# Cambrian–Ordovician magmatism and extension in New Mexico and Colorado

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## Abstract

Cambrian–Ordovician alkaline and carbonatite igneous rocks in southern Colorado and New Mexico show that the region was tectonically active in the opening years of the Paleozoic era. Intrusions with apparent ages between 574 and 427 Ma in southern Colorado and between 664 and 457 Ma in New Mexico consist of calcic and ferrocarbonatites, syenites, alkali feldspar granites, and mafic dikes and plutons. Fenitization, or metasomatism associated with alkaline magmatism, is a common phenomenon in this suite that can result in extremely high whole-rock $K_2O$ concentrations (as much as 16%) and low $Na_2O$ and CaO concentrations. In some cases syenitic intrusions as well as the host rocks were fenitized; it is locally difficult to discriminate between primary magmas and host rocks altered during fenitization. However, the immobile incompatible trace elements Nb (niobium), Y (yttrium), and Zr (zirconium) appear to have been only slightly affected by fenitization. High concentrations of these elements in the alkaline rocks (as much as 360 ppm Nb, 1,400 ppm Zr, and 240 ppm Y), and the presence of carbonatites are consistent with magmatism caused by extension.

This period of extension-related magmatism in western Laurentia occurred after Neoproterozoic rifting of the western continental margin and immediately before early Paleozoic marine transgression and deposition of the thick passive margin sequence. We postulate that the event was related to a series of aulacogens that extended continentward from the rifted eastern margin of Laurentia (Reelfoot rift, Rome trough, Rough Creek graben, southern Oklahoma aulacogen) and thus refer to it as the New Mexico aulacogen. The possible northeast-southwest orientation of the aulacogen, similar to other aulacogens in Laurentia, suggests that the New Mexico aulacogen was the youngest in a series of failed rifts that propagated into the continent as the southern margin of Laurentia was rifted in Neoproterozoic and early Paleozoic time. The New Mexico aulacogen and its associated tectonic elements connected the western, southern, and eastern rifted margins of Laurentia. Alternatively, the aulacogen could have had a north-south orientation. In this case the New Mexico aulacogen could have caused or enhanced north-south weaknesses that were reactivated during Cenozoic extension in the Rio Grande rift. Laramide reactivation of north-south Neoproterozoic normal faults in central Arizona prompted Timmons et al. (2001) to propose that north-south Laramide faults in New Mexico, as well as the north-south normal faults of the Cenozoic Rio Grande rift, could be reactivated Neoproterozoic faults. Because the details of reactivation have not been researched in New Mexico, it is difficult to ascertain whether the Cenozoic north-south trend was inherited from initial Neoproterozoic or Cambrian structures. In either case Cambrian–Ordovician extension in Colorado and New Mexico could have had a profound influence on the evolution of the continent by permanently weakening the lithosphere and focussing subsequent tectonic events in a zone between the stable lithospheric blocks of the Colorado Plateau and the Great Plains.

## Introduction

The fundamental shape of the North American continental lithosphere was sculpted by late Proterozoic–early Paleozoic rifting. The western margin was created during late Proterozoic extension (800–700 Ma), subsequently smoothed by early Paleozoic deposition, and deformed by multiple orogenies in Paleozoic and Mesozoic times (Hoffman 1989; Oldow et al. 1989). The eastern and southeastern margins, similarly, were formed during late Proterozoic–early Paleozoic rifting (Thomas 1991). Subsequent deposition and deformation in Paleozoic through modern times have modified the lithosphere of eastern North America. This paper suggests that the two margins were joined in Cambrian–Ordovician time across northern Mexico and the southwestern United States. The evidence for this connection lies largely in a series of Cambrian–Ordovician alkaline and carbonatite igneous rocks in southern Colorado and New Mexico (Fig. 1). The ages, compositions, and spatial distribution of these intrusions suggest that the region was affected by extensional magmatism early in the Paleozoic prior to marine transgression and deposition of the lower Paleozoic passive margin sequence.

The existence of Cambrian–Ordovician igneous rocks in Colorado and New Mexico has been recognized by many geologists (Table 1). This paper compiles available geochemical and geochronologic data in order to interpret the origin of the igneous rocks and place them into a tentative tectonic model that is consistent with known tectonic elements of North America.

## Methods

Data used in this report have been compiled from the literature and unpublished work by the authors. Locations, available data, age determinations, and references are listed in Table 1. Most of the whole-rock geochemical data were determined by X-ray fluorescence spectrometry, which determines the major elements and a suite of trace elements (Rb, Sr, Ba, V, Nb, Zr, Y, Ni, and Cr, in most cases). Many of the carbonatite analyses were performed by wet chemical and other classical analytical methods (McLemore 1980a, 1982). Some suites were analyzed by inductively coupled plasma atomic emission spectrometry, which determines the major elements and a slightly different suite of trace elements (Sr, Ba, V, Zr, Y, Sc, Cr, and Ni). Instrumental neutron activation analysis data, which include Hf, Ta, U, Th, and the rare earth elements, are reported for only a few areas. Radiogenic isotopic analyses also are very sparse.

In an attempt to exercise quality control on analyses in this compilation, whole-rock analyses with totals less than 98.5% or more than 101.5%, calculated with total iron as $Fe_2O_3$ and including loss on ignition (LOI, a measure of the

TABLE 1—Compilation of known and suspected Cambro–Ordovician igneous rocks of New Mexico and Colorado. **bt** = biotite, **hbld** = hornblende, **zrc** = zircon, **pyx** = pyroxene, **neph** = nepheline, **wr** = whole-rock, **musc** = muscovite, **verm** = vermiculite, **plag** = plagioclase, **XRF** = X-ray fluorescence, **INAA** = instrumental neutron activation, **ICP** = inductively coupled plasma, **Nd** = Neodynium, **Majors** = major element analysis only

| Map # | Location | Lithology | Age determinations | Avail. data | References |
|---|---|---|---|---|---|
| 1 | Florida Mountains, NM | syenite, orthoclase, granite | 503 ± 10 Ma & 514 ± 3 Ma, U-Pb (zrc), 491 ± 5, $^{40}$Ar/$^{39}$Ar (bt), 485.5 ± 4.9 Ma, $^{40}$Ar/$^{39}$Ar (hbld) | ICP, INAA, Nd | Evans and Clemons (1988), Matheny et al. (1988), Ervin (1998), Clemons (1998) |
| 2 | Lemitar Mountains, NM | carbonatite | 449 ± 16 Ma, K-Ar (bt) | XRF | McLemore (1980b, 1982, 1983b, 1987) |
| 3 | Lobo Hill, NM | syenite, carbonatite | 518 ± 5.7 Ma, $^{40}$Ar/$^{39}$Ar (bt) | XRF | McLemore et al. (1999) |
| 4 | Black Canyon of the Gunnison, CO | diabase | 495 ± 15 Ma, Rb-Sr (mineral separates), 533 ± 20 Ma, K-Ar (wr), 504 ± 16 K-Ar (wr) | Majors | Larson et al. (1985) |
| 5 | Democrat Creek, CO | syenite, mafic-ultramafic, carbonatite | 504 ± 25 Ma, (bt), 519 ± 13 Ma, (bt), 534 ± 16 Ma, (hbld), 485 ± 24 Ma, (wr), 560 ± 28 Ma, (wr), 427 ± 22 Ma, (wr), K-Ar | Majors | Olson et al. (1977), Armbrustmacher (1984) |
| 6 | Gem Park, CO | carbonatite, mafic-ultramafic, alkalic suite | 551 ± 30 Ma, K-Ar (riebeckite) | Majors | Olson et al. (1977) |
| 7 | McClure Mountains, CO | carbonatite, alkalic suite, mafic-ultramafic | 534 ± 4 Ma, U-Pb (zrc); K-Ar: 510 ± 13 Ma, 523 ± 14 Ma, (hbld), 506 ± 13 Ma, (bt), 516 ± 11 Ma, (hbld), 509 ± 11 Ma, (hbld), 507 ± 17 Ma, (bt), 532 ± 15 Ma, (hbld), 510 ± 13 Ma, (bt), 536 ± 17 Ma, (pyx), 479 ± 12 Ma, (neph); 520.4 ± 1.7 Ma, Ar-Ar (hbld) | Majors | Fenton and Faure (1970), Olson et al. (1977), Armbrustmacher (1984), Bickford et al. (1989), d), Samson and Alexander , (1987) |
| 8 | Iron Hill, CO | carbonatite, alkalic suite | K-Ar: 567 ± 10 Ma, (bt), 568 ± 9 Ma, (bt), 574 ± 9 Ma, ( bt), 731 ± 23 Ma, (aegirine), 543 ± 8 Ma, (bt), 561 ± 10 Ma, (musc), 573 ± 14 Ma, (bt), 574 ± 9 Ma, (verm), 553 ± 9 Ma, (verm), 762 ± 15 Ma, (plag) | Majors | Fenton and Faure (1970), Olson et al. (1977) |
| 9 | Costilla Creek, NM | mafic dikes | 500 Ma, Rb-Sr whole-rock “isochron” | none | Reed (1984) |
| 10 | Houston Oil and Mineral Levelling No. 2 oil test well near Tularosa, NM | mafic fine-grained rock | 514 ± 21 Ma, K-Ar (wr) | none | Loring and Armstrong (1980) |
| 11 | Pedernal Hills, NM | syenite | 469 ± 7, 496 Ma max, Rb-Sr whole-rock isochron (?) | Majors | Loring and Armstrong 1980) |
| 12 | Trans-Pecos Resources Latigo Ranch Nos. 1A well | Qtz-fsp porphyry | 604 ± 30 Ma, K-Ar (wr) | none | Setter and Adams (1985) |
| 13 | Yates Petroleum T-4 Cattle Co. Nos. 1 and 2 | granite | 664 ± 35Ma, K-Ar (wr) | none | Setter and Adams (1985) |
| 14 | Burro Mountains, NM | syenite and diabase | cross cutting relationships | XRF | Gillerman and Whitebread (1956), Hedlund (1978a, 1978b, 1978c), McLemore and McKee (1988) |
| 15 | Caballo Mountains, NM | syenite | cross cutting relationships | XRF | Staatz et al. (1965), McLemore (1986) |
| 16 | Chupadera Mountains, NM | carbonatite | cross cutting relationships | XRF | Kent (1982), McLemore (1983b), Van Allen et al. (1986) |
| 17 | Little Hatchet pluton, NM | granite | cross cutting relationships | XRF | Channell et al. (2000) |
| 18 | Monte Largo Hills, NM | carbonatite, alkalic suite | cross cutting relationships | XRF | Lambert (1961), McLemore (1983b) |
| 19 | Nacimiento Mountains, NM | syenite | cross cutting relationships | none | Woodward et al. (1977) |
| 20 | Red Hills, NM | syenite | cross cutting relationships | XRF, INAA | McLemore (1986), McMillan and McLemore (unpublished) |
| 21 | Sangre de Cristo Mountains, NM | syenite | cross cutting relationships | XRF | Reed et al. (1983), Klich (1983) |

total volatile content), were rejected. Major element analyses for silicate rocks were normalized to 100% with total iron as FeO and no volatiles for plotting purposes. Major element analyses for carbonatites were left as analyzed.

## Age determinations

The ages of Cambrian–Ordovician plutons in New Mexico and Colorado have been compiled by previous authors (Olson et al. 1977; Loring and Armstrong 1980; Armbrustmacher 1984; McLemore et al. 1999). All of the intrusions listed in Table 1 share the same fundamental geologic relationships: they are non-foliated, non-metamorphosed, and cross cut Precambrian foliations. In mountain ranges with exposures of Phanerozoic rocks, the intrusions are non-

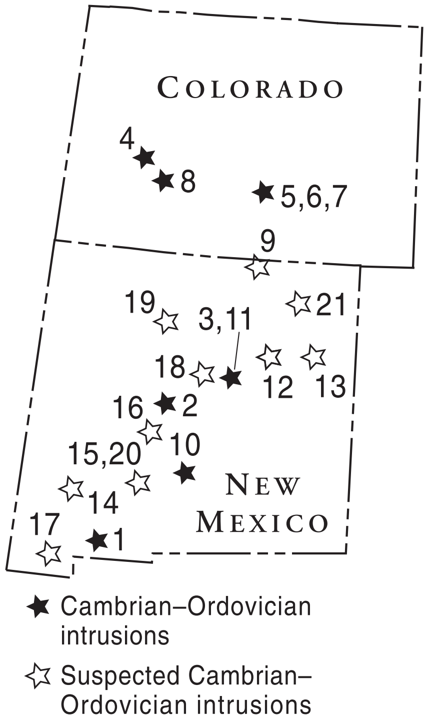

FIGURE 1—Locations of known (filled symbols) and suspected (open symbols) Cambrian–Ordovician intrusions in New Mexico and Colorado.

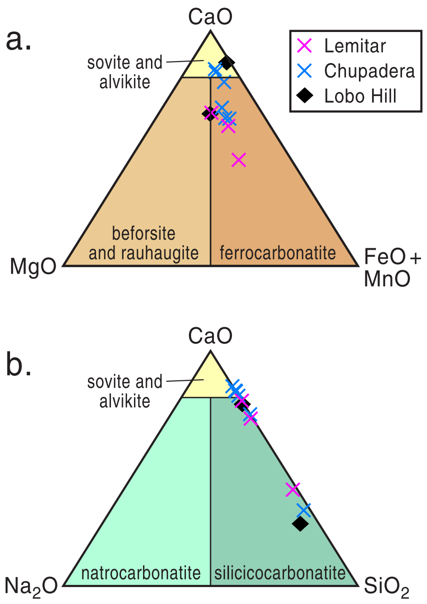

FIGURE 2—Chemical composition of Cambrian–Ordovician carbonatites (classification of Woolley and Kempe 1989).

conformably overlain by Paleozoic or younger sedimentary rocks. Many areas have yet to be dated (Table 1), but we suspect that they belong to the Cambrian–Ordovician suite because they are alkaline silicate intrusions or carbonatites. In the Red Hills and Caballo Mountains, clasts of syenite are found in the basal conglomerate of the Cambrian–Ordovician Bliss Formation, indicating that intrusion and erosion occurred before deposition (McLemore 1986). Suites with reasonable age determinations are plotted in Figures 2–8 in larger symbols than suites with unreliable or no age determinations.

Geochronologic data for this suite are still insufficient to resolve the major chronologic issues. Nonetheless, Cambrian–Ordovician intrusions with reliable age determinations show that a magmatic event occurred in New Mexico and Colorado sometime between 570 Ma and 450 Ma (Table 1). There are not yet enough age determinations to examine the spatial distribution of magmatism through time. In southern New Mexico, the Florida Mountains intrusion crystallized at about 511 ± 10 Ma and the Lemitar carbonatites have been dated at 457 ± 16 Ma. In central and northern New Mexico, age determinations exist for plutonic rocks between 664 and 514 Ma. The alkaline complexes in Colorado have received more geochronological attention. K-Ar and U-Pb zircon age determinations range between 485 and 570 Ma; an Ar-Ar age determination of hornblende from a syenite in the McClure Mountains yielded an age of 520.4 ± 1.7 Ma. It is not clear at this point whether the range of ages is an analytical artifact, a record of several unrelated igneous events, or a record of one prolonged event. For the purposes of this compilation, the suites listed in Table 1 will be considered as part of the same event, based on similar cross cutting relationships and the alkaline/carbonatitic nature of the magmatism.

One aspect of these rocks that has frustrated attempts at determining their age and origin is pervasive fenitization, or metasomatism associated with alkaline intrusions and carbonatites. As discussed in detail below, fenitization appears to have been related to igneous activity because both alkaline dikes and their host rocks were affected. In some areas, it is difficult to determine whether rocks that were altered during fenitization were originally alkaline intrusions or the Precambrian igneous or metamorphic host rocks.

Almost all areas with Cambrian–Ordovician age determinations in Table 1 are carbonatitic or alkaline silicic intrusions. However, mafic rocks also were emplaced during this event. For instance, the diabase intrusions in the Black Canyon of the Gunnison yield K-Ar ages around 533–504 Ma, and produce a Rb-Sr isochron of 495 Ma (Larson et al. 1985). The Colorado suites have a significant mafic and ultramafic component. Mafic dikes that accompany alkaline intrusions in the Red Hills and at Lobo Hill also record a mafic component in Cambrian–Ordovician magmatism. Whole-rock Rb-Sr isochron ages on samples of a diorite dike (500 Ma, Reed 1984) and diabase dikes (670 Ma, Lipman and Reed 1989) in the Costilla Creek area near Taos, New Mexico, must be interpreted with caution, because whole-rock isochrons can be incorrect by hundreds of millions of years if assimilation of crustal rocks occurred during magma evolution. Furthermore, it is uncertain what effect Tertiary magmatism and hydrothermal activity associated with the Questa caldera had on these age determinations.

## Lithology and structure

### Carbonatites

Cambrian–Ordovician carbonatites are found in several locations throughout New Mexico and Colorado (Table 1 and Fig. 1). Age determinations of New Mexico carbonatites range from 457 ± 16 Ma (K-Ar biotite; McLemore et al. 1982, 1983b) in the Lemitar Mountains to 518 ± 5.7 Ma ($^{40}$Ar/$^{39}$Ar biotite from associated syenite, McLemore et al. 1999) in the Lobo Hills alkaline complex in central New Mexico. Ages range from 574 to 479 Ma in the alkaline complexes in the Wet Mountains of southern Colorado. The carbonatite dike in the Monte Largo Hills northeast of Albuquerque, New Mexico, is undated but intrudes Precambrian quartz-feldspar gneiss.

Carbonatite intrusions exhibit two main styles: dike swarms and roughly circular, locally brecciated stocks. In the Lemitar, Chupadera, and Monte Largo areas, carbonatite dikes intruded Precambrian igneous and metamorphic rocks and are not associated with other Cambrian–Ordovician alkaline rocks (McLemore 1983b). Fenitization is pervasive. In the Chupadera Mountains the dikes consistently trend east to east-northeast (Kent 1982), but dike orientations are variable in the Lemitar swarm. The carbonatites at Lobo Hill intruded associated syenitic and monzonitic rocks as well as Precambrian metamorphic rocks that are host to the entire complex (McLemore et al. 1999). Similarly, carbonatite dikes, stocks, and cone sheets in the Wet Mountains, Colorado, intruded slightly older mafic-ultramafic layered lopoliths and syenitic intrusions (Fenton and Faure 1970; Olson et al. 1977; Armbrustmacher 1984). At Monte Largo the carbonatite is mapped as a few dikes in a circular body of explosive breccia (Lambert 1961).

Carbonatite textures and mineralogy vary widely. The dominant carbonate minerals are calcite, dolomite, and ankerite. However, a variety of accessory minerals, including thorite, bastnaesite, monazite, synchysite, ancylite, vermiculite, apatite, barite, and fluorite has encouraged mineral exploration in the past. In general the carbonatites have not been profitable, although locally there has been minor production of barite, fluorite, thorium, vermiculite, and aggregate. Replacement carbonatites preserve relic textures and trace element compositions of original plutonic or metamorphic rocks; primary carbonatites have primary igneous carbonatite textures and high concentrations of incompatible trace elements (especially Nb, Ta, and Th). Both are present in the suite.

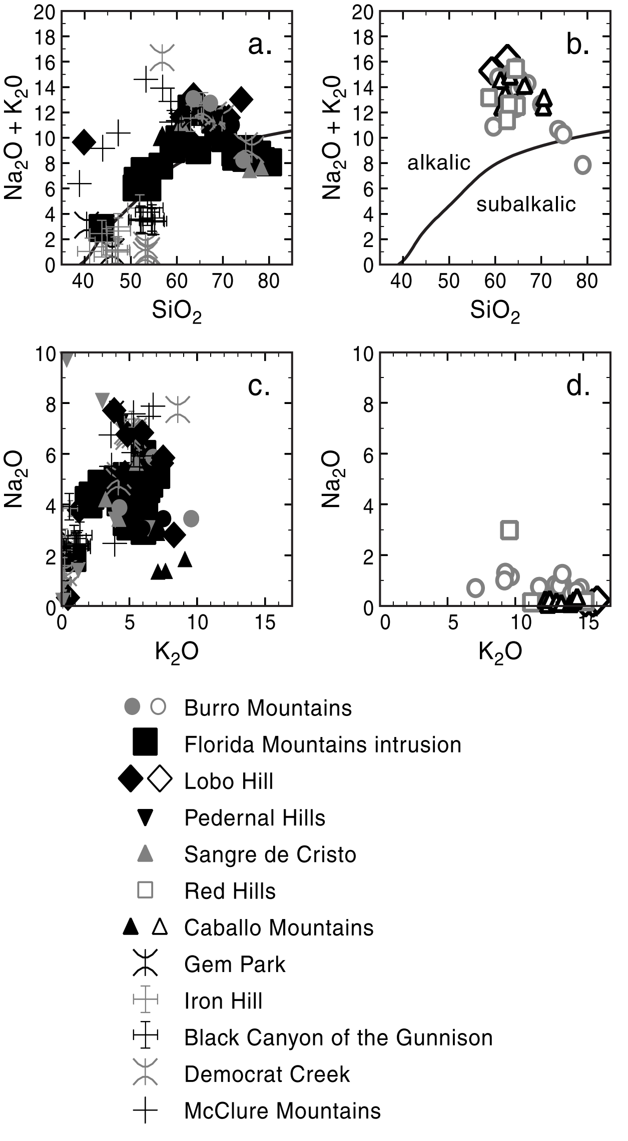

FIGURE 3—Alkalinity diagrams for Cambrian–Ordovician silicate igneous rocks. **a,b**: Total alkalis vs. $SiO_2$ for non-fenitized (**a**) and fenitized (**b**) rocks; alkaline/subalkaline boundary from Irvine and Baragar (1971). **c,d** $Na_2O$ vs. $K_2O$ for normal (**c**) and fenitized (**d**) rocks. Larger symbols denote suites with reliable age determinations.

### Syenites and alkaline rocks

The dominant rock type in the Cambrian–Ordovician suite is syenite, although the entire range of alkaline rocks ranges from rare ultramafic rocks to alkali feldspar granite. Many suites, including the Pedernal Hills, Burro Mountains, Nacimiento Mountains, Red Hills, Sangre de Cristo Mountains, and Lobo Hill, contain swarms of brick-red syenitic dikes, plugs, or elongate areas that may be fracture zones of intense fenitization. Fenitization is very common in these occurrences, to the degree that it is sometimes difficult to determine whether the feature represents metasomatized syenitic dike or host rock that has been completely recrystallized along a fracture.

Emplacement of large silicic plutons was uncommon; only two are known, the Florida Mountains intrusion and the Little Hatchet pluton in the Little Hatchet Mountains. Exposed over 20 $km^2$, the Little Hatchet pluton consists of hornblende granite, rapakivi granite, and diabase. The granitic rocks have not yet been dated and could be Proterozoic or Cambrian in age (Channell et al. 2000; McLemore et al. 2001; Rämö et al. 2002); however, geochemical and Nd isotopic data indicate that the granites are similar to the 1,220 Ma Red Rock granite in the northern Burro Mountains (Rämö et al. 2002). We include the Little Hatchet pluton here for completeness, recognizing that age determinations may prove it to be Proterozoic in age. The Florida Mountains intrusion ranges in composition from syenite to alkali feldspar granite (Ervin 1998). Neither pluton was fenitized, although some areas were strongly affected by Laramide and mid-Tertiary hydrothermal activity. Both plutons contain numerous dikes and pillows of co-mingled mafic magma.

### Mafic and ultramafic rocks

Cambrian–Ordovician mafic and ultramafic igneous rocks are common in southern Colorado, but less common in New Mexico. The Colorado intrusions are roughly circular in map pattern (Armbrustmacher 1984). Intrusions in the Wet Mountains are complex, consisting of mafic nepheline-clinopyroxene rocks, mafic and ultramafic rocks, monzonites, lamprophyres, syenites, and quartz syenites. In general, the intrusions are funnel-shaped bodies of mafic/ultramafic rock that were intruded by stocks or dikes of syenitic rocks. Carbonatite and lamprophyre dikes intruded the entire complex in the last phase of magmatism. Existing K-Ar age determinations (Table 1) demonstrate that all magma compositions were intruded in a geologically short time period (less than 20 million years). Mafic dikes are found in the Black Canyon of the Gunnison area (Larson et al. 1985), in the Costilla Creek area in northernmost New Mexico (Reed 1984), as pillows of mingled magma in the Florida Mountains and Little Hatchet intrusions, and in New Mexico drill cores (Table 1). Lamprophyre dikes are found at Lobo Hill and Monte Largo. Non-metamorphosed mafic dikes are found throughout Proterozoic igneous and metamorphic terranes in southern New Mexico, but their ages are currently unknown.

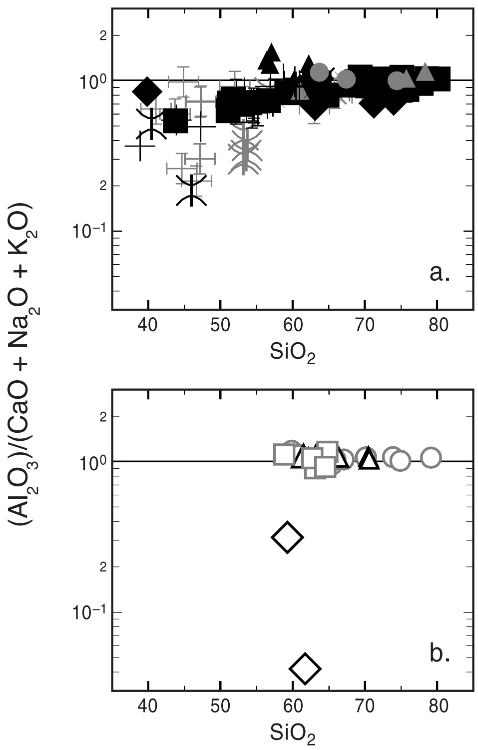

FIGURE 4—Aluminum-saturation diagram for non-fenitized (**a**) and fenitized (**b**) Cambrian–Ordovician rocks. Symbols as in Figure 3.

## Geochemistry

The New Mexico carbonatite suite is dominated by sovite and alvikite (coarse-grained and medium- to fine-grained calcic carbonatite, respectively), ferrocarbonatites, and carbonate-bearing alkaline rocks (Fig. 2a). Rauhaugite and beforsite (coarse-grained and medium- to fine-grained dolomitic carbonatite, respectively) are rare; natrocarbonatites are unknown (Fig. 2b). Fenton and Faure (1970) report that carbonatites at Iron Hill are dominated by ankeritic dolomite. Three New Mexico carbonatites have significant $SiO_2$ concentrations (Fig. 2b); these replacement carbonatites exhibit relic textures and compositions from parental igneous and metamorphic protoliths, usually with lower CaO, MgO, MnO, Th, Nb and total rare earth elements and higher $SiO_2$, $Al_2O_3$, $K_2O$, Ba, and Cs than primary carbonatites (McLemore 1983b; McLemore and Modreski 1990).

The silicate rocks in the suite are mildly alkaline (Fig. 3; Irvine and Baragar 1971). Samples affected by fenitization related to the intrusion of syenitic or carbonatitic magmas are shown in Figure 3 and subsequent figures as open symbols. Fenitization in the suite is characterized by apparent addition of $K_2O$ at the expense of $Na_2O$ and CaO (Figs. 3c, d). Another common chemical parameter used in the classification of granitic rocks is alumina saturation, calculated as the ratio of molar $Al_2O_3$ to the sum of molar CaO, $K_2O$, and $Na_2O$ (A/CNK; Fig. 4). Essentially, this ratio expresses the amount of $Al_2O_3$ in a rock relative to the $Al_2O_3$ used with Ca, Na, and K in feldspar. Rocks with A/CNK >1 are considered to be peraluminous, those with A/CNK <1 are peralkaline, and those with A/CNK near 1 are metaluminous. Most of the granitic and syenitic rocks in this suite ($SiO_2$ >55%) are metaluminous or mildly peralkaline (Fig. 4a); A/CNK is quite similar for most fenitized rocks (Fig. 4b), except for two highly peralkaline fenites from Lobo Hill.

Fenitization affected mainly the alkalis; $Al_2O_3$, $TiO_2$, FeO, and MgO concentrations are very similar in fenitized and non-fenitized samples (Fig. 5), permitting petrogenetic interpretations from the major element data. The largest pluton in the suite studied to date, the Florida Mountains intrusion, exhibits two consistent major element trends. From 50% to 60% $SiO_2$, $Al_2O_3$ increases modestly whereas $TiO_2$, FeO, and MgO all decrease. $Al_2O_3$ starts to decrease at >60% $SiO_2$, and $TiO_2$, FeO, and MgO decrease but at a different ratio than in the more mafic rocks. Ervin (1998) interpreted these trends to reflect two petrogenetic processes. The mafic trend contains samples that are hybrids of mafic magma and partially molten orthoclase granite that mixed when the mafic magma intruded the base of the cooling granitic intrusion. The silicic trend is dominantly a fractionation trend, with crystallization of orthoclase, Fe-Ti oxides, biotite, and apatite. $\varepsilon_{Nd,\ 500\ Ma}$ along this trend varies slightly, from +2.7 to +0.4 with increasing $SiO_2$ because of a small amount of assimilation during differentiation (Ervin 1998). Many syenite suites fall along this assimilation-fractional crystallization trend for major elements, suggesting that fractionation from parental syenitic magmas was a common differentiation mechanism.

Evaluation of the composition of Cambrian–Ordovician mafic magmas is complicated by the paucity of pristine examples of magma compositions. Although mafic and ultramafic rocks are common in the Colorado localities, most of these rocks are cumulates and do not represent liquid or magma compositions. We interpret the wide variation in major element composition of these rocks (Figs. 5a, b, d) as reflecting the proportions of cumulate minerals rather than a liquid line of descent. The mafic rocks in the Florida Mountains intrusion are also not representative of mantle-derived melts, because they are hybrids, and all contain some mixed orthoclase

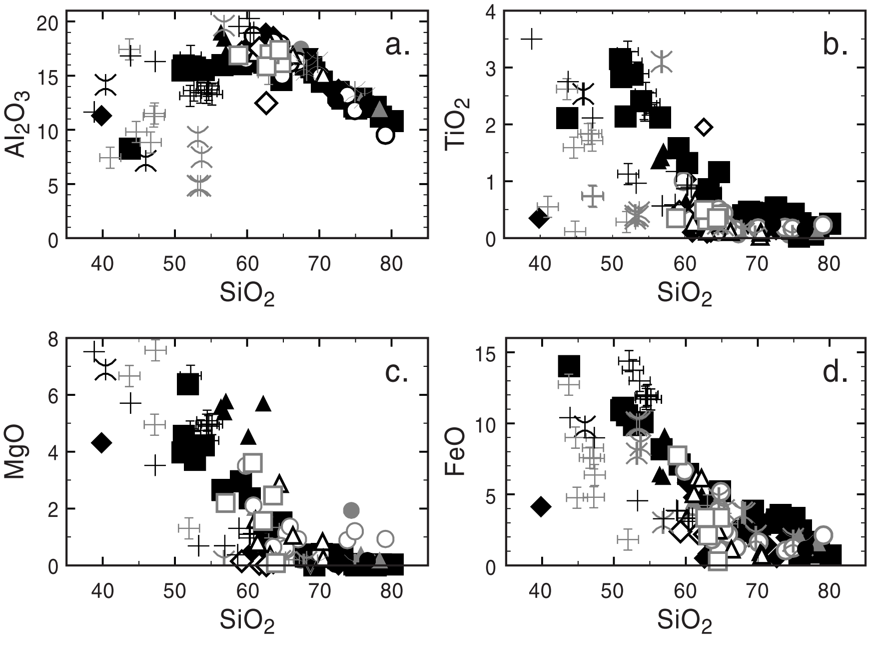

FIGURE 5—Whole-rock variation diagrams for known and suspected Cambrian–Ordovician rocks. Symbols as in Figure 3. **a**. $Al_2O_3$ vs. $SiO_2$. **b.** $TiO_2$ vs. $SiO_2$. **c.** MgO vs. $SiO_2$. **d.** FeO vs. $SiO_2$.

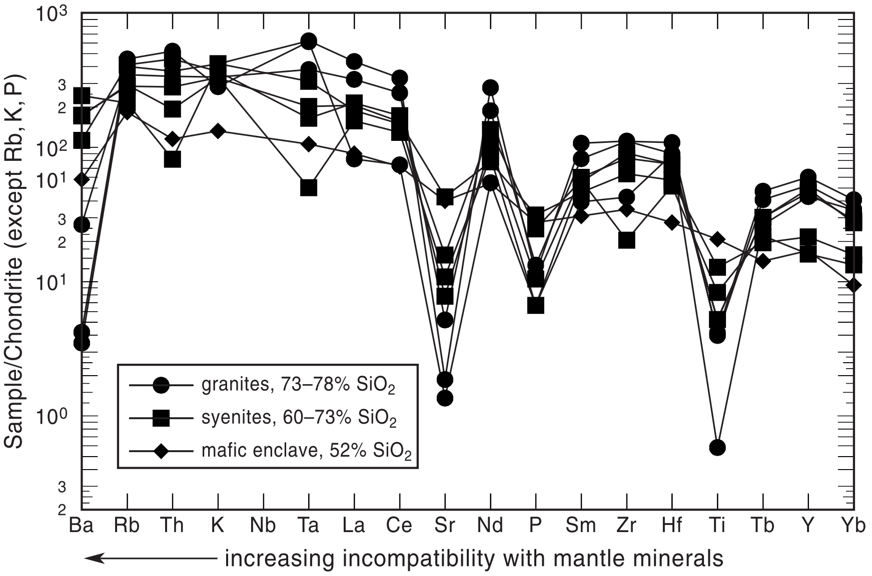

FIGURE 6—Chondrite-normalized incompatible trace element diagram for Florida Mountains rocks, using the normalization parameters of Thompson (1982). Data are from Ervin (1998).

granite component. The lamprophyre at Lobo Hill has been extensively altered. Thus, the suite of mafic magmas is limited to the mafic dikes near Gunnison, Colorado (Larson et al. 1985), the most pristine samples from the Florida Mountains intrusion (Ervin 1998), mafic dikes from the Costilla Creek area, and a few mafic rocks from the Powderhorn and McClure Mountains regions that probably represent magma compositions. These rocks span a wide compositional range from the nepheline- and leucite-normative rocks in the McClure Mountains to the mildly nepheline-normative rocks in the Florida Mountains intrusion to the hypersthene- and quartz-normative mafic dikes near Gunnison. The Gunnison suite is similar to the Florida Mountains mafic rocks in $Al_2O_3$, $TiO_2$, and MgO but has high FeO at the same $SiO_2$ concentration (Fig. 5). Careful analysis of mafic samples with reliable age determinations is needed to assess the composition and significance of the mafic component of Cambrian–Ordovician magmatism.

Trace elements are often used to interpret differentiation mechanisms, identify mantle and crustal source regions, and discern the tectonic setting of suites of igneous rocks. Unfortunately, fenitization has overprinted the trace element signatures of some Cambrian–Ordovician rocks, making interpretations difficult. Fenitization associated with syenites and carbonatites has been shown to mobilize a wide range of elements (Heinrich 1980; McLemore and Modreski 1990; Flohr 1994; White-Pinilla 1996) including the high field strength elements that are typically immobile during weathering, diagenesis, and hydrothermal alteration. However, several geochemical clues exist in the current data set that help to constrain petrogenetic parameters. Rocks in the Florida Mountains intrusion are not fenitized, although they did experience weathering in Cambrian and Quaternary times and hydrothermal alteration during Laramide and Basin and Range tectonism. The trace element patterns of granitic, syenitic, and mafic rocks from the intrusion (Fig. 6) are consistent with the major element model of fractional crystallization from parental syenites, which themselves are fractionates of mantle-derived mafic magma (Ervin 1998). Troughs at Sr, P, and Ti reflect crystallization of feldspar, apatite, and Fe-Ti oxides; the parallelism of the patterns for the incompatible elements on Figure 6 and the small range in Nd isotopic composition ($\varepsilon_{\text{Nd, 500 Ma}}$ = from +2.7 to +0.4, Ervin 1998) suggest that assimilation was much less important than fractional crystallization. The tectonically significant aspect of these patterns is the high Ta concentrations relative to elements of similar compatibility. Subduction-related magmas typically have very low Ta and Nb concentrations that produce a deep trough, and because much new continental crust is generated as arc magmas, average continental crust also has low Nb and Ta concentrations (Taylor and McClennan 1985). Thus, the parental magmas for the Florida Mountains magmas were probably derived from a mantle source that was not affected by subduction fluids, i.e., from a mantle plume or upwelling asthenosphere under a continental rift.

The high field strength elements Nb and Y have been used to interpret the origin of rock melted to form granitic magmas (Pearce et al. 1984). Before such an interpretation can be made for the Cambrian–Ordovician suite, it is necessary to evaluate the effect of fenitization on Nb and Y. Three suites contain both fenitized and non-fenitized syenites (Fig. 7). Y and Nb concentrations do not appear to have been affected by fenitization for the Burro Mountains (Figs. 7a, b) and Lobo Hill (Figs. 7e, f) suites. In contrast, the non-fenitized Caballo syenites have higher Nb and Y than their fenitized counterparts (Figs. 7c, d). This relationship could have two causes. Either Nb and Y could have been mobilized and removed during fenitization or the protolith for the fenites was a Precambrian rock with low Nb and Y concentrations rather than Cambrian–Ordovician syenite. These data suggest that Nb and Y were variably mobile during fenitization, and that high concentrations probably represent a primary igneous signature.

Cambrian–Ordovician silicate and carbonatite samples are plotted on the Y-Nb diagram (Pearce et al. 1984) in Figure 8. The majority of the Lobo Hill, Chupadera carbonatite, and non-fenitized syenites from the Caballo Mountains suite plot in the within-plate granite field at high Nb and Y concentrations. We interpret these in a similar fashion to the Florida Mountains intrusion; the carbonatites and parental mafic magmas were produced by decompression melting from asthenospheric or plume mantle perturbed during continental rifting, and syenites evolved from parental mafic magmas in the crust by fractional crystallization. Clearly, additional trace element and isotopic data are needed to support this model. The Lobo Hill samples with low Nb and Y concentrations are a silica-rich carbonatite and a fenitized syenite that were probably formed by replacement rather than intrusion.

The other suites plotted in Figure 8 are suspected to be Cambrian–Ordovician in age and plot near the intersection of the three diagnostic fields, which could be interpreted in several ways. One possibility is that the suites that do not plot in the within-plate granite field are not Cambrian–Ordovician, and were generated in a different tectonic setting. A second possibility is that syenites in this group represent thoroughly fenitized Proterozoic rocks; the final trace element composition is strongly affected by the composition of the protolith, which could have been produced in an arc or orogenic setting. The third possibility is that these samples evolved from Cambrian–Ordovician mantle-derived mafic magmas by fractional crystallization accompanied by large amounts of assimilation of older, arc-derived (low Nb) crustal rocks, so the final trace element composition mimics that of the assimilant rather than that of the parent magma. These hypotheses can be tested by rigorous trace element, isotopic, and geochronologic analysis.

### Preliminary tectonic model

The distribution and geochemistry of Cambrian–Ordovician igneous rocks demonstrate that the New Mexico–Colorado region was tectonically active in early Paleozoic time. The presence of carbonatites in the suite is significant. Carbonatites are typically associated with continental extension, mantle plumes, major faults or lineaments, or kimberlites in continental shields (Woolley 1989; Bell 2001). Models for the origin of carbonatites conclude that the mantle must be perturbed (Eggler 1989; Wyllie 1989). Although carbonatites sometimes occur in or near foreland belts, detailed analysis indicates that they were emplaced during episodes of extension (Pell and Hoey 1989). In addition, major and trace element models for syenitic and granitic rocks are consistent with partial melting of upwelling asthenosphere in an extensional environment or mantle plume to produce parental mafic magmas, which then fractionate in the crust to produce the more evolved rocks. The trace element data on well-dated suites are also consistent with a mantle source that is not related to subduction.

Three tectonic models for this event are proposed here. First, the elongate zone of magmatism might be the trace of a mantle plume. Further geochronologic studies are required to determine whether the magmatism moved along the zone through time. However, the available high-quality dates refute this hypothesis. For instance, the Florida Mountains intrusion in southern New Mexico, the Lobo Hill alkalic complex in northern New Mexico, and the McClure Mountains suite in Colorado all have age determinations near 510 Ma (Table 1).

An alternative interpretation is that the magmatic province formed in a zone roughly parallel to the rift segments in the Thomas (1991) reconstruction of the Appalachian–Ouachita rifted margin (Fig. 9). This model suggests that the magmas were produced in a failed rift, the New Mexico aulacogen. Aulacogens often form by differential movement along major transform margins. Goetz and Dickerson (1985) suggested that an intermittently active transform zone composed the southwestern margin of North America from late Proterozoic through Triassic time. Accumulation of lower Paleozoic sedimentary rocks in shallow basins above Precambrian granitic basement rocks demonstrate that the southwestern continental margin was not a rifted passive margin with a thick passive margin sequence as found on the western margin of North America in latest Proterozoic time. Differential movement across the transform fault could have caused extension and passive

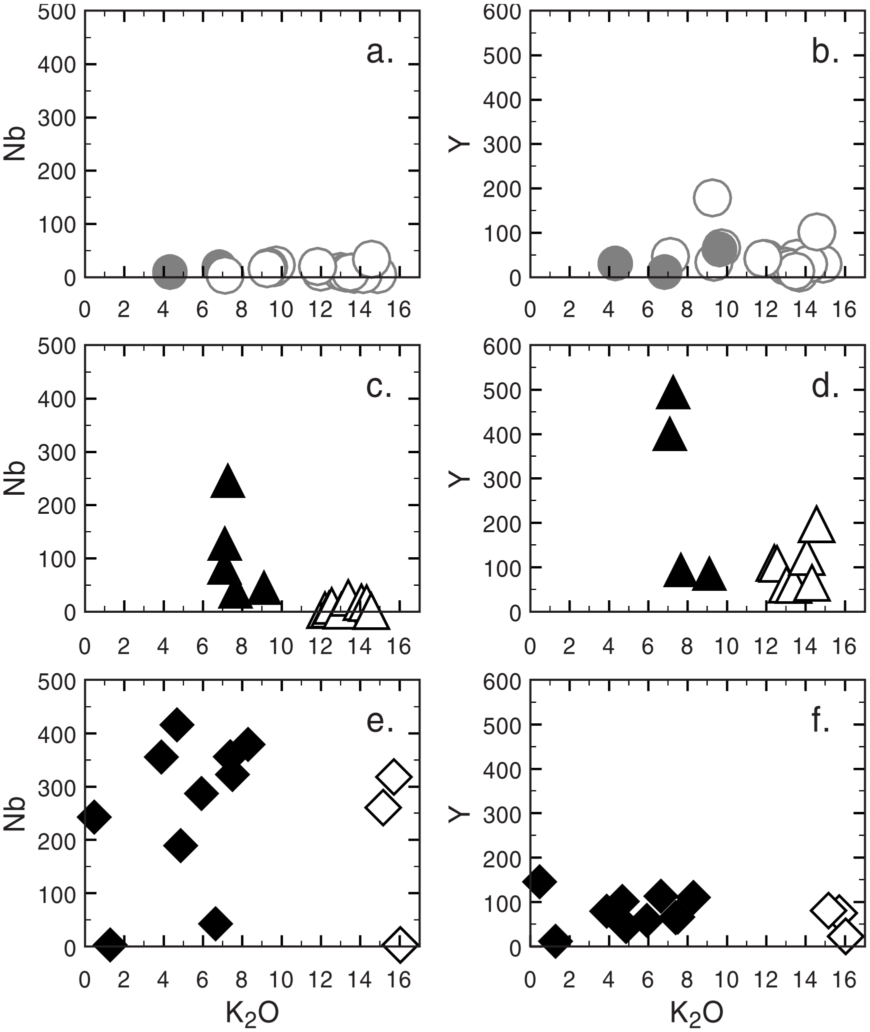

FIGURE 7—Nb and Y vs. K$_2$O for suites of rocks with both fenitized (open symbols) and non-fenitized (filled symbols) samples. **a, b**: Burro Mountains. **c, d**: Caballo Mountains. **e, f:** Lobo Hill. Note that complete trace element analyses have not been published for many of the known and suspected Cambrian–Ordovician suites. Symbols as in Figure 3.

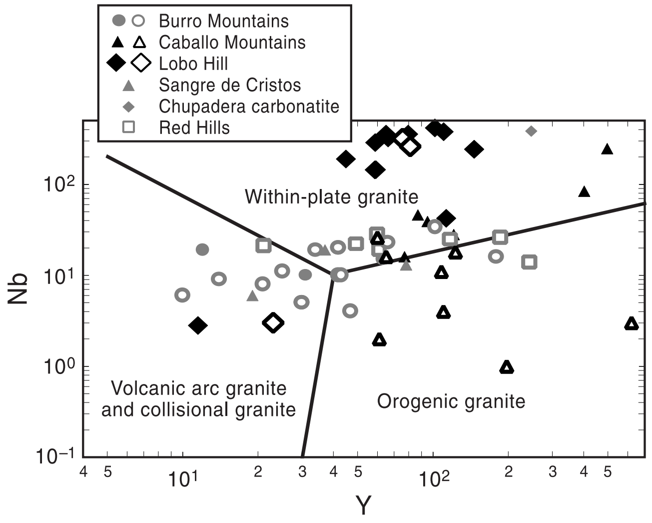

FIGURE 8—Trace element evidence for tectonic environment of known and suspected Cambrian–Ordovician igneous rocks (Pearce et al. 1984). All suites in Table 1 with published Y and Nb data are included in this diagram.

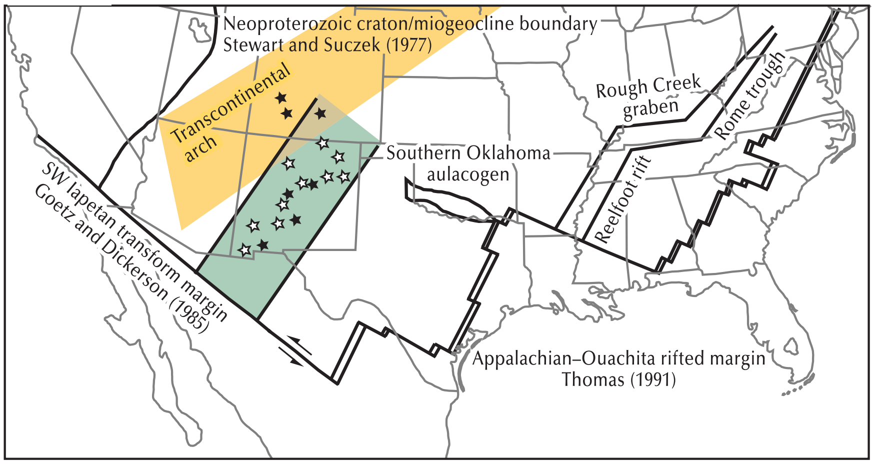

FIGURE 9—The location of igneous rocks of the New Mexico aulacogen in relationship to the western and eastern rifted margins of North America in Cambrian–Ordovician time. Filled stars represent known Cambrian–Ordovician igneous rocks; open stars represent suspected intrusions.

upwelling of asthenospheric mantle that is recorded by igneous rocks of the rift.

The classic Cambrian aulacogens of southern North America share several significant features; they are fault-bounded basins filled with thick Cambrian sedimentary sequences. The aulacogens became broad depositional basins in early to middle Paleozoic time; subsidence was presumably caused by cooling of a deep mafic igneous root (Kolata and Nelson 1997). The proposed Cambrian New Mexico aulacogen has many characteristics that differ from known Cambrian aulacogens. In many ways, it is more similar to the Cambrian southern Oklahoma aulacogen, which is sub-parallel to the transforms in the Thomas (1991) reconstruction (Fig. 9). For instance, syn-rift sedimentary rocks have yet to be identified in the New Mexico aulacogen; few syn-rift sediments exist in the southern Oklahoma aulacogen except possibly beneath the Anadarko basin (Gilbert 1983; Keller and Baldridge 1995). Similarly, the southern Oklahoma aulacogen and New Mexico aulacogen are dominated by igneous rocks, whereas the Reelfoot rift has a paucity of igneous rocks in the upper crust. Because of compressional and extensional deformation throughout the Phanerozoic in New Mexico and Colorado, it is difficult to assess any relationship between the New Mexico aulacogen and depositional patterns in Paleozoic sedimentary basins.

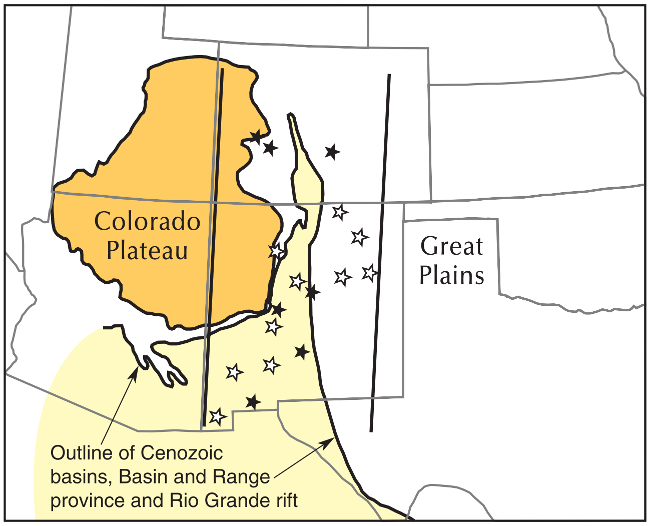

FIGURE 10—Possible north-south orientation of New Mexico aulacogen igneous rocks. Plotted for comparison is the outline of Cenozoic basins formed during Basin and Range/Rio Grande rift extension, which follow a dominantly north-south trend.

Northeast-trending Cambrian rifts of the eastern and southern margins of Laurentia become progressively younger from east to west (Hogan and Gilbert 1997). The Long Range dikes in southeast Labrador yield a U-Pb zircon and baddeleyite age of 615 ± 2 Ma, suggesting that the northeast rifting of Laurentia started in Vendian time (Kamo et al. 1989). Farther south, comenditic lavas and tuffs of the Tibbit Hill Formation, exposed east of Montreal, Quebec, Canada, have been dated by U-Pb zircon at 554 +4/-2 Ma, and are interpreted as rift-related volcanism (Kumarapeli et al. 1989). Rifting is younger yet to the south, where syn-rift sedimentary rocks in the Reelfoot rift in Arkansas and Mississippi are Cambrian in age (Kolata and Nelson 1997). The age of extension and associated magmatism continues to become younger to the west; the main pulse of bimodal magmatism in the southern Oklahoma aulacogen occurred at 535–530 Ma (Hogan and Gilbert 1997). Ages of igneous rocks in the New Mexico aulacogen extend to younger ages (Table 1), suggesting that the rift was the last stage in tectonism that connected the eastern Cambrian rift system (Thomas 1991) to the structures of the Neoproterozoic rift system that formed the western margin of North America (Fig. 9).

The New Mexico aulacogen could also have had a north-south orientation (Fig. 10). East-west extension could have been caused by movement along a major transform boundary, as in the previous model, or controlled by reactivation of older north-south structures. This opens the question of whether the north-south structural grain in New Mexico that apparently controlled the orientation of the Cenozoic Rio Grande rift (Fig. 10) was produced in Cambrian–Ordovician time or earlier. Timmons et al. (2001) recognize 800–750 million year old north-south normal faults in the Grand Canyon, Arizona, that were reactivated by Cretaceous–Paleocene Laramide compression. By analogy they suggest that north-south Laramide structures throughout New Mexico represent reactivated Neoproterozoic normal faults, although the older history of the faults has not yet been determined. Alternatively, Davis (1979), Bilodeau (1984), Bayona and Lawton (2000), and Lawton (2000) demonstrate that Laramide structures in Arizona and southern New Mexico represent reactivated mid-Mesozoic normal faults. Cambrian–Ordovician extension could have either produced or enhanced north-south faults that later controlled the position of the Rio Grande rift between the Colorado Plateau and the Great Plains (Fig. 10). Careful study of fault history and a more thorough understanding of Cambrian–Ordovician tectonics are necessary to resolve this issue.

An extensional Cambrian–Ordovician setting in New Mexico and Colorado has broad implications beyond the early Paleozoic tectonics of southwestern North America. For instance, the position of the Transcontinental Arch coincides with the western margin of the New Mexico aulacogen (Fig. 9). The Transcontinental Arch was a long-standing structural and topographic high that served as the Continental Divide and controlled sedimentation patterns of western North America during the Paleozoic era. However, its origin is still being debated (e.g., Carlson 1999). The lack of syn-rift sediments within the New Mexico aulacogen implies that the rift was a topographically high feature. Thus, we propose that the Transcontinental Arch originally was the western flank of the aulacogen that became a stable high topographic feature. The wide distribution of zircons of Cambrian and Ordovician age in Paleozoic and Mesozoic sedimentary rocks (Gehrels and Dickinson 1995; Riggs et al. 1996; Stewart et al. 2001) corroborates the idea that igneous rocks of the rift eventually resided at high structural and topographic levels. If the aulacogen flank was indeed a long-lived topographic high, then the ca. 500 Ma zircons found in Mesozoic sandstones such as the Chinle Formation (Gehrels and Dickinson 1995; Riggs et al. 1996) did not necessarily come from a point source but rather from a wider geographic range. Similarly, the igneous rocks of the New Mexico aulacogen may have been the source for Cretaceous heavy mineral, beach-placer sandstone deposits in the San Juan Basin of the Colorado Plateau (McLemore 1983a).

## Conclusions

The existence of Cambrian–Ordovician igneous rocks in New Mexico and Colorado has long been recognized; however, this is the first attempt to compile and interpret the entire body of data on these rocks and reconcile it with the early Paleozoic tectonics of North America. The high Nb, Ta, and Y character of some of the magmas and presence of carbonatites and lamprophyres imply that the mantle was perturbed, which suggests that a period of extension and magmatism preceded transgression of the lower Paleozoic passive margin sequence. Cambrian–Ordovician igneous rocks are distributed in a broad linear zone roughly parallel to rift zone in the Thomas (1991) reconstruction of North America's eastern rifted margin, prompting us to propose that the igneous rocks formed in the New Mexico aulacogen, a zone of extension and high topography that extended into the continent from a transform fault on southwest margin of North America.

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