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Cambrian alkaline rocks at Lobo Hill, Torrance County, New Mexico: More evidence for a Cambrian-Ordovician aulacogen

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CAMBRIAN ALKALINE ROCKS AT LOBO HILL, TORRANCE COUNTY, NEW MEXICO: MORE EVIDENCE FOR A CAMBRIAN–ORDOVICIAN AULOGOGEN

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Abstract—Alkali-feldspar syenite, monzonite, quartz syenite, monzogranite, lamprophyre, and carbonatite dikes that intrude Proterozoic metamorphic rocks at Lobo Hill, a small hill in the Estancia basin, southeast of Moriarty in Torrance County, are part of a widespread Cambrian–Ordovician alkaline magmatic event that occurred throughout New Mexico and southern Colorado. The dikes are unfoliated, unmetamorphosed, fine to medium grained, 1–2 m wide, and vary in attitude from nearly flat-lying to nearly vertical. Chemically, the dikes are metaluminous and can be differentiated into two groups based on differences in mineralogy and chemistry: high-K alkali-feldspar syenites and high-Na monzonites, quartz syenites, and monzogranites. An $^{40}Ar/^{39}Ar$ biotite-plateau age of 518 ± 5.7 Ma records the age of monzonite emplacement due to the rapid cooling of this high-level intrusion. Unlike similar alkaline rocks elsewhere in New Mexico, the Lobo Hill alkaline rocks do not have significant economic potential, except for aggregate. The magmatic compositions at Lobo Hill are consistent with those generated in a continental rift system, although geologic data such as rift-basin sediments and geophysical signatures are absent for this time period in New Mexico. Recognition of widespread Cambrian–Ordovician magmatic activity in New Mexico, evidence of relatively rapid uplift and erosion in the Florida Mountains, and the presence of carbonatites suggest that New Mexico was not a simple passive margin during the Cambrian–Ordovician, but rather experienced sufficient extension to perturb the mantle and initiate magmatism. Thus, we propose that an aulacogen, similar to the southern Oklahoma aulacogen, existed in New Mexico during Cambrian and Early Ordovician time.

INTRODUCTION

A widespread Cambrian–Ordovician alkaline magmatic event occurred throughout New Mexico and southern Colorado (Fig. 1) and is evidenced by the intrusion of carbonatites, syenites, monzonites, and alkaline granites and associated K-metasomatism. Only a few of these alkaline rocks have been well dated (Table 1; Loring and Armstrong, 1980; McLemore, 1983; Evans and Clemons, 1988; Ervin, 1998), but similar field relationships, textures, mineralogies, and geochemistries of these unmetamorphosed alkaline rocks suggest a common Cambrian–Ordovician age. Alkali-feldspar syenite, monzonite, quartz syenite, monzogranite, lamprophyre, and carbonatite dikes intruded Proterozoic metamorphic rocks near Lobo Hill, a small hill in the Estancia basin, southeast of Moriarty in Torrance County (Fig. 2). Geologic, geochemical, and geochronological data for the Lobo Hill alkaline rocks are presented in this paper, as part of a regional study of alkaline rocks in New Mexico. This regional study is intended to characterize the alkaline rocks, evaluate their economic potential, and to provide insight into tectonic setting and origin.

GEOLOGY

Lobo Hill is part of the Pedernal uplift, although Lobo Hill is separated by some 25 km from the Pedernal Hills. Together, they represent a remnant of the ancestral Rocky Mountains uplift. The Proterozoic and Cambrian rocks at Lobo Hill are well exposed in the Mountain States (Davis) rock quarry and a small knob of alkali-feldspar syenite (samples LOBO 3, 4) south of the quarry; but the rocks are poorly exposed outside of the quarry (Fig. 2). Moriarty Concrete Products drilled at least 13 holes (up to 13 m deep) along Hill 6389, east of the quarry, and found that similar rocks continue eastward beneath the alluvial cover (Fig. 2).

Proterozoic foliated metamorphic rocks consist of felsic schist (quartz, plagioclase, alkali-feldspar, chlorite, biotite, amphibole, sillimanite, and garnet) and amphibolite schist (quartz, plagioclase, hornblende, biotite, chlorite, locally garnet and a trace of pyrite). The metamorphic rocks exhibit a well-developed foliation, are metamorphosed to the greenschist and amphibolite facies, and are part of the Torrance Metamorphic Group (Grambling, 1986). Metamorphism probably occurred about 1400 Ma (Mukhopadhyay et al., 1975; Grambling, 1986).

Brick-red to reddish-orange alkali-feldspar syenite, monzonite, quartz syenite, and monzogranite dikes intruded the Proterozoic meta-

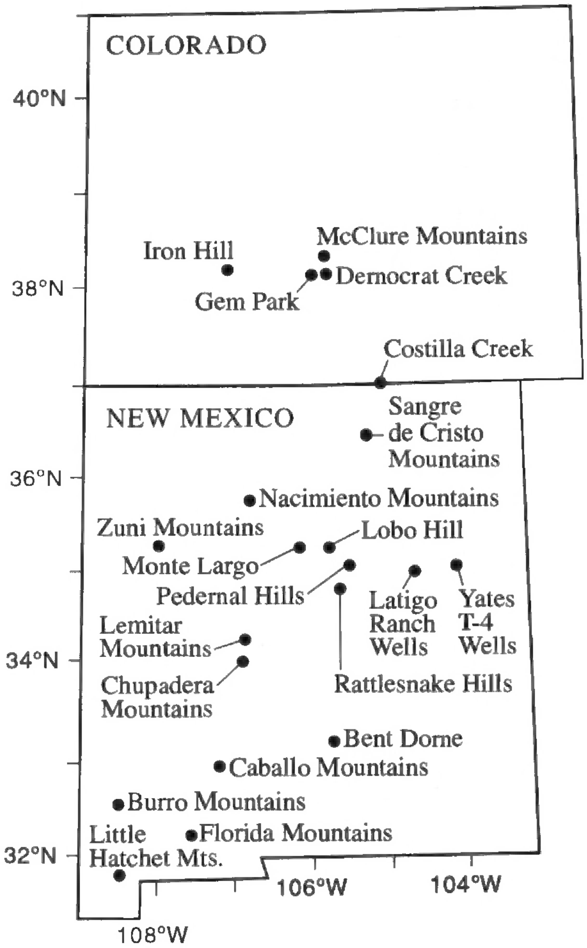

FIGURE 1. Locations of known and possible Cambrian–Ordovician carbonatites and alkaline igneous rocks in New Mexico and southern Colorado (modified from McLemore, 1987b, 1989; Loring et al., 1987; Evans and Clemons, 1988).

TABLE 1. Known and possible Cambrian–Ordovician carbonatites and alkaline igneous rocks in New Mexico and southern Colorado. Locations are on Figure 1.

AREA	LITHOLOGY	AGE	MINERAL DEPOSITS	REFERENCES
McClure Mountains	carbonatite-alkaline complex	517–704 Ma (K-Ar, Rb-Sr, fission track)	Th-REE veins	Fenton and Faure (1970), Olson et al. (1977), Ambrustmacher (1984)
Democrat Creek	syenite	520–546, Ma (K-Ar, Rb-Sr, fission track)	Th-REE veins	Olson et al. (1977), Armbrustmacher (1984)
Gem Park	carbonatite, syenite	?	Vermiculite, Nb	Olson et al. (1977), Armbrustmacher (1984)
Iron Hill	carbonate	550–579 Ma (K-Ar, Rb-Sr, fission track)	Th-REE veins	Fenton and Faure (1970, Olson et al. (1977)
Sangre de Cristo Mountains (Elk Mt.-Spring Mt. Area)	high-Na syenites	?	None	Klich (1983), Reed et al. (1983), McLemore (1989)
Nacimiento Mountains	high-K syenites	?	None	Woodward et al. (1977), McLemore (1989)
Zuni Mountains	high-Na syenites	?	None	Lambert (1983), McLemore and McKee (1989)
Pedernal Hills	high-Na syenites	469 ± 7 (Rb-Sr)	U-REE-fluorite	Loring and Armstrong (1980), McLemore (1984)
Lobo Hill (Moriarty)	high-K syenite, monzonites, carbonatite	518 ± 5.7 (^{40}Ar/^{39}Ar)	U-Th-REE-fluorite veins, aggregate	Loring and Armstrong (1980), McLemore (1984), McKeown (1991), this report
Monte Largo (Sandia Mountains)	carbonatites, melterzite sill	?	None	Lambert (1961), McLemore (1984)
Lemitar Mountains	carbonatites	457 ± 16 (K-Ar, biotite)	Uranium veins, silver-lead veins, barite-fluorite veins	McLemore (1982, 1983, 1987a), McLemore and Modreski (1990)
Chupadera Mountains	carbonatites	?	None	Kent (1982), McLemore (1987a), Van Allen et al. (1986)
Caballo Mountains	high-K syenites	?	U-REE-fluorite veins	Staatz et al. (1965), McLemore (1986)
Florida Mountains	high-Na syenites	490–515 (Rb-Sr, K-Ar, ^{40}Ar/^{39}Ar)	None	Evens and Clemons (1988), Loring et al. (1987), Matheny et al. (1988, 1990) Clemons (1998), Ervin (1998)
Burro Mountains	high-Na, high-K syenites	?	Minor REE veins	McLemore and McKee (1988)
Little Hatchet Mts.	alkaline granite	605, 640 Ma (zircons)	None	Zeller (1965)
Bent dome (Sacramento Mts.)	granite, diorite	?	Cu vein deposits at Virginia Mine	Foord and Moore (1991), Bauer and Lozinsky (1991)
Costilla Creek	diorite dike	500 Ma (Rb-Sr)	None	Reed (1984)
Houston Oil and Minerals Lewelling No. 2 oil test	basalt or andesite	514 ± 21 Ma (K-Ar)	None	Loring and Armstrong (1980)
Trans-Pecos Resources Latigo Ranch #1A and 1D oil tests	gneiss, feldspar porphyry	720 ± 36, 604 ± 30 Ma (K-Ar)	None	Setter and Adams (1985)
Yates Petroleum T-4 Cattle Co. #1 & #2	granite	376 ± 19, 664 ± 35, 766 ± 38 Ma (K-Ar)	None	Setter and Adams (1985)
Rattlesnake Hills	basalt	848 ± 42 Ma (K-Ar)	None	Setter and Adams (19850, Setter (1985)

morphic rocks. Loring and Armstrong (1980), and subsequently, McLemore (1984) and Jackson et al. (1988) described the Lobo Hill alkaline rocks as a syenitic stock. However, exposure in the Mountain States quarry indicates that the alkaline rocks vary in lithology and are dikes. The alkali-feldspar syenite outcrop south of the rock quarry may be a stock, pipe, or a flat-lying dike; the contacts with the metamorphic rocks are not exposed. The dikes are unfoliated, unmetamorphosed, fine to medium grained, 1–2 m wide, and vary in attitude from nearly flat-lying to nearly vertical. Some dikes contain xenoliths of Proterozoic amphibolite schist that are several centimeters in diameter. Chilled margins are locally common in some dikes. Some contacts between the dikes and metamorphic rocks are sharp and cut across the foliation. Other contacts are brecciated and are characterized by a thin shear zone of iron oxides, clay, and carbonate. Local, small displacement faults offset the dikes and metamorphic rocks. Thin zones (up to several centimeters wide) of red to reddish-orange, alkali-feldspar alteration occur along fracture and joint surfaces of the metamorphic rocks. This alteration zone is probably related to K-metasomatism, resulting from intrusion of the alkaline rocks.

In thin section, the alkaline rocks are aphanitic porphyritic and typically vesicular, with altered plagioclase phenocrysts set in felty to intergranular groundmasses; the rocks are almost devoid of ferromagnesian minerals. Mineralogically, there are two groups of felsic alkaline rocks, alkali-feldspar syenites and alkaline dikes containing both alkali-feldspar and plagioclase. The alkali-feldspar syenites contain 90–95% alkali-feldspar with varying amounts of quartz, hematite, plagioclase, fluorite, and biotite, almost completely altered to chlorite. Some alkali-feldspar crystals are more than 1 cm long. Iron oxides exist as fine-grained, red-brown disseminations within the alkali-feldspar, producing the brick-red color. Fluorite is locally common as disseminations and along fractures cutting the syenite dikes. Locally, the fluorite is zoned from colorless to purple in as many as three bands.

The two-feldspar alkaline dikes vary in lithology from monzonites, quartz syenites, and monzogranites according to the classification of Le Maitre (1989) and contain 20–50% alkali-feldspar, 20–60% plagioclase, 0–20% quartz, 1–5% opaque minerals (predominantly iron oxides), trace–5% biotite (partially to completely altered to chlorite), and trace amounts of apatite, sericite, calcite, and carbonate. Some alkali-feldspar crystals are more than 1 cm long. Plagioclase is commonly altered to carbonate, hematite, and clay and exhibits relict Carlsbad and albite twinning. Iron oxides occur as fine-grained red-brown disseminations within the feldspars, and as small red cubes, that were probably once magnetite or pyrite. The dikes also contain green lath-shaped crystal masses of chlorite and iron oxides that appear to have replaced biotite, hornblende, other amphiboles, or feldspar.

Lamprophyre dikes, less than 1 m wide, also intruded the Proterozoic schist. These highly altered dikes contain plagioclase, alkali-feldspar, calcite, altered biotite, altered hornblende, and magnetite and are tentatively classified as spessartites (LeMaitre, 1989). In thin section, the rock is aphanitic porphyritic, with phenocrysts of plagioclase. In the Mountain States rock quarry, a lamprophyre dike (LOBO 8) appears to be the oldest of the post-metamorphic rocks and was intruded by a carbonatite dike (LOBO 10) and then by a monzonite dike (LOBO 9).

Thin carbonatite dikes, less than 15 cm wide intruded the Proterozoic schist. The Lobo Hill carbonatite consists of calcite and dolomite with subordinate magnetite, apatite, hematite/goethite, and trace fluorite. Chemically, it is a calciocarbonatite (LeMaitre, 1989). The quartz that is present is probably a contaminant derived from the metamorphic host rocks.

AGE

Loring and Armstrong (1980) were the first to recognize that a Cambrian-Ordovician magmatic event affected New Mexico. They determined a Rb-Sr whole-rock isochron age of the Lobo Hill and Pedernal syenites of 469 ± 7 Ma, with a maximum age of 604 Ma for the Lobo Hill syenite. Only one sample came from Lobo Hill. However, paleomagnetic data presented by Jackson et al. (1988) are consistent with a late Paleozoic age, not a middle Ordovician age. Because of the uncertainty associated with this age date, we resampled for an additional $^{40}Ar/^{39}Ar$-age determination.

A sample of a monzonite dike (LOBO-1) was collected and analyzed by furnace incremental heating age spectrum method by the New Mexico Geochronological Research Laboratory at NMBMMR (Table 2) in order to determine the age of cooling and provide information regarding the thermal history of the area. Biotite and alkali-feldspar mineral separates were obtained by standard heavy liquid, Franz magnetic, and hand picking techniques and were packaged in copper foil. The mineral separates were irradiated in machined aluminum discs for 24 hrs in the L67 position of the Ford Reactor (University of Michigan), along with a neutron flux monitor (the Fish Canyon Tuff sanidine (FC-1) with an assigned age of 27.84 Ma (Deino and Potts, 1990) relative to Mmhb-1 at 520.4 Ma (Samson and Alexander, 1987). After irradiation, samples were step-heated in a Mo double-vacuum resistance furnace with a heating duration of 8 min. Reactive gases were removed by reaction with 3 SAES GP-50 getters, 2 operated at ~450ºC and 1 at 20ºC. Gas was also exposed to a W filament operated at ~2000ºC. Total gas ages and errors were calculated by weighting individual steps by the fraction of ^{39}Ar released. The plateau age was calculated by weighting each step by the inverse of the variance, and the plateau errors were calculated using the method of Taylor (1982). MSWD values are calculated for n-1 degrees of freedom for the plateau age. If the MSWD is outside the 95% confidence window (Mahon, 1996), the error is multiplied by the square root of the MSWD. Decay constants and isotopic abundances are after Steiger and Jäger (1977). All final errors are reported at ±2σ, unless otherwise noted.

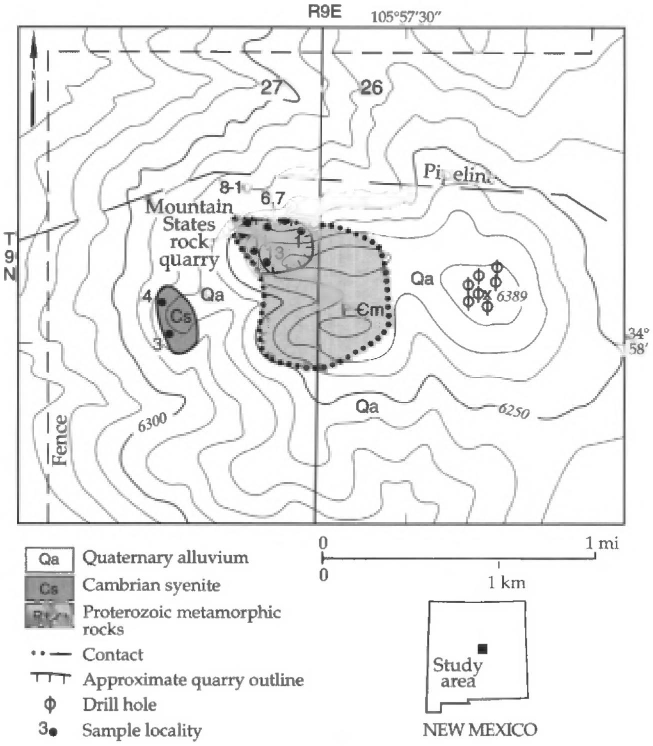

FIGURE 2. Geologic sketch map of Lobo Hill.

The alkali-feldspar reveals an overall age gradient from ~310–525 Ma with anomalous behavior for some of the low-temperature heating steps (Fig. 3). This anomalous behavior corresponds to low K/Ca values that may be related to plagioclase contamination. The biotite age spectrum is relatively flat, but does show minor complexity for some of the intermediate heating steps (Fig. 3). An age of 518 ± 5.7 Ma is calculated for the heating steps comprising nearly 98% of the total ^{39}Ar released. The high MSWD value of 65 for the calculated plateau age indicates significant scatter above, which can be attributed to analytical error.

Biotite plateau ages from plutonic rocks generally represent the time when the sample cooled below ~300ºC (Harrison et al., 1985). The observed textures within the monzonite and its small volume imply rapid cooling and high-level of emplacement, so the plateau age of 518 ± 5.7 Ma records the age of monzonite emplacement. The age spectrum complexity is most likely related to the substantial chlorite alteration of the biotite and associated effects of ^{39}Ar recoil (Lo and Onstott, 1989).

The alkali-feldspar age gradient is related to post-emplacement argon loss. The initial ages of ~310 Ma (Fig. 3) indicate that there was significant Paleozoic burial or fluid migration that caused re-heating and argon loss. Arrhenius data for the alkali-feldspar (not given) are quite complex and cannot be used to quantify the argon diffusion properties of this sample and therefore a quantitative measure of the closure temperature is not possible. It is likely that the sample was heated to ~200ºC during the Paleozoic and was exhumed during the ancestral Rocky Mountain uplift activity.

GEOCHEMISTRY

Fourteen samples of the Lobo Hill alkaline rocks were sampled and analyzed for major and trace elements (Table 3). All of the samples were collected from or adjacent to the Mountain States rock quarry. Samples 4282 and 4283c were collected in 1983 from a shallow prospect pit at the site of the rock quarry, prior to aggregate mining (McLemore, 1984). The samples prefixed LOBO were analyzed by x-ray fluorescent spectrometry (XRF) on fused glass discs and trace elements were analyzed using pressed powder briquettes. Major elements

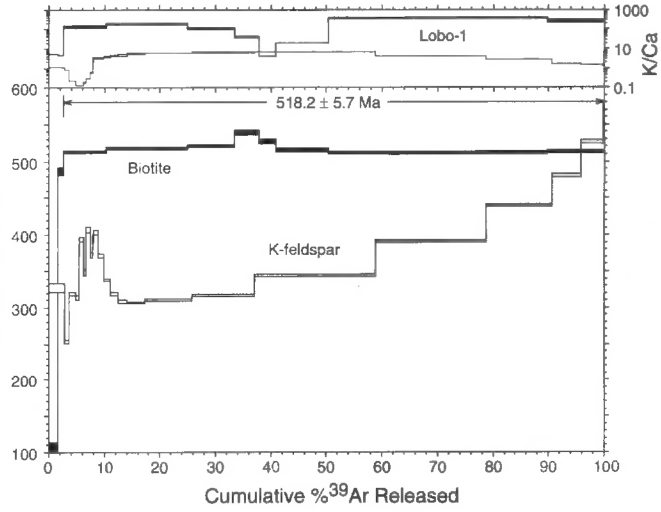

FIGURE 3. Age spectra for LOBO-1 biotite and K-feldspar.

TABLE 2. Argon isotopic results for sample LOBO-1. Isotopic ratios corrected for blank, radioactive decay, and mass discrimination, but not corrected for interfering reactions. Individual analyses show analytical error only; plateau, preferred and total-gas-age errors include error in J and irradiation parameters. N = number of heating steps. K/Ca = molar ratio calculated from reactor produced ^{39}ArK and ^{37}ArCa. *2σ error.

ID	Temp	^{40}Ar/^{39}Ar	^{37}Ar/^{39}Ar	^{36}Ar/^{39}Ar (x 10^{-3})	^{39}Ar$_k$ (x 10^{-15} mol.)	K/Ca	^{40}Ar*%	^{39}Ar%	Age (Ma)	±1σ (mA)
A	500	128.4	0.4918	264.6	5.24	1.0	39.1	2.7	326.9	3.0
B	500	45.31	0.6296	24.17	1.89	0.81	84.3	3.7	253.7	1.2
C	550	54.49	2.254	19.79	2.20	0.23	89.6	4.8	318.7	1.1
D	550	53.56	3.951	20.25	1.17	0.13	89.4	5.5	313.5	1.5
E	600	69.43	3.988	27.37	1.49	0.13	88.8	6.2	394.4	1.6
F	600	59.07	2.832	19.39	0.809	0.18	90.7	6.7	347.0	1.9
G	650	72.74	1.755	30.20	1.37	0.29	87.9	7.4	406.9	1.9
H	650	62.34	0.8972	15.05	0.766	0.57	92.9	7.8	372.2	1.9
I	700	67.61	0.1923	19.03	0.498	2.7	91.7	8.0	395.3	2.8
J	750	72.51	0.1536	30.91	1.49	3.3	87.4	8.8	403.2	1.6
K	800	65.05	0.1500	24.62	1.98	3.4	88.8	9.8	371.0	1.3
L	850	57.59	0.1376	18.51	2.28	3.7	90.5	11.0	337.8	1.1
M	900	52.88	0.1251	13.18	2.68	4.1	92.6	12.4	319.2	1.0
N	950	50.54	0.1122	11.61	3.14	4.5	93.2	14.0	307.94	0.91
O	1000	50.44	0.0950	11.95	6.38	5.4	93.0	17.3	306.70	0.65
P	1050	51.29	0.0831	12.66	16.3	6.1	92.7	25.8	310.55	0.64
Q	1100	52.44	0.0793	13.49	21.8	6.4	92.4	37.1	315.96	0.68
R	1100	57.32	0.0781	14.42	41.8	6.5	92.5	58.8	343.33	0.82
S	1100	65.45	0.1227	14.42	38.4	4.2	93.5	78.8	390.65	0.81
T	1100	74.73	0.1980	16.27	22.7	2.6	93.6	90.5	440.16	0.81
U	1100	83.25	0.3248	20.49	10.3	1.6	92.7	95.9	480.47	0.93
V	1100	96.40	0.3775	36.68	7.58	1.4	88.8	99.8	525.6	1.2
W	1180	97.99	0.3743	14.34	0.390	1.4	95.7	100.0	568.8	3.9
Total gas age		N = 23			192.7	4.4			371.12	0.91
Biotite, wt = 1.14 mg, J = 0.0039916, NM-95, Lab# = 9545-02										
A	580	45.19	0.0991	101.1	1.21	5.2	33.9	1.6	107.0	3.1
B	680	92.69	0.1153	47.68	0.764	4.4	84.6	2.5	486.8	2.6
C	760	85.14	0.0037	9.010	6.06	138	96.8	10.3	513.29	0.96
D	830	84.62	0.0026	4.400	11.5	195	98.4	25.0	517.84	0.91
E	900	85.19	0.0045	4.383	6.57	114	98.5	33.4	520.98	0.96
F	980	88.97	0.0122	5.744	3.46	42	98.1	37.8	539.1	1.2
G	1050	87.84	0.1262	9.674	2.45	4.0	96.7	40.9	526.9	1.4
H	1110	84.88	0.0260	6.765	7.38	20	97.6	50.4	515.5	1.1
I	1170	83.18	0.0014	3.162	30.8	374	98.8	89.8	512.05	0.89
J	1280	83.35	0.0019	2.821	8.00	264	99.0	100.0	513.52	0.89
Total gas age		N = 10			78.1	227			509.35	0.98
Plateau age	Mswd = 65.5	N = 8		Steps C–J	76.2	233		97.5	518.2	5.7*

were analyzed by Uniquant semi-quantitative XRF methods using pressed powder briquettes for sample LOBO 13.

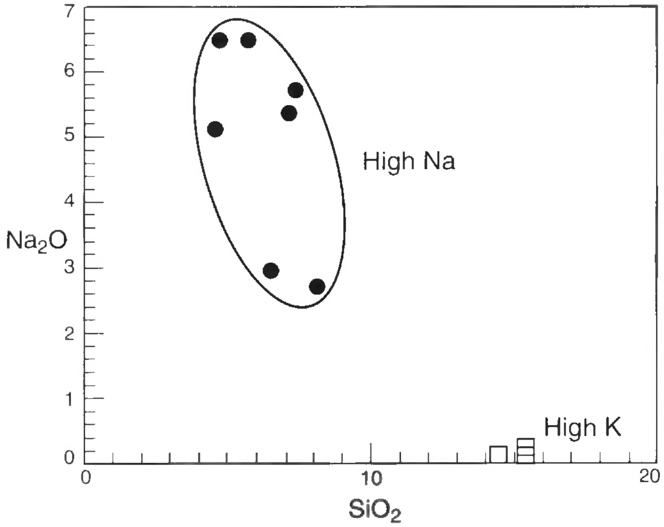

FIGURE 4. Plot of Na_2O verses K_2O of Lobo Hill felsic alkaline rocks, showing two geochemical groups; high-K syenites (squares) and high-Na monzonites, quartz syenites, and monzogranites (filled circles).

Chemically, the Lobo Hill alkali-feldspar syenites, monzonites, quartz syenites, and monzogranites are metaluminous and can be differentiated into two geochemical groups as a result of differences in mineralogy (abundance of alkali-feldspar and plagioclase) and chemical composition: high K and high Na (Table 3, Figs. 4, 5A). The high-K alkali-feldspar syenites contain predominantly alkali-feldspar and are higher in K_2O (14–15%), Rb (844–956 ppm), Th (268–341 ppm), Pb (67–86 ppm), Zn (354–771 ppm), Y (102–113 ppm) and low in Na_2O (0.11%). The high-Na monzonites, quartz syenites, and monzogranites contain both alkali-feldspar and plagioclase and are lower in K_2O (3–8%), Rb (125–500 ppm), Th (12–60 ppm), Pb (5–25 ppm), Zn (11–181 ppm), Y (23–66 ppm) and higher in Na_2O (2–7%). K_2O/Na_2O ratios range from 0.34 to 2.96 in the high-Na group, to 72–130 in the high-K group.

ECONOMIC POTENTIAL

Unlike similar alkaline rocks elsewhere in New Mexico (Table 1), the Lobo Hill alkaline rocks do not have any significant economic potential, except for aggregate (crushed stone). The area was quarried, presumably for road material, in the late 1980s and early 1990s. The quarry rocks are diverse in lithology and are highly fractured, and therefore, are suitable only for use as crushed stone. A few of the dikes are radioactive, containing elevated U and Th and possibly REE, but the distribution of these elements is sporadic and low grade. Malachite is locally present along fractures, especially adjacent to the carbonatite dikes, but not in economic concentrations (Table 3).

TABLE 3. Chemical analyses of alkali-feldspar syenites (4282, LOBO 3, 4), monzonites (LOBO 1, 7, 9, 12), quartz syenite (LOBO 6), monzogranites (LOBO 2, 11), lamprophyres (LOBO 8, 13), and carbonatites (LOBO 10, 4283c) from Lobo Hill. [1]From McLemore (1984). — not analyzed.

	4282[1]	LOBO 3	LOBO 4	LOBO 1	LOBO 7	LOBO 9	LOBO 12	LOBO 6	LOBO 2	LOBO 11	LOBO 8	LOBO 13	LOBO 10	4283c[1]
SiO_2	59.83	60.05	56.34	57.98	59.70	60.16	62.22	69.10	70.70	72.41	58.09	26.1	39.85	12.08
TiO_2	1.86	0.50	0.48	1.00	0.10	0.08	0.10	0.14	0.14	0.31	0.10	5.4	0.35	0.23
Al_2O_3	11.86	17.07	16.28	17.09	18.04	17.23	18.21	13.51	13.38	12.17	16.76	15.2	11.30	3.25
Fe_2O_3-T	—	2.46	2.53	6.21	0.54	0.88	4.27	1.56	0.59	2.13	5.07	21.10	4.59	—
Fe_2O_3	1.3	—	—	—	—	—	—	—	—	—	—	—	—	5.5
FeO	0.92	—	—	—	—	—	—	—	—	—	—	—	—	1.04
MnO	—	0.01	0.03	0.31	0.07	0.10	0.08	0.07	0.05	0.05	0.09	0.25	0.16	—
MgO	0.01	0.06	0.14	0.35	0.06	0.07	0.06	0.22	0.02	0.08	0.18	3.29	4.31	0.64
CaO	4.12	1.59	4.57	2.15	4.45	4.70	0.18	1.78	2.84	1.42	4.28	9.5	15.71	41.94
K_2O	15.29	15.29	14.41	4.68	7.05	5.65	7.33	8.04	4.55	6.50	3.69	2.8	1.27	0.46
Na_2O	0.21	0.11	0.11	6.51	5.37	6.51	5.71	2.72	5.09	2.95	7.34	0.36	3.78	0.33
P_2O_5	0.15	0.45	0.44	0.60	0.05	0.05	0.08	0.02	0.02	0.10	0.05	2.99	0.07	0.03
LOI	2.52	1.38	3.23	2.73	4.22	4.21	1.34	1.98	2.45	1.55	4.07	9.43	18.61	32.64
TOTAL	98.05	98.97	98.56	99.61	99.65	99.64	99.57	99.14	99.84	99.67	99.72	96.32	99.99	98.14
Sr	41	219	244	306	49	63	150	50	29	47	135	335	251	211
Rb	191	844	756	125	406	304	409	500	288	361	157	97	99	—
Th	12	268	341	17	35	38	36	84	60	88	34	17	<2	230
Pb	12	67	86	9	25	11	9	25	10	5	12	9	3	—
Ga	17	22	22	20	30	24	30	28	26	13	26	21	11	—
Zn	219	354	771	63	33	24	53	181	11	23	22	274	33	138
Cu	85	15	13	11	7	9	8	<2	18	16	24	55	7	2900
Ni	14	4	8	5	3	11	4	4	5	7	8	231	99	28
Cr	346	13	13	5	4	13	<2	7	5	11	<2	640	473	10
Ba	233	661	199	1500	107	108	228	141	87	168	72	69	132	160
V	56	53	39	24	9	8	23	9	30	61	24	194	154	—
As	—	153	713	3	7	5	24	17	19	264	6	7	3	—
U	3	14	14	5	11	8	9	13	10	7	9	5	<2	1080
Y	23	76	81	45	65	59	66	110	102	113	80	59	12	146
Zr	93	1100	1100	531	1100	903	996	1100	798	651	1400	402	35	—
Nb	3	318	261	189	356	287	323	379	416	42	356	145	3	243
Mo	—	2	4	5	7	5	7	2	1	2	4	<2	<2	—

DISCUSSION

Origin of the Lobo Hill syenite

The Lobo Hill alkaline rocks are near-surface intrusions. The high-Na monzonites, quartz syenites, and monzogranites most likely represent a primary magma emplaced in Proterozoic metamorphic rocks. Primary igneous textures, field relationships, geochemical distributions, and similarity to other syenites and monzonites from throughout the world support a magmatic origin.

The high-K alkali-feldspar syenites are probably metasomatic, as indicated by textures similar to the high-Na dikes, K-feldspar metasomatism along fractures and joints, high K_2O/Na_2O ratios (Fig. 4), and distributions of trace elements (Fig. 5B–E). Many high-K rocks are associated with alkaline complexes, carbonatites, and kimberlites by introduction of external fluids; this process is known as metasomatism or fenitization where the metasomatism is associated with alkaline intrusions.

Geochemical trends (Figs. 4–5) are consistent with two possible models for the origin of the Cambrian rocks: (1) a single magma that was later affected by K-metasomatism, or (2) two or more separate magmas. High-Na monzonites, quartz syenites, and monzogranites first intruded the Proterozoic terrain and were subsequently metasomatized by late-stage K-rich solutions associated with the alkaline intrusions. The Y verses SiO_2 plot is consistent with a co-magmatic suite (Fig. 5A). However, significant scatter in the Nb, Zr, Ba, and Sr-versus-SiO_2 plots (Fig. 5B–E) could be a result of K-metasomatism. All three samples of the high-K alkali-feldspar syenites are from the upper part of the sequence, suggesting that K-metasomatism selectively occurred at the top of and possibly along the edges of the intrusion. Alternatively, late-stage magmatic fluids, possibly related to a second deeper syenitic magma, may have migrated along fractures and faults and formed the K-rich alkali-feldspar syenites. Similar models are envisioned for the origin of the alkaline rocks in the Caballo, Burro, and Zuni Mountains (McLemore, 1986; McLemore and McKee, 1988, 1989). Detailed geochemical and isotopic studies are needed to evaluate these models.

Regional implications

The Cambrian–Ordovician magmatic event is well-documented in southern Colorado and New Mexico (Fig. 1, Table 1; McLemore, 1987b, 1989). The Lobo Hill alkaline rocks are part of this event. Such alkaline magmatism is consistent with continental rift and aborted rift systems, although no Cambrian–Ordovician rift-basin sediments or rift-related structures have been observed for this time period in New Mexico. Specific geographic boundaries of such a rift would be difficult to observe because of complex overprinting related to the ancestral Rocky Mountains orogeny, Laramide orogeny, and Rio Grande rifting and other tectonic events (Fig. 6). Recognition of widespread Cambrian–Ordovician magmatic activity in New Mexico, evidence of relatively rapid uplift and erosion in the Florida Mountains (Evans and Clemons, 1988; Clemons, 1998; Ervin, 1998), and the presence of carbonatites (McLemore, 1983, 1987a) suggest that New Mexico was not a simple passive margin during the Cambrian–Ordovician, but instead, experienced sufficient extension to perturb the mantle and initiate magmatism. Thus, we propose that an aulacogen, similar to the southern Oklahoma aulacogen (Lambert et al. 1988; McConnell and Gilbert, 1990), existed in New Mexico during Cambrian and Early Ordovician time (Fig. 6). Additional studies are underway to characterize fully and evaluate the tectonic history during the Cambrian–Ordovician of New Mexico and southern Colorado.

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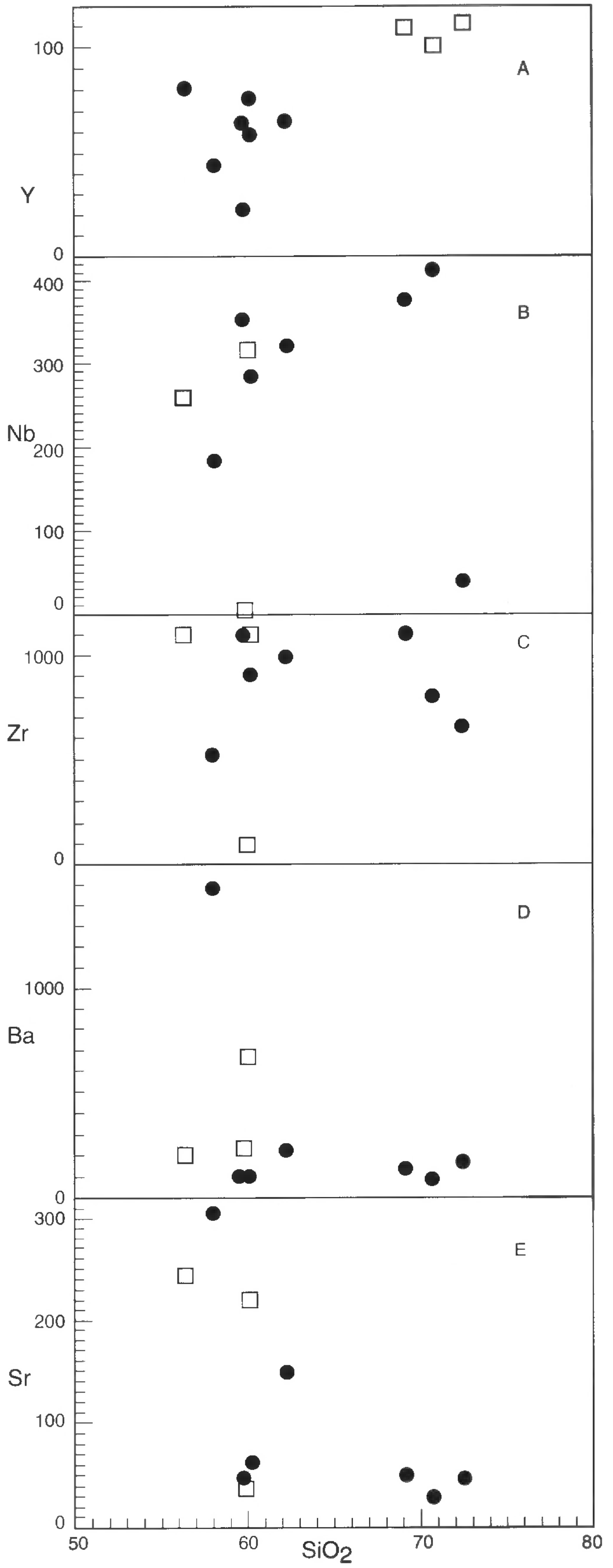

FIGURE 5. Plot of selected trace elements verses SiO_2 of Lobo Hill felsic alkaline rocks.

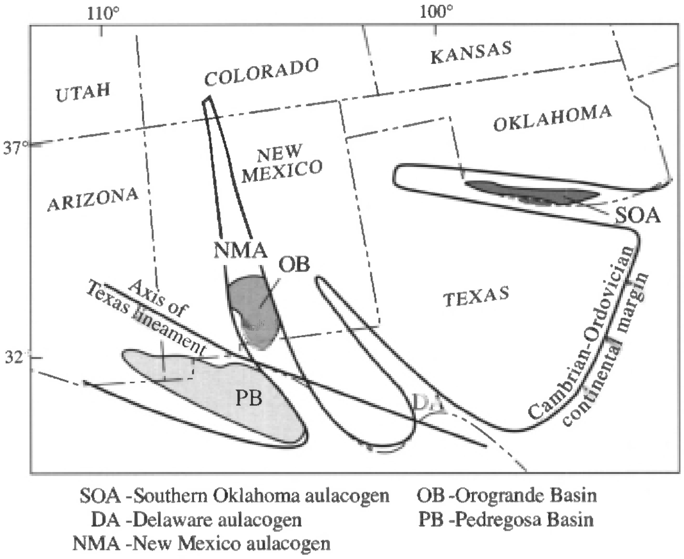

FIGURE 6. Cambrian–Ordovician tectonic features in Oklahoma, west Texas, and New Mexico (modified from Larson et al., 1985; Evans and Clemons, 1988; Lambert et al., 1988; Ervin, 1998).

ples by X-ray-fluorescence using the Phillips PW 2400 instrument purchased with funds from NSF grant EAR-9316467. Lynn Brandvold (NMBMMR) analyzed other samples (4282, 4283c) by atomic-absorption spectrometry and induced coupled plasma spectrometry methods. Lisa Peters and Rich Esser carried out the mineral separations and $^{40}Ar/^{39}Ar$ age determinations at the New Mexico Geochronology Laboratory at the New Mexico Bureau of Mines and Mineral Resources. Robert Thompson and Janice Boller assisted with the sample preparation. The New Mexico Bureau of Mines and Mineral Resources Cartography Department drafted the figures.

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Jack Cunningham with a full bag of wind and doing his thing at the 1994 NMGS Field Conference to the Mogollon Slope in west-central New Mexico and east-central Arizona (photograph courtesy of George Austin).