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Geochronology of Mount Taylor, Cebollita Mesa, and Zuni–Bandera volcanic fields, Cibola County, New Mexico

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Introduction

A large amount of whole-rock major- and trace-element and isotopic data is available on volcanic rocks from the Zuni–Bandera (ZBVF) and Mount Taylor (MTVF) volcanic fields in west-central New Mexico (Baker and Ridley, 1970; Renault, 1970; Laughlin et al., 1971, 1972a, 1972b, 1979, 1982; Lipman and Moench, 1972; Dellechaie, 1973; Carden and Laughlin, 1974; Brookins et al., 1975; Gawell, 1975; Ander et al., 1981; Crumpler, 1980, 1982; Perry et al., 1987, 1990; Menzies et al., 1991). In contrast, the geochronology of the area, particularly that of the Zuni–Bandera volcanic field, is not well constrained, and neither geochemical nor geochronological data are available for basalts capping Cebollita Mesa east of the ZBVF.

The poor geochronological constraints for the Zuni–Bandera basalts in part result from analytical problems associated with the K–Ar dating of very young basaltic rocks. Unpublished data of Laughlin, Damon, and Shafiqullah (1985) suggest that many of these Quaternary flows contain excess ^{40}Ar causing them to yield anomalously old K–Ar apparent ages. In addition, some K–Ar ages published by Laughlin et al. (1979) and Ander et al. (1981) are apparently in error because of the presence of excess ^{40}Ar.

We have recently obtained 19 new K–Ar and ^{40}Ar/^{39}Ar ages and XRF whole-rock analyses for basalts from the three volcanic fields. Our results refine the geochronology of the MTVF, provide reconnaissance geochronological data for correlative basalts of the Cebollita Mesa volcanic field (CMVF), and establish a framework for the geochronology of the ZBVF. Additional work in progress on the very young basalts of the ZBVF employing the ^{3}He, U-series, ^{14}C, and ^{40}Ar/^{39}Ar methods will be reported in a separate publication.

Geological background

The Mount Taylor, Cebollita Mesa, and Zuni–Bandera volcanic fields are located along the Jemez lineament in west-central New Mexico (Mayo, 1958; Laughlin et al., 1976, 1982; Fig. 1). The fields lie within the transition zone between the Colorado Plateau and Basin and Range tectonic provinces (Thompson and Zoback, 1979; Zoback and Zoback, 1980; Baldridge et al., 1983, 1991; Aldrich and Laughlin, 1984; Olsen et al., 1987). Extension in this re-

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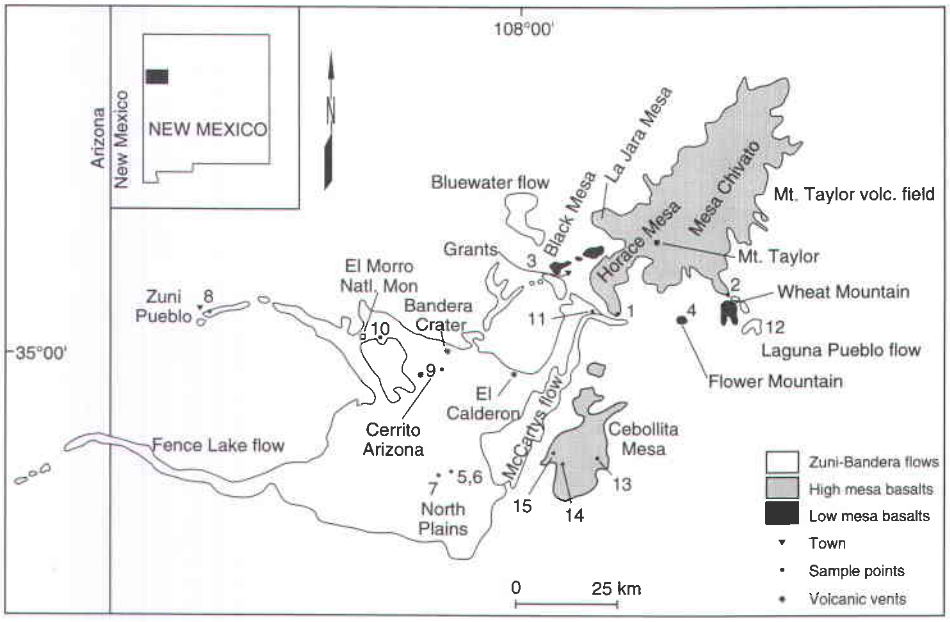

FIGURE 1—Localities of basalt samples of the Mount Taylor, Cebollita Mesa, and Zuni–Bandera volcanic fields, New Mexico.

Also in this issue

gion began in the middle Tertiary (Aldrich et al., 1986) and continued into the Holocene as recognized by Aldrich and Laughlin (1984) and Maxwell (1986).

Volcanic rocks of the MTVF range from basalt (sensu lato) to rhyolite in composition (Hunt, 1938; Baker and Ridley, 1970; Lipman and Moench, 1972; Crumpler, 1980; and Perry et al., 1990). Perry et al. (1990) report an area for the MTVF of 1100 km^2 (425 mi^2) with about 80% of this being basalts covering two levels of mesa tops peripheral to the main Mount Taylor volcanic cone. In contrast to the younger ZBVF, where basalts range from alkalic to tholeiitic in composition, all basaltic rocks of the MTVF are alkalic (basanite, alkali olivine basalt, hawaiite). Mount Taylor is a composite cone consisting primarily of latite and quartz latite lava flows and associated volcaniclastic deposits. The composition of lavas erupted from Mount Taylor changed systematically with time. The earliest eruptions, between 3.3 and 3.0 Ma, were dominantly rhyolitic, followed by eruption of quartz latite between 3.0 and 2.6 Ma (the most active period of cone growth), and eruption of latite between 2.6 and 1.5 Ma (Perry et al., 1990). Considerable geochronological data are available for volcanic rocks of the MTVF beginning with the pioneering studies of Bassett et al. (1963). Published ages for the MTVF are summarized in Table 1, and suspect ages (anomalously old) are indicated. Geologically reasonable ages for the MTVF range from 3.73 to 1.57 Ma.

To the south of Mount Taylor, Cebollita Mesa lies east of the ZBVF. This mesa (~300km^2; ~116 mi^2) is capped by basalt, and reconnaissance geologic work identifies several shield volcanoes and numerous maars on the mesa top. The map of Luedke and Smith (1979) shows 12 volcanic centers on the mesa top. Because Cebollita Mesa lies at approximately the same elevation as the high mesas that surround Mount Taylor, it has been generally assumed (F. V. Perry and A. W. Laughlin, unpubl. data 1992) that basalts in the two areas are equivalent in age. Previously unrecognized geochemical differences in the basalts from Mount Taylor and Cebollita Mesa, however, lead us to conclude that it would be appropriate to define Cebollita Mesa as a separate volcanic field, the CMVF.

In preparation for the El Malpais National Monument and the El Malpais Conservation Area, Maxwell (1986) mapped much of the geology of the ZBVF. Maxwell's excellent map supplements work by Nichols (1946), Hatheway and Herring (1970), Causey (1970), Laughlin et al. (1971, 1972a, 1972b, 1976, 1982), Carden and Laughlin (1974), Dellechaie (1973), Gawell (1975), Brookins et al. (1975), and Menzies et al. (1991), who focused on the geomorphology, petrology, geochemistry, and isotope geochemistry of the basalts and incorporated ultramafic xenoliths but did no systematic mapping of the field.

In contrast to the MTVF, only basaltic volcanism occurred within the ZBVF, where over 100 vents have been recognized (Luedke and Smith, 1979). Many of the vents are aligned along N38°E trends, e.g. the Chain of Craters, and there is a suggestion of orthogonal N52°W trends controlling the location of some of the vents within the field. Ander et al. (1981) recognized a tendency for vents to be elongated parallel to the dominant N38°E trend. Flows from these vents cover approximately 2460 km^2 (950 mi^2). Ander et al. (1981) cite composite flow thicknesses of 61 m (200 ft) at El Morro, 20–60 m (65–197 ft) near Grants, and 36 m (118 ft) near the center of the Bluewater flow west of Grants. Robert Lee (oral comm. 1992) reports flow thicknesses of as much as 145 m (475 ft) in water wells near the center of the ZBVF. If the average thickness of the flows within the ZBVF is a very conservative 30 m (100 ft), the total volume of the basaltic lavas is about 74 km^3 (18 mi^3). Individual flows such as the Fence Lake flow may be as long as 100 km (60 mi).

The basalts of the ZBVF range in composition from low-silica alkali basalts to high-silica, high-aluminum tholeiites (Laughlin et al., 1972b; Ander et al., 1981; Menzies et al., 1991). Unpublished data of Laughlin and Perry (1992) suggest that basalts from many of the vents are chemically distinctive and that basalt compositions are an important tool for correlation within the ZBVF. Typically the basalts are aphanitic to microporphyritic in texture. Small olivine phenocrysts are present in many flows, and coarsely porphyritic basalts with large phenocrysts of plagioclase occur south of Cerro Rendija, west of Bandera Crater, and as a stubby flow from the Cerro Chato–Cerro Lobo vent complex (Ander et al., 1981). Kyle (oral comm. 1993) reports that these large plagioclase porphyritic basalts are common in the southern part of the Chain of Craters. Crustal xenoliths of sandstone, limestone, granite, gabbro, and granodiorite are present in some flows, and both crustal- and mantle-derived xenoliths are common in the cinder pits near Bandera Crater (Laughlin et al., 1971). Anorthoclase megacrysts, which may be suitable for conventional K–Ar and $^{40}Ar/^{39}Ar$ dating, are present in flows and cinders from Bandera Crater (Laughlin et al., 1971) and in flows from the Oso Ridge volcano.

Few radiometric ages are available for the ZBVF, and several of these are suspect because of the presence of excess ^{40}Ar in these young basalts. These ages are summarized in Table 2, and suspect ages are identified. The albedo of basalt flows shown on Landsat and U-2 imagery has proven very useful in establishing relative ages of the basalts of the ZBVF. In general, these relative ages agree with the mapping results of Maxwell (1986) for the main part of the field.

Laughlin et al. (1979) published four K–Ar ages ranging from 1.57 to 0.199 Ma for basalts of the ZBVF; two of these appear to be too old. The sample of the Laguna flow collected about 5 km (3 mi) east of Grants along I-40 gave an apparent age of 1.57 ± 0.26 Ma. Based upon the degree of weathering, soil cover, and geomorphology, this date appears to be too old. Champion and Lanphere (1988) reported an age of 0.128 ± 0.033 Ma for a sample of the Laguna flow collected by Laughlin about 1.5 km (1 mi) east of the intersection of I-40 and NM-117. Lipman and Mehnert (1979) reported an age of 0.38 ± 0.25 Ma for a sample of what may be the same flow from near Laguna Pueblo. A second anomalously old K–Ar age of 1.41 ± 0.29 Ma was obtained for the tholeiitic Fence Lake flow near the Arizona border. Unpublished data (conventional K–Ar and $^{40}Ar/^{39}Ar$) of McIntosh, WoldeGabriel, and Laughlin (1993) suggest that the correct age of the Fence Lake flow is between 0.60 and 0.70 Ma and that some samples of the flow may contain excess ^{40}Ar.

Ander et al. (1981) also reported four K–Ar ages for basalts of the ZBVF. At least three of these are apparently in error, pre-

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TABLE 1—Summary of published radiometric ages for the Mount Taylor volcanic field.

Sample no.	Unit	Age (Ma)	Reference	Evaluation
6	Grants Ridge basalt plug	4.1, 9.2	Bassett et al. (1963)	Too old
1–5,7	Grants Ridge rhyolite	3.3±0.3	Bassett et al. (1963)	Reasonable
6	Basalt flow, Mesa Chivato	2.8±0.2	Bachman and Mehnert (1978)	Reasonable
68L–204B	Grants Ridge rhyolite	3.34±0.16	Lipman and Mehnert (1979)	Reasonable
68L–201B	Upper basalt, flow 11, SE flank of Mount Taylor	1.56±0.17	″	Reasonable
68L–200C	Upper basalt, flow 6, SE flank of Mount Taylor	2.65±0.15	″	Reasonable
68L–202A	Lower basalt, lower flows, SE flank of Mount Taylor	2.92±0.86	″	Reasonable
74L–104A	Lower basalt, lower flows, SE flank of Mount Taylor	9.87±1.52	″	Too old
68L–216B	Basalt of low mesas, flow 13, SE flank of Mount Taylor	2.42±0.18	″	Reasonable
74L–16	Basal basalt, north end of Mesa Chivato	2.87±0.20	″	Reasonable
74L–117	Cerros de Guadaloupe cinder cone, Mesa Chivato	2.75±0.30	″	Reasonable
74L–113	Cerros de Guadaloupe trachyte dome, Mesa Chivato	3.30±0.20	″	Reasonable
74L–118B	Plagioclase basalt, Mount Taylor	6.03±0.60	″	Too old
74L–134B	Andesitic pyroclastic flow, Mount Taylor	2.51±0.25, 2.73±0.16	″	Reasonable
74L–111	Trachyte dome, Mount Taylor	4.37±0.27	″	Too old
MT18, same unit as 74L–111	Trachyte dome, Mount Taylor	3.30±0.08	Perry et al. (1990)	Reasonable
MT144	Rhyolite, Mount Taylor	3.03±0.11	″	Reasonable
MT1	Quartz latite radial dike, Mount Taylor	2.88±0.12	″	Reasonable
MT79	Quartz latite radial dike, Mount Taylor	2.87±0.08	″	Reasonable
MT3	Quartz latite flow, Mount Taylor	2.79±0.05	″	Reasonable
MT27	Quartz latite flow, Mount Taylor	2.64±0.08	″	Reasonable
7–13–3	Hornblende latite flow, Mount Taylor	2.60±0.05	″	Reasonable
MT97	Hornblende latite flow, Mount Taylor	2.52±0.07	″	Reasonable
MT135	Latite flow, Mount Taylor	2.37±0.14	″	Reasonable
MT38	Latite flow, Mount Taylor	1.50±0.06	″	Reasonable
MT138	Basanite flow, Mount Taylor	3.26±0.31	″	Reasonable
MT9	Basanite, basal flow on NW edge of Horace Mesa	3.73±0.09	″	Reasonable
MT7	Basalt, basal flow on SE edge of La Jara Mesa	2.89±0.07	″	Reasonable
MT22	Basalt, upper flow on north end of Horace Mesa	2.01±0.05	″	Reasonable

TABLE 2—Summary of published radiometric ages for the Zuni–Bandera volcanic field.

Sample no.	Unit	Age (Ma)	Reference	Evaluation
FL–3–74	Fence Lake flow	1.41±0.29	Laughlin et al. (1979)	Too old
BR–2–74	Black Rock flow on Zuni River	0.70±0.55	″	Reasonable but large error
B–1–74	Flow beneath Bandera Crater	0.199±0.042	″	Reasonable
AWL–2–77	Laguna flow	1.57±0.26	″	Too old
AWL–1–86	Laguna flow	0.128±0.033	Champion and Lanphere (1988)	Reasonable
—	Laguna flow	0.38±0.25	Lipman and Mehnert (1979)	Reasonable
—	Big plag. basalt near Cerro Rendija	3.80±0.40	Ander et al. (1981)	Too old
—	North Plains basalt	3.70±0.40	″	Too old
—	Cerro Alto basalt	1.50±0.30	″	Too old
—	Cerro Brillante basalt	0.94±0.40	″	Questionable

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TABLE 3—K–Ar ages of Zuni–Bandera and Mount Taylor basalts.

Sample no. and locality in Fig. 1	Description & location	K content (%)		Radiogenic ^{40}Ar (pm/g)		Atmospheric ^{40}Ar (%)		Age (Ma)
		Individual	Mean	Individual	Mean	Individual	Mean	
157 (1)	Groundmass feldspar concentrate, basalt; lower flow, southeast end of Horace Mesa near Grants; 35°05′10″N, 107°42′30″W	0.534 0.535 0.533 0.525 0.519	0.529	3.084 2.922 2.903 2.985	2.974	40.2 53.3 52.5 49.4	48.9	3.238 ± 0.085
158 (2)	Groundmass feldspar concentrate, basalt; high mesa surface on southeast flank of Mount Taylor 1 km north of Wheat Mountain; 35°10′33″N, 107°25′21″W	1.275 1.266 1.283 1.272 1.283 1.271 1.284	1.276	6.319 6.648 6.423 6.515 6.512	6.483	80.1 80.4 82.7 80.1 80.8	80.8	2.928 ± 0.120
160 (3)	Groundmass feldspar concentrate, basalt; Black Mesa; 35°10′33″N, 107°52′34″W	0.550 0.544 0.547 0.555 0.557 0.537	0.548	2.409 2.410 2.471 2.494 2.452	2.447	84.4 85.1 85.3 84.6 84.8	84.8	2.573 ± 0.130
NMG–89–107 (4)	Groundmass feldspar concentrate, basaltic andesite; lowermost flow, Flower Mountain; 35°02′59″N, 107°52′34″W	1.575 1.554 1.562 1.558	1.562	6.411 6.523 6.570 6.477 6.409	6.478	45.5 42.2 46.2 44.8 43.1	44.4	2.390 ± 0.057
AWL–5–89 (5)	Groundmass feldspar concentrate, basalt flow on North Plains; 34°44′55″N, 108°04′30″W	0.640 0.653 0.646 0.633 0.631 0.629 0.620 0.619	0.635	0.565 0.962	0.764	95.4 93.1	94.3	0.694 ± 0.126
AWL–1–90 (6)	Groundmass feldspar concentrate, basalt flow on Nort Plains; same site as AWL–5–89; 34°44′55″N, 108°04′30″W	0.514 0.536 0.516 0.525 0.516 0.527	0.522	0.757 0.524 0.641 0.766 0.555 0.644 0.703	0.656	89.7 95.5 93.1 88.3 94.1 93.1 89.7	91.9	0.724 ± 0.102
AWL–3–90 (7)	Groundmass feldspar concentrate, basalt flow on North Plains; 34°37′17″N, 108°15′00″W	0.498 0.520 0.497 0.504	0.505	0.541 0.501 0.514 0.520	0.519	96.4 96.7 94.3 96.6	96.0	0.593 ± 0.086
153 (8)	Groundmass feldspar concentrate, basalt; Black Rock flow along the Zuni River; previous apparent age was 0.700 ± 0.550 Ma; 35°05′12″N, 108°44′18″W	0.476 0.486 0.500 0.498 0.472	0.486	0.137 0.151 0.134 0.132	0.139	97.8 98.0 92.2 88.1	94.0	0.164 ± 0.035

sumably because of the presence of excess ^{40}Ar. Additional geological and geochronological work indicates that only the 0.94 ± 0.40 Ma age on the Cerro Brillante flow could be close to correct.

Analytical methods

Most of the ages reported here were obtained at the University of Arizona and Case Western Reserve University using the methods of Damon et al. (1983) and Hart (1982), respectively. One K–Ar age was obtained from a commercial laboratory. The ^{40}Ar/^{39}Ar age determinations were made at the New Mexico Geochronology Research Laboratory. Whole-rock major-element analyses were performed at Los Alamos by XRF analysis using procedures described by Vaniman et al. (1982).

Results and discussion

The results of our new geochronological work are presented in Tables 3–5 and in Figs. 2–6. The chemical compositions of these basalts are given in Table 6, and a Harker diagram showing the variation of $Na_2O + K_2O$ vs. SiO_2 in these samples is presented in Fig. 7.

Mount Taylor and Cebollita Mesa volcanic fields

Two dozen previously published K–Ar ages provide a reasonably detailed chronology of the MTVF (Table 1). We present four new ages from the MTVF, which were obtained to refine the ages of Pliocene geomorphic surfaces and their relationship to the magmatic evolution of the MTVF. We also report K–Ar and ^{40}Ar/^{39}Ar ages on basalts capping Cebollita Mesa.

Volcanic rocks of the MTVF erupted on two major Pliocene surfaces (Ortiz and Wheat Mountain) that are separated by

TABLE 3—continued.

Sample no. and locality in Fig. 1	Description & location	K content (%)		Radiogenic ^{40}Ar (pm/g)		Atmospheric ^{40}Ar (%)		Age (Ma)
		Individual	Mean	Individual	Mean	Individual	Mean	
AWL–2–89 (9)	Groundmass feldspar concentrate, basalt from north wall of lava tube from Cerrito Arizona; 34°57′46″N, 108°,07′38″W	0.824 0.814 0.820 0.822 0.817 0.815 0.796	0.815	0.153 0.296 0.177	0.209	99.3 98.6 99.2	99.0	0.148±0.087
AWL–6–90 (10)	Groundmass feldspar concentrate, vesicular aa basalt on a small remnant of a flow top; flow east of El Morro, north side of NM–53; 35°02′40″N, 108°24′28″W	0.397 0.405 0.395 0.403 0.399 0.406 0.402	0.401	-0.078 0.104 0.150 0.060 -0.500 0.082 0.062 0.188 0.062 0.177	0.076	100.2 99.5 97.9 99.3 100.3 98.6 100.0 99.7 99.9 99.1	99.5	0.109±0.044
AWL–10–80 (11)	Groundmass feldspar concentrate, basalt, (Laguna flow); 35°07′31″N, 107°20′33″W	0.934 0.934 0.939 0.937	0.936	0.093 0.102 0.090 0.061 0.125 0.149 -0.003	0.088	99.7 99.7 99.8 99.8 99.6 99.9 100.0	99.8	0.054±0.050
63 (12)	Groundmass feldspar concentrate, basalt, (Laguna Pueblo flow); 35°02′34″N, 107°20′33″W	0.712 0.698 0.692 0.707 0.692 0.687 0.673	0.694	0.111 0.099 0.166 0.152	0.132	98.1 99.7 98.4 99.2	98.9	0.110±0.076
	Reanalysis of sample 63	0.695 0.701 0.709 0.720 0.685 0.704 0.699 0.715 0.720	0.705	0.149 0.110 0.176 0.153	0.147	97.7 99.5 98.4 99.5	98.8	0.120±0.073
AWL–19–92 (13)	Whole-rock basalt, maar volcano on Cebollita Mesa		0.548		3.34	89.7		3.51±0.61
AWL–21–92 (14)	Whole-rock basalt, Cerro Pelon		1.19		7.68	50.4		3.73±0.08
AWL–22–92 (15)	Whole-rock basalt, basal flow in Cebollita Mesa	0.606 0.586 0.622	0.605	5.48 5.18 6.18	5.60	86.4 83.6 75.4	81.8	5.3±0.3
″	″		0.564		4.69		57.1	4.79±0.14

50–100 m (164–328 ft) of relief (Moench and Schlee, 1967; Bachman and Mehnert, 1978; Lipman and Mehnert, 1979; Drake et al., 1991). Previously dated lava flows lying on the higher Ortiz surface (Mesa Chivato, La Jara Mesa, southeast flank of Mount Taylor, northeast Horace Mesa) range in age from 2.9 to 3.7 Ma. The only age previously reported for a basalt lying on the lower Wheat Mountain surface was 2.4 Ma (Lipman and Mehnert, 1979), indicating that 50–100 m (164–328 ft) of incision occurred between 2.9 and 2.4 Ma.

Basalts capping the higher surface around Mount Taylor (samples 157 and 158) yielded ages of 3.24 and 2.93 Ma (Table 3), confirming previous results. Two basalts (samples 160 and NMG–89–107) from Black Mesa and Flower Mountain that lie on the lower surface were also dated. These samples yielded ages of 2.57 and 2.39 Ma, respectively. The new ages indicate that the age of the Wheat Mountain surface is between 2.6 and 2.4 Ma and that rates of incision were between 0.1 and 0.3 m/ka (0.3 and 1.0 ft/ka) between formation of the Ortiz and Wheat Mountain surfaces. In contrast, incision rates dropped to an average of about 0.06 m/ka (0.2 ft/ka) between formation of the Wheat Mountain surface and a third surface, the Mush Mountain. The latter, which is overlain in places by basalts of the ZBVF, yielded an age of about 0.8 Ma (Drake et al., 1991). The relatively high incision rates between 2.9 and 2.6–2.4 Ma correspond to the period of maximum eruptive activity of intermediate to felsic magmas (Perry et al., 1990) and of basaltic magmas (Perry

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TABLE 4—^{40}Ar/^{39}Ar analytical data for basalts of Cebollita Mesa. ^{40}Ar* = radiogenic ^{40}Ar.

Temp. °C	^{40}Ar/^{39}Ar^{1,2}	^{37}Ar/^{39}Ar^{1,2,3}	^{36}Ar/^{39}Ar^{1,2}	^{40}Ar*/^{39}Ar$_K$	Moles ^{39}Ar$_K$	% ^{39}Ar$_K$	% ^{40}Ar*^{2}	Age (Ma)	Error (Ma) (± 1 σ)
AWL–19–92, Cebollita basalt (J = 0.000176 wt. = 50.3 mg)									
625	119.4896	1.0697	0.3557	14.4526	1.3973E-16	3.0	12.1	4.57	0.69
700	91.6262	2.4962	0.2701	12.0102	9.3290E-16	19.8	13.1	3.79	0.19
750	61.1657	3.9150	0.1679	11.8524	1.5566E-15	33.0	19.3	3.74	0.08
850	31.8443	5.6152	0.0649	13.1212	1.2073E-15	25.6	41.0	4.15	0.05
950	29.6814	7.6620	0.0654	10.9953	4.0920E-16	8.7	36.9	3.47	0.10
1200	76.2922	31.6883	0.2299	10.9959	3.9726E-16	8.4	14.1	3.47	0.21
1450	78.9191	121.2418	0.2673	10.0546	7.4827E-17	1.6	11.7	3.18	0.69
Plateau	700–850							4.04	0.13
AWL–21–92, Cebollita basalt (J = 0.000172 wt. = 50.6 mg)									
625	16.0296	1.0860	0.0261	8.3894	4.0475E-14	11.0	52.3	2.65	0.07
650	15.2888	0.8658	0.0220	8.8528	3.6375E-14	9.9	57.9	2.80	0.05
750	14.2290	0.7706	0.0099	11.3596	7.4503E-14	20.3	79.8	3.59	0.04
850	14.5306	0.7710	0.0119	11.0680	8.9433E-14	24.4	76.1	3.50	0.02
950	15.6875	1.2156	0.0152	11.2915	4.0550E-14	11.0	71.9	3.57	0.06
1200	20.3396	7.4954	0.0327	11.2821	6.6841E-14	18.2	55.2	3.56	0.05
1450	35.3429	15.3248	0.0805	12.8474	1.8854E-14	5.1	36.0	4.06	0.15
Plateau	850–1200							3.51	0.03
AWL–22–92, Cebollita basalt (J = 0.000174 wt. = 54.2 mg)									
600	26.6183	4.8275	0.0679	6.9291	5.7060E-17	0.7	25.9	2.19	0.36
625	24.2736	4.8066	0.0389	13.1661	6.0737E-16	7.5	54.1	4.16	0.07
750	23.4590	4.1808	0.0368	12.9269	1.5691E-15	19.3	54.9	4.08	0.04
850	17.8306	3.6602	0.0188	12.5733	1.7699E-15	21.8	70.3	3.97	0.02
950	21.3311	2.9586	0.0304	12.5891	1.5679E-15	19.3	58.9	3.98	0.03
1200	35.9088	4.8478	0.0805	12.5276	2.3774E-15	29.2	34.8	3.96	0.04
1450	50.8923	84.5350	0.1530	12.8751	1.8762E-16	2.3	23.9	4.07	0.21
Plateau	850–1450							3.97	0.02

[1] Corrected for interfering reactions (^{40}Ar/^{39}Ar)$_K$ = 0.025, (^{36}Ar/^{37}Ar)$_{Ca}$ = 0.00026, (^{39}Ar/^{37}Ar)$_{Ca}$ = 0.0007

[2] Blank corrected

[3] Corrected for ^{37}Ar decay

et al., 1990; Fig. 5). Both incision and volcanism may be related to a period of increased tectonism.

Three basalt samples from Cebollita Mesa were dated by both the conventional K–Ar and ^{40}Ar/^{39}Ar methods, and one sample (AWL–22–92) was dated by the K–Ar method in two different laboratories. Analytical data for these age determinations are given in Tables 3 and 4. Age spectra for the ^{40}Ar/^{39}Ar measurements are given in Figs. 2–4. For ease of comparison the apparent ages are summarized in Table 5. With the exception of the commercially obtained apparent age of 5.3 ± 0.3 Ma for sample AWL–22–92, there is excellent agreement between the conventional K–Ar and ^{40}Ar/^{39}Ar methods, and the age spectra show no evidence of the presence of excess ^{40}Ar in these samples. We conclude that, as suspected, the basalts of the CMVF were erupted at the same time as the high mesa basalts of the MTVF (Figs. 5 and 6).

Radiometric ages on basalts overlying the Ortiz surface within the MTVF and CMVF are very similar to the ages (2.94, 3.67, and 3.87 Ma) of tholeiitic basal basalts on mesa tops east of Springerville, Arizona, reported by Laughlin et al. (1979, 1980), suggesting that the Ortiz surface is correlative with the Zuni surface of western New Mexico and eastern Arizona (Cooley and Akers, 1961; S. G. Wells, unpubl. data 1991). Baldridge et al. (1987) suggested that the Ortiz surface in the Sierra Luceros may be compound because basalt flows of different ages (4.1 and 3.3 Ma) overlie surfaces of different elevations (Mesa Lucero and Mesa del Oro, respectively). Geochronological data from the Springerville, Mount Taylor, Cebollita Mesa, and Sierra Lucero volcanic fields (Fig. 6) strongly suggest that the Zuni/Ortiz surface was developed during a gap in volcanism extending from about 6–5.3 to 4 Ma. The cause of the reinitiation of volcanism at about 4 Ma over this large area is unknown, but, as pointed out by Baldridge et al. (1987), the lull extending

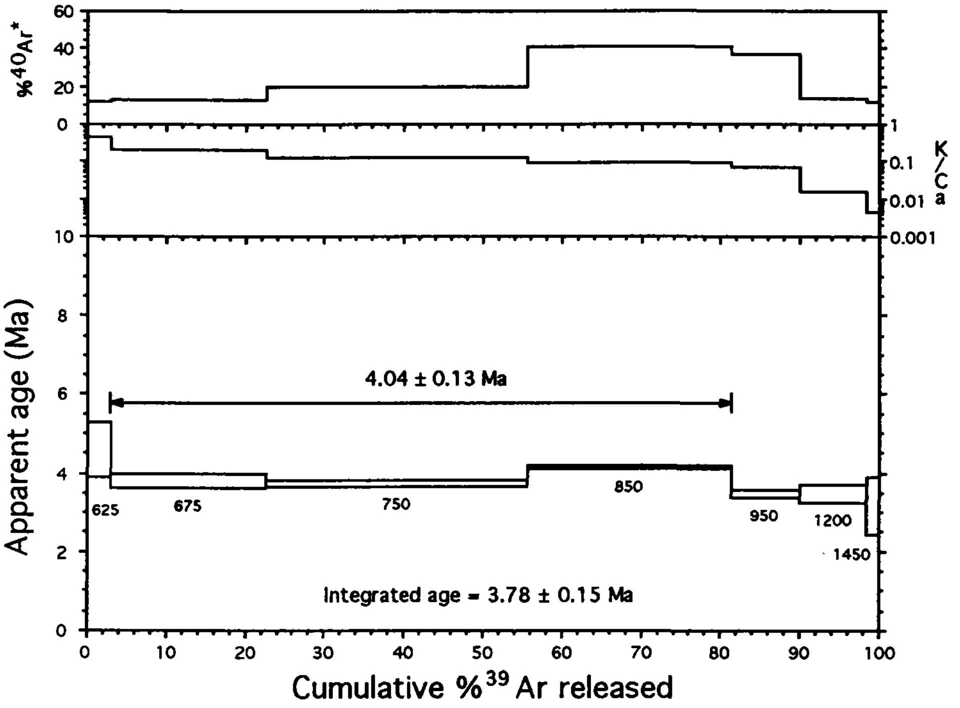

FIGURE 2—Age spectrum for sample AWL–19–92.

TABLE 5—Summary of K–Ar and $^{40}Ar/^{39}Ar$ ages for basalts of Cebollita Mesa volcanic field.

Sample no.	Location	Material	Method	Age (Ma)
AWL–19–92	Wall of maar	Whole rock	K–Ar	3.51 ± 0.61
			$^{40}Ar/^{39}Ar$ (Plat.)	4.04 ± 0.13
			$^{40}Ar/^{39}Ar$ (Integ.)	3.78 ± 0.15
AWL–21–92	Cerro Pelon	Whole rock	K–Ar	3.73 ± 0.08
			$^{40}Ar/^{39}Ar$ (Plat.)	3.51 ± 0.03
			$^{40}Ar/^{39}Ar$ (Integ.)	3.42 ± 0.09
AWL–22–92	Basal flow on mesa top	Whole rock	K–Ar	5.3 ± 0.3
			K–Ar	4.79 ± 0.14
			$^{40}Ar/^{39}Ar$ (Plat.)	3.97 ± 0.02
			$^{40}Ar/^{39}Ar$ (Integ.)	3.99 ± 0.04

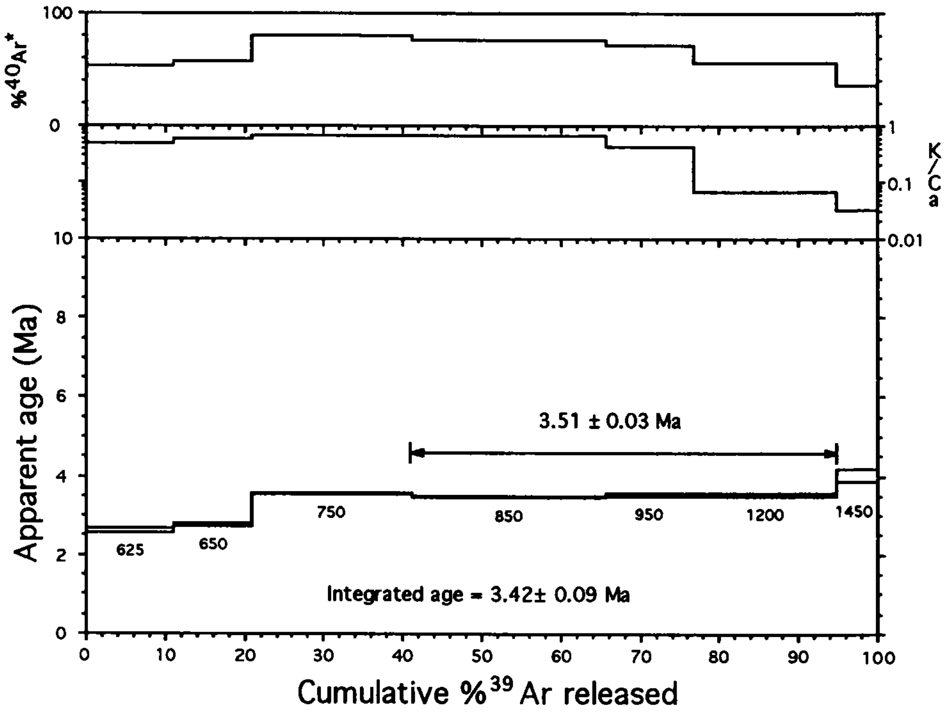

FIGURE 3—Age spectrum for sample AWL–21–92.

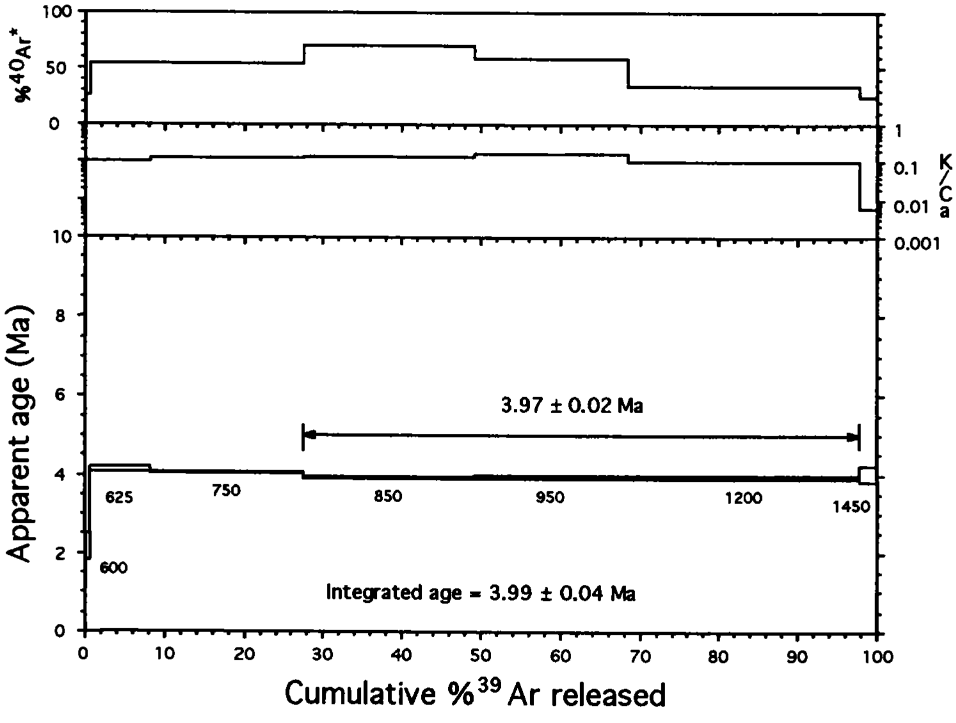

FIGURE 4—Age spectrum for sample AWL–22–92.

to 4 Ma is widespread on the southeastern Colorado Plateau and in the central Rio Grande rift but not on the Great Plains.

Basalts from Black Mesa (sample 160), Horace Mesa (sample 157), and the southeastern flank of Mount Taylor (sample 158) are evolved hawaiites typical of those erupted throughout the history of the MTVF (Perry et al., 1990). In contrast, basalts of Cebollita Mesa (AWL–19–92, AWL–20–92, AWL–21–92, AWL–22–92) range from tholeiitic to strongly alkaline. The two basal basalts (AWL–19–92 and AWL–22–92) are tholeiitic. Cebollita Peak (AWL–20–92), one of the shield volcanoes, is a mildly alkaline basalt, while Cerro Pelon (AWL–21–92), another shield, is an alkaline basalt very similar in composition to the high mesa basalts of the MTVF.

The basalt from Flower Mountain (NMG–89–107) is an alkali olivine basalt distinguished from hawaiites of the MTVF by its primitive composition (Mg number = 66 vs. 63–49 for MTVF hawaiites) indicating less fractionation from a primary, mantle-derived basalt and more rapid ascent through the crust. This basalt may have ascended more rapidly through the crust because it was farther from the magmatic focus of the MTVF.

Zuni–Bandera volcanic field

Examination of Landsat and aerial-photo imagery of the ZBVF suggests that the Fence Lake flow and the basalts of the North Plains are similar in age and are the oldest flows within the field. Ander et al. (1981) reported an age of 3.70 ± 0.40 Ma for one of the North Plains basalts (Table 2). Because original flow features are well preserved on the surface of this flow and because the flow covers the present valley floor, it is believed that this age is too old. For this report, basalts from two new sites on the North Plains were dated (AWL–5–89, AWL–1–90, AWL–3–90). At one site, two different samples were dated. Ages of 0.694 ± 0.126, 0.724 ± 0.102, and 0.593 ± 0.086 Ma on these samples (Table 3) are concordant and agree with results of 0.60–0.70 Ma obtained by McIntosh, WoldeGabriel, and Laughlin for the Fence Lake flow (unpubl. data 1993). Because the Fence Lake flow is currently the subject of intensive study by McIntosh, WoldeGabriel, and Laughlin using both the

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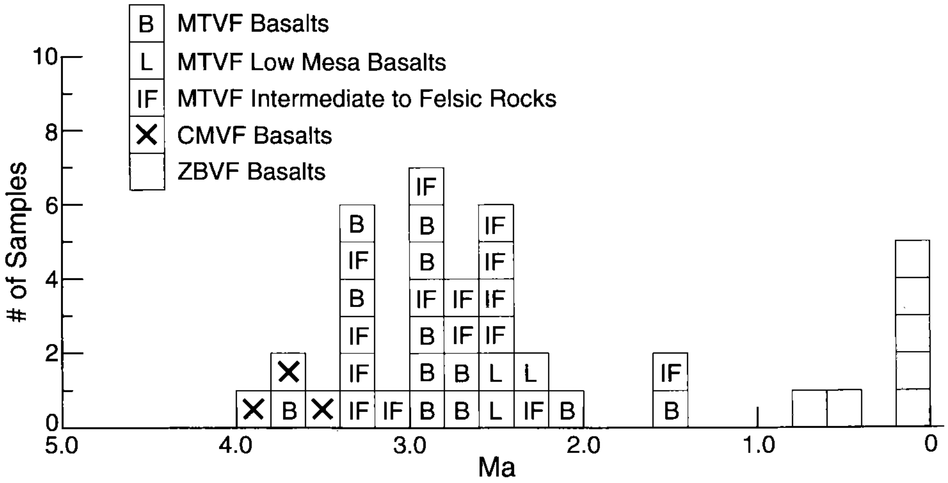

FIGURE 5—Histogram of K–Ar and ^{40}Ar/^{39}Ar ages for the Mount Taylor (MTVF), Cebollita Mesa (CMVF), and Zuni–Bandera (ZBVF) volcanic fields. Ages are from this work and references cited in Tables 1 and 2. Only one age is shown for each flow.

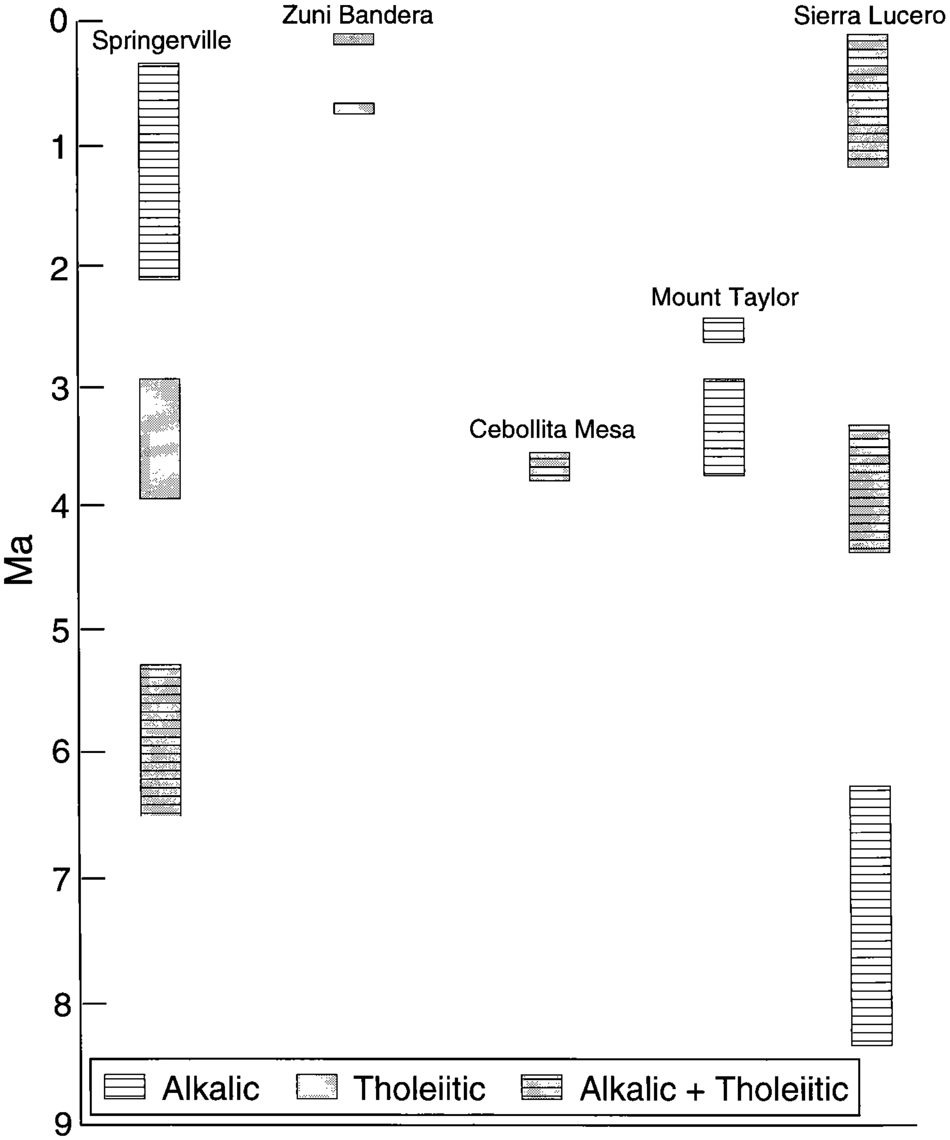

FIGURE 6—Duration of basaltic volcanism in the Springerville, Zuni–Bandera, Cebollita Mesa, Mount Taylor, and Sierra Lucero volcanic fields. Modified from Baldridge et al. (1987). Geochronological data for the Springerville volcanic field taken from Laughlin et al. (1979, 1980), Condit et al. (1989), and Cooper et al. (1990).

conventional K–Ar and ^{40}Ar/^{39}Ar methods, these results will be reported later.

Laughlin et al. (1979) reported an age of 0.199 ± 0.042 Ma (Table 2) for the basalt covering the valley floor west of Bandera Crater and an age of 0.700 ± 0.550 Ma (Table 2) for the basalt at Black Rock in the Zuni River valley near the Zuni Pueblo. The large error on the Black Rock sample does not preclude the possibility that these two samples are concordant in age. We have recollected and dated the flow from the Black Rock site (sample 153), obtaining an age of 0.164 ± 0.035 Ma (Table 3), suggesting that the Black Rock flow is the same age as the flow west of Bandera Crater, although their compositions are distinctly different. A sample of basalt (AWL–6–90), also lying on the present valley floor, was collected from near the entrance to El Morro National Monument along NM–53. This sample yielded an age of 0.109 ± 0.044 Ma (Table 3), further indicating an age of about 0.15 Ma for flows covering the present valley floor west of Bandera Crater. A fourth sample (AWL–2–89), from the wall of a lava tube emerging from the Cerrito Arizona cone north of Cerro Rendija, also yields an age of about 0.15 Ma. This lava tube collapsed and was later filled by the basalt flow from Bandera Crater. Flow albedo on Landsat imagery suggests that the Cerrito Arizona flow should be correlative with the 0.199 Ma flow beneath Bandera Crater, and this was confirmed by an age of 0.148 ± 0.087 Ma (Table 3).

As discussed above, the original age on the Laguna flow (Laughlin et al., 1979), which lies beneath McCarty's flow along I–40 about 5 km (3 mi) east of Grants was believed to be anomalously old. A new sample (AWL–10–80) from near the original site yielded an age of 0.054 ± 0.050 Ma. Because the error on this sample is very large, it is concordant with the 0.128 ± 0.033 Ma age of Champion and Lanphere (1988) on a sample from near the intersection of I–40 and NM–117. Maxwell (1986) suggested that the Laguna flow originated from the El Calderon cone (Fig. 1) near the north-central part of the ZBVF. A flow of similar composition covers the floor of the San Jose River valley near Laguna Pueblo. Drake et al. (1991) interpret this as the distal end of the Laguna flow with the part of the flow between the town of McCartys and Laguna Pueblo being buried by alluvium. The results of chemical and Sr and Nd isotopic analyses (Table 6; Perry et al., 1987) of the Laguna flow at the I-40–NM-117 intersection, the flow at Laguna Pueblo, and the flow at El Calderon are permissive of this interpretation. Duplicate age determinations run on a sample (63) collected near the pueblo yielded ages of 0.110 ± 0.076 and 0.120 ± 0.073 Ma. The combination of chemical and geochronological results suggests that these two flows may indeed be the same and that the age is about 110–128 ka.

TABLE 6—Whole-rock chemical compositions of Zuni–Bandera and Mount Taylor basalts; * = average of two samples, ** = Laughlin et al. (1979).

	North Plains AWL-1-90*	**North Plains AWL-3-90***	**Fence Lake FL-3-74****	**Ramah AWL-5-90***	**Ramah AWL-7-92***	**El Morro AWL-6-90***	**El Morro AWL-13-91***	**Black Rock BR-2-74****
SiO_2	50.66	52.06	50.22	49.91	50.70	51.23	52.26	48.25
TiO_2	1.42	1.45	1.34	1.33	1.17	1.22	1.28	1.36
Al_2O_3	15.15	15.72	15.25	15.44	15.05	15.42	15.49	15.40
Fe_2O_3	12.01	10.95	1.62	12.34	11.66	11.40	11.63	1.77
FeO	—	—	10.01	—	—	—	—	10.42
MnO	0.16	0.15	0.17	0.17	0.16	0.16	0.16	0.17
MgO	8.42	6.34	8.40	8.36	8.34	8.29	8.23	9.84
CaO	9.15	9.99	9.30	9.96	9.57	9.38	9.55	8.99
Na_2O	2.85	2.78	2.64	2.44	2.44	2.52	2.52	2.71
K_2O	0.62	0.66	0.42	0.18	0.36	0.41	0.44	0.50
P_2O_5	0.19	0.22	0.16	0.18	0.14	0.18	0.17	0.17
Total	100.63	100.32	99.53	100.31	99.59	100.21	101.73	99.58
Mg#	62	58	54	61	63	63	62	65
Ba	335	445		464	119	412	144	
Rb	10	14	10	4	10	6	7	5
Sr	254	268	243	212	229	240	244	244
V	251	251		249	166	232	241	
Cr	248	130		240	294	222	219	
Ni	146	84		168	190	169	145	
Zn	55	67		72	93	66	105	
Y	20	23		24	14	20	20	
Zr	104	122		86	79	95	91	
Nb	12	12		12	17	12	12	

TABLE 6—continued.

	Black Rock 153*	**Bandera B-1-74****	**Bandera AWL-12-91***	**Laguna AWL-8-91***	**Laguna Pueblo AWL-11-92***	**El Calderon AWL-5-92***	**McCartys AWL-9-91***	**Bluewater AWL-10-91***	**Bluewater AWL-4-92***
SiO_2	47.48	46.76	44.45	50.99	49.34	49.79	51.48	53.02	51.62
TiO_2	1.36	2.05	2.85	1.60	1.22	1.48	1.41	1.29	1.25
Al_2O_3	15.16	15.25	14.74	14.59	15.16	14.65	15.18	15.32	15.13
Fe_2O_3	13.12	4.40	13.06	12.39	12.48	12.04	11.87	11.61	11.49
FeO	—	7.18	—	—	—	—	—	—	—
MnO	0.18	0.17	0.18	0.17	0.17	0.17	0.16	0.16	0.16
MgO	10.11	9.38	10.32	8.77	8.59	8.43	8.29	7.55	7.42
CaO	9.13	9.20	9.44	8.88	8.82	8.87	9.11	9.47	9.30
Na_2O	2.76	3.09	3.53	2.87	2.86	2.90	2.78	2.60	2.60
K_2O	0.45	1.34	1.70	0.76	0.58	0.73	0.69	0.45	0.42
P_2O_5	0.17	0.49	0.65	0.23	0.17	0.21	0.19	0.16	0.15
Total	99.92	99.31	100.92	101.25	99.39	99.27	101.16	101.63	99.54
Mg#	64	64	65	62	62	62	62	60	60
Ba	200		233	231	164	190	270	240	120
Rb	8	10	16	16	17	17	14	9	12
Sr	291	672	747	271	251	301	254	212	229
V	179		389	268	177	165	252	231	166
Cr	380		188	270	301	331	222	186	241
Ni	233		136	152	197	182	123	107	155
Zn	101		101	75	99	106	97	90	100
Y	16		25	26	16	22	25	20	16
Zr	101		241	137	96	124	117	89	88
Nb	21		28	12	19	22	12	12	18

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Our new ages for the ZBVF suggest that the eruption of basaltic lavas within the field was episodic. Large areas in the southern part of the field were covered by the tholeiitic North Plains and Fence Lake flows at about 0.700 Ma. These flows were very fluid and flowed long distances (up to 100 km; 60 mi) both east and west from the present location of the Continental Divide where the vents for these circa 0.700 Ma flows are apparently covered by flows and cinder cones of the Chain of Craters. Examination of Landsat imagery and aerial photos suggests that these lavas also may have flowed to the north through the valley west of El Morro. Volcanism then lapsed until approximately 0.200 Ma when tholeiitic and alkalic lavas began erupting in the central part of the field. This pulse continued until about 0.110 Ma. Tholeiitic lavas from this pulse were also very fluid. If El Calderon cone is the source of the Laguna flow (Maxwell, 1986), then this flow must have traveled about 66 km (41 mi) to its distal end near Laguna Pueblo. Other lavas of this age flowed westward down the valleys of the Rio Pescado and Zuni River terminating at Black Rock near Zuni Pueblo. These 0.200–0.110 Ma flows may have buried the 0.700 Ma flows north and west of El Morro.

Landsat and aerial-photo imagery suggests another gap in volcanism between eruption of the Laguna flow at about 0.110–0.128 Ma and eruption of the very young flows, e.g. McCartys and Bandera flows of the ZBVF. Work in progress on the dating of these very young flows using the ^{14}C, ^{3}He, $^{40}Ar/^{39}Ar$, and U-series methods will be reported later.

Chemical compositions of ZBVF basalts reported in Table 6 support the previous conclusions of Laughlin et al. (1972b) and Menzies et al. (1991) that both tholeiitic

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TABLE 6—continued.

	Oso Ridge AWL-11-91*	Horace Mesa 157*	Wheat Mountain 158*	Black Mesa 160*	Flower Mountain NMG-89-107*	Cebollita Mesa maar AWL-19-92*	Cebollita Peak AWL-20-92*	Cerro Pelon AWL-21-92*	Cebollita Mesa basal flow AWL-22-92*
SiO_2	46.36	48.30	47.57	48.89	46.60	50.00	49.50	47.31	49.50
TiO_2	2.48	2.75	2.76	2.41	2.34	1.47	1.69	2.02	1.63
Al_2O_3	15.91	15.95	15.91	16.66	13.65	15.67	16.07	15.44	15.15
Fe_2O_3	13.96	12.62	12.82	11.88	11.58	12.31	12.54	11.94	12.52
FeO	—	—	—	—	—	—	—	—	—
MnO	0.17	0.16	0.17	0.18	0.16	0.16	0.16	0.17	0.16
MgO	5.77	5.75	6.35	3.98	9.46	7.05	6.32	8.65	7.68
CaO	7.47	7.99	8.56	7.69	9.36	8.95	9.10	8.70	8.75
Na_2O	5.33	3.85	3.85	4.31	3.40	3.24	3.56	3.63	3.14
K_2O	2.38	1.37	1.31	1.64	1.70	0.69	0.77	1.40	0.69
P_2O_5	0.92	0.66	0.64	0.89	0.74	0.18	0.23	0.42	0.19
Total	100.75	99.40	99.94	98.53	98.99	99.72	99.94	99.68	99.41
Mg#	49	52	54	44	66	57	54	63	59
Ba	444	388	420	564	816	227	278	434	280
Rb	21	25	23	29	33	17	12	21	11
Sr	1182	634	691	753	855	293	380	587	324
V	296	173	173	117	189	185	196	196	179
Cr	72	100	136	62	354	234	109	217	227
Ni	46	72	90	38	181	130	82	136	134
Zn	173	123	114	90	113	104	73	75	106
Y	19	24	21	31	20	27	27	28	25
Zr	325	211	218	255	217	105	128	179	113
Nb	37	46	47	53	54	15	16	36	17

and alkalic basalts were erupted within the ZBVF (Fig. 7). Our work, however, suggests that the 0.700–0.600 Ma pulse was exclusively tholeiitic and that it was only during the two youngest pulses of volcanism that alkalic and tholeiitic basalts were erupted. A similar change in composition with time was reported for the Springerville volcanic field by Condit et al. (1989).

Effusion rates of volcanism

It is interesting to compare basalt effusion rates in the CMVF, MTVF, and ZBVF to rates in other volcanic fields around the boundaries of the Colorado Plateau. Comparisons for seven volcanic fields in New Mexico and Arizona are presented in Table 7. These rates vary from 2 km^3/m.y. (0.5 mi^3/m.y.) in the low volume–long duration Sierra Lucero volcanic field to 300 km^3/m.y. (72 mi^3/m.y.) for the large volume–long duration San Francisco volcanic field. Results for the San Francisco volcanic field are not directly comparable to those from the other fields, however, because for the San Francisco field, volumes of intermediate to felsic rocks were included with the basalts. For the three volcanic fields under consideration in this paper, the slightly older (Fig. 5) CMVF has an effusion rate of 18 km^3/m.y. (4.3 mi^3/m.y.), the MTVF has a rate of 12 km^3/m.y. (2.9 mi^3/m.y.), and the youngest field, the ZBVF, has a rate of 105 km^3/m.y. (25 mi^3/m.y.; Table 7). This pattern of increasing rate with decreasing age is similar to that reported by Tanaka et al. (1986) for the San Francisco volcanic field. In contrast, Condit et al. (1989) report that in the Springerville volcanic field, effusion rates decreased steadily from a maximum of 246 km^3/m.y. (59 mi^3/m.y.) between 2.0 and 1.0 Ma to cessation of volcanism at 0.3 Ma.

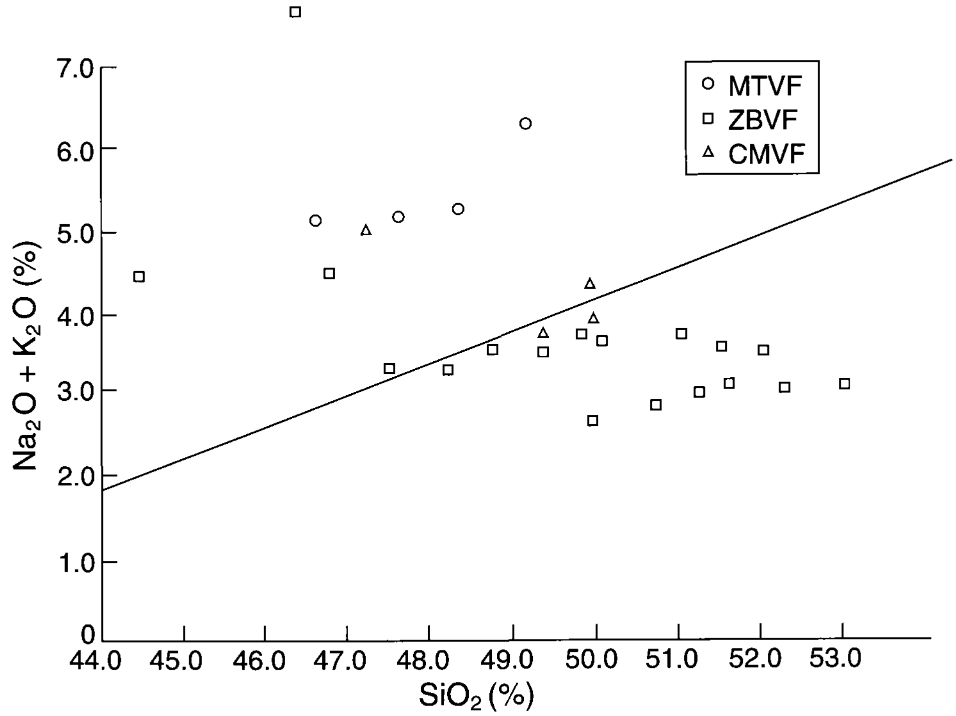

FIGURE 7—Harker diagram showing variation of $Na_2O + K_2O$ vs. SiO_2 for basalts from the Mount Taylor (MTVF), Cebollita Mesa (CMVF), and Zuni–Bandera (ZBVF) volcanic fields.

Conclusions

Alkalic basaltic volcanism in the MTVF occurred mainly between 3.3 and 2.4 Ma, coincident with the most active period of cone growth at Mount Taylor. The oldest basalts (3.8–2.9 Ma) in both the MTVF and the CMVF overlie the Ortiz geomorphic surfaces, while younger basalts (2.6–2.4 Ma) overlie the Wheat Mountain surface indicating major incision between 2.9 and 2.6 Ma. Between 2.4 Ma and 0.800 Ma, the age of the younger Mush Mountain surface, incision rates decreased to 0.06 m/ka (0.2 ft/ka).

The previously undated basalts of the CMVF are correlative with the high mesa basalts of the MTVF and mesa-capping basalts of the Springerville and Sierra Lucero volcanic fields, suggesting that the Ortiz surface correlates with the Zuni sur-

TABLE 7—Effusion rates of basaltic volcanism. Data from ^{1}Condit et al. (1989), ^{2}Baldridge et al. (1987), ^{3}Tanaka et al. (1986), and ^{4}Duncker et al. (1991).

Volcanic field	Area (km^2)	Average thickness (m)	Volume (km^3)	Duration (m.y.)	Rate (km^3/m.y.)
Cebollita Mesa	300	30	9.0	0.5	18
Mount Taylor	880	30	26	2.2	12
Zuni–Bandera	2460	30	74	0.70	105
Springerville^1	3000	100	300	1.8	170
Sierra Lucero^2	not reported	not reported	7.3	4.2 (cum.)	2
San Francisco^3	4800	not reported	1485	5.0	300
Cerros del Rio^4	600	100	60	0.5	120

face of eastern Arizona and western New Mexico.

Basal basalt flows on Cebollita Mesa are tholeiitic in contrast to the alkaline basalts of the MTVF. Two small shield volcanoes overlying these tholeiites are mildly to strongly alkaline.

Three pulses of volcanism have been recognized within the ZBVF. An early tholeiitic pulse occurred between 0.700 and 0.600 Ma and is represented by the voluminous Fence Lake flow and the basalts of the North Plains. Both alkalic and tholeiitic basaltic volcanism occurred during the second pulse, apparently from about 0.200 to 0.110 Ma. The youngest pulse, which is represented by most of the vents within El Malpais National Monument, also consisted of alkalic and tholeiitic volcanism.

Within the three volcanic fields, basaltic effusion rates have increased with decreasing age from 18 km^3/m.y. (4.3 mi^3/m.y.) in the CMVF to 105 km^3/m.y. (25 mi^3/m.y.) in the ZBVF.

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Summary of New Mexico state taxes on natural resource production as of July 1, 1993

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Commodity	Tax	Rate and base
Potash	Resource Processor; Service* Severance	0.50% of taxable value 0.125% of taxable value 2.5% of taxable value
Molybdenum	Resource Processor; Service* Severance	0.333% of taxable value 0.75% of taxable value 0.125% of taxable value
Other taxable resources (except potash and molybdenum)	Resource; Processor; Service*	0.75% of taxable value
Copper	Severance Service; Processor* Ad valorem	0.50% of taxable value 0.75% of taxable value Mil rate depends on local county and school district (see 7-39-4, NMSA 1978)
Gold, silver	Severance	0.20% of taxable value
Lead, zinc, molybdenum, manganese, thorium, rare-earth, and other metals	Severance	0.125% of taxable value
Clay, sand, gravel, gypsum, pumice, and other nonmetals	Severance	0.125% of taxable value
Coal: surface underground	Severance Severance	$1.17 per short ton $1.13 per short ton $0.57 surtax exempt (surface) (see SB 187) $0.55 surtax exempt (underground) (see SB 187)
Uranium	Resource Severance	0.75% of taxable value 3.5% of 50% of sales price
Oil, natural gas, and carbon dioxide	Severance Ad valorem	3.75% of taxable value Many rates (counties certify annually on September 1 to Taxation and Revenue Department)
Oil, geothermal energy, carbon dioxide, coal, and uranium	Conservation School	0.18% of taxable value 3.15% of taxable value
Natural gas	Conservation School	0.18% of taxable value 4.00% of taxable value
Natural gas and hydrocarbons incidental to processing	Natural gas processor	0.45% of taxable value

*Subject to only one of these taxes at a time. Data source: Taxation and Revenue Department, P.O. Box 2308, Santa Fe, New Mexico 87504–2308 (505/827–2700). For information about severance and resource taxes contact Cindy Lovato (505/827–0812); for oil and gas taxes contact Michael Holden (505/827–0805); for copper ad valorem tax contact Richard Martinez (505/827–0895).