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GEOLOGY AND MINERAL RESOURCES OF THE LAUGHLIN PEAK MINING DISTRICT, COLFAX COUNTY, NEW MEXICO

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ABSTRACT—The Laughlin Peak district in the Laughlin Peak-Chico Hills igneous complex is in the southern portion of the younger Raton-Clayton volcanic field, southeast of Raton in northeastern New Mexico, along the Jemez Lineament, and is part of the North American Cordilleran alkaline-igneous belt that extends from Alaska and British Columbia southward into New Mexico and eastern Mexico. The Laughlin Peak-Chico Hills complex was emplaced just before or at the beginning of Rio Grande rift extension (22–37 Ma). Host rocks in the Laughlin Peak district are alkaline, predominantly ferroan, predominantly metaluminous to peralkaline and plot as A-type granites, WPG (within-plate granites), and active continental margins zone. The igneous rocks exhibit typical light rare earth elements (REE) enriched chondrite-normalized REE patterns of alkaline rocks with no europium anomaly. The alkaline igneous rocks in the district are similar in composition and texture to igneous rocks found in two other REE districts in the North American Cordilleran alkaline-igneous belt (also known as the Great Plains Margin or GPM) in New Mexico, the Gallinas and Cornudas Mountains. Although there has been no mineral production from the Laughlin Peak district, three types of mineral deposits have been identified: (1) carbonatites, (2) breccia pipe deposits, and (3) Th-REE hydrothermal veins. Since 1987, only minor exploration of these deposits occurred because of low commodity prices and environmental concerns. However, as the current demand for critical commodities like REE has increased, new exploration programs have encouraged additional research on the geology of these deposits. Thorium, REE and possibly gold are potential commodities in the Laughlin Peak district, but additional drilling is required to fully understand the mineral resource potential. Detailed studies on the mineralogy and paragenesis also are required in the Laughlin Peak district and should be completed before advanced exploration. These studies will greatly enhance exploration efforts. The diversity of igneous rocks and associated mineral deposits along the boundary of the Great Plains with the Southern Rocky Mountain and Basin and Range provinces suggests that this region is characterized by multiple pulses of highly fractionated and differentiated magmas. In the Laughlin Peak-Chico Hills complex, two different chemical trends of phonolite are found that could be a result of differences in fractionation. Both upper mantle and lower crustal source rocks may be involved, although in the Laughlin Peak-Chico Hills complex, a lower crustal source with possible mixing of upper crustal rocks is suggested by geochemical data. Deep-seated fracture systems or crustal lineaments, such as the Jemez Lineament, apparently channeled the magmas and hydrothermal fluids. Once magmas and metal-rich fluids reached shallow levels, the distribution and style of these intrusions, as well as the resulting associated mineral deposits, were controlled by local structures and host rock compositions.

INTRODUCTION

The North American Cordilleran alkaline-igneous belt extends from Alaska and British Columbia southward into New Mexico and eastern Mexico (Fig. 1). Along this belt, gold, fluorine, zirconium, rare earth elements (REE), and other elements have been found and exploited from several types of mineral deposits. In New Mexico, the belt extends from the Sangre de Cristo Mountains, southward to the Cornudas Mountains, in the northern Trans-Pecos alkaline-igneous belt (Fig. 2). North and McLemore (1986) and McLemore (1996, 2015a, b) summarized the deposits in this belt and called them Great Plains Margin (GPM) deposits. Significant gold production in New Mexico has come from some deposits within this belt. Alternative classifications by other workers include Au-Ag-Te veins (Cox and Bagby, 1986; Bliss et al., 1992; Kelley et al., 1998), alkalic-gold or alkaline-igneous related gold deposits (Fulp and Woodward, 1991; Thompson, 1991a, b; Bonham, 1988; Mutschler et al., 1985, 1991; Richards, 1995; Jensen and Barton, 2000), porphyry gold deposits (Rytuba and Cox, 1991) and the Rocky Mountain Gold Province.

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Since 1987, only minor exploration and development of these deposits occurred because of low commodity prices and environmental concerns. However, as the current demand for critical commodities like REE and tellurium has increased, new exploration programs elsewhere in the North American Cordilleran alkaline-igneous belt have encouraged additional research on the geology of these deposits. The origin of these deposits is still not well understood, but compilation of past data, including geologic mapping, age dates, and isotopic and chemical analyses of igneous rocks and associated mineral deposits, allows for a better understanding of the characterization and origin of these deposits.

The Laughlin Peak district is in the Laughlin Peak-Chico Hills igneous complex southeast of Raton in northeastern New Mexico (Fig. 2). The older Laughlin Peak-Chico Hills igneous complex (22–37 Ma) is overprinted by the younger Raton-Clayton volcanic field (3.5–9 Ma; Staatz, 1985; Stroud, 1997), and both igneous fields lie along the Jemez Lineament.

A number of previous workers have examined the geology and mineral resources of the Laughlin Peak district (Staatz, 1985, 1986, 1987; Schreiner, 1991; Potter, 1988), but a re-examination of the Laughlin Peak district is warranted in light of today's potential economic importance of REE and gold. Therefore, the purposes of this report are to (1) summarize the previous work and exploration history of the Laughlin Peak district; (2) describe the geology, geochemistry, and mineral deposits in the district; (3) summarize the mineral resource potential of the district; and

(4) summarize the origin of the igneous rocks and mineral deposits of the district.

PREVIOUS WORK, EXPLORATION HISTORY, AND METHODS OF STUDY

The Laughlin Peak-Chico Hills area was first mapped by Wood et al. (1953) as part of oil and gas investigations in northeastern New Mexico. Some of the early studies of the igneous rocks were by Collins (1949) and Stobbe (1949). Tschanz (1958) was the first to report the Th-REE veins and McLemore (1983) examined the uranium and thorium potential in the area. Staatz (1985, 1986, 1987) conducted geologic mapping and described the Th-REE veins and Scott and Pillmore (1993) presented a geologic map of the Raton 30 by 60 degree quadrangle. McLemore et al. (1988a, b) summarized the REE potential and North and McLemore (1986, 1988) and McLemore (2001) examined the gold potential in the district. Potter (1988, 2007) studied the geochemistry of the igneous rocks. Schreiner (1991) examined the mineral resource potential of the carbonatites, Th-REE veins, and breccia pipes. Geochronology has been part of regional studies by Stormer (1972), Staatz (1985, 1986, 1987), Scott et al. (1990) and Stroud (1997).

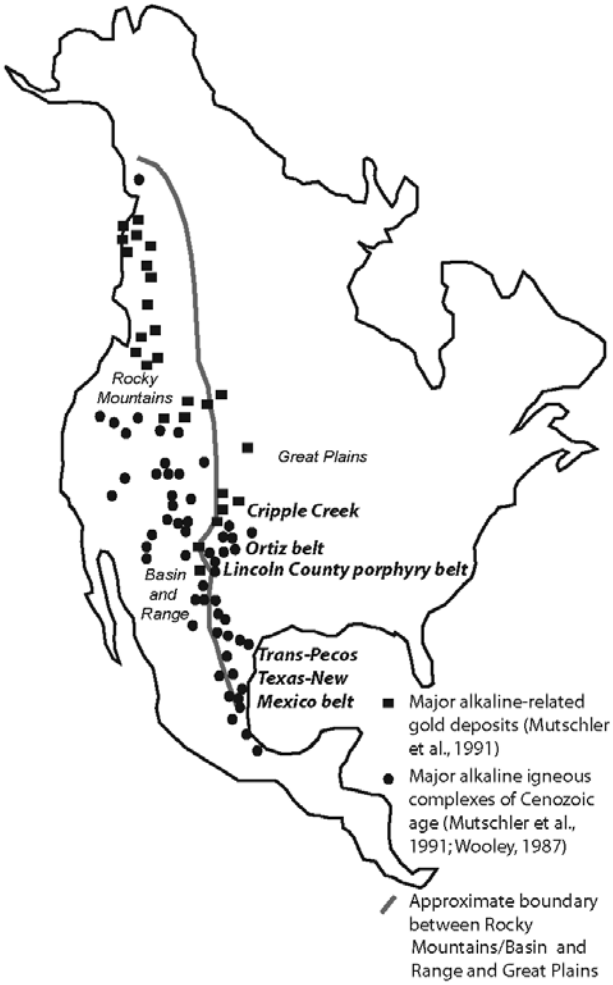

FIGURE 1. Extent of the North American Cordilleran alkaline-igneous belt (Woolley, 1987; Mutschler et al., 1991; McLemore, 1996). The Laughlin Peak district is between the Ortiz Belt and Cripple Creek.

There has been no mineral production from the Laughlin Peak district, except for some quarried rock for construction purposes, although numerous shallow pits, trenches, and shafts were dug since the 1950s exploring for predominantly uranium and thorium. A few shallow holes were drilled in the 1950s for uranium and thorium (Table 1). In 1986, two holes were drilled in breccia pipes to determine the potential for REE and gold mineralization in the western portion of the district (Table 1) by James Hennigan in cooperation with the New Mexico Bureau of Mines and Mineral Resources (now New Mexico Bureau of Geology and Mineral Resources, NMBGMR). Some of these data are contained in this report. Since then several mining and exploration companies have briefly examined the area for REE and gold potential, but there has been no additional drilling. Most of the area is privately owned, although some areas are state and federal mineral ownership.

TABLE 1. Locations of drill holes for uranium, thorium, REE, and gold exploration in the Laughlin Peak district, shown in Figure 3. Coordinates are NAD27.

Latitude (degrees)	**Longitude** (degrees)	**Approximate date of drilling**	**Depth** (m)
36.6063623	104.2270253	1950s	?
36.6024581	104.2197842	1986	35
36.6019016	104.2187249	1986	76

Data used in this report have been compiled from a literature review, field examination, and NMBGMR unpublished data, including mineralogy and geochemistry of the igneous rocks and the mineral deposits. Chemical compositions of igneous rocks and mineral deposits in the Laughlin Peak district are in Appendix 1 and were obtained from Staatz (1985, 1986, 1987), Potter (1988), and Schreiner (1991). Analytical methods are described in these cited reports. The chemical data were plotted on various geochemical and tectonic diagrams (Shand, 1943; Irvine and Baragar, 1971; Pearce et al., 1984; Whalen et al., 1987; Frost et al., 2001; Schandl and Gorton, 2002), as described below. A variety of nomenclatures for the igneous rocks in these districts were used in previous studies, because the rocks typically are porphyritic in a fine-grained matrix and include shallow intrusions as well as extrusive volcanic rocks. The nomenclature of igneous rocks in this report mostly conforms to the International classification proposed by LeMaitre (1989), where the primary classification of igneous rocks is based upon mineralogy and, if too fine-grained to determine mineralogy, by the use of whole-rock geochemical analyses using the TAS (Cox et al., 1979) and R1-R2 (de la Roche et al., 1980) diagrams.

Published and unpublished data on existing prospects within the Laughlin Peak district were inventoried and compiled in the New Mexico Mines Database (Appendix 2; McLemore et al., 2005a, b). Chemical analyses of carbonatites are in Appendix 3 and of veins and breccia pipes in Appendix 4 (from Staatz, 1985; Schreiner, 1991; NMBGMR unpublished data).

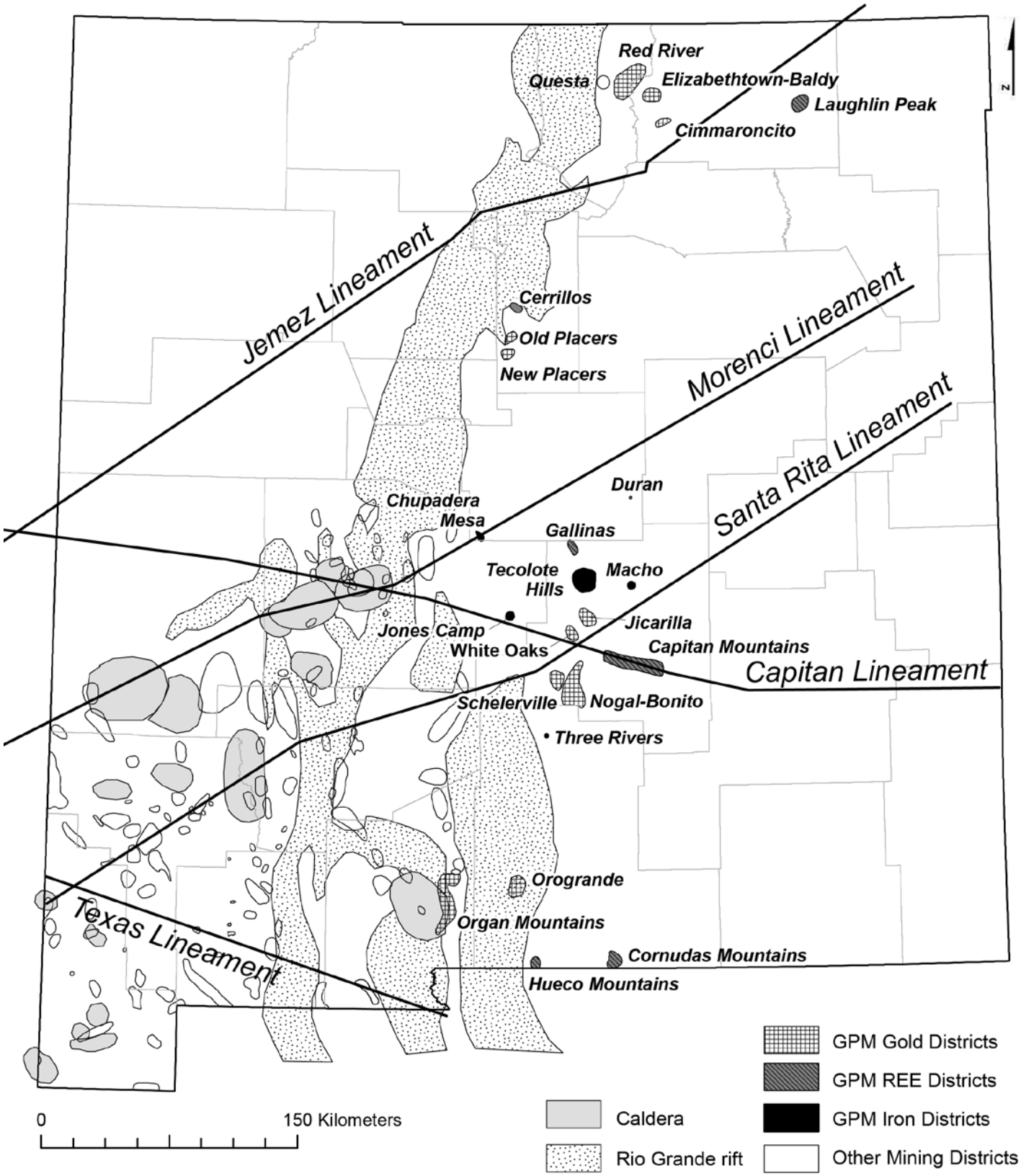

FIGURE 2. Mining districts related to the North American Cordilleran alkaline-igneous belt (GPM or Great Plains Margin deposits), lineaments, Rio Grande rift, calderas, and other Eocene-Miocene mining districts in New Mexico (Chapin et al., 1978, 2004; McLemore, 1996, 2001; Sims et al., 2002; McLemore et al., 2005a, b). Descriptions of GPM districts, including mineral production, are summarized in McLemore (2015b).

REGIONAL GEOLOGY

Jemez Lineament

Deep crustal structures play critical roles in controlling large-scale emplacement of magmas, crustal fluid flow and the formation of mineral deposits (Chernicoff et al., 2002; Crafford and Grauch, 2002; Woolley and Bailey, 2012). The Jemez Lineament (Fig. 2) is one of these regional crustal structures that was originally defined as an alignment of Tertiary-Quaternary volcanic centers and northeast-trending faults (Mayo, 1958; Aldrich, 1986; Chamberlin, 2007). A better definition of the Jemez Lineament is a northeast-trending zone characterized by active uplift (Nereson et al., 2013), low seismic velocity in the mantle (Magnani et al., 2004, 2005; Chamberlin, 2007), and repeated igneous activity and reactivation along faults that extends from Springerville, Arizona through the Jemez caldera and into the Raton-Clayton volcanic field (Fig. 2). The lineament also coincides with the southern edge of a 300-km wide transition zone between the Yavapai (1.8–1.7 Ga) and Mazatzal (1.7–1.6 Ga) Proterozoic provinces (Magnani et al., 2004, 2005).

Raton-Clayton volcanic field

The Raton-Clayton volcanic field is along the northeasternmost extension of the Jemez Lineament in northeastern New Mexico along the boundary between the Great Plains and Sangre de Cristo Mountains and represents the easternmost extent of Neogene-Quaternary volcanic activity in New Mexico. The field consists predominantly of alkali olivine basalt flows and cones, and lesser amounts of basaltic to feldspathoidal flows and cones, andesite to dacite domes, and olivine nephelinite to tridymite-bearing hornblende dacite and was emplaced during late Rio Grande rifting (Jones et al., 1974; Stormer, 1972, Phelps et al., 1983; Scott et al., 1990; Stroud, 1997). Three phases of eruption occurred (Stroud, 1997): Raton (9.0–7.3 and 5.6–3.6 Ma), Clayton (3.0–2.2 Ma) and Capulin (1.68 Ma–56 ka). Geochemical and isotopic compositions suggest a lithospheric mantle source (Phelps et al., 1983; Zhu, 1995).

GEOLOGY OF THE LAUGHLIN PEAK-CHICO HILLS DISTRICT

The Laughlin Peak-Chico Hills igneous complex forms most of the district, is older than the Raton-Clayton volcanic field, and was emplaced just before or at the beginning of Rio Grande rift extension at 22–37 Ma. The Laughlin Peak-Chico Hills igneous complex is dominated by the Chico Sill Complex, which has domed and intruded Cretaceous sedimentary rocks (Wood et al., 1953; Scott et al., 1990). The Laughlin Peak-Chico Hills igneous complex consists of a variety of alkaline extrusive (trachyandesite (32.3 ±1.5, K/Ar), basalt, trachybasalt, rhyodacite) and intrusive lithologies, including trachyte (36.7 ±1.3 Ma, K/Ar, Staatz, 1985), trachyphonolite, trachyandesite, phonotephrite (25.3 ±0.9 Ma, K/Ar, Staatz, 1986), Chico Phonolite (25.80 ±0.88 Ma, K/Ar, Staatz, 1985; 22.8 ±0.23 $^{40}Ar/^{39}Ar$, Stroud, 1997), lamprophyre (24.06 ±1.01 Ma, K/Ar; Staatz, 1986), and carbonatite (Fig. 3). The Chico Phonolite occurs in large sills and dikes as much as 1 m thick. Many of the volcanic and intrusive rocks have a porphyritic texture, suggesting emplacement near or at the surface.

Carbonatites are carbonate-rich rocks of apparent magmatic derivation and typically contain REE, U, Th, Nb, Ta, Zr, Hf, Fe, Ti, V, Cu, apatite, vermiculite, and barite (Woolley and Kempe, 1989; Verplanck et al., 2014). Some of the world's largest economic REE deposits are associated with carbonatites, such as Mountain Pass, California and Bayan Obo, Inner Mongolia, China (Verplanck et al., 2014).

GEOCHEMISTRY OF IGNEOUS ROCKS

Chemical analyses of some Laughlin Peak-Chico Hills igneous rocks are in Appendix 1. The igneous rocks are alkaline (Fig. 4A), predominantly ferroan, alkali-calcic to alkali (Frost et al., 2001), metaluminous to peralkaline (Fig. 4B) and plot as A-type granites (Whalen et al., 1987), WPG (within-plate granites; Pearce et al., 1984), and active continental margins zone (Schandl and Gorton, 2002). Two chemical trends of phonolite are observed; high Zr and low Zr (Fig. 4C; Potter, 1988). The high Zr phonolites are peralkaline and have high concentrations of Zr, Y, U, Th and Rb and low Mg numbers, Cr, and Ba. The igneous rocks exhibit typical light REE-enriched chondrite-normalized REE patterns of alkaline rocks with no europium anomaly (Fig. 4D). Initial strontium isotope compositions (0.7042–0.7053; Potter, 2007) are similar to other GPM districts (McLemore, 2015a, b), and slightly higher than initial strontium isotope compositions of the younger rocks in the Raton-Clayton volcanic field, implying a different source region (0.7028–0.7050; Jones et al., 1974; Zhu, 1995). Epsilon Nd values are in the range of 2.1 to -1.5 ($^{143}Nd/^{144}Nd$ between 0.51275 and 0.51256; Potter, 2007). Collectively, the geochemical and isotopic data suggest the Laughlin Peak-Chico Hills rocks are derived from a lower crustal source with possible mixing of upper crustal rocks.

DESCRIPTION OF MINERAL DEPOSITS

Three types of mineral deposits have been identified, as defined by mineralogy and chemistry: (1) carbonatites, (2) breccia pipe deposits, and (3) Th-REE hydrothermal veins (Staatz, 1985, 1986, 1987; Schreiner, 1991). Table 2 summarizes the mineralogy of the carbonatites, veins, and breccia pipes for each deposit type and Figure 3 shows their locations.

Carbonatite

Radioactive carbonatite dikes intrude an Oligocene phonotephrite (Staatz, 1985; Schreiner, 1991) and have the chemical composition of predominantly ferruginous calciocarbonatite (Fig. 5; after Woolley and Kempe, 1989; Gittins and Harmer, 1997), with some calciocarbonatite (also known as calcite carbonatite or sövite) and magnesiocarbonatite (also known as dolomite carbonatite or beforsite). The carbonatites are poorly exposed and range in size from 12 m to 1219 m long and less than 1 m wide

and consist of predominantly calcite, dolomite, barite, with trace amounts of apatite, goyazite (including REE-rich end member florencite to calcium-rich end member crandallite), bastnaesite, monazite, pyrite, and quartz (Table 2; Schreiner, 1991; NMBGMR unpublished data). The Laughlin Peak carbonatites contain <1.6% total REE (Fig. 6; Appendix 3).

TABLE 2. Selected minerals found in the carbonatites, veins, and breccias in the Laughlin Peak district (Staatz, 1985; Schreiner, 1991; NMBGMR unpublished data).

Mineral	Chemical formula	Carbonatites	Th-REE veins	Breccia pipes
quartz	SiO_2	?	X	X
calcite	$CaCO_3$	X	X	X
dolomite	$CaMg(CO_3)_2$	X		
magnetite	Fe_3O_4	X	X	X
barite	$BaSO_4$	X	X	X
apatite	$Ca_{10}(PO_4)_6(OH,F,Cl)_2$	X		
goyazite	$(Sr,Ca,Ce)Al_3(PO_4)_2(OH)_5$	X		
florencite	$(La,Ce)Al_3(PO_4)_2(OH)_6$	X		
crandallite	$CaAl_3(PO_4)_2(OH)_5 \cdot H_2O$	X		
bastnaesite	$[Ce, La, (CO_3)]F$	X		
ancylite	$SrCe(CO_3)_2(OH) \cdot (H_2O)$	?		
monazite	$(Sm,Gd,Ce,Th,Ca)(PO_4)$	X		
pyrite	FeS_2	X	X	X
gold	Au	X		X
fluorite	CaF_2	?	X	X
niobium rutile	TiO_2	X		X
xenotime	$(Yb,Y,Er)PO_4$	X		?
churchite	$YPO_4 \cdot 2(H_2O)$			?
brockite	$(Ca,Th,Ce)PO_4 \cdot H_2O)$	X		
zircon	$ZrSiO_4$	X	X	X

Th-REE veins

The radioactive Th-REE veins cut Cretaceous sedimentary rocks and Tertiary volcanic flows, dikes and sills, strike predominantly west to northwest with steep north or south dips, and are less than 600 m long and less than 1 m wide (Fig. 3). The veins are linear zones of brecciated and fractured host rock. Crandallite, xenotime, thorite, and brookite are the predominant REE minerals in a gangue of quartz, calcite, feldspar, and trace amounts of barite, fluorite, rutile, zircon, pyrite, magnetite, and iron and manganese oxides (Table 2; Staatz, 1985; Schreiner, 1991). The veins contain <1.2% total REE and <165 ppb Au and exhibit light REE enriched chondrite-normalized REE patterns (Schreiner, 1991; NMBGMR unpublished data). The veins also contain as much as 2200 ppm F, 2000 ppm Ba, 532 ppm Nb,

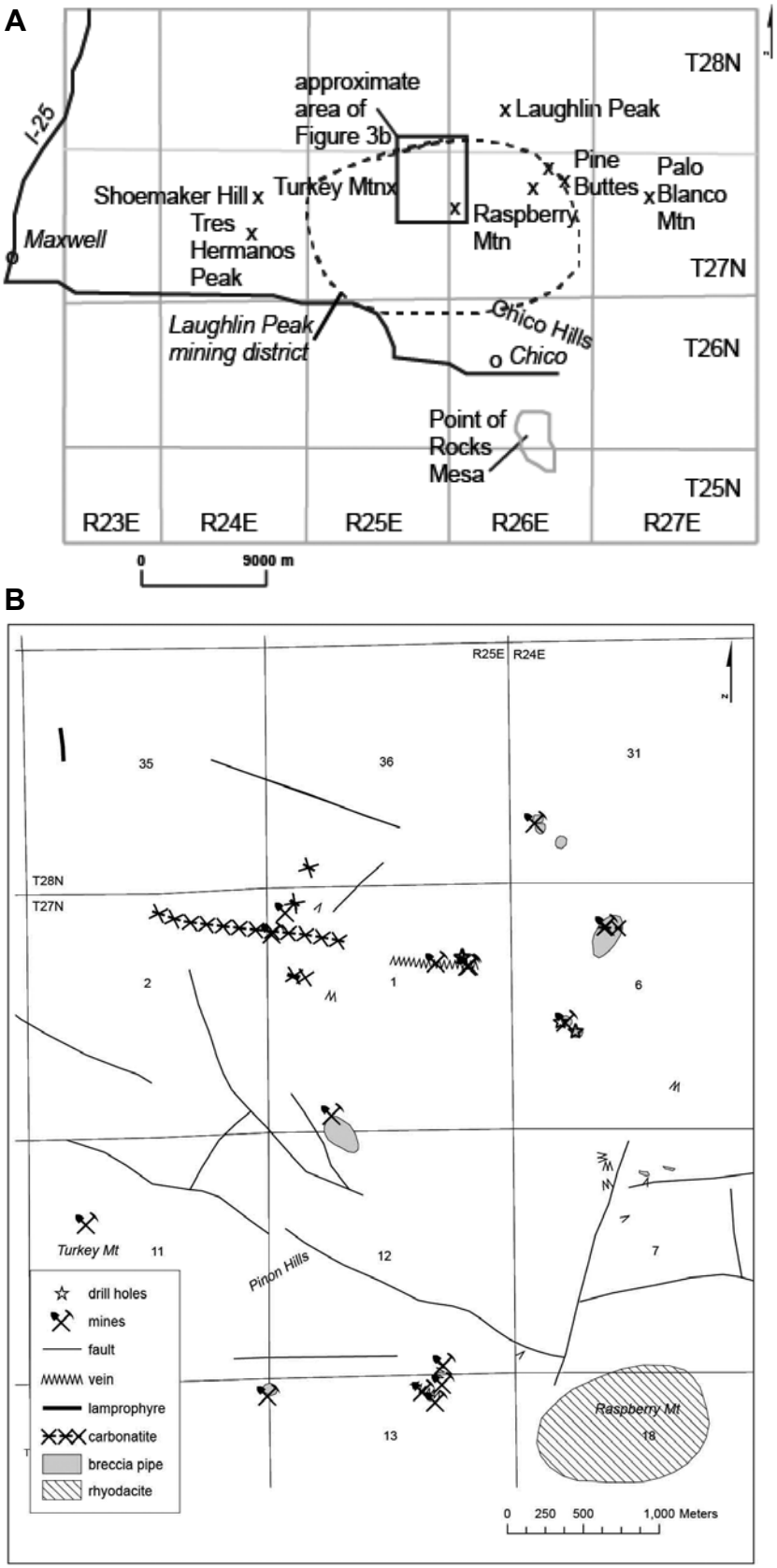

FIGURE 3. Location maps of the Laughlin Peak district, Colfax County, New Mexico (simplified from Staatz, 1986, 1987; Schreiner, 1991). Prospects and drill holes are summarized in Appendix 2 and Table 1. A. Regional. B. Northern portion of the district.

172 ppm U, 75 ppm Ta, and 68 ppm Mo, with low or no Te (Appendix 4). The veins exhibit light REE enriched chondrite-normalized REE patterns (Fig. 7).

Breccia Pipe Deposits

The radioactive breccia pipes are intrusive (Fig. 3) and consist of various iron and manganese oxide-stained, angular to subrounded rock fragments (less than 0.6 m diameter) in a fine-grained siliceous and carbonate matrix of quartz and feldspar. The breccia pipes are circular to oval shaped and six of the largest pipes range in size from 46 to 366 m (Fig. 3); smaller pipes have been mapped. Quartz, feldspar, and clay are the predominant minerals with trace amounts of gold, niobium rutile (?), pyrite, zircon, xenotime or churchite (Table 2; Schreiner, 1991; NMBGMR unpublished data). The total REE is less than 3017 ppm (Fig. 7). The breccia pipes also contain as much as 5900 ppm F, 9050 ppm Ba, 535 ppm Nb, 54 ppm U and 82 ppb Au (Appendix 4; Schreiner, 1991; NMBGMR unpublished data).

Core from the holes drilled in 1986 consists of predominantly grayish breccia cut by feldspar and iron oxide veinlets. Pyrite and marcasite were disseminated in portions of the core from drill

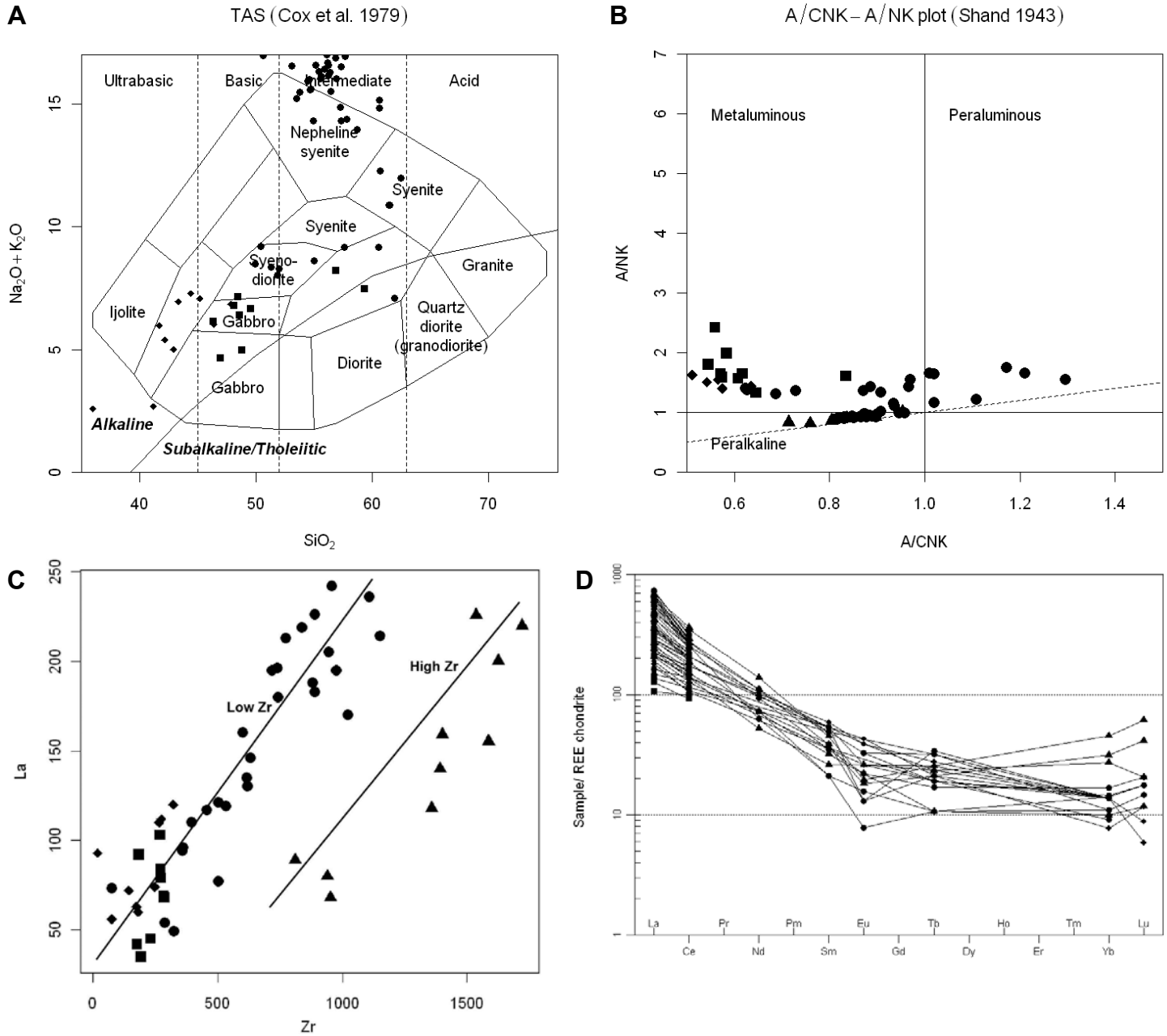

FIGURE 4A. A. TAS (total alkali-silica) in percent, after Cox et al. (1979). B. A/CNK-A/NK, after Shand (1943). C. Zr-La plot in ppm. D. Chondrite-normalized (Nakamura, 1974) REE plots for the igneous rocks from the Laughlin Peak district (data in Appendix 1; Staatz, 1986; Potter, 1988; Schreiner, 1991; NMBGMR unpublished data). Black squares are Low Zr Trend basalts; diamonds are Low Zr Trend lamprophyres; circles are Low Zr Trend phonolite, rhyodacite, and trachyte; and triangles are High Zr Trend phonolites.

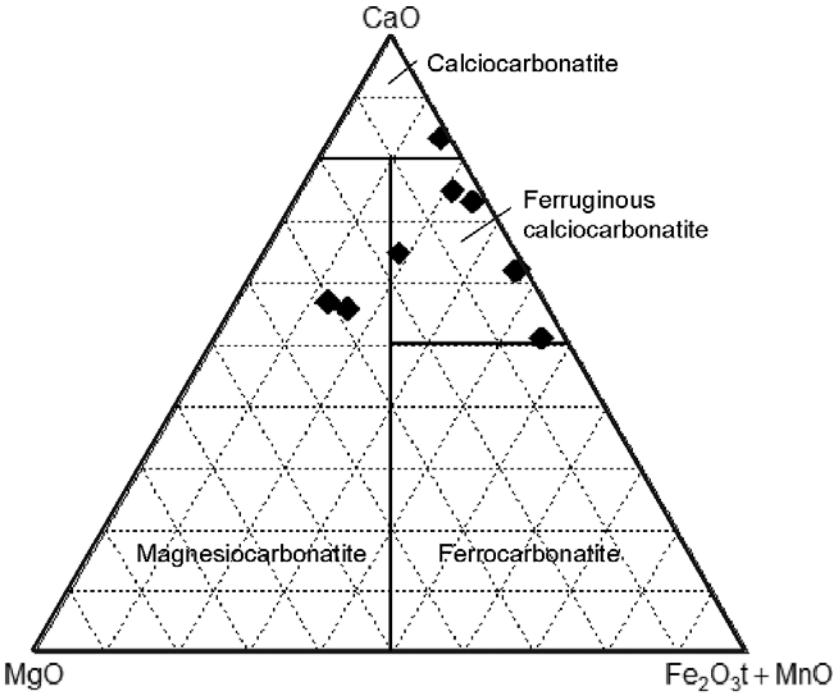

FIGURE 5. Chemical classification of Laughlin Peak carbonatites, in percent (after Woolley and Kempe, 1989 and Gittins and Harmer, 1997). Data compiled in Appendix 3.

hole 2. Only low concentrations of gold, silver, and tellurium were found in the core samples (Appendix 2).

OUTLOOK FOR MINERAL RESOURCE POTENTIAL IN THE FUTURE

There is thorium, REE and possibly gold potential in the Laughlin Peak district, but additional drilling is required to more completely understand the mineral resource potential. The best potential is in the carbonatites and Th-REE veins. However, the Laughlin Peak district is not as faulted as other GPM districts in New Mexico and this could prevent large deposits from forming. Detailed studies on the mineralogy, geochronology, and paragenesis are still required in the Laughlin Peak district and should be completed before advanced exploration. Such studies will greatly enhance exploration efforts. Any sampling should include multi-element analyses, especially gold, thorium, REE, niobium, tungsten, and tellurium.

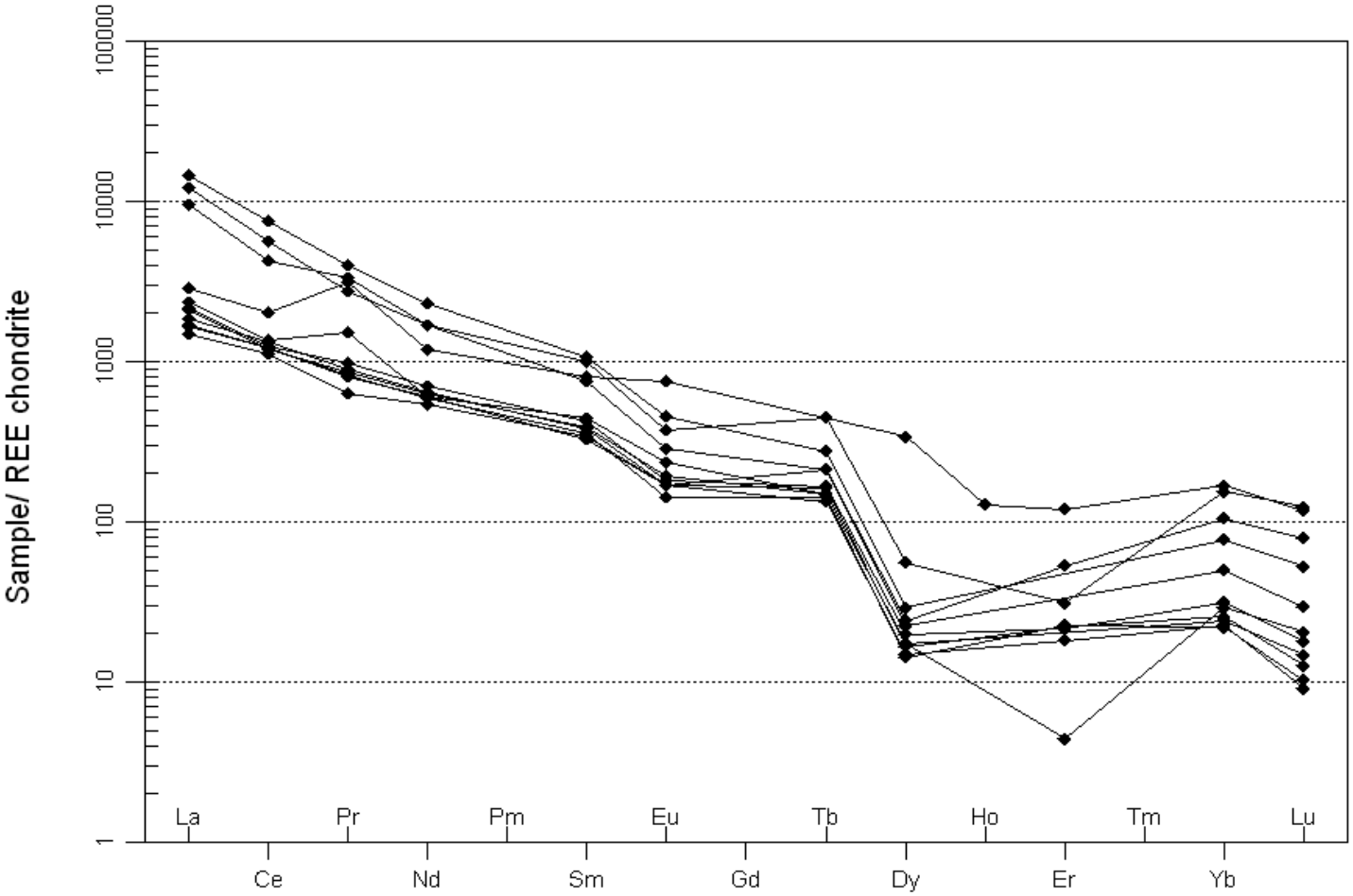

FIGURE 6. Chondrite-normalized (Nakamura, 1974) REE plots of carbonatites from Laughlin Peak. Data are from Schreiner (1991) and NMBGMR unpublished data.

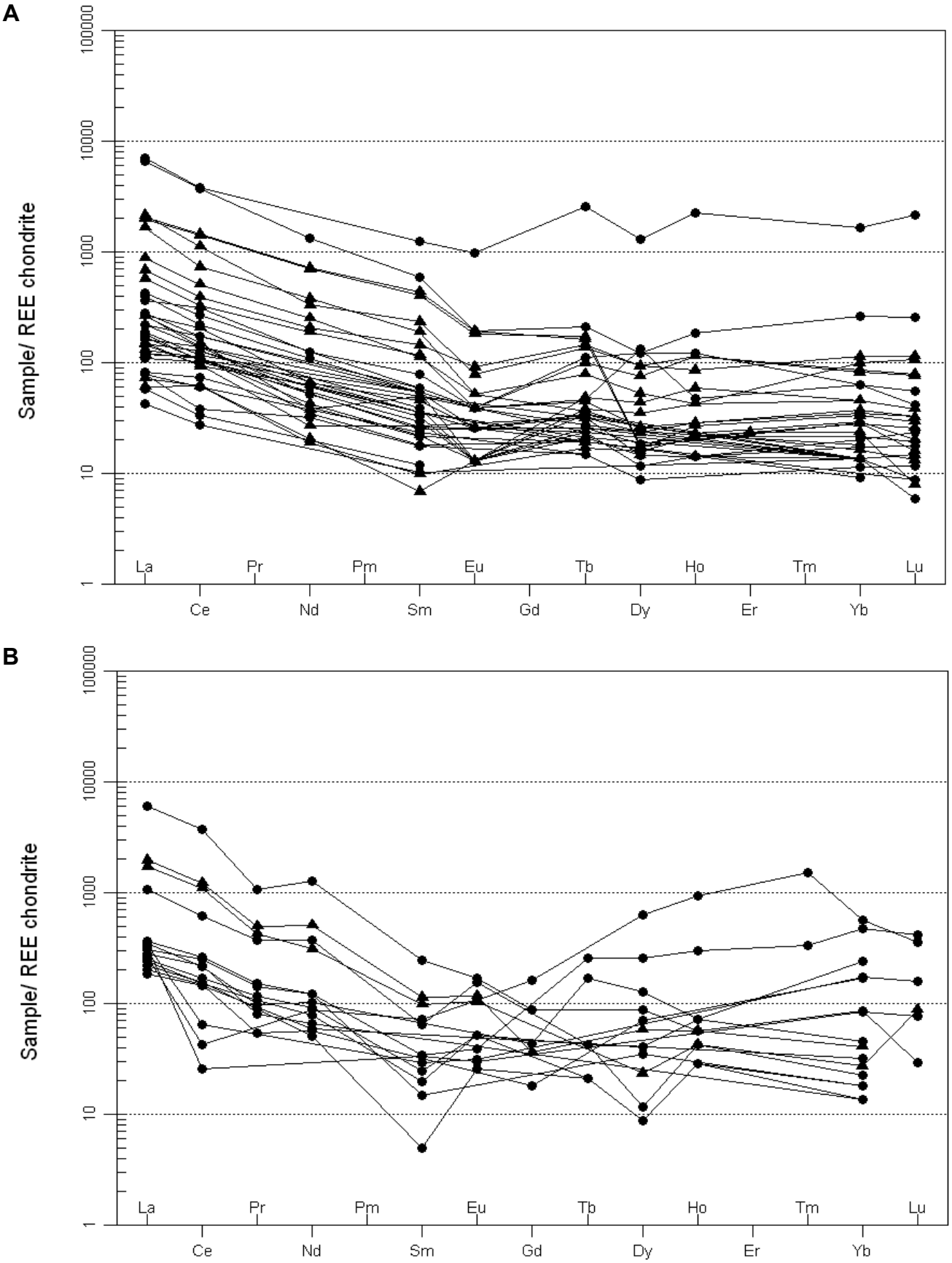

FIGURE 7. Chondrite-normalized (Nakamura, 1974) REE plots of veins (squares), breccia pipes (triangles), and altered rocks (diamonds) from the Laughlin Peak district. A. Data from Schreiner (1991). B. Data from NMBGMR unpublished files (Appendix 4).

DISCUSSION AND CONCLUSIONS

Some of the youngest ages of igneous rocks associated with New Mexico GPM deposits (22–24 Ma) are in northern New Mexico (Questa, Red River, and Laughlin Peak districts; McLemore, 2015a, b). Alkaline igneous rocks in the Laughlin Peak district are similar in composition and texture to igneous rocks in two other REE districts in the GPM belt, the Gallinas and Cornudas Mountains (Fig. 2; McLemore, 2015a, b), and are ferroan, alkali-calcic to alkali (according to Frost et al., 2001). However, igneous rocks associated with the other GPM districts, which contain predominantly gold, copper, and iron deposits are predominantly ferroan to magnesian, calc-alkalic to alkali-calcic to alkalic (McLemore, 2015a, b). Geochemically, the Laughlin Peak rocks plot as WPG (within-plate granites), according to Pearce et al. (1984), and active continental margins, according to Schandl and Gorton (2002). In contrast, igneous rocks associated with the Colorado Mineral Belt (including Cripple Creek district), also part of the North American Cordilleran alkaline-igneous belt, are magnesian, alkali-calcic to calc-alkalic and metaluminous to peraluminous (Anthony, 2005). Strontium and Nd isotope compositions of igneous rocks are similar with other GPM districts (McLemore, 2014; 2015a, b). The similar compositions of GPM igneous rocks suggest that the magmas had a common origin and were produced from similar source regions. Small differences in geochemical composition between igneous rocks are probably related to subtle differences in fractional crystallization, especially of minerals such as garnet, zircon, and apatite, and also possible water-rock interactions that could account for variations in K_2O, Na_2O, barium, rubidium, and strontium.

In New Mexico, the style of mineralization differs from that found in Colorado. Tellurium is common in many of the Colorado districts, but most GPM districts in New Mexico have elevated concentrations of tungsten, with only trace amounts or no tellurium (Kelley and Ludington, 2002; McLemore, 2013; compilation by the author). Tellurium and tungsten in most Laughlin Peak samples are below detection limits (Appendix 3, 4). However, tellurium analyses of samples from New Mexico GPM districts are limited and therefore, tellurium could be present in specific mineral zones within New Mexico districts. More detailed mineralogical and chemical analyses are required. Most GPM districts in New Mexico contain iron skarns (McLemore, 2015a, b), but there are none reported in the Laughlin Peak district. Fluorite veins are only significant in the Gallinas district where fluorite was produced, but fluorite is present only in small quantities in the Laughlin Peak district and in most GPM and Colorado districts (Kelley and Ludington, 2002; McLemore, 2015a, b).

The diversity of igneous rocks and associated mineral deposits along the boundary of the Great Plains with the Southern Rocky Mountain and Basin and Range provinces suggests that this region is characterized by multiple pulses of highly fractionated and differentiated magmas (Fig. 8). In the Laughlin Peak-Chico Hills igneous complex, two different chemical trends of phonolite are found that could be a result of differences in fractionation of a single magma or emplacement from two separate pulses of magmas. Both upper mantle and lower crustal source rocks may be involved, although in the Laughlin Peak-Chico Hills

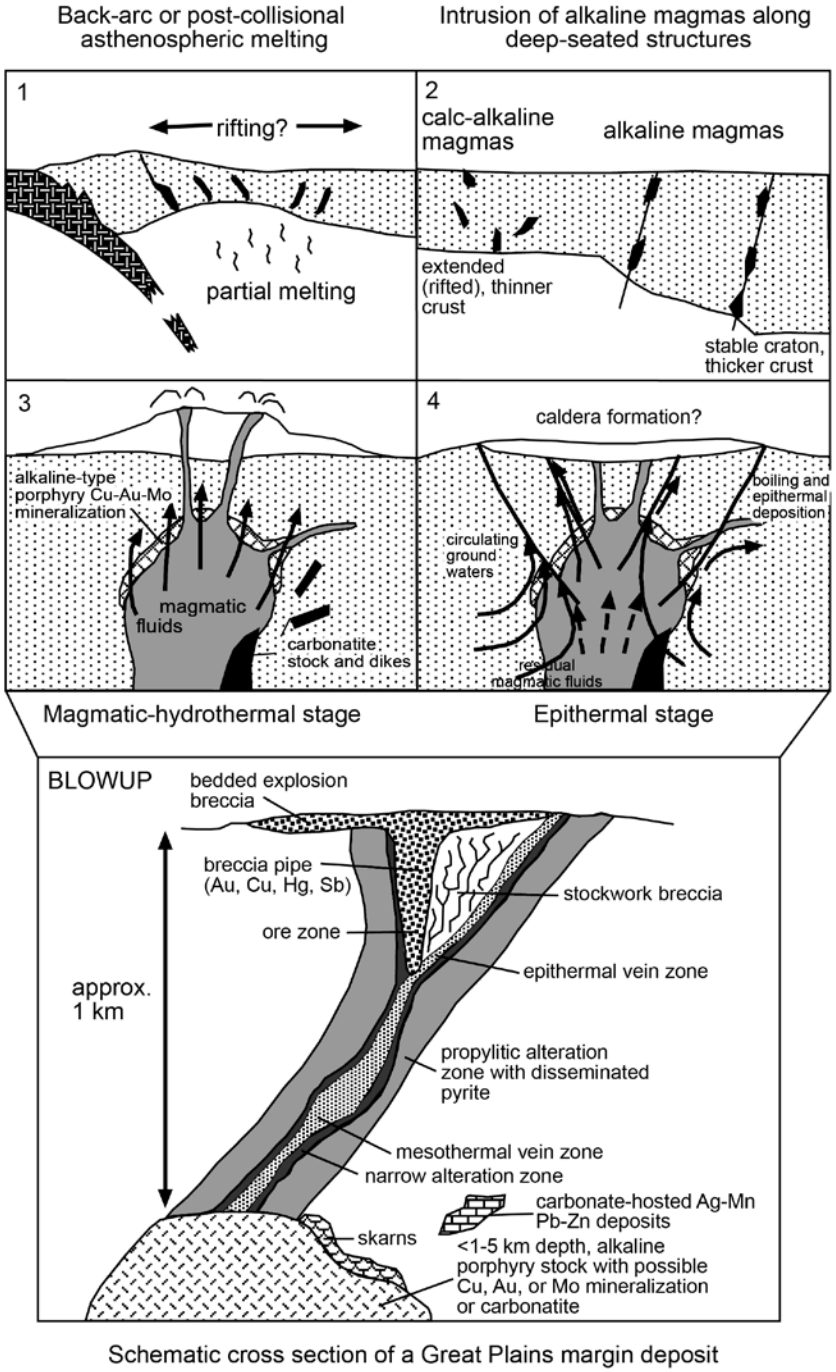

FIGURE 8. Schematic model for formation of Great Plains Margin deposits (modified from Richards, 1995).

complex, a lower crustal source with possible mixing of upper crustal rocks is suggested by geochemical data. Carbonatites in the GPM belt are present only in the Laughlin Peak district, although they are suspected in the subsurface in the Gallinas Mountains (McLemore, 2010).

Several studies have attributed changes in the chemistry and source of the magmas to the tectonic transition between Eocene-early Oligocene subduction (Laramide, 36–75 Ma) and mid-Tertiary extension (20–36 Ma; Allen and Foord, 1991; McMillan et al. 2000; Anthony, 2005), that was triggered by changes in the subducting Farallon plate. Rollback of the Farallon flat slab occurred 23–37 Ma and resulted in a tremendous pulse of calc-alkaline ignimbrite eruptions in southwestern New Mexico (Fig. 2) and central Mexico (Chapin et al., 2004; Chapin, 2012). As the Farallon slab fragmented (Henry et al., 2010; Chapin, 2012), the asthenosphere filled gaps between the sinking slab and overlying lithosphere, producing magmas and thereby accounting for slight differences between chemical composition of the exposed igneous rocks within the GPM belt. The source regions shifted from asthenosphere and upper crust during Eocene-early Oligocene to lower crust during the late Oligocene (McMillan et al., 2000). The alkaline igneous rocks within the Laughlin Peak district and other GPM districts are likely derived from partial melting within the lower crust and lithosphere mantle, possibly reflecting metasomatism of the upper mantle (Mutschler et al., 1985; Kelley and Ludington, 2002; Pilet et al., 2008) and/or mixing of upper crustal rocks (Potter, 2007). In northeastern New Mexico, the period between 9 and 22 Ma was amagmatic, similar to the 10–24 Ma amagmatic period in southern New Mexico (McMillan et al., 2000) and was followed by <9 Ma lithosphere-derived volcanic suites, such as the Raton-Clayton volcanic field.

Deep-seated fracture systems or crustal lineaments, such as the Jemez Lineament, probably channeled the magmas and hydrothermal fluids (Chamberlin, 2007; McLemore and Zimmerer, 2009). As magmas and metal-rich fluids reached shallow levels, local structures and wall rock compositions determined distribution and final style of intrusions and resulting mineral deposits (Fig. 8).

The GPM mineral deposits are likely genetically related to the host alkaline igneous rocks. Supporting evidence for a magmatic origin elsewhere in the GPM belt includes: (1) fluid inclusion and stable isotope data from the Nogal-Bonito deposits (Douglass, 1992; Douglass and Campbell, 1994, 1995); (2) fluid inclusion, stable isotope, and age data from the Capitan quartz-REE-Th veins (Phillips et al., 1991; Banks et al., 1994; Campbell et al., 1995; Dunbar et al., 1996); (3) the nature of stockwork molybdenum deposits at Questa, including geochemical data (Ross et al., 2002; Rowe, 2012); (4) the close spatial association of mineral deposits with alkaline igneous rocks (Allen and Foord, 1991; McLemore, 2015a, b); (5) presence of skarn deposits along the contacts of intrusive rocks in many GPM districts (McLemore, 2010, 2015a, b); (6) $^{40}Ar/^{39}Ar$ studies in the Old Placers (Ortiz) district indicating a similar age of mineralization (31.56–32.20 Ma, adularia) and of the alkaline igneous rocks (31.68–33.27 Ma, Maynard, 2014); and (7) similarity in composition and texture to other deposits at Cripple Creek, Colorado and elsewhere where a magmatic origin is favored (Maynard et al., 1989, 1990; Kelley et al., 1998; Kelley and Ludington, 2002)..

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