Volcanic stratigraphy, geochemistry, and structure of the Steeple Rock district, Grant County, New Mexico, and Greenlee County, Arizona

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VOLCANIC STRATIGRAPHY, GEOCHEMISTRY, AND STRUCTURE OF THE STEEPLE ROCK DISTRICT, GRANT COUNTY, NEW MEXICO, AND GREENLEE COUNTY, ARIZONA

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Abstract—Rocks exposed in the Steeple Rock district consist of a sequence of Oligocene–Miocene (34–18? Ma) andesite, basaltic andesite, and dacitic lavas interbedded with sandstone, volcanic breccia, and rhyolitic ignimbrite. This sequence is locally intruded by intermediate–silicic plugs, dikes, and domes (33 and 28–18 Ma), some of which are associated with epithermal vein formation, brecciation, and faulting. The ignimbrites in the district are outflow sheets that were erupted from calderas in the Mogollon-Datil and Boot Heel volcanic fields. Extensional deformation of the volcanic rocks in the district produced a series of half-grabens and horsts with district-wide, northeastward dips of bedding planes and foliation. The stratigraphic nomenclature of two units in the area (Summit Mountain and Dark Thunder Canyon formations) is formalized in this report. The Summit Mountain Formation is approximately 240 m thick at the type locality and includes intrusive andesite and volcaniclastic sedimentary rocks, but the base of the unit is faulted. The Dark Thunder Canyon Formation consists of multiple gray to brown to purple to red porphyritic amygdaloidal andesitic to basaltic andesite lava flows with interbedded <28-Ma ignimbrites and volcaniclastic sandstones and is nearly 800 m thick at the type locality. Geochemical data suggest that pre-28-Ma (Summit Mountain and Bloodgood Canyon Tuff) and 28–20-Ma (Dark Thunder Canyon Formation and <28-Ma ignimbrites) volcanic rocks represent predominantly lithosphere-derived magmas, with increasing amounts of asthenosphere-derived magmas from 28–20 Ma.

INTRODUCTION

The Steeple Rock district in the Summit Mountains in Grant County, New Mexico, and Greenlee County, Arizona (Fig. 1) derived its name from a prominent mountain peak, Steeple Rock, in the southern part of the area. The district lies in a tectonically active and structurally complex area in southwestern New Mexico that is known for a variety of mineral deposit types (McLemore, *in press a*). Although the numerous maps and reports summarized below address the geology and mineralization of the district, none of them comprehensively describes the geology of the district. One purpose of this report is to summarize the geologic setting, stratigraphy, and structure of the district from prior studies. The second purpose of this report is to integrate new geochemical data and correlations of stratigraphic units from a Ph.D. dissertation (McLemore, 1993) with previous studies. A third purpose of this paper is to formalize the stratigraphic nomenclature of two units in the area (Summit Mountain and Dark Thunder Canyon formations). This paper is the second in a series of three articles describing the geology and mineral deposits of the district. Only brief descriptions of the mineral deposits (McLemore, 1996) and alteration (McLemore, *in press b*) in the Steeple Rock district are presented here (see Supplemental Road Log 2, this volume).

PREVIOUS WORK

Lindgren et al. (1910) first recognized that the deposits in the Steeple Rock district are epithermal mineral deposits. During World War II, the U.S. Geological Survey (USGS) and U.S. Bureau of Mines (USBM) examined the mineral deposits along the Carlisle fault and conducted surface and underground mapping, drilling, and sampling as part of the national strategic minerals evaluation (Johnson, 1943; Russell, 1947; Griggs and Wagner, 1966). These investigations failed to locate any additional base-metal orebodies based on the economics at that time. The fluorspar vein deposits were described by Trace (1947), Wilson (1950), Williams (1966), Rothrock et al. (1946), McAnulty (1978), and McLemore (1993). Hedlund (1990b) briefly summarized the mineral deposits in the Steeple Rock district. Sharp (1991) presented geochemical analyses of some igneous rocks in the district. Additional mineral-resource reports described some of the mineral deposits in the Steeple Rock district and adjacent areas (Gillerman, 1964; Richter and Lawrence, 1983; Wahl, 1980; Keith et al., 1983).

Geologic mapping of the area has been accomplished only in the last 40 yrs. Elston (1960) published a reconnaissance geologic map at a scale of 1:126,720 as part of the state geologic map compilation. Griggs and Wagner (1966) mapped the Carlisle and Center mines area. More recent mapping included several dissertations and theses that were completed as exploration for porphyry copper deposits intensified in southwestern New Mexico (Wargo, 1959; Biggerstaff, 1974; Powers, 1976; Wahl, 1980). In the late 1970s and early 1980s, geologic mapping of six quadrangles, in the Steeple Rock area, was completed as part of the Silver City CUSMAP project (Tillie Hall Peak, Crookson Peak, Applegate Mountain, Goat Camp Spring, Steeple Rock, Walker Canyon, and parts of Canador Peak and Nichols Canyon) (Hedlund, 1990a, c, d; 1993). McLemore (1993) mapped the entire district covered previously by Powers (1976), shown in Figure 2. Numerous unpub-

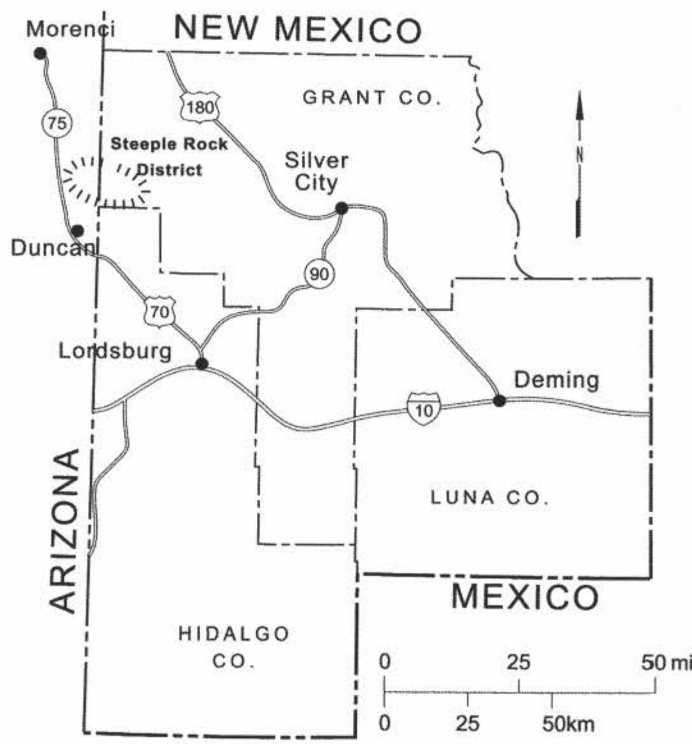

FIGURE 1. Location of Steeple Rock district, New Mexico and Arizona.

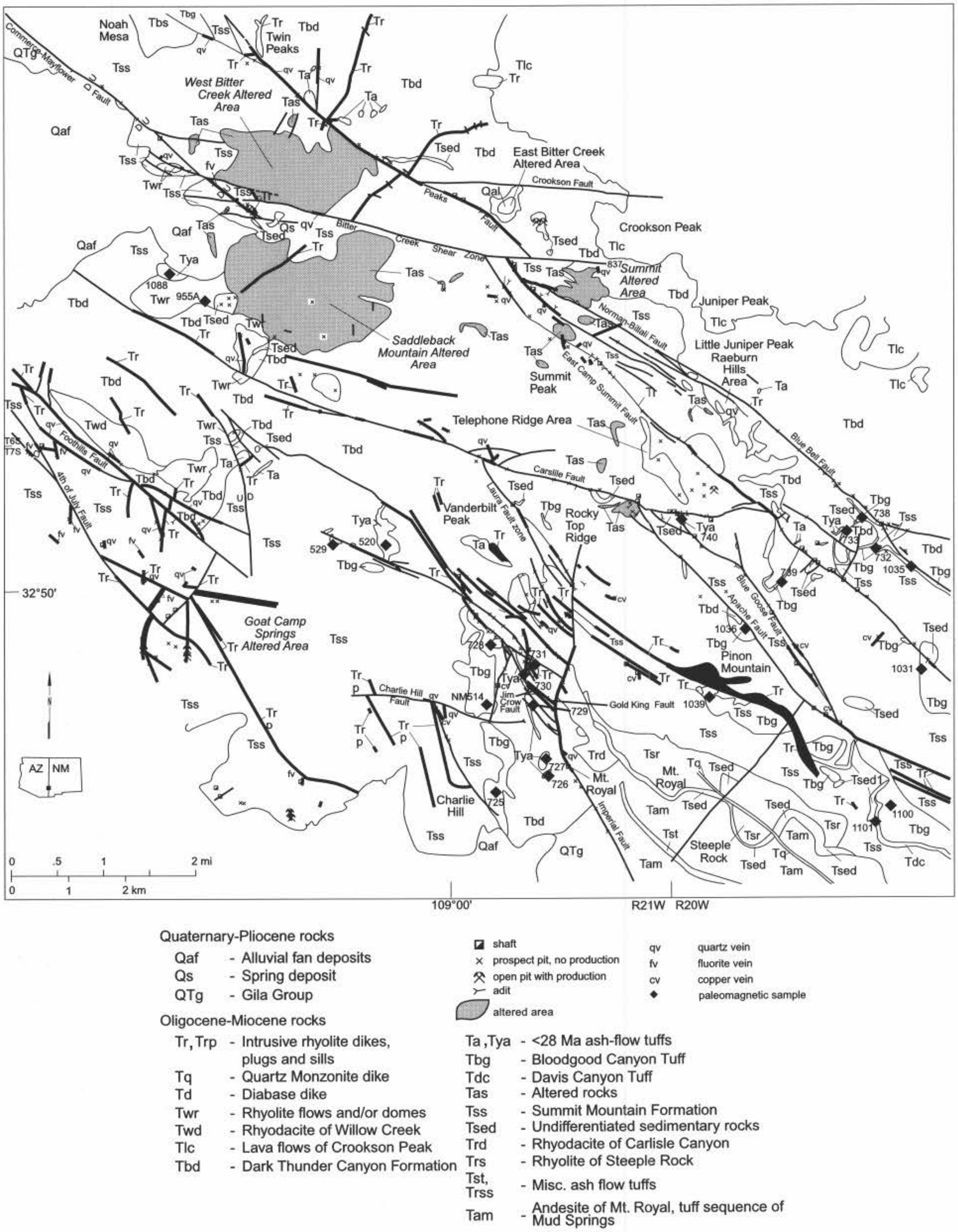

FIGURE 2. Generalized geologic map of the Steeple Rock district (from McLemore, 1993).

lished mine and exploration reports concerning the various mines and exploration projects in the Steeple Rock mining district were examined as part of this study. Many of these reports included geochemical data, production data, and mine maps. This information was synthesized and utilized whenever pertinent. The reports are on file at New Mexico Bureau of Mines and Mineral Resources (NMBMMR).

REGIONAL GEOLOGIC SETTING

Since Late Cretaceous time, the southwestern United States and northern Mexico have undergone almost constant tectonic and volcanic activity related to motions of the lithospheric plates off the coast of present-day California. Laramide contraction from Late Cretaceous–early Tertiary formed a series of northeast–northwest-trending uplifts and broad shallow basins in southern New Mexico and Arizona (Seager et al., 1986; Drewes, 1991). This deformation style persisted into the Miocene in the Steeple Rock district. Arc magmatism migrated eastward as subduction of the Farallon plate beneath North America continued (Coney and Reynolds, 1977; Dickinson, 1981) and resulted in intrusive and extrusive intermediate magmatism and formation of numerous Laramide porphyry copper deposits in Arizona and New Mexico; including Safford, Morenci, Santa Rita, Tyrone, and Copper Flat (Hillsboro).

Starting at 40–35 Ma and persisting until at least 18 Ma, extensive intermediate–silicic calc-alkaline volcanism and associated plutonism occurred throughout much of New Mexico and Arizona. The numerous widespread silicic calderas and andesitic–basaltic volcanic centers which erupted in this interval represent only part of a regional late Eocene–Oligocene volcanic province that extends from southern Colorado southward into the Sierra Madre Occidental of Mexico (McDowell and Claubaugh, 1979; McIntosh et al., 1992a, b). Within southwestern New Mexico and adjacent Arizona, the silicic caldera volcanism is informally divided into the Mogollon-Datil volcanic field to the north and the Boot Heel volcanic field to the south (Fig. 3). No formal dividing line between the two volcanic fields has been proposed, but most published maps suggest a boundary near I-10. Approximately 15 calderas have been identified in the Mogollon-Datil field and eight in the Boot Heel field, and regional ignimbrites linked to most of the calderas have been identified (Rattè at al, 1984; Elston, 1984; McIntosh et al., 1992a, b; McIntosh and Bryan, this volume). Caldera volcanism in these two volcanic fields occurred in two temporally distinct pulses: 36–32 Ma, and 29–24 Ma. The Steeple Rock district lies at the southwestern corner of the Mogollon-Datil volcanic field and is immediately north of the northern margin of the Boot Heel volcanic field. At least six ignimbrites crop out in the Steeple Rock district as outflow sheets and provide excellent, local stratigraphic markers (Fig. 4; McLemore, 1993; Appelt, 1993). However, there is no structural or lithologic evidence to support the presence of any calderas in the Steeple Rock district, contrary to earlier interpretations (Biggerstaff, 1974; Elston, 1978). As described below, ignimbrites in the Steeple Rock district are distal facies of ignimbrites erupted from both Mogollon-Datil and Boot Heel calderas; the Steeple Rock area is effectively a zone of overlap between the two informally defined volcanic fields.

Structures in the Steeple Rock district have been partially influenced by regional lineaments, including the Texas and Morenci lineaments. The structural trend in the district is predominantly northwest- to west-northwest (Figs. 2, 3), and is subparallel to the west-northwest-trending Texas lineament (Fig. 4) of Wertz (1970a, b), Lowell (1974), Chapin et al. (1978), and Muehlberger (1980). The Steeple Rock district also lies on the northwestern edge of the Burro uplift that forms the northern margin of the Texas lineament. Regional structural features of this type appear to control the emplacement of many intrusive and volcanic centers in New Mexico and Arizona (Lowell, 1974; Chapin et al., 1978).

The Texas lineament (Fig. 3) extends from Trans-Pecos Texas west-northwestward into southeastern Arizona where it probably joins the Arizona transitional zone (Muehlberger, 1980; Wertz, 1970a, b). It is a prominent 80–150-km-wide zone that is defined by basins, ranges, and structural features (Lowell, 1974; Wertz, 1970a, b; Turner, 1962; Schmitt, 1966; Drewes, 1991). Dip-slip (normal, steep reverse or thrust) movements are common throughout this zone and locally strike-slip movement has been documented (Turner, 1962; Wertz, 1970a, b; Muehlberger, 1980; McLemore, 1993).

The northeast-trending Morenci lineament of Chapin et al. (1978) lies immediately north of the district (Fig. 3). The Morenci lineament can be traced from Safford, Arizona, northeastward to Datil, New Mexico and includes the Safford and Morenci porphyry copper deposits. The epithermal silver-gold deposits of the Mogollon district lie on the southern edge of the Morenci lineament (Lowell, 1974; Chapin et al., 1978). The lineament also includes the Morenci uplift (Cather and Johnson, 1986; Cather, 1999).

A third potential, less-accepted, lineament is positioned south of the Steeple Rock district and is known as the New Mexico mineral belt (Lowell, 1974) or the Santa Rita lineament (Chapin et al., 1978). This lineament extends from Cananea in Sonora, Mexico northeastward to Santa Rita, New Mexico, and includes the Cananea, Bisbee, Santa Rita, and Tyrone porphyry copper deposits and numerous smaller epithermal districts (Lowell, 1974). It may continue to the northeast through the Kingston and Hillsboro districts in Sierra County, New Mexico (Fig. 3; Rose and Baltosser, 1966; McLemore et al., 1999). This lineament is defined by Laramide intrusions and northeast-trending faults (Rose and Baltosser, 1966) and is subparallel to the Morenci lineament.

METHODS OF STUDY

Approximately 171 km^2 were mapped in detail at a scale of approxi-

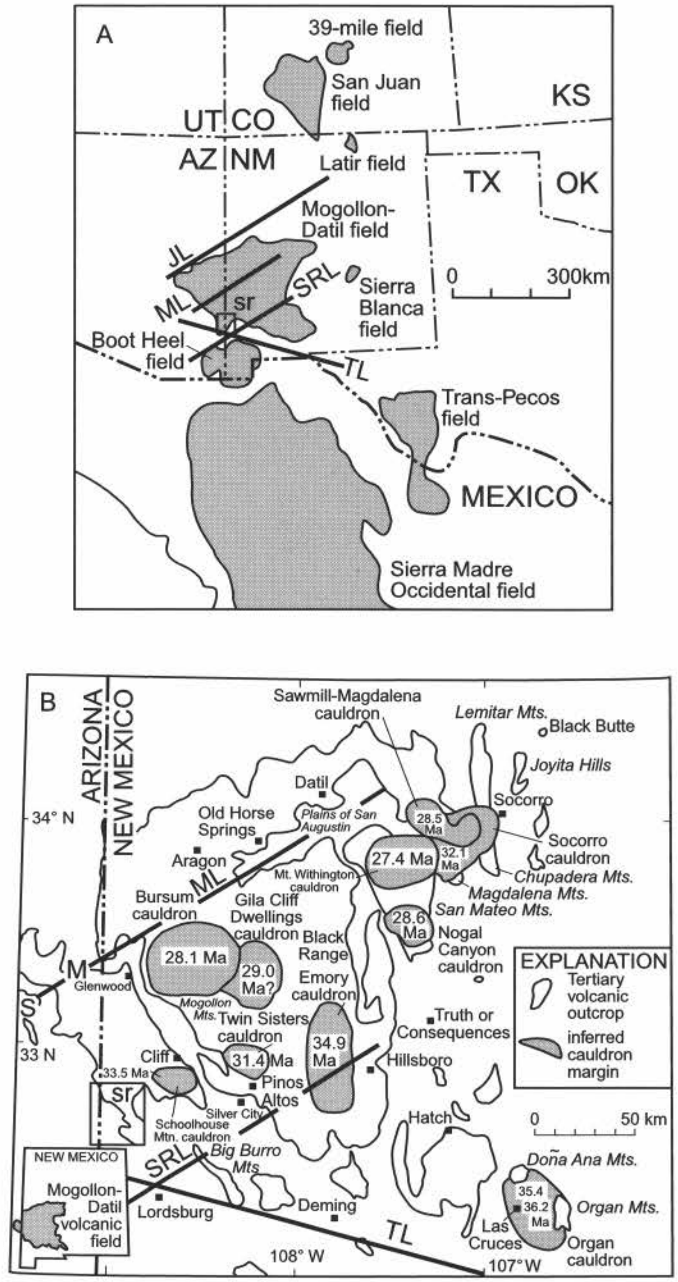

FIGURE 3. Index maps showing volcanic fields of the Mogollon-Datil volcanic field in New Mexico and adjacent areas. **A**, Regional map, **B**, detailed map of the Mogollon-Datil volcanic field. JL—Jemez lineament, ML—Morenci lineament, SRL—Santa Rita lineament, TL—Texas lineament, M—Morenci porphyry copper deposit, S—Safford porphyry copper deposit. Small box (sr) represents approximate location of the Steeple Rock mining district. Modified from McIntosh et al. (1990, 1991) and Chapin et al. (1978).

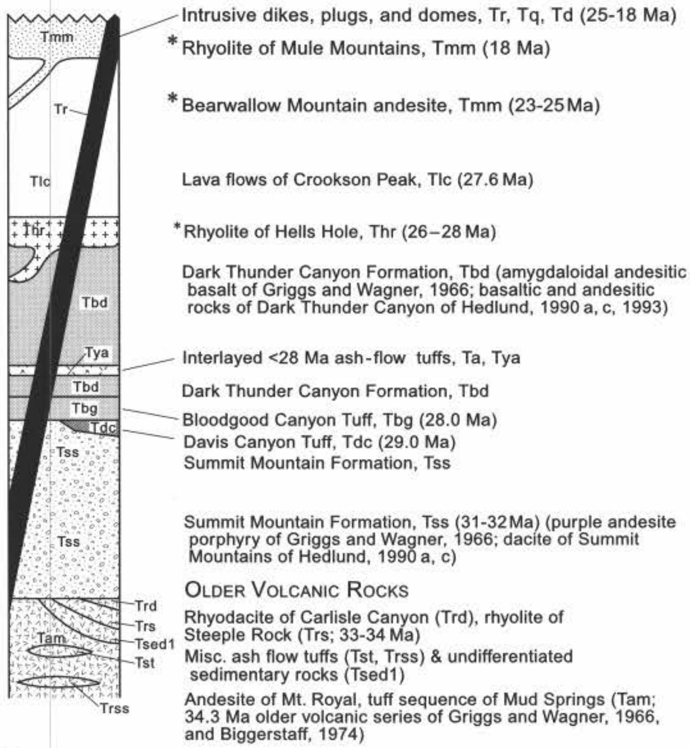

FIGURE 4. Generalized stratigraphy of the Steeple Rock district (modified after Hedlund, 1990a, c, d, 1993). See McLemore (1993) for compilation of age dates. * Rocks not exposed in Steeple Rock district. See Table 2 for references on age determinations.

mately 1:12,000 and compiled at a map scale of 1:24,000 (Fig. 2; McLemore, 1993) using standard USGS 7½-minute topographic quadrangle maps (Goat Camp Springs, Steeple Rock, Crookson Peak, and Tillie Hall Peak). In addition, the eastern portion of the area was mapped at a scale of 1:4800, using topographic base maps provided by Nova Gold Resources, Ltd. and transferred to 1:24,000 maps.

Major element compositions of altered and unaltered country rock were determined by X-ray fluorescence spectrometry (XRF) using fused glass discs following the method of Norrish and Hutton (1969) on a Rigaku SYN 3064 model at standard operating conditions. USGS rock standards were used to calibrate the instrument. Some major element compositions also were determined by XRF using the fundamental parameters program of Criss Software (Criss, 1980). Trace elements were determined by XRF using pressed-powder briquettes (Obenauf and Bostwick, 1988). Specific geochemical analyses and estimates of accuracy and precision are in McLemore (1993).

Paleomagnetic studies and limited $^{40}Ar/^{39}Ar$ dating have been performed to address the ignimbrite correlation question, in the Steeple Rock area. The paleomagnetic work is described below. $^{40}Ar/^{39}Ar$ dating has been limited in the Steeple Rock district by the advanced degree of alteration and consequent paucity of datable sanidine. $^{40}Ar/^{39}Ar$ results from four samples in or near the Steeple Rock district are detailed in McIntosh et al. (1992a, b) and McIntosh and Bryan (this volume), and are discussed in this paper.

Paleomagnetic studies in the Steeple Rock district include analyses of 236 oriented samples that were field drilled from 37 sites (Table 1). Sample locations are in Figure 2 and detailed in McLemore (1993). Sample and analytical procedures are similar to those detailed in McIntosh (1991) and McIntosh et al. (1991), where results from five of the 35 Steeple Rock area sites were previously reported. Samples were drilled in the field in situ using portable rock drills. Sun and magnetic compasses were used to orient samples. The orientation of the paleohorizontal was determined at each site using attitudes of pumice foliations, welding zones, and bedding contacts. Remanent magnetizations were measured using spinner and cryogenic magnetizations according to standard techniques described by McIntosh (1991). Demagnetization paths were analyzed using Zijderveld plots and principle component analyses to determine paths of univectoral decay. Mean directions alpha-95 confidence circles for each site were calculated from PCA or blanket AF demagnetization data using Fisher statistics (Fisher, 1953; Kirschvink, 1980; Zijderveld, 1967). Data from four sites with alpha-95 $\geq 10°$ were considered unacceptable and are excluded from interpretations discussed below. For more details concerning the use of paleomagnetic data in silicic volcanic fields, the reader is referred to McIntosh (1991).

PALEOMAGNETIC RESULTS AND IGNIMBRITE CORRELATION

Paleomagnetic results, combined with $^{40}Ar/^{39}Ar$ geochronology, mapping, and lithologic data, help to determine how ignimbrites exposed in the Steeple Rock district fit into established time-stratigraphic frameworks for the adjacent Mogollon-Datil and Boot Heel volcanic fields. As described below, one group of ignimbrites occurs low in the sequence and a second group of ignimbrites occurs higher in the section, near the contact of the Summit Mountain and Dark Thunder Canyon formations. Within each group, and especially within the younger group, individual ignimbrites are difficult to correlate because of similarities in appearance and composition and, in some cases, because of hydrothermal alteration and poor exposure.

Ignimbrites provide excellent time-stratigraphic markers throughout the Mogollon-Datil volcanic field (McIntosh et al., 1992a, b) and the Boot Heel volcanic field (McIntosh and Bryan, this volume). Some of these ignimbrites extend as far as 140 km from their source calderas and provide excellent regional stratigraphic markers. However, regional correlations of many ignimbrites are complicated by Basin-and-Range extension. In addition, lithologic and geochemical similarities between different ignimbrites hamper regional correlations (Hildreth and Mahood, 1985; Bornhorst, 1980, 1986, 1988). Precise $^{40}Ar/^{39}Ar$ ages from sanidine-bearing ignimbrites have contributed greatly to regional correlation of ignimbrite outflow sheets in the silicic volcanic fields in the southwestern U.S. and elsewhere (McIntosh et al., 1991, 1992a; McIntosh and Bryan, this volume). Paleomagnetic studies have also proven to be useful for correlating ignimbrites, especially where used in conjunction with detailed mapping and $^{40}Ar/^{39}Ar$ dating. Paleomagnetic correlation takes advantage of reversals and secular variations of the magnetic field, which can provide distinctive remanence directions for rapidly cooled regional ignimbrites. Because paleomagnetic remanence in ignimbrites is often carried, in part, by chemically stable hematite (McIntosh, 1991), the technique can be applied to some altered ignimbrites, which are common in the Steeple Rock district.

Combined mapping, paleomagnetic work, and limited $^{40}Ar/^{39}Ar$ results suggest that most Steeple Rock ignimbrites are distal facies of regional ignimbrites erupted from calderas 20–120 km to the northeast and south in the Mogollon-Datil and Boot Heel volcanic fields. As detailed in Figures 5 and 6 and Table 1, two of the ignimbrites near the base of the Steeple Rock sequence are interpreted as distal facies of two regional ignimbrites erupted in the Boot Heel field. The ignimbrite mapped as Tst has a normal paleomagnetic direction with a distinctive declination of about 40° (Fig. 5a, site 512). This paleomagnetic direction and an a $^{40}Ar/^{39}Ar$ age of 34.30 ± 0.18 Ma strongly indicate correlation with the 34.4-Ma tuff of Steins from the Steins caldera 35 km to the south. Another of the older Steeple Rock district ignimbrites (mapped as Trss) has a paleomagnetic direction similar to that of the 34.4-Ma Oak Creek Tuff from the Boot Heel field (Fig. 5a, site 513). Although Trss was not dated, it is stratigraphically and lithologically similar to two ignimbrites exposed just east of the eastern boundary of the Steeple Rock district (mapped as Ttm6 and Ttm8 by Hedlund (1990a). $^{40}Ar/^{39}Ar$ and paleomagnetic data from these units suggest that both may represent cooling units of the 34.4-Ma Oak Creek Tuff. Alternatively, eruption of one or both of these units from the similar age, but poorly understood Schoolhouse Mountain caldera in the Cliff area is also a possibility (McIntosh, 1991; McLemore, this volume, p. 245).

Table 1. Paleomagnetic data from Steeple Rock area ignimbrites.

Lab No.	Field No.	Unit	n	Demag	Inc	Dec	K	a95	Ref
Older (>32 Ma) ignimbrites									
nm512	nm512	Tst	8	50 mT	50.8	26.7	140.5	4.7	1
nm513	nm513	Toc	8	30 mT	-62.1	159.9	180.6	4.1	1
nm691	nm691	Toc	8	40 mT	-60.6	148.6	756.0	2.0	2
nm692	nm692	Toc	8	30 mT	-51.4	167.5	227.6	3.7	2
nm690	nm690	Tdp	8	10 mT	-52.0	189.4	1416.3	1.5	2
Davis Canyon Tuff (29.0 Ma)									
nm267	nm267	Tdc	8	0 mT	-53.9	166.2	104.3	5.5	1
nm689	nm689	Tdc	8	20 mT	-55.5	167.1	198.8	3.9	2
nm988	1101	Tdc?	4	PCA	-54.8	10.8	123.6	#8.3	3
Bloodgood Canyon Tuff (28.1 Ma)									
nm266	nm266	Tbg	6	30 mT	-28.5	180.2	283.5	4.0	1
nm514	nm514	Tbg	5	30 mT	-36.0	172.0	151.6	6.2	1
nm685	529	Tbg	9	20 mT	-24.3	169.6	522.3	2.3	3
nm856	725	Tbg	8	40 mT	-25.2	170.2	234.6	3.6	3
nm864	732	Tbg	8	40 mT	32.6	148.4	88.4	#5.9	3
nm867	738	Tbg	7	20 mT	-8.9	162.2	1075.1	1.8	3
nm868	739	Tbg	8	40 mT	-39.7	165.3	2170.0	1.2	3
nm976	1031	Tbg	5	PCA	-33.6	170.1	95.4	7.9	3
nm977	1031	Tbg	5	PCA	-43.2	177.2	132.7	6.7	3
nm978	1035	Tbg	3	PCA	-11.3	152.3	303.3	7.1	3
nm979	1036	Tbg	6	PCA	-11.8	168.1	70.6	8.0	3
nm980	1039	Tbg	6	PCA	-21.7	164.4	501.8	3.0	3
nm987	1100	Tbg	8	PCA	-15.7	185.5	26.2	*11.0	3
Younger (<28 Ma) ignimbrites									
nm686	520	Tya	6	0 mT	62.3	350.6	65.1	8.4	3
nm990	nm990	Tya	8	PCA	64.6	61.9	39.1	#9.0	3
nm858	727	Tya1	8	20 mT	51.3	342.6	299.7	3.2	3
nm863	731	Tya1	8	50 mT	66.0	358.5	155.4	4.5	3
nm865	733	Tya1	8	10 mT	57.0	336.3	149.4	4.6	3
nm984	1088	Tya1	7	PCA	58.1	329.0	28.3	*11.5	3
nm989	nm989	Tya1	8	PCA	66.7	307.8	51.2	#7.8	3
nm857	726	Tya2	6	PCA	74.4	356.9	503.5	3.0	3
nm861	729	Tya3	5	PCA	50.7	16.7	112.4	7.3	3
nm862	730	Tya3	8	PCA	62.2	26.9	49.5	8.0	3
nm869	740	Tya3	7	PCA	44.6	16.9	116.8	5.6	3
nm859	728	Tya?	3	PCA	76.2	259.4	124.0	*11.1	3
nm985	955A	Twr	3	PCA	8.7	338.9	139.5	*10.5	3
nm982	1084	Ta	5	PCA	16.9	7.0	71.1	#9.1	3
Unit mean directions									
mean direction		Tst	8		57.7	36.2	140.5	6.6	2
mean direction		Toc	8		-54.7	161.8	180.6	7.8	2
mean direction		Tdc	8		-53.9	159.6	198.8	7.5	4
mean direction		Tbg	7		-27.1	165.3	1075.1	3.1	4
mean direction		Trc	5		58.0	349.0	80.0	5.0	2
mean direction		Tpk	10		62.8	349.5	29.0	9.1	2
mean direction		Thc	17		48.0	17.7	8.0	13.5	2

Notes: n is number of samples, demag is demagnetization level or PCA (principal component analysis) used for calculation of site mean directions, inc and dec are site mean inclination and declination, K is Fisher's (1953) precision parameter, a_{95} is radius of cone of 95% confidence. * denotes data rejected because $a_{95} \geq 10°$, # denotes anomalous site-mean directions. Unit symbols are explained in Figure 4. Field number refers to location in Figure 2 and McLemore, 1993 (map 1). References: (1) McIntosh et al., 1991, (2) McIntosh and Bryan, this volume, (3) McLemore, 1993, (4) McIntosh et al., 1992 b.

Paleomagnetic data and a single $^{40}Ar/^{39}Ar$ age suggest that the group of ignimbrites near the contact of the Summit Mountain and Dark Thunder Canyon formations represent outflow facies of calderas from both the Mogollon-Datil and Boot Heel volcanic field. Steep, reversed paleomagnetic directions (Fig. 5b) help to identify outcrops of the 29.0-Ma Davis Canyon Tuff, and distinctively shallow, reversed paleomagnetic directions (Fig. 5c) are characteristic of the 28.0-Ma Bloodgood Canyon Tuff. Both are large-volume ignimbrites erupted from caldera in the southern Mogollon-Datil volcanic field (Ratté et al; 1984; McIntosh et al., 1992a, b). One Davis Canyon Tuff site gives an anomalous upward, northerly direction (Fig. 5b, site 988), and Bloodgood Canyon Tuff sites give somewhat scattered results relative to the well-defined unit mean direction (Fig. 5c). Both of these discrepancies may reflect effects of alteration on the paleomagnetic remanence.

Normal paleomagnetic directions (Fig. 5d) from the youngest Steeple Rock district ignimbrites indicate that most represent distal facies of and one or more units from a closely spaced sequence of three regional ignimbrites erupted from the Boot Heel field: the 27.60-Ma tuff of Horseshoe Canyon, the 27.4-Ma Park Tuff, and the 27.0-Ma tuff of Rhyolite Canyon) (McIntosh and Bryan, this volume). The paleomagnetic directions of these three normal-polarity Boot Heel ignimbrites are too similar to allow unambiguous one-to-one correlation with individual sites in the youngest Steeple Rock area ignimbrites. The normal polarity of the youngest Steeple Rock area sites, though, is sufficient to rule out correlation with the lithologically similar reversed-polarity Bloodgood Canyon Tuff.

STRATIGRAPHY

Rocks exposed in the Steeple Rock district consist of a complex sequence of Oligocene–Miocene (34–18? Ma) andesitic, basaltic andesitic, and dacitic lavas interbedded with andesitic to dacitic tuff, sandstone, volcanic breccia, and rhyolite ignimbrite (Figs. 2, 4). The district is highly fractured and faulted; stratigraphic relations are only partially preserved. The oldest volcanic rocks crop out in the southernmost portion of the district, and rock units generally decrease in age to

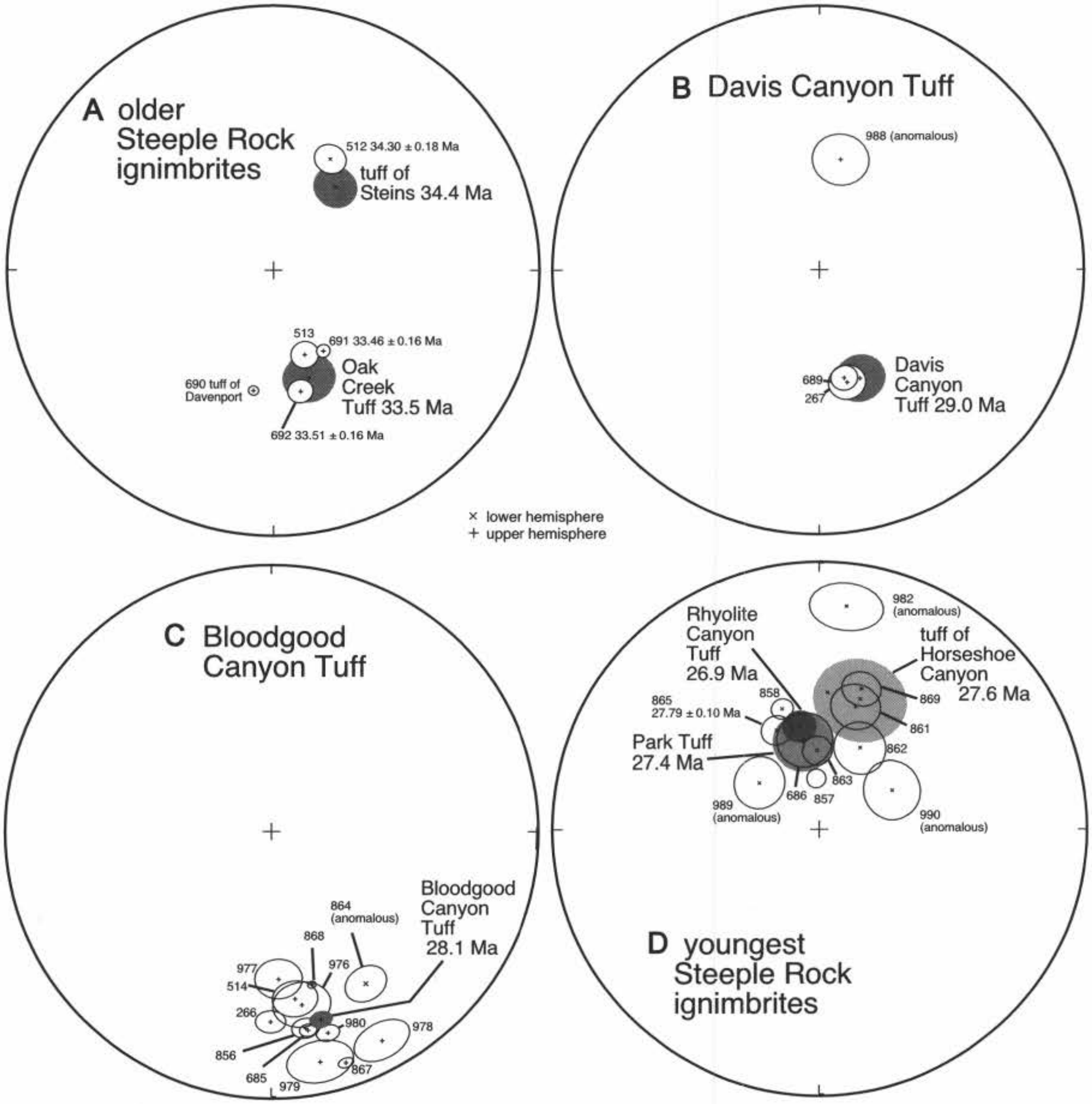

FIGURE 5. Stereographic projections of paleomagnetic data from the Steeple Rock area. Sample numbers refer to Table 1. **A**, Older ignimbrites. Paleomagnetic direction and $^{40}Ar/^{39}Ar$ of site 512 support correlation with 34.4-Ma tuff of Steins. Directions and $^{40}Ar/^{39}Ar$ ages of sites 513, 692, and 692 support correlation with 33.5-Ma Oak Creek Tuff. Site 690 in the lithologically distinct tuff of Davenport has reversed polarity, but has not been correlated with any regional ignimbrite. Shaded ellipses in this and other figures represent unit-mean paleomagnetic directions. **B**, Davis Canyon Tuff. Paleomagnetic directions of sites 267 and 689 support correlation with 29.0-Ma Davis Canyon Tuff. Site 968 has an anomalous northerly, upward remanence direction, possibly a consequence of alteration. **C**, Bloodgood Canyon Tuff. Shallow-inclination, reversed-polarity paleomagnetic directions support correlation of several Steeple Rock sites with 28.1-Ma Bloodgood Canyon Tuff. Scatter relative to the Bloodgood Canyon mean direction may reflect inaccuracies in measurement of paleohorizontal. Site 968 has an anomalous southerly, downward remanence direction, possibly due to alteration. **D**, Younger ignimbrites. Normal paleomagnetic directions of the youngest Steeple tuffs demonstrate that they are distinct from Bloodgood Canyon Tuff, and probably represent distal facies of one or more of the three youngest regional ignimbrites from the Boot Heel volcanic field, although the paleomagnetic data are insufficient to establish confident one-to-one correlations. Site 692, 989, and 990 have somewhat anomalous directions, possible due to inaccuracies in measurement of paleohorizontal. The $^{40}Ar/^{39}Ar$ age of site 865 supports correlation with either 27.4-Ma Park Tuff or 27.6-Ma tuff of Horseshoe Canyon.

the north and northeast (Fig. 2; Hedlund, 1990a, c, d, 1993; Ratté and Hedlund, 1981; Biggerstaff, 1974; McLemore, 1993). After emplacement, the volcanic rocks were subsequently intruded by rhyolite plugs, dikes, and domes during two separate periods (33 and 28–18? Ma). Many of the lithologic units in the area have not been previously formalized. Two units are formalized in this report, based on McLemore (1993); in other cases informal names are used.

Older volcanic rocks

The oldest volcanic rocks exposed in the Steeple Rock district are about 34 Ma old (Hedlund, 1990a, c). Biggerstaff (1974) called these rocks the Steeple Rock group, whereas Hedlund (1990a) referred to them as a series of andesites, rhyolites, and tuffs with specific informal names (e.g., andesite of Mt. Royal, tuff sequence of Mud Springs). These older flows vary in thickness. Several ignimbrites interlayered with the andesite of Mt. Royal and tuff sequence of Mud Springs crop out south of Steeple Rock. Two of these are correlated to the Oak Creek Tuff and tuff of Steins that were erupted from the Boot Heel volcanic field (Figs. 3, 6; Hedlund, 1990a; McIntosh and Bryan, this volume). In the Steeple Rock area, these two ignimbrites are <50 m thick and contain lithic fragments of andesite and andesite porphyry. Rhyolite of Steeple Rock (Steeple Rock flow of Biggerstaff, 1974) is a prominent,

MOGOLLON MOUNTAINS	STEEPLE ROCK DISTRICT, SUMMIT MOUNTAINS	BOOTHEEL FIELD
	Dome related tuffs (Tya3; 25.3 Ma)	
	<28 Ma tuffs (Tya1, Tya2)	Rhyolite Canyon Tuff (27.0 Ma)
		Park Tuff (27.4 Ma)
		tuff of Horseshoe Canyon (27.6 Ma)
Bloodgood Canyon Tuff (28.0 Ma)	Bloodgood Canyon Tuff	
Shelley Peak Tuff (28.1 Ma)		
Vicks Peak Tuff (28.6 Ma)		
Davis Canyon Tuff (29.0 Ma)	Davis Canyon Tuff	
Fall Canyon Tuff (31.7 Ma)	rhyolite of Steeple Rock and miscellaneous tuffs (Trs, Trst, Trss; 33-34 Ma)	Gillespie Tuff (32.7 Ma)
Cooney Tuff (34 Ma)		tuff of Bill Black Canyon (33.5 Ma)
		Oak Creek Tuff (34.4 Ma)
		tuff of Steins (34.4 Ma)

FIGURE 6. Stratigraphic correlations of ignimbrites in the Steeple Rock district with those in the Mogollon Mountains and the Boot Heel in Hidalgo County (Appelt, 1993; McIntosh et al., 1990, 1991; Bryan, 1995).

massive rhyolite flow or dome up to 61 m thick that covers much of the Mt. Royal and Steeple Rock areas (Hedlund, 1990a; McLemore, 1993) and unconformably overlies older sedimentary rocks and the andesite of Mt. Royal. It is unconformably overlain by the Summit Mountain Formation and is ~33 Ma (K/Ar, Hedlund, 1990a).

Summit Mountain Formation (new nomenclature)

The Summit Mountain Formation consists of lava flows, breccias, intrusions, and volcaniclastic sedimentary rocks. Griggs and Wagner (1966) and Biggerstaff (1974) referred to this unit as the purple andesite porphyry. Hedlund (1990a, c, d, 1993) designated this unit as the dacite or dacite porphyry of Summit Mountain. Intrusive andesite of the Summit Mountain Formation crops out near the Hext mine, which may be a vent. Alteration of this unit is extensive; unaltered outcrops are rare. In addition, this unit is highly faulted and nowhere is there a complete unfaulted section exposed.

The Summit Mountain Formation is named after Summit Mountain or Peak in the northern part of the area. The proposed type locality of this unit extends from the Hext Windmill in sec. 20, T17S, R21W to the Bloodgood Canyon Tuff outcrop southeast of the New Seep windmill in sec. 21, T17S, R21W (McLemore, 1993). It is approximately 240 m thick in this area and includes intrusive andesite and volcaniclastic sedimentary rocks, but the base of the unit is faulted. A second reference locality for this unit is along the southern slope of Summit Mountain, in sec. 35, T6S, R21W, where the unit is 370 m thick; but neither the intrusive andesite nor the volcaniclastic sedimentary rocks are exposed at this locality. The base of the unit is covered at Summit Mountain and the top is eroded. The unit unconformably overlies the andesite of Mount Royal and the rhyolite of Steeple Rock. The Summit Mountain Formation is overlain by Bloodgood Canyon Tuff, <28-Ma ignimbrites, or Dark Thunder Canyon Formation. The age of the Summit Mountain Formation is ~31 Ma (K/Ar, Hedlund, 1993).

Total thickness of this unit is uncertain because of faulting, but probably exceeds 760 m near Summit Peak. Griggs and Wagner (1966) report a minimum thickness of 457 m. Biggerstaff (1974) reports a minimum thickness of 700 m based on drilling east of Twin Peaks, whereas Hedlund (1990a) reports a thickness of 610 m. Drill holes along the East Camp-Summit and Norman King-Billali faults are as much as 518 m deep and remain within the Summit Mountain Formation. The Bitter Creek #1 drill hole is 762 m deep and remains in andesite, presumably of the Summit Mountain Formation, although the bottom of the hole may actually be in older andesites of Mount Royal or Mud Springs Peak, which are similar in appearance and composition to the Summit Mountain Formation (McLemore, 1993).

Davis Canyon Tuff

The Davis Canyon Tuff is an outflow sheet erupted from the Bursum caldera complex in the Mogollon Mountains northeast of the study area (Ratté et al., 1984; Hedlund, 1990a). It crops out in the Summit Mountains east of Steeple Rock (Fig. 2); the Steeple Rock district is its southwestern extent (McIntosh et al., 1991; McLemore, 1993). The tuff is a light gray to tan to white, locally welded, devitrified, ignimbrite that is crystal poor and characterized by coarse stringy white to gray to brown pumice several millimeters long (Ratté et al., 1984; Hedlund, 1990a). The ignimbrite commonly contains <5% small phenocrysts (<3 mm long) of sanidine, plagioclase, quartz, and biotite with accessory titanite. Lithic fragments of andesite are common (up to several centimeters in diameter). The Davis Canyon Tuff in the Steeple Rock district unconformably overlies volcaniclastic sandstone or andesite of the Summit Mountain Formation and it is unconformably overlain by the Bloodgood Canyon Tuff.

Bloodgood Canyon Tuff

The Bloodgood Canyon Tuff in the Steeple Rock district is a light-gray–white, typically welded, devitrified ash-flow tuff, which contains of 10–20% phenocrysts of sanidine, quartz, and accessory titanite, biotite, hornblende, and iron oxides. Distinctive characteristics include round "eyes" of sanidine and bipyramidal quartz (Ratté et al., 1984; Hedlund, 1990a, c, d, 1993). The ignimbrite was mapped as Noah Mesa Tuff by Wahl (1980) and younger ignimbrite units were mapped incorrectly as Bloodgood Canyon Tuff by Hedlund (1990a, c, d, 1993). Paleomagnetic studies readily differentiate reversed polarity Bloodgood outcrops from normal polarity <28-Ma ignimbrites. Bloodgood Canyon Tuff, probably one of the most widespread ignimbrites in the Mogollon-Datil volcanic field, extends from the Bursum caldera northward to Aragon, as far south as a few kilometers south of Steeple Rock, as far west as Clifton, and as far east as Beaverhead (McIntosh et al., 1990, 1991). The age of the unit has been determined by high-precision $^{40}Ar/^{39}Ar$ dating as 28.05 ± 0.01 Ma (McIntosh et al., 1990, 1991).

<28-Ma ignimbrites

Several ignimbrites are interbedded within the lower portion of the Dark Thunder Canyon Formation, although locally they may also lie unconformably on Summit Mountain Formation (Fig. 2; McLemore, 1993). The ignimbrites are lighter in color than the andesites, from various shades of yellow, gray, brown–white, and contain essential quartz, sanidine, and biotite phenocrysts in a groundmass of pumice, quartz, and feldspar. Some are lithic-rich and crystal-poor; lithic fragments, typically andesite and andesite porphyry, are common and range in size from microscopic to 0.8 m in diameter. These ignimbrites can be distinguished from one another and from the Bloodgood Canyon Tuff primarily by paleomagnetic analyses; they typically have a normal paleomagnetic direction as opposed to the reversed, shallow inclination paleomagnetic direction characteristic of the Bloodgood Canyon Tuff. Paleomagnetic evidence suggests that several ignimbrite units were emplaced within a short time period. One ignimbrite has an age of 27.79 ± 0.10 Ma ($^{40}Ar/^{39}Ar$, #733, McLemore, 1993). One or more of these tuffs may correlate with the tuff of Horseshoe Canyon (27.4 Ma), Park Tuff (27.4 Ma), or the tuff of Rhyolite Canyon (27.0 Ma) that are found in the Boot Heel volcanic field in Hidalgo County (Fig. 6; McIntosh and Bryan, this volume). The thickness of individual tuffs varies from 0 to 30 m. Welding varies from nonwelded to densely welded. These ignimbrites commonly form ridges and hill tops. Volcanic-epithermal veins cut some ignimbrite units in the Steeple Rock district.

Dark Thunder Canyon Formation (new nomenclature)

The Dark Thunder Canyon Formation (basaltic and andesitic rocks of Dark Thunder Canyon of Hedlund, 1990a, c, 1993) consists of multiple gray to brown to purple to red porphyritic amygdaloidal andesitic to basaltic andesitic lava flows with interbedded <28-Ma ignimbrites and volcaniclastic sandstone (Griggs and Wagner, 1966; Biggerstaff; 1974). Griggs and Wagner (1966) called this unit the amygdaloidal andesitic basalt, whereas Biggerstaff (1974) called it andesitic basalt. The unit is 27–28 Ma in age, because it unconformably overlies the Bloodgood Canyon Tuff (28 Ma) and is overlain by the lava flows of Crookson Peak.

The type locality of the Dark Thunder Canyon Formation is north of the Steeple Rock district in Dark Thunder Canyon in secs. 34, 33, T15S, R20W and sec. 4, T16S, R20W, where it is nearly 800 m thick (McLemore, 1993). The base is not exposed at Dark Thunder Canyon. The unit is unconformably overlain by lava flows of Crookson Peak and it unconformably overlies <28-Ma ignimbrites, Bloodgood Canyon Tuff, or Summit Mountain Formation. Individual lava flows are typically uniform in composition and range up to 15 m thick.

In thin section, the lavas are fine–medium grained, hypocrystalline (original glass content probably as much as 15%), trachytic, porphyritic, and locally seriate. The flows typically consist of plagioclase (Hedlund, 1990a, c, 1993), magnetite, hornblende, pyroxene, and biotite. Local accessory minerals include apatite, zircon, and titanite. The unit is characterized by abundant vesicles or amygdules, typically filled with quartz, calcite, and thomsonite (Biggerstaff, 1974). Lithic fragments of andesite and andesite porphyry up to 0.8 m in diameter are common.

Lava flows of Crookson Peak

The dacitic to andesitic lava flows of Crookson Peak [the brown andesite porphyry unit of Biggerstaff (1974) and Griggs and Wagner (1966)] form prominent southwest-facing cliffs on the eastern border of the Steeple Rock district from Apache Box southward to Crookson and Juniper Peaks (Fig. 2). Maximum thickness is approximately 460 m (Hedlund, 1990b, c). Lavas within this unit contain 10–20% oligoclase to andesine phenocrysts, locally glomeroporphyrtic, in a felted to pilotaxitic groundmass with disseminated iron oxides and clinopyroxene granules. A K/Ar date of 27.6 Ma was reported for the lava flows of Crookson Peak (Hedlund, 1990c).

Intrusive rocks

Numerous dikes, plugs, and domes occur throughout the Steeple Rock district (Fig. 2). Compositions include diabase dikes, quartz-monzonite dikes, and rhyolite and rhyodacite dikes, plugs, and domes (including Apache Box, Vanderbilt Peak, Piñon Mountains, and Twin Peaks rhyolites, McLemore, 1993). The diabase dikes are green–greenish-gray, fine–medium grained with a trachytic texture of white plagioclase needles in a fine-grained, chloritized matrix. The quartz-monzonite dike is medium–coarse grained, porphyritic–glomerophyritic, and holocrystalline and contains quartz, plagioclase, K-feldspar, and several trace minerals. The rhyolites and rhyodacites are fine grained, pink to red to white to gray, foliated to flow-banded, aphanitic to slightly porphyritic.

Most intrusive rocks appear to be fault controlled. Some rhyolite dikes, domes, and plugs are cut by faults and younger rhyolite intrusions and many are emplaced along faults (Fig. 2). The Apache Box rhyolite complex north of the Steeple Rock district consists of a series of rhyolite plugs and dikes, that have intruded the Dark Thunder Canyon Formation and the lava flows of Crookson Peak (Hedlund, 1990c; Ratté and Hedlund, 1981). Numerous rhyolite dikes, probably from the same source (Biggerstaff, 1974), extend southward from Vanderbilt Peak where they become part of the Piñon Mountains rhyolite plug and form dike swarms around Vanderbilt Peak. Ignimbrites and volcanic breccia deposits surround some of the plugs, indicating that the plugs breached the surface, producing small, local pyroclastic deposits. In the Piñon Mountains, a large rhyolite plug intruded the Summit Mountain Formation and Bloodgood Canyon Tuff.

Although the ages of many of the intrusive rocks are uncertain, most are younger than 27 Ma because they intrude rocks of that age. A vitrophyre from a rhyolite dome near Saddleback Mountain in the district is 25.3 ± 0.10 Ma ($^{40}Ar/^{39}Ar$, Table 2). The quartz-monzonite dike is 21.4 ± 1.6 Ma (K/Ar, Table 2; Hedlund, 1990a). Similar rhyolite intrusions north of Steeple Rock record ages ranging from 28–18 Ma and suggest that several ages of emplacement occurred (Table 3). Therefore, it is likely that the intrusions in the Steeple Rock district range in age from 28–18 Ma.

GEOCHEMISTRY

Despite variably intense alteration, the Steeple Rock samples are grossly similar in chemical composition to similar unaltered lithologies elsewhere in the Mogollon-Datil volcanic field (Bornhorst, 1980, 1986,

TABLE 2—Compilation of ages of intrusive rocks within the Steeple Rock and adjacent area.

Location (sec, township, range)	Unit	Age (Ma)	Method	Reference
Samples within mapped area				
Unknown	rhyolite dike	18	K-Ar	Wahl (1983; pers. comm. April 1992)
25 T17S R20W	quartz monzonite dike	21.4 ± 1.6	Fission track on zircon	Hedlund (1990a)
30 T16S R21W	vitrophyre, rhyolite dome (#955A, McLemore, 1993, map 2)	25.3 ± 0.10	$^{40}Ar/^{39}Ar$	W. McIntosh and R. Appelt (unpublished data, Aug. 1993)
Selected samples adjacent to mapped area				
3 T14S R20W	rhyolite of Mule Mountains	17.7 ± 1.0	Fission track, zircon	Finnell (1987); Marvin et al. (1988, #65)
18 T16S R18W	rhyolite flow	21.3 ± 0.7	K-Ar, biotite	Strangway et al. (1976, IIRB, RB9B); Marvin et al. (1987, #174)
7 T15S R21W	Rhyolite of Hells Hole	26.7 ± 2	Fission track, zircon	Ratté and Brooks (1983)
33 T4S R3W	Rhyolite of Hells Hole	27.1 ± 1 28.7 ± 3.7	K-Ar Fission track, zircon	Ratté and Hedlund (1981)

TABLE 3—Summary of age relations in the Steeple Rock district (modified from McLemore, 1993, *in press b*).

LITHOLOGIC UNIT OR PARAGENETIC STAGE	APPROXIMATE AGE (Ma)	EVIDENCE FOR AGE RELATIONSHIPS
Deposition of volcanic rocks (older volcanic rocks, Summit Mountain and Dark Canyon formations)	33–27	Age determinations, stratigraphic relationships (rhyolite of Steeple Rock—33 Ma, Marvin et al., 1988; Hedlund, 1993; andesite in Summit Mountain Formation—31 Ma; Hedlund, 1993; Bloodgood Canyon Tuff—28.1 Ma, McIntosh et al., 1990, 1991; lava flows of Crookson Peak)
Minor faulting		
Pre-mineralization alteration including acid-sulfate alteration	31–28	Age determinations, stratigraphic relationships (acid-sulfate alteration—31 Ma, Hedlund, 1993; lower beds of Dark Thunder Canyon Formation are altered, locally andesite flows of Dark Thunder Canyon overlie altered andesites of Dark Thunder Canyon, lava flows of Crookson Peak are unaltered)
Faulting and intrusion of rhyolites	27–18	Age determinations (rhyolite of Hells Hole—27 Ma, Rattè and Hedlund, 1981; vitrophyre from rhyolite dome—25.3, McLemore, 1993; quartz monzonite dike—21 Ma, Hedlund, 1993; rhyolite dike—18 Ma, Wahl, 1983)
Mineralization and syn-mineralization alteration, continued faulting and intrusion of rhyolites	as old as 27, as young as 18	Stratigraphic relationships, age determinations (fissure veins cut Summit Mountain and Dark Thunder Canyon formations and rhyolite dikes, some rhyolite dikes cut fissure veins; adularia from East Camp vein—18 Ma, Wahl, 1983)
Post mineralization alteration, burial, erosion, faulting	after 18	Affects all volcanic and intrusive rocks. Some faults offset Gila Group conglomerates (Quaternary).

1988; Sharp, 1991; Davis and Hawkesworth, 1995). The Steeple Rock samples are predominantly peraluminous (i.e., $Al_2O_3/(CaO + K_2O + Na_2O) > 1.0$), high K, basaltic andesite to rhyolite. Most of the Steeple Rock samples are subalkaline and form trends typical of calc-alkaline igneous rocks, according to the definition of Irvine and Baragar (1971). Andesites belonging to the Dark Thunder Canyon Formation plot in the alkaline field (Fig. 7) and are higher in TiO_2 than andesites and dacites belonging to the Summit Mountain Formation.

The ignimbrites also can be distinguished by their chemical composition. Samples of the Bloodgood Canyon Tuff are chemically distinct from <28-Ma ignimbrites and intrusive rhyolites; they are higher in Y and Zr compared to the <28-Ma ignimbrites and intrusive rhyolites (Fig. 8). Some of the <28-Ma ignimbrites and intrusive rhyolites have similar major and trace element composition and contain rhyolite fragments, which suggests that they may be derived from local rhyolite domes.

Igneous petrologists commonly compare geochemical data to results from various studies that relate chemical compositions of igneous rocks from throughout the world to plate tectonic settings. A study by Pearce et al. (1984) refers to these settings as ocean ridge, volcanic arc, syn-collision (formed by the collision of two plates), and within-plate fields. Rocks formed in these tectonic settings are characterized by well defined fields on chemical variation plots. Most andesites from the Summit Mountain Formation plot within the volcanic arc and syn-collision fields, whereas most andesites from the Dark Thunder Canyon Formation plot along the boundary between arc and within-plate fields (Fig. 9). Most of the Steeple Rock rhyolites and ignimbrites plot near the boundaries between established tectonic fields of volcanic arc, syn-collision, and within plate granites (Fig. 10).

The fact that the Steeple Rock volcanic rocks do not plot in well-defined tectono-chemical fields suggests that their origin is more complex than simple subduction or rifting. These chemical trends are consistent with current interpretations of the tectonic evolution of southwestern New Mexico. Similar geochemical trends are observed in the 27.6–26.9-Ma ignimbrites found in the Boot Heel volcanic field, southwestern New Mexico and southeastern Arizona (Bryan, 1995; McIntosh and Bryan, this volume). Similar geochemical differences between mafic and intermediate volcanic rocks of pre-30 Ma and 30–20 Ma have been described by Davis and Hawkesworth (1995), who attribute these differences to the peak of extension in southwestern New Mexico at about 28.5 Ma. Their data suggest that pre-30-Ma and 30-20-Ma mafic-and-intermediate composition volcanic rocks were derived from predominantly lithosphere-derived magmas, with increasing amounts of asthenosphere-derived magmas from 28–20 Ma.

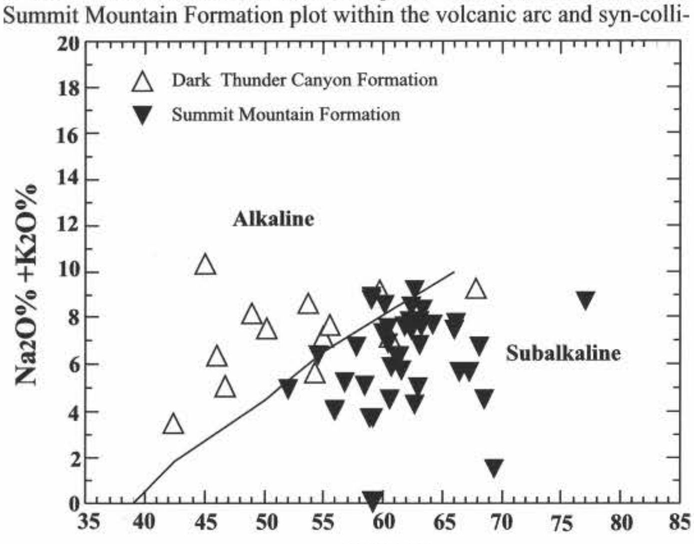

FIGURE 7. Alkali (Na_2O+K_2O) versus SiO_2 diagram of andesites and dacites from the Steeple Rock mining district. Alkaline-subalkaline fields from Irvine and Baragar (1971). Analyses are in McLemore (1993, appendix 4).

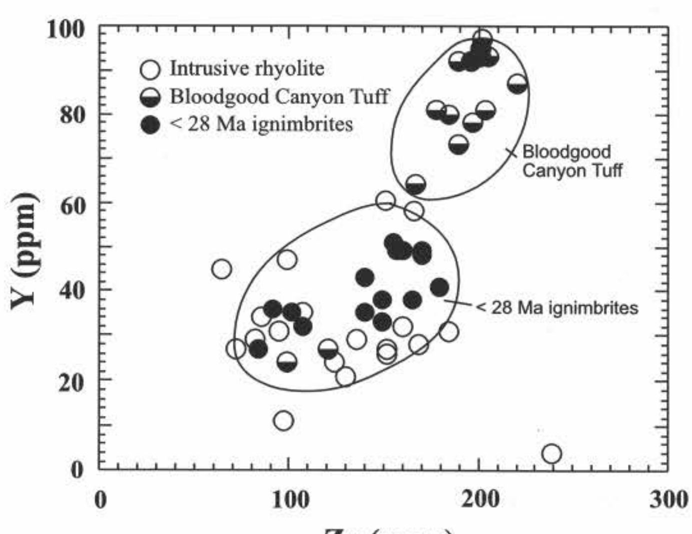

FIGURE 8. Y versus Zr of ignimbrites from the Steeple Rock mining district. Analyses are in McLemore (1993, appendix 4). Four samples of Bloodgood Canyon Tuff and <28-Ma ignimbrites are altered and do not plot in the appropriate groups.

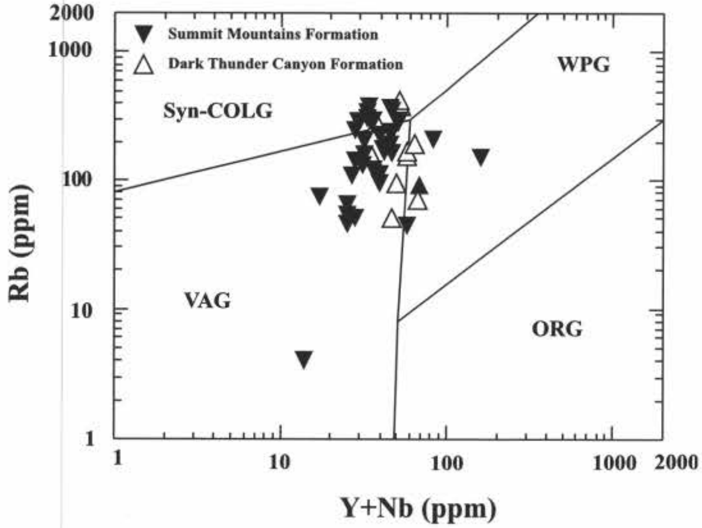

FIGURE 9. Rb vs. Y+Nb scatterplot of andesite and dacite samples from the Steeple Rock district. Tectonic fields from Pearce et al. (1984). Syn-COLG = syn-collision granites. WPG = within-plate granites. VAG = volcanic-arc granites. ORG = orogenic granites. Analyses are in McLemore (1993, appendix 4).

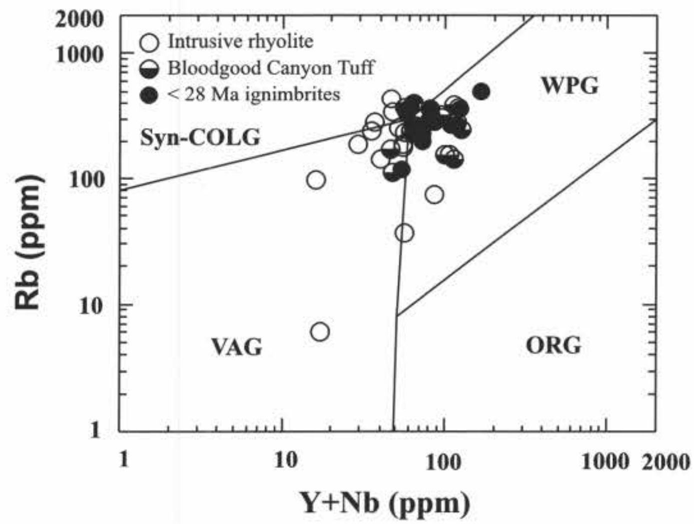

FIGURE 10. Rb vs. Y+Nb scatterplot of ignimbrite and intrusive rhyolite samples from the Steeple Rock district. Tectonic fields from Pearce et al. (1984). Analyses are in McLemore (1993, appendix 4).

STRUCTURAL GEOLOGY

Faulting and tilting of the volcanic rocks in the district produced a series of half-grabens and horsts with a district-wide, regional northwest strike of foliation and bedding planes that dip northeast (Fig. 11; Griggs and Wagner, 1966; Powers, 1976; Biggerstaff, 1974; McLemore, 1993). Rhyolite dikes, plugs, and domes were emplaced along some of these faults and then locally cut by younger faults.

Most faults in the Steeple Rock district are high-angle and well exposed, because they are filled with quartz veins and/or silicified, brecciated country rock. Some faults exhibit oblique-slip movement as evidenced by slickensides and offsetting dikes or veins (Griggs and Wagner, 1966; McLemore, 1993).

The faults can be classified by orientation as (1) northwest-trending faults, (2) north-trending faults, (3) west-northwest-trending faults and shear zones, and (4) northeast-trending faults (McLemore, 1993). Relative ages of these faults are difficult to interpret because of conflicting field relationships and multiple periods of movement (i.e., reactivation). The term "shear zone" is used in this report to describe a zone of parallel to subparallel anastomosing faults or brittlely shattered or pulverized rock (Marshak and Mitra, 1988). Only the two major faults, Carlisle and East Camp-Twin Peaks faults, are described here; the reader is referred to McLemore (1993) for descriptions of other faults in the district.

Carlisle fault

The Carlisle fault is the major west-northwest-trending fault in the Steeple Rock district (Fig. 11). The strike ranges from N75°W to N85°E with numerous local variations and it dips 60–70° to the south. The fault can be traced from the East Camp-Summit fault westward past Laura Canyon, where it curves northwest. The fault is covered by alluvium northwest of the mapped area (Fig. 11; Hedlund, 1993). Ruff (1993) implies that the Carlisle fault is part of the East Camp-Twin Peaks fault system, but they are considered two separate faults in this report and in McLemore (1993).

The Carlisle fault is a prominent quartz-breccia vein or silicified zone along much of its strike; it is mineralized from the Carlisle mine eastward to the Ontario mine. Locally, two parallel or subparallel fracture zones are present, and both constitute the Carlisle fault. The fault is downthrown to the south and has variable displacement. The fault varies in width from <1–30 m. West of the Pennsylvania mine, near the intersection with the Blue Goose fault, the displacement is approximately 210 m; west of the Apache fault the displacement is approximately 270 m (Griggs and Wagner, 1966). The Carlisle fault has a displacement of as much as 610 m west of the Laura fault where Dark Thunder Canyon Formation to the south is adjacent to Summit Mountain Formation to the north (Figs. 2, 11). Further to the west, where the Carlisle fault cuts a rhyolite dome west of Saddleback Mountain, the displacement is only 140–180 m. The difference in displacement is the result of northwest-trending faults, downthrown to the south, that are truncated by the Carlisle fault. Some oblique movement is indicated by fault slickensides plunging 45–60°SW. The Blue Goose and Apache faults do not offset the Carlisle fault, but produce bends in the Carlisle fault, suggesting that movement along these northwest faults occurred after or during formation of the Carlisle fault. These bends localized mineralization and are evidence of different periods of oblique-slip movement.

East Camp-Twin Peaks fault system

The East Camp-Twin Peaks fault system is one of the most prominent northwest-trending fault systems in the district. It consists of three segments, East Camp-Summit, Norman-Billali-Blue Bell, and Twin Peaks faults (Fig. 11). The fault system begins near Blue Creek, southeast of the mapped area (Drewes et al., 1985) and can be traced as one or more parallel to subparallel faults for approximately 30 km to the northwest, where it joins the Twin Peaks fault of Hedlund (1990a). It is cut off by a northeast-trending fault and covered by alluvium northwest of the mapped area.

The fault system strikes N50–55°W, but has numerous local variations, and typically dips steeply to the northeast, but locally to the southwest as well. It is downthrown to the northeast. Throughout most of its length, the individual faults are silicified and mineralized and form prominent outcrops. Rhyolite dikes intruded along the fault at the junction with the Carlisle fault, east and north of Telephone Ridge, and possibly at the Bank mine, where intense acid-sulfate alteration has obscured the lithologies. Numerous mines are located along the fault system. The fault typically exceeds 9 m in width and at the Summit mine the fault is 45 m wide at the surface.

Displacement and age of the East Camp-Twin Peaks fault system are uncertain. The fault cuts the Dark Thunder Canyon Formation, Summit Mountain Formation, and a <28-Ma ignimbrite. In addition, the fault places acid-sulfate altered rocks (typically found near the base of the unit) adjacent to relatively unaltered Dark Thunder Canyon andesites north of Bitter Creek. This along with complex brecciation suggests a large displacement has occurred along the fault (>100 m), perhaps at different times, suggesting multiple periods of movement. Hedlund (1990a) suggests total displacement is approximately 420 m. The East Camp-Twin Peaks fault system also is intruded by rhyolite dikes and offsets other rhyolite dikes. Right-lateral strike separation of about

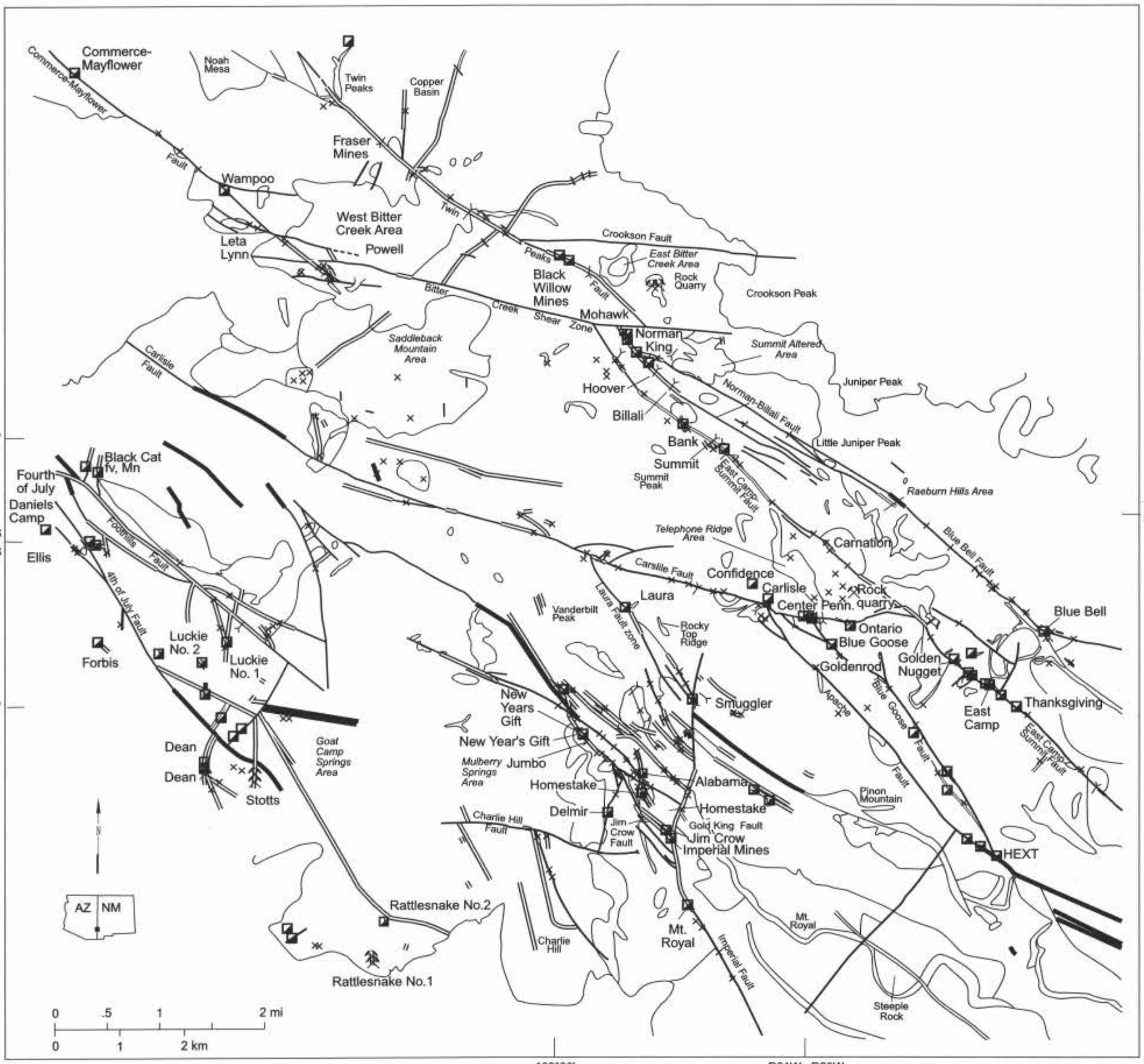

FIGURE 11. Mines, prospects, and major faults in the Steeple Rock district (from McLemore, 1993).

150–200 m is indicated north of Bitter Creek where the fault offsets a rhyolite dike (Powers, 1976; McLemore, 1993). Therefore, the East Camp-Twin Peaks fault system is probably of a similar age as the Blue Bell fault, and older than the youngest rhyolite intrusions and quartz veins.

The East Camp-Summit fault is the southernmost segment and is the site of numerous mines with significant production including the Thanksgiving, Davenport, McDonald, East Camp, Golden Nugget, Summit, and Bank mines (Fig. 11). The fault extends northwestward past the Bank mine, where it is cut by the Bitter Creek shear zone. It is mineralized along the southern part in the mapped area. All of the past production from mines south of the Bank mine, except the Blue Bell mine, has come from mines along the East Camp-Summit fault. The Blue Bell mine is a copper-gold-silver mine with relatively minor production (McLemore, 1993).

North of the Bank mine, the East Camp-Twin Peaks fault system consists of a wide zone with three major faults, East Camp-Summit, Norman King-Billali, and an unnamed fault (Fig. 11). The unnamed fault is narrow and poorly exposed along much of its strike length and may be the extension of the Blue Bell fault. It intersects the Norman King-Billali fault at the Mohawk mine. The middle and most prominent fault is the Norman King-Billali fault. The East Camp-Summit fault is poorly exposed north of the Bank mine, <1 m wide, and is only locally silicified and filled with quartz. All of the past production from mines between the Bank mine and Bitter Creek has been from mines that are localized along the Norman King-Billali fault.

The Norman King-Billali-Blue Bell fault is a prominent, quartz-filled zone that is mineralized along its entire length, from the Bank mine to the Bitter Creek shear zone. Numerous mines including the Billali, Hoover Tunnel, Norman King, and Mohawk mines are located along this segment of the fault. North of the Mohawk mine, the Norman King-Billali fault is cut by the Bitter Creek shear zone.

North of the Bitter Creek shear zone, only one major fault of the East Camp-Twin Peaks system is exposed, the Twin Peaks fault. Much of this fault is also silicified and mineralized along strike, and it locally exceeds 6 m in width. The Fraser and Black Willow mines occur along this fault segment, but production has not been as significant as from mines south of Bitter Creek. The Twin Peaks fault offsets two rhyolite dikes and the Twin Peaks rhyolite plug.

Several crossfaults have caused either minor bends or offsets in the faults of the East Camp-Twin Peaks fault system or are truncated by the fault system. Two minor east-west to northeast-trending faults southwest of the East Camp mine are truncated by the East Camp-Summit fault. A third fault northwest of the mines, is also truncated by the East Camp-Summit fault. The west-northwest-trending Carlisle fault appears to be truncated by the East Camp-Summit fault. However, the Carlisle fault did produce a small offset (less than 5 m) or bend in the East Camp-Summit fault. The Carlisle fault could not be found northeast of the East Camp-Summit fault. The Carlisle fault may have formed as part of the East Camp-Summit system. Later movement along the fault occurred, producing the slight offset in the East Camp-Summit fault.

MINING HISTORY

The earliest report of exploration in the Steeple Rock district was in 1860 when the military dispatched troops from Ft. Thomas (near Duncan, Arizona) to protect miners in the area from interference by Apache Indians. Production began in 1880 when a 20-stamp amalgamating mill was erected at the Carlisle mine (Fig. 11). By 1886, the mill was enlarged to 60 stamps. Most of the mines were located and under development by 1897. Production prior to 1904 is uncertain. The Carlisle mine was the largest producer and most of the production prior to 1904, approximately 112,000 short tons (st), is attributed to the Carlisle mine. Many of the mines closed in the early 1900s. An estimated $10 million worth of metals were produced from the district in New Mexico between 1880 and 1991, which includes approximately 151,000 oz Au, 3.4 million oz Ag, 1.2 million lbs Cu, 5 million lbs Pb, and 4 million lbs Zn (McLemore, 1993). In addition, approximately 11,000 st 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, 2000 long tons of ore containing 74,500 lbs Mn was produced, probably in the 1940s. Two rock quarries were opened and mined for decorative or building stone, but total production is not known.

In the 1970s, 1980s, and 1990s exploration for gold in the district intensified and resulted in drilling and some production, mainly for silica flux for local copper smelters. Queenstake Resources, Ltd. estimated reserves at the Jim Crow, Imperial, and Gold King veins as 155,535 st of ore averaging 3.8 ppm Au and 118 ppm Ag (Queenstake Resources, Ltd., press release, April 2, 1987). In the late 1980s and early 1990s, Biron Bay Resources Ltd., in joint venture with Nova Gold Resources, Ltd., drilled along the Summit vein and estimated reserves as 1,450,000 st of ore grading 6.1 ppm Au and 352 ppm Ag (Petroleum and Mining Review, May 1992, p. 2). None of these deposits has been mined. R & B Mining Co. operated the Center mine in 1987–1993. Doug Hanson, in a joint venture with Micrex Mineral Development Corp., mined a small amount of gold, silver, and silica flux at the Bank mine in 1996, including approximately 500 st of stockpiled ore grading 12 ppm Au and 374 ppm Ag (Rubin, 1997). In 1998, Doug Hanson built a mill at the Center mine to process mine waste piles and remaining ore reserves, but no concentrates have been shipped to date (June 1999).

MINERAL DEPOSITS

It is beyond the scope of this paper to describe fully the mineral deposits and alteration in the district; only a summary is presented (Table 3). The reader is referred to McLemore (1993, 1996, *in press b*) and Supplemental Road Log 2 (this volume) for more details. The mineralization in the Steeple Rock district occurs as volcanic-epithermal precious- and base-metal fissure veins along faults. Five types of vein deposits occur in the district (McLemore, 1993, 1996, *in press b*): (1) base with precious metals, (2) precious metals, (3) copper-silver, (4) fluorite, and (5) manganese. A sixth type of deposit, high-sulfidation (quartz-alunite) gold deposits, may occur in areas of acid-sulfate alteration; but no production has occurred (McLemore, 1993). District-wide zoning of the fissure veins is present (McLemore, 1996). The base-metal veins, with significant amounts of gold and silver, occur only along the Carlisle fault near the center of the district. Outward from the base-metal veins, precious-metal veins occur along northwest- and north-trending faults. Locally, these veins grade vertically downward to trace amounts of base-metal sulfides. Some precious-metal veins grade vertically upward to copper-silver veins without any gold. Fluorite and manganese veins occur along the fringe or outer margins of the district (McLemore, 1996). The epithermal veins are all low-sulfidation (quartz-adularia) veins, structurally controlled, and deposited by low salinity (<5 eq. wt. % NaCl), slightly acidic–neutral pH fluids at temperatures between 240° and 325°C at relatively shallow depths (360–1300 m; McLemore, 1993, 1996, *in press b*; McLemore and Clark, 1993).

In the Steeple Rock district, the vein deposits occur exclusively along faults and fractures within fault zones. Some vein deposits occur along, and cut across, rhyolite dikes and plugs, which are intruded along faults. In some places, later faults offset the vein deposits and rhyolite dikes. The veins typically form prominent outcrops and are bifurcating, sinuous, and pinch-and-swell along 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. At least four stages of mineralization separated by periods of brecciation occurred.

Several areas of acid-sulfate alteration are cut by epithermal veins and are superimposed and surrounded by argillic to chloritic (neutral pH) alteration. These areas of acid-sulfate alteration were formed in a magmatic-hydrothermal environment as evidenced by mineral, chemical, and temperature zonation, preserved textures, sulfur isotopic data, and age determinations. Some areas contain anomalous concentrations of gold.

The age of mineralization in the Steeple Rock district is uncertain. Epithermal veins fill faults that cut the Tertiary volcanics in the Steeple Rock district, the youngest of which are lava flows of Crookson Peak dated as 27.6 Ma (K/Ar, Hedlund, 1990c). Wahl (1983) reports that adularia from the East Camp vein has an age of 18 Ma, but provides no additional data. Adularia from the Mogollon district, northeast of the Steeple Rock district, has an age of 16.7 Ma ($^{40}Ar/^{39}Ar$, Kamilli and Rattè, 1995). Since the adularia in both districts may be younger than the metal mineralization, these age are probably minimum ages. The adularia occurs late in stage 2 and in stage 3 mineralization in the Steeple Rock district (McLemore, 1993, *in press b*). In Mogollon, the adularia occurs as late crystals on the quartz breccia.

In the Steeple Rock district, epithermal veins in most areas are spatially related to rhyolite dikes. Some rhyolite dikes in places offset some epithermal veins. Ages of intrusions in the Mule Creek-Summit Mountains area range from 28 to 18 Ma (Table 3). Therefore, epithermal veins in the Steeple Rock district are probably between 28 and 18 Ma and may be closer to 20–18 Ma in age. The acid-sulfate alteration is older than the epithermal veins.

CONCLUSIONS

Detailed mapping, stratigraphic, paleomagnetic, and geochemical studies have refined our understanding of the geologic history of the Steeple Rock mining district (Table 2). Geochemical data suggest that pre-28 Ma (Summit Mountain and Bloodgood Canyon Tuff) and 28–20-Ma (Dark Thunder Canyon Formation and <28-Ma ignimbrites) magmas were derived from predominantly lithosphere-derived magmas, with increasing amounts of asthenosphere-derived magmas from 28–20 Ma (Davis and Hawkesworth, 1995; Bryan, 1995; this study). A complex sequence of vein formation, brecciation, and rhyolite intrusion was accompanied by faulting. Paleomagnetic studies have shown that ignimbrites can be differentiated by paleomagnetic methods, even if they are too altered to be dated by geochronological methods.

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REFERENCES

Appelt, R. M., 1993, Paleomagnetic correlation of ignimbrites in the Steeple Rock mining district, southwestern New Mexico: Geological Society of America, Abstracts with Programs, v. 25, no. 5, p. 4.

Biggerstaff, B. P., 1974, Geology and ore deposits of the Twin Peaks area, Grant County, New Mexico [M.S. thesis]: University of Texas at El Paso, 102 p.

Bornhorst, T. J., 1980, Major- and trace-element geochemistry and mineralogy of upper Eocene to Quaternary volcanic rocks of the Mogollon-Datil volcanic field, southwestern New Mexico [Ph.D. dissertation]: Albuquerque, University of New Mexico, 1108 p.

Bornhorst, T. J., 1986, Granophile elements in mid-Cenozoic calc-alkalic rhyolitic volcanic rocks, Mogollon–Datil volcanic field, southwestern New Mexico; *in* Taylor, R. P. and Strong, D. F., eds., Recent advances in the geology of granite-related mineral deposits: The Canadian Institute of Mining and Metallurgy, Special Volume 39, p. 331–341.

Bornhorst, T. J., 1988, Character of mid-Cenozoic andesites, basaltic andesites and related volcanic rocks, Mogollon-Datil volcanic field, southwestern New Mexico; *in* Drexler, J. W. and Larson, E. E., Cenozoic volcanism in the Southern Rocky Mountains updated: A tribute to Rudy C. Epis—Part 2: Colorado School of Mines Quarterly, v. 83, p. 1–13.

Bryan, C. R., 1995, Stratigraphy, chemistry, and petrogenesis of volcanic rocks of the mid-Tertiary Boot Heel volcanic field, southwestern New Mexico and southeastern Arizona [Ph.D. dissertation]: Albuquerque, University of New Mexico, 272 p.

Cather, S. M., 1999, Implications of Jurassic, Cretaceous, and Proterozoic piercing lines for Laramide oblique-slip faulting in New Mexico and rotation of the Colorado Plateau: Geological Society of America Bulletin, v. 111, p. 849–868.

Cather, S. M. and Johnson, B. D., 1986, Eocene depositional systems and tectonic framework of west-central New Mexico and eastern Arizona; *in* Peterson, J. A., ed., Paleotectonics and sedimentation in the Rocky Mountain Region, United States: American Association of Petroleum Geologists, Memoir 41, p. 623–652.

Chapin, C. E., Chamberlin, R. M. and Hawley, J. W., 1978, Socorro to Rio Salado; *in* Hawley, J. W., ed., Guidebook to the Rio Grande rift in New Mexico and Colorado: New Mexico Bureau of Mines and Mineral Resources, Circular 163, p. 121–137.

Coney, P. J. and Reynolds, S. J., 1977, Cordilleran Benioff zones: Nature, v. 270, p. 403–406.

Criss, J., 1980, Fundamental-parameters calculations in a laboratory microcomputer: Advances in X-ray Analysis, v. 23, p. 93–97.

Davis, J. M. and Hawkesworth, C. J., 1995, Geochemical and tectonic transitions in the evolution of the Mogollon-Datil volcanic field, New Mexico, USA: Chemical Geology, v. 119, p. 31–53.

Dickinson, W. R., 1981, Plate tectonic evolution of the southern Cordillera; *in* Dickinson, W. R. and Payne, W. D., eds., Relations of tectonics to ore deposits in the southern Cordillera: Arizona Geological Society Digest, v. 14, p. 113–136.

Drewes, H., 1991, Description and development of the Cordilleran orogenic belt in the southwestern United States and northern Mexico: U.S. Geological Survey, Professional Paper 1512, 92 p.

Drewes, H., Houser, B. B., Hedlund, D. C., Richter, D. H., Thorman, C. H. and Finnell, T. L., 1985, Geologic map of the Silver City 1° x 2° quadrangle, New Mexico and Arizona: U.S. Geological Survey, Map I-1310C, scale 1:250,000.

Elston, W. E., 1960, Reconnaissance geologic map of the Virden quadrangle: New Mexico Bureau of Mines and Mineral Resources, Geologic Map 15, scale 1:126,720.

Elston, W. E., 1978, Mid-Tertiary cauldrons and their relationship to mineral resources, southwestern New Mexico: A brief overview; *in* Chapin, C. E., Elston, W. E. and James, H. L., eds., Field guide to selected cauldrons and mining districts of the Datil-Mogollon volcanic field, New Mexico: New Mexico Geological Society, Special Publication No. 7, p. 107–113.

Elston, W. E., 1984, Mid-Tertiary ash-flow-tuff cauldrons, southwestern New Mexico: Journal of Geophysical Research, v. 89, p. 8733–8750.

Finnell, T. L., 1987, Geologic map of the Cliff quadrangle, Grant County, New Mexico: U.S. Geological Survey, Miscellaneous Investigations Series Map I-1768, scale 1:50,000.

Fisher, R. A., 1953, Dispersion on a sphere: Proceedings of the Royal Society of London, Series A, v. 217, p. 295–305.

Gillerman, E., 1964, Mineral deposits of western Grant County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 83, 213 p.

Griggs, R. L. and Wagner, H. C., 1966, Geology and ore deposits of the Steeple Rock mining district, Grant County, New Mexico: U.S. Geological Survey, Bulletin 1222-E, 29 p.

Hedlund, D. C., 1990a, Geologic map and sections of the Steeple Rock quadrangle, Grant and Hidalgo Counties, New Mexico: U.S. Geological Survey, Open-file Report 90-240, scale 1:24,000, 14 p.

Hedlund, D. C., 1990b, Geology and mineral deposits of the Steeple Rock and Duncan mining districts, Grant and Hidalgo Counties, New Mexico and Greenlee County, Arizona: U.S. Geological Survey, Open-file Report 90-239, 27 p.

Hedlund, D. C., 1990c, Preliminary geologic map of the Goat Camp Spring quadrangle, Grant and Hidalgo Counties, New Mexico and Greenlee County, Arizona: U.S. Geological Survey, Open-file Report 90-490, scale 1:24,000.

Hedlund, D. C., 1990d, Preliminary geologic map of the Crookson Peak quadrangle, Grant and Hidalgo Counties, New Mexico and Greenlee County, Arizona: U.S. Geological Survey, Open-file Report 90-252, scale 1:24,000.

Hedlund, D. C., 1993, Geologic map of the Tillie Hall Peak quadrangle, Greenlee County, Arizona and Grant County, New Mexico: U.S. Geological Survey, Map GQ-1715, scale 1:24,000.

Hildreth, W. and Mahood, G., 1985, Correlation of ash-flow tuffs: Geological Society of America Bulletin, v. 96, p. 968–974.

Irvine, T. N. and Baragar, W. R. A., 1971, A guide to the chemical classification of the common volcanic rocks: Canadian Journal of Earth Sciences, v. 8, p. 523–548.

Johnson, C. H., 1943, Steeple Rock district, Grant County, New Mexico: U.S. Bureau of Mines, War Minerals Report 188, 11 p.

Kamilli, R. J. and Rattè, J. C., 1995, Geologic studies of the Mogollon mining district, New Mexico; Does a porphyry system lie below?; *in* Pierce, F. W. and Bolm, J. G., eds., Porphyry copper deposits of the American Cordillera: Arizona Geological Society, Digest 20, p. 455–463.

Keith, S. B., Gest, D. E., DeWitt, E., Tull, N. W. and Everson, B. A., 1983, Metallic mineral districts and production in Arizona: Arizona Bureau of Geology and Mineral Technology, Bulletin 194, 58 p.

Kirschvink, J. L., 1980, The least-squares line and plane and the analysis of paleomagnetic data: Geophysical Journal Royal Astron. Society, v. 62, p. 699–718.

Lindgren, W., Graton, L. C. and Gordon, C. H., 1910, The ore deposits of New Mexico: U.S. Geological Survey, Professional Paper 68, p. 327–328.

Lowell, J. D., 1974, Regional characteristics of porphyry copper deposits of the southwest: Economic Geology, v. 69, p. 601–617.

Marshak, S. and Mitra, G., 1988, Basic methods of structural geology: Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 445 p.

Marvin, R. F., Mehnert, H. H. and Naeser, C. W., 1988, U.S. Geological Survey radiometric ages—compilation C: Part 2: Arizona and New Mexico: Isochron/West, v. 51, p. 5–13.

Marvin, R. F., Naeser, C. W., Bikerman, M., Mehnert, H. H. and Ratté, J. C., 1987, Isotopic ages of post-Paleocene igneous rocks within and bordering the Clifton 1° x 2 quadrangle, Arizona-New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 118, 63 p.

McAnulty, W. N., 1978, Fluorspar in New Mexico: New Mexico Bureau of Mines and Mineral Resources, Memoir 34, 64 p.

McDowell, T. W. and Claubaugh, S. E., 1979, Ignimbrites of the Sierra Madre Occidental and their relation to the tectonic history of western Mexico: Geological Society of America, Special Paper 180, p. 113–124.

McIntosh, W. C., 1991, Evaluation of paleomagnetism as a correlation criterion for Mogollon-Datil ignimbrites, southwestern New Mexico: Journal of Geophysical Research, v. 96, no. B8, p. 13,459–13,483.

McIntosh, W. C., Chapin, C. E., Ratté, J. C. and Sutter, J. F., 1992a, Time-stratigraphic framework for the Eocene-Oligocene Mogollon-Datil volcanic field southwestern New Mexico: Geological Society of America Bulletin, v. 104, p. 851–871.

McIntosh, W. C., Geissman, J. W., Chapin, C. E., Kunk, M. J. and Henry, C. D., 1992b, Calibration of the latest Eocene–Oligocene geomagnetic polarity time sale using $^{40}Ar/^{39}Ar$ dated ignimbrites: Geology, v. 20, p. 459–463.

McIntosh, W. C., Sutter, J. F., Chapin, C. E. and Kedzie, L. L., 1990, High-precision $^{40}Ar/^{39}Ar$ sanidine geochronology of ignimbrites in the Datil-Mogollon volcanic field, southwestern New Mexico: Bulletin of Volcanology, v. 52, p. 584–601.

McIntosh, W. C., Kedzie, L. L. and Sutter, J. F., 1991, Paleomagnetic and

$^{40}Ar/^{39}Ar$ dating database for Mogollon-Datil ignimbrites, southwestern New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 135, 79 p.

McLemore, V. T., 1993, Geology and geochemistry of the mineralization and alteration in the Steeple Rock district, Grant County, New Mexico and Greenlee County, Arizona [Ph.D. dissertation]: University of Texas at El Paso; *also* New Mexico Bureau of Mines and Mineral Resources, Open File Report 397, 526 p.

McLemore, V. T., 1996, Geology and zoning in the Steeple Rock district, New Mexico and Arizona: Society for Mining, Metallurgy, and Exploration, Inc., Transactions, v. 298, p. 1851–1859.

McLemore, V. T., *in press a*, Silver and gold occurrences in New Mexico: New Mexico Bureau of Mines and Mineral Resources, Resource Map 21.

McLemore, V. T., *in press b*, Alteration and epithermal mineralization in the Steeple Rock district, Grant County, New Mexico and Greenlee County, Arizona; *in* Geology and ore deposits 2000: The Great Basin and beyond: Geological Society of Nevada, Symposium volume.

McLemore, V. T. and Clark, K. F., 1993, Alteration and epithermal mineralization in the Steeple Rock mining district, Grant County, New Mexico and Greenlee County, Arizona (abs.): Conference Program and extended abstracts, Integrated Methods in Exploration and Discovery, Society of Economic Geologists, p. AB69–70.

McLemore, V. T., Munroe, E. A., Heizler, M. T. and McKee, C., 1999, Geochemistry of the Copper Flat porphyry and associated deposits in the Hillsboro mining district, Sierra County, New Mexico, USA: Journal of Geochemical Exploration, v. 66, p. 167–189.

Muehlberger, W. R., 1980, Texas lineament revisited: New Mexico Geological Society, Guidebook 31, p. 113-121.

Norrish, K. and Hutton, J. T., 1969, An accurate X-ray spectrographic method for the analysis of a wide range of geologic samples: Geochimica et Cosmochimica Acta, v. 33, p. 431–454.

Obenaulf, R. H. and Bostwick, R., eds., 1988, SPEX handbook of sample preparation and handling: SPEX Industries, Inc., 94 p.

Pearce, J. A., Harris, N. B. W. and Tindle, A. G., 1984, Trace element discrimination diagrams for the tectonic interpretation of granitic rocks: Journal of Petrology, v. 24, p. 956–983.

Powers, R. S., 1976, Geology of the Summit Mountains and vicinity, Grant County, New Mexico and Greenlee County, Arizona [M.S. thesis]: University of Houston, 107 p.

Ratté, J. C. and Brooks, W. E., 1983, Geologic map of the Mule Creek quadrangle, Grant County, New Mexico: U.S. Geological Survey, Map MF-1666, scale 1:24,000.

Ratté, J. C. and Hedlund, D. C., 1981, Geologic map of the Hells Hole further planning area (RARE II), Greenlee County, Arizona and Grant County, New Mexico: U.S. Geological Survey, Map MF-1344-A, scale 1:62,500.

Ratté, J. C., Marvin, R. F., Naeser, C. W. and Bikerman, M., 1984, Calderas and ash-flow tuffs of the Mogollon Mountains, southwestern New Mexico: Journal of Geophysical Research, v. 89, p. 8713–8732.

Richter, D. H. and Lawrence, V. A., 1983, Mineral deposit map of the Silver City 1° x 2° quadrangle, New Mexico and Arizona: U.S. Geological Survey, Map I-1319-B, scale 1:250,000.

Rose, A. W. and Baltosser, W. W., 1966, The porphyry copper deposit at Santa Rita, New Mexico; *in* Titley, S. R. and Hicks, C. L., eds., Geology of the porphyry copper deposits, southwestern North America: The University of Arizona Press, Tucson, p. 205–220.

Rothrock, H. E., Johnson, C. H. and Hahn, A. D., 1946, Fluorspar resources in New Mexico: New Mexico Bureau of Mines and Mineral Resources, Bulletin 21, 245 p.

Rubin, B., 1997, Small mines have high hopes too!: Paydirt, March 1997, p. 4-5.

Ruff, R. K., 1993, Gas analysis of fluid inclusions: application toward precious metal exploration, Steeple Rock mining district, Grant County, New Mexico [M.S. thesis]: Socorro, New Mexico Institute of Mining and Technology, 83 p.

Russell, P. L., 1947, Steeple Rock zinc-lead district, Grant County, New Mexico: U.S. Bureau of Mines, Report of Investigations 4073, 13 p.

Schmitt, H. A., 1966, The porphyry copper deposits in their regional setting; *in* Titley, S. R. and Hicks, C. L., eds., Geology of the porphyry copper deposits, southwestern North America: The University of Arizona Press, Tucson, p. 17–33.

Seager, W. R., Mack, G. H., Raimonde, M. S. and Ryan, R. G., 1986, Laramide basement-cored uplift and basins in south-central New Mexico: New Mexico Geological Society, Guidebook 37, p. 123–130.

Sharp, W. N., 1991, Petrochemistry of igneous rocks, Silver City 1° x 2° quadrangle, New Mexico and Arizona: U.S. Geological Survey, Miscellaneous Investigations Series Map I-1310H, scale 1:250,000.

Strangway, D. E., Simpson, J. and York, D., 1976, Paleomagnetic studies of volcanic rocks from the Mogollon Plateau area of Arizona and New Mexico: New Mexico Geological Society, Special Publication 5, p.119–124.

Trace, R. D., 1947, The Fourth of July and Luckie No. 1 and No. 2 fluorspar veins, Greenlee County, Arizona: U.S. Geological Survey, Strategic Minerals Investigations Report 3-207, 6 p.

Turner, G. L., 1962, The Deming axis, southeastern Arizona, New Mexico, and Trans-Pecos Texas: New Mexico Geological Society, Guidebook 13, p. 59–71.

Wahl, D. E., 1980, Mid-Tertiary volcanic geology in parts of Greenlee County, Arizona and Grant County, New Mexico [Ph.D. dissertation]: Tucson, Arizona State University, 144 p.

Wahl, D. E., 1983, Comments on economic volcanology between Redrock, New Mexico and Clifton, Arizona (abs.): New Mexico Geology, v. 5, p. 67.

Wargo, J. G., 1959, The geology of the Schoolhouse Mountain quadrangle, Grant County, New Mexico [Ph.D. dissertation]: Tucson, University of Arizona, 187 p.

Wertz, J. B., 1970a, Arizona's copper province and the Texas lineament: Mining Engineering, v. 5, p. 80–81.

Wertz, J. B., 1970b, The Texas lineament and its economic significance in southeastern Arizona: Economic Geology, v. 65, p. 166–181.

Williams, F. E., 1966, Fluorspar deposits of New Mexico: U.S. Bureau of Mines, Information Circular 8307, 143 p.

Wilson, E. D., 1950, Fluorspar in Arizona: Arizona Bureau of Mines, Circular 151, 13 p.

Zijderveld, J. P. A., 1967, Demagnetization of rocks—analysis of results; *in* Collinson, D. W., Creer, K. M. and Runcorn, S. K., eds., Methods in paleomagnetism: Elsevier, Amsterdam, p. 254–286.