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GEOLOGY OF THE CAMBRIAN LEMITAR CARBONATITES, SOCORRO COUNTY, NEW MEXICO: REVISITED

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ABSTRACT—Carbonatites are igneous rocks of magmatic origin that are composed of more than 50% carbonate minerals, less than 20% SiO₂, and they can form economic deposits containing significant amounts of rare earth elements (REE), barite, fluorite, and niobium. REE are critical minerals and are essential to the functioning of information-age technologies because of their unique properties, e.g., high electric conductivity, strong magnetism, fluorescence, and luminescence. In this respect, carbonatites serve as the principal source of REE on Earth. Carbonatites in the Lemitar Mountains are light REE enriched and contain as much as ~1.1 wt% REE in total. While previously described, new analytical techniques have allowed for additional and more precise description, age, and model of their origin. The age of Lemitar carbonatites has been newly established at ~515 Ma using ⁴⁰Ar/³⁹Ar and U/Pb geochronological methods. Petrographic observations combined with whole-rock geochemical and isotope data indicate the Lemitar carbonatites are mantle-derived and that their origin is related to the Cambrian-Ordovician belt of alkaline igneous rocks and carbonatites in southern Colorado and New Mexico. The Lemitar carbonatites are not economic at the present time because of small tonnage and low grades. Nevertheless, further drilling is required to determine if the carbonatites increase in REE and Nb concentrations at greater depth (1.1% total REE in a surface sample is significant). Detailed geophysical surveys are required to determine if the Lemitar Mountains could contain a large carbonatite body emplaced in the subsurface.

INTRODUCTION

Carbonatites are igneous rocks of magmatic origin that are composed of more than 50% carbonate minerals and less than 20% SiO₂ (Streckeisen, 1980), which can form economic deposits containing significant amounts of rare earth elements (REE), barium (Ba), fluorine (F), uranium (U), thorium (Th), and niobium (Nb). Carbonatite magmas are associated with continental rift environments and have been attributed to either subduction and subsequent melting of oceanic crust (Walter et al., 2008) or to the melting and partial differentiation of lithospheric-mantle material (Jones et al., 2013; Stoppa et al., 2019; Ackerman et al., 2021). Carbonatite intrusions are frequently surrounded by a halo of fenitization, a type of alkali metasomatism associated with carbonatites and alkaline igneous activity that involves the addition of potassium and/or sodium and depletion of silica (e.g., Andersen, 1989; Le Bas, 2008). Fenitized halos are typically larger than carbonatites themselves, so they frequently provide a substantial footprint in the field to aid in the exploration of carbonatites.

REE, comprising atomic numbers 57–71 (lanthanum to lutetium) and yttrium (Y) and scandium (Sc), are generally considered critical minerals. For example, REE are necessary for the functionality of information-age technologies because of their unique properties, e.g., high electric conductivity, strong magnetism, fluorescence, and luminescence (Van Gosen et al., 2014). In this respect, carbonatites are currently the predominant source of REE in the world.

One area in New Mexico that has REE potential is the Lemitar Mountains north of Socorro in central New Mexico,

which is part of a regional Cambrian-Ordovician belt hosting alkaline igneous rocks and carbonatites (Fig. 1; McMillan and McLemore, 2004; McLemore et al., 2020). Cambrian-Ordovician carbonatites are found as dikes and associated veins and stockworks in five areas in New Mexico: Lobo Hill, the Monte Largo area in the Sandia Mountains, Caballo Mountains (Perry, 2019), and the Lemitar and Chupadera Mountains (Fig. 1; Woolley 1982; McLemore et al., 2020). Younger Oligocene carbonatite dikes also are found at Laughlin Peak in the Chico Hills (McLemore, 2015), but are not discussed in this report. Although the Lemitar carbonatites have been previously examined, this paper summarizes previous work as well as presents new data in terms of geochronology, whole-rock geochemistry, and C–O isotope data and details a current model for the generation of Lemitar carbonatites proposed by Ackerman et al. (2021).

GEOLOGY AND MINERAL DEPOSITS IN THE LEMITAR MOUNTAINS

The Lemitar Mountains (designated as the Lemitar Mountains mining district; McLemore, 2017) contain rocks ranging from Proterozoic granite, gneiss, diorite, gabbro, metasediments, arkoses, and pegmatites, Pennsylvanian limestone, Oligocene tuff and andesite, and Oligocene-Pleistocene fluvial and piedmont sediments. Rift extension and uplift have exposed the Proterozoic basement. The carbonatite dike swarm spanning the eastern half of the district is the product of Cambrian-Ordovician alkaline magmatism, a possible aulacogen (McMillan and McLemore, 2004; McLemore et al., 2020) that

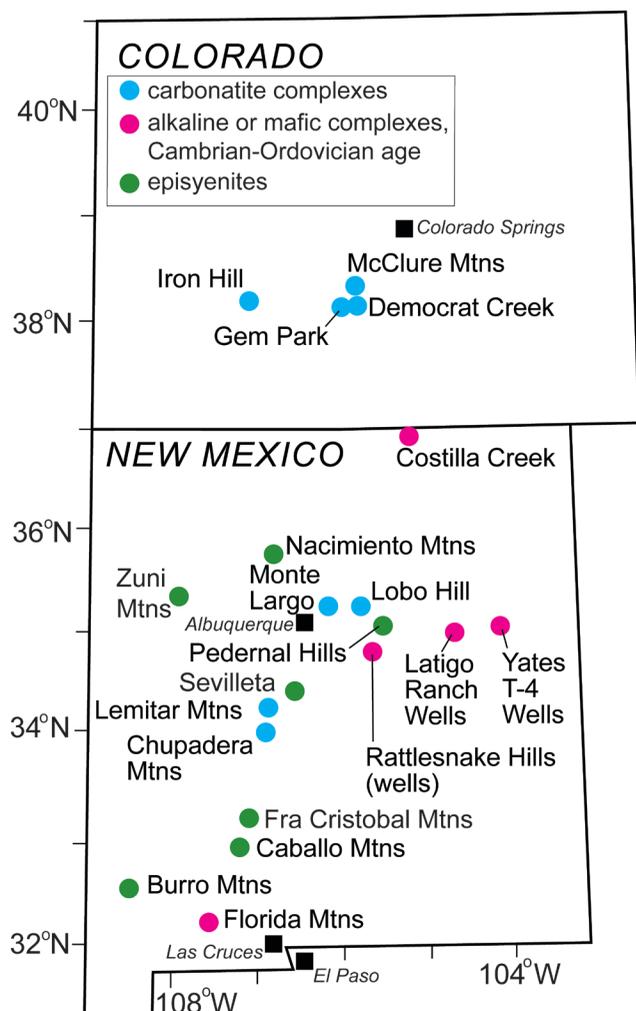


FIGURE 1. Location of areas with carbonatites, episyenites, and syenites in New Mexico and southern Colorado (from McLemore et al., 1999, 2018; McLemore and Lueth, 2017).

extends from southern Colorado into New Mexico (Fig. 1). More than 150 carbonatite dikes and veins are found at the surface-intruding igneous basement rock in the eastern foothills of the Lemitar Mountains. Mineral deposits found in the Lemitar Mountains district include Cambrian-Ordovician carbonatites and Tertiary barite-galena Rio Grande rift deposits, polymetallic veins, and carbonate-hosted replacement deposits.

Mining in the district may have occurred as early as the 1600s (Benavides, 1630), but historic silver workings were first officially reported by the United States Mint in the late 1800s (Burchard, 1881). Prospecting in the early 1900s resulted in approximately 40 short tons of manganese production from the northern Lemitar Mountains (Howard, 1967). Lasky (1932) first mentioned small galena-barite fissure-filling veins in the Proterozoic rocks and in limestones along the unconformity between the Proterozoic rocks and Paleozoic sedimentary rocks in the district. Carbonate-hosted replacement lead-zinc deposits are found in the Kelley Limestone at the Box Canyon mine, similar to but much smaller than the carbonate-hosted replacement lead-zinc deposits in the Magdalena district to the southwest. Over 40 mines and prospects are found in the

district; all extensive underground workings have been remediated. Total mineral production is estimated as \$1000 worth of copper, lead, barite, silver, manganese, and uranium (Anderson, 1957; Howard, 1967; North and McLemore, 1986; McLemore, 2017).

The first mining claims for uranium, fluorite, and sulfides, primarily in carbonatites, were filed in 1954 (McLemore, 1980). Uranium was first described in the district by Stroud and Collins (1954) and Anderson (1954, 1957). Western Nuclear Corp. drilled one borehole in the arroyo draining Corkscrew Canyon in 1978, but the results of that drilling are unknown. In the late 1970s, geologists at the New Mexico Bureau of Geology and Mineral Resources (NMBGMR) were actively mapping the Lemitar Mountain mining district (Chamberlin et al., 2001; McLemore, 1980). It was McLemore (1980, 1982, 1983, 1987) and McLemore and Modreski (1990) that ultimately geochemically characterized and identified the carbonatite dikes and intrusions emplaced in the Lemitar Mountains. In 1979–1980, U.S. Barite Corp. produced a small amount of barite from carbonatite dikes in the northern Lemitar Mountains (Jackpot, Western Silver, and Gypsum mines; McLemore, 1982). In 2010, Red Basin LLC drilled a single borehole along an arroyo north of Corkscrew Canyon. Unfortunately, the drill core did not intersect any major carbonatites, although fenitization was encountered. The core is available for inspection at the NMBGMR.

METHODS OF STUDY

An important step in economic geology projects is to compile all published and unpublished data from existing mines and prospects within the study area. Previous reported chemical analyses of carbonatites from the Lemitar Mountains were compiled from McLemore (1980, 1983, 1987), McLemore and Modreski (1990), and Ackerman et al. (2021). Additional representative channel chips were collected across outcrops as well as select grab-samples that were collected on the basis of mineralogy and visible alteration between 2015 and 2021. Billets and slabs of selected samples were prepared in-house with an MK-Diamond MK101 wet saw, and select billets were finished as polished thin sections by Quality Thin Sections in Tucson, Arizona. Petrography was conducted in transmitted and polarized light on an Olympus BH-2. Reflected light observations were performed using a Nikon Optophot-Pol microscope. New samples for whole rock chemistry were sent to ALS Geochemistry in Reno, Nevada, where rock chips were digested in acid and then analyzed with inductively coupled plasma mass spectrometry (ICP-MS) and inductively coupled plasma atomic emission spectroscopy (ICP-AES). Description of methods used can be found at <https://www.alsglobal.com/en-us>. Duplicate samples and standards were assessed, and uncertainty of analyses are generally <5%. Specific analytical methods and additional quality assurance and quality control (QA/QC) are discussed in McLemore et al. (2021, appendix 5). Samples of previous studies and new data were included in the geochemical dataset (Appendix 1).

Carbon ($\delta^{13}\text{C}$) and oxygen ($\delta^{18}\text{O}$) stable isotope compositions

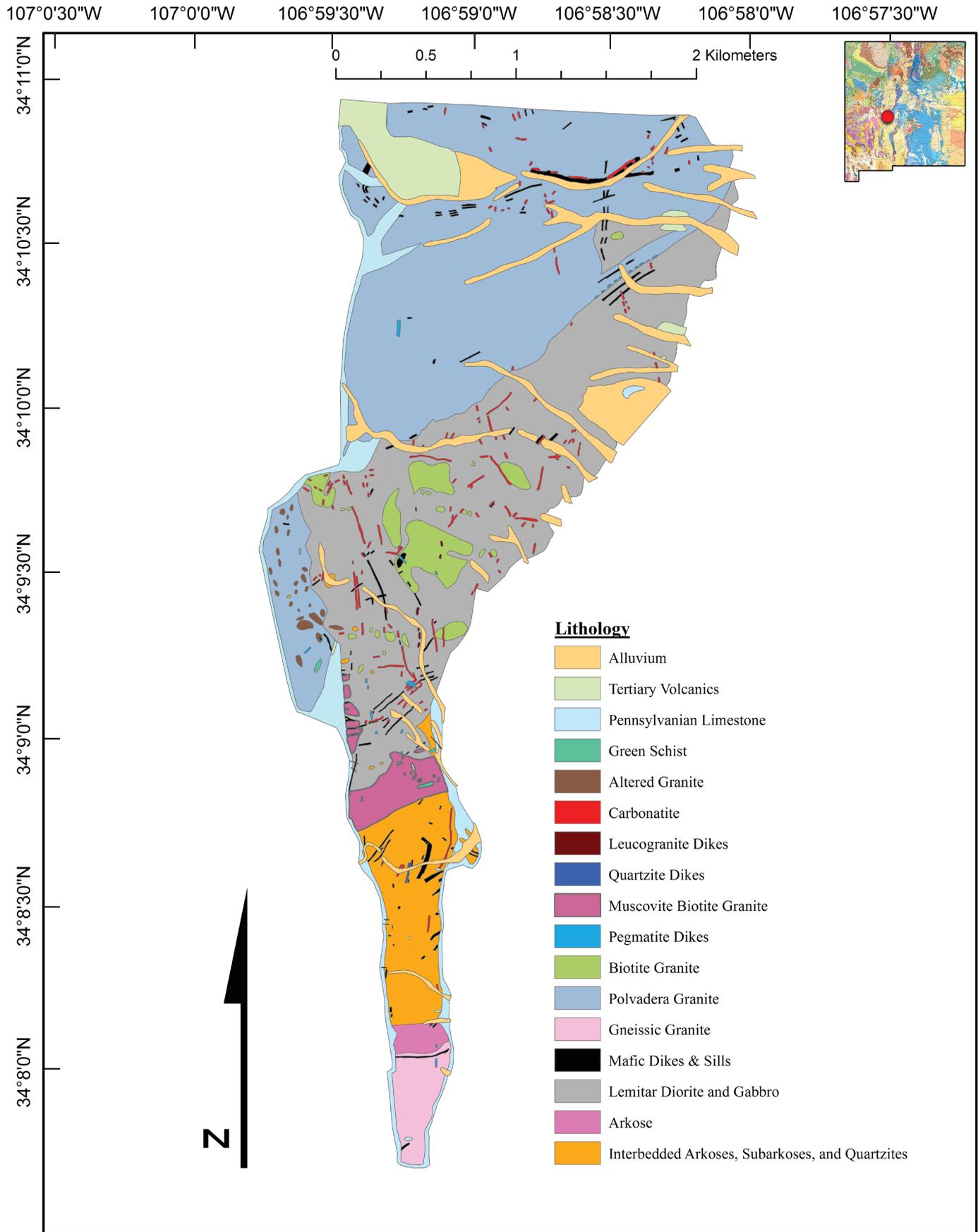


FIGURE 2. Geologic map of the Lemitar carbonatites (McLemore, 1983).

were determined using phosphoric acid digestion of carbonate at the University of New Mexico's Center for Stable Isotopes (<http://csi.unm.edu/>). $\delta^{13}\text{C}$, $\delta^{18}\text{O}$, neodymium (Nd), and samarium (Sm) isotopic data from Ackerman et al. (2021) was also included (Appendix 2). The Sm-Nd whole-rock isotope method used in this study is described in Rämö et al. (2003), and the data are in Appendix 2.

$^{40}\text{Ar}/^{39}\text{Ar}$ dates for Lemitar carbonatite phlogopite were obtained at the NMBGMR's Argon Geochronology Laboratory. Analytical methods are described in McLemore et al. (2021), and data are in Appendix 3.

Zircon grains were separated at the University of California, Santa Barbara using conventional crushing, magnetic, and heavy liquids separation methods. Isotopes of U and Pb were measured on a Nu Instruments Plasma HR-ES multicollector (MC)-ICPMS. Zircon U-Pb analyses employed 91500 (1065 Ma, ID-TIMS; Wiedenbeck et al., 1995) as the primary bracketing standard and Plesovice (337 Ma, ID-TIMS; Sláma et al., 2008), GJ1 (602 Ma, ID-TIMS; Jackson et al., 2004), and R33 (419 Ma, ID-TIMS; Black et al., 2003) as secondary standards. Concordia and U-Pb weighted averages were calculated and plotted in IsoplotR (Vermeesch, 2018). All uncertainties and error ellipses are 2 SD. U-Pb for zircon secondary reference materials were typically within 2% of accepted ages. Data are in Appendix 4.

PETROGRAPHY OF THE LEMITAR CARBONATITE

The Lemitar carbonatites are heterogeneous, comprising four compositionally distinct species: (1) primary carbonatites (dark brown to gray composed of calcite, dolomite, ankerite, biotite, magnetite, apatite, muscovite, chlorite, apatite, zircon, baddeleyite, REE-bearing oxides and phosphates, and titanite), (2) replacement/secondary carbonatites (dark brown to gray consisting of feldspar and amphiboles replaced by carbonate, as well as calcite, dolomite, magnetite, apatite, hematite, micas, REE-bearing oxides, and phosphates and quartz), (3) sövites (white, coarse-grained calcite carbonatites), and (4) ankerite-dolomite (previously known as rauhaugite, reddish-brown carbonatites that consist of ankerite, dolomite, calcite, hematite, barite, fluorite, and quartz). Identified mineral species are in Table 1. The Lemitar carbonatites intrude Proterozoic basement granite, gneiss, and diorite mostly in two trends: north-south and northeast-southwest, which McLemore (1983) mapped in detail (Fig. 2). McLemore (1980, 1983) described local enrichment of U, Th, and total REE (up to >1000 ppm, ~550 ppm, and 11,000 ppm, respectively) in the primary carbonatites and enrichment to a lesser extent in the other three carbonatite types. The carbonatites are variable in composition, texture, clast/grain size, and mineralogy, with dikes ranging in width from 1.5 m to 1 mm, which may extend longitudinally hundreds of meters or more. Primary carbonatites are generally the predominant carbonatites observed; they include xenoliths of country rock as large as 20 cm in diameter and are differentiated from other carbonatites on the basis of primary magmatic texture, higher carbonate concentrations, and higher REE and zircon contents.

At the contact between carbonatite intrusions and host rocks, there are three distinct and intimately interrelated alteration types: chloritization, fenitization (McLemore and Modreski, 1990), and white phyllosilicate alteration (also known informally as sericitization). All carbonatites are associated with these three suites of alteration. The alteration will be described in future reports.

GEOCHEMISTRY

Chemically, the Lemitar carbonatites plot to ferrocarbonatite, magnesiocarbonatite, and calciocarbonatite fields, according to the international classification scheme (Fig. 3). They are enriched in light REE (Fig. 4). Note that sample LEM2000 contains more than 1.1 wt% total REE (Appendix 1).

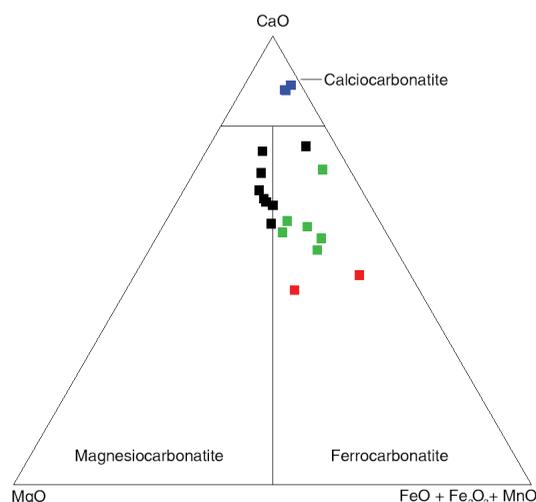


FIGURE 3. Classification of Lemitar carbonatites according to the international classification system (Woolley, 1982; Le Maitre, 2002). Black = primary carbonatite, green = secondary carbonatite, blue = calciocarbonatite/sövite, red = ankerite-dolomite carbonatite, previously known as rauhaugite. Includes calciocarbonatites from Ackerman et al. (2021) and recently collected Lemitar carbonatites (Appendix 2).

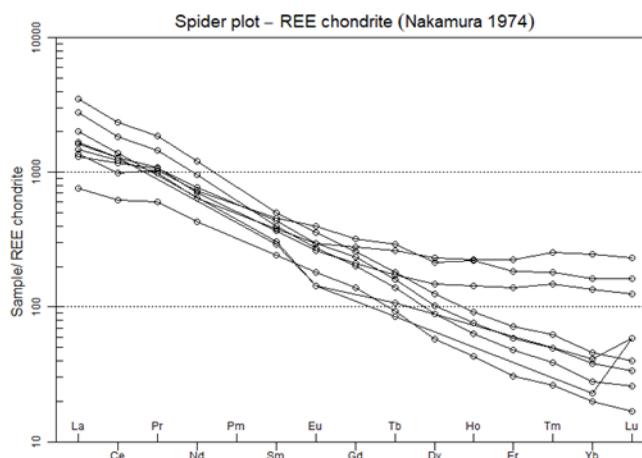


FIGURE 4. Chondrite-normalized REE spider plot of primary Lemitar carbonatites and veins collected for this study. REEs normalized using Nakamura's (1974) values for chondrites. Elevated concentrations of REE are most prevalent in primary carbonatites. Geochemistry is available for these samples in Appendix 2.

TABLE 1. Summary of the mineralogy of the Lemitar carbonatites from petrographic and electron microprobe techniques.

Mineral	Composition	Description
Quartz	SiO ₂	Colorless euhedral crystals. Comb-forming veins to massive.
Albite	NaAlSi ₃ O ₈	Magmatic phenocrysts in diorite xenoliths, polysynthetic twinning.
Sanidine	KAlSi ₃ O ₈	Magmatic phenocrysts in diorite xenoliths and disseminated grains, diagnostic carlsbad twinning.
Microcline	KAlSi ₃ O ₈	After albite, tartan twinning. Partially replaced by white phyllosilicate.
Perthite	(Na,K)AlSi ₃ O ₈	Partially fenitized albite grains; microcline inclusions.
Biotite	K(Mg,Fe)AlSi ₃ O ₁₀ (OH) ₂	One perfect cleavage, tan to dark brown, pleochroic.
Muscovite	KAl ₂ (AlSi ₃ O ₁₀)(OH) ₂	Colorless to pleochroic pink. One perfect cleavage.
Chlorite var. Chamosite	(Fe,Mg,Al) ₆ (Si,Al) ₄ O ₁₀ (OH, ₈) ₈	Yellow-purple-blue interference colors, acicular habit. Associated with hematite and magnetite, after biotite.
Phlogopite	KMg ₃ (AlSi ₃ O ₁₀)(OH) ₂	After biotite, ragged, dark brown.
White Phyllosilicate	KAl ₂ (AlSi ₃ O ₁₀)(OH) ₂	Commonly replacing feldspars, represents surficial weathering.
Hornblende	(Ca,Na) ₂ (Mg,Fe,Al) ₅ (Al,Si) ₈ O ₂₂ (OH) ₂	Yellow-green to forest green euhedral crystals, amphibole cleavage, pleochroic.
Arfvedsonite	Na ₃ (Fe,Mg) ₄ FeSi ₈ O ₂₂ (OH) ₂	Cyan to teal elongate lathes, amphibole cleavage, strong pleochroism.
Actinolite	Ca ₂ (Mg,Fe) ₅ Si ₈ O ₂₂ OH ₂	Forms fine fibrous aggregates within miarolitic micro-cavities.
Ferro-edenite	NaCa ₂ Fe ₅ (Si ₇ Al)O ₂₂ OH ₂	Patchy acicular to tabular crystals in altered diorite xenoliths.
Aegirine	NaFeSi ₂ O ₆	Light brown to verdant green hexagonal to elongate euhedra, cleavage at 56 and 124 degrees. Moderate pleochroism.
Enstatite	Mg ₂ SiO ₃	Massive to prismatic crystals with first order gray-tan birefringence.
Epidote	Ca ₂ (Al ₂ ,Fe)(SiO ₄)(Si ₂ O ₇)O(OH)	Colorless to pale green, very fine grains. Associated with fenitization.
Scapolite	(Ca,Na) ₄ (Al ₆ Si ₆ O ₂₄)(SO ₄ ,CO ₃)	Associated with aegirine, high relief, requires further EMPA to confirm.
Sillimanite	Al ₂ (SiO ₄)O	Fibrolitic to acicular, very fine, after phlogopite. Vug-filling.
Titanite	CaTi(SiO ₄)O	Tan to light peach sphenoidal crystals. Associated with rutile.
Zircon	Zr(SiO ₄)	Fine subhedral grains with 4th+ order birefringence, often clustered.
Baddeleyite	ZrO ₂	Coarse zircon phase in primary carbonatites.
Ilmenite	FeTiO ₃	Associated with titanite, amorphous to irregular habit, in fenite xenoliths.
Rutile	TiO ₂	Associated with magnetite, very fine platy to acicular crystals.
Magnetite	Fe ₃ O ₄	Trigonal to hexagonal. Partially replaced by hematite.
Hematite	Fe ₂ O ₃	Pervasive, red/dark brown to opaque. Irregular to cubic and acicular habit. After pyrite. Stockwork forming.
Calcite	CaCO ₃	Coarse crystalline veins to massive sheets, 4th order birefringence.
Dolomite	CaMg(CO ₃) ₂	Dusty sheets and irregular grains associated with calcite.
Apatite	Ca ₅ (PO ₄) ₃ (F,OH)	Very fine elongate euhedra present as disseminated inclusions within calcite and dolomite
Xenotime	YPO ₄	Colorless to pinkish tan. Irregular crystallinity, high relief, anomalously high birefringence.
Pyrochlore	(Na,Ca) ₂ Nb ₂ O ₆ (OH,F)	Irregular form, likely metamict. No cleavage, light brown, isotropic.
Bastnaesite	(Ce,La,Y)CO ₃ F	Tabular, one perfect cleavage. Transparent, high relief, and anomalous birefringence. Silver-gray in reflected light.
Fluorite	CaF ₂	Purple to dark purple/black, cubic, isotropic. Very rare.
Barite	BaSO ₄	Coarse euhedral crystals with light yellow 1st order birefringence.
Pyrite	Fe ₂ S	Occurs in trace amounts. Near completely altered to hematite.

GEOCHRONOLOGY

A new $^{40}\text{Ar}/^{39}\text{Ar}$ date obtained on phlogopite phenocrysts from a Lemitar carbonatite dike (Lem2000) yields a Cambrian age of 516.7 ± 0.7 Ma (Fig. 5), which is a more precise and older age than the previously reported K/Ar age of 449 ± 16 Ma (K-Ar method; McLemore, 1983).

U-Pb analysis of zircons from the Lemitar carbonatite gives an average age of 514.06 ± 2.7 Ma (Fig. 6, sample LEM2000). Most zircons had moderate to low U (Th/U ~ 1.9 – 0.5). Therefore, error ellipses, while small, can mostly be explained by high common lead content. Zircons separated from the Lemitar carbonatite are large (from 200–600 μm in diameter) and irregularly shaped. They range from clear to slightly pinkish. Cathodoluminescence imaging revealed oscillatory zoning, indicating an igneous origin. Although they have poor crystallinity, no core-rim textures were observed, suggesting these zircons precipitated directly out of the carbonatitic melt and were not inherited.

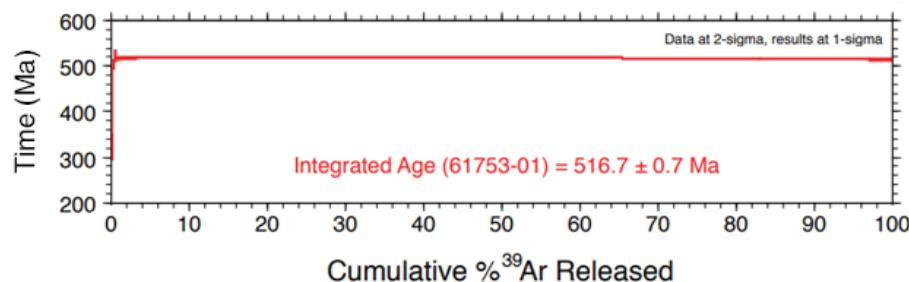


FIGURE 5. $^{40}\text{Ar}/^{39}\text{Ar}$ spectral line plot indicating age date of 516.7 ± 0.7 Ma from Lemitar carbonatite phlogopite. Includes discordant projection of altered microcline, giving a mean age of 812.5 ± 1.2 Ma, which is not reliable due to fentization.

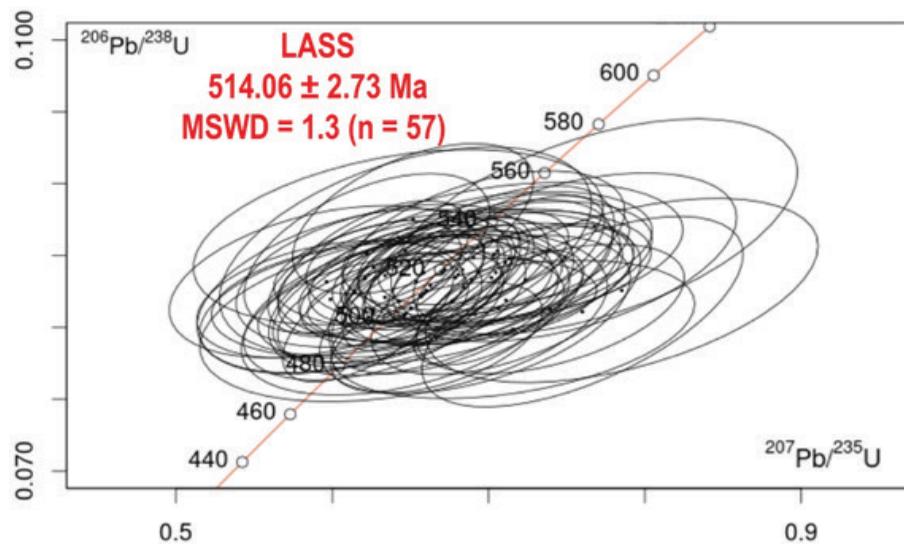


FIGURE 6. A Wetherill Plot of U-Pb isotopic data collected from Lemitar carbonatite zircons. All analyses are concordant and give an age of 514.06 ± 2.73 Ma (2 SD).

RADIOGENIC AND STABLE ISOTOPES

The $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ isotope compositions of Lemitar carbonatites indicate a primary mantle source. Ackerman et al. (2021) attributed the Lemitar carbonatites to be primary and mantle-derived, with variability in $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values attributed to alteration by meteoric waters and hydrothermal fluids. New isotopic data corroborates Ackerman's interpretations; however, ankerite-dolomite carbonatites are anomalously heavy in $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ relative to other types (see outlier in Fig. 7).

Seven whole-rock Nd isotope analyses are available for the Lemitar carbonatites, six published by Ackerman et al. (2021) and one from this study (Fig. 8; Appendix 2). The analyzed carbonatites include four magnesiocarbonatites (LEM-1001, UC04, UC07A, UC09) and three silicified calciocarbonatites (UC02, UC03A, UC8). They all show high, yet varying, values of Sm (49 to 148 ppm) and Nd (267 to 909 ppm), and low (but varying) $^{147}\text{Sm}/^{144}\text{Nd}$ ratios of 0.088 to 0.112. The calciocarbonatites have high values of the HREE relative to the magnesiocarbonatites (Ackerman et al., 2021, fig. 7B). At 515 Ma, the ϵ_{Nd} values of the calciocarbonatites vary from +1.0 to +3.6, and those of the magnesiocarbonatites from +3.5 to +4.8, with the exception of sole calciocarbonatite sample UC02 (+1.0).

The carbon and oxygen isotope composition of the six Lemitar carbonatites analyzed by Ackerman et al. (2021) shows a positive trend in a $\delta^{18}\text{O}$ vs. $\delta^{13}\text{C}$ plot (Ackerman et al., 2021, fig. 8B), but the two types of carbonatites are not distinguished from each other. In $^{87}\text{Sr}/^{86}\text{Sr}$ vs. ϵ_{Nd} plots, however, carbonatites plot at different values: calciocarbonatites show higher values (Ackerman et al., 2021, fig. 8A). Radiogenic isotope systems provide a means to differentiate and classify carbonatites (Fig. 7); primary carbonatites, calciocarbonatites, and ankerite-dolomite carbonatites have distinct C–O signatures. These differences are related to post-crystallization hydrothermal alteration (UC03A, UC08) and possibly also to Si–F enrichment (UC02).

The initial Nd isotope composition of the Lemitar carbonatites is shown relative to Mg/Fe of the carbonatite whole-rock samples in Figure 8. In this plot, the Mg/Fe ratio differentiates the magnesiocarbonatites (high values) from the calciocarbonatites (low values). The magnesiocarbonatites have an average ϵ_{Nd} value of 4.1 ± 0.5 (1 SD). This may reflect the Nd isotope composition of the primary magma of the Lemitar carbonatite. The value is lower than the ϵ_{Nd} (515 Ma) value of the depleted mantle of DePeolo (1981), +7.0. Whether or not the ϵ_{Nd} value of the magnesiocarbonatites reflects the source

of the Lemitar carbonatite in a mildly depleted sublithospheric mantle or in the subcontinental mantle of the Mazatzal province remains an open question.

Compared to the Mesoproterozoic Mountain Pass carbonatite in the Mojave province of southeastern California, the Lemitar carbonatites are much more radiogenic in terms of

their initial Nd isotope composition (Fig. 8). The Mountain Pass carbonatite shows unvarying initial Nd isotope composition across the lithologic window observed at Mountain Pass (magnesiocarbonatite through calciocarbonatite), with an average ϵ_{Nd} (1380 Ma) value of -3.1 ± 0.4 (1 SD), which is incompatible with the depleted mantle at 1380 Ma (4.8). The Mountain Pass carbonatite has been related to an ancient, metasomatically enriched subcontinental mantle source underneath Mojavia (e.g., Haxel, 2005, 2007). In the more juvenile lithosphere environment of Mazatzal (cf. Karlstrom and Humphreys, 1998), the Lemitar carbonatite may mark a juvenile lithospheric mantle source tapped during Cambrian tectonothermal events.

DISCUSSION

Collectively, primary carbonatites were the first to be emplaced, followed by secondary/replacement carbonatites (both magnesiocarbonatite) and then by ankerite-dolomite carbonatites (ferrocarbonatite) and sövites (calciocarbonatite). Perry (2019) indicated that at least four generations of calcite occurred, therefore more study on the paragenesis is needed. Potassic fenitization follows magnesio- and ferrocarbonatite intrusions.

The presence of trace amounts of actinolite, sillimanite, and titanite in Lemitar primary carbonatite indicate a magmatic crystallization temperature at or above 700°C (Hayden et al., 2008). Fenitization in country rock, arfvedsonite/aegirine mineralization, and successive generations of calcite and dolomite

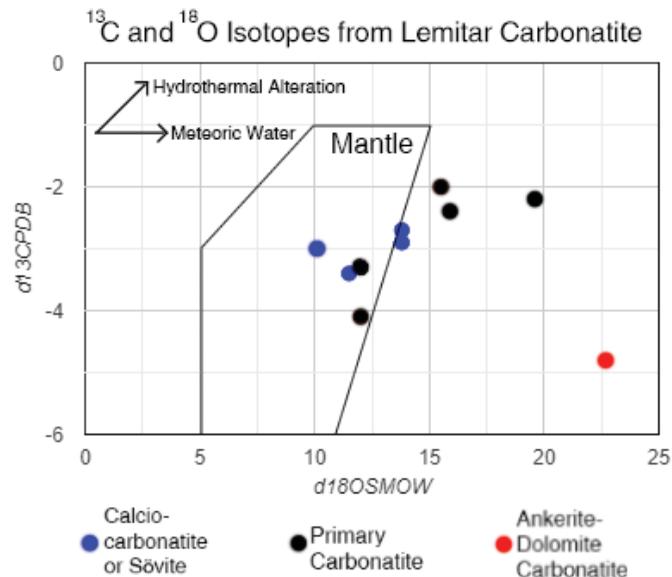


FIGURE 7. $\delta^{13}C$ and $\delta^{18}O$ stable isotope composition of Lemitar carbonatite; includes new data and data from Ackerman et al. (2021). $\delta^{13}C$ values given to Pee Dee Belemnite (PDB) whereas $\delta^{18}O$ to mean oceanic water (SMOW).

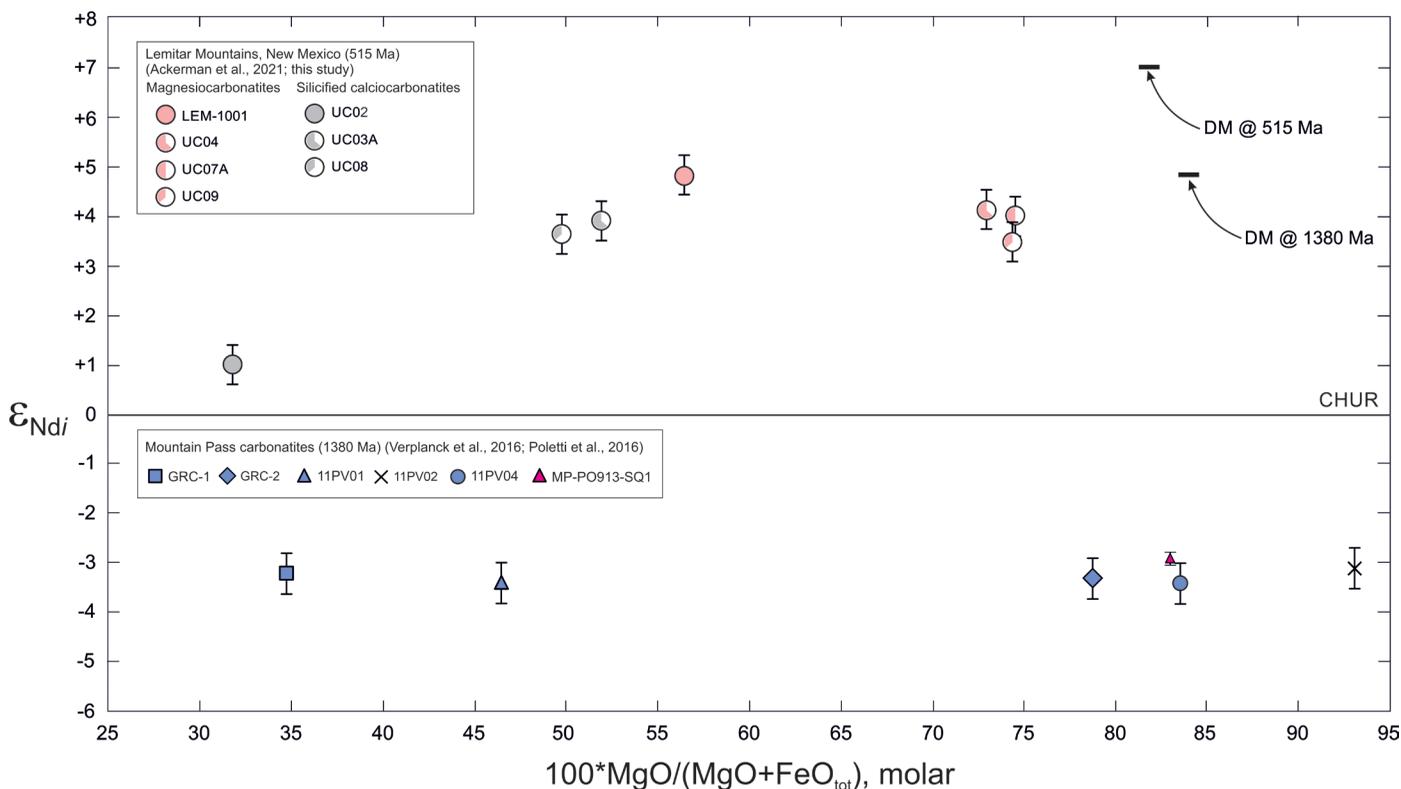


FIGURE 8. Molar $100 * MgO / (MgO + FeO_{tot})$ vs. ϵ_{Nd} diagram showing the initial Nd isotope composition of the ~515 Ma Lemitar carbonatites (Ackerman et al., 2021; this study) and the ~1380 Ma Mountain Pass carbonatite (Verplanck et al., 2016; Poletti et al., 2016). DM is the depleted mantle of DePaolo (1981), with ϵ_{Nd} shown at the two times of interest, CHUR is the Chondritic Uniform Reservoir of DePaolo and Wasserburg (1976). Error bars are 2 SD external.

in Lemitar carbonatites show a hydrothermal environment persisted after initial carbonatite emplacement. Alteration of biotite to hematite and chlorite likely occurred with the decrease of hydrothermal activity (~500–300°C). Replacement carbonatites and rauhaugites (ankerite-dolomite carbonatite) represent the most oxidized portions of the Lemitar carbonatite system because of the predominance of hematite over magnetite.

A model proposed by Ackerman et al. (2021) involves the fractionation of a mantle-derived CO₂-H₂O-F silicate melt that fractionates to “wet” phlogopite-bearing carbonatites, “dry” aegirine carbonatites, and nephelinite/ijolite (i.e., syenites) alkaline rocks. “Wet” carbonatites are found in the Lemitar and Chupadera Mountains, Monte Largo Hills, Caballo Mountains, Lobo Hills, and Wet Mountains. “Dry” carbonatites are found at Iron Hill and in the Wet Mountains, Colorado. Syenites, ijolites, and other alkaline rocks are found at Iron Hill and in the Wet Mountains and Florida Mountains. The different magma compositions depend upon Si-Na-K-Mg contents, water activity, and melt ascent rate. However, more work is required to test this model.

CONCLUSIONS

- The Lemitar carbonatites are magmatic, mantle-derived rocks that are enriched in light REE and Nb, as shown by mineralogy, whole-rock chemistry, and Sm–Nd isotopic systematics.
- The newly obtained age of ~515 Ma is corroborated by ⁴⁰Ar/³⁹Ar (phlogopite) and U–Pb (zircon) geochronology, indicating that the Lemitar carbonatite belongs to the Cambrian-Ordovician magmatic event in New Mexico and Colorado.
- The model presented by Ackerman et al. (2021) provides a testable hypothesis for the origin of the Lemitar carbonatites and other magmatic and metasomatic rocks emplaced during the Cambrian-Ordovician magmatic event. Available Nd isotope data point to a relatively radiogenic primary source in the mantle beneath Mazatzal crust.
- The Lemitar carbonatites are not economic at the present time, because of small tonnage and low grades. Drilling is required to evaluate if they increase in REE and Nb concentrations at depth (note that 1.1 wt% REE determined in surface sample LEM2000 is significant). Exploration efforts should be paralleled by high-resolution geophysics and conductivity surveys to test whether or not there may be a larger carbonatite intrusion in the subsurface.

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Appendices can be found at

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Rhyolite cliffs at rosedale mine