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Elizabeth Y. Anthony, Jerry Hoffer, Wendi J. Williams, Jane Poths, and Brian Penn

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GEOCHEMISTRY AND GEOCHRONOLOGY OF QUATERNARY MAFIC VOLCANIC ROCKS IN THE VICINITY OF CARRIZOZO, NEW MEXICO

ELIZABETH Y. ANTHONY[1], JERRY HOFFER[1], WENDI J. W. WILLIAMS[1], JANE POTHS[2], and BRIAN PENN[1]
[1]Department of Geological Sciences, University of Texas at El Paso, El Paso, TX 79968; [2]CST-7, Los Alamos National Laboratory, Los Alamos, NM 87545

Abstract—We report here elemental and chronologic information for the Quaternary lavas from the vicinity of Carrizozo, New Mexico. The geochemistry of these lavas is transitional between hypersthene and nepheline normative and is very similar to other lavas in the region, e.g., the Jornado del Muerto volcanic field. The magmatic noble gas signature, here given in terms of $^3He/^4He$, correlates well with radiogenic isotopes and indicates that the magmas either were derived from a mantle source more enriched in incompatible elements than average asthenosphere or have seen some crustal contamination.

We have measured the age of the Carrizozo upper flow using ^3He cosmogenic surface exposure dating. The age of 4800 ± 1700 yrs before present (ybp) agrees well with other recent determinations. The Broken Back portion of the field is older. Cone morphology and degree of surficial alteration of magnetite to hematite, as deduced from remote sensing, indicates that the cones may be approximately 100 ka old.

INTRODUCTION

The mafic volcanic rocks near Carrizozo, New Mexico, consist of two eruptive centers. They are (1) the Broken Back cinder cones and associated flows and (2) the long, sinuous upper and lower units of the Carrizozo flows (Fig. 1). These two eruptive centers are referred to collectively as the Carrizozo volcanic field. They belong to a group of young (Miocene to recent) volcanic centers associated with Rio Grande rift normal faulting. The location of the Carrizozo volcanic field and other centers, along with the principal physiographic and tectonic features of the region, are shown in Figure 2. This paper reports new data on the ages of the Carrizozo field and on the geochemistry of samples.

GEOLOGIC DESCRIPTION OF THE FIELD

The Broken Back area is located a short distance northwest of the upper Carrizozo flows. The area covers approximately 20 mi² and consists of two cinder cones (Broken Back and an unnamed cone) surrounded by mafic flows. Broken Back, located in the northwest corner of the area, is a cinder cone approximately 185 ft high and 1300 ft in diameter. The cone is breached on the southeast by a lava flow (sample BB2). The second, unnamed cone is located 0.5 mi southeast of Broken Back. It is about 155 ft high and almost 1200 ft in diameter. Two tongues of lava (sample BB1) are exposed on the south side of the cone. The flows from the two cones probably represent the youngest activity in the area.

The main volume of lava in the Broken Back area was emplaced not as flows associated with the cones but from a north-trending fissure. Samples BB3 through BB6 are from this unit. The flows in the Broken Back area are overlapped by the Carrizozo flows and both flows and cinder cones show a greater degree of weathering (Weber, 1963) indicating that volcanism in this area pre-dated the Carrizozo flows.

The Carrizozo flows have been mapped as an upper and a lower unit. The samples for geochemistry (23A) and for dating come from near US-380 and thus are part of the upper unit. Emplacement mechanisms for the Carrizozo flows were studied by Keszthelyi and Pieri (1993) who found that the flows are a 120 mi long, compound, tube-fed pahoehoe system. Effusion rates were 176 ft³ per second and the eruption duration was three decades. They conclude that the length of the flows are more a function of the long eruption duration rather than high effusion rates. Additional geologic and petrographic description and geochemical data for the Carrizozo

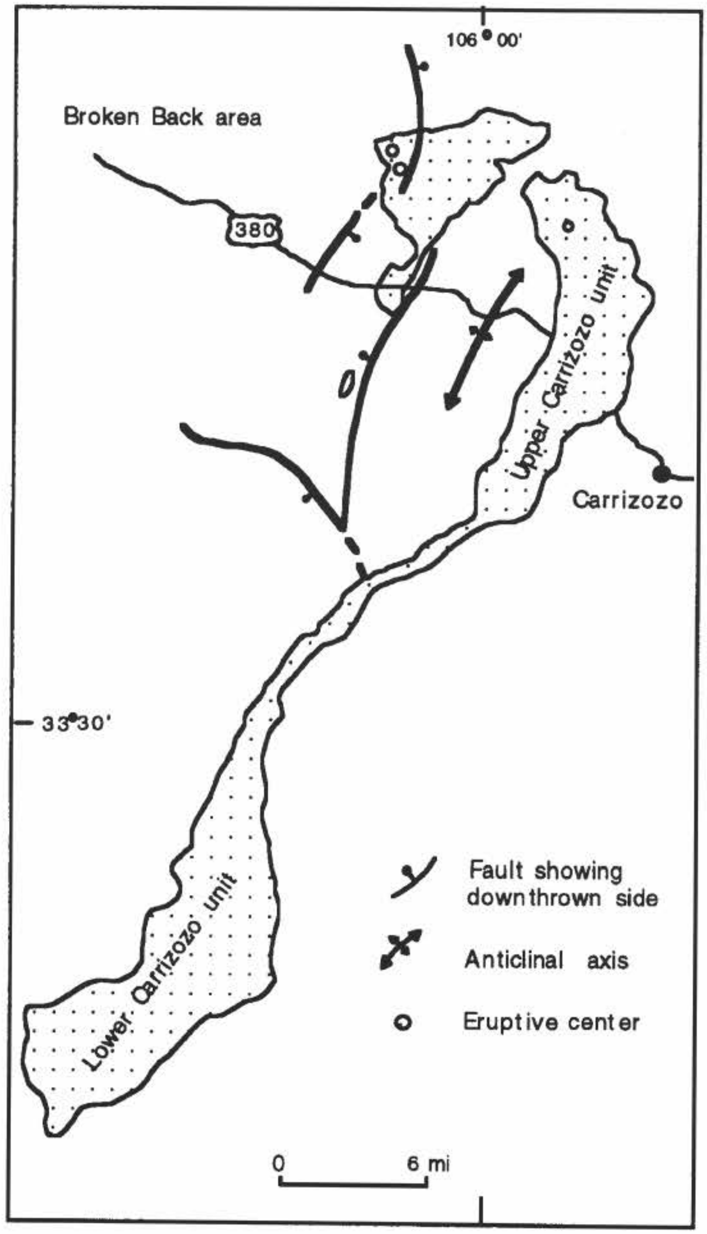

FIGURE 1. Map of the Carrizozo volcanic field (from Renault, 1970).

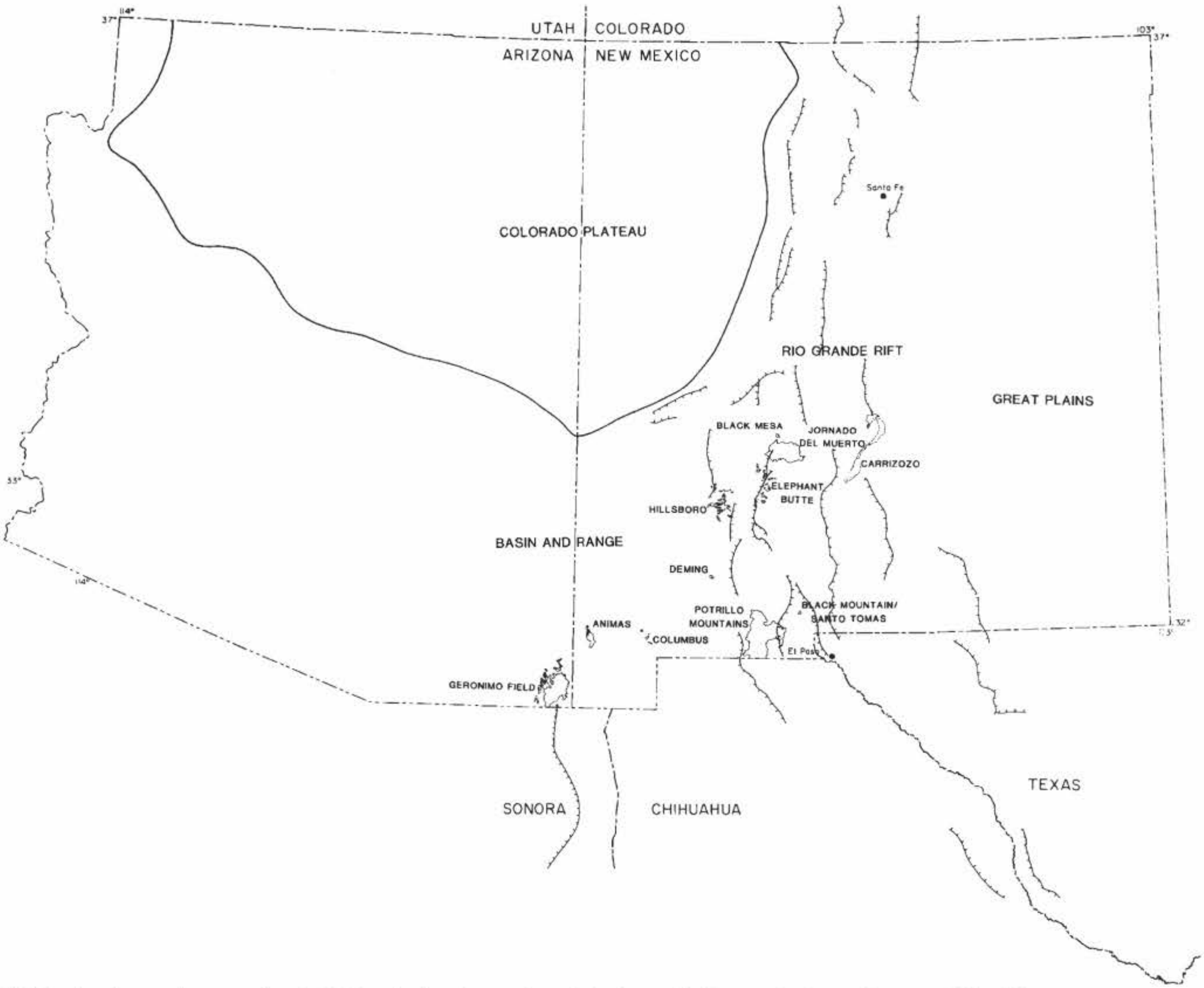

FIGURE 2. Regional map of young volcanic fields and related tectonic and physiographic features in the southwestern United States.

field may be found in the references above and in Renault (1970), Faris (1980), and McLemore (1991).

ANALYTICAL METHODS

Major element geochemistry (Table 1) was obtained from both X-ray fluorescence (XRAL Labs of Canada) and ICP-AES (Texas Tech University). Duplicate analyses of one sample, BB5, indicate that agreement between the two methods is good. Three samples, 23A from the upper Carrizozo unit, BB3, and BB5, have trace-element data from ICP-AES (Texas Tech University) and instrumental neutron activation analyses (INAA) obtained at the University of Texas at El Paso (Table 2).

Age determinations reported in this paper are by cosmogenic nuclide surface-exposure dating (Table 3). The technique relies on the build-up of cosmogenic helium in a surface exposed to cosmic radiation. For lava such as the Carrizozo flows, which have been continuously exposed since formation, the exposure age is equivalent to the eruption age. In order to correct for the non-cosmogenic, magmatic helium trapped in the crystals, it is necessary to crush the samples and obtain the magmatic $^{3}He/^{4}He$ prior to melting the samples and obtaining their cosmogenic yield. This magmatic $^{3}He/^{4}He$ has become increasingly interesting as an isotopic tracer similar to Sr, Nd, and Pb. Additional details of analysis may be found in Anthony and Poths (1992) and Anthony (1993).

ANALYTICAL RESULTS

Geochronology

The ^{3}He surface exposure date for the upper Carrizozo unit is 4800 ± 1700 yrs before present (ybp). This compares within error for recent cosmogenic ^{36}Cl determinations by Phillips et al., (1997) who reported three duplicate analyses yielding 5300 ± 500, 5400 ± 900, and 6000 ± 900 ybp. This age for the eruption places the Carrizozo flows as the second youngest volcanism in New Mexico. The McCartys flow near Grants, which has been dated by ^{14}C at approximately 3010 ± 70 ybp and by ^{3}He at 2400 ± 600, is younger (Laughlin et al., 1994).

As mentioned in the section on geologic description, we know that the Broken Back area pre-dates the Carrizozo flows. We have been developing a semi-quantitative method for dating volcanism that combines remote sensing and cone morphology, that is, radius-to-height ratios. Small radius-to-height ratios (steep cones) correlate with a lack of reflectance in the band characterized by hematite. In other words, steep cones are characterized by a lack of surficial weathering of igneous magnetite to hematite. We have calibrated these data for features of known age in the Potrillo and Palomas fields (see Hoffer et al., this guidebook). Based on this calibration, Broken Back and the other unnamed cone are not more than 100 ka old.

TABLE 1. Major element geochemistry for samples from the Carrizozo volcanic field.

	23A	BB1	BB2	BB3	BB3X	BB4	BB5	BB5X	BB6
SiO2	51.08	50.1	49.5	50.12	49.2	49.8	50.12	50.4	49.8
TiO2	1.7	1.7	1.64	1.79	1.65	1.62	1.71	1.67	1.74
Al2O3	16.03	15.7	15.5	15.53	15.5	15.2	15.87	15.6	15.8
Fe2O3	11.18	10.4	10.3	10.59	10.1	10.6	10.6	10.8	10.4
MnO	0.16	0.16	0.16	0.16	0.16	0.16	0.15	0.16	0.16
MgO	7.1	6.16	6.69	6.42	6.2	7.32	7.22	7.22	6.34
CaO	8.45	8.51	8.48	9.2	9.1	8.42	8.48	8.43	8.41
Na2O	3.85	3.56	3.4	3.77	3.49	3.4	3.67	3.56	3.53
K2O	1.46	1.7	1.67	1.63	1.66	1.54	1.627	1.67	1.7
P2O5	0.38	0.39	0.38	0.46	0.39	0.34	0.42	0.38	0.4
LOI	-0.1	1.2	0.75	0.77	0.75	-0.05	0.02	0	0.15
Total	101.29	99.58	98.47	100.44	98.2	98.35	99.887	99.89	98.43
	ICP-AES	XRF	XRF	ICP-AES	XRF	XRF	ICP-AES	XRF	XRF
Normative minerals									
Or	6.67	10.04	9.85	9.8		9.1	9.85		9.79
Ab	31.81	30.12	28.76	27.58		28.76	30.01		29.78
An	22.62	21.83	22.09	21.72		21.66	21.65		21.77
Ne				1.05			0.05		
Cpx	14.77	14.63	14.31	17.1		14.6	14.46		14.58
Opx	5.29	0.62	1.48			2.51			0.14
Ol	9.8	13.89	14.75	13.74		15.36	17.22		14.44
Mt	2.47	1.5	1.49	1.5		1.53	1.56		1.47
Il	3.09	3.22	3.11	3.13		3.07	3.17		3.19
Ap	0.37	0.92	0.9	0.92		0.8	0.9		0.92

Helium isotope signature

$^3He/^4He$ ratios are often expressed as the ratio measured in the sample relative to the ratio in the atmosphere, that is, R/R_a. Values R/Ra for mid-ocean ridge basalt (MORB), i.e., depleted mantle, are approximately 8 R/R_a. Values lower than this are interpreted to represent derivation of the magma from a source region, either enriched mantle or continental crust, with a high uranium content, which results in production of alpha particle ^4He. The Carrizozo flow has an average value of 5.7 ±1.0 R/R_a, which is lower than typical MORB and thus indicates that the magmas have been influenced by either enriched mantle or crustal contamination. This low $^3He/^4He$ is correlated with a low, non-MORB (Nd and high $^{87}Sr/^{86}Sr$ (Table 4 and Gibson et al., 1992). This correlation between $^3He/^4He$ and radiogenic isotopes for continental lavas from the southwestern United States has recently been discussed by Reid and Graham (1996). Table 4 gives the values for the Carrizozo sample and compares it to some of the other volcanic fields in the region. Fields such as Potrillo and Cima are characterized by MORB-like R/R_a and radiogenic signatures compared to Carrizozo and Lathrop Wells. The Zuni-Bandera field shows that a long-lived field, which contains both alkaline and subalkaline lavas, may not show such clear distinctions. It has uniformly high R/R_a and variable ε_{Nd}.

Elemental geochemistry

In an earlier study (Anthony et al., 1992), we discussed general characteristics of magma chemistry for the young mafic lavas of the region. We noted that there is a group of magmas characterized by being hypersthene normative and having low concentrations of the incompatible elements (for example, the Servilleta basalts of the Taos Plateau volcanic field) and a group of highly alkaline, nepheline normative lavas with elevated concentrations of incompatible elements (e.g., the Geronimo and Potrillo volcanic fields). Between these two extremes are lavas that are either marginally hypersthene or nepheline normative and have intermediate concentrations of incompatible elements (e.g., Jornada del Muerto, Hillsboro, and Black Mesa). Using the same plots as the 1992 study with the new data added (Figs. 3 and 4), it is apparent that the Carrizozo field belongs to this intermediate group. We have added rare-earth element (REE) concentrations to the data set since 1992 and show that the light REEs show similar trends (Fig. 5). The most alkaline fields have the highest concentrations, the fields of transitional alkalinity have intermediate values, and the hypersthene normative fields have the lowest concentrations.

DISCUSSION

We concluded in 1992 that the high degree of correlation between silica saturation and concentrations of incompatible elements argues for the variable melt fraction as a fundamental control for generating the diversity of magma chemistries. Under this hypothesis, the alkaline magmas represent a small melt fraction relative to the subalkaline magmas. We note here that the volume of eruptive material is, in a general sense, consistent with this hypothesis. The volume of the Servilleta basalts is large. Carrizozo and Jornado del Muerto have a large volume of magma considering that they are essentially a single eruptive center. The Potrillo, Cima,

TABLE 2. Trace element geochemistry for samples from the Carrizozo volcanic field.

	23A	BB3	BB5
ICP-AES			
Sc	21.4	21.6	21.7
V	146	151	150
Cr	271	217	261
Ni	173	115	136
Cu	49	29	23
Zn	98	90	96
Rb	26	27	28
Sr	454	535	503
Y	31	30	29
Zr	160	163	160
Nb	34	40	37
Ba	339	414	407
INAA			
Sc	24	23.3	23.5
Cr	258	201	244
Fe2O3	12	10.8	11.4
Co	47	41	39
Ni	125	91	123
Rb	27	26	27
Sr	445	492	474
Zr	157	170	166
Ba	405	463	443
La	22.9	26.6	25.9
Ce	45	51	50.8
Nd	24	24.8	25.6
Sm	5.4	5.6	5.6
Eu	1.71	1.73	1.71
Tb	0.88	0.86	0.85
Yb	2.61	2.5	2.42
Lu	0.39	0.37	0.38
Hf	4.16	4.13	4.11
Ta	1.63	2	1.9
Th	2.8	3.1	3.2

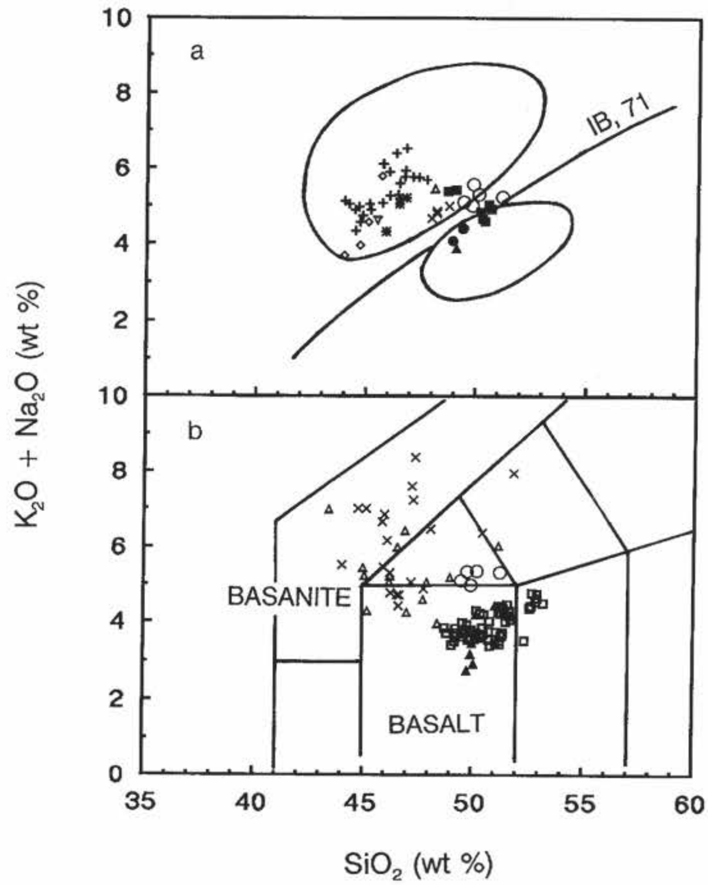

FIGURE 3. Silica vs. $K_2O + Na_2O$. The figure is as published in Anthony et al. (1992) with the addition of analyses reported in Table 1 from the Carrizozo volcanic field (open circles). **A,** crosses: Potrillo volcanic field; diamonds: Palomas volcanic field; inverted triangle: Columbus; asterisks: Elephant Butte; triangle: Hillsboro; filled squares: Jornado del Muerto volcanic field; x's Black Mesa; filled triangle: Deming; filled circle: Animas. IB, 71 is the boundary between subalkaline and alkaline fields as defined by Irvine and Baragar (1971). Ellipses encompass the compositional variation for groups from Figure 3b. **B,** x's: Geronimo volcanic field (Kempton et al., 1987); open triangles: alkaline rocks from New Mexico (Perry et al., 1987); filled triangles: subalkaline rocks from New Mexico (Perry et al., 1987); open squares: Taos Plateau volcanic field (Dungan et al., 1986).

and Geronimo fields are dominated by low-volume eruptive centers, i.e., cinder cones and breach flows.

It is clear, however, from isotopic variability throughout the region that processes are more complicated than simple variation in degree of melting and that source heterogeneity is required. For continental magmas, the debate is over how to distinguish signatures caused by enriched mantle versus those resulting from crustal contamination. Both sources are characterized by low $^3He/^4He$, low ε_{Nd}, and high $^{87}Sr/^{86}Sr$. The addition of helium data, although interesting because it shows a correlation between noble gas and radiogenic isotopes, does not help to resolve the debate.

We have recently completed an investigation of isotopic variability for the San Quintín volcanic field in Baja California (Williams et al., in review; Luhr et al., 1995). For this field we determined that the combination of $^3He/^4He$ and Pb isotopes can be used to distin-

TABLE 3. ^3He surface exposure dating summary.

	Crush		Melt				Production Rate	Age
	$[^4He]$ $(10^{-9}$ cc/g)	$^3He/^4He$ R/R_a	$[^4He]$ $(10^{-9}$ cc/g)	$[^3He]$ $(10^{-12}$ cc/g)	$[^3He_c]$ surface $(10^{-6}$ atoms/g)	$^3He/^{21}Ne$	(atoms/g)	(ka)
Carrizozo, New Mexico								
CF1#1	12.0	5.5 +/- 1.1	3.6 +/- 0.2	0.093 +/- 0.022	1.8 +/- 0.6	--	369	4.8 +/- 1.7
CF2#1	11.7	5.9 +/- 1.0	--	--	--	--		

TABLE 4. Isotopic characteristics of lavas from the southwestern United States.

	R/Ra	87Sr/86Sr	Nd	Ref
Potrillo	7.8 + 1.0 (n=15)	0.703	+6	1
Cima	8.5 + 1.5 (n=14)	0.70316 (n=4)	+9.4 (n=4)	2
Carrizozo	5.7 + 1.0 (n=2)	0.704 (n=1)	+1 (n=1)	3
Lathrop Wells	5.8 + 0.9 (n=21)	0.70704 (n=1)	-9.1 (n=1)	2
Zuni-Bandera volcanic field				
Bluewater flow	7.0 + 0.4 (n=5)	--	--	
Bandera flow	6.9 + 0.5 (n=3)	0.70366 (n=1)	+5.4 (n=1)	4
McCartys flow	7.1 + 1.0 (n=1)	0.7055 (n=1)	--	5
El Calderon flow	8.7 + 1.1 (n=1)	0.70521 (n=1)	+1.4 (n=1)	4

References for Sr and Nd data

1. Roden et al. (1988)
2. Farmer et al. (1989)
3. Allen and Foord (1991)
4. Perry et al. (1987)
5. Menzies et al. (1991)

guish between mantle heterogeneity and crustal contamination: enriched mantle is characterized by low $^3He/^4He$ coupled to high $^{206}Pb/^{204}Pb$, whereas crustal contamination is indicated by low $^3He/^4He$ coupled to low $^{206}Pb/^{204}Pb$. We do not know whether this

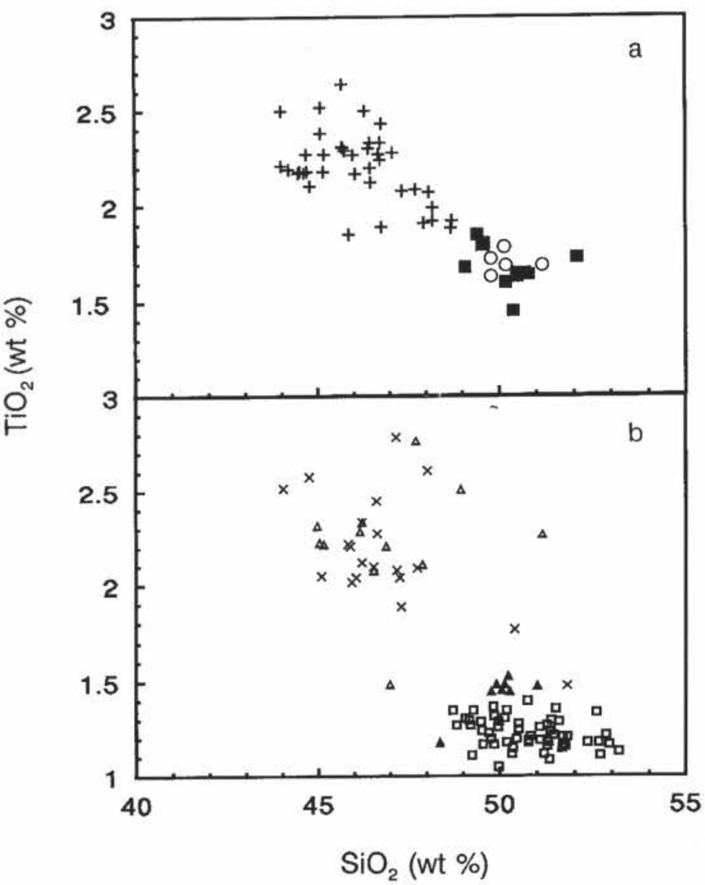

FIGURE 4. TiO_2 vs. SiO_2 (modified from Anthony et al., 1992). **A,** crosses represent alkaline samples from Figure 3a; squares, subalkaline samples from 3a; open circles, Carrizozo samples from this study. **B,** samples from Taos Plateau volcanic field, Geronimo volcanic field, and New Mexico. Sample designations are as in Figure 3B.

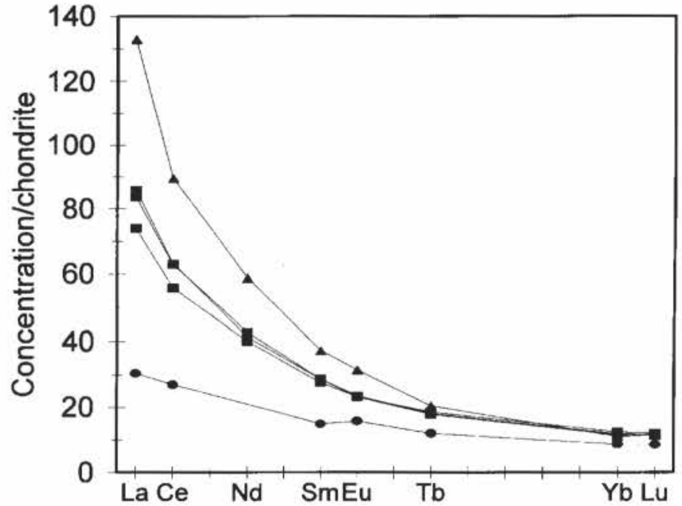

FIGURE 5. Rare-earth element diagram for samples from this study (squares), compared to a typical sample from the Potrillo volcanic field (triangle), and the Taos Plateau volcanic field (circles, Dungan et al., 1986).

correlation will have general applicability, and we are not aware of $^{206}Pb/^{204}Pb$ analyses for the Carrizozo field. It would seem to be, however, an area where the findings from the San Quintín volcanic field could be tested.

CONCLUSIONS

(1) The age of the Carrizozo flows has been determined by ^3He surface exposure dating to be approximately 4800 ypb. This estimate agrees with Cl surface-exposure dating. The Broken Back area is older. Cone morphology and remote-sensing reflectance suggest that it is not older than 100 ka.

(2) The geochemistry of the field is mildly alkaline and is very similar to the Jornado del Muerto, Hillsboro, and Black Mesa lavas. The helium magmatic signature is low, indicating interaction of the magmas with a uranium-rich source region. The low $^3He/^4He$ is correlated to "enriched" signatures for both ε_{Nd} and $^{87}Sr/^{86}Sr$. It is not possible, however, with the available data to resolve whether this signature results from an enriched mantle or crustal contamination.

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