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2013, pp. 131-142. https://doi.org/10.56577/FFC-64.131

in:

Geology of Route 66 Region: Flagstaff to Grants, Zeigler, Kate; Timmons, J. Michael; Timmons, Stacy; Semken, Steve, New Mexico Geological Society 64th Annual Fall Field Conference Guidebook, 237 p. https://doi.org/10.56577/FFC-64

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GEOLOGY AND MINERAL RESOURCES IN THE ZUNI MOUNTAINS MINING DISTRICT, CIBOLA COUNTY, NEW MEXICO: REVISITED

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ABSTRACT—The Zuni Mountains district is in the central and southern Zuni Mountains in north-central New Mexico. The earliest mining in the Zuni Mountains was by Native Americans, who recovered obsidian (eroded from the Mt. Taylor region), basalt, turquoise, malachite, azurite, and possibly fluorite for ornaments and stone tools. The major types of deposits in the Zuni Mountains include 1) veins and replacements in Proterozoic rocks, 2) stratabound, sedimentary-copper deposits, and 3) fluorite veins, although 4) REE (rare earth elements)-Th-U metasomatic bodies, 5) high-calcium limestone, 6) volcanic cinders (scoria), and 7) iron deposits also are found in the Zuni Mountains district. Total fluorite production exceeded 224,000 short tons of crude ore. Total reported metals production from the district amounts to more than 30,000 pounds copper, 260 oz silver, and 2 oz gold from 1923 to 1965; additional copper, gold, and silver production probably occurred during the late 1800s. There is some economic potential for gold, silver, and possibly copper in the veins and replacement deposits in Proterozoic Zuni and Mt. Sedgwick granites and metarhyolite. The Proterozoic dark syenite and amphibolite bodies and gold-silver veins in the Zuni Mountains should be geochemically evaluated for their platinum group metals (PGE) potential. It is unlikely that the stratabound, sedimentary-copper deposits or fluorite veins have any remaining significant economic potential, because the highest grades have been mined and remaining deposits appear to be discontinuous and low grade. The REE-Th-U metasomatic bodies and iron deposits also have low economic potential because of low grade and small size. The Zuni Mountains continue to have high economic potential for high-calcium limestone and volcanic cinders (scoria). The veins and replacement deposits appear to be Proterozoic in age and are associated with the Zuni and Mt. Sedgwick granites and metarhyolite, while the late Proterozoic episyenites appear to be associated with the Mt. Sedgwick granite. The fluorite veins are much younger and perhaps associated with other Rio Grande rift barite-fluorite deposits in New Mexico.

INTRODUCTION

The Zuni Mountains mining district is in the central and southern parts of the Zuni Mountains, west and southwest of Grants in Cibola County, New Mexico (Fig. 1). After 1983, the Zuni Mountains were in Cibola County, which was created from the western portion of what was Valencia County. The major types of deposits in the Zuni Mountains include 1) veins and replacements in Proterozoic rocks, 2) stratabound, sedimentary-copper deposits, and 3) fluorite veins, although 4) REE (rare earth elements) -Th-U metasomatic bodies, 5) high-calcium limestone, 6) volcanic cinders (scoria), and 7) iron deposits also are found in the Zuni Mountains district. The only active mining in the Zuni Mountains is for limestone.

METHODS OF INVESTIGATION

This work is part of ongoing studies of mineral deposits in New Mexico and includes updates and revisions of prior work by North and McLemore (1986, 1988), McLemore et al. (1986), McLemore and McKee (1989), and McLemore (1983, 1989, 2001). Investigations of the mineral deposits and plutonic rocks in the Zuni Mountains by the author began in 1983 in order to assess their economic potential and tectonic setting (McLemore, 1983; McLemore and McKee, 1989). Continued investigations occurred in 1985-1986, as part of the evaluation of mineral resources within Cibola County (McLemore et al., 1986). During 2011-2012, the author resumed investigations in the area in order to understand the origin of the granitic and metasomatic rocks, the tectonic setting, and to evaluate the mineral resource potential.

Published and unpublished data were compiled and examined. Mineral occurrences, deposits, mines, prospects, and mills were identified, plotted on base maps (Fig. 2), and compiled in the New Mexico Mines Database (McLemore et al., 2005a, b). Igneous rock lithologies were characterized on the basis of mineralogy and chemistry. Types of deposits are from Cox and Singer (1986)

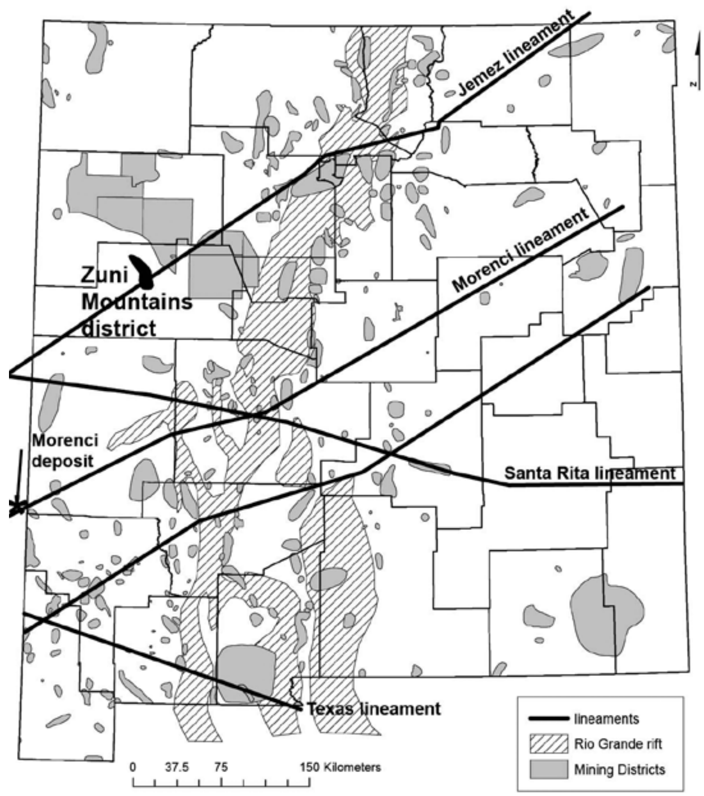

FIGURE 1. Lineaments and mining districts in New Mexico (Chapin et al., 1978, 2004; McLemore, 2001; Sims et al., 2002; McLemore et al., 2005a). The Zuni Mountains mining district is along the Jemez lineament.

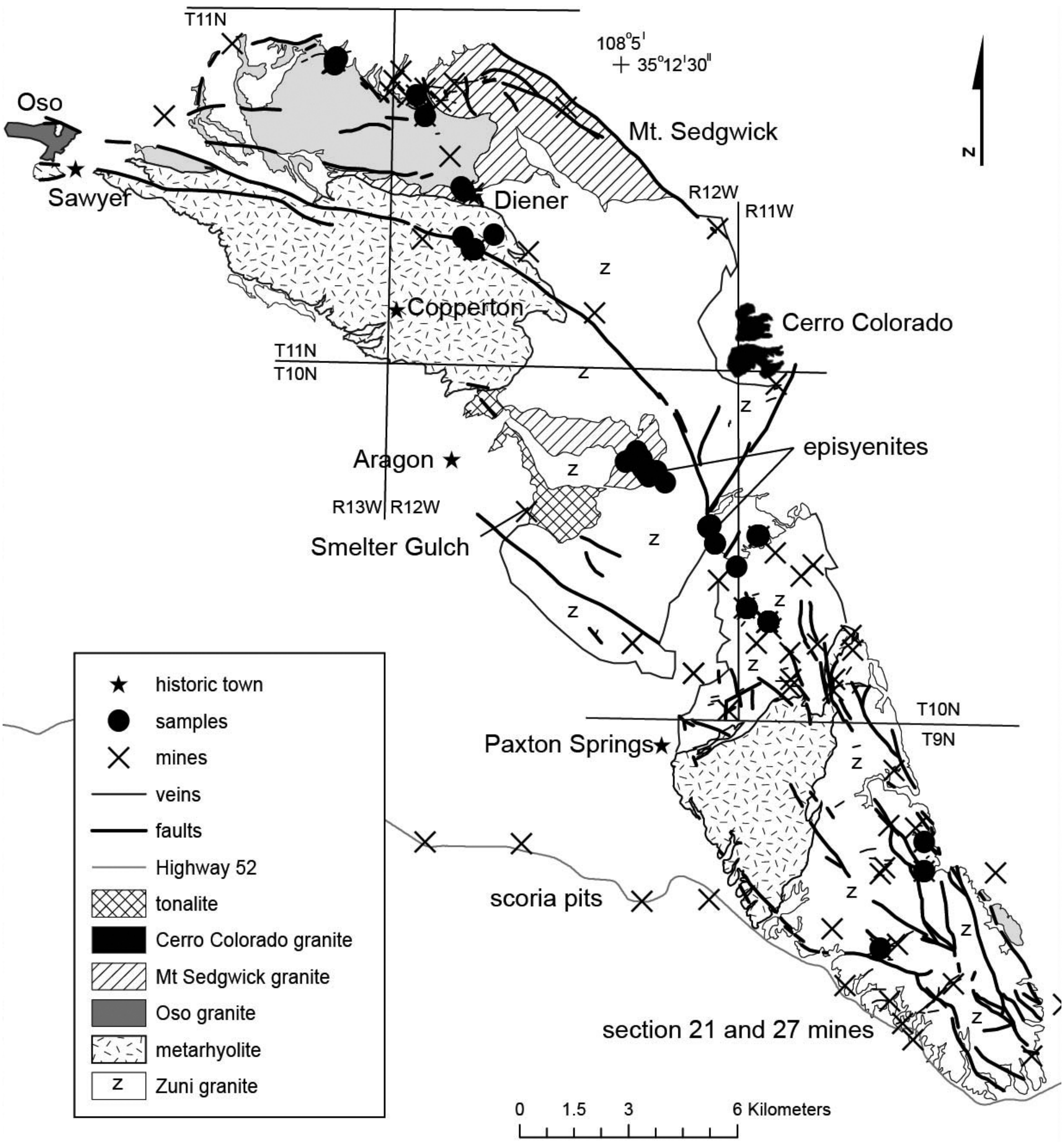

FIGURE 2. Simplified geologic map of the Zuni Mountains (modified by the author from field reconnaissance from Goddard, 1966), showing mines, occurrences, and sample locations (Tables 3, 4). Zuni granite includes metamorphic rocks and aplite.

and McLemore (2001). Production is in Tables 1 and 2. Selected samples were collected and analyzed by a variety of methods as explained in Tables 3 and 4.

MINING HISTORY AND PRODUCTION

The Zuni, Acoma, and Navajo people have lived, traveled, and hunted throughout the Zuni Mountains for centuries. Native Americans recovered obsidian (eroded from the Mt. Taylor region), basalt, turquoise, malachite, and azurite for ornaments and stone tools. Fluorite also may have been used by the Zunis for decorative ornaments (Lindgren et al., 1910; Oakes et al., 2006; Zamora, 2008).

Base and precious metals were found in the Zuni Mountains circa 1900 and at least one metals mill was built in the district. Total reported production from the district amounts to more than 30,000 lbs copper, 260 oz silver, and 2 oz gold from 1923 to 1965 (Table 1); additional copper, gold, and silver production probably occurred during the late 1800s.

Fluorite was discovered about 1908. A fluorite mill-concentrator was constructed in the 1910s, but was destroyed by fire in 1927 (Lasky and Wootton, 1933). In 1943, the Zuni Milling Co. (formerly Navajo Fluorspar Mines) opened a fluorspar mill in Los Lunas, where fluorite mined from the Zuni Mountains was processed. The lack of water and electricity prevented a mill from being built in the Zuni Mountains. The Los Lunas mill had a capacity of 100 short tons/day and could yield a 98% concentrate at 165 mesh (Kutnewsky, 1944). Chemical (93% fluorite), ceramic (95%) and metallurgical (85%) grades were shipped from the mill (Warner, 1947). In 1944, the mill increased its capacity, making it the third largest fluorite mill in the U.S. at the time (Kutnewsky, 1944; Messenger, 1979).

Other production has come from the Zuni Mountains (Table 2). In 1961-1962, U.S. Sericite produced 10 short tons of flake mica, worth approximately $255. An unknown amount of limestone and volcanic cinder also has been produced from the Zuni Mountains. Iron ore was found and prospected during WW II; production, if any, is unknown.

TABLE 1. Reported metals production from the Zuni Mountains mining district, Cibola County (from U.S. Geological Survey, 1902-1927; U.S. Bureau of Mines, 1927-1990); McLemore, 1989; NMBGMR file data). Production data can change as better data are obtained. — no reported production. W withheld or not available.

Year	Ore mined (short tons)	Gold (oz)	Silver (oz)	Copper (lbs)	Total value $
1905	W	—	—	W	W
1923	16	—	36	4,884	748
1925	30	—	27	3,300	487
1930	57	—	57	6,600	880
1937	59	—	88	11,000	1,399
1940	12	—	28	2,700	325
1959	—	2	12	W	81
1963	W	—	W	W	W
1965	15	—	12	2,000	901
Total (excluding withheld values)	189	2	260	30,484	4,821

TABLE 2. Additional mineral production from the Zuni Mountains (Goddard, 1966; McLemore et al., 1986).

Commodity	Reported production	Value (dollars)	Years Produced	Comments
Fluorite	192,657 short tons 224,000 short tons	unknown	1946-1953	Additional production withheld 1953-1962
Mica	10 short tons	255	1909-1953	U.S. Sericite Co.
Scoria	unknown	—	—	—
High-calcium Limestone	unknown	—	—	—

GEOLOGIC SETTING

The Zuni Mountains lie along the Jemez lineament (Fig. 1; Chapin et al., 1978; Aldrich et al., 1986) and geophysical data suggest that a mafic intrusion underlies the Zuni uplift (Ander and Huestis, 1982). The Jemez lineament is defined by northeast-trending alignment of late Cenozoic basaltic magmatism that extends from the Springerville volcanic field in Arizona to the Raton-Clayton volcanic field in northeastern New Mexico (Fig. 1). In New Mexico, much research has been focused on the association of magmatism, structure, and mineralization along the Jemez lineament (Mayo, 1958; Aldrich and Laughlin, 1984; Sims et al., 2002; Cather et al., 2006; Chamberlin, 2007).

Lineaments have played a role in localizing magmatic activity and can locally control 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 lineaments. Lineaments, especially where they intersect other structural features could be viable exploration targets. At least two periods of magmatic activity have been focused along the Jemez lineament and are found within the Zuni Mountains (Proterozoic and Cenozoic; Goddard, 1966). The mineral deposits in the Zuni Mountains could be a result of this crustal feature.

Proterozoic granite and metamorphic rocks form the core of the Zuni Mountains (Fig. 2) that was uplifted during the Ancestral and Laramide orogenies (Aldrich et al., 1986). The oldest rocks are hornblendite and serpentinized peridotite (1630.2±1.9 Ma, $^{40}Ar/^{39}Ar$, Strickland et al., 2003), and a metarhyolite with

TABLE 3. Chemical analyses of selected samples from the Zuni Mountains. Sample no. 7981 is from the Abo Formation; all other samples are from Proterozoic or fluorite veins. Analyses are from McLemore et al. (1986). Au and Ag were by fire assay and other elements by atomic adsorption spectroscopy (AA) at the NMBGMR laboratory.

Sample	Name	Mine Id	Latitude	Longitude	Au oz/ton	Ag oz/ton (ppm)	Cu%	Pb%	other	U_3O_8%%	type of sample	type of deposit
7977	Irene 2	NMCI0123	35.01655	-107.9853	0	0.26 (8.13)			no Pt, 16.5 CaF2%, 0.12 BaSO4%		dump	fluorite vein
7978	21	NMCI0128	34.98971	-107.998	0.06 (1.88)	4.24 (133)			no Pt, 32.2 CaF2%, 0.25 BaSO4%		dump	fluorite vein
8811	Fool's Gold Canyon	NMCI0124	35.00924	-107.985	0	0.02 (0.63)	26 ppm				South dump	Precambrian vein
8810	Fool's Gold Canyon	NMCI0124	35.00924	-107.985	0	0	62 ppm				North dump	Precambrian vein
8692		NMCI0113	35.09178	-108.0373	0	0	3.62			0.003	shear zone	Precambrian vein
8693		NMCI0113	35.09178	-108.0373	0	0	0.008				quartz vein	Precambrian vein
8694			35.09173	-108.0379	0	0					quartz vein	Precambrian vein
8695		NMCI0142	35.07379	-108.0406	Trace (<0.63)	4.18 (131)	7.41				shear zone	Precambrian vein
8696		NMCI0142	35.07379	-108.0406	0	0.42 (13.1)	0.41				quartz vein	Precambrian vein
8697		NMCI0142	35.07379	-108.0406	0	0	<0.02				quartz vein	Precambrian vein
8698		NMCI0142	35.07379	-108.0406	0	0	0.83	<0.04	375 ppm Zn		dump	Precambrian vein
8699		NMCI0144	35.07044	-108.0341	Trace (<0.63)	1.42 (44.4)	6.24				dump	Precambrian vein
8700		NMCI0144	35.07044	-108.0341	0	0.28 (8.75)	0.91				vein	Precambrian vein
8701		NMCI0144	35.07044	-108.0341	0.02 (<0.63)	6.12 (191)	3.83		no Pt		vein	Precambrian vein
8702		NMCI0144	35.07044	-108.0341	0	0	1.02				dump	Precambrian vein
8703		NMCI0144	35.07044	-108.0341	0	3.76 (118)	2.56				dump	Precambrian vein
8813		NMCI0144	35.07044	-108.0341	0	0.72 (22.5)	<20 ppm					Precambrian vein
8808		NMCI0144	35.07044	-108.0341	0	0.1 (3.13)	192 ppm				dump	Precambrian vein
8807	Trail Canyon	NMCI0152	35.11212	-108.0749	0	0.02 (0.63)					dump	Precambrian vein
9017	Trail Canyon	NMCI0152	35.11212	-108.0749	0	0.18 (5.63)					dump	Precambrian vein
8805	Diener Canyon	NMCI0158	35.16149	-108.1257	0	0.28 (8.75)					quartz vein	Precambrian vein
8806		NMCI0158	35.16149	-108.1257	0	1.36 (42.5)	2.94					Precambrian vein
8809	Diener Canyon	NMCI0158	35.16149	-108.1257	Trace (<0.63)	0.74 (23.1)	1.14					Precambrian vein
8814	Diener Canyon		35.1644	-108.1292	0	0.28 (8.75)	<20 ppm				dump	Precambrian vein
8815	Diener Canyon		35.16154	-108.1265	0	0.08 (2.5)					quartz vein	Precambrian vein
9671	Diener Canyon		35.16532	-108.1197	Trace (<0.63)	Trace (<0.63)					quartz vein	Precambrian vein
7979	Mt. Sedgwick		35.17602	-108.1292	0	1.1 (34.4)	4.55	<0.02	no Pt	0.003	dump	Precambrian vein
7980	Mt. Sedgwick		35.17602	-108.1292	0	0.74 (23.1)	3.5	<0.02	no Pt	0.002	shear zone	Precambrian vein
8049			35.17703	-108.1301	Trace (<0.63)	0	0.06	<0.02	0.006% Zn		shear zone	Precambrian vein
7982	Gabby	NMCI0154	35.19456	-108.1415	0	0.48 (15)	0.46	<0.02		0.002	shear zone	Precambrian vein
7982		NMCI0154	35.19456	-108.1415	0	0.48 (15)	103 ppm				dump	Precambrian vein
7981		NMCI0155	35.19967	-108.1444	0	1.02 (31.9	3.7	<0.02		0.005		sandstone
8058	McGaffey				0	1.62 (50.6)					quartz vein	Precambrian vein
8050	McGaffey				0	0.22 (6.88)					quartz vein	Precambrian vein

a U/Pb age of about 1655 Ma (Bowring and Condie, 1982). Strickland et al. (2003) also dated hornblende and biotite in two shear zones with $^{40}Ar/^{39}Ar$ ages of 1432±5.7 Ma and 1432.7±1.8 Ma. Other lithologies in the Zuni Mountains Proterozoic terrain include gneiss, schist, amphibolite, syenite, pegmatites, and diabase dikes (Goddard, 1966; Fitzsimmons, 1967; Lambert, 1983; Mawer and Bauer, 1989; Strickland et al., 2003). The diabase dikes are 1130±20 Ma ($^{40}Ar/^{39}Ar$, Strickland et al., 2003).

Existing data suggest four geographically and geochemically distinct granites are present in the Zuni Mountains (Figs. 2 and 3; Condie, 1978; Brookins and Rautman, 1978): Mt. Sedgwick granite (high calcium), Zuni granite (high silica), Cerro Colorado gneissic aplite (high silica), and Oso granite (high potassium). A fifth pluton in the northern Zuni Mountains has not been sampled. The megacrystic granite, the Mt. Sedgwick granite, has a $^{40}Ar/^{39}Ar$ age of 1432±1.9 Ma (Strickland et al., 2003). The metarhyolite is similar geochemically to the Oso granite and the Zuni and Cerro Colorado granites are geochemically similar. The Zuni Mountain granites are calcic to calc-alkaline and peraluminous granites. Condie (1978) suggested that the high-calcium granites were formed by partial melting of siliceous granulite in the lower crust and the high-silica and high-potassium granites formed by fractional crystallization of shallow high-calcium magmas.

The Proterozoic rocks are unconformably overlain by sedimentary deposits of Pennsylvanian and Permian age (Abo, Yeso and San Andres formations; Goddard, 1966). The youngest volcanic formations are Quaternary basalt flows and cinder volcanoes.

DESCRIPTION OF THE MINERAL DEPOSITS

Vein and replacement deposits

Copper veins with galena, silver, and gold are found in thin quartz veins along fault and shear zones and disseminated in Proterozoic Zuni and Mt. Sedgwick granites and metarhyolite (Fig. 2; Schrader, 1906; Lindgren et al., 1910; McLemore et al., 1986). None of the deposits are spatially associated with the Oso or Cerro Colorado granites. Minerals include malachite, azurite, chalcopyrite, chalcocite, native copper, bornite, galena, and sphalerite with trace turquoise, and some silver and gold. Pyrite and quartz are common. Platinum group elements (PGE) were not detected in any samples collected by McLemore et al. (1986); but recently prospectors have verified the presence of platinum assays and a platinum sulfide mineral in mafic portions of a shear zone. Some shear zones (mapped as faults in Fig. 2) are up to 243 m wide, several hundred meters long, and contain as much as 3-6% Cu, 156 to 313 ppm Ag and 0.94 to 3.44 ppm Au (Schrader, 1906; Lindgren et al., 1910). Individual mineralized veins are as much as 1 m wide and less than 100 m long. The mineralized areas are structurally controlled by shear and fault zones.

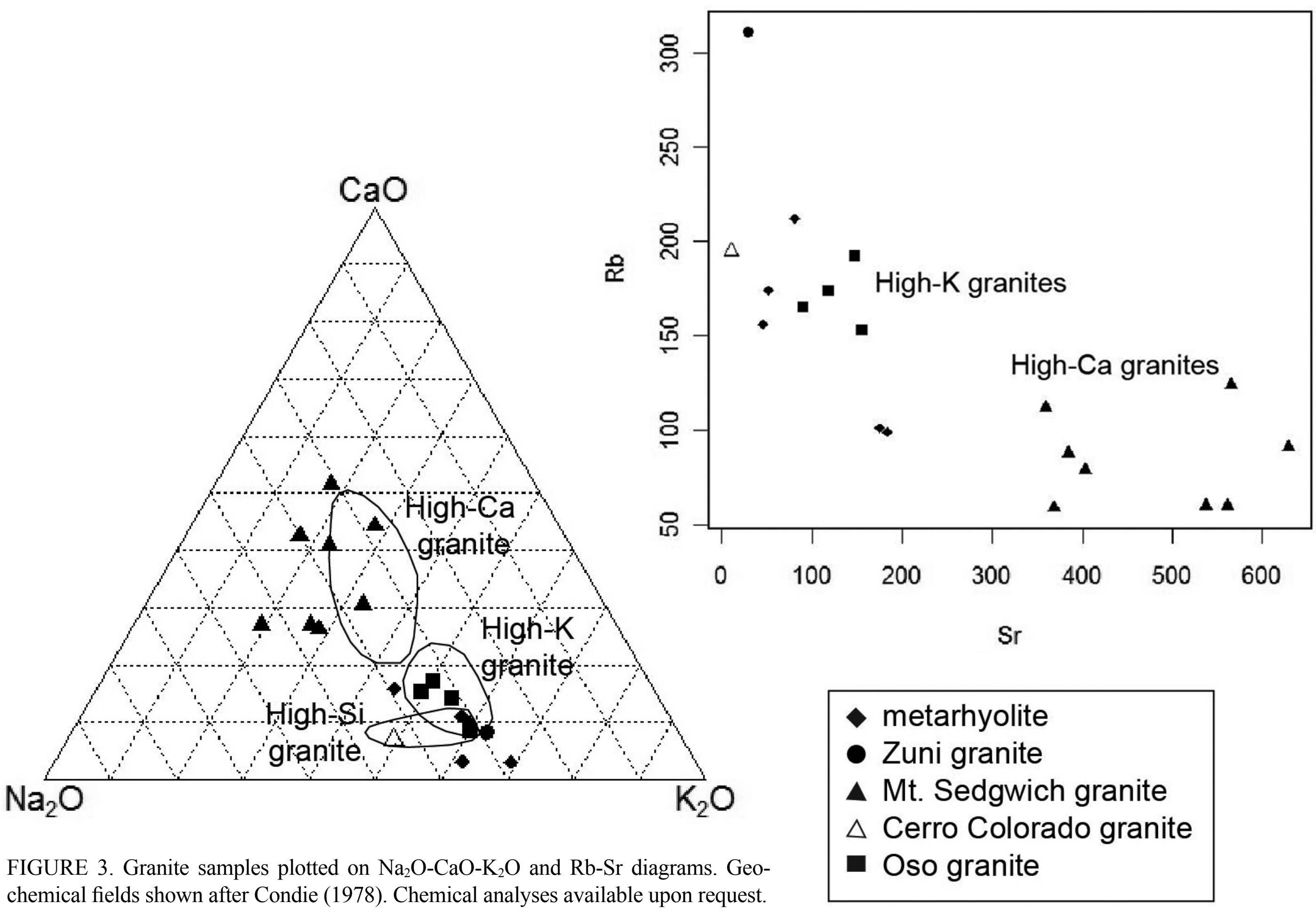

FIGURE 3. Granite samples plotted on Na_2O-CaO-K_2O and Rb-Sr diagrams. Geochemical fields shown after Condie (1978). Chemical analyses available upon request.

TABLE 4. Partial chemical analyses of episyenites and adjacent granites and metarhyolites in the Zuni Mountains. Analyses are in parts per million (ppm), except for K_2O, which is in percent (%). Total REE (rare earth elements) = sum of REE. K_2O, U, Th, Y, Nb were by x-ray fluorescence spectroscopy (XRF) and REE were by induced coupled plasma spectroscopy. Samples prefixed with REE are new analyses for this report collected in 2012 and were by Activation Laboratory, Canada. Samples prefixed with Z were collected in 1983-1989 and were by XRF at the NMBGMR laboratory (McLemore and McKee, 1989).

Sample	Lithology	Latitude	Longitude	K_2O%	Th	U	Y	Nb	La	Ce	Total REE
REE44	Meta-rhyolite	35.10608	-108.0712	4.98	15.1	3.6	51	11	52	108	262.02
REE45	edge of episyenite	35.10628	-108.0713	14.62	7.4	1.7	16	7	3.9	8.3	30.58
REE46	center episyenite	35.10645	-108.0714	15.24	5	1.6	16	2	2.3	6.4	23.19
REE47	altered gneissic granite	35.10712	-108.0719	1.76	8.4	1.9	8	7	25.2	49.4	104.94
REE48	episyenite	35.10738	-108.0725	14.47	10.2	1.5	10	3	13.5	26.3	61.98
REE49	gneissic granite	35.08404	-108.0439	3.51	8.2	2.1	22	8	33.9	74.4	168.88
REE50	episyenite	35.08962	-108.0507	15.28	15.9	3.8	24	14	6.4	17.5	51.46
REE51	coarse grained episyenite, same as REE52	35.09375	-108.0528	14.61	5.6	2	15	7	3.7	8	28.24
REE52	fine grained episyenite	35.09375	-108.0528	15.73	5.8	1.1	10	5	2.5	4.6	16.55
REE53	gneissic granite (ap)	35.08962	-108.0507	2.57	5.2	1.5	8	4	19.3	40.3	88.29
REE54	pink granite dike in ag	35.11017	-108.0734	5.42	1.8	0.8	2	< 1	6.2	12	25.7
REE55	gneissic granite (ag)	35.10732	-108.069	1.82	4.7	1	6	4	25.9	51.5	110.33
Z-1	granite	35.1078	-108.0715	4.66		38	124				
Z-12	granite	35.10726	-108.072	4.72		9	105				
Z-3	episyenite	35.10667	-108.0716	14.4		12	85				
Z-5	episyenite	35.10645	-108.0714	14.8		20	135				
Z-9	episyenite	35.10628	-108.0713	14		28	162				
Z-10	episyenite	35.10712	-108.0719	11		13	75				
Z-14	episyenite	35.10739	-108.0719	13.1		4	77				
Z-16	episyenite	35.1077	-108.0725	15.1		29	147				
Z-17	episyenite	35.10804	-108.073	15.6		9	55				
Z-sy	episyenite	35.09375	-108.0528	13.8		147	337				
Z-24	episyenite	35.09405	-108.052	14		15	99				

Several quartz veins subparallel to schistosity are mineralized, but typically are low in gold and silver (Table 3). The age of mineralization is uncertain, but presumed Proterozoic because the mineralized zones are found exclusively in the Proterozoic rocks and are associated with faults and shear zones of Proterozoic age (Goddard, 1966; Strickland et al., 2003). Locally, disseminated sulfides are parallel to foliation and schistosity.

Deposits in the Diener area (Fig. 2), including the Mirabel mine, are found in an east-west-trending shear zone in granite and granite gneiss and samples assay a trace of gold (<0.06 ppm), up to 42.5 ppm Ag and 4.55% Cu with minor zinc and uranium (Table 3). A shaft and several pits have developed parts of the zones. Drilling in the 1970s in the Diener area indicates that mineralization extends to 30 m with reported assays 1-2 % Cu, 40-70 ppm Ag and 0.39 ppm Au (D. Sayala, unpublished report, NMBGMR file data, 1970). Production from this area is unknown but most of the reported metals production from the Zuni Mountains in the 1950s was from the Mirabel mine near Diener. Fulp and Woodward (1981) suggest that the potassic alteration associated with the copper deposits in the Diener area is similar to porphyry copper deposits and could be indicative of a Proterozoic porphyry copper deposit at depth.

Mineral deposits in section 18, 30 T10N, R11W (northeast of Paxton Springs) also are found along shear zones in granite and samples assay up to a trace of gold, 191 ppm Ag, and 7.41% Cu with minor uranium, zinc, and lead (Table 3). These deposits are in the vicinity of fluorite veins, but fluorite is not present in the gold-silver veins (McLemore et al., 1986).

The age of mineralization is unknown, but presumed Proterozoic because mineralized bodies are found along Proterozoic structures and shear zones within Proterozoic rocks. Hornblende and biotite from two shear zones in the Zuni Mountains have $^{40}Ar/^{39}Ar$ ages of 1432±5.7 Ma and 1432.7±1.8 Ma (Strickland et al., 2003), indicating deformation during the Proterozoic. Many mineralized veins and replacements are found along these shear zones. Most of the known mineral deposits are associated with the Zuni and Mt. Sedgwick granites and metarhyolite (Fig. 2). More work is needed to determine the origin of these deposits.

Stratabound, sedimentary-copper deposits

Stratabound, sedimentary-copper deposits containing copper, silver, and locally gold, lead, zinc, uranium, vanadium, and molybdenum are found throughout New Mexico, including the

Zuni Mountains. These deposits have also been called “red-bed” or “sandstone” copper deposits by previous workers (Soulé, 1956; Phillips, 1960; Cox and Singer, 1986). They typically occur in bleached gray, pink, green, or tan sandstones, siltstones, shales, and limestones within or marginal to typical thick red-bed sequences of red, brown, purple, or yellow sedimentary rocks deposited in fluvial, deltaic or marginal-marine environments of Pennsylvanian, Permian, or Triassic age. The majority of sedimentary-copper deposits in New Mexico occur at or near the base of these sediments; some deposits, such as those in the Zuni Mountains districts, are in sedimentary rocks that unconformably overlie mineralized Proterozoic granitic rocks.

In the Zuni Mountains, stratabound, sedimentary-copper deposits are typically found in bleached pink or light gray sandstones, siltstones, and conglomerates of the Pennsylvanian (?)-Permian units deposited unconformably on the Proterozoic rocks near the Mirabel Copper mine in the Diener area. At one locality, the Proterozoic granite beneath the mineralized conglomerate consists of thin veinlets and disseminations of malachite and chalcocite. The deposits are predominantly in the Abo Formation (Permian), but some replacements of the Pennsylvanian rocks also are found. The mineralized bodies typically occur as lenses or blankets of disseminated and/or fracture coatings of copper minerals, predominantly chalcopyrite, chalcocite, malachite, and azurite with local uranium minerals, galena, sphalerite, and barite. Ore minerals in these sedimentary-copper deposits are typically associated with organic debris and other carbonaceous material. Locally, sedimentary features such as bedding, crossbedding, paleochannels, and intraformational slumping also appear to control mineralization. The copper deposits are found in small, meandering stream channels and tend to be discontinuous, small, and low grade. Assays as high as 36.5% Cu and 116 ppm Ag are reported (Lindgren et al., 1910) and a sample collected by the author contained no gold, 33 ppm Ag, 3.7% Cu, and 0.005% U_3O_8 (Table 2, no. 7981). The average thickness of mineralized zones is less than 2 m and as many as four horizons or zones are found.

Copper and other metals were probably transported in low-temperature solutions through permeable sediments, along bedding planes, and along faults shortly after burial. Replacement textures and diagenetic features of the organic material indicate that mineralization occurred during or after diagenesis. Oxidizing waters could have leached copper and other 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 (LaPoint, 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. Transport of metal-bearing waters occurred laterally through the aquifers from Proterozoic highlands or, in some cases, by circulating, ascending fluids (Brown, 1984). Geologic, mineralogic, and isotopic studies of similar deposits elsewhere in the United States suggest that these waters are in approximate chemical equilibrium with quartz, feldspar, hematite, and mica at temperatures less than 75°C (Rose, 1976). Precipitation occurred at favorable oxidation-reduction interfaces in the presence of organic material or H_2S-rich waters. Subsequent processes, such as groundwater, intrusions, and/or structural events (i.e., Jemez lineament) may have modified, altered, or even destroyed some deposits (LaPoint, 1979). Most sedimentary-copper deposits are low grade, low tonnage, and inaccessible to existing mills for current development for copper. They are generally low in silica and are not suitable as silica flux material.

Fluorite veins

Some of the state’s largest fluorite veins in terms of production and potential are in the southern and central Zuni Mountains district. Total fluorite production exceeded 224,000 short tons of crude ore (Goddard, 1966). Fluorite was discovered in 1908 and produced in 1909. Significant fluorite production occurred in 1943 when Zuni Milling Co. (formerly Navajo Fluorspar Mines) opened a fluorspar mill in Los Lunas.

Fluorite veins are found along north-trending, steeply-dipping faults and fracture zones in Proterozoic and Permian rocks in three areas (Rothrock et al., 1946; Goddard, 1966): 1) Mirabel mine near Diener, 2) northeast of Paxton Springs in T10N, R11W and 3) sections 21 and 27 mines in southeastern Zuni Mountains. Most fluorite veins are in Proterozoic Zuni or Mt. Sedgwick granites, but a few veins cut sandstones of the Permian Abo Formation (Rothrock et al., 1946; Peters, 1958; Goddard, 1966; Williams, 1966; V.T.M. field notes). Locally, Quaternary basalt flows covered fluorite veins. Fluorite veins do not cut the basaltic lava (Rothrock et al., 1946: V.T.M. field notes), indicating that the fluorite veins are older than the basalt flows. Green, purple, colorless, and pink fluorite is found as open-space fillings with minor replacements and cementation of brecciated zones. Massive, crystalline fluorite is found in veins up to 0.5 m thick. A few veins are over 300 m long and have been explored to only a couple of hundred meters deep. The veins contain predominantly fluorite with varying amounts of calcite, quartz, aragonite, and wallrock fragments. Hematite alteration is common producing a reddening of the adjacent granite. Sulfide minerals are rare, although trace amounts of sphalerite, galena, and chalcopyrite are found in the Section 21 and 27 mines (Goddard, 1966). Barite is found locally in trace amounts, although a barite vein, up to 30 cm wide and a few hundred meters long, is found near the Mirabel mine near Diener and contained 78% $BaSO_4$ and some fluorite and malachite (Table 2, no. 8812).

The grade of fluorspar varies throughout the district with the highest grades (85-93% fluorite) in the Sections 21 and 27 mines. Production varied from 17 to 86% CaF_2. Most fluorite veins do not have any precious- or base-metals, but two samples collected contained up to 133 ppm Ag and 1.88 ppm Au (Table 2). Rare earth (REE) minerals, likely bastnaesite, are reported in some fluorite veins (Zandra et al., 1952; Emanuel, 1982). The best concentrated sample contained 68% TREO (total rare earth oxides; Zandra et al., 1952) and could have included ore from the Gallinas Mountains.

Several studies have suggested that the Zuni Mountain fluorspar deposits are similar in origin and age as the uranium-fluorite deposits found in the Todilto limestone in the Ambrosia Lake subdistrict of the Grants uranium district (Emanuel, 1982; Gilkey, 1953; Rapaport et al., 1952; Peters, 1956; Gableman, 1956; McLaughlin, 1963). Primary ore minerals in the Todilto deposits include uraninite, coffinite, and blue-black vanadium minerals, with accessory calcite, fluorite and barite. The disseminated and replacement fluorite found in the Todilto uranium deposits is quite different in character compared to the massive, structurally-controlled fluorite veins in the Zuni Mountains. The Todilto fluorite is typically found as small crystals or replacements in the limestone and is purple or colorless. The age of primary Todilto mineralization is estimated at 150-155 Ma based on concordant and nearly concordant U/Pb ages for uraninite (Berglof, 1989; McLemore, 2011a). The fluorite was deposited at the same time as the uranium minerals by uraniferous waters derived from a highland to the southwest migrated through the Entrada Sandstone. These waters were then drawn into the Todilto limestone through evapotranspiration or evaporative pumping. Uranium and fluorite precipitated in the presence of organic material within the intraformational folds and associated fractures and dissolution cavities in the limestone (Berglof, 1989; McLemore, 1983, 2011a).

North and McLemore (1986), McLemore et al. (1998), and McLemore (2001) suggested that the Zuni Mountains fluorite deposits are Rio Grande rift (RGR) deposits formed by low-temperature formation waters or basinal brines found within the Rio Grande rift and are similar to Mississippi Valley-type (MVT) deposits. Recent work by Partey et al. (2009) suggest that fluorite deposits in southern New Mexico are indeed related to the Rio Grande rift and the source of fluorine is consistent with an asthenospheric magma. The mafic magma body beneath the Zuni Mountains (Ander and Huestis, 1982) could be the source of the fluorite deposits found in the Zuni Mountains and the Jemez lineament would allow fluid migration. Uranium minerals are absent in the southern Zuni Mountains fluorite deposits, although the deposits near Diener are slightly radioactive (Goddard, 1966; McLemore, 1983), further supporting a different age and origin from the Todilto uranium deposits.

The Zuni Mountains fluorites contain fluid inclusions with relatively low to moderate homogenization temperatures (108-220°C) and moderate salinities (7-20.4 eq wt%) suggestive of basinal brines (Emanuel, 1982; Hill, 1994; Hill et al., 2000). Stable isotopes are consistent with formation by meteoric waters (Hill, 1994; Hill et al., 2000). Emplacement occurred at depths of approximately 2286 m (Emanuel, 1982). These characteristics suggest a formation similar to that described for RGR barite-fluorite-galena deposits (McLemore et al., 1998).

POTENTIAL FOR OTHER COMMODITIES

REE-Th-U metasomatic bodies

McLemore and McKee (1989) briefly described and mapped the known brick red, K-feldspar-rich metasomatic episyenite/syenite deposits east of Aragon in the Zuni Mountains. Another small body was found and mapped south of the known bodies. The term episyenite, as used by Leroy (1978), is used to describe rocks that were desilicated and metasomatized and are composed predominantly of alkali-feldspar formed by hydrothermal fluids. These rocks now resemble syenites. The metasomatic episyenites in the Zuni Mountains are discontinuous tabular bodies, narrow lenses, and breccia zones along faults, fractures, and shear zones in Proterozoic Mt. Sedgwick granite and metarhyolite (McLemore and McKee, 1989). The bodies are slightly radioactive (2-4 times background), suggesting anomalous concentrations of U and Th. The similarity between the metasomatic episyenites in the Zuni Mountains to those found in the Caballo Mountains, which contain anomalous concentrations of REE, Th, and U (McLemore, 1986), suggested that the Zuni Mountains metasomatic episyenites also could contain anomalous concentrations of REE, Th, and U (McLemore et al., 1988a, b; McLemore, 2012). However, selected samples of episyenites in the Zuni Mountains contain <16 ppm Th, <4 ppm U, <14 ppm Nb, <147 ppm Y, <200 ppm total REE (Table 4), which are uneconomic. A feldspar from the metasomatic episyenite has a $^{40}Ar/^{39}Ar$ age between 700 and 1180 Ma (Strickland et al., 2003). More research is underway on these deposits by the author.

Limestone (crushed stone and high-calcium limestone)

Limestone in the Permian San Andres Formation has been quarried throughout the Zuni Mountains for crushed stone for road construction and for stack scrubbers. The Escalante Plant used limestone from the El Morro quarries in the Zuni Mountains in the stack scrubber system (McLemore et al., 1986; Kottlowski and Armstrong, 1995). Only local areas are high enough in calcium (i.e., >95%) to be suitable for high-calcium end uses (McLemore et al., 1986; Kottlowski and Armstrong, 1995). A sample from Nutria, NM (west of Sawyer) contained 94.2% $CaCO_3$, 1.04% CaO, 0.18% K_2O, 0.78% Na_2O, 0.16% Fe_2O_3, 0% Al_2O_3, 3.26% SiO_2, 0.23% H_2O and 0.01% S and is marginal for high-calcium limestone uses (C.H. Maxwell and L.G. Nonini, written communication, 1977). The San Andres limestone is 30-100 meters thick and found along the northeast and southwest limbs of the Zuni Mountains (Goddard, 1966). Detailed sampling of the San Andres limestone is required to properly assess the potential for high-calcium limestone.

Scoria

Scoria is a highly vesicular, dark-colored volcanic rock of mafic composition (commonly basalt or basaltic andesite), generally found in volcanic cinder cones and on the surface of lava flows. In industrial usage, scoria is known as volcanic cinders. Scoria differs from pumice by a more mafic composition, darker color, higher density, coarser vesicles (gas cavities), more crystalline texture, and generally higher strength and ranges in color from black to brown to red (Clippinger, 1946). Uses of scoria include natural lightweight concrete aggregate, road surfacing aggregate, railroad ballast, and decorative stone for landscaping. Scoria used in lightweight aggregate provides less weight reduction accompanied by higher strength than pumice. The vesicular nature of scoria provides excellent insulating properties for heat, cold, and sound and the glassy composition is fireproof. Scoria used in concrete, road surfacing, and ballast must meet the same specifications as any other aggregate material, including abrasion resistance, immersion disintegration, and aggregate degradation. Most scoria is friable and fragmental and can be ripped with little blasting, resulting in lower production costs than nonvesicular rock that must be crushed (Presley, 2006; Bush et al., 2006). Red scoria is locally desired for landscaping. The difference in color is a result of differences in magma temperatures in the vent that causes oxidation (Osburn, 1980, 1982).

Scoria was produced from several pits northeast and northwest of Bandera Crater, along U.S. Highway 53 in the southern Zuni Mountains (Fig. 2), and is used mostly for road material.

Iron deposits

Precambrian iron formations are stratigraphic units composed of layered, bedded rocks that contain 15% or more iron mixed with quartz, chert, and/or carbonate and are among the largest iron ore deposits mined for steel in the world (Bekker et al., 2010), although known deposits in New Mexico are quite small in comparison (McLemore, 2011b).

Several small deposits of iron oxides are found in the Zuni Mountains, but there has not been any reported production (Kelley, 1949; Harrer and Kelly, 1963; McLemore et al., 1986). The Smelter Gulch deposit in section 16, T11N, R12W (Fig. 2) consists of small veins (less than a meter wide) of limonite, hematite, and magnetite in a sheared and brecciated zone in Proterozoic rocks, and could be indicative of Precambrian iron formations at depth.

The Kirchan deposit in section 11, T13N, R15W (northern Zuni Mountains) consists of a hematite replacement in limestone of the Chupadera Formation (D.A. Carter and D.G. Ellingwood, unpublished report, NMBGMR files, 1960) and is only a few meters wide and a few meters long. Similar deposits are found in limestones throughout the Zuni Mountains. All of the iron deposits in the Zuni Mountains are small, isolated, and uneconomic.

Mica

Muscovite is common throughout the Proterozoic rocks in the Zuni Mountains district, especially in the Proterozoic schists. In 1961-1962, U.S. Sericite produced 10 short tons of sericite valued at $255 from an open pit in section 16, T11N, R12W, north of Diener (McLemore et al., 1986). Horst and Bhappu (1969) evaluated a separate sample of sericite from the Mount Sedgwick area and found it to be suitable for roofing-grade mica. However the mica from the Zuni Mountains typically is too dark and impure for most commercial applications, such as paint. Also, the mica deposits in the Zuni Mountains are small and discontinuous (lenses or pods few hundreds of meters in diameter). Mica is used as functional filler in building materials and in the manufacture of numerous industrial and consumer products such as joint compound, paints, automotive sound deadening materials, thermoplastics, coatings, and even cosmetics because of its unique physical characteristics, including color, flexibility, durability, thermal properties, and weight.

Uranium in granitic rocks

Brookins and Rautman (1978) and Brookins (1982) examined the Proterozoic granitic rocks to determine if these rocks would constitute a large in situ uranium deposit and if there could be any geothermal potential. Their data does not support any uranium or thorium potential. The average uranium content of 57 samples is 3.75 ppm U (range 1.82-7.37 ppm U) and the average thorium content of 25 samples is 17.5 ppm Th (range 4.07-41.76 ppm Th). The geothermal potential is beyond the scope of this paper.

Volcanogenic massive-sulfide deposits

Volcanogenic massive-sulfide (VMS) deposits are volcanogenic, polymetallic, stratabound deposits formed by stratiform accumulations of sulfide minerals that precipitated from circulating hydrothermal fluids associated with submarine volcanism on and below the seafloor (Sangster and Scott, 1976; Franklin et al., 2005; Barrie and Hannington, 1999; Stix et al., 2003), and consists of at least 50% sulfides, generally copper, lead, and zinc with some precious metals (Sangster and Scott, 1976; Franklin et al., 2005). In New Mexico, VMS deposits are rare and are restricted to Precambrian greenstone terrains; production has occurred only from the Pecos mine in the Willow Creek district in Santa Fe County (Robertson et al., 1986; McLemore, 2001). The mineralized metamorphosed volcaniclastic rocks in the Zuni Mountains district are suggestive of VMS deposits at depth (Robertson et al., 1986), but detailed mapping, geochemical analyses and drilling should be performed to examine this similarity and determine genesis of the deposits.

Proterozoic syenite/gabbro-hosted platinum group elements (PGE) deposits

Platinum group elements (PGE) typically occur in economic concentrations in ultramafic and associated mafic rocks (Eckstrand, 1984; Cox and Singer, 1986; Macdonald, 1988). PGE includes platinum, palladium, osmium, ruthenium, iridium, and rhodium. The average concentration of platinum in unmineralized mafic and ultramafic rocks is approximately 10 ppb, ranging from 0.1 to 500 ppb (Mcdonald, 1988). Combined PGE content of most ore deposits ranges from 1 to 20 ppm (Eckstrand, 1984). PGE ore occurs as conformable layers or lenses near the base of layered ultramafic and mafic complexes, thin stratiform layers, and irregular pipe-like bodies within ultramafic and mafic complexes. Although, none of these features are found in the Zuni dark syenite and amphibolite, which are fine- to medium-grained and massive, the Proterozoic dark syenite and amphibolite bodies and gold-silver veins in the Zuni Mountains should be geochemically evaluated for their PGE potential. Proterozoic amphibolites (gabbro) from the Caballo Mountains contained 1-3 ppb Pt and 1-2 ppb Pd (McLemore et al., 2012). Similar Proterozoic gabbro/amphibolite from the Sacramento Mountains contained 1 ppb

Pt and 66 ppb Pd (New Mexico Bureau of Mines and Mineral Resources et al., 1998). There are no PGE proved reserves or ore deposits known in New Mexico that contain high enough concentrations of significant volume to be mined economically for PGE, including the mafic rocks in the Zuni Mountains (McLemore et al., 1989).

CONCLUDING REMARKS

There is some economic potential for gold, silver, and possibly copper in the veins and replacement deposits in Proterozoic Zuni and Mt. Sedgwick granites and metarhyolite and prospecting is underway by several individuals. The Proterozoic dark syenite and amphibolite bodies and gold-silver veins in the Zuni Mountains should be geochemically evaluated for their PGE potential. It is unlikely that the stratabound, sedimentary-copper deposits or fluorite veins have any remaining significant economic potential, because the highest grades have been mined and remaining deposits appear to be discontinuous and low grade. The REE-Th-U metasomatic bodies and iron deposits also have low economic potential because of low grade and small size. The Zuni Mountains continues to have high economic potential for high-calcium limestone and volcanic cinders (scoria). The veins and replacement deposits appear to be Proterozoic in age and are associated with the Zuni and Mt. Sedgwick granites and metarhyolite, while the late Proterozoic episyenites appear to be associated with the Mt. Sedgwick granite. The fluorite veins are much younger (younger than the Permain Abo Formation) and perhaps associated with other Rio Grande rift barite-fluorite deposits in New Mexico.

FUTURE WORK

One of the most important future research activities is detailed mapping, geochemical analysis, and precise dating of the various granitic rocks, veins, and shear zones to determine the relationship between the different granites, deformation, and vein mineralization. Fluid inclusion and isotopic studies are required to constrain temperatures of formation and other geochemical conditions of mineralization of the fluorite veins and of the fluorites found in the Todilto limestone deposits to determine their origin. Detailed mapping of the Proterozoic terrain west of Goddard's (1966) map also is required.

ACKNOWLEDGMENTS

This paper is part of an on-going study of the mineral resources of New Mexico at NMBGMR, Greer Price, Director and State Geologist. Some of the 2012 field work and chemical analyses of the episyenites was funded by the U.S. Geological Survey Mineral Resources External Research Program (award number G12AP20051). This manuscript was reviewed by David Ennis and Maureen Wilks and their comments were helpful and appreciated. James McLemore is acknowledged for field assistance and discussions.

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