Cosmogenic Chlorine-36 determined age of the Carrizozo lava flows, south-central New Mexico

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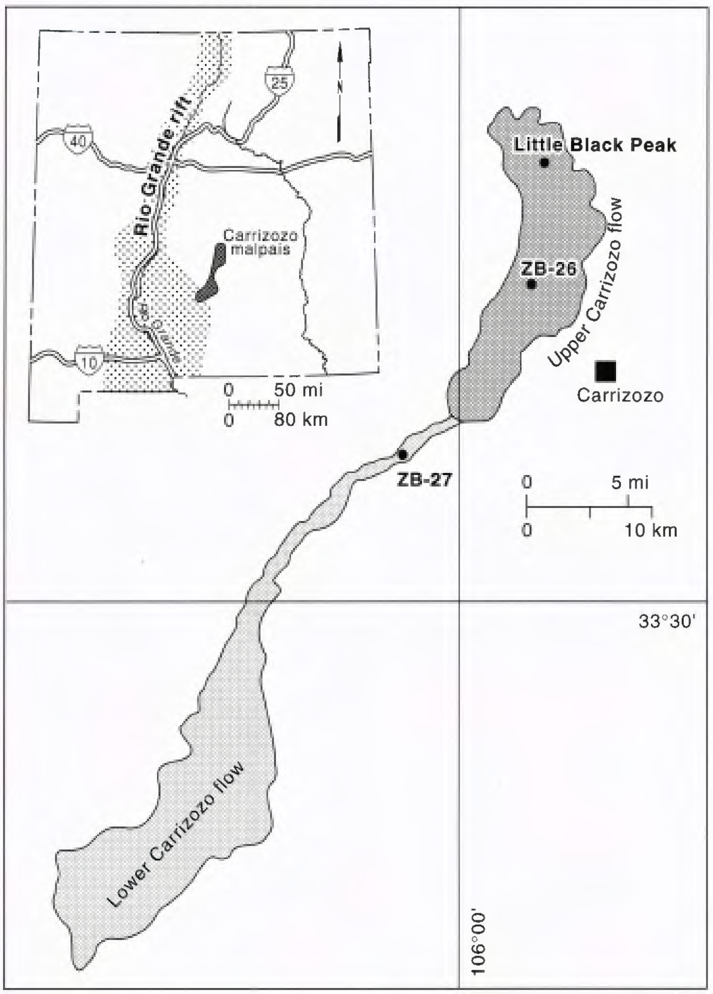

FIGURE 1—Map of the Carrizozo malpais lava flows and sample localities.

Introduction

The Carrizozo lava flows in south-central New Mexico are one of the youngest-appearing volcanic features in the contiguous United States. The two basaltic lava flows, which are features of the Valley of Fires State Park, display impressive, well-preserved pahoehoe ropes, pressure ridges, and collapsed lava tubes without extensive soil development or vegetation. These apparently young lava flows have proven very difficult to date. No carbon suitable for ^{14}C analysis has been found under the Carrizozo flows. Allen (1952) estimated, based on visual observation, that the flows are less than 1,000 yrs old, and Weber (1964) estimated the age as 1,500 yrs old. These ages may have been influenced by age estimates for the geomorphically similar and nearby McCarty's lava flow that was estimated to have erupted roughly 1,000 yrs ago, based on Acoma Indian legend and an apparent stratigraphic relationship with Pueblo I artifacts (Nichols, 1946). Since then, Salyards (1991) estimated an age for the Carrizozo lava flows of about 5,000 yrs, based on secular variation magnetostratigraphy. He notes, however, that there are potential problems with the confidence of this age determination and that an independent age determination would be necessary for confirmation.

Cosmogenic dating techniques have been successfully applied to dating of geomorphically young surfaces, such as glacial moraines, beach terraces, and basaltic lava flows that have intact surface features and hence have undergone little erosion (e.g. Phillips et al., 1997a, b; Dunbar and Phillips, 1994; Zreda et al., 1991, 1993; Zreda, 1994; Anthony and Poths, 1992; Laughlin et al., 1994). These techniques rely on 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 has been exposed more-or-less continuously since. In the case of an extrusive volcanic rock, buildup of cosmogenic nuclides begins when the rock is erupted, so measurement of the ratio of a cosmogenic isotope to a non-cosmogenic isotope can provide an estimate of eruption age (Phillips et al., 1986). This paper reports cosmogenic ^{36}Cl determinations of the age of the upper and lower Carrizozo basaltic lava flows.

Abstract

The Carrizozo lava flows in south-central New Mexico are one of the youngest-appearing volcanic features in the state. Cosmogenic ^{36}Cl dating of the two basaltic pahoehoe flows yields an eruption age of 5,200 ± 700 yrs ago. There is no apparent age difference between the upper and lower Carrizozo flows, suggesting that this lava field was formed by a monogenetic event. The determined age is in good agreement with secular variation magnetostratigraphy and ^{3}He ages but is much older than ages based on visual observations of the flow surface morphology and archeological evidence. The ^{36}Cl age of the Carrizozo lava flows is consistent with the ^{36}Cl and ^{14}C ages determined for the McCarty's flow, also in New Mexico, which, based on geomorphic features, appears slightly younger than the Carrizozo flows.

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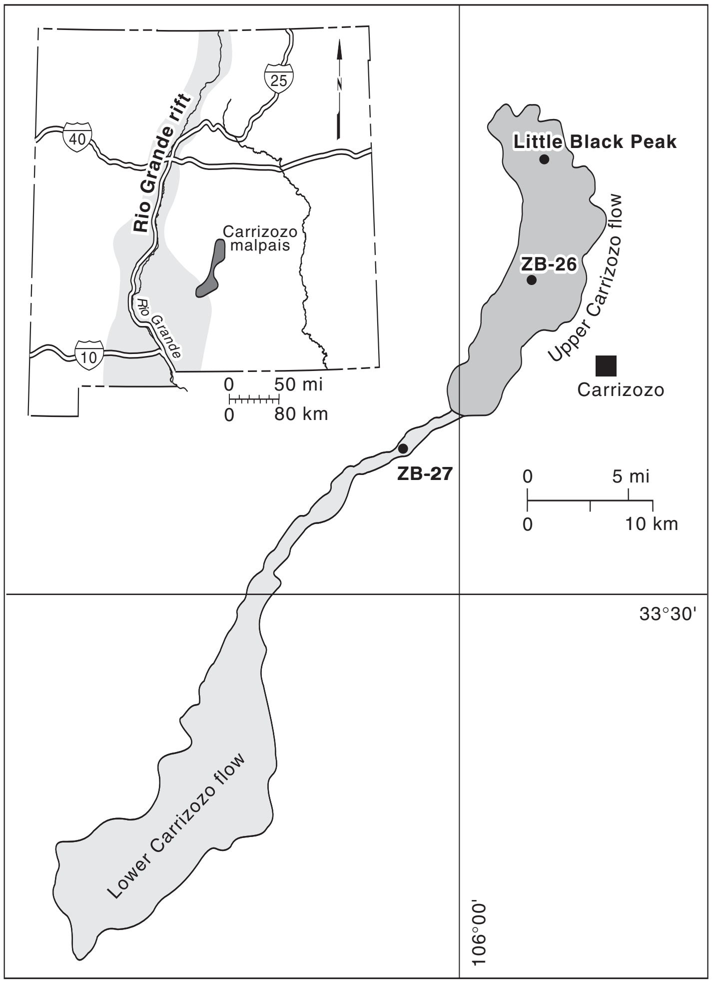

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Geological background

The Carrizozo malpais consists of two basaltic lava flows that erupted from within the Tularosa Basin, in south-central New Mexico (Fig. 1). The vent area for the lava flows, Little Black Peak, falls on the Capitan lineament, a zone of crustal weakness that extends across eastern New Mexico. The Capitan lineament is defined by a number of igneous features, including the Capitan pluton, the Carrizozo lava flows, and Broken Back crater and associated lava flow. The Capitan lineament is interpreted as a deeply penetrating zone of crustal weakness along which magmas have been able to rise and erupt (Chapin et al., 1978).

The total eruptive volume of the Carrizozo lava flows is estimated to be 2.8–4.3 km^3 (Allen, 1952); thickness averages 10–15 m, and the total length of the flow field is 75 km (Keszthelyi and Pieri, 1993). The flows are interpreted as tube-fed (Keszthelyi and Pieri, 1993) and are characterized by pahoehoe textures, such as ropey flow tops (Fig. 2), smooth lava sheets, toes, tumuli, and pressure ridges. The flow top of the lava is very well preserved and in some places even retains an iridescent appearance, typical of young lava flows (Fig. 3). Two distinct lava flows have been identified in the Carrizozo field (Renault, 1970). The lower flow extends for the full 75-km length. The central part of the flow is narrow, whereas the southern part spreads to a width of nearly 8 km (Fig. 1). The upper flow extends approximately 25 km from the vent, is wider, on average, than the lower flow, and, where both flows can be observed, is typically thicker (Weber, 1964). The contact between the upper and lower flows is brecciated but shows no evidence of erosion or soil development (Faris, 1980), suggesting that the time between eruption of the two flows was relatively short.

The lava that forms the Carrizozo flows is alkaline to transitional olivine basalt (Faris, 1980), and the rock is typically unaltered. Anthony et al. (1998) note that the lava that forms the Carrizozo flows is transitional between hypersthene and nepheline normative and that it is likely derived from mantle that is either enriched in incompatible elements or has undergone some crustal contamination. Although some compositional trends are observed within the Carrizozo lavas, consistent with a small degree of fractionation of olivine ± pyroxene, the chemical composition of the lower flow is, on average, very close to the upper (Faris, 1980; Renault, 1970).

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

The chlorine-36 method (Phillips et al., 1986) is based on the fact that ^{36}Cl is dominantly produced by cosmogenic reactions near the

FIGURE 2—Surface of the upper Carrizozo malpais lava flow showing ropey flow tops and collected samples.

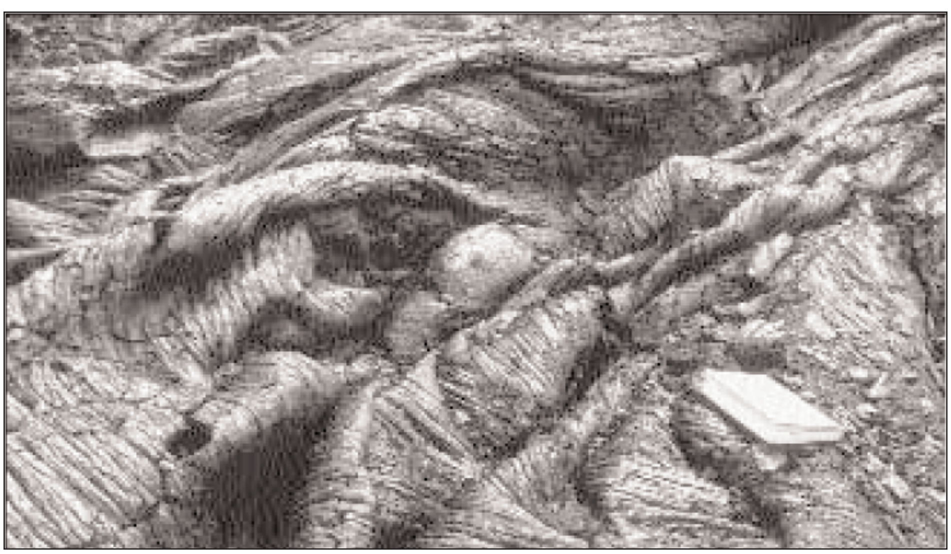

FIGURE 3—Surface of a recently erupted Hawaiian lava flow showing the glassy and friable nature of the pahoehoe flow top.

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Earth's surface, primarily in the upper 1 m of an exposed rock, as compared to a very small amount of production in the deeper subsurface. Chlorine-36 is produced in rocks at the Earth's surface almost entirely by cosmic-ray-induced reactions. These 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. Cosmic rays are also attenuated by any material overlying the dating surface, such as windblown sand or snow, so in order for a meaningful age to be obtained, either the surface must have remained bare since initial exposure or the cover history must be accurately known.

Analytical methods

Six samples were collected for ^{36}Cl dating, three from a locality (ZB-27) on the lower flow and three from a locality (ZB-26) on the upper (Fig. 1). The samples each consist of approximately 500 g of lava collected as a single piece from the upper 5 cm of well-developed pahoehoe ropes. Sample localities were selected on high-standing areas of the lava flow to minimize shielding of cosmogenic nuclides by surrounding topography. Collection from high-standing areas also reduces the likelihood that the samples were covered either with snow or windblown sand for any significant length of time following eruption.

In the laboratory, the samples were prepared for dissolution and collection of Cl. Samples were cleaned of any organic material using a wire brush, then crushed to 1-cm fragments using a hammer, and then ground for about 30 sec. in a TEMA swing mill with tungsten carbide vessel. The lightly crushed material was then sieved using a 150 mesh sieve to remove vesicle-filling clay and zeolite minerals that could contain meteoric Cl. The >100 micron-size fraction was then leached 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 using 18 micro-ohm 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 micro-ohm deionized water. An aliquot of the clean sample was separated at this point for elemental geochemical analysis. Extraction of Cl for ^{36}Cl analysis was accomplished using approximately 50 g of clean sample. The first step of Cl extraction involved dissolution of the sample in a mixture of hot nitric and hydrofluoric acid. The Cl released from the rock was precipitated using $AgNO_3$ following the method of Zreda (1994). Once dissolution of the rock was complete and the Cl was isolated from the rock residue, barium-nitrate [$Ba(NO_3)_2$] solution was added to the sample in order to precipitate any sulfur (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. The $^{35}Cl/^{36}Cl$ ratio of the final sample, precipitated as AgCl, was measured on the accelerator mass spectrometer (AMS) (Elmore et al., 1979) at the PRIME laboratory of Purdue University.

The major-element composition of the sample was determined by X-ray fluorescence analysis and B (boron) and Gd (gadolinium) by prompt gamma emission mass spectrometry. B and Gd concentrations should be determined because they have a large cross section for absorption of thermal neutrons that could otherwise create ^{36}Cl from ^{35}Cl. The total Cl content of the sample was determined using a combination ion-selective electrode.

The production of ^{36}Cl in a rock varies systematically with depth below the rock surface, as described by Liu et al. (1994). This means that the amount of ^{36}Cl in the sample and the sample's calculated age will vary as a function of erosion rate. Typically, if a volcanic rock has undergone high levels of erosion since eruption, the measured cosmogenic ^{36}Cl age will be younger than a same-aged rock that has undergone no erosion. However, in some cases, the reverse can be true because the abundance of thermal neutrons in the sample actually increases slightly with depth before decreasing at greater depth, due to slowing of cosmogenic fast neutrons and resultant conversion to 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, such as in rocks that have a Cl content over 500 parts per million (ppm). The effect of erosion on the cosmogenic ^{36}Cl age of a sample must be calculated on a case-by-case basis.

Results

Of the six samples collected for ^{36}Cl analysis, three yielded acceptable ^{36}Cl results (Table 1). Two of these are from the upper Carrizozo flow, and the third is from the lower. The other three suffered from S contamination despite attempts to chemically remove S, and the AMS errors were therefore unacceptably high.

Calculation of the age based on the $^{36}Cl/Cl$ ratio and chemical composition of the sample was accomplished using the CHLOE program (Phillips and Plummer, 1996) with production rates from Phillips et al. (1996). The cosmogenic ages of Carrizozo samples were calculated for erosion rates between 0 and 9 mm/k.y. (Table 2, Fig. 4). The erosion rate of a young basaltic lava flow is difficult to estimate. When a basaltic lava flow is emplaced, a glassy rind forms on the surface of the flow in response to the lava quenching as it comes in contact with air. This glassy rind can be observed on just-erupted Hawaiian lava flows (Fig. 3). The rind can be as much as 5 cm thick and is more fragile than the denser, crystalline, inner part of the flow. When the lava flow first erupts, the glassy rind is intact, but during cooling, fractures develop in the glass, probably

TABLE 1—Locations, geochemistry, and ^{36}Cl ages of samples from the Carrizozo malpais lava flow, east-central New Mexico.

Sample	Flow	Lat. (°N)	Long. (°W)	Elev. (m)	$^{36}Cl/Cl$ (10^{-15})	SiO_2 (wt. %)	TiO_2 (wt. %)	Al_2O_3 (wt. %)	Fe_2O_3 (wt. %)	MnO (wt. %)	MgO (wt. %)	CaO (wt. %)
ZB-26A	upper	33.705	106.937	1606	49.2 ± 5.4	50.99	1.81	15.63	10.96	0.15	6.13	7.90
ZB-26B	upper	33.705	106.937	1606	55.8 ± 8.9	51.31	1.81	15.56	11.22	0.16	6.37	7.93
ZB-27C	lower	33.592	106.41	1484	58.7 ±10.6	50.01	1.69	14.89	11.35	0.16	8.25	8.08

TABLE 1—continued.

Sample	Flow	Lat. (°N)	Long. (°W)	Elev. (m)	K_2O (wt. %)	Na_2O (wt. %)	P_2O_3 (wt. %)	Cl (ppm)	B (ppm)	Sm (ppm)	Gd (ppm)	U (ppm)	Th (ppm)
ZB-26A	upper	33.705	106.937	1606	1.39	3.79	0.40	306	8	5	5	1	2
ZB-26B	upper	33.705	106.937	1606	1.38	3.79	0.41	298	8*	5*	5*	1*	2*
ZB-27C	lower	33.592	106.41	1484	1.26	3.32	0.35	194	8*	5*	5*	1*	2*

*indicates approximate value

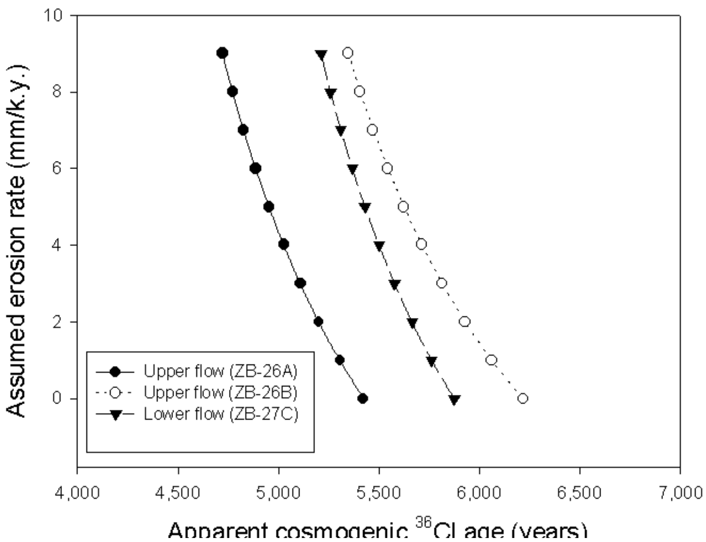

FIGURE 4—Cosmogenic ^{36}Cl age of samples ZB-26A, ZB-26B, and ZB-27C as a function of erosion rate.

due to thermal contraction (Fig. 3). Because of its delicate and fractured nature, the outer rind of a basaltic flow is readily stripped by mechanical weathering processes. In the case of the Carrizozo lava flows, there is virtually no glassy rind remaining, so it probably has been progressively stripped since the time of eruption. The McCarty's flow, of the Zuni–Bandera volcanic field, dated at about 3.2 ka by ^{14}C (Laughlin et al., 1994) and at 3.9 ± 1.2 ka by ^{36}Cl (Dunbar and Phillips, 1994; Phillips et al., 1997a), still retains some glassy rind, suggesting that the rind is stripped progressively through time, rather than being completely removed shortly after flow emplacement. We estimate, based on the presence of ropey features on the surface of the lava flow but absence of glassy rinds, that between 2 and 3 cm of material has been removed from the Carrizozo lava flows since the time of their emplacement. The stripped material could have been completely removed from the area, or it could have been deposited locally and weathered to form clay minerals. This yields an approximate erosion rate of 5 mm/k.y.

Based on the above-estimated erosion rate, the estimated cosmogenic ^{36}Cl ages for the three Carrizozo lava flow samples are 4.9 ± 0.5, 5.4 ± 1.0 and 5.6 ± 0.9 ka, yielding a weighted average of 5.2 ± 0.7 ka. The uncertainties cited here are based on the analytical error of the ^{36}Cl AMS determination, which is by far the largest single source of random error in the ^{36}Cl-determined age (Phillips et al., 1997b). 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 are also introduced based on uncertainty in the ^{36}Cl production coefficients. 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%, close to the statistical error cited for the weighted mean of our three ages. As can be seen from Fig. 4 and Table 2, the age is relatively insensitive to erosion rate. The calculated ages for an individual sample vary by about 600–700 yrs for an erosion-rate range from 0 to 9 mm/k.y.

Table 2—Cosmogenic ^{36}Cl age as a function of erosion rate.

	Erosion rate		
Sample	0 mm/k.y.	5 mm/k.y.	9 mm/k.y.
Upper flow			
ZB-26A	5,425 ± 597	4,953 ± 545	4,721 ± 519
ZB-26B	6,126 ± 994	5,625 ± 900	5,349 ± 856
Lower flow			
ZB-27C	5,875 ± 1058	5,430 ± 977	5,212 ± 983

Implications

The ^{36}Cl determined ages of between 4.9 ± 0.5 and 5.6 ± 0.9 ka for the Carrizozo lava flows are considerably older than early estimates of between 1,000 and 1,500 yrs for the age of the flow (Allen, 1952). However, our ages are in good agreement with the estimates of Salyards (1991) based on secular variation magnetostratigraphy. Salyards points out that he lacks complete confidence in his determined age because it depends on correlation to incomplete magnetic field direction curves and that the magnetic field represented by the Carrizozo samples may reflect a more recent excursion in field direction and hence a younger eruptive age. However, the correspondence between the ^{36}Cl and secular variation magnetostratigraphy ages suggests that the correct correlation was chosen. A ^{3}He age of 4.8 ± 1.7 ka has also been determined for the upper Carrizozo flow (Anthony et al., 1998). This age is consistent with the ^{36}Cl and magnetostratigraphy ages, adding further support of the 5,200-yr age for the Carrizozo lava flows.

Although the ^{36}Cl, ^{3}He, and magnetostratigraphy ages are significantly older than early estimates of flow ages based on geomorphic observations of the lava flow surfaces (Allen, 1952; Weber, 1964), they appear to be consistent with now-known ages for other recent basaltic lava flows within New Mexico. For instance, radiocarbon and ^{36}Cl ages for the McCarty's flow in the Zuni–Bandera volcanic field indicate that it erupted about 3,500 yrs ago. The McCarty's flow and the Carrizozo lava flows are geomorphically similar, but, upon close examination, the McCarty's flow appears distinctly younger. This interpretation is based on a greater degree of glassy pahoehoe rope preservation, larger amount of remaining iridescent glass, and less developed vegetation. Furthermore, the McCarty's flow would be expected to erode more rapidly than the Carrizozo lava flow because of its more northerly location and higher elevation and hence greater rainfall and temperature variations. At the time that the early age estimates of the Carrizozo lava flows were made, the McCarty's flow was thought to be as young as 1,000 yrs (Nichols, 1946), based on Acoma Indian legend and indirect stratigraphic relationship to Pueblo I artifacts (700–900 A.D.). Therefore, the early lava flow age estimates were internally consistent but too young.

From the ^{36}Cl dating of the Carrizozo lava flows we can infer that the lower and upper flows were erupted with no significant time break, at least no time break of greater than 1,000 yrs. This interpretation is consistent with the geochemically similar nature of the two lava flows observed by Faris (1980) as well as field observations of no soil development or significant weathering on the top of the lower flow before emplacement of the upper flow.

In terms of understanding geological processes, such as magmatic evolution and mantle processes in the New Mexico area, a 4,000-yr difference in the age of a basaltic lava flow could not be considered significant. However, an important aspect of studying basaltic lava flows within New Mexico is the ability to understand the potential volcanic hazards that could threaten the state. Limburg (1990) suggests that renewed basaltic volcanism is one of the greatest potential volcanic hazards in New Mexico and that there is approximately a 1% chance of some type of volcanic eruption occurring 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 when trying to predict future eruptions within the state.

Conclusions

Based on cosmogenic ^{36}Cl dating, our preferred eruption date for the Carrizozo malpais is 5,200 ± 700 yrs ago. This age is in good agreement with secular variation magnetostratigraphy and ^{3}He ages, but it is much older than ages based on visual observations of the flow surface morphology. The age of the Carrizozo lava flows is geomorphically consistent with the age of the well-dated McCarty's flow. There is no apparent age difference between the upper and lower Carrizozo flows, suggesting that these two flows were formed by an essentially monogenetic eruptive event.

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