Cosmogenic ^{36}Cl ages of lava flows in the Zuni–Bandera volcanic field, north-central New Mexico, U.S.A.

Nelia W. Dunbar[1] and Fred M. Phillips[2]
[1]*New Mexico Bureau of Geology and Mineral Resources, New Mexico Institute of Mining and Technology, Socorro, NM 87801*
[2]*Department of Earth and Environmental Science, New Mexico Institute of Mining and Technology, Socorro, NM 87801*

Abstract

The surfaces of seven basaltic lava flows from Zuni–Bandera volcanic field were sampled for measurement of cosmogenic ^{36}Cl buildup to determine the exposure ages. Samples were collected from the following flows: McCartys, Bandera, Twin Craters, southern and northern Paxton Springs, Laguna, and Bluewater. Because exposure of the lava flows begins at emplacement, the exposure ages date the time of eruption, and provide an alternative to radiometric techniques. Given a mean erosion rate of 0 and 5 mm/ka, the estimated cosmogenic ^{36}Cl ages for Zuni–Bandera lava flows are the following: McCartys flow, 3.9 ± 1.2 ka; Bandera Crater flow, 11.2 ± 0.6 ka; South Paxton Springs, 15.0 ± 1.0 ka; Twin Craters flow 18.0 ± 1.0; North Paxton Springs 20.7 ± 2.2 ka; Laguna flow 34.7 ± 3.0 ka, Bluewater flow, 36.0 ± 3.2 ka. The exposure ages of the McCartys, Bandera, and Twin Craters flows agree very well with ^{14}C ages from carbon found under the flows and ^{3}He exposure age determinations, and the Paxton Springs lava flows are in the same age range as the Twin Craters. The Paxton Springs vent area has produced two flows separated in time by approximately 5,000 yrs. The first flowed predominantly to the north, whereas the second flowed toward the south. The ^{36}Cl age of the Bluewater flow is younger than both ^{3}He exposure age and U-Th disequilibrium ages, and very much younger than those determined by K-Ar. The ^{36}Cl age of the Laguna flow is also significantly younger than ages from the K-Ar method. The difference between the ^{36}Cl and the K-Ar ages is likely due to excess Ar in the young, K-poor basalts causing anomalously old K-Ar ages. However, the difference between the ^{3}He and ^{36}Cl ages is not as easily explained and will require further work to resolve.

Introduction

The Zuni–Bandera volcanic field, located in west-central New Mexico, consists of at least 100 individual volcanoes that have produced many lava flows and cinder cones (Laughlin et al. 1982; Laughlin et al. 1993a). The Zuni–Bandera volcanic field has been extensively mapped (Luedke and Smith 1978; Maxwell 1986), and, based on morphology, the flows appear to have been erupted at a wide range of times, including one flow that appears to be among the youngest volcanic features in New Mexico. However, because the flows are all of basaltic composition, they have proved extremely difficult to date. A field conference was convened in 1993 with the expressed purpose of sampling lava flows of various ages to be dated using a number of analytical techniques, including ^{36}Cl, ^{14}C, ^{3}He, ^{40}Ar/^{39}Ar, and U-Th disequilibrium. Many of the results presented here were determined from samples we collected during that field conference, although some samples were collected during other field visits. Accurate dating of lava flows from the Zuni–Bandera volcanic field is important for a number of reasons. First, we seek to understand the recurrence intervals of volcanic activity in this area, and to evaluate that activity in the context of recurrence intervals of volcanism in New Mexico and the southwestern U.S. as a whole. Second, we hope to provide additional information on the monogenetic or polygenetic nature of basaltic cinder cone activity. Third, the Zuni–Bandera volcanic field is an area visited by many tourists, and accurate ages of these local volcanic events would be of interest to visitors.

The method we have chosen for dating these basalts is the ^{36}Cl cosmogenic dating technique (Phillips et al. 1986). Cosmogenic dating techniques have been successfully applied to dating of geomorphically young surfaces and landforms that have intact surface features, indicating that they may have undergone little erosion (Gosse and Phillips 2001); such surfaces include glacial moraines (Phillips et al. 1997b; Zreda 1994), beach terraces, and basaltic lava flows (Anthony and Poths 1992; Dunbar 1999; Dunbar and Phillips 1994; Laughlin et al. 1994b; Phillips et al. 1997a; Zreda et al. 1993). These techniques rely on the measurement of cosmogenic nuclides that begin to build up as soon as a rock is exposed to cosmic rays. Therefore, cosmogenic techniques can be applied to dating of any surface that is composed of material that was not exposed to cosmic rays before formation of the surface, and whose exposure at the earth's surface has been close to continuous. In the case of a volcanic rock, accumulation of cosmogenic nuclides begins when the lava is erupted, so measurement of the inventory of a cosmogenic nuclide can provide an estimate of eruption age (Phillips et al. 1986). This paper reports cosmogenic ^{36}Cl determinations of the ages of seven flows from the Zuni–Bandera volcanic field.

Geological background

The Zuni–Bandera volcanic field, in west-central New Mexico, contains a sequence of mafic lava flows erupted over the last 0.7 Ma (Laughlin et al. 1993b). Laughlin et al. (1993b) recognize three distinct pulses of basaltic activity, one between 0.7 and 0.6 Ma, one between 0.2 and 0.11 Ma, and a third, youngest pulse that has been difficult to date because of its young age. At least 100 vents have been recognized in the volcanic field (Luedke and Smith 1978), and the extensive field covers an area of 2,460 km^2. Combined flow thickness is as great as 145 m in some places, and the total volume of all flows is at least 74 km^3 (Laughlin et al. 1993b).

The Zuni–Bandera field volcanism coincides with the Jemez lineament, a zone of apparent crustal weakness defined by a concentration of late Cenozoic volcanism (Laughlin et al. 1982). The Zuni–Bandera volcanic rocks erupted in a transition zone between the Colorado Plateau, where crustal thicknesses are over 40 km, and the Rio Grande rift, where the crust is much thinner. The Jemez lineament trends north-northeast and includes the Zuni–Bandera volcanic field, the Mt. Taylor volcanic field, and the Jemez volcanic field. The Jemez lineament apparently has been a long-lasting tectonic feature that penetrates the lithosphere to great depth, and the basaltic lavas of the Zuni–Bandera volcanic field are interpreted to be mantle-derived melts (Laughlin et al. 1982).

The Zuni–Bandera volcanic field consists of a large number of basaltic lava flows and cinder cones, and exhibits a number of features characteristic of Hawaiian-style volcanism. Pahoehoe and aa lavas are both represented, along with extensive lava tube systems. Nichols (1946) mapped and catalogued the geomorphic features of the apparently young McCartys basalt flow and recognized many features of Hawaiian-style volcanism, including pahoehoe flow patterns, small spatter cones, gas cavities, large wedge-shaped cracks, collapse depressions, large pressure ridges, and tumescences. These features are also present in other, apparently older flows, although in some cases they are obscured by erosion or windblown sediment.

Geochemically, the lava flows of the Zuni–Bandera volcanic field include both tholeiitic and alkaline basalts, as well as minor basaltic andesites and one basanite (Menzies et al. 1991). Observed phenocryst mineralogy includes small olivine crystals, plagioclase crystals, and pyroxene. Groundmass contains the same phenocrysts phases, as well as opaque oxides (Laughlin et al. 1972). Feldspar megacrysts, as great as 2 cm long, either of anorthoclase or oligoclase, are present in some of the alkali basalt flows (Laughlin et al. 1974).

Perry et al. (1987) suggest that late Cenozoic basaltic rocks from the Colorado Plateau–Basin and Range transition area show some isotopic characteristics of enriched mantle and some of depleted mantle, and may come from the boundary between these two mantle types. Menzies et al. (1991) suggest that the chemical composition of the Zuni–Bandera lavas is typical of intraplate volcanism, possibly with contributions from both enriched and depleted mantle sources.

Surface exposure dating using the ^{36}Cl cosmogenic dating technique

The chlorine-36 method (Phillips et al. 1986) is based on the observation that ^{36}Cl is dominantly produced by cosmic ray reactions near the surface of the earth, primarily in the upper meter of exposed rock. Production in the deeper subsurface is small by comparison. The cosmic ray reactions that produce ^{36}Cl include spallation of ^{39}K and ^{40}Ca, and thermal neutron activation of ^{35}Cl. Cosmic rays are attenuated by interaction with the earth's magnetosphere and atmosphere, so the production of ^{36}Cl is dependent on the latitude and elevation at which the sample was collected (Gosse and Phillips 2001). Cosmic rays are also attenuated by any material overlying the dated surface, such as windblown sand or snow, so in order for accurate ages to be obtained, either the surface must have remained bare since initial exposure or the cover history must be known.

Analytical methods

Samples of lava flows that retained some remnant of ropey surfaces were collected from seven flows in the Zuni–Bandera volcanic field for ^{36}Cl dating. A number of other samples were collected also, but because of the poor surface conditions of the flow and resultant unreliable results, the data will not be presented here. The flows with surfaces that we considered acceptable include the Bluewater, the Laguna flow from El Calderon vent, McCartys, Twin Craters, Bandera Crater, Paxton Springs northern, and Paxton Springs southern flows (Fig. 1, Table 1). The samples of Bluewater, Laguna, McCartys, Twin Craters, and Bandera Crater flows were collected during the 1993 basalt geochronology workshop, and detailed descriptions of how to reach the sampling locations can be found in Laughlin et al. (1993a). Samples were collected from parts of the flows whose identification and origin were unambiguous. The Laguna flow from El Calderon vent should not be confused with the Laguna Pueblo flow that lies farther to the east. These flows are not correlative (Cascadden et al. 1997). In addition to the flows sampled as part of the 1993 field trip, two flows associated with a cinder cone located 2 km north of Paxton Springs, informally called the Paxton Springs cinder cone, were sampled in the spring of 1994 (Fig. 1). One of the flows extends to the south of the cinder cone, here called Paxton Springs S, and was sampled just at the base of the cinder cone. The second flow extends to the north of the cinder cone, here called Paxton Springs N. This flow was sampled near the confluence of La Jara, Bonita, and Zuni Canyons.

The samples each consisted of approximately 500 g of lava collected as a single piece from the upper 5 cm of the flow. Where possible, well-developed pahoehoe ropes were sampled, or at least areas that exhibited some sign of ropey textures. The sample localities were on high-standing areas of the lava flow to minimize the blocking of cosmogenic rays by surrounding topography.

In the laboratory, the samples were prepared for dissolution and collection of Cl. Samples were cleaned of any organic material using a wire brush, crushed to 1-cm fragments using a hammer, and then were ground in a TEMA swing mill with a tungsten carbide vessel for approximately 30 sec. The lightly crushed material was then sieved using a 150-mesh (106-μ) sieve to remove vesicle-filling clay and zeolite minerals that could contain meteoric Cl. The >100 μ size fraction (ranging from ~100 to 1,000 μ) was then leached for 12 hrs using a 3% nitric acid (HNO_3) solution to remove any meteoric Cl from grain boundaries, as well as any carbonate material present in vesicles or micropores. Following leaching, the samples were rinsed in 18 MS deionized water, and more 3% HNO_3 was added. If no effervescence was detected, the HNO_3 was decanted, and the sample was rinsed four times in 18 MΩ deionized water. An aliquot of the clean sample was separated for elemental geochemical analysis. Extraction of Cl for ^{36}Cl analysis was accomplished using approximately 50 g of clean sample. The first step of the Cl extraction involved dissolution of the sample in a mixture of hot nitric and hydrofluoric acid. $AgNO_3$ was added to the sample to precipitate Cl released from the rock as AgCl (following the method of Zreda 1994). Once dissolution of the rock was complete, the AgCl was dissolved using NH_4OH, and the solution was separated from the rock residue. Barium nitrate solution was added to the sample to precipitate any S that was in the Cl-bearing solution (Bentley et al. 1986). The process was necessary because of the isobaric interference of ^{36}S on ^{36}Cl during the analysis of ^{36}Cl by accelerator mass spectrometry. The ^{36}Cl/^{35}Cl ratio of the final sample was measured on the purified AgCl precipitate by accelerator mass spectrometry (AMS; Elmore et al. 1979) at the Purdue Rare Isotope Measurement Laboratory (PRIME Lab).

The major element composition of the sample was determined by X-ray fluorescence analysis and B and Gd by prompt gamma emission analysis. B (boron) and Gd (gadolinium) concentrations are measured because these elements have large cross sections for absorption of thermal neutrons that could otherwise create ^{36}Cl from ^{35}Cl. In other words, B and Gd will absorb thermal neutrons that would otherwise have allowed production of ^{36}Cl from ^{35}Cl, so the presence of those elements must be taken into account. The total Cl content of the sample was determined using a combination ion-selective electrode method (Aruscavage and Campbell 1983).

The production of ^{36}Cl in rock varies with distance below the sample surface, as described by Liu et al. (1994). As a

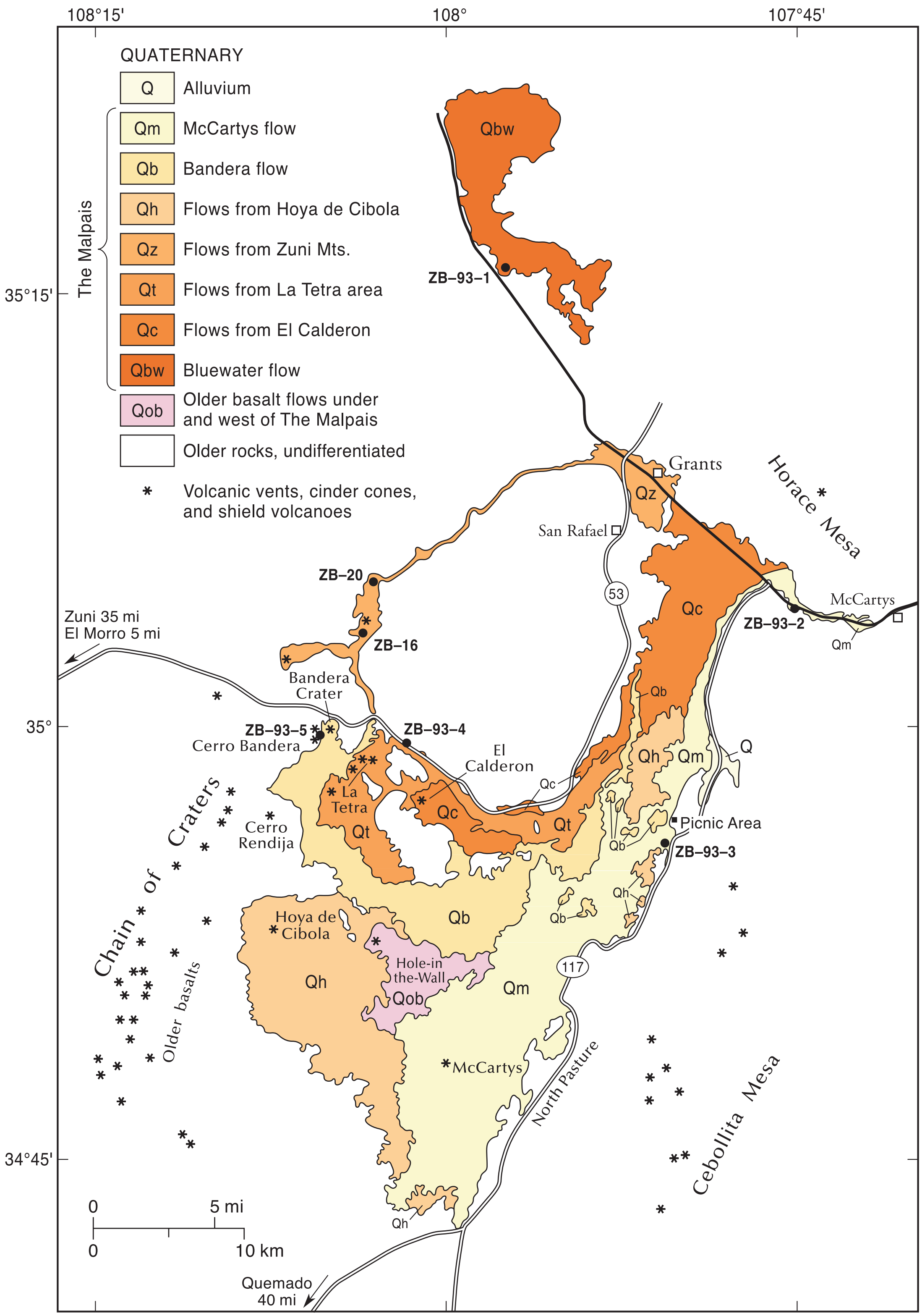

FIGURE 1—Map of the Zuni–Bandera volcanic field showing sample locations.

result, the calculated ^{36}Cl age will vary as a function of the rock surface erosion rate because the amount of ^{36}Cl in a sample that has had the surface removed by erosion will be different than the amount of ^{36}Cl in a sample of the same age and composition that has undergone no erosion. Typically, if a volcanic rock has undergone high levels of erosion since eruption, the measured cosmogenic ^{36}Cl age will appear to be younger than a same-aged rock that has undergone no erosion. However, in some cases, the reverse can be true, and the abundance of thermal neutrons actually increases slightly with the depth of the sample before decreasing at greater depth because of diffusion of thermal neutrons out of the rock and into the atmosphere, which more effectively absorbs thermal neutrons (Liu et al. 1994). In this case, a slightly eroded rock will yield an older age than an uneroded sample. This effect is particularly important to take into account for samples in which production of ^{36}Cl from ^{35}Cl by thermal neutron activation exceeds production from Ca and K. The effect of erosion on the cosmogenic ^{36}Cl age of a sample must be calculated on a case-by-case basis.

Results

During the sampling process, qualitative observations of the lava flow surfaces were made. The surface of the McCartys flow is very fresh (Fig. 2A) and still shows evidence of the glass that would have been present at the time of the initial eruption. The ropey surface of a fresh (<1 week old) Hawaiian lava flow is shown for comparison (Fig. 2B). The ropey features that were formed at the time of eruption are present in abundance on the top of the McCartys flow. The Bandera Crater flow also appears to be well preserved, although not as well preserved as the McCartys (Fig. 2C). Ropey features are present on the Bandera flow, but it completely lacks any of the original glassy surface and appears to be eroded. The Twin Craters (Fig. 2D) and northern and southern Paxton Springs flows not only lack any glass on the flow surface but have also lost much of the ropey top of the original pahoehoe flows. However, relict ropey textures do remain in some places, suggesting that erosion has not deeply affected the flow. Based on flow morphology alone, these three flows appear to be similar in age. The lava flow surface of the Laguna flow appears more degraded than that of the Twin Craters and Paxton Springs flows, and appears flat, with few surface features remaining (Fig. 2E). However, some relicts of original flow surface topography remain, more in the form of small pressure ridges than actual ropey surface. The Bluewater flow surface appears similar to that observed on the Laguna flow.

The seven samples collected for ^{36}Cl analysis all yielded acceptable ^{36}Cl results, with analytical errors mostly on the order of ± 10% or less, with the exception of the McCartys flow (Table 1). Calculation of the age based on the ^{35}Cl/^{36}Cl ratio and chemical composition of the sample was accomplished using the CHLOE program (Phillips and Plummer 1996) with production constants from Phillips et al. (2001). The cosmogenic ages of Zuni–Bandera lava flow samples were calculated for erosion rates ranging between 0 and 5 mm/k.y. (Table 2, Fig. 3). The erosion rate of young basaltic lava flows is difficult to estimate. When a basaltic flow moves across the earth's surface, the outer skin of the flow quenches to form a glassy rind. This glassy rind can be observed on just-erupted Hawaiian lava flows (Fig. 2B). The very glassy part of the rind can be several centimeters thick on a fresh flow and is very fragile compared with the rest of the flow. Initially, the glassy rind is intact, but during cooling fractures develop in the glass, probably from thermal contraction (Fig. 2B). Because of its delicate and fractured nature, the outer rind of a basaltic flow may be stripped by mechanical weathering processes. In the case of the McCartys lava flows, some glassy rind remains, but much has been stripped since the time of eruption. We suggest that the glassy rind is stripped progressively through time, rather than being completely removed shortly after flow emplacement. The Carrizozo lava flows, in central New Mexico, dated at 5,200 ± 700 yrs, show many surface flow features, but no glassy rind remains (Dunbar 1999). Based on the presence of ropey features on the surface of the lava flow but absence of glassy rinds, we estimate that between 2 and 3 cm of material has been removed from the Carrizozo lava flows since the time of their emplacement (Dunbar 1999). The stripped material could have been completely removed from the area, or could have been deposited locally and weathered to form clay minerals. The age and estimated surface loss from the Carrizozo flow yields an approximate erosion rate of 5 mm/k.y. Following removal of the glassy rind, erosion of the flow will continue, but probably at a reduced rate.

We have observed that pahoehoe lava flows in New Mexico and Hawaii can exhibit an outer, slabby layer of lava that is between 5 and 10 cm thick, that in a fresh flow would include the 2–3-cm-thick glassy rind. Between this outermost slab of lava and the main, more crystalline part of the flow, a distinct parting is typically present (Fig. 2D). This parting in the flow appears to be defined by a coalescence of large vesicles that produce a zone of weakness. In some cases, large void pockets 30 cm long and 3 cm high are present. When a flow is observed in cross section, the size and abundance of vesicles increases slightly toward the vesicle-defined parting. We speculate that the origin of this break is either from slow vesicle rise and coalescence through the flow, terminating against the viscous, cooler upper part of the flow, probably after main flow movement has ceased, or from shear-related gas release at the interface between the stagnant outer part of the flow and the flowing interior (Williams and McBirney 1979). If no outer slab is present, we assume that at least 10 cm of material has been removed from the surface of the flow since the time of emplacement. This type of flow break was observed on all sampled flows but is rare on the Bluewater and Laguna flows, suggesting that much of the latter two flows have undergone at least 10 cm of erosion.

Given a range of erosion rates between 0 mm/k.y. and 5 mm/k.y., the average estimated cosmogenic ^{36}Cl ages for Zuni–Bandera lava flows are the following: McCartys flow, 3.9 ± 1.2 ka; Bandera Crater flow, 11.2 ± 0.6 ka; Paxton Springs S, 15.0 ± 1.0 ka; Twin Craters flow 18.0 ± 1.0; Paxton Springs N 20.7 ± 2.2 ka; Laguna flow 34.7 ± 3.0 ka; Bluewater flow, 36.0 ± 3.2 ka. These ages are the mean of ages determined for 0 mm/k.y. and 5 mm/k.y. erosion rates, and the uncertainties cited here are either based on the range of ages defined by the range of erosion rates, or on the analytical error of the ^{36}Cl AMS determination, whichever is larger (Table 2). Other possible errors include uncertainty in geochemical parameters and production rates. These errors can be difficult to estimate but may add another 3–5% uncertainty to the determination (Phillips et al 1997b). Furthermore, systematic errors, based on uncertainty in the ^{36}Cl production coefficients, may be present. Phillips et al. (1997b) estimate, based on analysis of a large set of similar-aged samples, that the sum of random and systematic errors on a single, typical ^{36}Cl age determination is around 15%, which is larger than the errors on the ages cited above.

Discussion

The ^{36}Cl determined ages of the seven dated lava flows in the Zuni–Bandera volcanic field compare favorably with the apparent relative ages of the flows based on geomorphology of the flow surfaces. The Twin Craters, Bandera Crater,

FIGURE 2A—McCartys flow, showing distinct ropey flow tops (field of view ~3 m).

FIGURE 2B—Young Hawaiian flow, showing glassy and ropey flow top.

FIGURE 2C—Surface of Bandera pahoehoe lava flow, showing some ropey texture in foreground, but also generally more degraded surface than the McCartys flow.

FIGURE 2—Surfaces of Zuni–Bandera and young Hawaiian lava flows.

FIGURE 2D—Surface of Twin Crater flow, showing lack of ropey flow top, and also showing slabby upper crust of lava surface described in text.

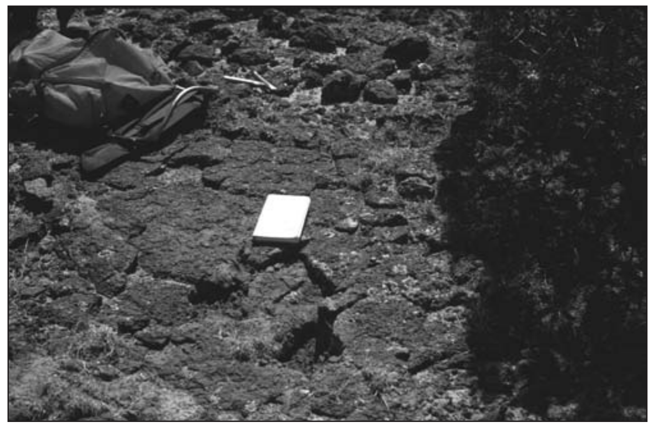

FIGURE 2E—Surface of Laguna flow, showing almost complete lack of surface.

and McCartys lava flows also compare favorably with those ages determined by ^{14}C and ^{3}He dating techniques (Table 2), reconfirming that the McCartys lava flow is the youngest volcanic event in New Mexico. For the McCartys and Bandera Crater flows, ages determined by all three techniques overlap within analytical error. However, for the Bandera Crater flow, the $^{40}Ar/^{39}Ar$ age is considerably older than those determined by the cosmogenic and ^{14}C techniques. This difference has been ascribed to excess Ar in the basalt (Laughlin et al. 1994b), which has the effect of greatly increasing the apparent $^{40}Ar/^{39}Ar$ ages for very young, low K samples (Dalrymple and Moore 1968; Laughlin et al. 1994b; Rittmann and Lippolt 1998). The ^{36}Cl ages for the McCartys and Bandera Crater flows bracket those of another young lava in New Mexico, the Carrizozo flow, dated at 5.2 ± 0.7 ka (Dunbar 1999). The geomorphic characteristics of the McCartys and Carrizozo flows are similar, but close examination suggests that the McCartys may be younger. The McCartys flow exhibits a greater degree of glassy pahoehoe rope preservation, a larger amount of remaining iridescent glass, and the vegetation is sparser. Furthermore, the McCartys flow would be expected to erode more rapidly than the Carrizozo lava flow because of its northerly location and higher elevation and hence greater rainfall and temperature variations. An early estimate of the age of the McCartys flow was as young as 1,000 yrs old (Nichols 1946), based on Acoma Indian legend and indirect stratigraphic relationship to Pueblo I artifacts (700–900 A.D.). The age of the Carrizozo lava flows was then thought to be around 1,500 yrs (Weber 1964), partially based on the McCartys estimate. The new ages of 3.9 and 5.2 ka for the McCartys and Carrizozo flows, respectively, show that the early age estimates were internally consistent, but both too young.

The set of flows that appear geomorphically closest in age to, although more degraded than, the Bandera Crater flow are the Paxton Springs and Twin Craters flows. Consistent with geomorphic observation, these three flows are older

TABLE 1—Locations, geochemistry, and ^{36}Cl determinations of samples from the Zuni–Bandera volcanic field.

Sample	Flow	Lat. °N	Long. °W	Elevation m	^{36}Cl ratio and error ($^{36}Cl/10^{15}Cl$)	SiO_2 wt.%	TiO_2 wt.%	Al_2O_3 wt.%	Fe_2O_3 wt.%	MgO wt.%	CaO wt.%	MnO wt.%	K_2O wt.%	Na_2O wt.%	P_2O_5 wt.%	Cl ppm	B ppm	Sm ppm	Gd ppm	U ppm	Th ppm
ZB-93-1BF	Bluewater	35°15.965	107°58.146	2086	1160 ± 105	52.50	1.38	14.50	10.60	7.70	9.63	0.17	0.27	2.27	0.16	54	9.0	9.0*	3.5	0.5	1.0
ZB-93-2LF	Laguna	35°04.492	107°45.289	1810	816 ± 69	49.10	1.57	13.50	12.90	9.57	8.55	0.18	0.60	2.35	0.23	62	9.0*	9.0*	3.5*	0.5*	1.0*
ZB-93-3AMCL	McCartys	34°55.969	107°50.448	2047	110 ± 33	51.50	1.48	13.70	13.10	8.39	8.77	0.18	0.71	2.53	0.21	63	8.0	9.0*	6.0	0.8	1.9
ZB-93-4TCF	Twin Craters	34°59.443	108°02.091	2242	501 ± 25	50	1.46	14	12.5	8.92	8.72	0.18	0.72	2.51	0.21	79	9.0	9.0*	3.5	0.5	1.0
ZB-93-5BCF	Bandera Crater	34°59.549	108°05.302	2367	431 ± 21	47.5	1.79	13.8	13.6	9.89	8.55	0.19	0.59	2.41	0.24	52	9.0*	9.0*	3.5*	0.5*	1.0*
ZB-16	Paxton Springs S	35°03.50	108°03.61	2380	334 ± 15	44.8	2.1	13.9	12.6	11.6	8.94	0.17	1.07	2.34	0.28	141	15.5	15.5*	6.0	0.7	1.7
ZB-20	Paxton Springs N	35°05.73	108°01.50	2254	547 ± 59	44.7	2.29	14.6	12.9	11.2	9.19	0.17	0.86	2.21	0.28	92	10.5	10.5*	3.0	0.5	1.7

* indicates approximate value

TABLE 2—Ages of basalt flows from the Zuni–Bandera volcanic field as determined by isotopic dating techniques.

	Dating method							
Flow	^{36}Cl age (ka) zero erosion	^{36}Cl age (ka) 5 mm/k.y.	^{36}Cl age (ka) mean *	^{14}C calibrated calendar yrs**	^{3}He (ka)	$^{40}Ar/^{39}Ar$ (ka)	K-Ar (Ma)	U-Th disequilibrium (ka)
McCartys flow	4.0 ± 1.2	3.8 ± 1.1	3.9 ± 1.2	3.2 ± 0.1[1]	2.45 ± 1.2[1]			
Bandera Crater flow	11.6 ± 0.6	10.9 ± 0.5	11.2 ± 0.6	10.07 to 12.5 ± ~0.06[1]	11.2 ± 1.1[1]	41 ± 7[3]		
Paxton Springs S	16.0 ± 0.7	14.0 ± 0.6	15.0 ± 1.0					
Twin Craters flow	19.0 ± 1.0	17.0 ± 0.8	18.0 ± 1.0	18.4–19.1[6]; 16.9–17.9[6]				
Paxton Springs N	22.0 ± 2.4	19.4 ± 2.0	20.7 ± 2.2					
Laguna flow	36.7 ± 3.1	32.7 ± 2.8	34.7 ± 3.0			54 ± 50, 110 ± 76[2]	0.128 ± 0.033[5], 1.57 ± 0.26[7]	
Bluewater flow	37.8 ± 3.4	34.2 ± 3.1	36.0 ± 3.2		57 ± 6[1]		5.69 ± 0.12, 2.23 ± 0.24[2]	79 + 40/-30[4]

* mean uncertainty is reported as the larger of (5 mm/k.y. age - zero erosion age)/2 or mean analytical uncertainty.
** Dates cited for reference 1 are calibrated using Stuiver and Reimer (1993). Calibration for dates citing reference 6 is unspecified.
[1]Laughlin et al. 1994b
[2]Laughlin et al. 1993b
[3]McIntosh 1994
[4]Sims et al. 1994
[5]Champion et al. 1988
[6]Laughlin and WoldeGabriel 1997
[7]Laughlin et al. 1979

than the Bandera Crater flow, ranging in age from 15.0 ± 1.0 to 20. 7± 2.2 ka. Two ^{14}C ages for the Twin Craters flow agree well with the ^{36}Cl ages. No independent age determination is available for the Paxton Springs flows, but the similarity of flow surface morphologies between these flows and the Twin Craters, along with the good agreement of the Twin Craters flow with ^{14}C ages, suggests that the ^{36}Cl ages for the Paxton Springs flows are likely to be accurate. The two flows associated with the Paxton Springs vent yield distinct ^{36}Cl ages (15.0 ± 1.0 and 20.7 ± 2.2). One of these traveled north through Zuni Canyon, and the second erupted around 5,000 yrs later and flowed to the south. The northern and southern Paxton Springs flows had previously been mapped as the same unit (Maxwell 1986), and based on the geomorphology of the flow surfaces alone, we suspected that both were the same age and were derived from a single eruptive event from the Paxton Springs vent. However, the ^{36}Cl ages suggest that the Paxton Springs vent area underwent two separate eruptive events. The same conclusion was reached by Laughlin et al. (1994a), on the basis of whole rock geochemistry. Our supporting interpretation would be stronger if we had analyzed multiple samples from each flow, because it is possible that one or the other of the samples is anomalous for some reason. A sample could yield anomalous results if it had been shielded from cosmic rays for a significant time following eruption, for example if it had been covered with windblown sediment and then exhumed. Although we cannot rule out some anomaly in the data obtained from single samples, the relative ^{36}Cl ages of the two flows with respect to the crater morphology is consistent with the relative determined ages of the two flows. The southern, younger Paxton Springs flow was sampled just south of the cinder cone. The surface of this flow ramps smoothly up to the flank of the cinder cone without any geomorphic breaks that could indicate later eruptive activity. This geomorphology suggests that the Paxton Springs cinder cone was constructed by the later eruptive event, and that this flow represents the most recent eruptive activity from this vent, consistent with the younger ^{36}Cl age. The lava flow that is found to the north of the Paxton Springs cinder cone appears to be derived from the same geographic area as the current cinder cone. No specific vent for this lava flow has been recognized, but the vent could have been disrupted or covered by the cinder cone and/or lava flow associated with the younger eruption. But, in any case, we suggest that the vents for the two eruptions were located close to each other. The question of polygenetic or monogenetic nature of eruptions associated with cinder cone vents has been debated, particularly with respect to the Lathrop Wells eruption (e.g., Heizler et al. 1999; Turrin et al. 1991; Zreda et al. 1993). As summarized in Heizler et al. (1999), the overlap between a number of the geochronology data sets does not preclude polycyclic activity at Lathrop Wells, but that the most recent and complete $^{40}Ar/^{39}Ar$ data suggest that the cone is monogenetic. In contrast, the ages of the Paxton Springs flows, if truly representative of flow ages, suggest that at least some vent areas associated with cinder cones may undergo multiple stages of activity.

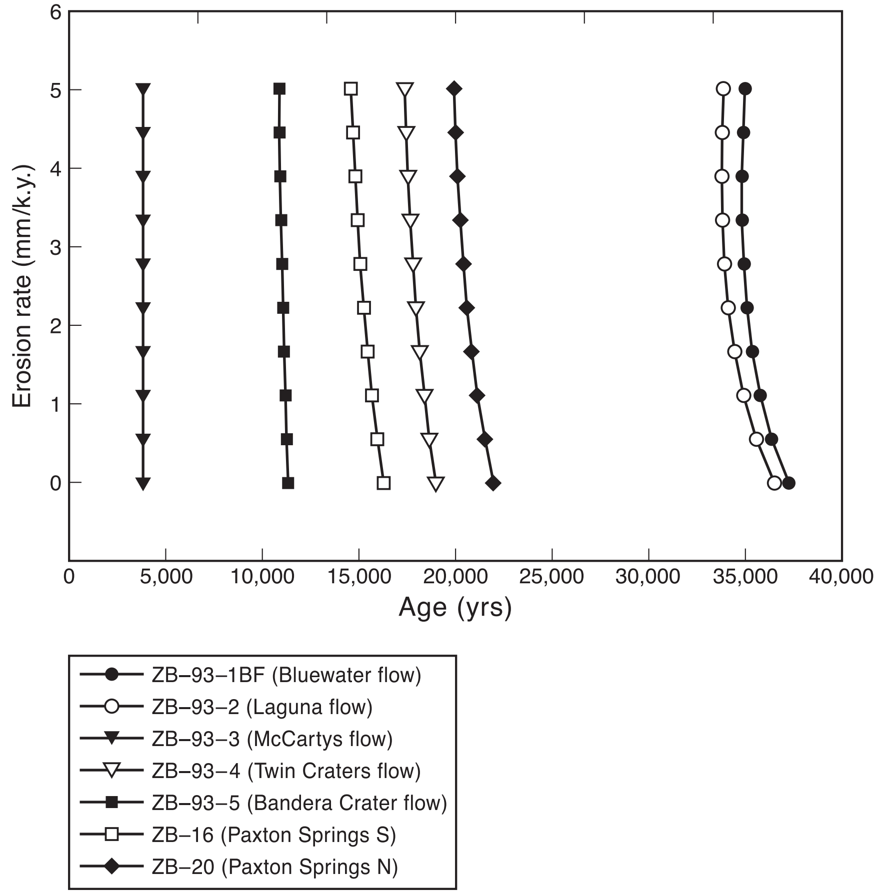

FIGURE 3—Cosmogenic ^{36}Cl ages of Zuni–Bandera volcanic field samples as a function of erosion rate.

The ages of the two oldest flows, Laguna and Bluewater, are more difficult to assess, both in terms of absolute and relative ages. The ^{36}Cl ages for both flows are significantly younger than the K-Ar ages (Table 2). The very old K-Ar ages are likely explained by the presence of excess Ar in the basaltic lava flows (Laughlin et al. 1994b). However, the ^{36}Cl age of the Bluewater flow is also younger than ^{3}He and U-Th disequilibrium ages for samples collected in the same geographic area (57 ± 6 and 79 + 40/ - 30 ka, respectively), which is more difficult to explain, particularly because the samples were taken at similar locations. The difference between the ^{36}Cl and U-Th disequilibrium could be related to magma chamber residence time of the phases dated using the U-Th technique. The differences between the ^{3}He and ^{36}Cl dates are harder to explain. The ^{3}He dates could be influenced by the uncertainty in the ^{3}He production. Alternatively, the ^{36}Cl age determinations for one or both flows could be too young. Furthermore, the ^{36}Cl ages suggest that the ages of the Laguna and Bluewater flows are not distinguishable. Investigation of a satellite image of New Mexico shows that the Bluewater flow appears blacker, hence possibly fresher, than the Laguna flow. However, other factors, such as the abundance of windblown sediment on the flow surface relative to flow elevation may also play a role in this coloration. Further work on these two flows, as well as on production rates of cosmogenic species may be needed to provide further insight into this problem.

In terms of understanding geological processes, such as magmatic evolution and mantle processes in the New

Mexico area, relative ages of basaltic lava flows are of less significance than detailed geochemical studies, although both are important. However, detailed understanding of the chronology of basaltic lava flows within New Mexico is critical to understanding the potential volcanic hazards that could impact the state. Limburg (1990) has suggested that renewed basaltic volcanism is one of the greatest potential volcanic hazards in New Mexico, and that there is around a 1% chance that some type of volcanic eruption will occur within the next 100 yrs. Statistical estimates, such as this one, are critically reliant on time of past volcanism as a key to future volcanic activity. Therefore, correct age estimates for eruptions, particularly young basaltic eruptions, are important for predicting future eruptions within the state.

Based on the dates of basaltic lava flows presented in this paper, plus the dates presented in Dunbar (1999), the recurrence interval of recent basaltic volcanism in New Mexico can be estimated. During the last 25 ka, basaltic eruptions have occurred in New Mexico at around 20.7, 18.0, 15.0, 11.2, 5.2, and 3.9 ka (Fig. 3), yielding recurrence intervals of between 1.3 and 3.8 ka. Given that the last eruption occurred at 3.9 ka, another episode of basaltic volcanism could currently be expected in New Mexico. Although there has been no evidence of renewal of volcanism in the Zuni–Bandera volcanic field or the Carrizozo area, an active magma chamber, called the Socorro magma body, has been recognized in the area around Bernardo, New Mexico (Sanford et al. 1977; Reilinger et al. 1980). This magmatic system could be a possible source for renewed magmatism. This magma body is located at 19 km depth and has an estimated surface area of at least 3,400 km^2 (Balch et al. 1997). The area around the magma body has been the location of elevated levels of seismic activity (Sanford et al. 1995), suggesting that there is some migration of magma, or instability, within the chamber. These combined factors imply that the Socorro magma body is a possible source of future volcanism.

Conclusions

Based on cosmogenic ^{36}Cl dating, our preferred eruption ages for lava flows from the Zuni–Bandera volcanic field are the following: McCartys flow, 3.9 ± 1.2 ka; Bandera Crater flow, 11.2 ± 0.6 ka; Paxton Springs S, 15.0 ± 1.0 ka; Twin Craters flow 18.0 ± 1.0 ka; Paxton Springs N 20.7 ± 2.2 ka; Laguna flow 34.7 ± 3.0 ka, Bluewater flow, 36.0 ± 3.2 ka. The ages for the flows younger than 20 ka are in good agreement with other age determinations for these flows made by other cosmogenic techniques, as well as ^{14}C, but are considerably younger than K-Ar or ^{40}Ar/^{39}Ar determinations, probably due to excess Ar in these young, K-poor rocks. The ages of the McCartys and Bandera Crater flows bracket the 5.2 ± 0.7 ka age for the Carrizozo lava flows in central New Mexico, but are older than previous ages based on geomorphic observations alone. Our ^{36}Cl age for the McCartys flow reconfirms that it is the youngest volcanic event in New Mexico. The relative ages of the flows older than 20 ka are consistent with observations of the condition of the flow surfaces. The Paxton Springs N and S lava flows, although geomorphically similar, are distinctly different in age, suggesting that the Paxton Springs vent area has undergone at least two episodes of activity. The age for the oldest dated flow, the Bluewater, is not in good agreement with other dating techniques. The reasons for this discrepancy are uncertain and will require further work to resolve.

Acknowledgments

This research was supported by the New Mexico Bureau of Geology and Mineral Resources, under the direction of State Geologists C. Chapin and P. Scholle. Thanks to A.W. Laughlin for arranging the 1993 geochronology of El Malpais National Monument field trip and for choosing the sampling sites for a number of samples used in this study, and also to Frank Perry and Giday WoldeGabriel for suggesting and showing us sampling sites. Thanks to the National Park Service and the Candelaria family for permission to sample and for access to sampling areas, to M. Plummer for the CHLOE program used for recalculation of the ^{36}Cl data, to the cartography section of NMBGMR for drafting assistance, and to P. Scholle for use of the McCartys flow photograph. Thanks to R. Ackert, S. Baldridge, and M. Zreda for providing insightful and helpful reviews.

References

Anthony, E. Y., and Poths, J., 1992, He-3 surface exposure dating and its implications for magma evolution in the Potrillo volcanic field, Rio Grande rift, New Mexico, USA: Geochimica et Cosmochimica Acta, v. 56, pp. 4105–4108.

Aruscavage, P., and Campbell, E., 1983, An ion-selective electrode method for determination of chlorine in geological materials: Talanta, v. 30, pp. 745–749.

Balch, R., Hartse, H., Sanford, A., and Lin, K., 1997, A new map of the geographic extent of the Socorro mid-crustal magma body: Seismological Society of America, Bulletin, v. 87, pp. 174–182.

Bentley, H. W., Phillips, F. M., and Davis, S. N., 1986, Chlorine-36 in the terrestrial environment; *in* Fritz, P., and Fontes, J. C. (eds.), Handbook of environmental isotope geochemistry: Elsevier, Amsterdam, pp. 427–479.

Cascadden, T. E., Geissman, J. W., Kudo, A. M., and Laughlin, A. W., 1997, El Calderon cinder cone and associated basalt flows; *in* Mabery, K. (comp.), Natural history of El Malpais National Monument: New Mexico Bureau of Mines and Mineral Resources, Bulletin 156, pp. 41–51.

Champion, D. E., Lanphere, M. A., and Kuntz, M. A., 1988, Evidence for a new geomagnetic reversal from lava flows in Idaho—discussion of short polarity reversals in the Brunhes and late Matuyama polarity chrons: Journal of Geophysical Research, v. 93, pp. 11,667–11,680.

Dalrymple, G. B., and Moore, J. G., 1968, Argon-40 excess in submarine pillow basalts from Kilauea volcano, Hawaii: Science, v. 161, pp. 1132–1135.

Dunbar, N., 1999, Cosmogenic ^{36}Cl-determined age of the Carrizozo lava flows, south-central New Mexico: New Mexico Geology, v. 21, no. 2, pp. 25–29.

Dunbar, N. W., and Phillips, F. M., 1994, ^{36}Cl surface exposure determinations of eruption ages for Quaternary lava flows of the Zuni–Bandera volcanic field (abs.): New Mexico Geology, v. 16, no. 4, p. 80.

Elmore, D., Fulton, B. R., Clover, M. R., Marsden, J. R., Gove, H., Naylor, H., Purser, K. H., Kilius, L. R., Beukins, R. P., and Litherland, A. E., 1979, Analysis of ^{36}Cl in environmental water samples using an electrostatic accelerator: Nature, v. 277, pp. 22–25.

Gosse, J. C., and Phillips, F. M., 2001, Terrestrial in situ cosmogenic nuclides—theory and application: Quaternary Science Reviews, v. 20, pp. 1475–1560.

Heizler, M. T., Perry, F. V., Crowe, B. M., Peters, L., and Appelt, R., 1999, The age of Lathrop Wells volcanic center—an ^{40}Ar/^{39}Ar dating investigation: Journal of Geophysical Research B: Solid Earth, v. 104, pp. 767–804.

Laughlin, A. W., Aldrich, M. J., Jr., Ander, M. E., Heiken, G. H., and Vaniman, D. T., 1982, Tectonic setting and history of late-Cenozoic volcanism in west-central New Mexico; *in* Wells, S. G., Grambling, J. A., and Callender, J. F. (eds.), Albuquerque country II: New Mexico Geological Society, Guidebook 33, pp. 279–284.

Laughlin, A. W., Brookins, D. G., and Causey, J. D., 1972, Late Cenozoic basalts from the Bandera lava field, Valencia County, New Mexico: Geological Society of America, Bulletin, v. 83, pp. 1543–1551.

Laughlin, A. W., Brookins, D. G., Damon, P. E., and Shafiqullah, M., 1979, Late Cenozoic volcanism of the central Jemez zone, Arizona–New Mexico: Isochron/West, no. 25, pp. 5–8.

Laughlin, A. W., Charles, R. W., Reid, K., and White, C., 1993a, Field-trip guide to the geochronology of El Malpais National Monument and the Zuni–Bandera volcanic field, New Mexico:

New Mexico Bureau of Mines and Mineral Resources, Bulletin 149, 23 pp.

Laughlin, A. W., Manzer, G. K., Jr., and Carden, J. R., 1974, Feldspar megacrysts in alkali basalts: Geological Society of America, Bulletin, v. 85, pp. 413–416.

Laughlin, A. W., Perry, F. V., Damon, P. E., Shafiqullah, M., WoldeGabriel, G., McIntosh, W., Harrington, C. D., Wells, S. G., and Drake, P G., 1993b, Geochronology of Mount Taylor, Cebollita Mesa, and Zuni–Bandera volcanic fields, Cibola County, New Mexico: New Mexico Geology, v. 15, no. 4, pp. 81–92.

Laughlin, A. W., Perry, F. W., and WoldeGabriel, G., 1994a, Geochronology and geochemistry of basalts of the Zuni–Bandera volcanic field—a review and update (abs.): New Mexico Geology, v. 16, no. 3, p. 60.

Laughlin, A. W., Poths, J., Healey, H. A., Reneau, S., and WoldeGabriel, G., 1994b, Dating of Quaternary basalts using the cosmogenic ^{3}He and ^{14}C methods with implications for excess ^{40}Ar: Geology, v. 22, pp. 135–138.

Laughlin, A. W., and WoldeGabriel, G., 1997, Dating the Zuni–Bandera volcanic field; *in* Mabery, K. (comp.), Natural history of El Malpais National Monument: New Mexico Bureau of Mines and Mineral Resources, Bulletin 156, pp. 25–29.

Limburg, E. M., 1990, Recent and potential volcanism of New Mexico: Unpublished M.S. thesis, New Mexico Institute of Mining and Technology, Socorro, 149 pp.

Liu, B., Phillips, F. M., Fabryka-Martin, J. T., Fowler, M. M., and Stone, W. D., 1994, Cosmogenic ^{36}Cl accumulation in unstable landforms, 1. Effects of the thermal neutron distribution: Water Resources Research, v. 30, pp. 3115–3125.

Luedke, R. G., and Smith, R., 1978, Map showing distribution, composition, and age of late Cenozoic volcanic centers in Arizona and New Mexico: U.S. Geological Survey, Miscellaneous Investigations Series, Map I-1091A, scale 1:1,000,000.

Maxwell, C., 1986, Geologic map of El Malpais lava field and surrounding areas, Cibola County, New Mexico: U.S. Geological Survey, Miscellaneous Investigations Series, Map I-1595, scale 1:62,500.

McIntosh, W. C., 1994, ^{40}Ar/^{39}Ar geochronology of late Miocene to Pleistocene basalts of the Zuni–Bandera, Red Hill–Quemado, and Potrillo volcanic fields, New Mexico (abs.): New Mexico Geology, v. 16, no. 3, pp. 60–61.

Menzies, M. A., Kyle, P. R., Jones, M., and Ingram, G., 1991, Enriched and depleted source components for tholeiitic and alkaline lavas from Zuni–Bandera, New Mexico—inferences about intraplate processes and stratified lithosphere: Journal of Geophysical Research, v. 96, pp. 13,645–13,671.

Nichols, R. L., 1946, McCartys basalt flow, Valencia County, New Mexico: Geological Society of America, Bulletin, v. 57, pp. 1049–1086.

Perry, F. V., Baldridge, W. S., and DePaulo, D. J., 1987, Role of asthenosphere and lithosphere in the genesis of late Cenozoic basaltic rocks from the Rio Grande rift and adjacent regions of the southwestern United States: Journal of Geophysical Research, v. 92, pp. 9193–9213.

Phillips, F. M., Dunbar, N. W., and Zreda, M., 1997a, A test of chlorine-36 for dating of late Quaternary basaltic volcanos: EOS, Transactions of the American Geophysical Union, v. 78, p. F760.

Phillips, F. M., Leavy, B. D., Jannik, N. O., Elmore, D., and Kubik, P. W., 1986, The accumulation of cosmogenic chlorine-36 in rocks—a method for surface exposure dating: Science, v. 231, pp. 41–43.

Phillips, F. M., and Plummer, M. A., 1996, CHLOE—a program for interpreting in-situ cosmogenic nuclide dating and erosion studies (abs.): Radiocarbon, v. 38, p. 98.

Phillips, F. M., Stone, W. D., and Fabryka-Martin, J. T., 2001, An improved approach to calculating low-energy cosmic-ray neutron fluxes near the land/atmosphere interface: Chemical Geology, v. 175, pp. 689–701.

Phillips, F. M., Zreda, M. G., Gosse, J. C., Klein, J., Evenson, E. B., Hall, R. D., Chadwick, O. A., and Sharma, P., 1997b, Cosmogenic ^{36}Cl and ^{10}Be ages of Quaternary glacial and fluvial deposits of the Wind River Range, Wyoming: Geological Society of America, Bulletin, v. 109, pp. 1453–1463.

Reilinger, R. E., Balazs, E. I., Oliver, J. E., Brown, L. D., and Sanford, A. R., 1980, New measurements of crustal doming over the Socorro magma body, New Mexico: Geology, v. 8, no. 6, pp. 291–295.

Rittmann, U., and Lippolt, H. J., 1998, Evidence for distortion of Tertiary K/Ar ages by excess argon—example given by 3 alkali olivine basalts from northern Hesse, Germany: European Journal of Mineralogy, v. 10, no. 1, pp. 95–110.

Sanford, A. R., Balch, R., and Lin, K., 1995, A seismic anomaly in the Rio Grande rift near Socorro, New Mexico (abs.): Seismological Research Letters, v. 66, no. 2, p. 44.

Sanford, A. R., Mott, R. P., Jr., Shuleski, P. J., Rinehart, E. J., Caravella, F. J., Ward, R. M., and Wallace, T. C., 1977, Geophysical evidence for a magma body in the vicinity of Socorro, New Mexico; *in* Heacock, J. G., Keller, G. V., Oliver, J. E., and Simmons, G. (eds.), The earth's crust—its nature and physical properties: American Geophysical Union, Geophysical Monograph 20, pp. 385–403.

Sims, K. W. W., DePaolo, D. J., Murrell, M. T., and Baldridge, W. S., 1994, ^{238}U-^{230}Th disequilibrium in young basalts—implications for eruptive ages, residence times and petrogenesis (abs): New Mexico Geology, v. 16, no. 4, pp. 79–80.

Stuiver, M., and Reimer, P. J., 1993, Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration program: Radiocarbon, v. 35, pp. 215–230.

Turrin, B. D., Champion, D., and Fleck, R. J., 1991, ^{40}Ar/^{39}Ar age of the Lathrop Wells volcanic center, Yucca Mountain, Nevada: Science, v. 253, no. 5020, pp. 654–657.

Weber, R. H., 1964, Geology of the Carrizozo quadrangle, New Mexico; *in* Ash, S. R., and Davis, L. V. (eds.), Ruidoso country: New Mexico Geological Society, Guidebook 15, pp. 100–109.

Williams, H., and McBirney, A. R., 1979, Volcanology: Freeman, Cooper and Company, San Francisco, 397 pp.

Zreda, M. G., 1994, Development and calibration of the cosmogenic ^{36}Cl surface exposure dating method and its applications to the chronology of late Quaternary glaciations: Unpublished Ph.D. dissertation, New Mexico Institute of Mining and Technology, Socorro, 318 pp.

Zreda, M. G., Phillips, F. M., Elmore, D., Kubik, P. W., Sharma, P., and Dorn, R. I., 1991, Cosmogenic chlorine-36 production rates in terrestrial rocks: Earth and Planetary Science Letters, v. 105, pp. 94–109.

Zreda, M. G., Phillips, F. M., Kubik, P. W., Sharma, P., and Elmore, D., 1993, Cosmogenic ^{36}Cl dating of a young basaltic eruption complex, Lathrop Wells, Nevada: Geology, v. 21, no. 1, pp. 57–60.