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Isotopic Evidence on the Structure and Origin of Subcontinental Lithospheric Mantle in Southern Nevada

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The trace element and Nd, Sr, and Pb isotopic compositions of extension-related late Cenozoic basalts in southern Nevada were determined in order to constrain models for the tectonic evolution of the subcrustal mantle in the southern Great Basin since 10 Ma. Basalts in southern Nevada between latitudes 36°N and 37°N have low ε_{Nd} (−8 to −10), high Δ8/4 (+70 to +107) and Δ7/4 (+8 to +12), high $^{87}Sr/^{86}Sr$, and low high field strength element (HFSE) concentrations relative to other Basin and Range basalts. Basalts with these chemical and isotopic traits have erupted semicontinuously in southern Nevada since 10 Ma. During the same period of time, basalts in central Nevada and east central California have shifted toward higher ε_{Nd}, lower $^{87}Sr/^{86}Sr$, lower Δ8/4 and Δ7/4, and higher HFSE contents than observed for the southern Nevada basalts. The latter isotopic characteristics are similar to other basalts in the western United States that are interpreted to have been derived from asthenospheric mantle similar isotopically to the sources of ocean island basalts. The isotopic and chemical characteristics of the southern Nevada basalts are not attributed to asthenospheric mantle but to lithospheric mantle that has been preserved beneath this region despite late Cenozoic extension. The lack of any apparent lithospheric erosion over this time period is attributed to the fact that southern Nevada has been an "amagmatic" zone throughout the Phanerozoic. As a result, the mantle lithosphere may have been more difficult to extend and displace during extension than lithosphere beneath adjacent portions of the Basin and Range. The lack of any extensive Phanerozoic magmatism in southern Nevada also allows the possibility that the lithosphere in southern Nevada originated in the Precambrian. Compared with basalt source regions in Proterozoic lithospheric mantle in northern Arizona and New Mexico, the lithospheric sources for the southern Nevada basalts have lower ε_{Nd}, higher $^{87}Sr/^{86}Sr$, and higher Δ8/4 values. We attribute these isotopic characteristics to lithospheric mantle associated with Proterozoic crust with Nd model ages from 2.0 to 2.3 Ga (province 1), a crustal province that is restricted spatially in the southwest United States to southern Nevada and vicinity.

INTRODUCTION

The structure of the subcontinental mantle is an important parameter in any model describing the tectonic modification of the continental lithosphere. But the structure, as well as the age and composition, of the deep continental lithosphere are inherently difficult to study by direct methods. However, an increasing body of geochemical data now supports the notion that the mantle portions of ancient continental lithosphere can develop unique Sr, Nd, and Pb isotopic signatures relative to oceanic mantle [e.g., *Menzies et al.*, 1983; *McDonough et al.*, 1985; *Hart*, 1984]. Because continental basaltic magmas are in many cases generated within the mantle lithosphere, such basalts can provide a measure of the isotopic compositions of the lithospheric mantle. As a result, continental basalt isotopic data represent an indirect means to study the chemical and physical nature of the continental mantle.

The response of the continental mantle to rifting is one tectonic process particularly amenable to study by basalt isotopic data because the rifting process is often accompanied by basaltic volcanism. *Perry et al.* [1987, 1988] illustrated that it is possible to study rift-related modification of the mantle lithosphere beneath the Rio Grande rift by monitoring shifts in the chemical and isotopic compositions of basalts as rifting progressed. These shifts were interpreted to have resulted from the synrifting replacement of isotopically distinctive lithospheric mantle by upwelling asthenospheric mantle. Based on the results of these studies, it seems likely that basalt isotopic data could be applied toward studying the structure and composition of the subcrustal mantle in other regions of lithospheric extension. In this paper we follow up the studies of Perry and coworkers by combining geochemical data from late Cenozoic basalts in the southern Great Basin with aspects of the geologic evolution of the western United States to study how the lithosphere beneath southern Nevada responded to extensional tectonism during the past 10 Ma.

GENERAL APPROACH

In the lithosphere erosion model of *Perry et al.* [1987, 1988], which corresponds to pure shear models for lithospheric extension [*Buck et al.*, 1988], the region of greatest mantle lithosphere thinning is localized directly beneath the region of greatest crustal thinning. As extension proceeds, the preexisting lithospheric mantle is progressively heated, thinned, and eventually displaced by upwelling asthenospheric mantle [*Perry et al.*, 1988]. As a result, the isotopic compositions of both alkali and tholeiitic basalts that erupt within the extended crust will vary from lithosphere to asthenosphere values as a function of time (Figure 1). Alkali basalts should attain asthenospheric values earlier in the period of extension than the tholeiitic basalts because the former are generated at greater mantle depths. An assessment of the temporal and spatial patterns of basalt isotopic compositions can therefore provide a qualitative measure of

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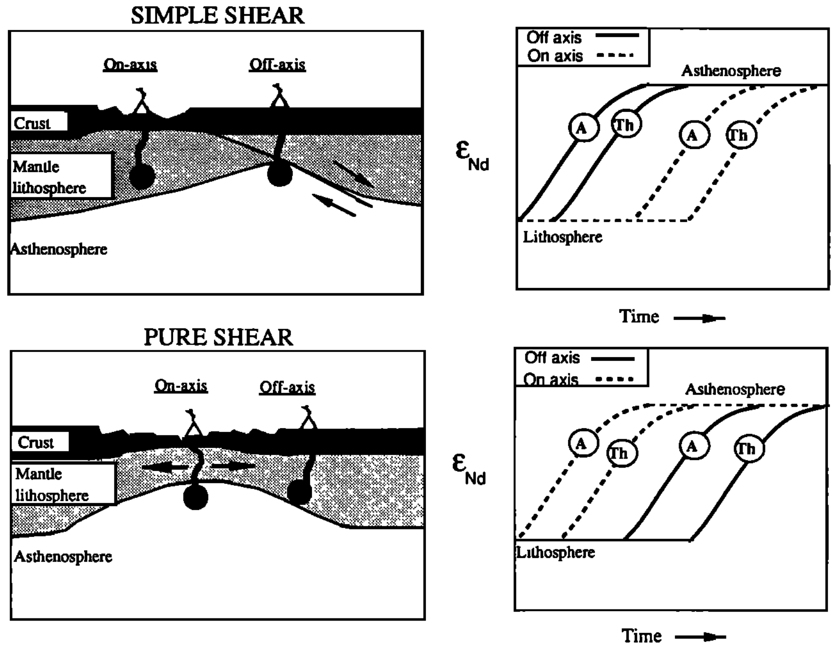

Fig. 1. Simplified model of the response of continental lithosphere to simple shear and pure shear extension and possible temporal and spatial variations in basalt isotopic compositions in each case. A, alkali basalt; Th, tholeiitic basalt.

the timing, localization, and amount of extension in regions where the continental lithosphere is being dilated.

Although not considered by *Perry et al.* [1987], the basalt isotopic compositions may also yield information regarding the mode of lithospheric extension. If extension proceeds via a simple shear, rather than a pure shear, mechanism, for example, the areas of greatest crustal and mantle lithosphere extension are no longer coincident (Figure 1) [*Buck et al.*, 1988; *Wernike*, 1981]. As a result, both alkali and tholeiitic basalts generated beneath the region of greatest crustal extension are likely to have lithospheric sources long after the initiation of extension. But basalts generated in "off-axis" positions [*Bosworth*, 1987], where the maximum mantle lithosphere thinning has occurred, are likely to tap asthenospheric sources early in the period of crustal extension.

Geologic Setting

Introduction

The basalts chosen for this study are late Tertiary and younger basalts in southern Nevada (Figure 2), particularly those basalts in the vicinity of the Nevada Test Site (NTS) for which detailed age and chemical data are available [*Vaniman et al.*, 1982; *Crowe*, 1986]. The southern Nevada basalts occupy a unique niche in the volcanotectonic evolution of the Basin and Range. As reviewed by *Stewart* [1980], *Coney* [1987], and *Wernike et al.* [1987], the portion of the Basin and Range Province between latitudes 36°N and 37°N began extension only at about 10 Ma, well after extension commenced in the remainder of the Basin and Range. For example, most of the Great Basin experienced two discrete and protracted periods of extension. The older period commenced about 36 Ma, in east central Nevada (Figure 3)

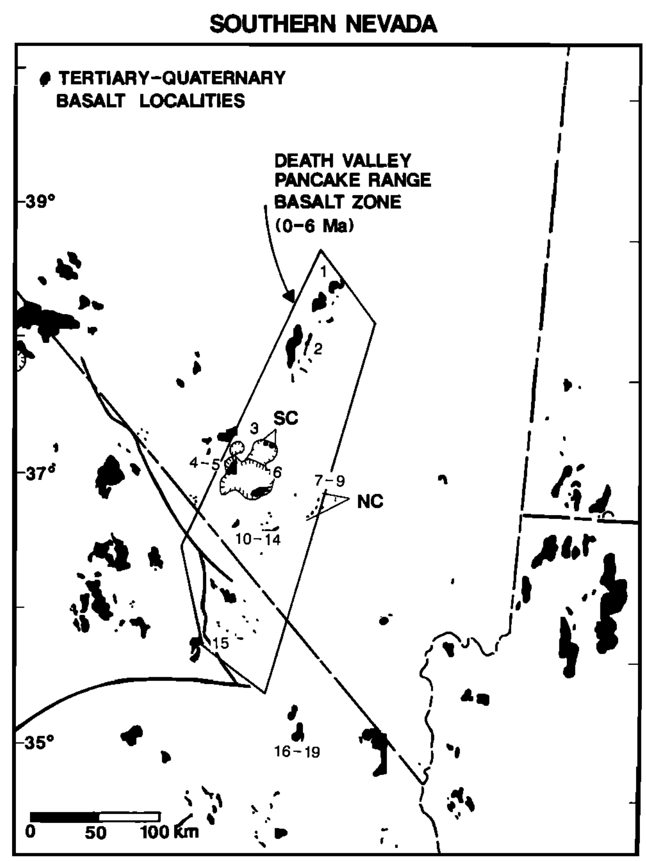

Fig. 2. Location of the Death Valley–Pancake Range (DVPR) basalt zone [*Vaniman et al.*, 1982]. Dashed line outlines the Timber Mountain/Oasis Valley calderas which mark the southern limit of Tertiary silicic volcanism in Nevada [*Snyder et al.*, 1976]. NC, Nye Canyon; SC, Silent Canyon. Numbers correspond to sample localities (Table 2).

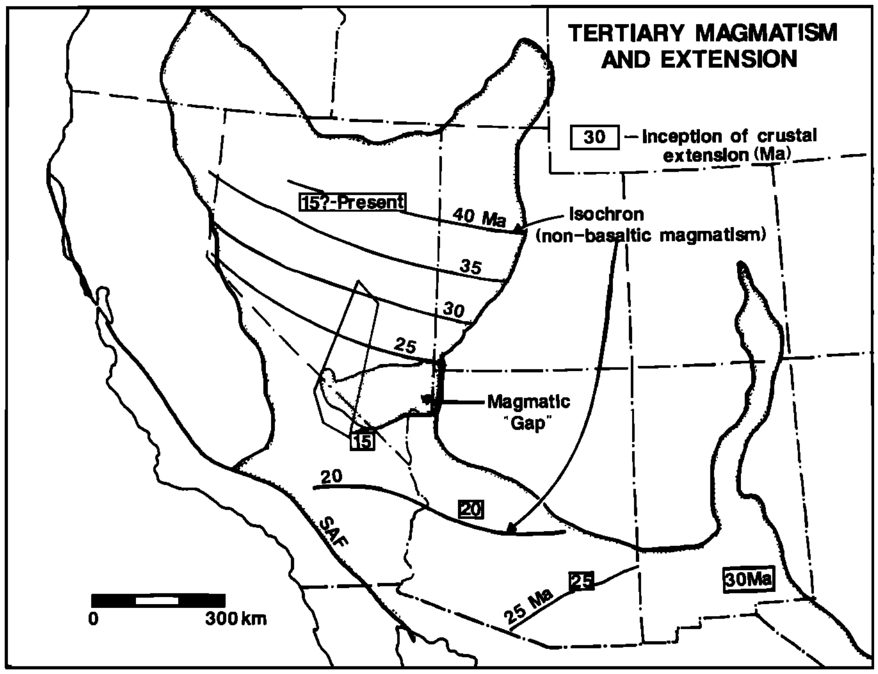

Fig. 3. Map showing extent of "amagmatic zone" in southern Nevada and vicinity [*Eaton*, 1982], and isochrons for nonbasaltic magmatism in the southern Basin and Range (in Ma) [*Glazner and Supplee*, 1982] and northern Great Basin [*Stewart*, 1980]. Boxed numbers are approximate times of inception of extensional tectonism in each region [*Glazner and Bartley*, 1984].

[*Gans and Miller*, 1983] and spread, along with associated silicic volcanism, to the west and south with time (Figure 3) [*Armstrong et al.*, 1969; *McKee*, 1971; *Snyder et al.*, 1976; *Stewart*, 1980]. Estimates of the amount of extension vary widely [*Zoback et al.*, 1981], but values as high as 250% have been proposed [*Gans and Miller*, 1983]. The younger period of extension (17 Ma to present; *Coney* [1987]) affected much of the same region that extended earlier, but magmatism associated with this younger extension has been primarily bimodal in composition [*Christiansen and Lipman*, 1972; *Best and Brimhall*, 1974]. In the southern Basin and Range, large-magnitude extension and intermediate composition magmatism also occurred between Oligocene and mid-Miocene time (35–15 Ma). A synthesis of the available data on the timing of extension and magmatism [*Glazner and Bartley*, 1984] suggests that both migrated from the southeast to northwest across the Sonoran and Mojave deserts during this time (Figure 3). In contrast to the northern Great Basin, however, volcanism and extension in the southern Basin and Range seem to have ceased after about 15 Ma, with the exception of the Rio Grande rift region [*Coney*, 1987].

The region between 36°N and 37°N in southern Nevada not only began extending much later than other portions of the Basin and Range, but also has experienced much less magmatic activity. As summarized by *Eaton* [1982] and *Wernike et al.* [1987], the corridor between 36°N and 37°N was an "amagmatic zone" throughout the Phanerozoic (Figure 3), the only magmatism occurring in conjunction with extension since 10 Ma. *Wernike et al.* [1987], in fact, have linked the lag in the time of initiation of extension in this corridor to the lack of magmatism, which resulted in lower temperatures and greater tensile strength for lithospheric mantle in this region relative to other portions of the Basin and Range. Both the relatively short period of extension and the lack of Phanerozoic magmatism in southern Nevada and vicinity favor the preservation of preextension continental mantle, a possibility that can be tested through a detailed investigation of the isotopic characteristics of basalts that erupted in this region.

Basaltic Volcanism in Southern Nevada

Basaltic volcanism has been the dominant form of igneous activity in the southern Great Basin since the cessation of silicic volcanism and concurrent with the establishment of extensional tectonism about 10 Ma ago. In general, the basaltic volcanism has migrated through time toward the margins of the southern Great Basin [*Christiansen and Lipman*, 1972; *Best and Brimhall*, 1974]. However, a discrete, semicontinuous band of Pliocene and younger basalts has been recognized that extends from southern Death Valley north-northeast through the NTS to the Pancake Range in central Nevada. This basalt zone has been termed the Death Valley–Pancake Range basalt zone (DVPR) [*Crowe et al.*, 1980]. Detailed chemical and petrographic data are available primarily for the DVPR basalts in the NTS region [*Vaniman et al.*, 1982]. Representative chemical analyses for these basalts are given in Table 1. The NTS basalts are all classified as transitional alkali-tholeiitic basalts (or "hawaiites") [*Vaniman et al.*, 1982], regardless of their age. The most primitive hawaiites (Mg/(Mg + Fe) = 0.6) straddle the transition between nepheline and hypersthene normative compositions, but with increasing fractionation the basalts trend toward either more hypersthene or more nepheline normative compositions. *Vaniman et al.* [1982] have recognized, however, a significant difference in the trace element characteristics of basalts that erupted before and after about 3.0 Ma, with the younger hawaiites having higher light rare earth element (LREE), U, Th, and Sr

TABLE 1. Selected Major and Trace Element Analyses on Basalts From the Southwestern Basin and Range Province

	Location From Figure 2								
	Southern DVPR								
	3–10 Ma				<3 Ma			Northern DVPR	CIMA Domes
	12	14	8	3	10	13	4	1	18
Sample	CF12610	TS9221	TS61474	TS6152	FB785	CF1171	SB9213	PR71231V	PB-34*
SiO_2	49.60	52.30	48.00	49.20	51.20	49.00	49.80	48.56	48.05
TiO_2	1.60	1.70	2.00	2.50	1.50	1.80	1.70	1.94	3.11
Al_2O_3	15.60	17.00	16.30	16.20	17.20	16.80	16.90	15.27	16.02
FeO	10.80	9.17	9.35	12.10	9.94	10.90	10.10	11.62	10.83
MnO	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.18	0.17
MgO	7.13	4.60	9.75	5.45	5.22	5.96	5.51	7.26	5.74
CaO	9.84	8.21	9.36	8.74	8.73	8.89	9.32	8.46	8.56
Na_2O	3.00	3.80	3.40	3.50	3.40	3.50	3.60	3.55	4.11
K_2O	1.60	2.20	1.10	1.50	1.60	1.80	1.70	1.17	1.81
P_2O_3	0.60	0.80	0.50	0.70	1.10	1.10	1.10	0.43	0.62
Total	99.97	99.98	99.96	100.09	100.09	99.95	99.93	98.44	99.02
Cs	0.7	0.4	1.3	0.2	2.0	1.5	1.6	···	···
Rb	65	31	···	20	20	19	28	···	39
Ba	780	1515	413	759	1140	1330	1404	···	···
Sr	840	815	600	683	1200	1380	1544	···	683
Th	6.2	5.2	3.6	3.4	10.0	6.7	11.2	···	···
U	1.2	1.2	0.8	0.8	3.4	2.2	2.7	···	···
Hf	6.2	8.9	3.9	6.3	8.5	8.0	7.9	···	···
Sc	29	19	27	20	22	19	18	···	···
La	72	83	28	41	137	92	111	···	···
Ce	132	162	71	118	192	181	···	···	···
Sm	8.3	10.4	5.4	7.9	9.6	7.1	12.3	···	···
Eu	2.40	2.66	1.73	2.66	3.60	3.00	3.19	···	···
Tb	1.90	1.15	0.91	1.16	1.50	2.00	1.50	···	···
Yb	3.60	3.11	2.11	3.16	3.20	3.40	2.29	···	···
Lu	0.75	0.32	0.33	0.34	0.97	0.54	0.30	···	···

Trace element determinations by INAA.
*Data from *Breslin* [1982].

contents, and lower U/Th ratios (Figure 4), than the older (10–3 Ma) basalts. As noted by *Vaniman et al.* [1982], the overall enrichment in alkali and alkali earth elements in the younger basalts does not include Rb, resulting in extremely low Rb/Sr ratios in the younger basalts (Table 1).

The low Rb/Sr ratios of the younger basalts are in marked contrast to their high $^{87}Sr/^{86}Sr$ ratios (~0.706), a feature also

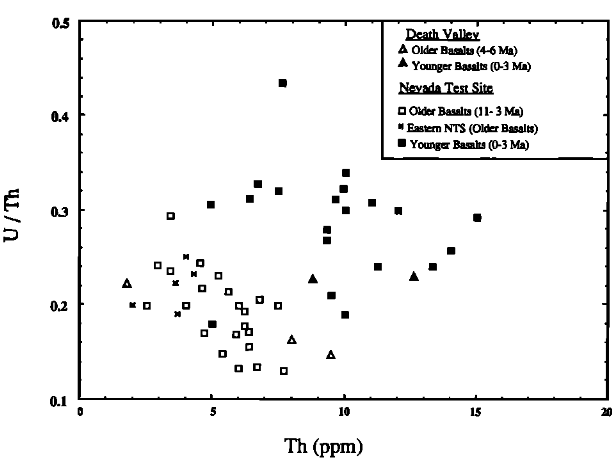

Fig. 4. U/Th concentration ratios versus Th concentrations (ppm) for Late Cenozoic basalts in the southern DVPR. Data from this study and *Crowe et al.* [1986]. Note that younger (<3.0 Ma) basalts clearly have higher Th contents and higher U/Th ratios than older (3–10 Ma) basalts.

characteristic of the older NTS basalt and for many other late Cenozoic basalts in the southwesternmost Great Basin [*Leeman*, 1982]. The origin of these high $^{87}Sr/^{86}Sr$ ratios is enigmatic. Most workers have discounted the possibility that the radiogenic Sr isotopic compositions are the result of crustal contamination, citing the homogeneous $^{87}Sr/^{86}Sr$ ratios, and the high Sr concentrations of many of the basalts [*Hedge and Noble*, 1971; *Menzies et al.*, 1983]. Instead, the basalts are generally interpreted to have been derived from a high $^{87}Sr/^{86}Sr$ mantle source, with a time-integrated high Rb/Sr ratio relative to typical oceanic mantle. But in this case, the mantle source still must have been relatively depleted in Rb relative to Sr at the time of basalt generation in order to account for the low basalt Rb contents [*Vaniman et al.*, 1982].

SAMPLES

Although some Sr [*Leeman*, 1970; *Hedge and Noble*, 1971], Pb [*Everson*, 1979], and Nd [*Menzies et al.*, 1983] isotopic data exist for basalts in southern Nevada, no systematic attempt has been made to integrate isotopic and trace element data with the temporal and spatial distribution of basaltic volcanism to study the response of the continental lithosphere to extension in this region. For this purpose, Sr, Nd, and Pb isotopic data and trace element compositions were determined for a suite of basalts from the DVPR zone. Twenty samples of alkali basalts from the DVPR zone, ranging from 10.5 to 0.3 Ma in age, were analyzed by

TABLE 2. Sample Descriptions

Map	Sample	Latitude/Longitude of Occurrence	Locality	Description (With Phenocryst Phases)
1	PR7-12-31V	38°38′, 116°4′ lava pond	older basalt of Basalt Butte, Sand Springs Valley, Nye County, Nev.	olivine hawaiite
2	RE10-2-53V	38°5′, 116°7′ dike in cone	small cone remnant, western Railroad Valley, Nye County, Nev.	olivine hawaiite
3	TS6-15-2	37°22′, 116°22′ lava flow	eastern center, Silent Canyon, Nevada Test Site, Nye County, Nev.	ol-cpx-plag hawaiite
4	SB9-21-3	37°9′, 116°44′ lava flow	young eastern cone, near Sleeping Butte, Nye County, Nev.	
5	NE5-20-5	37°5′, 116°37′ lava flow	flow west of Rocket Wash, Nye County, Nev.	olivine alkali basalt
6	TS6-13-6	37°5′, 116°20′ lava flow	dominant lava type, south Buckboard Mesa, Nevada Test Site, Nye County, Nev.	hawaiite
7	TS9-19-20FP	37°5′, 115°57′ lava flow	flow atop mesa at Paiute Ridge, Nevada Test Site, Nye County, Nev.	hawaiite
8	TS6-14-7A	36°56′, 115°51′ lava pond	central Nye Canyon maar volcano, Lincoln County, Nev.	olivine alkali basalt with gabrro xenoliths
9	TS6-14-12DV	36°53′, 115°53′ dike in cone	southern Nye Canyon volcanic center, Lincoln County, Nev.	olivine alkali basalt
10	FB78-5	36°47′, 116°35′ lava flow	Black Cone volcanic center, Crater Flat, Nye County, Nev.	hawaiite
11	CF1-8-3	36°43′, 116°35′ lava flow	older southwestern flow, Crater Flat, Nye County, Nev.	hawaiite
12	CF12-6-10	36°47′, 116°33′ lava flow	flows on east side of Crater Flat, Nye County, Nev.	ol-cpx-plag hawaiite (glomerophyric)
13	CF11-7-1	36°41′, 116°30′ lava flow	Lathrop Wells cone, south of Crater Flat, Nye County, Nev.	hawaiite
14	TS9-22-1	36°47′, 116°19′ lava	Cuesta in Jackass Flat, Nevada Test Site, Nye County, Nev.	hawaiite
15	DV3-30-23V	35°56′, 116°44″ bomb	Cinder Hill volcano, Death Valley National Monument, Inyo County, Calif.	ol-am hawaiite
16	CIM8142	35°14′, 115°43′ lava flow	flow C12-1, southeastern Cima Dome volcanic field, San Bernardino County, Calif.	ol-plag-cpx alkali basalt
17	CIM8143	35°12′, 115°52′ lava flow	flow C20-1, southwestern Cima Dome volcanic field, Calif.	ol-plag-cpx alkali basalt
18	PB34	35°10′, 115°52′ lava flow	flow C20-1, southwestern Cima Dome volcanic field, Calif.	ol-plag-cpx alkali basalt
19	ODC16-11	35°11′, 115°43′ inclusion in tephra	crater of cone 16, southern Cima Dome volcanic field, San Bernardino County, Calif.	cumulate gabbro xenolith in alkali basalt

From *Semken* [1984]. Ages and flow and cone numbers for maps 16–19 from *Katz and Boettcher* [1980] and *Katz* [1981]. Field data on sample 18 are from *Breslin* [1982] and on sample 19 are from A. Boettcher (personal communication, 1982).

Semken [1984]. Pb isotopic analyses were obtained for nine of these basalts at the Los Alamos National Laboratory. The basalts sample localities (Figure 2) span the entire length of the DVPR from north of the Reveille Range in central Nevada to Death Valley. Several samples of Recent age alkali basalts from the Cima Domes in southeastern California [*Breslin*, 1982] were also analyzed. Most of the samples, however, were obtained from the NTS area in southern Nevada. Five samples of the younger (<3.0 Ma) trace element enriched hawaiites and seven samples of the older basalts, including the easternmost DVPR basalts at Nye Canyon (Figure 2), were analyzed. Detailed sample descriptions are given in Table 2. Major and trace element data for many these samples are given in Table 1 [*Crowe et al.*, 1986].

All the isotopic measurements were obtained from fresh whole rock samples powdered in a tungsten carbide shatter box. The procedures for the Rb, Sr, Sm, and Nd separations and the Nd and Sr isotopic measurements were identical to those described by *DePaolo* [1981]. The Nd and Sr measurements were corrected for mass fractionation by normalization to $^{146}Nd/^{142}Nd = 0.63615$ and $^{86}Sr/^{88}Sr = 0.1194$. The ε_{Nd} and ε_{Sr} will refer to initial isotopic compositions, normalized to a model chrondritic reservoir (CHUR) for Nd, and to a model whole earth reservoir (UR) for Sr. The Pb isotopic measurements were conducted using the standard Si-gel technqiue. Ten replicate measurements of a Pb isotopic standard (NBS 981) yielded the following results: $^{206}Pb/^{204}Pb = 16.966 \pm 0.037$ (2σ external reproducibility), $^{207}Pb/^{204}Pb = 15.534 \pm 0.40$, and $^{208}Pb/^{204}Pb = 36.817 \pm 0.096$.

RESULTS

The Nd, Sr, and Pb isotopic data are reported in Tables 3 and 4 and depicted graphically in Figures 5–6. The instrumental neutron activation analysis (INAA) trace element data are given in Table 1, and isotope dilution data for Rb, Sr, Sm, and Nd are reported in Table 3. The basalt ε_{Nd} values range from $+10.1$ to -10.2 and vary regularly with

TABLE 3. Sr and Nd Isotopic Ratios and Trace Element Concentrations of Basalts From the Southwestern Basin and Range Province, Measured in This Study

Sample	Map	Age, Ma	Rb	Sr	($^{87}Sr/^{86}Sr$)	ε_{Sr}	±2σ	Sm	Nd	($^{143}Nd/^{144}Nd$)	ε_{Nd}	±2σ
					Northern DV-PR							
PR7-12-31V	1	10.2	24.6	443	0.70349	−14.31	0.50	6.06	27.8	0.512074	+4.66	0.44
RE10-2-53V	2	4–6	48.9	626	0.70356	−13.31	0.44	8.25	55.2	0.512060	+4.38	0.46
					Southern DV-PR							
TS6-15-2	3	8.8	26.3	694	0.70671	+31.30	0.38	8.52	43.5	0.511772	−1.26	0.44
SB9-21-3	4	0.3	20.2	1404	0.70698	+35.26	0.46	12.3	80.3	0.511404	−8.43	0.58
NE5-20-5	5	<7.5	22.5	849	0.70709	+36.76	0.50	7.09	42.9	0.511437	−7.80	0.46
TS6-13-6	6	2.7	34.7	1325	0.70690	+34.04	0.62	9.40	68.4	0.511313	−10.22	0.50
FB785	10	1.1	22.0	1297	0.70701	+35.56	0.34	12.0	78.1	0.511374	−9.02	0.34
CF1-8-3	11	10.5	20.4	1032	0.70725	+39.07	0.44	8.24	47.0	0.511454	−7.47	0.36
CF12-6-10	12	3.7	26.1	878	0.70747	+42.21	0.52	11.9	53.0	0.511303	−10.41	0.60
CF11-7-1	13	0.3	19.9	1444	0.70704	+36.08	0.30	12.3	77.2	0.511372	−9.06	0.54
TS9-22-1	14	10	32.1	805	0.70720	+38.26	0.50	8.75	64.6	0.511396	−8.61	0.34
DV3-30-23V	15	0.7	28.8	1238	0.70695	+34.84	0.76	11.3	70.8	0.511395	−8.61	0.58
					Nye Canyon							
TS9-19-20FP	7	8.7	30.3	560	0.70394	−7.94	0.44	6.55	31.9	0.512024	+3.67	0.52
TS6-14-7A	8	7	9.14	595	0.70387	−8.97	0.40	···	24.6	0.511949	+2.20	0.44
TS6-14-12DV	9	7	14.9	513	0.70471	+2.91	0.54	4.26	18.6	0.512025	+3.69	0.50
					Cima Domes							
CIM-8142	16	<1.0	36.8	576	0.70294	−22.13	0.56	7.14	32.1	0.512351	+10.06	0.30
CIM-8143	17	0.04	40.3	622	0.70298	−21.57	0.36	7.51	36.5	0.512303	+9.12	0.50
PB-34	18	···	40.2	644	0.70303	−20.88	0.42	7.60	36.0	0.512297	+9.00	0.42
OD-C16.11	19	···	2.02	189	0.70370	−11.42	0.44	0.87	2.28	0.512317	+9.40	0.44

Trace element concentrations are in ppm.

geographic position (Figure 5*a*). Specifically, the ε_{Nd} values of the DVPR basalts become progressively lower from north to south, from values of about +4.7 in the northernmost DVPR, to values to the south of +3.7 to −10.4. The majority of the samples from the NTS have ε_{Nd} less than −7, regardless of their age or the degree of LREE enrichment. Samples with higher ε_{Nd} values are restricted to the older basalts at Nye Canyon (ε_{Nd} = 2.2–3.7) and to an older basalt within the Silent Canyon caldera in the north central DVPR (sample TS6-15-2, location 3; Figure 2). At Cima Domes the three basalt samples and one cumulative gabbro xenolith all have extremely high and uniform ε_{Nd} values ranging from +9.0 to +10.1.

The basalt $^{87}Sr/^{86}Sr$ ratios covary with the Nd isotopic compositions, with the lowest $^{87}Sr/^{86}Sr$ values (0.703) being associated with the Cima Domes basalts and the highest associated with the hawaiites in the southern half of the DVPR (0.7070–0.7075; Figure 5*b*). Among the southern DVPR basalts there is no correlation between $^{87}Sr/^{86}Sr$ and Rb/Sr or Sr concentration, despite the fact that the younger (<3.0 Ma) basalts have considerably higher Sr contents than the older basalts (Table 1) [*Vaniman et al.*, 1982]. Basalts with ε_{Nd} values intermediate between the extreme values of the Cima Domes and southern DVPR basalts, at Nye Canyon and the northern DVPR, also have intermediate $^{87}Sr/^{86}Sr$ values (0.7035–0.7047). The basalt at Silent Canyon, on the other hand, has a very high $^{87}Sr/^{86}Sr$ value (0.7067) despite having a high ε_{Nd} value (−1.3).

Pb isotopic data were obtained only from basalts in the NTS region. Most of the analyzed basalts plot within a

TABLE 4. Pb Isotopic Ratio and Trace Element Concentrations of Basalts From the Southwestern Basin and Range Province Measured in This Study

Sample	Map	Pb	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Δ7/4*	Δ8/4
TS6-15-2	3	3.82	19.172	15.638	38.995	6.9	18.9
			0.029	0.027	0.063		
NE5-20-5	5	4.52	18.265	15.556	38.776	8.5	107
			0.030	0.029	0.084		
TS6-13-6	6	14.1	18.021	15.558	38.205	11.4	79.6
			0.023	0.027	0.048		
TS6-14-7A	8	2.89	18.491	15.599	38.258	10.4	27.5
			0.031	0.033	0.094		
TS6-14-12DV	9	1.02	18.426	15.572	38.621	8.4	71.6
			0.045	0.046	0.11		
FB785	10	14.9	18.515	15.599	38.752	10.2	73.8
			0.031	0.034	0.074		
CF12-6-10	12	10.9	18.539	15.610	38.914	10.9	86.9
			0.031	0.028	0.099		
TS9-22-1	14	10.0	18.359	15.598	38.737	11.7	91.7
			0.037	0.041	0.096		

Trace element concentrations are in ppm. Errors reported on isotopic ratios are 2σ.
*Δ values are defined according to *Hart* [1984].

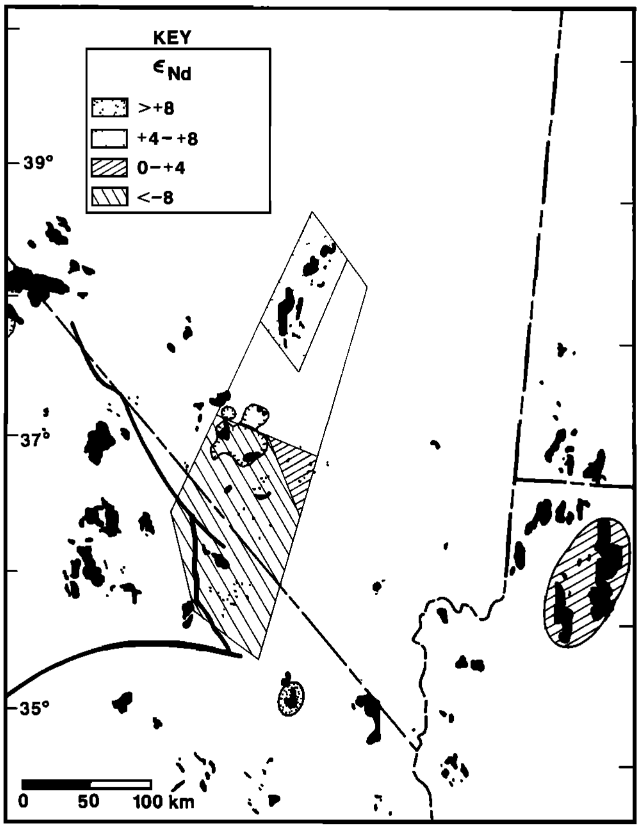

Fig. 5a

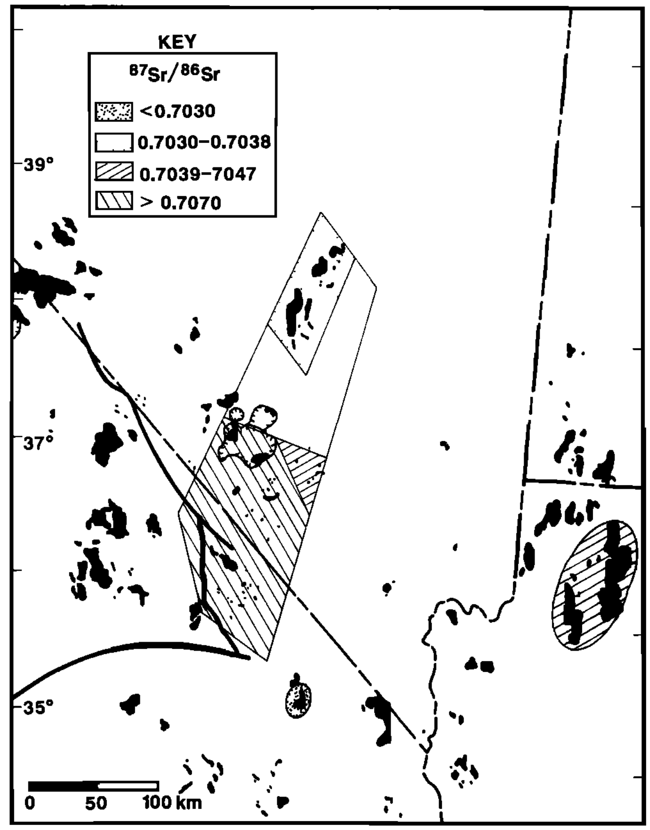

Fig. 5b

Fig. 5. Distributions of basalt (*a*) ε_{Nd}, (*b*) $^{87}Sr/^{86}Sr$, and (*c*) $^{206}Pb/^{204}Pb$ in the DVPR and vicinity. Data compiled from *Everson* [1979], *Alibert et al.* [1986], and this study.

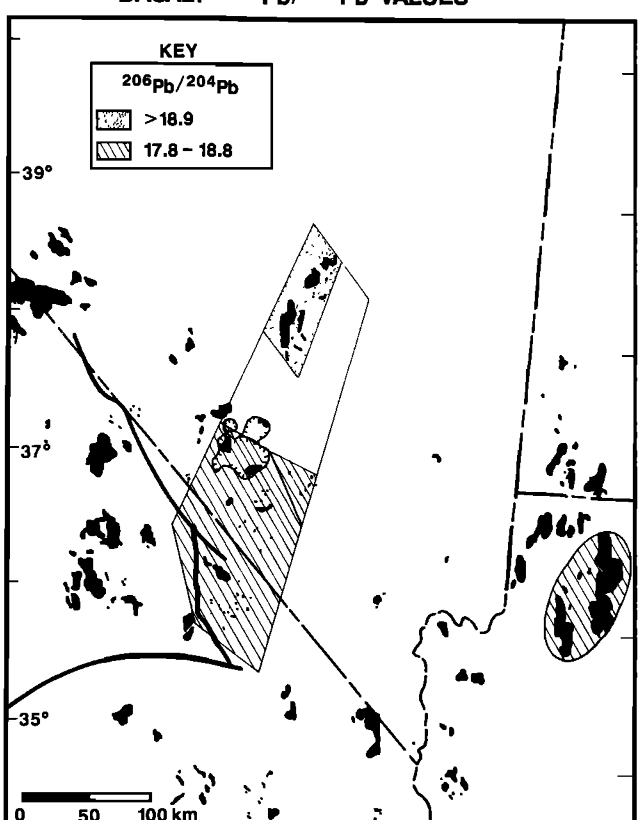

Fig. 5c

narrow range of $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$ values to the right of the geochron and above the "northern hemisphere reference line" (NHRL) [*Hart*, 1984] (Figures 5*c* and 6*a*–6*b*). These results are consistent with previous unpublished Pb isotopic studies of basalts in this region [*Everson*, 1979]. The narrow range of Pb isotopic compositions precludes any attempt to construct secondary Pb isochrons from the data. The two Nye Canyon samples analyzed have $^{206}Pb/^{204}Pb$ ratios similar to the other southern DVPR basalts (Figure 5*c*) but lower Δ8/4 values (+72 and +28 versus +107 to +74, with the Δ values defined according to *Hart* [1984]; Table 4). The Silent Canyon basalt has a significantly higher $^{206}Pb/^{204}Pb$ than any other basalt in the southern DVPR, and lower Δ7/4 (+7) and Δ8/4 (+19) values than any of the other analyzed samples.

INTERPRETATION

The combined Nd, Sr, and Pb isotopic data reveal that basalts from the northern and southern DVPR comprise two separate isotopic populations. The northern DVPR basalts were derived from a mantle reservoir with high ε_{Nd}, low $^{87}Sr/^{86}Sr$, and relatively high $^{206}Pb/^{204}Pb$ values. Basin and Range basalts at the Geronimo volcanic field and in the central and southern Rio Grande rift have similar isotopic compositions [*Menzies et al.*, 1983; *Crowley*, 1984; *Perry et al.*, 1987, 1988]. All have been interpreted to have been derived from upwelling asthenospheric mantle. This mantle has isotopic characteristics similar to ocean island (intraplate) basalts (OIB) [*White*, 1985]. A similar OIB-like asth-

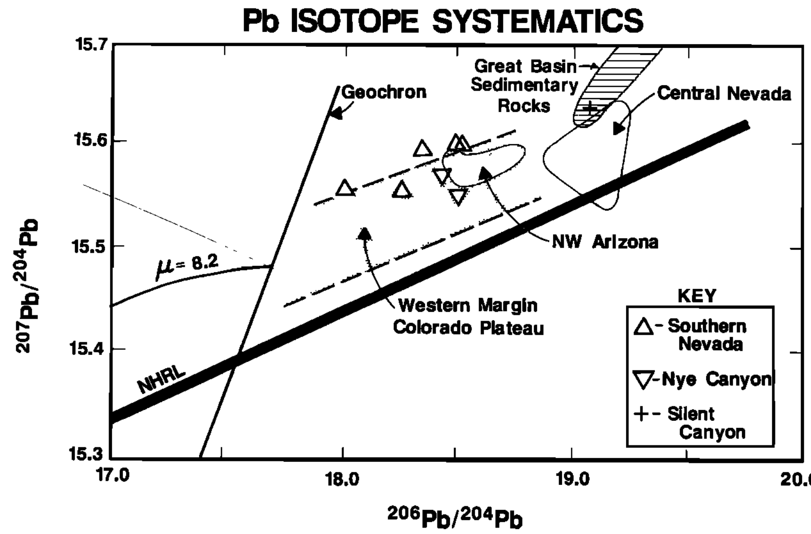

Fig. 6*a*. The $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ plot for DVPR and other western U.S. basalts. [from *Everson*, 1979; *Alibert et al.*, 1986; and this paper]. Great Basin sedimentary rocks values estimated by *Zartman* [1974]. NHRL is northern hemisphere reference line [*Hart*, 1984].

enospheric source for the northern DVPR basalts would be consistent not only with their isotopic compositions, but also with their trace element concentrations [*Lum et al.*, this issue] and with the Bouguer gravity anomalies which suggest that asthenospheric mantle is currently upwelling to shallow depths in this region [*Eaton et al.*, 1978].

It is important to emphasize, however, that our limited data set does not allow a discrimination to be made between an asthenosphere source, and a "young" lithospheric mantle source for these basalts. For example, the northern DVPR may not be underlain by Precambrian basement but by Phanerozoic accreted terranes (Figure 9). Mantle lithosphere originally underlying these terranes could have isotopic signatures similar to the DVPR basalts. Or the source of the DVPR could be lithospheric mantle that had "frozen-in" beneath this portion of the continent after mid-Tertiary extension and magmatism. Again this mantle could have isotopic characteristics very similar to modern day OIB mantle. However, more extensive isotopic data sets from these late Cenozoic basalts obtained by other workers reveal a shift since 10 Ma toward even higher ε_{Nd} and lower $^{87}Sr/^{86}Sr$ values, which suggests that some of the youngest basalts in the northern DVPR could have been derived from currently upwelling asthenosphere [*Foland et al.*, 1988].

On the other hand, most of the analyzed basalts from the southern DVPR, including those from eastern Death Valley and much of the NTS and vicinity, have exceptionally low ε_{Nd}, high $^{87}Sr/^{86}Sr$, and large Δ8/4 and Δ7/4 values, as expected from previous basalt isotopic studies in this region [*Leeman*, 1982; *Menzies et al.*, 1983; *Everson*, 1979]. These basalts were clearly not derived from the same mantle source as the northern DVPR basalts or many other Basin and Range basalts. The basalt isotopic compositions have also remained remarkably uniform since 10 Ma. In particular, there is no obvious difference in the isotopic characteristics of the older (<3 Ma) and younger basalts, despite the fact that the latter are significantly enriched in many trace elements relative to the older basalts.

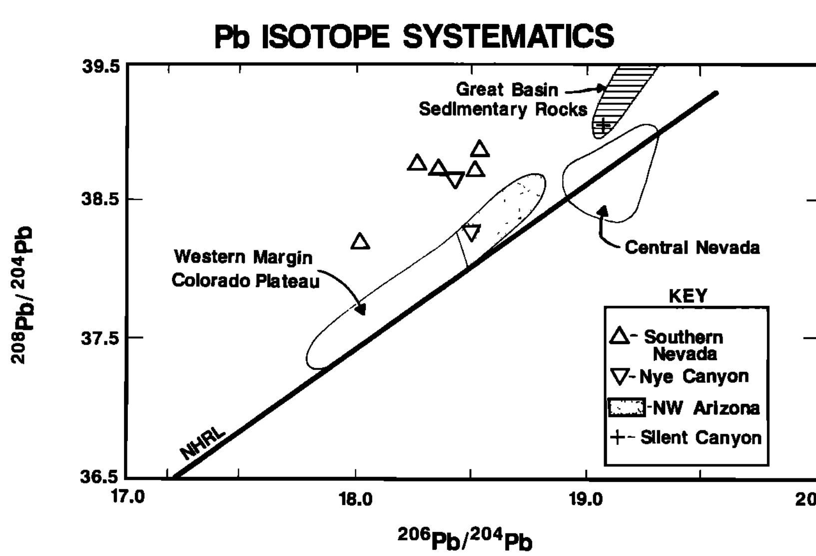

Fig. 6*b*. The $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ plot. Snake River plain basalt data from *Doe et al.* [1982].

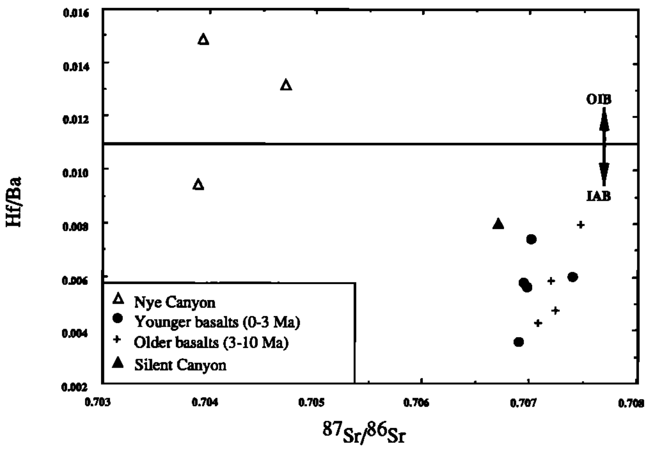

Fig. 7. Hf/Ba concentration ratio versus $^{87}Sr/^{86}Sr$ for southern DVPR basalts. Cutoff Hf/Ba value between ocean island basalts (OIB) and island arc basalts (IAB) estimated from *Pearce* [1982].

One possible explanation for the southern DVPR isotopic characteristics is that these basalts have simply undergone a greater amount of crustal contamination than other Basin and Range basalts. To counter this argument, many previous workers have cited the high basalt LREE and Sr contents which would require large amounts of crustal interaction if the basalts were derived, for example, from an asthenospheric source similar to those in the northern DVPR [*Vaniman et al.*, 1982; *Menzies et al.*, 1983]. But more recently the suggestion has been made that large amounts of crustal assimilation are not required if selective [*Watson*, 1982], and not bulk, assimilation has taken place [*Bacon et al.*, 1984]. We would like to reemphasize, however, the extremely uniform Nd, Sr, and Pb isotopic composition for basalts in southern Nevada since 10 Ma, which would not be expected if the basalts represented mixtures of mantle-derived magma and bulk, or selectively assimilated crust [cf. *Carlson et al.*, 1981; *Perry et al.*, 1987]. Our preferred interpretation of the southern DVPR isotopic data is that they accurately reflect the isotopic compositions of the mantle source of the southern DVPR basalts. And given that the basalt isotopic characteristics are unlike those of asth- enosphere-derived magmas, the simplest alternative source is lithospheric mantle, as concluded by earlier studies [*Menzies et al.*, 1983].

Ormerod et al. [1988] have shown that lithosphere- and asthenosphere-derived basalts in the southwestern Great Basin also can be discriminated on the basis of their trace element compositions, with the former being depleted in high field strength elements (HFSE) relative to the latter. Because our data set does not include Zr analyses, we cannot attempt to discriminate between asthenosphere- and lithosphere-derived magmas on the basis of Zr/Ba ratios as done by *Ormerod et al.* [1988]; hereafter referred to as OD (1988). But similar results are obtained using Hf/Ba ratios. As shown in Figure 7, all southern DVPR basalts with $^{87}Sr/^{86}Sr$ ratios greater than 0.706 have low Hf/Ba ratios (<0.01) relative to OIBs but values similar to island arc basalts [*Pearce*, 1982]. Following OD (1988), we consider the low Hf/Ba ratios to be diagnostic of the lithosphere-derived basalts. On this basis therefore even the trace element enriched younger (<3.0 Ma) basalts are lithosphere derived, because both the younger and older southern DVPR basalts have similar Hf/Ba ratios. This observation can also be extended to many other basalts from the southern DVPR for which trace element, but not isotopic, data are available [*Crowe et al.*, 1986]. Virtually all the southern DVPR basalts, including basalts from the NTS region and both younger (<3.0 Ma) and older (4.6 Ma) basalts in Death Valley, have low Hf/Ba ratios and can be interpreted to have been derived from lithosphere mantle (Figure 8).

The primary exception to the rule of high $^{87}Sr/^{86}Sr$, low ε_{Nd}, high $\Delta 7/4$ and $\Delta 8/4$ values, and low Hf/Ba ratios for southern DVPR basalts are the older basalts from the east central DVPR at Nye Canyon and vicinity. In general, the ε_{Nd} and $^{87}Sr/^{86}Sr$ values, but not the $^{206}Pb/^{204}Pb$ ratios, are intermediate between the values for asthenosphere-derived basalts from the northern DVPR and values for the bulk of the lithosphere-derived southern DVPR basalts (Figures 6*a*–6*b*). The Nye Canyon basalts also have the highest Hf/Ba ratios of any of the analyzed basalts (Figure 7). These data suggest that the Nye Canyon basalts could have derived from a mixture of lithosphere and asthenophere sources, unlike the remainder of the southern DVPR basalts. However, the Nd, Sr, and Pb isotopic characteristics of the Nye Canyon basalts, particularly for the central Nye Canyon sample (location 8; Figure 2), are identical to values for late Cenozoic basalts in the western Grand Canyon [*Alibert et al.*, 1986]. The latter basalts have been interpreted to have been derived from ancient (>1.7 Ga) mantle lithosphere, and so it is possible that the Nye Canyon basalts, the easternmost of all the analyzed samples, were derived largely from this same mantle lithosphere source. In this case, two isotopically distinct mantle sources for the southern DVPR basalts would have to exist, one corresponding to the source of the majority of the southern DVPR basalts and the other corresponding to the source of the Nye Canyon basalts.

The Silent Canyon basalt also has different isotopic characteristics than other southern DVPR basalts, but these isotopic characteristics do not match the Nye Canyon values and are not consistent with a simple mixed lithosphere and asthenosphere source. The radiogenic Pb isotopic compositions and high $^{87}Sr/^{86}Sr$ (for a basalt with $\varepsilon_{Nd} = -1.3$) suggest that the isotopic compositions have been affected by crustal contamination, possibly from the miogeoclinal sedimentary rocks through which the basalts intruded (Figures 6*a*–6*b*). However, this basalt does not have significantly different trace element characteristics than the other southern DVPR basalts (Figure 7), as might be expected if it had undergone significantly greater crustal interaction than the other basalts. We cannot yet account for the isotopic char-

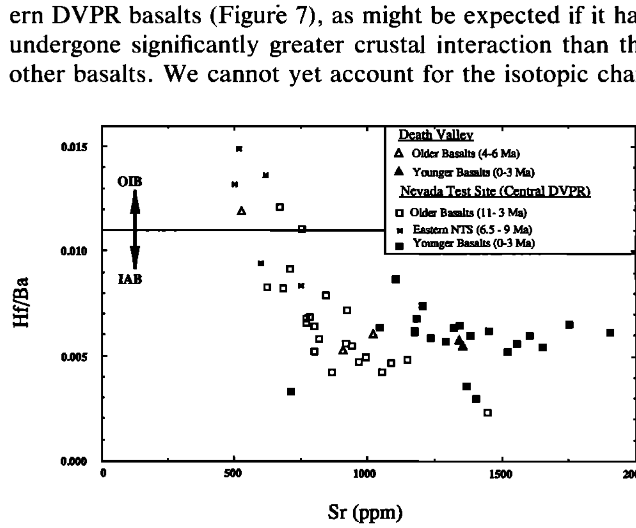

Fig. 8. Hf/Ba concentration ratio versus Sr contents for southern DVPR basalts. Data from this study and *Crowe et al.* [1986].

acteristics of this sample, but studies currently under way (G. L. Farmer and D. Broxton, manuscript in preparation, 1989) of other basalts associated with the older silicic volcanism in the NTS region may shed light on the origin of the Silent Canyon basalt.

The Cima Domes samples have the highest ε_{Nd} (+9.0 to +10.0) and lowest $^{87}Sr/^{86}Sr$ ratios (0.7029–0.7037) of any of the analyzed basalts. Although no trace element data are available for these samples, it is still reasonable to conclude that these samples were derived exclusively from a mantle source with isotopic compositions similar to modern day asthenospheric mantle. There is no evidence that the basalts incorporated any component from mantle lithosphere similar to that tapped by the southern DVPR basalts.

Application to Tectonic Models

The interpretations outlined above favor the possibility that lithospheric mantle has been preserved beneath the southern DVPR during the past 10 Ma of extensional tectonism. In contrast, basalts in the northern DVPR apparently record the progressive displacement of preextension lithosphere by upwelling asthenosphere mantle over the same time interval. Trace element and isotopic data reported by OD (1988) for late Cenozoic basalts in southeastern California, directly west of the DVPR, also record a progressive transition from lithosphere to asthenosphere sources. An important question arises, then, as to how lithosphere could have been preserved beneath the southern DVPR but not in regions directly to the north and west.

One possible explanation may lie in processes occurring beneath the continental lithosphere during this time. OD (1988), for example, have presented such an "external" model to account not only for the transition between lithosphere and asthenosphere sources for basalts west of the DVPR, but also the fact that the timing of this transition appears to become progressively younger from south to north. This model correlates the timing of the transition with the cessation of subduction, and the development of a slab "window" [cf. *Dickinson and Snyder*, 1979] beneath this region. With the growth of the slab window, these workers suggest that asthenospheric magmas, or diapirs, previously shielded from the continent by the subducted slab were then free to rise and interact with the overlying continental lithosphere, ultimately resulting in basaltic volcanism [e.g., *Crough and Thompson*, 1977].

As compelling as this model is for basalts in southeastern California, it cannot by itself adequately account for the lack of a transition from lithosphere to asthenosphere sources for the southern DVPR basalts. According to OD (1988), the transition between the two sources lags some 2–3 Ma after the trailing edge of the subducted lithosphere has passed beneath a given region. At the latitude of the NTS, then, the transition should have occurred at about 5 Ma, even allowing for the fact that this region is further inland than the area studied by OD (1988). But even the youngest NTS basalts show no evidence of the involvement of asthenospheric sources.

To account for the persistence of lithosphere-derived basalts in the southern DVPR, we suggest that factors inherent to the lithosphere itself must be considered. As described earlier, the southern DVPR traverses a region that had been amagmatic throughout the Phanerozoic. As a result, the mantle lithosphere may have been relatively cold and difficult to extend [*Glazner and Bartley*, 1985; *Sonder et al.*, 1987; *Kuznir and Park*, 1987]. In contrast, the northern Great Basin and east central California were both regions of extensive Mesozoic and/or Tertiary magmatism, and the mantle lithosphere may have been "softened" by preextension, subduction-related magmatism [*Wernike et al.*, 1987]. As a result, the mantle lithosphere may have been easier to extend and to displace by asthenospheric mantle [cf. *Olsen et al.*, 1987; *Perry et al.*, 1988], as evidenced by the appearance of asthenosphere-derived magmas in both regions as extension proceeded. We suggest therefore that the preservation of mantle lithosphere in southern Nevada was largely controlled by the preextension thermal gradient within the lithosphere itself.

Another factor that might have influenced the spatial and temporal distribution of asthenosphere and lithosphere in southern Nevada is the mode of lithospheric extension. Following a model proposed by *Wernike* [1981], *Jones* [1987] suggested that late Cenozoic lithospheric extension took place in the vicinity of the southern DVPR via a simple shear mechanism. In this model, extension is accommodated by west dipping low-angle normal faults that penetrate crustal levels in southern Nevada and mantle levels beneath the Sierra Nevada. As a result, there is a spatial offset between crustal and mantle lithosphere thinning (Figure 1). Jones cites the high P_n velocities (about 8 km/s), the low average elevation, and the high Bouguer gravity anomalies in southeast Nevada and vicinity as evidence that thick mantle lithosphere has been preserved in this region. Further to the west, beneath Owens Valley and the Sierra Nevada, the lithosphere may have been substantially thinned during extension. And in these regions, basalts with asthenospheric affinities are observed. Therefore Jones's model is at least qualitatively consistent with the basalt geochemistry in both east central California and the southern DVPR.

The Jones model does not readily account, however, for the progressive south-north decrease in the age of transition between basalts with lithosphere and asthenosphere sources in southeast California. This transition may still have been controlled in part by factors external to the continental lithosphere, such as the opening of a slab window. But the occurrence of asthenosphere-derived magmas in the Owens Valley region suggests that pre extension lithosphere was more easily displaced than in the southern DVPR, and this process would have been promoted by any mechanical mantle lithosphere thinning that might have occurred during extension. On the other hand, the timing of the major trace element enrichment in the southern DVPR basalts (~3 Ma) is roughly correlated with the opening of the slab window beneath this region. The enrichment could correspond to increased temperatures in the lowermost mantle lithosphere with increasing exposure to asthenosphere beneath the subducted slab, and the resulting remobilization of volatile components in lowermost lithospheric mantle. Therefore aspects of both our model and that of OD (1988) may be required to account for all aspects of the geochemistry of late Cenozoic basalts in the southern Great Basin.

The Cima Domes basalts lie outside of the amagmatic zone of southern Nevada, in a region than underwent both subduction-related magmatism in the Mesozoic and extension-related magmatism in the mid-Tertiary (Figure 3). The asthenospheric signatures of the Cima Domes basalts suggest that any pre-Mesozoic mantle lithosphere has been removed

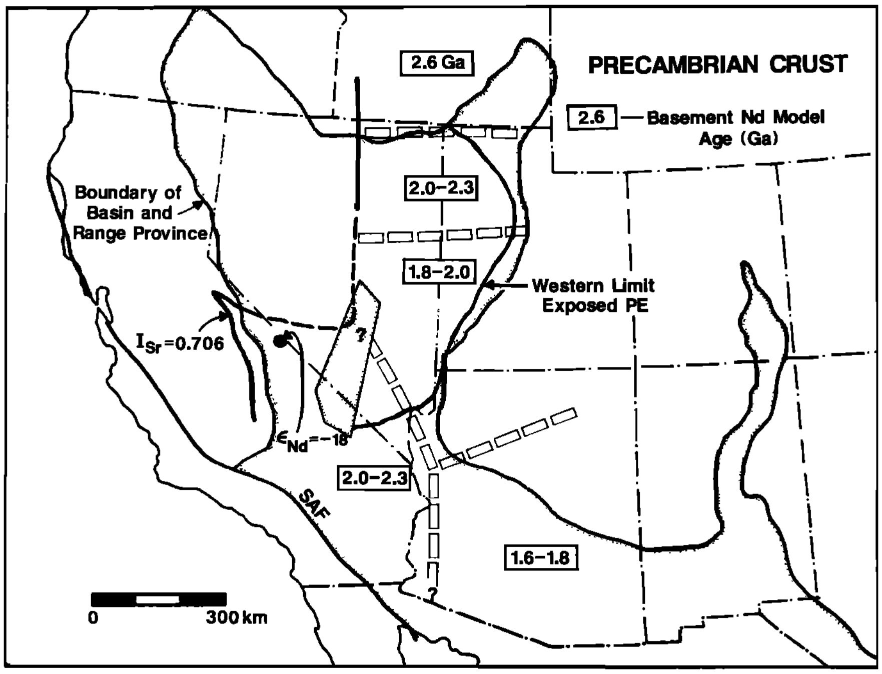

Fig. 9. Map showing surface and subsurface limits of Precambrian basement in Great Basin ($^{87}Sr/^{86}Sr$ = 0.706 line from *Kistler and Peterman* [1973] and *Farmer and DePaolo* [1983]), and distribution of Nd isotopic provinces within the Precambrian crust in the western United States (modified after *Bennett and DePaolo* [1987]). Location marked with $\varepsilon_{Nd} = -18$ is the peraluminous Birch Creek monzogranite pluton in the White-Inyo Mountains. Shaded region is the DVPR basalt zone. SAF is San Andreas fault. Province 1 crust corresponds to basement with Nd model ages between 2.0 and 2.3 Ga, and province 2 to basement with model ages between 1.8 and 2.0 Ga.

from beneath the Precambrian basement in this region. The removal of lithosphere could have occurred during the mid-Tertiary extension or during the earlier period of subduction by lithosphere delamination [*Bird*, 1988]. Detailed geochemical studies of Cenozoic basalts in the Mojave Desert are currently under way to distinguish between these two possibilities (G. L. Farmer and A. F. Glazner, manuscript in preparation, 1989).

Origin of Mantle Lithosphere in the Southern DVPR

The considerations outlined above suggest that mantle lithosphere has been preserved in southern Nevada despite the current episode of lithospheric extension. The low ε_{Nd} values and high $^{87}Sr/^{86}Sr$ ratios have led other workers to suggest that the mantle lithosphere represents ancient continental mantle associated with Precambrian continental crust [*Menzies et al.*, 1983]. This model is consistent with the available geologic and isotopic data from southern Nevada. For example, it is likely that the southern DVPR is underlain by Precambrian basement despite the lack of exposed crystalline crust. Exposed Precambrian (1.7 Ga) crust in southernmost Nevada and eastern California belongs to a crustal segment with Nd model ages ranging from 2.0 to 2.3 Ga (province 1, Figure 9) [*Bennett and DePaolo*, 1987]. Such basement probably extends much further north, to at least the latitude of the central DVPR (37°N). Evidence for this assertion comes from the low ε_{Nd} values (−18) of a late Cretaceous peraluminous granite in the White Mountains of eastern California (Figure 9), a value compatible with its derivation from felsic Precambrian basement at depth in the crust [cf. *Farmer and DePaolo*, 1983]. Any mantle lithosphere originally associated with the province 1 crust could have been preserved since the Precambrian, given that the lithosphere in southern Nevada has been largely unperturbed by Phanerozoic thermal events, including any effects of Mesozoic subduction-related magmatism.

If the southern DVPR basalts were derived from ancient lithospheric mantle, then the isotopic compositions of those portions of the lithosphere involved in basalt genesis are significantly different from the values inferred for mantle lithosphere associated with Proterozoic continental crust elsewhere in the western United States. For example, the lithospheric sources for Cenozoic age tholeiitic and alkalic basalts, basanites, nephelinites, and minettes in northern Arizona and New Mexico all have similar ε_{Nd} (+2 to −2) and $^{87}Sr/^{86}Sr$ values (0.704–0.705; Figure 10) [*Phelps et al.*, 1983; *Alibert et al.*, 1986; *Perry et al.*, 1987]. The lithosphere Pb isotopic compositions are variable but generally plot on ≥1.7 Ga secondary isochrons, to the right of the geochron but nearly coincident with the NHRL (Figures 6*a*–6*b*) [*Everson*, 1979; *Alibert et al.*, 1986]. These data suggest that Proterozoic mantle lithosphere involved in magma genesis in much of the southwest United States has a restricted range of isotopic compositions that is distinctly different from that observed for most of the southern DVPR basalts.

Lithosphere similar to that described above could have been the source of the Nye Canyon basalts in the east central DVPR but not for the remainder of the southern DVPR basalts. One important difference between the Precambrian lithosphere in northern Arizona and southwestern Nevada, however, is that the former belongs to Nd isotopic provinces 2 and 3, while the lithosphere in southern Nevada is most likely to belong to province 1 (Figure 9). On this basis we suggest that the southern DVPR basalts were derived from mantle lithosphere uniquely associated with province 1

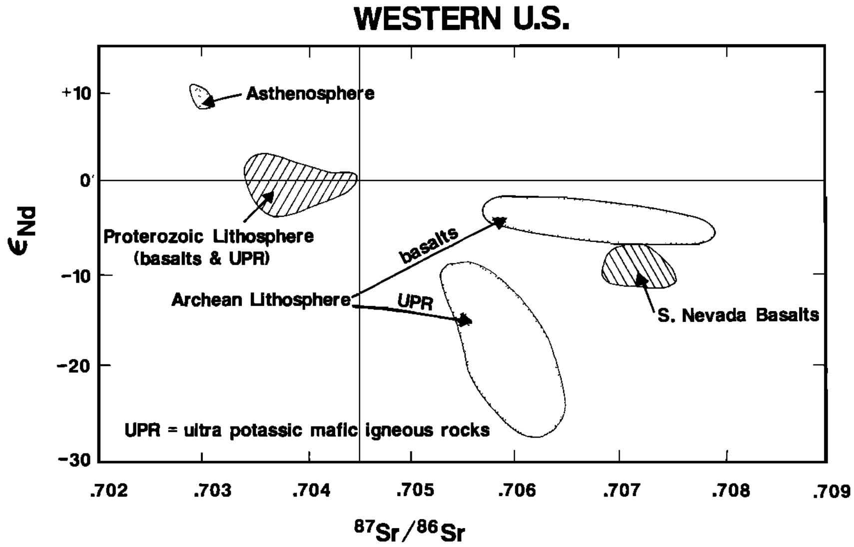

Fig. 10. The ε_{Nd} versus $^{87}Sr/^{86}Sr$ plot for Cenozoic volcanic rocks in the western United States. Data compiled from *Alibert et al.* [1986], *Perry et al.* [1987], *Dudas et al.* [1987], *Fraser et al.* [1986], *Phelps et al.* [1983], and *Menzies et al.* [1983].

crust. The origin of the unique isotopic signatures of this mantle is difficult to constrain, particularly given that the origin of the province 1 crust itself is not known. *Patchett and Arndt* [1986] and *Bennett and DePaolo* [1987] have suggested that this crustal segment formed at 1.7 Ga near the margin of preexisting Archean lithosphere. In these models, the 2.0- to 2.3-Ga Nd model ages for the province 1 crust are considered to be the result of mixing between magmas newly derived in the Proterozoic from the upper mantle and Archean continental crust. Lithospheric mantle developing beneath this crustal segment could also have received input of low ε_{Nd}, high $^{87}Sr/^{86}Sr$ Archean lithospheric material, for example, by sediment subduction. Alternatively, the province 1 crust could have been constructed upon Archean mantle lithosphere. The remains of this Archean mantle, subjected to interaction with subduction-related fluids and magmas during 1.7-Ga crust formation, could represent the source of the southern DVPR basalts. The isotopic compositions of the southern DVPR basalts are, in fact, much more similar to basalts derived from Archean mantle lithosphere, such as in the Snake River Plain, than to basalts derived from province 2 mantle (Figures 6*a*–6*b* and Figure 10). However, it is premature to suggest that the southern DVPR basalts were derived from a recycled segment of Archean mantle.

CONCLUSIONS

The isotopic and trace element data presented here support the hypothesis that preextension lithospheric mantle currently exists beneath portions of southern Nevada and eastern California. The preservation of the continental mantle appears to be related to the unique Phanerozoic tectonomagmatic history of this region relative to other portions of the Basin and Range, specifically to the relative lack of magmatism and/or heating of the mantle lithosphere during this time. We also agree with previous workers that this lithosphere could have been preserved since the Precambrian. But the isotopic compositions of this lithosphere are distinct from other segments of Proterozoic continental mantle in the western United States, and we suggest that this segment of mantle lithosphere represents the mantle associated with Nd isotopic province 1 continental crust. The preservation of such ancient lithospheric mantle in southern Nevada has implications not only for the Cenozoic tectonic evolution of the southern Great Basin, but also suggests that models for the Mesozoic tectonic evolution of the western United States that involve the whole-scale removal of mantle lithosphere during subduction [*Bird*, 1988] may need reevaluation.

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