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TEMPORAL AND SPATIAL MAGMATIC EVOLUTION OF THE RIO GRANDE RIFT

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Abstract—Three mantle source regions are recognized in the geochemistry of mafic Rio Grande rift basalts: asthenospheric mantle, subduction-modified lithosphere, and OIB (ocean island basalt)-modified lithosphere. The most common basalt type has low and variable ε_{Nd} (+2 to -8), moderate $^{87}Sr/^{86}Sr$ ratios (0.704 to 0.712), and low Nb/Ba and Ta/Ba ratios. The combination of enriched isotopic compositions and arc-like trace element signatures indicates that these basalts are partial melts of subcontinental lithosphere to which subduction-derived fluids have been added in the distant past. The second most common basalt type has high ε_{Nd} (+4 to +8), low $^{87}Sr/^{86}Sr$ (< 0.704), and high Nb/Ba and Ta/Ba ratios, similar to young Basin and Range basalts and ocean island basalts. The OIB-like trace element and isotopic signatures suggest that these basalts are partial melts of upwelling, decompressing asthenosphere. The least common basalt type has high Nb/Ba and Ta/Ba ratios similar to the asthenosphere-derived basalts, but lower ε_{Nd} (+2 to -7) and slightly higher $^{87}Sr/^{86}Sr$ (0.704 to 0.705). These basalts are interpreted to be melts of subcontinental lithosphere to which small degree partial melts of convecting asthenosphere have been added, again in the distant past. Basalts from lithospheric sources are found rift-wide; the lithosphere is the only source region that produced mafic magmas north of the Jemez lineament. In contrast, the southern half of the rift records a transition from lithospheric to asthenospheric source regions by 10 Ma in the Las Cruces and Socorro areas, at about 4 Ma in the Lucero volcanic field near Albuquerque, and in the Pleistocene–Holocene Zuni-Bandera volcanic field.

INTRODUCTION

Continental rifts produce magmas from a variety of source regions; upwelling asthenosphere, enriched lithospheric mantle, and upper and lower crust have been documented as important geochemical reservoirs in the genesis of rift magmas world wide. Of particular interest is the nature and evolution of the mantle sources, because melting mechanisms are quite different in asthenospheric (decompression melting) and lithospheric (dehydration melting) mantle sources. Quantitative models have shown that the mantle source should shift from the lithosphere early in rift history to the asthenosphere as extension proceeds (McKenzie and Bickle, 1988; Gallagher and Hawkesworth, 1992). This transition has been documented in the central Rio Grande rift near Albuquerque, NM, (Perry et al., 1987, 1988) and only occurs in the most extended part of the rift. Thus, the evolution of mantle source regions is related to the structural evolution of the rift.

Igneous rocks of the Rio Grande rift have been studied in detail for over two decades. As a result, most major volcanic fields, and many smaller fields, are represented by excellent data sets that contain major element, trace element, and isotopic data (Fig.1, Tables 1–3). This paper uses a compilation of these data to define the mantle sources tapped in the Rio Grande rift through time and space and refines the model of Perry et al. (1987, 1988) for the transition of lithospheric to asthenospheric sources in a rift-wide application.

EVOLUTION AND IDENTIFICATION OF MANTLE SOURCES

Mafic magmas in continental rifts show a wide range in major element, trace element, and isotopic composition. Lavas of the Rio Grande rift are no exception. Controversy exists, however, concerning the sources of Rio Grande rift basalts, especially in defining which chemical characteristics of the lavas should be used for fingerprinting various asthenospheric and lithospheric mantle sources. This is a significant aspect of the understanding of rift evolution and the mechanisms involved in continental extension, because the asthenosphere and lithospheric mantle melt by different mechanisms. The asthenosphere melts at mid-ocean ridges, in mantle plumes, and in sub-lithospheric diapirs in arcs and rifts by decompression melting. That is, the mantle moves upwards at a sufficient rate to decompress while maintaining its heat, crosses its solidus (which has a positive slope for dry or slightly hydrated mantle), and melts. Oceanic magmas derived from the asthenosphere exhibit a wide range of composition, from the light rare earth element (LREE) and isotopically depleted mid-ocean ridge basalts to the LREE-enriched and isotopically variable ocean island basalts (OIB).

Lithospheric mantle, in contrast, is unable to melt by decompression because it is, by definition, rigid. In fact, continental lithospheric mantle, which is initially stabilized as the crust first forms in a region by freezing of depleted upper mantle at the base of the crust, would not be a major magma source if it were not metasomatized. Many studies have shown that major lithospheric boundaries can be mapped by the isotopic composition of young mafic lavas that pass through, or are derived from, the lithospheric mantle. Lavas erupted on older lithosphere tend to have more radiogenic isotopic compositions, suggesting that the lithospheric mantle "ages" in the same way as the crust. However, the depleted mantle does not have sufficient Rb, U, Th, and Sm to produce the observed increases in Sr, Pb, and Nd. Thus, the lithospheric mantle must have experienced addition of these incompatible elements through time.

Two processes, which result in markedly different trace element signatures, have been proposed to be responsible for lithospheric mantle metasomatism. Many continental basalts that are interpreted as melts of the lithospheric mantle have "arc-like" trace element signatures, that is, low concentrations of Nb and Ta, and high concentrations of Ba, Rb, Sr, and the LREE La, Ce, Nd, and Sm. In this case, the lithosphere was enriched by volatile-rich magmas or fluids that were produced by flux melting of the asthenospheric wedge over a dehydrating subducted slab at some time in the geologic past. The high field strength elements, especially Nb and Ta, are retained in the slab, possibly by a mineral such as rutile. Dehydration fluids are rich in elements like Ba, Rb and Sr because these elements are more highly soluble in fluids, and thus melts produced in the overlying asthenosphere by flux melting have high Ba/La and low Nb/La, Ta/La, Nb/Ba, and Ta/Ba ratios. Some of these melts or fluids will freeze as they migrate through the overlying lithospheric mantle, generating an "arc-like" source region in

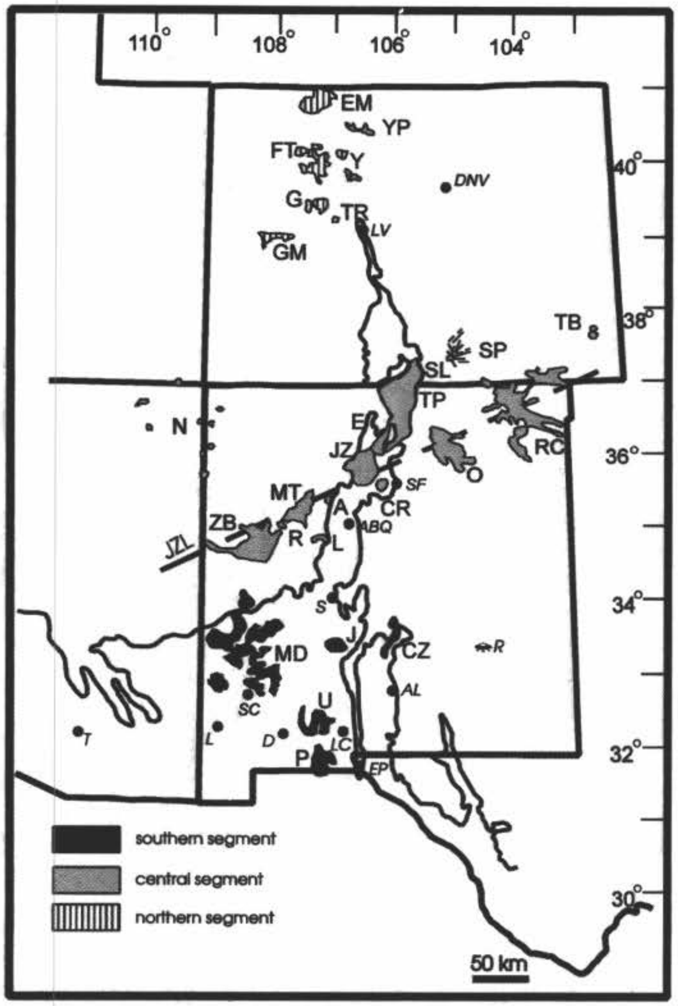

FIGURE 1. The Rio Grande rift in Colorado and New Mexico, showing the volcanic fields compiled in this paper, after Gibson et al. (1992), Baldridge et al. (1995), and Leat et al. (1988). Abbreviations are as follows. JZL = Jemez lineament. Volcanic fields: A = Albuquerque Basin volcanic field, CR = Cerros del Rio, CZ = Carrizozo, E = Espanola Basin, EM = Elkhead Mountains, FT = Flat Tops, G = Glenwood, GM = Grand Mesa, J = Jornada, JZ = Jemez, L = Lucero, MD = Mogollon-Datil, MT = Mount Taylor, N = Navajo dikes, O = Ocate, P = Potrillo, R = Riley dikes, RC = Raton-Clayton, SL = San Luis Hills, SP = Spanish Peaks, TB = Two Buttes, TP = Taos Plateau, TR = Triangle Peak, U = Uvas, Y = Yarmony, YP = Yampa, ZB = Zuni-Bandera. Cities (in italics): ABQ = Albuquerque, AL = Alamogordo, D = Deming, DNV = Denver, EP = El Paso, L = Lordsburg, LC = Las Cruces, R = Roswell, S = Socorro, SC = Silver City, SF = Santa Fe, T = Tucson.

the lithosphere. Sm/Nd and Rb/Sr ratios are sufficiently high to cause significant enrichment in the isotopic ratios ^{143}Nd/^{144}Nd and ^{87}Sr/^{86}Sr when the lithosphere is allowed to age for hundreds of millions of years. Subsequent extension causes melting because the volatiles have lowered the melting temperature of the lithospheric mantle.

Lithospheric mantle can also be enriched by fluids and melts that have trace element signatures similar to ocean island basalts (OIB), i.e., high Nb and Ta relative to Ba and La. Two models have been proposed for this mechanism. McKenzie (1989) presents a model in which convecting asthenosphere melts by very small amounts, producing incompatible trace element enriched melts that migrate upward into the base of the lithosphere. Because they are very small volume melts, they freeze readily and locally impart their trace element signature to the lithospheric mantle. There is no residual mineral in convecting asthenosphere to retain Nb and Ta; thus, the melts have a diagnostic signature with higher Nb/Ba, Ta/Ba, Nb/La, Ta/La, and lower Ba/La ratios than lithosphere that has been fluxed by arc melts. As before, Rb/Sr and Sm/Nd ratios are sufficiently high to produce a source region with enriched ^{143}Nd/^{144}Nd and ^{87}Sr/^{86}Sr ratios over geologic time. A similar geochemical signature could be imparted to the lithosphere by ancient mantle plumes beneath a continent.

Mantle sources can be identified by a combination of incompatible trace element and isotopic data. Young (<5 Ma) Basin and Range basalts that are partial melts of modern convecting asthenosphere under the western United States have $\varepsilon_{Nd} > +4$ to $+8$, low ^{87}Sr/^{86}Sr (less than 0.704), and high Nb/Ba and Ta/Ba ratios (Kempton et al., 1991; Fitton et al., 1991), similar to the most depleted basalts erupted at oceanic mantle plumes (Fig. 2a). The interpretation of enriched mantle sources is more equivocal. Because arc magmas and lithospheric mantle fluxed with arc-derived fluids have low Nb and Ta concentrations and high Ba concentrations relative to La, they typically exhibit troughs at Nb-Ta on chondrite-normalized incompatible trace element diagrams. Two definitions of the "trough" are illustrated on Figure 2. The simplest definition is that magmas can be considered to be depleted in Ta and Nb relative to Ba if the normalized value of Nb and Ta (NbN and TaN) is less than the normalized value of Ba. A Nb/Ba ratio of 0.0507 translates to NbN/BaN of 1.0, that is, the sample has neither a peak nor a trough at Nb (Fig. 2b). Similarly, a Ta/Ba ratio of 0.0029 corresponds to TaN/BaN of 1.0. Lavas with Nb/Ba or Ta/Ba higher than this would exhibit peaks at Nb and Ta (Figs. 2a, 2c); lower ratios produce troughs (Figs. 2b, 2d). Because most arc magmas have very low Nb/Ba and Ta/La ratios, Menzies et al. (1991) recommend using Nb/Ba = 0.0323 (Ba/Nb = 31) as the discriminatory ratio to separate arc-derived from non-arc mafic magmas. These ratios work well to separate Rio Grande rift mafic magmas (Figs. 3–5) and define mantle source regions. In this paper, a lithospheric mantle source that was enriched by arc-related processes is recognized by having low Nb/Ba and Ta/Ba ratios, ^{87}Sr/^{86}Sr >0.704, and $\varepsilon_{Nd} < +2$ and is referred to as the subduction-modified lithospheric source. Lithospheric mantle that was enriched by fluids from convective overturn or an ancient mantle plume is recognized by having high Nb/Ba and Ta/Ba ratios, ^{87}Sr/^{86}Sr > 0.704, and $\varepsilon_{Nd} < +2$, and is called the OIB-modified lithospheric source because of the trace element similarities between this source and the source of ocean island basalts.

Discrimination between modern OIB-like asthenospheric and ancient OIB-modified lithospheric sources is complicated by the fact that modern ocean island basalts exhibit a wide range of Sr- and Nd-isotopic compositions, comparable to much of the range in composition seen in all Rio Grande rift basalts. However, two key spatial relationships provide important constraints. Upper Cenozoic basalts from southern New Mexico fall in the same narrow range of isotopic composition as young Basin and Range basalts (Fig. 3). Thus, it is reasonable to conclude that the asthenosphere underlying the southwestern U.S. for the last 10 Ma has a relatively restricted isotopic composition compared to the range of asthenospheric compositions world wide. Furthermore, there is no reason to expect that the composition of the convecting asthenosphere has changed significantly in the last 40 Ma of rift evolution, or that asthenosphere underlying the rift has been replaced by convecting mantle of a different isotopic composition in the course of rifting.

Mafic Rio Grande rift basalts fall into two isotopic groups (Figs. 3–5): a well-constrained group with $\varepsilon_{Nd} > +4$, and a highly variable group with $\varepsilon_{Nd} < +2$. All of the high ε_{Nd} group have high Nb/Ba and Ta/Ba and are interpreted as asthenospheric melts. The low ε_{Nd} group contains examples of both high Nb/Ba, Ta/Ba and low

TABLE 1. Summary of data from volcanic fields in the southern section of the Rio Grande rift. Samples with >8% MgO are plotted in the diagrams of this paper and used for interpretation. For volcanic fields that lack analyzed samples of >8% MgO, Nb/Ba, Ta/Ba, eNdd, and interpretations are based on samples with >4% MgO. Alkalinity is based on the curve of Irvine and Baragar (1971). See text for discussion of Nb/Ba and Ta/Ba ratios. Abbreviations: n.a. = data not available; interm. = intermediate; LSUBD = subduction-modified lithospheric mantle; LOIB = OIB-modified lithospheric mantle; ASTH = asthenospheric mantle.

Volcanic field/region	Age Ma	>8% MgO?	Alkalinity	Nb/Ba, Ta/Ba	ε_{Nd}	Mantle Source	Data Source
Rubio Peak Fm.	51-36	yes	weakly alkaline basalts	low	n.a.	LSUBD	McMillan, unpublished data
Mogollon-Datil	45-36	no	subalkaline	low	-5.5	LSUBD	Davis and Hawkesworth, 1994
Bell Top Fm.	36-28	no	subalkaline	low	-2.5	LSUBD	McMillan, unpublished data
Mogollon-Datil	36-27	no	subalkaline	low	n.a.	LSUBD	Davis and Hawkesworth, 1994
Socorro area	45-10	yes	alkaline	n.a.	2.1	??	Heatherington, 1988
Uvas volcanic field	28-25	yes	subalkaline	low	0.9 to 1.1	LSUBD	McMillan, unpublished data; Gibson et al., 1992
Mogollon-Datil	27-20	no	subalkaline to alkaline	low	-3.5 to -6.1	LSUBD	Davis and Hawkesworth, 1994
Southern NM	<10	yes	alkaline & subalkaline	high	+4.7 to +7.4	ASTH	McMillan, unpublished data; Gibson et al., 1992; Everson, 1979
Mogollon-Datil	<16	yes	alkaline	high	n.a.	ASTH	Davis et al., 1993
Socorro area	<10	yes	alkaline	n.a.	+4.4 to +4.9	ASTH	Heatherington, 1988
Jornada young	<2	no	alkaline	high	4.5	ASTH	Gibson et al., 1992; Heatherington, 1988
Carrizozo	0.005	no	transitional	high	1.1	LOIB	Gibson et al., 1992; Heatherington, 1988; Allen and Foord, 1991; Anthony et al., this volume
Potrillos	<1	yes	alkaline	high	+4.7 to +6.3	ASTH	Anthony et al., 1992; McMillan, unpublished data
Basin and Range	<5	yes	alkaline	high	+5.5 to +7.1	ASTH	Kempton et al., 1991; Fitton et al., 1991

TABLE 2. Summary of data from volcanic fields in the central section of the Rio Grande rift. Specifications and abbreviations as in Table 1.

Volcanic field/region	Age Ma	>8% MgO?	Alkalinity	Nb/Ba, Ta/Ba	ε_{Nd}	Mantle Source	Data Source
Spanish Peaks	25	yes	alkaline	low	-1.8 to -0.3	LSUBD	Gibson et al., 1993
Two Buttes	28-35	yes	alkaline	low	-4.4 to -7.4	LSUBD	Gibson et al., 1993; Davis et al., 1996
San Luis Hills	26-28	yes	alkaline	low	-3.8 to -4.2	LSUBD	Johnson and Thompson, 1991; Thompson et al., 1991
Navajo dikes	26	yes	alkaline	low	+1.4 to -1.2	LSUBD	Gibson et al., 1992
Riley	28	no	alkaline	low	-2.5 to -3.5	LSUBD	Gibson et al., 1992
Dulce	25	yes	alkaline	low	-2.9	LSUBD	Gibson et al., 1993
Espanola basin	26-4.4	yes	alkaline	high	+3.0 to -0.4	LOIB	Gibson et al., 1993; Gibson et al., 1992
Keres Gp., Jemez	17-3	yes	subalkaline, alkaline	low	1.7	LSUBD	Ellisor et al., 1996; Goff et al., 1989
Raton-Clayton	<8	yes	alkaline	interm.	+1.0 to + 1.4	LOIB	Dungan et al., 1989; Phelps et al., 1983
Ocate	<8	yes	alkaline	low	n.a.	LSUBD	Nielsen and Dungan, 1985
Taos Plateau	2 to 5	yes	subalkaline	low	-2.8 to -3.3	LSUBD	Dungan et al., 1986; McMillan and Dungan, 1988
Cerros del Rio	2--4	no	subalkaline, alkaline	interm.	-1.0 to +1.3	LOIB?	Duncker et al., 1991
Mt. Taylor	3-1.5	yes	alkaline	n.a.	5	ASTH	Perry et al., 1990
Zuni-Bandera	<1.38	yes	alkaline	high	+4.8 to +6.1	ASTH	Menzies et al., 1991
			subalkaline	high	+0.9 to +1.5	LOIB	Menzies et al., 1991
Albuquerque volc	<5	yes	subalkaline	n.a.	+4.1 to +4.8	ASTH	Gibson et al. 1992; Perry et al., 1987
Lucero	1--8	yes	alkaline	n.a.	+3.3 to +6.6	ASTH	Perry et al., 1987
			subalkaline	n.a.	-0.3	??	Perry et al., 1987

TABLE 3. Summary of data from volcanic fields in the northern section of the Rio Grande rift. Specifications and abbreviations as in Table 1.

Volcanic field/region	Age Ma	>8% MgO?	Alkalinity	Nb/Ba, Ta/Ba	ε_{Nd}	Mantle Source	Data Source
Yarmony Mt	24-21.5	no	alkaline	interm.	-5.5	LOIB?	Leat et al., 1988
Flat Tops	20-23	yes	alkaline	low	-4.0 to -7.1	LSUBD	Gibson et al., 1991; Leat et al., 1988
Elkhead	9--12	yes	alkaline	low	-8.3	LSUBD	Leat et al., 1988
Yampa	10-7.5	yes	alkaline	high	-7.3 to -9.0	LOIB	Leat et al., 1988
Glenwood	11--8	yes	subalkaline	low	-6.2	LSUBD	Gibson et al., 1992; Leat et al., 1988
Grand Mesa	9.7	no	subalkaline	low	-7.9	LSUBD	Leat et al., 1988
Colorado Quat.	<1	no	alkaline	low	-4.3 to -5.7	LSUBD	Leat et al., 1989
Triangle Pk	<1	no	alkaline	low	-4.9	LSUBD	Leat et al., 1988

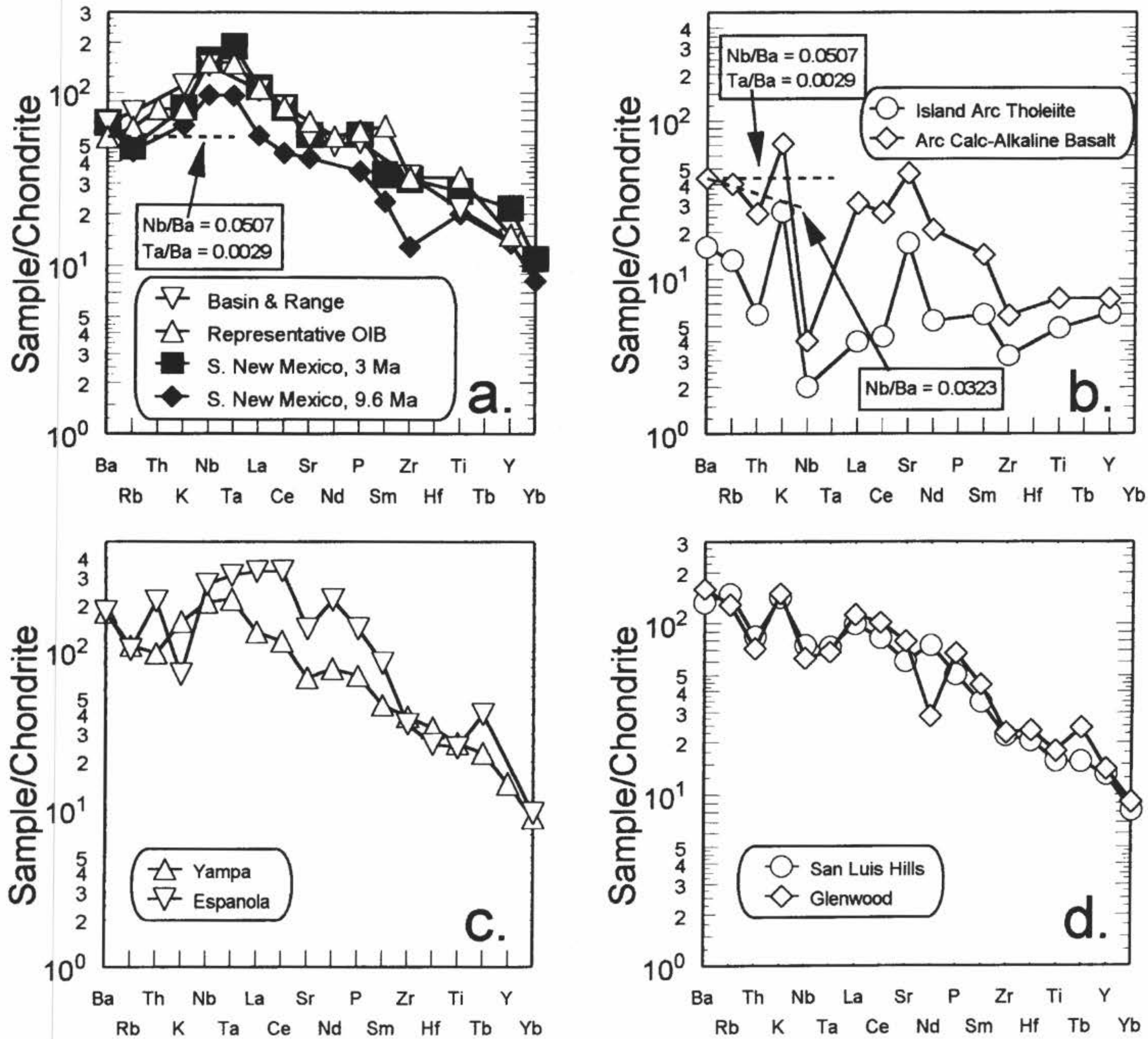

FIGURE 2. Chondrite-normalized (Thompson, 1982) incompatible trace element diagrams of various lithospheric and asthenospheric sources. **A,** High Nb/Ba and Ta/Ba lavas from the Basin and Range Province (Fitton et al., 1991), representative ocean island basalts (Sun, 1980), and southern New Mexico basalts (N. J. McMillan, unpubl.). **B,** Representative island arc tholeiite and calc-alkaline basalt (Sun, 1980). **C,** Representative examples of basalts from an OIB-modified lithospheric source (Gibson et al., 1992; Leat et al., 1988). **D,** Representative examples of basalts from a subduction-modified lithospheric source (Thompson et al., 1991; Leat et al., 1988).

Nb/Ba, Ta/Ba samples, which are interpreted as melts of OIB-modified and subduction-modified lithospheric sources, respectively. The type of mantle source for each of the volcanic fields examined in this study is presented in Tables 1–3, and the magmatic evolution of each segment of the rift is discussed in turn below.

METHODS

This paper is a compilation of several decades of petrologic research on igneous rocks of the Rio Grande rift by many authors (Tables 1–3). Stratigraphic and geochemical data were compiled from the literature. Major element analyses were normalized to 100% on a volatile-free basis, with FeO assumed to be 90% of the total iron. Initial $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios were used whenever elemental concentrations were published. Magma compositions in the Rio Grande rift span a wide range of composition, from strongly silica-undersaturated basanites to high-silica rhyolites. In order to focus on mantle source regions, the data set was filtered so that only samples with more than 8% MgO are considered in this paper. Although these magmas are not primitive and some crustal assimilation may have occurred, they are sufficiently mafic that their incompatible trace element and isotopic compositions are controlled mainly by the mantle source region.

SEGMENTS OF THE RIO GRANDE RIFT

The surface expression of Rio Grande rift extension is a series of continuous deep grabens and half grabens that extends from Leadville, Colorado, south through New Mexico and into northern Mexico (Baldridge et al., 1995, and references therein). North of Leadville, the rift continues to approximately the Wyoming-Colorado border as a series of discontinuous grabens and block-fault uplifts (Tweto, 1979). It is widely accepted that extension began rift-wide by 28 Ma, and was concentrated in two main phases, a late Oligocene–early Miocene stage of low-angle normal faulting (approximately 28–20 Ma) and a period of high-angle faulting from late Miocene (approximately 9–5 Ma) through Holocene. In this paper, the rift is divided into three segments that are characterized by distinct differences in the structural expression of extension that correlate with the compositions of rift magmas.

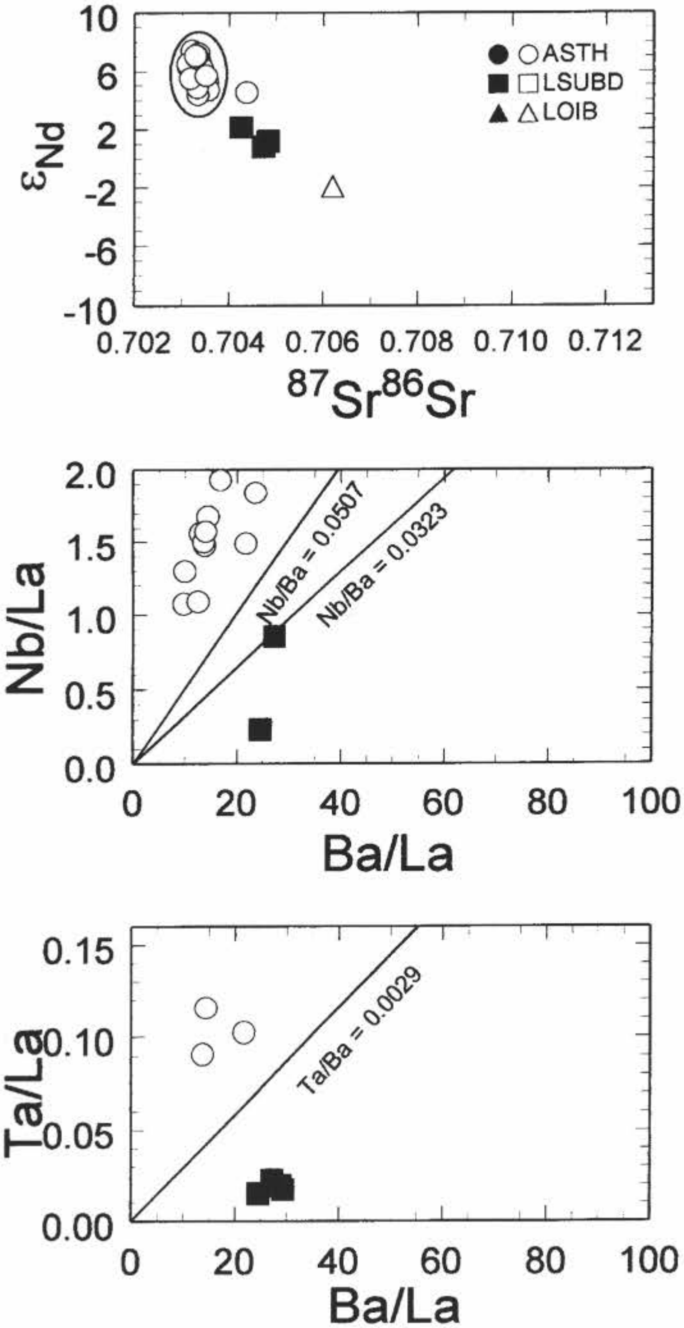

FIGURE 3. Isotopic and trace element diagnostic diagrams for the southern segment of the Rio Grande rift. Open symbols represent lavas younger than 15 Ma; closed symbols lavas older than 15 Ma. Abbreviations: ASTH = asthenospheric source, LSUBD = subduction-modified lithospheric source, LOIB = ocean island basalt-modified lithospheric source. **A,** $^{87}Sr/^{86}Sr$ vs. ε_{Nd}. The oval includes Basin and Range basalts younger than 5 Ma (Kempton et al., 1991) and asthenosphere-derived basalts from south-central New Mexico. **B,** Ba/La vs. Nb/La. **C,** Ba/La vs. Ta/La0

Southern segment: southern and central New Mexico

The segment of the Rio Grande rift south of Socorro, New Mexico is, in some ways, indistinguishable from the Basin and Range Province. For instance, south of 34°N latitude, the rift widens from a single rift basin to a series of basins; south of 33°N latitude, the rift consists of numerous horsts and grabens across the southwestern corner of New Mexico (Fig. 1).

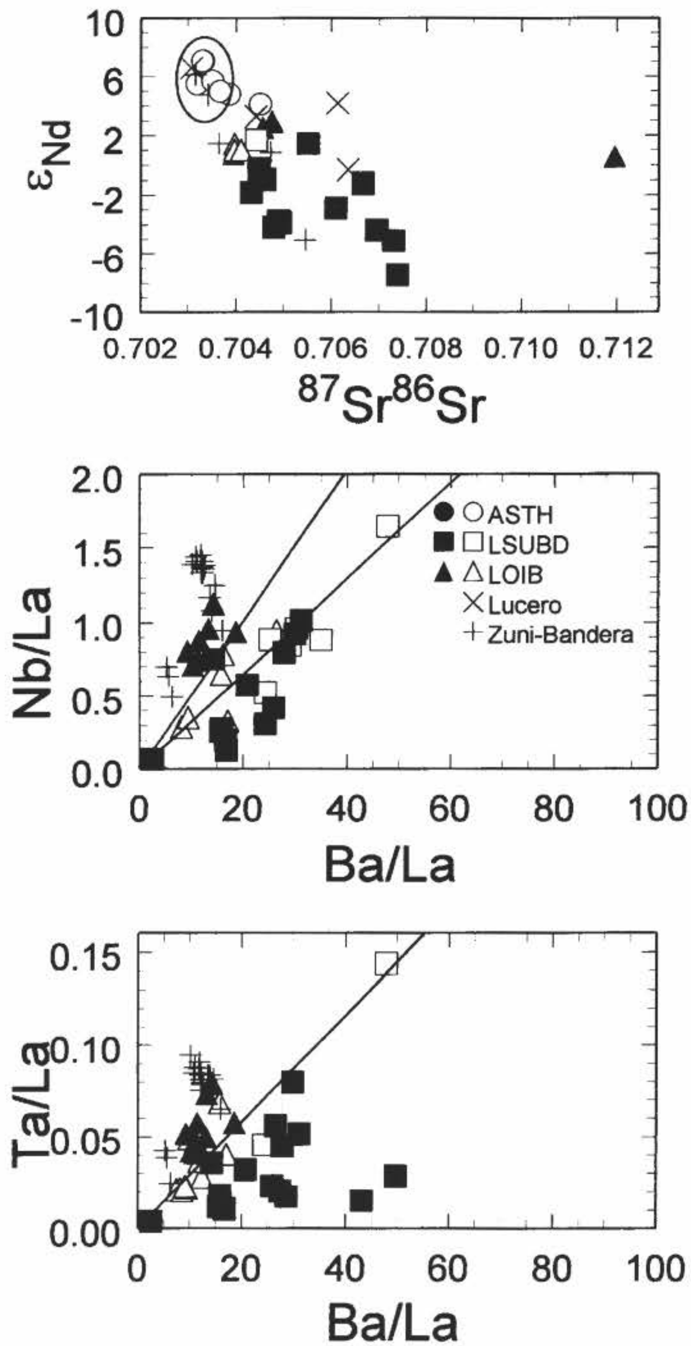

FIGURE 4. Isotopic and trace element diagrams for the central segment of the Rio Grande rift. Symbols and abbreviations are the same as in Figure 3.

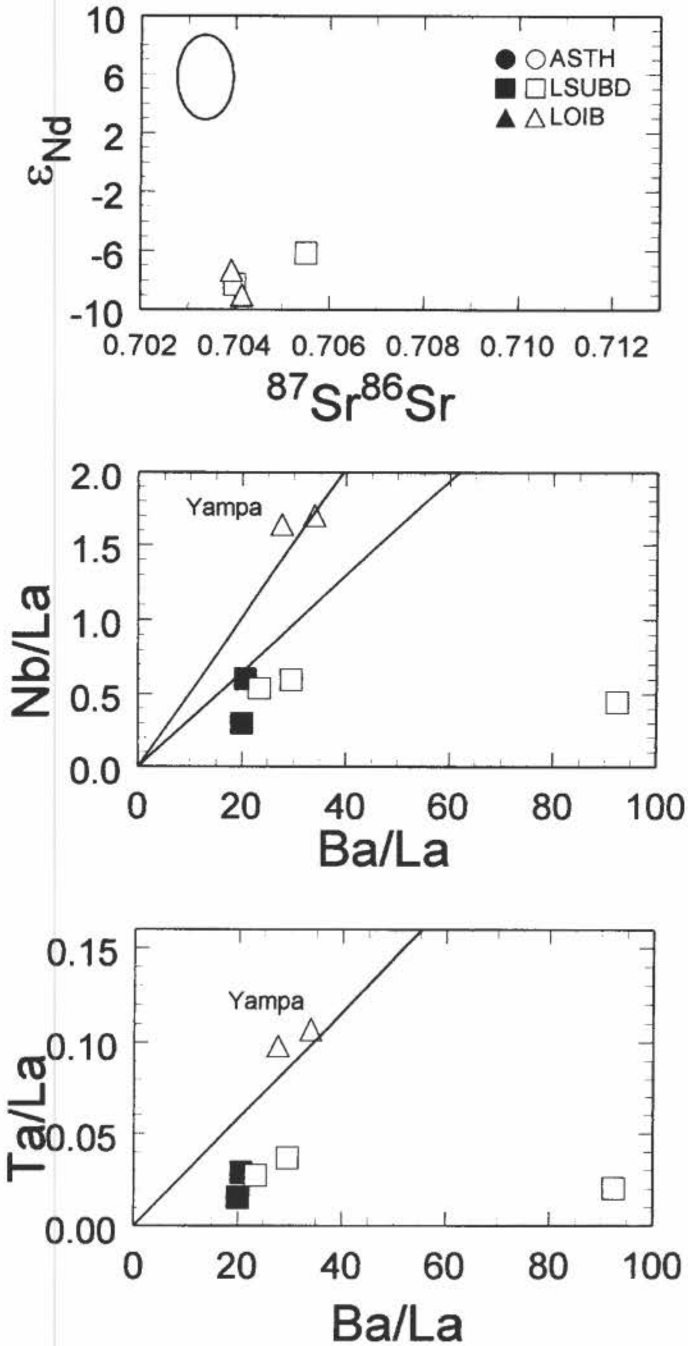

FIGURE 5. Isotopic and trace element diagrams for the northern segment of the Rio Grande rift. Symbols and abbreviations are the same as in Figure 3.

South-central New Mexico

Volcanism accompanied tectonic activity in south-central New Mexico since the end of the Laramide orogeny (Table 1). The earliest post-Laramide volcanic rocks comprise the Rubio Peak and Palm Park Formations. Published ages range from 51 Ma to 37.1 Ma (Clemons, 1979; Seager et al., 1978, 1982). These sequences consist of dominantly andesitic composite cones and associated ring plain deposits, although basaltic and rhyolitic lavas were also erupted. Intermediate calc-alkaline volcanism was abruptly replaced in southern New Mexico by the bimodal rhyolitic ash-flow/basaltic andesite suite of the Bell Top Formation, which ranges in age from 35.7 to 28.6 Ma (McIntosh et al., 1991). The geometry of contemporaneous basins as indicated by intercalated conglomerates (Mack et al., 1994) suggests that out-flow sheets filled a half graben and that the initiation of crustal extension and the onset of ignimbrite eruptions were contemporaneous at about 36–35 Ma. Basalts and basaltic andesites intercalated with the ash-flow sheets are very similar in major element, trace element, and isotopic composition to the overlying calc-alkaline lavas of the Uvas volcanic field. Uvas tholeiitic basalts and calc-alkaline basaltic andesites and andesites range in age from 25.9 to 27.4 Ma, and were clearly erupted during extension (Seager et al., 1984). The next 16 Ma were a period of continued extension and deposition of alluvial fanglomerates in rift basins, but very few volcanic rocks between 26 Ma and 10 Ma are preserved in south-central New Mexico. Volcanic activity resumed at 9.6 Ma with the eruption of the Selden Basalt, and continued sporadically in time and space with the eruption of tholeiitic and alkali basalts (Seager et al., 1984).

A major shift in magma compositions and source regions is recorded between the Oligocene lavas of the Uvas volcanic field and the Upper Miocene and younger basalts. Basalts from the Rubio Peak, Bell Top, and Uvas suites have low Nb/Ba and Ta/Ba ratios (Table 1; Fig. 3), and ε_{Nd} near +1 (Fig. 3), regardless of whether the basalts are slightly nepheline-normative (Rubio Peak basalts) or hypersthene-normative (Bell Top and Uvas basalts). These characteristics indicate that subduction-modified lithospheric mantle was melting during the early history of the rift in south-central New Mexico.

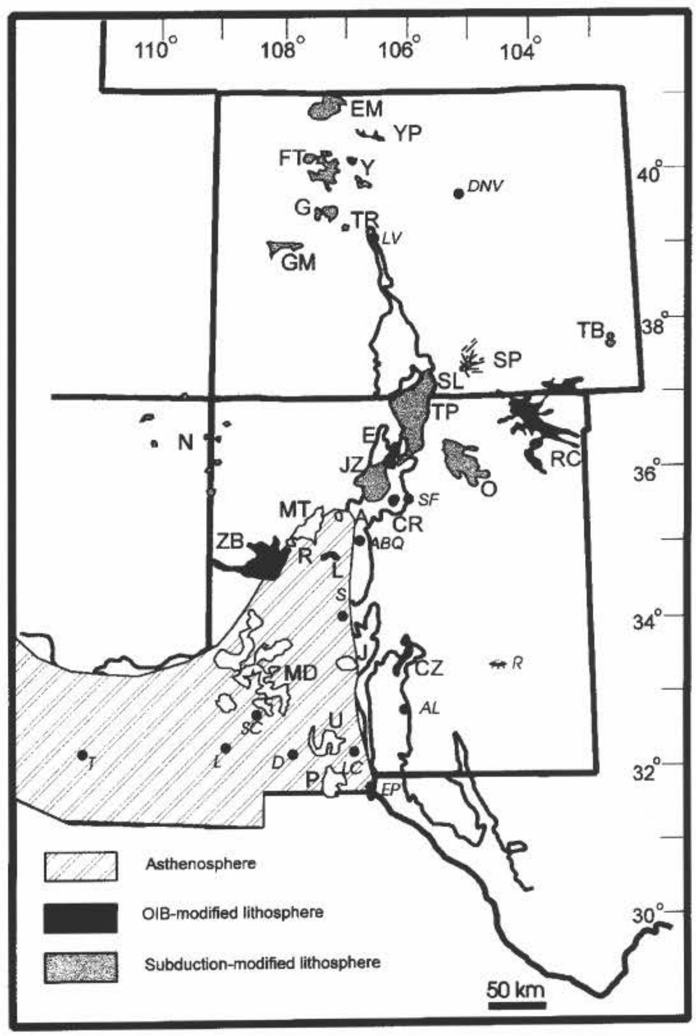

FIGURE 6. Spatial and temporal distribution of the three mantle source regions involved in Rio Grande rift magmatism: asthenosphere, subduction-modified lithosphere, and OIB-modified lithosphere.

Upper Cenozoic basalts in south-central New Mexico have distinctly different isotopic and trace element signatures. Tholeiitic and alkalic basalts erupted after 10 Ma have high Nb/Ba and Ta/Ba ratios and high positive ε_{Nd} values between +7 and +4 (Fig. 3). These lavas are remarkably similar to modern ocean island basalts and to Basin and Range basalts erupted since 5 Ma (Fitton et al., 1991; Kempton et al., 1991), and were produced by partial melting of upwelling asthenosphere.

Mogollon and Socorro areas

Detailed petrologic analysis of Rio Grande rift igneous rocks has been accomplished in the Mogollon-Datil volcanic field by Davis and Hawkesworth (1994), based on earlier work by Clemons et al. (1982), Elston (1957, 1984a, 1984b, 1989), and Bornhorst (1980), and in the Socorro area by Heatherington (1988). Volcanism occurred in nearly the same pulses as in south-central New Mexico: calc-alkaline andesites and dacites dominated from 38 Ma to 35.4 Ma, followed by eruption of silicic ash-flows tuffs intercalated with basalts and andesites, followed by a dominantly mafic suite. Davis and Hawkesworth (1994) note two major shifts in composition. Between 30 Ma and 20 Ma, volcanism was dominated by weakly alkaline to calc-alkaline basalts and basaltic andesites, although lavas as evolved as 69% SiO_2 were erupted. All mafic volcanic rocks from the Mogollon and Socorro regions erupted between 40 and 20 Ma have geochemical characteristics of the subduction-modified lithospheric source. After 20 Ma, nepheline-normative alkali basalts were erupted; the youngest of these have low $^{87}Sr/^{86}Sr$ and high Nb/Ba ratios (Fig. 3; Davis and Hawkesworth, 1994) and were derived from upwelling asthenosphere.

One young basalt flow (4.1 Ma) in Socorro Canyon west of Socorro, New Mexico, reported by Heatherington (1988) is unusual in that it has ε_{Nd} of -1.9. Trace element data are not available for this sample, so it is not known whether it represents melting of subduction-modified lithosphere or OIB-modified lithosphere. Similarly, the Holocene Carrizozo basalt flow in the Tularosa Basin has ε_{Nd} of +1, $^{87}Sr/^{86}Sr$ = 0.70477–0.70496 and high Nb/Ba and Ta/Ba ratios (Table 1), although it does not appear on Figure 3 because it has less than 8% MgO. These two basalt localities suggest that OIB-modified lithosphere was being tapped on the western and eastern flanks of the rift. This supports the Perry et al. (1987, 1988) model of Rio Grande rift mantle source evolution, which predicts that the subcontinental lithosphere will be the first source tapped across the rift and the only source melted on the flanks of the rift.

Central segment: central Colorado to central New Mexico

The central section of the Rio Grande rift, from 34°N at Socorro, New Mexico, to 39°N at Leadville, Colorado, consists of a series of north-trending rift basins that are offset from each other by accommodation zones. Rift volcanism was concentrated along two major zones: volcanic centers erupted within or on the margins of the rift basins, and those along the Jemez lineament. The Jemez lineament is marked by a line of Miocene volcanic fields located along the southern margin of the Colorado Plateau in Arizona and New Mexico, running to the northeast through central New Mexico and terminating with the Raton-Clayton field in northeastern New Mexico.

Volcanic fields of the central section of the rift do not exhibit the simple changes in volcanic style and composition that are seen in the southern section. The oldest rift magmatism is represented by alkalic suites, mostly along the rift margins (Two Buttes, Spanish Peaks, Navajo, Riley, and Dulce), although the Hindsdale lavas in the San Luis Hills and some lavas in the Española Basin are Oligocene–early Miocene eruptions within rift basins. Some silicic cauldrons, such as the Questa caldera in the Sangre de Cristo Mountains near Taos, New Mexico, were also active at this time. Activity in the Jemez volcanic field started at about 17 Ma with the eruption of basalts and andesites of the Keres Group (Goff et al., 1989; Ellisor et al., 1996). Miocene and younger volcanism is dominated by the development of dominantly mafic volcanic fields such as the Taos Plateau, Ocate, Raton-Clayton, Zuni-Bandera, Cerros del Rio, Albuquerque, Lucero, and Mt. Taylor fields. The young silicic eruptions of the Jemez volcanic field and Valles caldera are an important exception.

The geochemistry of volcanic centers of the central section of the rift (Table 2, Fig. 4) does not show evidence of a simple transition from lithospheric to asthenospheric sources through time like the southern section of the rift. Oligocene and early Miocene centers (35–15 Ma) are alkaline, have relatively low Nd (+2 to -8), and exhibit both high Ta/Ba, Nb/Ba and low Ta/Ba, Nb/Ba trace element signatures. Young volcanic fields (<15 Ma) range from tholeiitic to highly silica-undersaturated, with a large range in isotopic composition and examples of high Nb/Ba, Ta/Ba and low Nb/Ba, Ta/Ba lavas.

The interpretation of mantle source is not always straightforward. For instance, the Two Buttes and Spanish Peaks fields plot at lower ε_{Nd} than known modern ocean island basalts, and are probably best ascribed to lithospheric, rather than asthenospheric, sources. Two Buttes and Spanish Peaks both have low Nb/Ba and Ta/Ba ratios and represent partial melts of subduction-modified lithosphere. In contrast, the Española Basin suite has high Nb/Ba and Ta/Ba ratios, prompting Gibson et al. (1992, 1993) to interpret them as asthenospheric melts. Two lines of evidence indicate that a lithospheric source is more likely. First, some of the data plot outside the field of modern oceanic basalts (Gibson et al., 1992). Second, the asthenospheric source that has been active in the southern Rio Grande rift and across the Basin and Range for the last 10 Ma has produced basalts of a relatively small isotopic range. Thus, if the Española Basin basalts are asthenosphere-derived, then the Oligocene asthenosphere must have been not only significantly more enriched than modern asthenosphere, but also significantly more heterogeneous. The alternative interpretation proposed here, that the Española Basin basalts are partial melts of OIB-modified lithosphere, is a simpler model and does not require the introduction of asthenosphere with dramatically differently isotopic composition.

Several young volcanic fields also have OIB-modified lithospheric signatures: Raton-Clayton, Zuni-Bandera, Lucero(?), and Cerros del Rio. Mafic lithospheric lavas from these fields have ε_{Nd} near +1 (Tables 1–3) and intermediate to high Nb/Ba and Ta/Ba ratios. They differ from asthenosphere-derived melts in their enriched isotopic composition and from subduction-modified lithosphere-derived melts in their trace element signature.

Northern segment: northern Colorado

North of Leadville, Colorado, the rift consists of discontinuous grabens and half grabens with associated basin-fill sediments and igneous rocks, in contrast to the continuous string of basins extending from the Arkansas Basin near Leadville south to northern Mexico. Normal faults that form the eastern border of the Arkansas Basin in central Colorado continue northward and clearly indicate that Rio Grande rift extension occurred in northern Colorado (Tweto, 1979), as do half grabens in the Gore Range. However, extension in the northern segment of the rift was not as extensive as that south of Leadville. Tweto (1979) suggests that the rift terminates near the Wyoming-Colorado border, where regional fault strikes switch abruptly from the north-northwest and north trend of the rift bounding faults in central Colorado to west-northwest to west. Rift basin sediments of the Brown's Park and North

Park Formations were deposited from about 26 Ma–8 Ma, concurrent with the eruption and intrusion of rift magmas (Leat et al., 1988).

Magmatism occurred in three pulses in northern Colorado (Table 3), from 24 Ma to 20 Ma at the State Bridge area and in the Flat Tops volcanic field; from 13.4 Ma to 7.5 Ma at Flat Tops, Grand Mesa, Glenwood, Yampa, and the Elkhead Mountains; and a series of lavas and cinder cones younger than 2 Ma at Triangle Peak, McCoy, Willow Peak, and Dotsero (Leat et al., 1988). These lavas exhibit a wide range in composition, from basanite through rhyolites, but are clearly dominated by alkalic silica-undersaturated mafic rocks such as basanites, alkali basalts, and potassic-trachybasalts. Analyses in Leat et al. (1988) show that the northern Rio Grande rift basalts all have somewhat radiogenic $^{87}Sr/^{86}Sr$ ratios of 0.704–0.7067 and low ε_{Nd} ranging from -4.9 to -10.3. These low ε_{Nd} values suggest that the basalts were derived from a lithospheric source (Fig. 5, Table 3). In fact, both lithospheric sources are observed in the northern segment of the rift. The Yarmony and Yampa suites exhibit high Nb/Ba and Ta/Ba ratios, and are best ascribed to OIB-modified lithosphere. The Elkhead Mountains, Flat Tops, Glenwood, Grand Mesa, and Quaternary samples (including Triangle Peak) were all derived from subduction-modified lithosphere.

SPATIAL AND TEMPORAL DISTRIBUTION OF MANTLE SOURCES

Perry et al. (1987, 1988) proposed a model for the evolution of mantle sources in the Rio Grande rift based on data from volcanic fields in the central section of the rift. In their model, lithospheric mantle melts first across the rift as it is warmed by upwelling asthenosphere. The physical properties of the lithospheric mantle are converted to those of asthenosphere (warm, ductile, and able to convect) while maintaining its chemical signature. The transition from lithospheric to asthenospheric sources was reproduced in quantitative models that trace the evolving geothermal gradients during extension (Gallagher and Hawkesworth, 1992). The presence of a small amount of hydrous minerals lowers the solidus sufficiently to allow melting of the lithosphere. As extension proceeds, the base of the lithosphere is eroded and eventually replaced by the underlying asthenosphere. The composition of basalts erupted along the axis of the rift changes as the asthenosphere melts by decompression; basalts erupted on the flanks of the rift continue to be produced from lithospheric sources.

This transition from lithospheric to asthenospheric sources is seen in the Rio Grande rift (Fig. 6). Asthenospheric basalts have been found in south-central New Mexico, and along the rift axis as far north as the Zuni-Bandera, Lucero, Mount Taylor, and Albuquerque Basin volcanic fields. The Zuni-Bandera and Lucero fields contain both asthenospheric and lithospheric basalts. No analyzed samples to the east of the rift or north of the Jemez lineament have asthenospheric compositions. Subduction-modified lithosphere is the most common lithospheric source found from southern New Mexico through northern Colorado. OIB-modified lithosphere, in contrast, is less widespread, found in northern Colorado (Yampa and Yarmony), along the Jemez lineament (Raton-Clayton, Cerros del Rio, Espanola, Lucero, and Zuni-Bandera), and in south-central New Mexico at Carrizozo.

It is apparent, then, that the transition from lithospheric to asthenospheric sources was related to the amount of lithospheric extension and that the rift unzipped from the south, allowing a bulge of upwelling asthenosphere to migrate northward to its present position under the Albuquerque Basin. As rifting began, the lithosphere was tapped rift-wide; all Oligocene mafic lavas were generated from chemically heterogeneous lithosphere. In southern New Mexico as far north as Socorro, the transition to an asthenospheric source occurred at about 10 Ma as extension became great enough to permit decompression melting. However, even young lavas on the flank of the rift, like the Carrizozo flow, are lithospheric melts because decompression is restricted to the central, most extended, part of the system. Two fields, Lucero and Zuni-Bandera, record the transition from lithospheric to asthenospheric sources. At Lucero, the transition appears to have occurred between 8 Ma and 4 Ma (Perry et al., 1988); the two compositions were erupted essentially simultaneously at the Pleistocene–Holocene Zuni-Bandera field. If extension continues in the rift, the asthenospheric bulge will probably continue to migrate northward, producing a series of mafic volcanic fields.

CONCLUSIONS

A rift-wide compilation of the major element, trace element, and isotopic compositions of mafic Rio Grande rift lavas ranging in age from Eocene through Holocene permits the definition of three mantle sources that were active in the evolution of the rift. Two sources reside in the lithosphere and are recognized in mafic rocks (>8% MgO) with low ($\varepsilon_{Nd} < +2$), and $^{87}Sr/^{86}Sr > 0.704$. The lithosphere develops an enriched isotopic composition because incompatible-rich fluids, specifically high Rb/Sr and Sm/Nd, freeze in the lowermost lithosphere and are isolated from the convecting asthenosphere. These fluids have two distinctly different sources. The most common source is subduction-related fluids or melts produced over Precambrian subduction zones during the assembly of the continent. The combination of low Nb/Ba and Ta/Ba ratios with enriched isotopic signatures are used to identify subduction-modified lithosphere. The second fluid source is convecting asthenosphere (McKenzie, 1989), which produces small amounts of small degree partial melts under the continents. These fluids impart high Nb/Ba, Ta/Ba, and low Ba/La ratios to the lithospheric mantle. An alternative method for producing the OIB-modified lithospheric source is freezing of melts in the lithosphere as it passes over a mantle plume. In either case, the fluids have high Rb/Sr and Sm/Nd, and will cause an enriched isotopic signature similar to that of subduction-modified lithosphere.

The distribution of these three mantle sources in space and time correlates with the amount of extension, and shows the transition from lithospheric to asthenospheric sources predicted by Perry et al. (1987, 1988) and Gallagher and Hawkesworth (1992). Throughout the rift, lithospheric sources were tapped along the axis early in its development. Although rifting started at approximately the same time in the northern segment as in the southern segment, extension has been more rapid in the south, producing several north-trending basins that resemble Basin and Range structures. The greater degree of extension created room for upwelling asthenosphere, which started to produce melts as early at 10 Ma in south-central New Mexico and as far north as Socorro. As extension proceeded, the upwelling asthenospheric bulge migrated northward, reaching the Lucero volcanic field between 8 Ma and 4 Ma. The northern nose of the asthenospheric bulge, as identified by the presence of asthenosphere-derived basalts, is currently under the Albuquerque basin. No asthenospheric basalts have been identified north of the Jemez lineament.

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