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Lead isotopic evidence for synextensional lithospheric ductile flow in the Colorado River extensional corridor, western United States

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Abstract. Temporal changes in the Pb isotopic compositions of Miocene lavas erupted in the northern Colorado River extensional corridor suggest that lithospheric mantle and middle to deep crust migrated from beneath the Colorado Plateau into the corridor during extension. Basaltic to rhyolitic lavas erupted in the extensional corridor prior to 12.2 Ma have Pb isotopic values that are similar to those of Tertiary to Quaternary lavas erupted through Proterozoic Mojave crust, which comprises surface exposures of basement in the corridor and much of the extended territory to the west. In contrast, most post-12.2 Ma lavas from the same region have Pb isotopic compositions similar to those of lavas erupted through Arizona crust, which forms the basement of the Colorado Plateau. The changes in isotopic compositions of the basaltic lavas, and perhaps a portion of the changes in isotopic compositions of silicic lavas, are attributed to a change in the composition of the mantle source. However, the $^{206}Pb/^{204}Pb$ ratios for lavas erupted before and after 12.2 Ma in the corridor decrease with decreasing MgO concentrations, suggesting that the Pb isotopic compositions of crustal assimilants changed at about the same time as the composition of the mantle. In the area of the Black Mountains accommodation zone, the surface boundary between the Arizona and Mojave crustal provinces lies a minimum of 60-80 km to the east of the westernmost lava with an Arizona Pb isotopic signature. This distance cannot be accounted for by displacements along nearby major faults, suggesting that middle to deep Arizona crust flowed a significant distance to the west during extension.

1. Introduction

One enigma of the Basin and Range province and many other extended terranes is that despite significant heterogeneity in upper crustal strain, crustal thicknesses are relatively uniform [*Wernicke*, 1992; *Parsons and McCarthy*, 1995; *Wernicke et al.*, 1996]. Seismic reflection and refraction data indicate a significantly overthickened middle crust beneath some highly extended regions in the Basin and Range province [e.g., *McCarthy et al.*, 1991; *McCarthy and Parsons*, 1994; *Parsons and McCarthy*, 1995]. Although seismic velocities of this crust suggest that injection of mantle-derived magma may have been responsible for as much as one third to one half of the added material [*McCarthy and Parsons*, 1994], the rest has been attributed to lateral ductile flow of middle to lower crust. Such ductile flow also may account for the relative uniformity of total crustal thickness [e.g., *Block and Royden*, 1990; *Wernicke*, 1992; *McCarthy and Parsons*, 1994].

An excellent example of a highly extended terrane that contains a substantially overthickened layer of middle crust is the Colorado River extensional corridor (Figure 1) in the southern Basin and Range province [*McCarthy and Parsons*, 1994; *Parsons and McCarthy*, 1995]. The welt of overthickened middle crust corresponds to the locus of upper crustal thinning within the corridor and follows a chain of metamorphic core complexes that stretches from central Arizona to southeastern California [see *Spencer and Reynolds*, 1989]. Ductile flow of middle to lower crust from beneath the unextended Colorado Plateau into the highly extended corridor can account for (a) the relatively uniform crustal thickness of ~30 km [*McCarthy et al.*, 1991; *Wilson et al.*, 1991] throughout the corridor, (b) seismic refraction evidence of thinner than normal middle crust beneath the adjacent, southwestern margin of the Colorado Plateau [*McCarthy and Parson*, 1994], (c) relatively small variations in total crustal thickness, gravity, and topographic elevation between the corridor and Colorado Plateau despite demonstrable variations in upper crustal thinning [*Kruse et al.*, 1991], and (d) mylonitic fabrics, timing of uplift, and isostatic rebound of the metamorphic core complexes [*Beratan and Nielson*, 1996]. *Kruse et al.* [1991] demonstrated, using finite element modeling of Newtonian flow and power law creep, that ductile flow of lower crust, with effective viscosities of 10^{21} Pa s can be driven by lateral pressure gradients associated with lateral variations in upper crustal thinning. They further suggested that up to 150 km of lower crustal ductile flow may have occurred in the northern part of the extensional corridor. *Campbell and John* [1996] concluded on the basis of gravity data that the overthickening of middle crust resulted from

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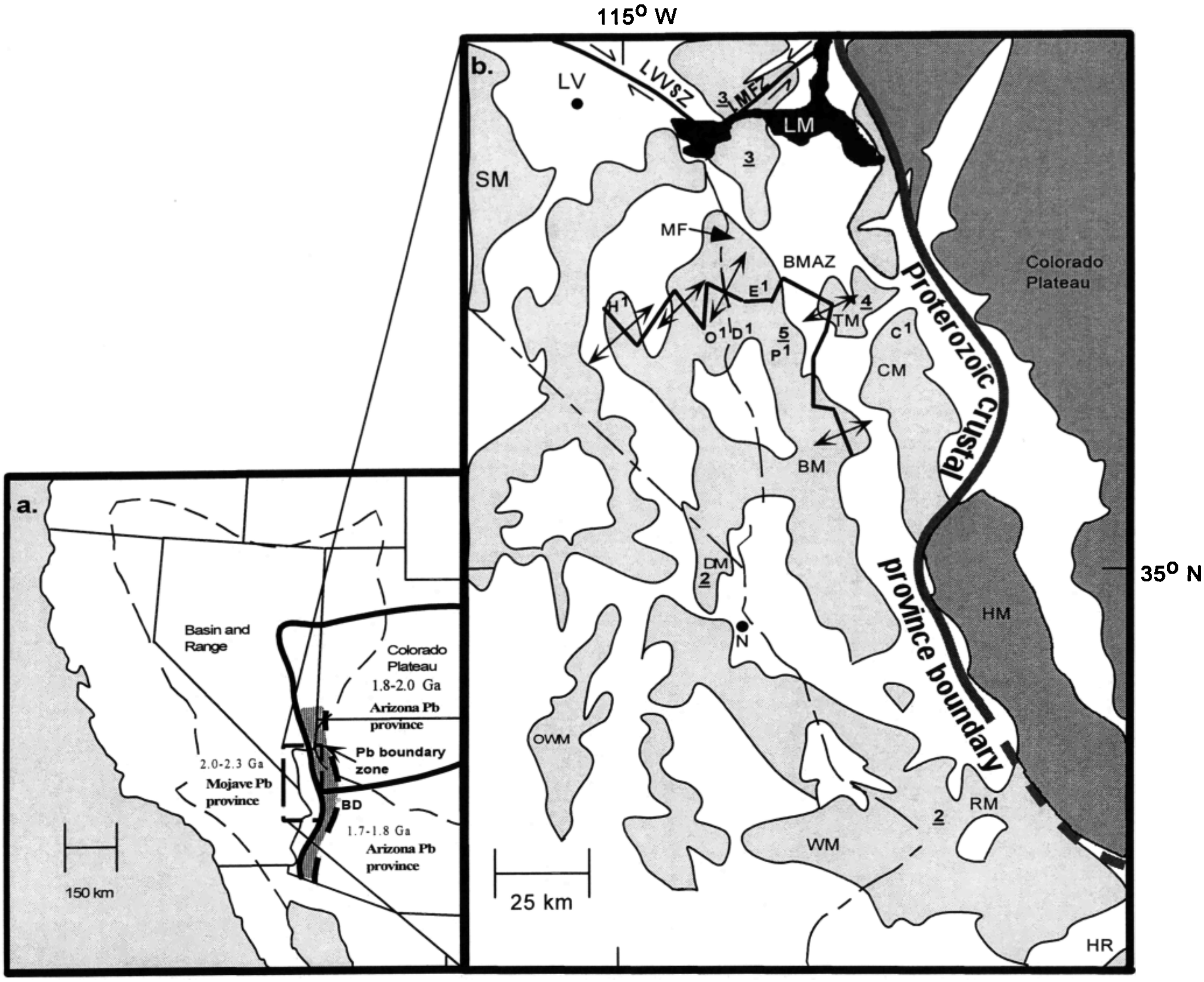

Figure 1. (a) Map showing location of the Colorado River extensional corridor (dashed rectangle) with respect to regional Proterozoic provinces of the southwestern U.S., as defined by Nd [*Bennett and DePaolo*, 1987] and Pb isotopes [*Wooden and DeWitt*, 1991]. The solid bold line separates the provinces as defined by Nd. Ages indicated are Nd model ages from *Bennett and DePaolo* [1987]. Shaded area indicates the Pb boundary zone that separates the Arizona Proterozoic province from the Mojave Proterozoic province as defined by *Wooden and DeWitt* [1991]. BD is Bagdad, Arizona. (b) Sample locations and pertinent geographic locations within the Colorado River extensional corridor as discussed in the text. The bold line indicates the location of the Proterozoic crustal boundary. In the vicinity of Lake Mead the boundary is defined by Nd, whereas the rest of the bold line and dashed bold line marks the western edge of the boundary zone defined by Pb isotopes. The light shaded area indicates bedrock exposures in the Mojave Proterozoic province, whereas the dark shaded area indicates bedrock exposures in the boundary zone separating the Arizona and Mojave provinces. H^1, E^1, O^1, D^1, P^1 and C^1 are locations for samples analyzed in this study: H^1 is Highland Spring Range; O^1, Opal Mountain area; E^1, Eldorado Canyon; P^1, Mount Perkins area; C^1, Cerbat Mountains. The remaining labels are defined as follows: 2, samples from *Bradshaw* [1991], *Bradshaw et al.* [1993], and *Hawkesworth et al.* [1995]; 3, samples from *Feuerbach et al.* [1993]; 4, samples from *McDaniel* [1995]; 5, samples from *Metcalf et al.* [1995], and *Faulds et al.* [1995], BM, Black Mountains; BMAZ, Black Mountains accommodation zone; CM, Cerbat Mountains; DM, Dead Mountains; HM, Hualapai Mountains; HR, Harcuvar Mountains; LM, Lake Mead; LMFZ, Lake Mead fault zone; LV, Las Vegas; LVVSZ, Las Vegas Valley shear zone; N, Needles; OWM, Old Woman Mountains; RM, Rawhide Mountains; SM, Spring Mountains; TM, Table Mountain Plateau; WM, Whipple Mountains; MF, Malpais Flattop.

emplacement of mantle-derived subvertical mafic dikes that mixed with laterally flowing crustal material or ponded between the lower and middle crust. Although compatible with seismic refraction and reflection data and rheologic models of continental extension [e.g., *Block and Royden*, 1990], the extent, timing, and rates of ductile flow within the crust are difficult to constrain.

One approach to tracking ductile flow within an extensional orogen is to analyze the isotopic signatures of synextensional magmas erupted in the vicinity of a major crustal province boundary [*Walker and Coleman*, 1991]. Spatial and temporal changes in isotopic compositions of crustal assimilants can be utilized to track the incursion of one crustal domain into another.

Pb isotopic signatures are particularly sensitive because continental crust generally has higher concentrations of Pb than does mantle-derived basalt. In addition, potential crustal assimilants from Proterozoic lithospheric provinces have significantly different Pb isotopic ratios [*Wooden and DeWitt*, 1991]. Pb isotopic ratios of relatively young volcanic rocks have been used successfully to delineate basement domains in many Phanerozoic orogens [e.g., *Worner et al.*, 1992; *Aitcheson et al.*, 1995]. Because the Pb isotopic compositions of lithospheric mantle domains that underlie Proterozoic crust appear to mimic those of the overlying crust [e.g., *Kempton et al.*, 1991], the isotopic compositions of mantle-derived basalts also may be utilized to track the lateral migration of lithospheric mantle.

Because magmatism immediately preceded and accompanied a discrete episode of major Miocene extension [e.g., *Anderson et al.*, 1972; *Howard and John*, 1987; *Davis and Lister*, 1988; *Faulds et al.*, 1994, 1995; *Campbell and John*, 1996], the highly extended northern Colorado River extensional corridor is an ideal location to chronicle the ductile flow of middle to lower crust. Moreover, a boundary between major Proterozoic lithospheric provinces with differing Nd and Pb isotopic signatures lies just east of highly extended portions of the corridor in northwestern Arizona (Figure 1) [*Condie*, 1986; *Bennett and DePaolo*, 1987; *Chamberlain and Bowring*, 1990; *Wooden and Miller*, 1990; *Wooden and DeWitt*, 1991]. The purpose of this paper is to (a) determine whether the isotopic compositions of preextensional, synextensional, and postextensional lavas record the lateral migration of this boundary during Miocene extension and (b) constrain the relative contributions of ductile flow and detachment faulting to any recorded migration of the boundary.

2. Geological Setting

2.1. Colorado River Extensional Corridor

The Colorado River extensional corridor (Figure 1) is a 70-100 km wide region of moderately to severely extended crust situated between the relatively unextended Colorado Plateau to the east and Spring Range/Old Woman Mountains region to the west [*Howard and John*, 1987; *Faulds et al.*, 1990]. The corridor consists of a northern east tilted domain and southern west tilted domain. The two domains coalesce in the Black Mountains accommodation zone [*Faulds et al.*, 1990; *Faulds*, 1994]. The Las Vegas Valley shear zone and the Lake Mead fault system bound the east tilted domain to the north. The southern domain extends southward to include the metamorphic core complexes exposed in the Whipple, Rawhide, and Harcuvar Mountains [e.g., *Spencer and Reynolds*, 1989]. Samples composing our data set were collected from the northern Colorado River extensional corridor, which we define as the region extending south from Lake Mead to the Lake Havasu region just east of the Whipple Mountains. This region includes all of the east-tilted domain, the Black Mountains accommodation zone, and the northern portions of the west-tilted domain.

Miocene strata within the northern Colorado River extensional corridor consist of 2- 5-km-thick sections of mafic to felsic lavas, ash-flow tuffs, clastic sedimentary rocks, and evaporites that rest directly on early Proterozoic and Cretaceous crystalline rocks [e.g., *Sherrod and Nielson*, 1993]. These strata were deposited just prior to and during extension, which fragmented the corridor into complex arrays of tilted fault blocks [e.g., *Anderson*, 1971; *Anderson et al.*, 1972; *Frost and Martin*, 1982; *Spencer*, 1985; *Howard and John*, 1987; *Weber and Smith*, 1987; *Davis and Lister*, 1988; *Faulds et al.*, 1990, 1995]. The magnitude of extension across the corridor ranges from 75% to >100% [*Reynolds and Spencer*, 1985; *Davis and Lister*, 1988; *Faulds et al.*, 1990]. The north-northwest strike of both normal faults and tilted strata as well as slip data suggest an east-northeast/west-southwest extension direction in the northern part of the west tilted domain and the entire east tilted domain [*Anderson*, 1971; *Faulds et al.* 1990, 1995; *Anderson and Barnhard*, 1994].

Radiometric ages obtained on variably tilted volcanic sequences within major growth-fault basins tightly bracket the timing of extension and volcanism throughout much of the northern extensional corridor [*Anderson et al.*, 1972; *Gans et al.*, 1992, 1994; *Smith and Faulds*, 1994; *Faulds et al.*, 1994, 1995]. Extension and magmatism both migrated to the north-northwest during the latest Oligocene and Miocene time [*Glazner and Bartley*, 1984; *Faulds et al.*, 1994; *Smith and Faulds*, 1994]. Extension occurred between 23 and 12 Ma south of Needles [e.g. *Howard and John*, 1987; *Richard et al.*, 1990; *John and Foster*, 1993; *Campbell and John*, 1996], 16 and 8 Ma in the vicinity of the Black Mountains accommodation zone [*Faulds et al.*, 1992, 1995; *Olson*, 1996; *Price and Faulds*, 1997], and 13 and 9 Ma in the western Lake Mead area [*Duebendorfer and Wallin*, 1991]. Magmatism began 1-2 m.y. prior to major extension and continued through the entire episode of extension in many parts of the northern corridor [*Faulds et al.*, 1994; *Smith and Faulds*, 1994].

The geochemical data reported here are from basaltic to rhyolitic lavas erupted in the oppositely tilted fault-block domains on either side of the Black Mountains accommodation zone (Figure 1). Samples were collected from structurally intact, continuous sections in several well-documented growth-fault basins [*Faulds et al.*, 1990, 1995, 1997; *Faulds*, 1993, 1995, 1996; *Olson*, 1996] along an east-west transect across the extensional corridor from the northern Cerbat Mountains on the east to the Highland Spring Range on the west. Volcanism in this area persisted from ~19 to 9 Ma [*Faulds et al.*, 1995; *Price and Faulds*, 1997], whereas most of the extension occurred between ~16 and 8 Ma [*Faulds et al.*, 1995; *Olson*, 1996; *Price and Faulds*, 1997]. Each suite of samples typically includes (a) the youngest, most steeply tilted volcanic unit, (b) youngest most gently tilted assemblage, and (c) oldest and youngest volcanic units. Thus the sample suites generally chronicle nearly the entire episode of both magmatism and extension within a particular basin. However, a definitive record of very late synextensional or postextensional conditions is difficult to obtain in most areas, because flat-lying lavas that clearly postdate extension are sparse. The youngest datable units typically are gently tilted (5-10°).

2.2. Lithospheric Provinces

The basement of the Colorado River extensional corridor and western part of the Colorado Plateau consists of early Proterozoic terranes referred to here as the Mojave and Arizona provinces (Figure 1). The Mojave province extends east from the Death Valley region to the southwestern edge of the Colorado Plateau [*Bennett and DePaolo*, 1987]. Precambrian silicic plutonic rocks from the province yield Nd model ages between 2.0 and 2.3 Ga, which are somewhat older than their 1.65-1.8 Ga crystallization ages [*Bennett and DePaolo*, 1987]. The Mojave crust is characterized by lower time-integrated U/Pb and higher Th/Pb and Th/U ratios than those of the average crust of the Arizona province to the east [*Wooden and Miller*, 1990; *Wooden and DeWitt*, 1991]. Present-day Mojave Proterozoic rocks yield $^{206}Pb/^{204}Pb$ values ranging from 16 to 25, $^{207}Pb/^{204}Pb$ values ranging from 15.4 to 15.85, and $^{208}Pb/^{204}Pb$ values ranging from 36 to 47 (Figure 2). Tertiary magmas erupted through Mojave crust also have relatively high and consistent $^{208}Pb/^{204}Pb$ values (38.5-39.3) with decreasing $^{206}Pb/^{204}Pb$ values (Figure 3) and gen-

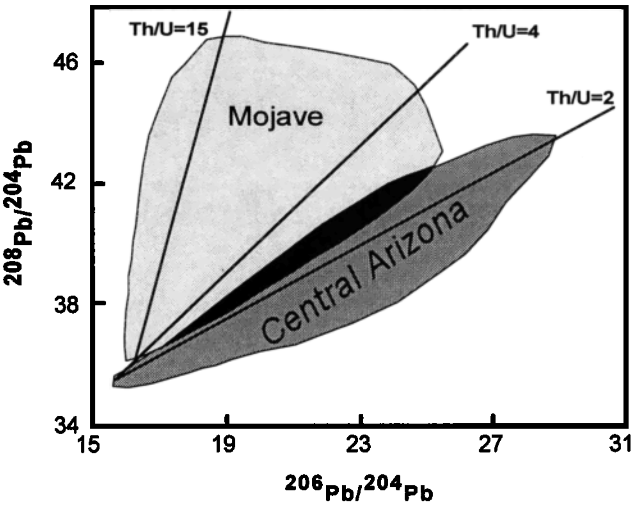

Figure 2. Fields showing the relationship of present day ^{208}Pb/^{204}Pb to ^{206}Pb/^{204}Pb values for Proterozoic crust of the southwestern United States [from *Wooden and DeWitt*, 1991]. Note the significant difference in time-integrated Th/U ratios between the Mojave and central Arizona Proterozoic rocks.

erally lower ^{206}Pb/^{204}Pb values with decreasing MgO concentrations [*Miller and Miller*, 1991; *Kempton et al.*, 1991; *Rogers et al.*, 1995].

The Arizona province (Figure 1) includes Nd province 2 of *Bennett and DePaolo* [1987] and the central Arizona Pb province of *Wooden and DeWitt* [1991]. It extends from central and northern Arizona to New Mexico and Colorado and bounds the study area to the east. Silicic plutons in the Arizona crust have Nd model ages ranging from 1.8 to 2.0 Ga [*Bennett and DePaolo*, 1987]. Proterozoic Arizona province rocks have systematically lower ^{207}Pb/^{204}Pb and ^{208}Pb/^{204}Pb ratios for a given ^{206}Pb/^{204}Pb ratio than for Proterozoic crust in the Mojave province (Figure 2; *Wooden and Miller*, 1990; *Wooden and DeWitt*, 1991]. Similarly, Tertiary and Quaternary lavas erupted within the Arizona crust have lower ^{208}Pb/^{204}Pb ratios for a given ^{206}Pb/^{204}Pb ratio than Tertiary lavas erupted in the Mojave crust (Figure 3; *Kempton et al.*, 1991; *Wenrich et al.*, 1995; *Hawkesworth et al.*, 1995].

The Nd isotopic compositions of silicic igneous rocks indicate that the boundary between the Mojave and Arizona lithospheric provinces extends southward along the eastern margin of the extensional corridor from west of the Gold Butte block, to east of the Cerbat Mountains, and through the northwest portion of the of the Hualapai Mountains (Figure 1). Bennett and DePaolo [1987] proposed that the Mojave crust may have been displaced to the south along a 400 km northerly striking left-lateral fault system, juxtaposing the Mojave block against the Arizona crust. A boundary of this type probably would be sharp and relatively vertical.

In contrast, the Pb isotopic data for Proterozoic rocks [*Wooden and Miller*, 1990; *Wooden and DeWitt*, 1991] suggest that the boundary between the Mojave and Arizona lithospheric provinces is somewhat gradational. *Wooden and DeWitt* [1991] and J.L. Wooden [personal communication, 1997] interpreted this boundary zone to be a 75 km wide zone consisting of a mixed assemblage of volcanic arcs and sedimentary basins that have Pb isotopic compositions dominated by the Mojave province, with variable proportions of Pb derived from the Arizona province. *Bennett and DePaolo*'s [1987] Nd boundary approximately corresponds to the western edge of this boundary zone (the delta-Jerome equals 5 contour of *Wooden and DeWitt* [1991]). The eastern edge of this boundary zone, which lies just east of Bagdad, Arizona (Figure 1), marks the western edge of crust dominated by the Pb isotopic signatures characteristic of Arizona Proterozoic crust. A 1.1-Ga diabase dike swarm intruded into Mojave crust in the southern part of the northern corridor (e.g., Sacramento, Homer, and Buckskin Mountains) has Pb isotopic signatures similar to Proterozoic rocks from the Arizona province. This suggests that some Arizona province mantle may have projected beneath Mojave crust as early as 1.1 Ga [Hammond and Wooden, 1990].

3. Composition of Miocene Lavas

To comprehensively describe the geochemistry of lavas from the northern Colorado River extensional corridor, we combine new data in Table 1 with previously published geochronologic and geochemical data from the central Black Mountains [*Faulds et al.*, 1995; *Metcalf et al.*, 1995] and White Hills [*McDaniel*, 1995] along the east-west transect, as well as from the Lake Mead area to the north [*Feuerbach et al.*, 1993] and Whipple Mountains region to the south (Figure 1) [Bradshaw, 1991; *Bradshaw et al.*, 1993; *Hawkesworth et al.*, 1995]. The discussion focuses on the Pb, Nd, and Sr isotopic data for basalts and intermediate to rhyolitic lavas.

3.1. Basalts

Several recent studies of extension-related volcanism have shown that lavas with >8 wt % MgO generally retain incompatible trace element ratios and isotopic compositions of primitive mantle-derived melts [e.g., *Kempton et al.*, 1991; *Fitton et al.*, 1991]. Therefore the compositions of lavas with more than 8 wt % MgO are used here to characterize the probable compositions of mantle-derived parental magmas in the Colorado River extensional corridor. Lavas with MgO concentrations of 6-8 wt % also are used to discern geochemical traits associated with the mantle. Although these lavas are more differentiated and more likely to have assimilated crust, the amount of assimilation needed to change magma compositions from 6 to 8 wt % MgO minimally impacts incompatible trace element and Nd and Sr isotopic compositions. This is because concentrations of the incompatible trace elements of interest (e.g., Nb, REE, and Sr) for assimilants are approximately equal to or lower than those for mantle-derived melts in this region, and the rate of assimilation to crystallization is probably something less than 0.5 [e.g. *DePaolo*, 1981].

Pb, however, is strongly enriched in the crust, and assimilation has the potential to more strongly affect the Pb isotopic compositions of magmas. However, assimilation/fractional crystallization modeling assuming 12 ppm Pb and ^{206}Pb/^{204}Pb = 18.5 for a basalt (an average value for preextensional basalts from the northern corridor [*Bradshaw et al.*, 1993], 21 ppm Pb and ^{206}Pb/^{204}Pb = 17.0 for the crust, and values for the assimilation/crystallization ratio (r = 0.5) and the final to initial magma ratio (F = 0.9) that are consistent with a change in MgO concentrations from 8.0 to 6.0 wt % indicates that ^{206}Pb/^{204}Pb ratios would change by ~0.25. This is only a small fraction of the variation in Pb isotopic compositions observed for the mafic lavas (Figure 3).

Extension-related mafic basalts were derived from lithospheric mantle throughout the Colorado River extensional corridor. These basalts have varying La/Nb ratios (2-8), low ε Nd values (-4 to -8.5), and high ^{87}Sr/^{86}Sr ratios (0.7052-0.7085; Figures 4 and 5). The common explanation for Nd and Sr isotopic values of this type is that lithospheric sources for the basalts became enriched in light rare earth elements and Rb early in their history,

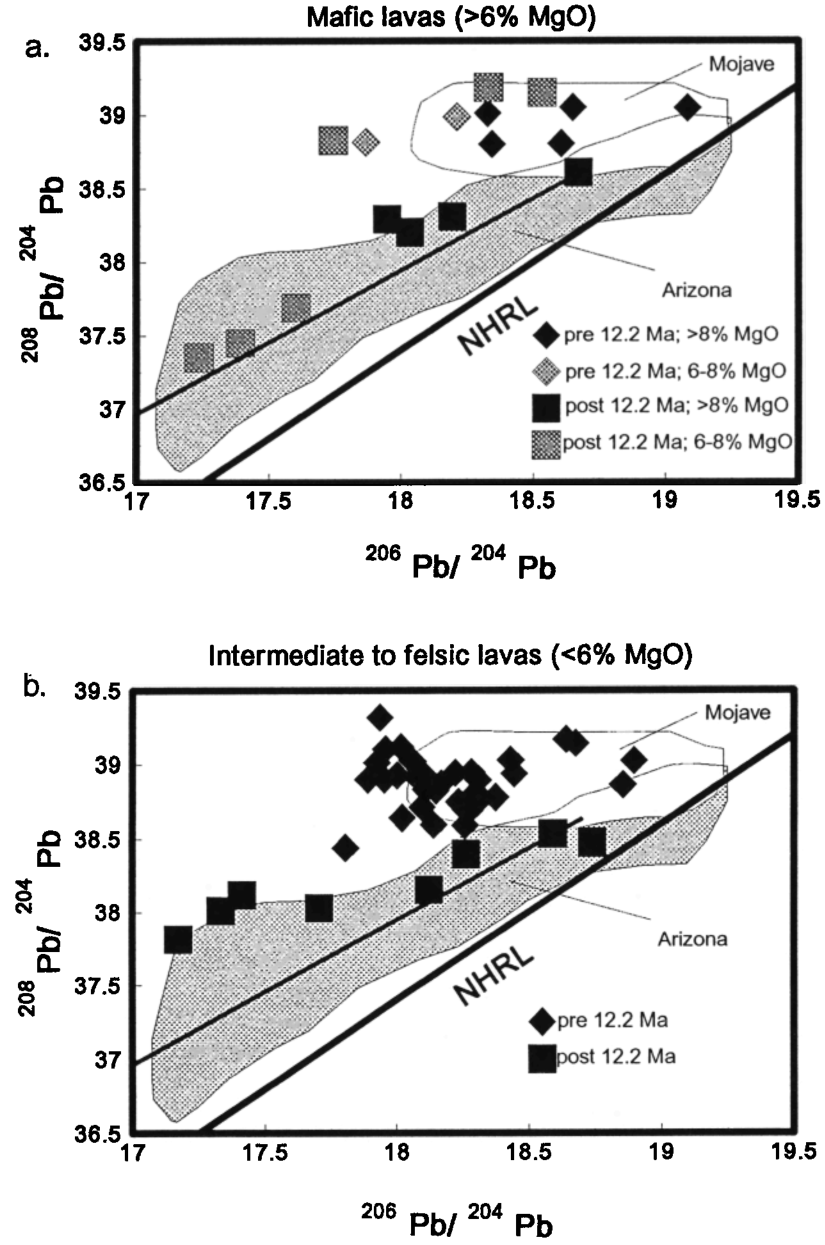

Figure 3. (a) Plot of present-day ^{208}Pb/^{204}Pb against ^{206}Pb/^{204}Pb values for Miocene mafic igneous rocks from Colorado River extensional corridor. Data are from this study and references listed in Figure 1. Also shown are the fields for Tertiary to Quaternary lavas erupted through Arizona crust (shaded area enclosed by a solid line) and Tertiary to Quaternary lavas erupted through Mojave crust (unshaded area enclosed by a solid line) [*Miller and Miller,* 1991; *Kempton et al.*, 1991; *Wenrich et al.*, 1995; *Rogers et al.*, 1995]. The thin solid line represents the Pb evolution model of *Stacey and Kramers* [1975]. (b) Plot of present-day ^{208}Pb/^{204}Pb against ^{206}Pb/^{204}Pb values for Miocene intermediate to felsic (<6% MgO) igneous rocks from Colorado River extensional corridor. Solid diamonds are pre-12.2-Ma lavas; solid squares are post-12.2-Ma lavas. Data are from this study and previous studies (locations and references delineated in Figure 1).

probably in the early Proterozoic [e.g., *Menzies et al.*, 1983; *Hart*, 1985]. The higher range of La/Nb ratios (5-8) implies that this ancient lithospheric mantle probably was affected by subduction sometime in its past [e.g., *Ormerod et al.*, 1991; *Hawkesworth et al.*, 1995]. The sparse data for these lithospherically derived basalts suggest that their ε Nd, ^{87}Sr/^{86}Sr, and La/Nb values do not vary consistently with time, although some of the less primitive basalts (6-8% MgO) erupted after 12.2 Ma do have lower ^{87}Sr/^{86}Sr values for a given ε Nd value (Figure 5). Pb isotopic values, however, do change consistently with time. Basalts erupted before 12.2 Ma have relatively constant ^{208}Pb/^{204}Pb ratios but varying ^{206}Pb/^{204}Pb ratios, whereas those erupted after 12.2 Ma have generally lower ^{208}Pb/^{204}Pb ratios that positively correlate with ^{206}Pb/^{204}Pb ratios (Figure 3a).

Another mantle source, represented by the 6.01-4.3 Ma Fortification Hill alkalic basalts, has higher ε Nd values (-1-+2.2) and low La/Nb (0.88-1.2) ratios [*Feuerbach, et al.*, 1993]. These values approach those of modern ocean-island basalts, suggesting

Table 1. Selected New Major and Trace Element Analyses and Nd, Sr, and Pb Isotopic Analyses.

Sample	Locality	Age Ma	SiO_2	MgO	Total	^{143}Nd/^{144}Nd	^{87}Sr/^{86}Sr	^{206}Pb/^{204}Pb	^{207}Pb/^{204}Pb	^{208}Pb/^{204}Pb	La	Nb	La/Nb
MD-34	D	14.79[a]	50.8	7.4	99.7	0.512395	0.707646	18.855	15.589	38.864	46.03	13.2	3.49
MD-40	D	15	52.3	4.3	99.6	0.512416	0.706925	18.021	15.523	38.642	39.88	23.5	1.70
MD-43	D	15.3[a]	52.0	7.1	99.3	0.512477	0.706521	18.259	15.543	38.592	44.14	27.6	1.60
92-263	C	17.97[d]	55.7	4.6	98.6	0.512184	0.710001	18.640	15.605	39.170	180.71	41.86	4.32
CM-87	C	17.90	46.1	13.0	96.9	0.512211		19.081	15.642	39.047	174.21	32.74	5.32
OM-14	O	13.6[a]	57.7	3.7	98.6	0.512218	0.709834	18.169	15.550	38.870	88.94	30.22	2.94
OM-16	O	11.35[a]	62.7	3.5	99.6	0.5122226	0.707430	17.706	15.512	38.028	42.66	20.63	2.07
OM-50	O	12.78[a]	54.1	6.8	96.5	0.51225	0.707615	17.867	15.526	38.818	70.83	48.28	1.47
EC-26	E	16.1[b]	60.0	3.4	99.3	0.512213	0.709034	18.309	15.576	38.893	82.29	24.28	3.39
EC-31	E	15.9[b]	58.3	3.8	98.7	0.512235	0.708834	18.272	15.57	38.763	79.86	23.23	3.44
EC-25	E	16.00	57.3	4.4	98.3	0.51226	0.708561	18.309	15.572	38.780	67.86	18.95	3.58
94-71	H	16.15[c]	59.5	4.7	98.1	0.512244	0.708530	18.280	15.576	38.741	75.10	22.13	3.39
HS-77	H	17.00	59.0	3.9	98.9	0.51225	0.708623	18.140	15.550	38.594	73.71	22.00	3.35
94-80	H	15.81[c]	57.0	5.2	99.7	0.512241	0.708476	18.303	15.567	38.742	66.06	20.15	3.28
94-81	H	16.2[c]	58.8	5.1	99.2	0.512263	0.708529	18.317	15.583	38.776	71.74	20.91	3.43
94-62	H	16.2[c]	70.8	0.5	98.5	0.512144	0.710398	17.806	15.538	38.441	89.24	34.47	2.59
MP-1	P	17	56.5	5.5	92.3	0.512217	0.709450	18.676	15.618	39.143	152.01	22.42	6.78
92-244	P	16	51.6	7.8	96.9	0.512318	0.708531	18.431	15.584	39.029	139.44	16.59	8.41
93-90	P	16	66.7	1.3	100.2	0.512193	0.710364	18.057	15.556	39.027	57.1	21.05	2.71
MP-3	P	15.8	62.4	2.3	90.9	0.512161	0.709310	18.149	15.589	38.825	68.19	17.95	3.80
93-79	P	15.8	65.6	2.1	97.9	0.512097	0.709855	18.222	15.612	38.942	58.92	13.38	4.40
93-84	P	15.93[a]	72.5	0.5	98.0	0.512078	0.711224	17.890	15.551	38.899	59.89	20.52	2.92
93-76	P	15.7	73.0	0.3	99.8	0.512113	0.711156	17.925	15.548	39.012	58.99	20.31	2.90
93-77	P	15.7	76.2	0.0	99.9	0.51213	0.711822	17.952	15.545	38.898	45.04	21.7	2.08

SiO_2 and MgO were obtained by x-ray fluorescence analysis and Nb and La obtained by inductively coupled plasma-mass spectrometry at Washington State University. SIO_2 and MgO are normalized to 100%. Isotopic analyses were obtained at the isotope geochemistry lab, University of Kansas. The ^{143}Nd/^{144}Nd values are normalized to ^{146}Nd/^{144}Nd=0.7219 and referenced to LaJolla ^{143}Nd/^{144}Nd=0.511850; the error is +/- 0.000031. Pb isotopic ratios are normalized to National Bureau of Standards (NBS) 981 using ^{207}Pb/^{206}Pb=0.91464; the error is +/- 0.1-0.2%. The ^{87}Sr/^{86}Sr values are normalized to ^{86}Sr/^{88}Sr=0.1194 and biased corrected for NBS 987 to be 0.710250; the ^{87}Sr/^{86}Sr error is +/- 0.000015.

P represents the lavas from the Mount Perkins block; D represents the Mount Davis lavas; E represents the lavas exposed in Eldorado Canyon; H represents the lavas from the Highland Spring Range; C represents the lavas in the northern Cerbat Mountains.

[a] indicates the date is from Faulds et al. [1995]; [b] indicates the date is from Faulds [1996]; [c] indicates the date is from Olson [1996]; [d] indicates the date is from Faulds and Gans [unpublished data]. Dates without footnotes indicates the age is estimated on the basis of known geochronologic data and field relationships.

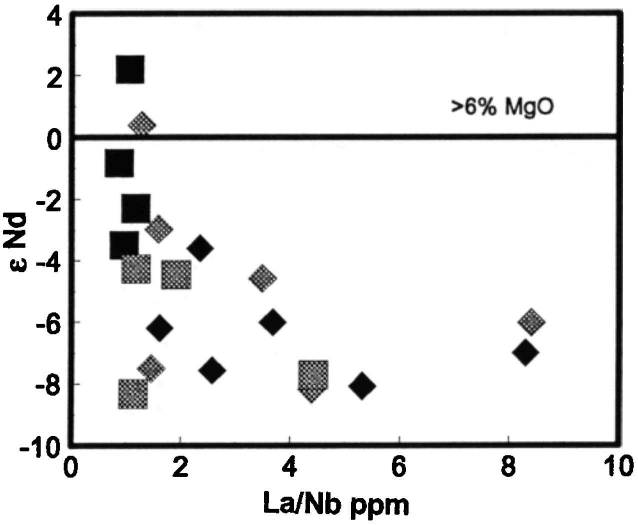

Figure 4. Plot of initial epsilon Nd against La/Nb for Tertiary lavas with >6% MgO erupted in the Colorado River extensional corridor. Symbols delineated in Figure 3a. Data are from this study and those listed in Figure 1.

that at least one mantle end-member for the source of latest syn-extensional to postextensional basaltic lavas within the corridor was modern convecting asthenosphere. These lavas have a relatively restricted range of Pb isotopic ratios (^{206}Pb/^{204}Pb = 18.8-19.1, ^{207}Pb/^{204}Pb = 15.55-15.6, and ^{208}Pb/^{204}Pb = 39-39.2 [Feuerbach et. al., 1993].

3.2. Differentiated Magmas

Volcanic rocks with differentiated compositions (< 6 wt % MgO basalt through rhyolite) that erupted prior to 12.2 Ma in the northern extensional corridor have high and relatively consistent ^{208}Pb/^{204}Pb ratios (38.5-39.2) and ^{206}Pb/^{204}Pb ratios ranging from 19.2 to 17.9 (Figure 3b). In contrast, most lavas erupted after 12.2 Ma have lower ^{208}Pb/^{204}Pb ratios (37.4-38.5), and these ratios are positively correlated with ^{206}Pb/^{204}Pb ratios. In addition, lavas erupted before 12.2 Ma have generally higher ^{207}Pb/^{204}Pb ratios than lavas erupted later, although there is considerable overlap (Figures 3 and 6). Only two post-12.2-Ma volcanic sections have ^{208}Pb/^{204}Pb ratios >38.5. These are the 11.59- 11.28 Ma tholeiitic basalts from Malpais Flattop near Willow Beach, Arizona [*Feuerbach et al.*, 1993; J.E. Faulds and P.B. Gans, unpublished data, 1997], and a 10.6 Ma lava from the Lake Havasu region [*Bradshaw et al.*, 1993]. For both pre- and post-12.2-Ma lavas, ^{206}Pb/^{204}Pb ratios decrease with decreasing MgO. However, the trends for the >12.2-Ma lavas and the <12.2-Ma lavas diverge because the ^{206}Pb/^{204}Pb ratio decreases sharply for <12.2-Ma lavas with decreasing MgO, whereas this ratio only decreases slightly for >12.2-Ma lavas (Figure 7c).

As discussed above, basalts with MgO > 6 wt % erupted before, during, and after extension have widely ranging Sr and Nd isotopic compositions reflecting the variation in the lithospheric and asthenospheric mantle sources. However, with progressive differentiation and lowering MgO concentrations, Sr and Nd isotopic compositions for lavas erupted both before and after 12.2 Ma appear to converge on restricted but distinct ranges of values (Figures 7a and 7b). The Sr and Nd isotopic compositions of differentiated lavas erupted after 12.2 Ma generally have lower ^{87}Sr/^{86}Sr ratios for given ε Nd values than lavas erupted before 12.2 Ma (Figure 5a, b).

4. DISCUSSION

4.1. Sources for Basaltic Lavas

The most compelling interpretation of the Pb isotopic data for the basalts with > 6 wt % MgO is that the mantle sources for mafic lavas erupted in the northern Colorado River extensional corridor changed at ~12.2 Ma from that associated with the Mojave province to that associated with the Arizona province. Mafic lavas erupted before 12.2 Ma maintain relatively constant ^{208}Pb/^{204}Pb ratios as the ^{206}Pb/^{204}Pb ratio decreases. This trend is similar to that of primitive lavas derived from lithospheric mantle that lies beneath the Mojave crust (Figure 3a). Relatively primitive mafic lavas erupted in the Colorado River extensional corridor after 12.2 Ma have decreasing ^{208}Pb/^{204}Pb ratios with decreasing ^{206}Pb/^{204}Pb ratios. These ratios are similar to those of

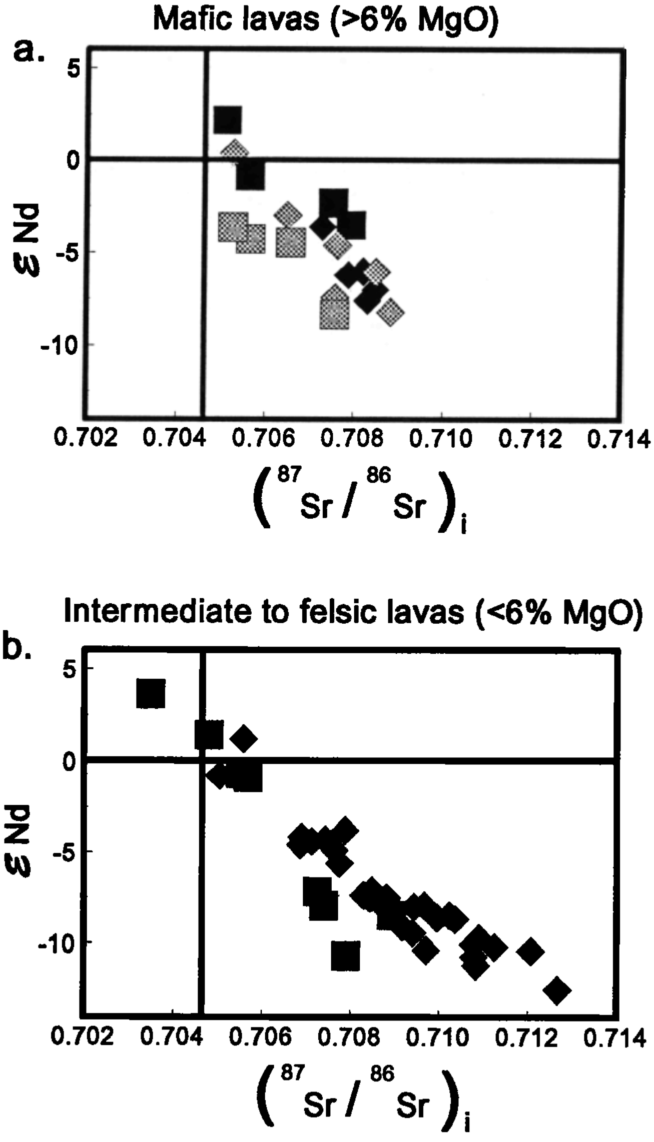

Figure 5. (a) Plot of initial epsilon Nd against initial ^{87}Sr/^{86}Sr values for mafic Tertiary lavas erupted in the Colorado River extensional corridor. Symbols are described in Figure 3a. (b) Plot of initial epsilon Nd against initial ^{87}Sr/^{86}Sr values for intermediate to felsic Tertiary lavas erupted in the Colorado River extensional corridor. Symbols are described in Figure 3b. Data are from this study and those listed in Figure 1.

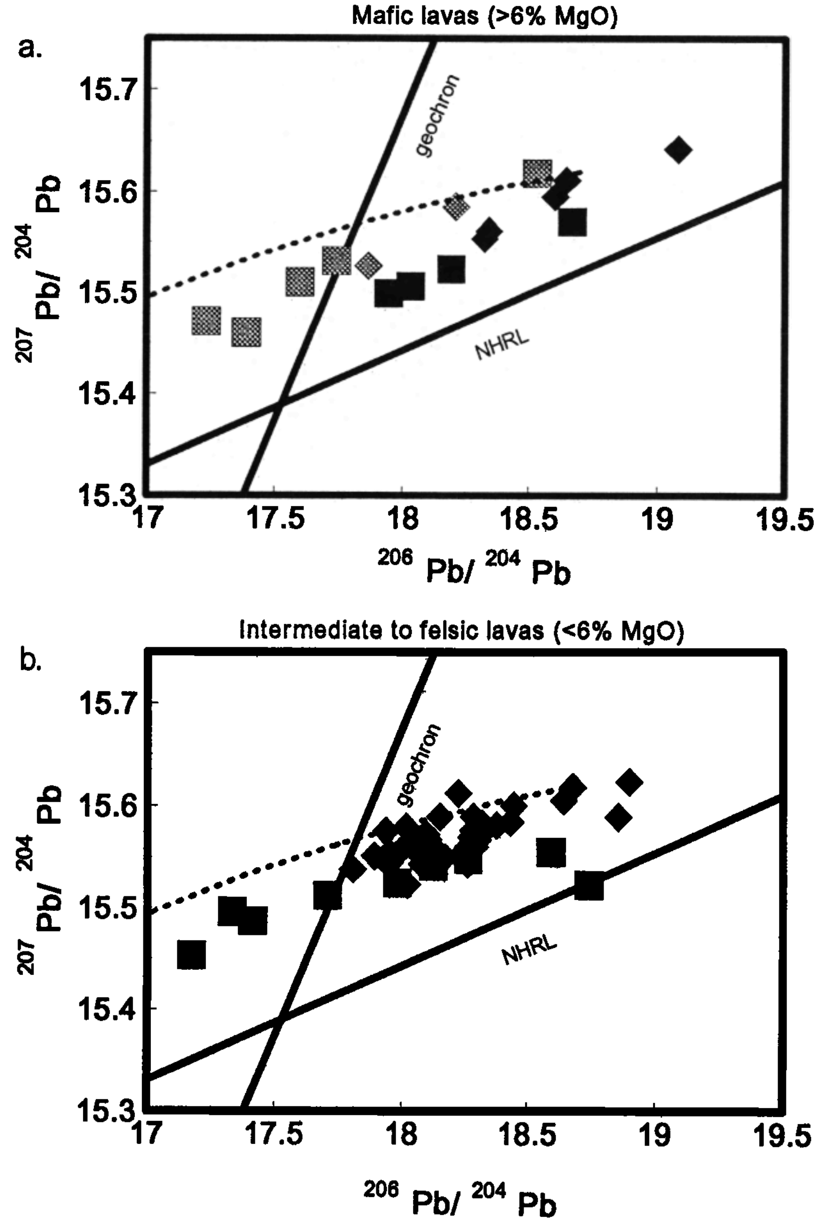

Figure 6. (a) Plot of present-day ^{207}Pb/^{204}Pb against ^{206}Pb/^{204}Pb values for mafic igneous rocks from the Colorado River extensional corridor. Symbols are described in Figure 3a. The dotted line represents the Pb evolution model of *Stacey and Kramers* [1975]. (b) Plot of present-day ^{207}Pb/^{204}Pb against ^{206}Pb/^{204}Pb values for intermediate to felsic (<6% MgO) igneous rocks from the Colorado River extensional corridor. Symbols are described in Figure 3b. Data are from this study and those listed in Figure 1.

primitive lavas erupted within the Arizona province (Figure 3a). The Fortification Hill basalts are derived at least in part from the asthenospheric mantle, but still fall within the trend for lavas erupted after 12.2 Ma on the plot of ^{206}Pb/^{204}Pb versus ^{208}Pb/^{204}Pb values. It is also significant that post-12.2 Ma mafic lavas have lower ^{87}Sr/^{86}Sr values for a given ε Nd value than lavas erupted prior to 12.2 Ma (Figure 5a). The timing of this slight shift in ^{87}Sr/^{86}Sr coincides with the timing in the change of Pb isotopic ratios.

The change in the Pb isotopic compositions of basaltic lavas with time in the Colorado River extensional corridor may reflect a change in the depth or location of melting in the lithospheric mantle. The Pb isotopic data from 1.1-Ga diabase intrusions in the Whipple Mountains region suggest that Arizona lithospheric mantle was present beneath the Mojave crust as early as the late Proterozoic in at least the southern part of the study area [*Hammond and Wooden*, 1990]. Thus the basalts may have been generated from Mojave lithosphere during the early stages of Miocene extension and from overlying or underlying Arizona lithospheric mantle during later stages.

A second possibility is that the lithospheric mantle below the Colorado River extensional corridor generally had a Mojave lithospheric mantle signature before extension, and it was replaced by mantle with a Pb isotopic signature of Arizona lithospheric mantle during extension. The migration of Arizona lithospheric mantle may have been facilitated by heating associated with mantle upwelling, conversion of lithosphere to the rheological equivalent of asthenosphere in a manner similar to that postulated

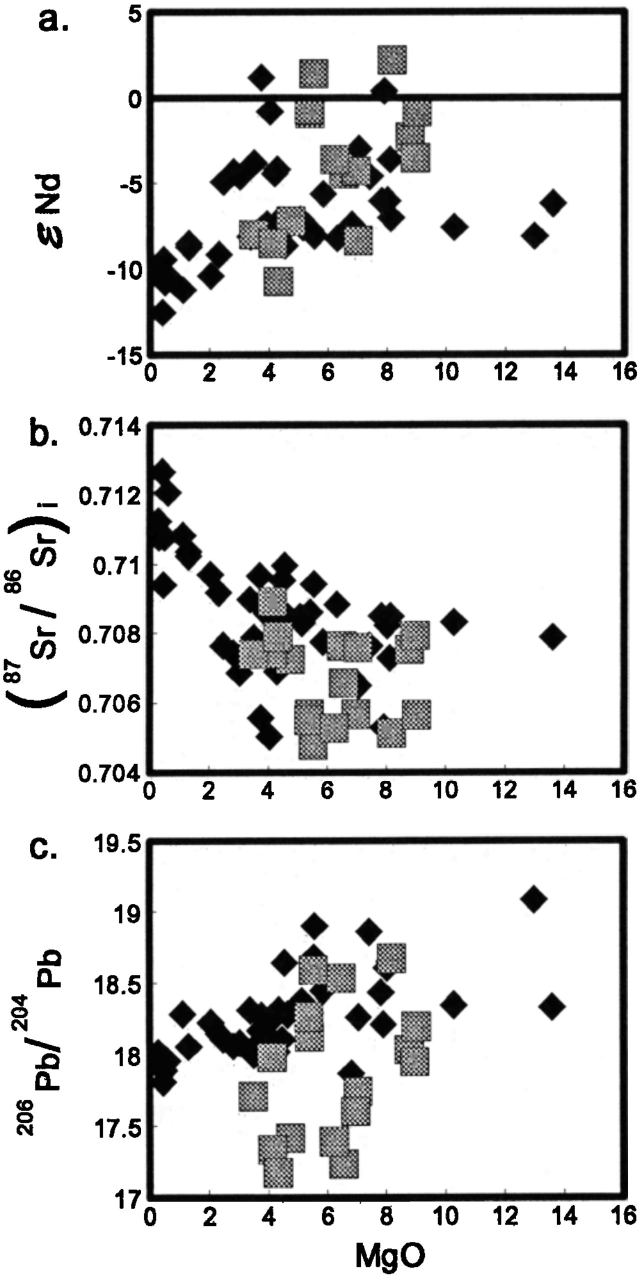

Figure 7. Plots of (a) initial epsilon Nd, (b) initial ^{87}Sr/^{86}Sr, and (c) present day ^{206}Pb/^{204}Pb against MgO for Tertiary lavas erupted in the Colorado River extensional corridor. Solid diamonds represent lavas erupted prior to 12.2 Ma, and shaded squares represent lavas erupted after 12.2 Ma. Data are from this study and those listed in Figure 1.

by *Harry et al.* [1993], and lateral pressure gradients associated with lateral variations in crustal thinning. Isostatic disequilibrium in the severely extended lithosphere may have been partially compensated for by the lateral migration of the Arizona mantle lithosphere (Figure 8).

4.2. Sources for Intermediate and Felsic Lavas

Similar to basaltic lavas, the Pb isotopic compositions of differentiated lavas change at ~12.2 Ma in the Colorado River extensional corridor. Intermediate and felsic lavas erupted after 12.2 Ma have low ^{208}Pb/^{204}Pb ratios that decrease with decreasing ^{206}Pb/^{204}Pb ratios, similar to differentiated lavas erupted within the Arizona lithosphere (Figure 3b). In contrast, intermediate to felsic lavas erupted prior to 12.2 Ma maintain high ^{208}Pb/^{204}Pb ratios as ^{206}Pb/^{204}Pb ratios decrease. The covariance of Nd, Sr, and Pb isotopic compositions with MgO concentrations (Figure 7) in the lavas erupted in both the Mojave [*Kempton et al.*, 1991; *Rogers et al.*, 1995] and Arizona provinces [*Kempton et al.*, 1991; *Wenrich et al.*, 1995] strongly suggest that assimilation of crust is involved in differentiation of these lavas and that this assimilation affects Pb isotopic ratios. The convergence of ε Nd to lower values and ^{87}Sr/^{86}Sr isotopes toward higher values in differentiated pre-12.2 Ma lavas compared to the post-12.2 Ma lavas also suggests that the compositions of crustal assimilants changed at ~12.2 Ma (Figure 7).

Crustal contamination has been documented previously in the Colorado River extensional corridor [e.g. *Smith et al.*, 1990]. On the basis of major and trace element compositions, Sr, Pb, and Nd isotopic compositions, and petrographic data, *Feuerbach et al.* [1993] suggested that late synextensional to postextensional lavas from Callville Mesa were contaminated by Mojave-like crust. However, the more complete Pb isotopic data reported here implies that the crustal contaminant for the Callville Mesa volcanics probably is Arizona and not Mojave crust. Just to the east of the Colorado River extensional corridor, in the Grand Canyon region,

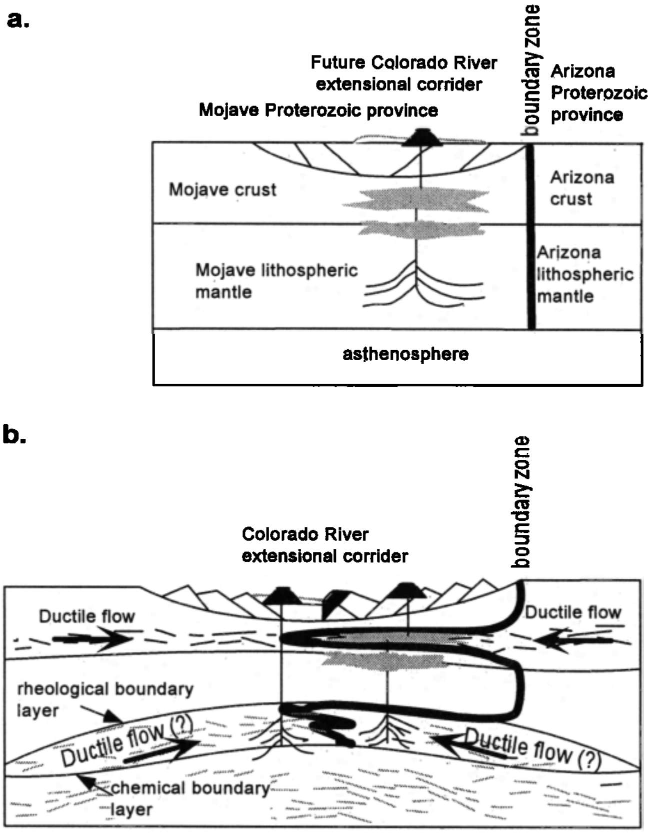

Figure 8. (a) Schematic cross section showing the presumed relationship of the Proterozoic Arizona and Mojave lithospheres before extension of the Colorado River extensional corridor. (b) The post extensional configuration of the crust and mantle in the Colorado River extensional corridor. The model shows ductile flow of crust and subcontinental lithosphere toward the corridor in response to Tertiary extension. Shaded areas on Figures 8a and 8b represent magma intruded into the crust.

Wenrich et al. [1995] documented decreasing $^{208}Pb/^{204}Pb$ ratios with increasing SiO_2 and a trend toward Arizona crustal compositions with increasing SiO_2 for Tertiary and Quaternary basalts.

The isotopic compositions of crustal assimilants within the corridor changed at ~12.2 Ma from those similar to Mojave crust to those more similar to Arizona crust. Several mechanisms may account for these changes. First, Arizona crust may have migrated westward from beneath the Colorado Plateau along an east rooted detachment system. This explanation is consistent with the well-documented system of gently east dipping Miocene detachment faults exposed in the Whipple Mountains region of the Colorado River extensional corridor [e.g., *Reynolds and Spencer*, 1985; *Howard and John*, 1987; *Davis and Lister*, 1988; *John and Foster*, 1993]. However, in the area just south of the Black Mountains accommodation zone, cumulative displacement along the east dipping normal fault system does not exceed 35-40 km across the width of the corridor [*Faulds et al.*, 1995; *Faulds*, 1995; *Shaw et al.*, 1995; J.E. Faulds unpublished data, 1997]. If these faults sole into a major detachment fault that projects beneath the Colorado Plateau, they could only account for 35-40 km of lateral translation of Arizona crust toward the west. This may account for at least a portion of the lateral translation, but it cannot explain the 60-80 km of translation indicated by the westernmost contaminated lavas within this area (see below).

Alternatively, the mid-Tertiary pre-extensional boundary between the Mojave and Arizona crusts may have dipped shallowly to the west, such that the Arizona crust projected under Mojave crust in the Colorado River extensional corridor. In this case, the change in Pb isotopic compositions for lavas within the corridor lavas could coincide with an increase in the depth of crustal assimilation. Unfortunately, we do not have sufficient data to quantitatively address this possibility. We do know that lavas containing Mojave and Arizona Pb isotopic signatures in the vicinity of the accommodation zone have similar major element compositions and abundances of phenocrystic phases, suggesting that they had similar densities and differentiated at similar depths within the crust

A third possibility is that the assimilants involved in differentiation of the lavas from the Colorado River extensional corridor were young crystallized magmas derived from the lithospheric mantle. Beginning at some time during the extensional event, the crust in the corridor may have been invaded by basalts generated in Arizona lithospheric mantle. Plutons resulting from crystallization of these magmas could have partially and progressively transformed the composition of the crust toward that of the underlying Arizona mantle (Figure 8). In this case, the entire shift in Pb isotopic compositions of all lavas, including the rhyolites, would be related to the change in mantle composition discussed above. However, this cannot be the complete explanation as it does not explain the entire shift in the Pb, Nd, and Sr isotopes with decreasing MgO contents. This is especially true for the Sr and Nd isotopic compositions, which attain values in the trachydacites and rhyolites which do not overlap with those of the basaltic rocks (Figure 5).

Our favored explanation for the change in crust composition involves both westward directed ductile flow of middle to lower crust from beneath the unextended Colorado Plateau toward the highly extended Colorado River extensional corridor and emplacement of magmas derived from changing mantle sources. This explanation is compatible with our isotopic data, seismic reflection and refraction evidence [*Flueh and Okaya*, 1989; *McCarthy et al.*, 1991; *Wilson et al.*, 1991; *McCarthy and Parsons*, 1994; *Parsons and McCarthy*, 1995; *Faulds et al.*, 1996], rheological models of extended continental crust [*Block and Royden*, 1990; *Kruse et al.*, 1991], gravity studies [*Campbell and John*, 1996], and other geologic and geophysical evidence for appreciable ductile flow within the middle to lower crust [*Wernicke*, 1992; *Anderson and Barnhard*, 1994; *Beratan and Nielson*, 1996; *Wernicke et al.*, 1996]. It is also compatible with studies suggesting that a substantial amount of mid-crustal thickening resulted from the emplacement of mantle-generated magmas in Neogene time [*McCarthy and Parsons*, 1994; *Campbell and John*, 1996].

4.3. Implications

The timing of the first appearance of Arizona Pb isotopic compositions in Miocene lavas was broadly synchronous at ~12.2-11 Ma throughout the northern Colorado River extensional corridor. However, the relative timing of changes in lithospheric Pb isotopic compositions with respect to extension varied in different portions of the corridor (Figure 9). In the southern part of the study area, where major extension occurred 23-12 Ma, lavas with Arizona $^{208}Pb/^{204}Pb$ values erupted first in latest synextensional, 12.2-Ma basalts erupted in the Dead Mountains and in postextensional, 10-Ma basaltic andesites erupted in the Lake Havasu area (Figure 9). In the vicinity of the Black Mountains accommodation zone, Arizona $^{208}Pb/^{204}Pb$ isotopic values are found in a flat-lying 11.3-Ma andesite near Dupont Mountain in the southern Eldorado Mountains and in gently tilted (5°-10°), 8.7 Ma capping basalts at Table Mountain Plateau [*Price and Faulds*, 1997] in the southern White Hills. Extension swept through this area 16-8 Ma, implying that lavas with Arizona Pb isotopic values near the accommodation zone are late synextensional (Figure 9). In the northernmost corridor, near Lake Mead, basaltic andesite lavas at Callville Mesa (10.46- 8.49 Ma) have Arizona $^{208}Pb/^{204}Pb$ ratios and are variably tilted from 60° at the base to nearly flat lying at the top [*Feuerbach et al.*, 1991]. Here the sampled lavas are tilted nearly 30°, implying that the incursion of Arizona lithosphere began during the major phase of extension. Thus Arizona crust arrived contemporaneous with the major faulting and tilting of strata in the Lake Mead region and coincidental with latest faulting and tilting in other areas of the corridor.

It is noteworthy that preextensional to synextensional volcanic rocks within the corridor were largely generated from Mojave lithospheric mantle and further contaminated by Mojave crust, whereas late synextensional to postextensional lavas were primarily generated from Arizona mantle lithosphere and contaminated by Arizona crust. This implies that the composition of lithospheric sources for magmas erupted in the northern Colorado River extensional corridor changed in association with the extensional event.

The differences in the timing of the first appearance of low $^{208}Pb/^{204}Pb$ lavas with respect to extension in various parts of the corridor may reflect the relative proximity to the crustal province boundary (Figure 7), variations in the relative velocity of ductile flow, and/or a sampling bias resulting from the restricted distribution of lavas with certain geochemical traits or ages. For example, relative to the timing of extension, the earlier onset of contamination by Arizona crust within the Lake Mead region may be due to the proximity of the crustal province boundary (Figure 7). *Bennett and DePaolo* [1987] located the Nd model-age boundary in the Gold Butte block only 30-35 km to the east northeast of Callville Mesa, which represents the best constraint on the location of the crustal boundary in the Lake Mead area. The western edge of the Pb boundary zone [*Wooden and DeWitt*, 1991] commonly lies near the Nd model-age boundary.

The tightest constraints on the arrival of Arizona crust and mantle lithosphere into the Colorado River extensional corridor

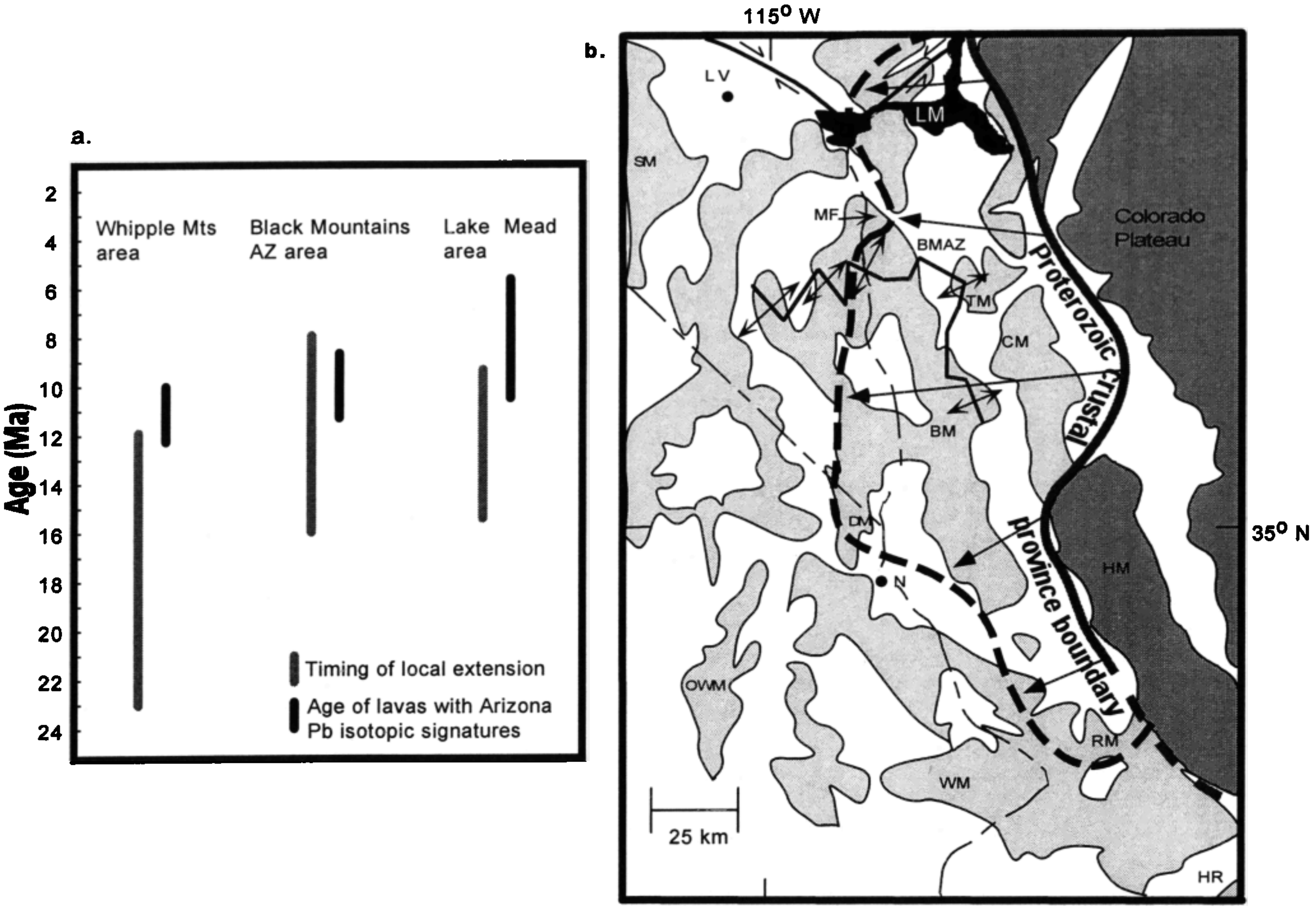

Figure 9. (a) Diagram showing timing of extension relative to age of lavas containing Arizona Pb isotopic signatures for the three regions discussed in the text. (b) Map of the Colorado River extensional corridor showing the possible extent of mid-Miocene encroachment of Arizona lithosphere. The dashed bold line indicates the westernmost extent of documented Arizona Pb isotopic signatures. Arrows schematically show the direction of possible lithospheric ductile flow. Abbreviations and map patterns are defined in Figure 1b.

come from the east-west transect of detailed sampling in the vicinity of the Black Mountains accommodation zone (Figure 9). Here the distance between the western edge of the Proterozoic Pb boundary and westernmost lava affected by Arizona crust (60-80 km), limits on the maximum cumulative displacement on major normal-fault systems (35-40 km), time constraints on Tertiary extension (16-8 Ma), and age of lavas containing an Arizona Pb isotopic signature (11.35-8.73 Ma) versus those with Mojave signatures (19-12.8 Ma) constrain the rates of lithospheric mantle and deep crustal lateral flow to between 1.1 and 1.6 cm yr^{-1}. These rates are compatible with estimated Miocene spreading rates of 1-3 cm yr^{-1} throughout the extensional corridor [e.g., Gans et al., 1992]. We therefore conclude that the influx of Arizona lithosphere into the northern part of the extensional corridor is best explained by lateral translations in the upper brittle crust through simple shear processes, accompanied by relative westward flow in the ductile middle to lower crust and mantle lithosphere (Figure 8).

It is important to note, however, that isotopic evidence for the invasion of Arizona crust into the northern Colorado River extensional corridor is not ubiquitous. Neither the 11.55-11.28-Ma lavas that cap Malpais Flattop, 25 km south of Lake Mead, nor some of the 10.6 Ma lavas erupted in the Lake Havasu region (Figure 9) have isotopic signatures characteristic of Arizona crust. The rates and extent of encroachment of Arizona crust and mantle lithosphere probably varied because of the differences in temperature and crustal structure, the original (i.e., pre-Tertiary) and modified diffuse nature of the crustal boundary, and the amount and timing of intrusion of mantle-derived magma into the crust.

The lateral translation of crust during extension has been documented elsewhere in the Basin and Range province. A study of crustally contaminated lavas erupted in the Death Valley area suggested that middle to deep crustal material may have migrated eastward from beneath the Sierra Nevada into the Death Valley region along west dipping detachment faults with >100 km of displacement [*Walker and Coleman*, 1991]. Ductile flow of middle to lower Sierra Nevada crust into the Death Valley region also can explain these observations. The latter explanation is consistent with seismic reflection data suggesting that continental crust may have flowed from beneath the Sierra Nevada toward highly extended regions of the Basin and Range province [*Wernicke et al.*, 1996].

An additional implication of the Pb isotopic data from the Colorado River extensional corridor is that severe extension and magmatism may serve to smear out lithospheric boundaries and mix the crust both horizontally and vertically such that the crust ultimately becomes more homogeneous. *Wooden and DeWitt* [1991] have suggested that the present boundary between the

Mojave and Arizona crust, as recorded in Proterozoic rocks, is a zone that contains variable amounts of both provinces. They attributed the mingling between the two provinces to plutonism and tectonism associated with the extended period of crustal formation from ~1760 to 1600 Ma. Prior to Tertiary extension this boundary zone may have become more diffuse by several tectonic events including Middle Proterozoic (1.4 Ga) magmatism, Late Proterozoic (1.1 Ga) magmatism and extension [e.g., *Hoffman*, 1989; *Hammond and Wooden*, 1990; *Wooden and DeWitt*, 1991; *Dalziel et al.*, 1994], and Mesozoic shortening and magmatism. Tertiary extension may have simply served to further homogenize the crust (Figure 9).

5. Conclusions

The Pb isotopic compositions of Miocene intermediate to silicic lavas from the Colorado River extensional corridor changed at roughly 12.2 Ma. Lavas erupted earlier than 12.2 Ma have Pb isotopic compositions similar to lavas erupted elsewhere through the Proterozoic crust of the Mojave province, whereas most lavas erupted later than 12.2 Ma have compositions similar to lavas erupted through the Arizona crustal province to the east. In both cases the ^{206}Pb/^{204}Pb ratios of the lavas decrease with decreasing MgO concentrations, suggesting that the change in Pb isotopic compositions at least partially resulted from changes in compositions of crustal assimilants. In addition, the Pb isotopic compositions of relatively primitive basalts in the corridor changed in a manner similar to that of the intermediate to silicic lavas. Both changes occurred near the end of extension in the Whipple Mountains area and in the vicinity of the Black Mountains accommodation zone but essentially contemporaneous with major extension in the northernmost part of the corridor.

The changes in basalt Pb isotopic values from Mojave to Arizona may have resulted from melting a preexisting heterogeneous mantle that contained both Mojave and Arizona compositions. Alternatively, the Arizona signature may reflect lateral migration of heated and rheologically transformed Arizona lithospheric mantle into the corridor in response to extension. Although a portion of the change in crustal composition recorded in the differentiated lavas may have resulted from intrusion and crystallization of mantle-derived melts, the rest probably resulted from ductile flow of lower crustal material from beneath the Colorado Plateau region into the Colorado River extensional corridor during major Miocene extension. This is the first isotopic evidence that supports models of middle to lower crustal ductile flow from regions of little upper crustal thinning to those that are highly extended. Our estimate of the lateral flow rate of the deep crust and subjacent mantle in this region is ~1.1-1.6 cm yr^{-1}, which is compatible with estimated rates of spreading within the corridor.

Finally, the Pb isotopic data presented here suggest that severe extension and magmatism may cause lithospheric boundaries to become less distinct as the crust is mixed both horizontally and vertically. This may partly explain the transitional nature of some Proterozoic crustal province boundaries, including that between the Mojave and Arizona provinces [*Wooden and DeWitt, 1991*], that have been affected by earlier magmatic and tectonic events.

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