GEOLOGY AND MINERAL RESOURCES IN THE HOPEWELL AND BROMIDE NO. 2 DISTRICTS, NORTHERN TUSAS MOUNTAINS, RIO ARRIBA COUNTY, NEW MEXICO

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Abstract—Vein and replacement bodies (Au, Ag, Cu, Pb, Zn), volcanogenic massive-sulfide (VMS) deposits, iron formations, U-Th-REE veins, and placer gold deposits are found in the Hopewell and Bromide No. 2 mining districts in the northern Tusas Mountains in Rio Arriba County, New Mexico. The mineral deposits are found in Proterozoic rocks that can be divided into four assemblages, 1) Moppin Metavolcanic Complex, 2) Vadito Group, 3) Hondo Group (includes the Ortega Quartzite and an aluminous schist), and 4) granitic intrusive rocks, including the Tres Piedras Granite, Maquinita Granodiorite, granite of Hopewell Lake, trondhjemite of Rio Brazos, and Tusas Mountain Granite. Most of the granites are peraluminous, calc-alkalic and alkali-calcic (i.e., subalkaline) and form trends typical of calc-alkaline igneous rocks. Gold, silver, copper, lead, uranium, and vanadium have been produced from the Hopewell and Bromide No. 2 districts. The known veins, replacements, VMS, placer gold, and iron formations in the Hopewell and Bromide No. 2 districts are too small to be economic today, except perhaps for gold. More exploratory work and chemical analyses are needed to determine the undiscovered potential for gold, U, and REE in the Bromide No. 2 district. Past production from mineral deposits in the Hopewell and Bromide No. 2 districts has not been significant and limited exploration did not encourage additional investigation at the time. There is no potential for silica or kyanite in the Hopewell and Bromide No. 2 districts. The Hondo Group in these districts could have potential for scrap mica in today's economic market. The increased demand for new raw materials, especially gold, U, and REE, needed for energy technologies, such as solar panels, wind turbines, batteries, and electric motors, in the last few years has led to an increase in exploration and production worldwide, including in New Mexico. Therefore, additional investigation in the Hopewell and Bromide No. 2 districts is recommended to determine the resource potential for these commodities.

INTRODUCTION

The Hopewell and Bromide No. 2 mining districts are in the northern Tusas Mountains in Rio Arriba County, New Mexico (Fig. 1). Bingler (1968) defined the boundaries of the Hopewell district as Rio Vallecitos on the west, Jawbone Mountain on the north, Rio Tusas on the east, and Burned Mountain on the south (Fig. 2), whereas the Bromide No. 2 district includes Tusas Mountain, Rock Creek, Cunningham Gulch, Cleveland Gulch, and the upper reaches of Cow Creek (Fig. 3; Bingler, 1968). Vein and replacement bodies (Au, Ag, Cu, Pb, Zn), volcanogenic massive-sulfide (VMS) deposits, iron formation, U-Th-REE veins, and placer gold deposits are found in the Hopewell and Bromide No. 2 districts. The purposes of this paper are to 1) summarize the geology, geochemistry, and mineral production of the districts, 2) discuss the age and formation of these deposits, and 3) comment briefly on the future economic potential of mineral deposits in the districts. The geology and stratigraphy of these districts are summarized below.

This work is part of ongoing studies of mineral deposits in New Mexico and includes updates and revisions of prior work by Bingler (1965, 1968), North and McLemore (1986, 1988), McLemore et al. (1988a, b), McLemore (1983; 1992; 2001), and McLemore and Hoffman (2005). Published and unpublished data were inventoried and compiled on existing mines and mills within the Hopewell and Bromide No. 2 districts. Mineralized areas were examined and sampled in 1979-1982, 1991, 1993 and 2010. Geochemical data were obtained from published sources. Production data are in Tables 1 and 2.

GEOLOGIC SETTING

The Proterozoic rocks of the Tusas Mountains can be divided into four assemblages, 1) Moppin Metavolcanic Complex, 2) Vadito Group, 3) Hondo Group (includes the Ortega Quartzite and an aluminous schist), and 4) granitic intrusive rocks, including the Tres Piedras Granite, Maquinita Granodiorite, granite of Hopewell Lake, trondhjemite of Rio Brazos, and Tusas Mountain Granite (Manley and Wobus, 1982a, b; Wobus and Manley, 1982; Williams, 1987; Gablemen, 1988; Bauer and Williams, 1989; Williams et al., 1999; Karlstrom et al., 2004). These rocks correlate

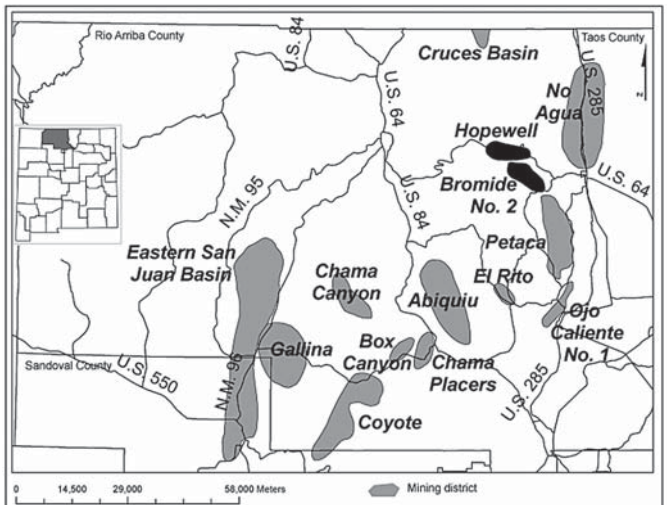

FIGURE 1. Location of Hopewell and Bromide No. 2 districts, Rio Arriba County, New Mexico.

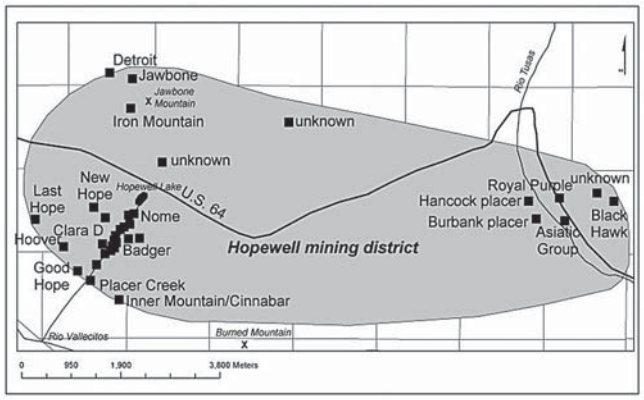

FIGURE 2. Location of major mines in the Hopewell district, Rio Arriba County. Unknown = name of prospect is not known.

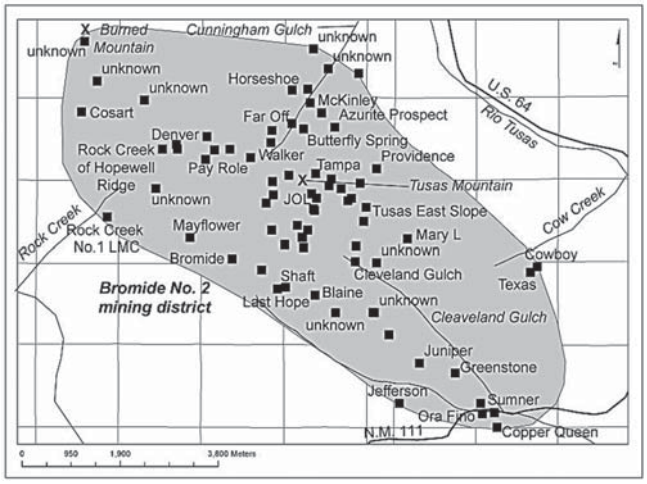

FIGURE 3. Location of major mines in the Bromide No. 2 district, Rio Arriba County.

to similar Proterozoic rocks in the Picuris and Pecos areas (Bauer and Williams, 1989). The metamorphic rocks are likely related in part to the Yavapai orogenic event at 1800-1700 Ma. Some of the deformation could be related to the Mazatzal orogenic event at 1660-1600 Ma (Karlstrom and Bowring, 1988, 1993; Karlstrom et al., 1990, 2001; 2004; Karlstrom and the CD-ROM working group, 2002). The younger Tusas Mountain Granite, previously thought to be related to the Late Proterozoic granitic plutonism at 1450-1350 Ma, found throughout southwestern New Mexico (Karlstrom and Bowring, 1988; 1993; Karlstrom et al., 1997; Karlstrom and Humphreys, 1998; McLemore et al., 2002; Karlstrom et al., 2004), now has a U-Pb zircon radiometric age determinations of 1700-1690 Ma (Davis et al., 2009; this guidebook) and may be related to the Tres Piedras Granite.

The Moppin Metavolcanic Complex includes the oldest rocks in the Tusas Mountains and some of the oldest in New Mexico, and contains metamorphosed mafic volcanic rocks, dominated by chlorite-amphibole and muscovite schist and gneiss with interbeded metamorphosed conglomerate and banded iron formation. The Mopin Metavolcanic Complex is approximately 1755 Ma (U-Pb dates on zircon, Williams, 1991; Williams et al., 1999).

The Vadito Group structurally overlies the Moppin Metavolcanic Complex and consists predominantly of rhyolite and tuffs metamorphosed to feldspathic schists and gneisses with local quartzite, muscovite-feldpsathic quartzite, biotite-muscovite schist, pelitic schist, amphibolites, and chlorite schist. The Hondo Group includes the Burned Mountain rhyolite of Barker (1958) and likely correlates with the Cerro Colorado metarhyolite and Arroyo Rancho metarhyolite (Koning et al., 2007). The Cerro Colorado metarhyolite has been dated as ~1700 Ma (U-Pb dates on zircon, Koning et al., 2007). The Vadito Group is approximately 1700 Ma (U-Pb dates on zircon, Williams et al., 1999).

The Hondo Group overlies the Vadito Group and consists of the Ortega Quartzite and an aluminous, muscovite schist. The Ortega Quartzite is a massive, relatively pure, gray to white to light pink, cross-bedded orthoquartzite with minor amounts of muscovite, kyanite, and iron oxides (predominantly hematite) and, locally, a basal conglomerate. The Ortega Quartzite represents deposition by transgressive-regressive seas (McLeroy, 1970; Soegaard and Eriksson, 1985) and has a minimum age of 1670-1689 Ma (Kopera, 2003; Jones et al., 2009). Zircons from the Ortega Quartzite are 1723-1726 Ma (Jones et al., 2009). The muscovite schist is foliated- to- massive, muscovite quartzite and locally consists of >80% muscovite and quartz. The muscovite ranges from a few percent to 40% in thin aluminous interbeds and partings and also is interbedded locally with biotite and biotite-garnet schist.

The Ortega Quartzite and the Vadito Group uncomformably overlie the the Maquinita Granodiorite and are intruded by the Tres Piedras Granite, Tusas Mountain Granite, pegmatites and aplites, and quartz veins. The Mopin Metavolcanic Complex northeast of Hopewell Lake is intruded by the light pink trondhjemite of Rio Brazos and is similar in composition to the granite of Hopewell Lake (Boadi, 1986; Gablemen, 1988). The Maquinita Granodiorite is gray to dark gray, strongly foliated grano-

TABLE 1. Reported and estimated base and precious metals production in the Hopewell and Bromide No. 2 districts, Rio Arriba County, New Mexico (updated from McLemore, 2001).

District	Years	Ore (short tons)	Copper (lbs)	Gold (oz)	Silver (oz)	Lead (lbs)	Estimated value
Bromide No. 2 Total	1881-1957	—	(<100)	(300)*	(4,500)	—	$50,000
Hopewell placer gold	1880-1910	—		(14,300)*			$300,000
Hopewell	1933-1940	1,445		94	734	7,100	$1,000
Hopewell Total	1880-1960	—	400	(24,000)*	(10,000)		$480,000

Notes: — no reported production. W withheld or not available. * includes placer gold production. ( ) estimated data. Data is from Anderson (1957), North and McLemore (1986), Johnson (1972), Bingler (1968), McLemore (1992), and NMBGMR file data and can change as better data are obtained.

TABLE 2. Reported uranium and vanadium production in the Bromide No. 2 district, Rio Arriba County, New Mexico (Chenoweth, 1974; McLemore, 1983, from U.S. Atomic Energy Commission files archived at the NMBGMR).

Mine	Year	Ore (short tons)	U_3O_8 (lbs)	$\%U_3O_8$	V_2O_5 (lbs)	$\%V_2O_5$	Company
JOL	1956	7.95	6.36	0.04	5	0.03	Arriba Uranium Co.
Tusas East Slope	1954	8.10	6.48	0.04	4.86	0.03	Colonial Uranium Co.

diorite that includes inclusions of the older schists. The granite of Hopewell Lake is in the Hopewell Lake area, intruded the Moppin Metavolcanic Complex, and has a Rb-Sr isochron radiometric age of 1467±43 Ma (Gibson, 1981; Boadi, 1986). Based upon field relationships with other dated rocks, this age is probably too young (Gableman, 1988) and instead is likely correlated with the 1750 Ma Maquinita Granodiorite or the 1700-1690 Ma Tusas Mountain granite. The low initial $^{87}Sr/^{86}Sr$ ratio of 0.70256 suggests that the granite was formed by partial melting of a preexisting rock derived from a depleted mantle source (Boadi, 1986). The Tres Piedras granite is a slightly foliated granite gneiss consisting of quartz, feldspar, biotite, and muscovite and intrudes the Vadito Group. The Tres Piedras granite is 1650 Ma (U-Pb; Maxon, 1976) to 1700±9 Ma based on U-Pb dates (Davis et al., 2009; this guidebook).

The Tusas Mountains Granite is a small stock forming the core of Tusas Mountain and previously had minimum ages of 1421-1501 Ma using U-Pb and Rb-Sr dating techniques (Maxon, 1976; Wobus and Hedge, 1982). However, recent U-Pb zircon dating by Davis et al. (2009; this volume) suggests that the Tusas Granite is ~1700 Ma. The Tusas Mountain Granite is white to pink to red, quartz-rich, alkali granite to granite porphyry and enriched in F, Be, Li, Mo, and Sn (Wobus and Hedge, 1982; Corbett, 1986). Three textural and compositional variations of the Tusas Mountain Granite are recognized (Kent, 1980; Goodknight and Dexter, 1984): 1) reddish-orange to gray to white, poorly to moderately foliated granite; 2) dark red, hematite-stained granite associated with the older Moppin metavolcanic rocks at the contact zone and quartz veins; and 3) pink to white and gray biotite-rich granite. The intrusive contact between the Tusas Mountain Granite and the older Moppin Metavolcanic Complex generally is sharp and well exposed. The distinctive features of this contact are the abundance of epidote veins, euhedral garnets and hornblende, and disseminated fluorite in the Moppin schists within 150 m of the contact (Kent, 1980; Goodknight and Dexter, 1984). The Tusas Mountain Granite is locally altered to sericite, fluorite is disseminated in the granite, and the granite contains anomalously high concentrations of Be, Li, Mn, Sn, and F (Wobus and Hedge, 1982; Corbett, 1986).

Rapakivi texture is found locally in the Tusas Mountain Granite (Fig. 4). *Rapakivi* is Finnish for rotten or crumbly rock and describes the tendency of the rapakivi granite to weather easily. The rapakivi texture refers to the mantling of K-feldspar phenocrysts by plagioclase (Haapala and Rämö, 1990; Rämö and Haapala, 1995; 2005). Many of the 1.45-1.35 Ga granites in the southwestern U.S. have rapakivi textures, but similar textures also can be found in early Proterozoic, and some Phanerozoic and Archean granites. Feldspars from the Tusas Mountain Granite forming the rapakivi texture are albite and microcline with little or no calcium content (Corbett, 1986). Corbett (1986) believes the calcium was leached from the feldspars and reprecipitated as fluorite (Corbett, 1986). Rapakivi granites elsewhere in the world are associated with Fe oxide-Cu-Au mineral deposits (i.e., Olympic Dam-type deposits) that also contain uranium and rare-earth elements (REE) and with greisen-, vein-, and skarn-type tin (± tungsten, beryllium, zinc, copper, and lead) mineral deposits (Haapala, 1995; Müller, 2007). More research is required to determine the origin and tectonic setting of the rapakivi texture in the Tusas Mountain Granite.

The youngest intrusive rocks in the Proterozoic section are pegmatites, aplites, and quartz veins. Pegmatites in the northern Tusas Mountains are rare and basically are simple quartz, feldspar, and muscovite pegmatites, unlike the complex mineralogically zoned pegmatites found in the Petaca and Ojo Caliente districts in the central and southern Tusas Mountains (Just, 1937; Jahns, 1946; Bingler, 1968; McLemore, this guidebook). Most of the pegmatites found in New Mexico are associated with the Late Proterozoic granite plutonism of 1450-1350 Ma (McLemore et al., 1988a, b). The quartz veins commonly grade into the pegmatites and consist of white to colorless quartz with minor amounts of muscovite and feldspar locally. These quartz veins generally lack economic mineralization.

GEOCHEMISTRY OF THE GRANITES

Geochemical analyses of the granitic intrusions from the northern Tusas Mountains were compiled from published references and theses (Table 3) in order to classify and characterize the intrusive rocks. The TAS (total alkali-silica) diagram of Le Bas et al. (1986) is widely used in classifying igneous rocks by lithology

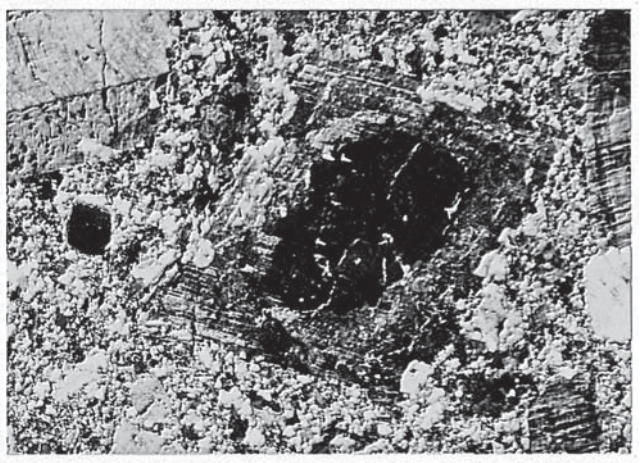

FIGURE 4. Rapakivi texture in the Tusas Mountain Granite. A ragged microcline phenocrysts is 2 mm in diameter and rimmed by plagioclase. Crossed-polarized light. Field of view is approximately 5 mm.

TABLE 3. Average chemical analyses of granitic intrusions from the north Tusas Mountains. Major elements are in percent and trace elements are in parts per million (ppm).

	average Tusas Mountain Granite	average Maquinita Granodiorite	average Tres Piedras Granite	average granite of Hopewell Lake	Averagerhyolite/ metarhyolite	Average trondhjemite
SiO2	74.08	68.64	76.38	65.44	77.32	75.65
TiO2	0.20	0.35	0.16	0.34	0.20	0.14
Al2O3	12.72	15.86	12.34	16.56	11.90	12.91
Fe2O3	0.87	1.66	1.08	1.75	1.33	1.24
FeO	0.57	1.54	0.58	1.53	0.76	0.89
MnO	0.11	0.05	0.03	0.06	0.11	0.26
MgO	0.17	1.13	0.11	1.32	0.45	1.22
CaO	0.60	1.93	0.43	1.97	0.56	1.22
Na2O	4.14	4.87	2.84	5.61	3.14	5.19
K2O	4.10	2.46	4.55	1.60	2.75	0.68
P2O5	0.20	0.32	0.06	0.14	0.21	0.05
LOI	0.71	0.93	0.49	3.26	0.78	0.57
F	0.47	0.09				
Total	98.46	99.58	98.40	99.56	99.28	99.99
Rb		46		36	65	12
Ba	299	959		1178	281	244
Sr	58	590		608	103	103
Pb	55	55		12	22	3
Th				1	9	6.5
U	13	3			6	5.5
V		46		67	101	144
Cr		68		80	198	346
Ni		16		10	6	4.5
Cu	9	66		44	12	8.5
Zn	79	54		42	98	19.5
Ga		13		16	17	11.5
Y	34	7		7	58	29.5
Zr		130		109	212	107.5
Nb		8		8	20	
Co		78				
Be	6					
Li	92					
Mo	14					
Sn	9					
number of analyses	12	10	6	7	7	2

Note: Analyses are from Kent (1980), Gibson (1981), Wobus and Hedge (1982), Goodknight and Dexter (1984), Boadi (1986), Smith (1986), and Gableman (1988).

(Fig. 5). Most granitic samples in the northern Tusas Mountains plot in or near their respective lithologic fields using these diagrams; i.e., granites as granites and granodiorites as granodiorites.

The granitic samples from the Tusas Mountains plot in the volcanic-arc granite field of Pearce et al. (1986) and the rhyolites/metarhyolite samples plot within the continental plate granite field. Most of the granites are peraluminous (Fig. 6), calc-alkalic and alkali-calcic (i.e., subalkaline) and form trends typical of calc-alkaline igneous rocks, according to the definition of Irvine and Baragar (1971) and Frost et al. (2001). The granite of Hopewell Lake and trondhjemite of Rio Brazos are similar in chemical composition to the Maquinita Granodiorite and are likely coeval with

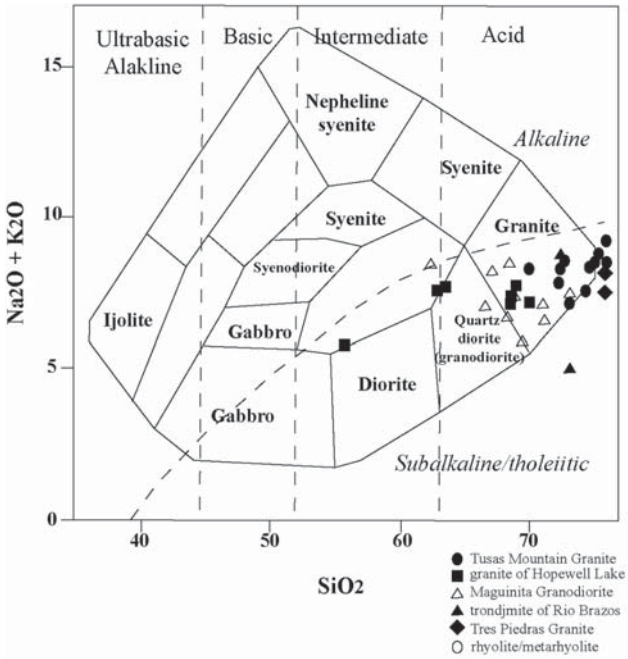

FIGURE 5. TAS diagram (Le Bas et al., 1986) showing the classification of the samples from the Tusas Mountains as predominantly subalkaline to alkaline granites. TAS is Total alkali (NaO_2+K_2O) verses SiO_2. Solid black circles are Tusas Mountain Granite, solid triangles are trondhjemite of Rio Brazos, solid squares are granite of Hopewell Lake, open triangles are Maquinita Granodiorite, solid diamonds are Tres Piedras Granite, open circles are rhyolite/metarhyolite.

the granodiorite. The granite of Hopewell Lake, trondhjemite of Rio Brazos, and Maquinita Granodiorite have a distinctive chemical composition that differs from the composition of the Tusas Mountain Granite (Figs. 6, 7). The granite of Hopewell Lake and Maquinita Granodiorite have more calcium and sodium and less fluorine and uranium then the Tusas Mountain Granite. These chemical differences suggest that the granite of Hopewell Lake and Maquinita Granodiorite are possibly related to the deposition and metamorphism of the Vadito rocks and the Tusas Mountain Granite is younger. Alternatively, the three granites could be from the same source and differ in chemistry because of differences in crustal differentiation and mixing. Additional chemical analyses, especially trace element and isotopic analyses, are required to further characterize these granitic rocks.

MINING HISTORY AND PRODUCTION

Reported and estimated metals and uranium production from the two districts are in Tables 1 and 2. Mining and production records are generally poor, particularly for the earliest times, and many early records are conflicting. These production figures are the best data available and were obtained from published and unpublished sources. However, production figures are subject to change as new data are obtained.

Once the Hopewell and Bromide No. 2 districts were part of the larger Headstone district, and were separated into two separate districts before 1910 (Lindgren et al., 1910; Benjovsky, 1945). Gold was discovered and mined at the Fairview placers in the Hopewell district about 1870 and the district was named for Hopewell Lake, a major source of water for the placer operations (Lindgren at al., 1910; Bingler, 1968; Gibson, 1981). Further exploration located and developed some of the major veins along Placer Creek. Most oxidized portions of the lode deposits were mined out by 1890. In 1903, extensive placer operations drained the small natural lakes and the miners dammed Placer Creek near the Fairview placer where the gorge narrowed (Bingler, 1968). Total placer production until 1910 is estimated as $300,000 or approximately 8,500 oz (Johnson, 1972). The Amarillo Gold Co. constructed a mill at the Mineral Point mine in 1935, but closed in 1937. Additional placer production occurred in the early 1960s by the Amistad Mining Co., but total production is minor (Gibson, 1981). Now the area is popular for recreational gold panning.

Ore was first discovered about 1881 at the Bromide mine in the Bromide No. 2 district. The silver mineral was misidentified as silver bromide, which resulted in the name of the district as Bromide No. 2. Sporadic mining and exploration occurred in the district from 1881 until 1957. Several car loads of copper, gold, and silver ore were shipped prior to 1905. Several mining and exploration companies re-examined both districts about 1960 to mid-1980s.

In the 1950s, anomalously high radioactivity was discovered in the Bromide No. 2 district at and surrounding Tusas Mountain during prospecting for radioactive veins and pegmatites (Stroud, 1954; Hilpert, 1969; Goodknight and Dexter, 1984). Small ship-

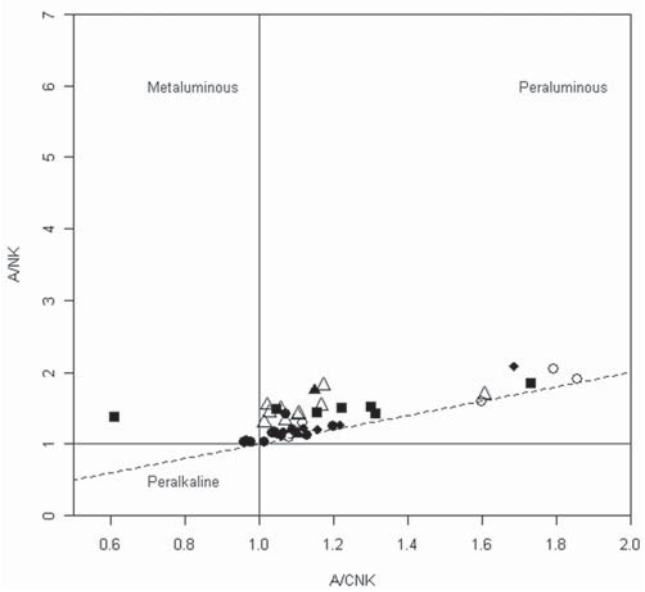

FIGURE 6. A/CNK-A/NK diagram (Shand, 1943) showing the classification of the samples from the Tusas Mountains as predominantly peraluminous granites. A/CNK (Al_2O_3/(CaO+Na_2O+K_2O) verses A/NK (Al_2O_3+Na_2O+K_2O) (Shand, 1943). Solid black circles are Tusas Mountain Granite, solid triangles are trondhjemite of Rio Brazos, solid squares are granite of Hopewell Lake, open triangles are Maquinita Granodiorite, solid diamonds are Tres Piedras Granite, open circles are rhyolite/metarhyolite.

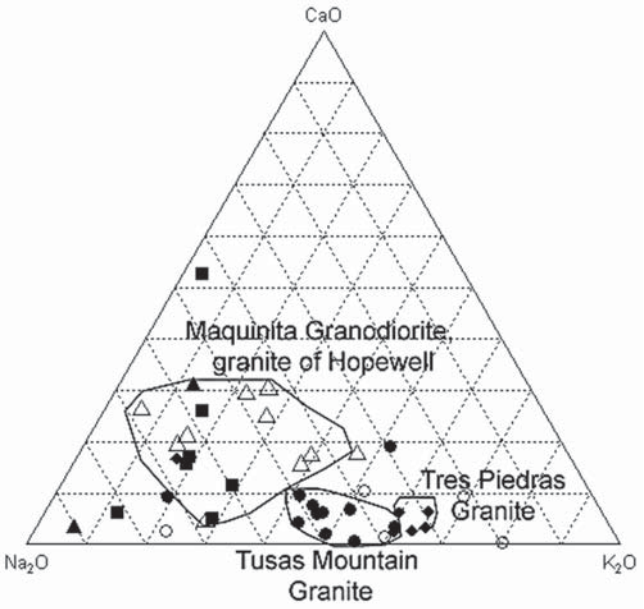

FIGURE 7. Na_2O-CaO-K_2O diagram of granite intrusions in the Tusas Mountains showing the differences in chemical composition between the granitic rocks. Solid black circles are Tusas Mountain Granite, solid triangles are trondhjemite, solid squares are granite of Hopewell Lake, open triangles are Maquinita Granodiorite, solid diamonds are Tres Piedras Granite, open circles are rhyolite/metarhyolite.

ments of uranium ore were made from the JOL and Tusas East Slope properties in 1954-1956 (Table 2). Urania Exploration Company and Phillips Petroleum Company examined the area for possible uranium deposits in the 1970s to 1980s.

DESCRIPTION OF THE MINING DISTRICTS

Hopewell district

Most of the gold deposits in the Hopewell district are in the Moppin Metavolcanic Complex and recent alluvial sediments. Altered rocks of the Moppin Metavolcanic Complex in the Hopewell district typically contain 1-10 ppm Au; one sample from near the Croesus mine contained 1,160 ppm Au (Boadi, 1986). Four types of mineral deposits are found in the Hopewell district: sulfide-vein and replacement bodies, gold-quartz veins, iron formations, and placer gold deposits.

Vein and replacement bodies

Gold is found in quartz veins, locally with calcite, and in massive, sulfide-bearing vein and replacement bodies (Bingler, 1968; Boadi, 1986). Vein and replacement bodies typically are less than 30 cm wide and several meters long, and are parallel to layering, schistocity, and shear zones. Brecciation is common. The quartz (± carbonate) veins typically occur in the felsic units of the series, whereas the massive, sulfide-bearing vein and replacement bodies typically are restricted to the altered mafic rocks. Pyrite halos commonly surround the deposits and sericite commonly is present. The deposits consist of pyrite, chalcopyrite, sphalerite, galena, fluorite, and hematite with trace amounts of gold, stibnite, and arsenopyrite in a gangue of calcite, dolomite, quartz, tourmaline, iron oxides, chlorite, and sericite (Bingler, 1968; Gibson, 1981; Boadi, 1986). Gold is associated with pyrite and chalcopyrite. Rock and vein samples from the district assayed <0.15-1,160 ppm Au, <0.002-2.37% Cu, 0.003-3.8% Pb, 0.002-6.26% Zn, 1-240 ppm As, and 0.5-29 ppm Sb (Boadi, 1986).

Proterozoic iron formation

Precambrian iron formations are stratigraphic units composed of layered or 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 those in NM are quite small in comparison. Precambrian banded iron formations are found in the Moppin Metavolcanic Complex in the Iron Mountain area in the northern Hopewell district, and are similar to those found in the Bromide No. 2 district. There has not been any iron production in either locality. In the Iron Mountain area, two layers, ranging in thickness from 3 to 6 m and several hundred meters long, are present (Lindgren et al., 1910; Bingler, 1968). Two types of iron formation are found at Iron Mountain: 1) very fine-grained, magnetite-quartz banded iron lenses interbedded with metapelites (BIF, banded iron formation, Bekker et al., 2010) and 2) sugary-textured, unbanded, hematite-quartz-±magnetite ironstone (GIF, granular iron formation, Bekker et al., 2010) that is interbedded with amphibolites and gneisses (Kent, 1980). The BIF lenses typically are 1.5 to 3 m thick and are discontinuously interbedded with the metapelites (i.e., chlorite and felsic phyllites). The banding is formed by alternating bands of magnetite and quartz, 1-10 mm thick. The GIF lenses are 3 to 15 m thick, with irregular, discontinuous to no banding and contain 40-50% magnetite, 30-40% quartz, and 15-20% chlorite, with minor hematite (Smith, 1986). A sample contained 40.1% Fe, 0.26% P, 0.12% S, 0.1% TiO_2, <0.1% Mn, and 38.4% SiO_2 (Harrer and Kelly, 1963). The iron formations at Iron Mountain are similar to those found in the Yavapai Series in central Arizona, but contain more magnetite and less hematite than the Iron Ranges in Minnesota (Bayley and James, 1973).

Placer gold deposits

Alluvial placer gold was predominantly produced from Placer Creek; small flakes and nuggets are still found by persistent gold panning (Johnson, 1972; Boadi, 1986). The Proterozoic conglomerates in the Ortega Quartzite were examined for fossil placer gold deposits, without any success (Barker, 1969).

Bromide No. 2 district

Vein and replacement bodies

Quartz-sulfide veins with copper, gold, and silver in Precambrian rocks form the bulk of the metals deposits in the Bromide No. 2 district (Fig. 1), were discovered in 1881, and are similar to those found in the Hopewell district. In addition to quartz, the

veins contain chalcopyrite, gold, tetrahedrite, calcite, malachite, and pyrite.

Volcanogenic massive-sulfide deposits

Volcanogenic massive-sulfide (VMS) deposits are volcanogenic, polymetallic, stratabound deposits which consist 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, massive-sulfide 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 of the Moppin Metavolcanic Complex in the Hopewell and Bromide No. 2 districts are suggestive of volcanogenic massive-sulfide deposits (Robertson et al., 1986). The ore occurs in two textural types: 1) low- to moderate-grade (approximately 50% sulfides) massive or banded ore, and 2) stringer ore containing low-grade veinlets and stringers of sulfides. Some of the copper-silver-gold mineralization is found along the contacts of the mafic and rhyolitic rocks. At the Pay Role mine, chalcopyrite, galena, bornite, pyrite, pyrrhotite, magnetite, and calcite are found as thin stringers and veins along the foliation planes of the sericite-chlorite schist (Lindgren et al., 1910; NMBGMR file data), typical of VMS deposits. However, much of the copper-silver-gold mineralization is associated with quartz veins, which are not consistent with VMS deposits.

Uranium-Th-REE veins

Uranium-Th-REE occurrences are found in and surrounding the Tusas Mountain Granite in three distinct types: 1) quartz-fluorite veins and disseminations in both granite and schist along the contact between the Tusas Mountain Granite and older Moppin Metavolcanic Complex, 2) along fractures, shear zones, and faults within altered Tusas Mountain Granite, and 3) along boundaries and fractures of amphibolite-schist xenoliths and roof pendants in the Tusas Mountain Granite. These veins, disseminations, and fracture coatings and fillings locally contain uraninite, sabugalite, meta-torbernite, thorite, huttonite, uranothorite, thorogummite, zircon, monazite, xenotime, and allanite (Bingler, 1968; Chenoweth, 1974; Goodknight and Dexter, 1984; McLemore et al., 1988a, b). Alteration, specifically silicification and epidotization forms a thin halo along both sides of the veins and mineralized rocks. Hydrothermal brecciation and hydrofracturing are common textures. Chemical analyses of samples contain as much as 0.17% U_3O_8 and 2% Th and anomalous high concentrations of Nb (720 ppm) and La (580 ppm) are present in some samples (McLemore, 1983; Goodknight and Dexter, 1984). More chemical analyses are needed to determine the potential for these other commodities.

Proterozoic iron formation

Precambrian iron formations are found in the Moppin Metavolcanic Complex in the Cleaveland Gulch, Cana Plaza, and Burned Gulches and are similar to those found in the Hopewell district, described above (Bertholf, 1960; Harrer and Kelly, 1963; Harrer, 1965; Bingler, 1968). The multilayered BIF deposits in the Bromide No. 2 district are 1.8 to 2.1 m thick, 30.5 to 45.7 m wide, 915 m long, contain 32% iron, and are interbeded with quartzite and schist (McLeroy, 1970, 1972; Harrer and Kelly, 1963; Kent, 1980). Two samples contained 29.7-37.7% Fe, 0.1-0.15% P, 0.04-0.12% S, 0.1-0.16% TiO_2, 0.2% Mn, and 44.4-53.2% SiO_2 (Harrer and Kelly, 1963). More than 100 million short tons of low-grade iron resources are estimated to occur in this part of the district (Harrer and Kelly, 1963), but these deposits are smaller in size and lower in grade than most economic iron formations in the world and would require drilling to confirm these resource estimates.

POTENTIAL FOR OTHER COMMODITIES

Mica

Muscovite is common throughout the Proterozoic rocks in the Hopewell and Bromide No. 2 districts, especially in the Hondo Group. Scrap mica was produced in 1990-2004 from the U. S. Hill mine (formerly the MICA mine) in Taos County (Oglebay-Norton Inc.). The mica was produced from a muscovite quartz schist of Proterozoic age (Nelson, 1996) similar to the mica schists in the Hondo Group. The U.S. Hill mine closed in 2004 because of increased opposition to mine expansion from the nearby Picuris Pueblo. Mica is used as functional filler in building materials because of its unique physical characteristics, including color, flexibility, durability, thermal properties, and weight. Mica is used in the manufacture of numerous industrial and consumer products such as joint compound, paints, automotive sound deadening materials, thermoplastics, coatings, and even cosmetics.

Mica has been produced in the past from the pegmatites in the Petaca and Ojo Caliente districts (McLemore, this guidebook), but not from mica schists in the Tusas Mountains. Most mica schists are too dark colored and impure to be considered economic, but some muscovite schists are light in color, especially in the Hondo Group and could be suitable. Additional field, mineralogical, and chemical investigation is required to determine if the muscovite schists have any potential for scrap mica in today's economic market.

Silica

High silica sands can be mined and used in the manufacture of glass, foundry operations, and as fillers and extenders. Economic deposits must consist of nearly pure quartz with little or no iron oxides. The Ortega Quartzite locally consists of nearly pure quartz and could be a silica resource. However, the well-cemented nature of the Ortega Quartzite and distance to potential markets makes the Ortega Quartzite an unlikely silica resource, unless a local market is developed. The quartzite could be used as an aggregate, but it is too far from known markets to be economic.

Kyanite

Kyanite is a white to blue to green aluminium silicate mineral that occurs in metamorphic rocks and pegmatites and is mined for use in the manufacture of heat-resistant refractory ceramics, for smelting and processing of ferrous metals, and manufacture of chemicals, glass, nonferrous metals, and other materials (Sweet et al., 2006). Kyanite expands irreversibly by up to 18%, thereby offsetting the firing shrinkage of other raw materials, especially clay, in ceramic bodies and refractories. Kyanite increases the fired strength, resistance to deformation under load, and thermal resistivity of refractories. The world's largest producer of kyanite is Kyanite Mining Corporation in Virginia and remaining reserves are adequate for the near future (Sweet et al., 2006). Kyanite is found in the Proterozoic metamorphic rocks of the northern Tusas Mountains, but kyanite is only found in trace amounts in the Hopewell and Bromide No. 2 district and is not of economic potential. Better deposits of kyanite are found in the Petaca district (McLemore, this guidebook).

ORIGIN OF MINERAL DEPOSITS

Proterozoic iron formation

McLeroy (1970) believed the iron formation to be formed by hydrothermal replacements of muscovite and chlorite schist by iron-rich fluids associated with the Tusas Mountain Granite. However, Beutner (1970) and Kent (1980) refuted evidence presented by McLeroy (1970) and proposed that the banded iron formation was part of the sedimentary sequence deposited during a pause in volcanic activity, similar to the formation of other iron formations found in the world (Bekker et al., 2010).

Vein and replacement bodies

The age of veins and replacement mineralization in the two districts is unknown, but presumed Proterozoic because mineralized bodies are found along Proterozoic structures within Proterozoic rocks. Limited fluid inclusion studies of deposits in the Hopewell district indicate that mineral deposition occurred at 250-330°C at pressures of approximately 1.5 kb during unmixing of a CO_2-rich fluid (Boadi, 1986). The deposits appear to be coeval with the granite of Hopewell Lake and Maquinita Granodiorite (Boadi, 1986). More work is needed to determine the origin of these deposits, especially to determine if the veins are indeed epithermal and their relationship with fluid CO_2.

Volcanogenic massive-sulfide (VMS) deposits

The association of marine volcanic rocks of the Mopin Volcanic Complex and potentially cogenetic granodioritic intrusions of the Maquinita Granodiorite, suggest a volcanogenic massive-sulfide (VMS) association, similar to that seen in the Yavapai Series of Arizona and other VMS deposits in Colorado. Volcanogenic massive-sulfide deposits were 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., 1981; Barrie and Hannington, 1999; Stix et al., 2003). Similar deposits are forming today on the seafloor. The deposits in the Bromide No. 2 district have similarities to VMS deposits (Robertson et al., 1986), but additional investigation should be performed to examine the similarity and determine genesis of the deposits.

Uranium-Th-REE veins

The U-Th-REE veins are associated with the Tusas Mountain Granite and have textures and mineral assemblages typical of hydrothermal veins associated with granitic systems. The Tusas Mountain Granite is enriched in these and other lithophile elements (Table 3; Wobus and Hedge, 1982; Corbett et al., 1988). These veins are likely hydrothermal or magmatic-hydrothermal veins related to the intrusion of the Tusas Mountain Granite, possibly related to crustal melting during the Mazatzal orogeny deformation.

Placer gold deposits

Four hypotheses could explain the source of the placer gold deposits in the Hopewell district. The gold could have been eroded from Proterozoic veins and bedrock at Hopewell Lake, carried by the streams and deposited in Placer Creek (Johnson, 1972). The gold could have been deposited in the geologic past as a colluvial deposit along the Proterozoic-Tertiary boundary and later exposed by the down cutting of Placer Creek and redeposited along the creek. The gold also could have been deposited in the Oligocene Ritito Conglomerate. The forth hypothesis is that the gold was derived from a combination of Proterozoic and Tertiary sources and deposited in Placer Creek.

OUTLOOK FOR MINERAL RESOUCE POTENTIAL IN THE FUTURE

The known veins, replacements, VMS, placer gold, and iron formations in the Hopewell and Bromide No. 2 districts are too small to be economic today, except perhaps for gold. The iron ore deposits found at Bromide are large enough to be interesting, but the grade and size are well below what would be economically feasible today. Beneficiation tests should be done though to see if it can be upgraded to ~50%, as material of this grade is currently being mined, at least in Utah. More chemical data and mapping are needed to determine the potential for additional gold, U, and REE in the Bromide No. 2 district. Past production from mineral deposits in the Hopewell and Bromide No. 2 districts has not been significant and limited exploration did not encourage additional investigation at the time. There is no potential for silica or kyanite in the Hopewell and Bromide No. 2 districts. Additional field, mineralogical, and chemical investigation is required to determine if the Hondo Group in these districts has any potential for scrap mica in today's economic market. The increased demand for new raw materials, especially gold, U, and REE, needed for energy technologies, such as solar panels,

wind turbines, batteries, and electric motors, in the last few years has led to an increase in exploration and production worldwide, including in New Mexico. Therefore, additional investigation for gold, U, and REE in the Hopewell and Bromide No. 2 districts is recommended.

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