpretations of temporal relationships. Fluid inclusion and isotopic studies are required to constrain temperatures of formation and other geochemical conditions of mineralization. Geochemical studies of igneous rocks, mineralization, and alteration will aid in a better understanding of the systematics of igneous intrusion and mineralization. Stable and radiometric isotope analyses are invaluable in differentiating between mantle and crustal sources. In addition, examination of the dextral separations in the crust north of the Chupadera Mesa area defined by Cather et al. (2006) needs to be evaluated.

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