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LETTER

^{3}He surface exposure dating and its implications for magma evolution in the Potrillo volcanic field, Rio Grande Rift, New Mexico, USA

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Abstract—Dating of very young igneous activity has been hampered by lack of suitable chronometers. We report here the results of ^{3}He surface exposure dating (KURZ, 1986a,b; CRAIG and POREDA, 1986) for lavas from the Potrillo volcanic field. This field is particularly suited to the technique because it has well-preserved, young (<700 ka) surfaces. The study applies ^{3}He dating in a systematic manner to a well-characterized volcanic field and shows the power of the technique in deciphering both relative and absolute chronologies. Dates are reproducible to within 14% for different samples from the same surface and are similar to within 8% for samples which, based on field relations, represent synchronous events. Cosmogenic ^{3}He/^{21}Ne confirms that ^{3}He is retained by the samples. Comparison of the relative chronology with compositional trends of the lavas suggests that eruptive centers within the volcanic field are fed by individual magma chambers. Ages range from 80 ka to 17 ka, consistent with estimates from geomorphology, soil profile development, and some K/Ar determinations.

INTRODUCTION

THE POTRILLO VOLCANIC field is a large field of alkaline (i.e., nepheline-normative) basanitic lavas and cinder cones (ANTHONY et al., 1992) which lies within the axis of the Rio Grande rift in southernmost New Mexico (Fig. 1). The lavas in the central and eastern part of the field rest on a constructional surface called La Mesa, which formed between 900 and 700 Ka. This age is based on preservation of the Jaramillo paleomagnetic subchron (900 Ka) in the upper portion of La Mesa sediments and deposits of ash from the Bishop Tuff (700 Ka) and Lava Creek "B" (600 Ka) in valleys incised into it (GILE, 1987, 1990; MACK et al., 1992). The ages are consistent with preliminary paleomagnetic data on the lavas, which show all flows are normal polarity and belong to the Brunhes chron (≤730 Ka; POTHS et al., 1991).

Surfaces from three separate eruptive centers are reported here (Table 1). They are (1) flows from the Afton eruptive center (samples 22B, 22D), which lie directly upon La Mesa and are in the central part of the field and (2) the Aden complex, a crater and series of flows that lie stratigraphically above the Afton flows. We include three samples from the Aden complex—a flow emanating from the crater (23C1, 23C2), a spatter cone (24B, 24C) from within the crater, and a lava lake (25A) also from within the crater. The third area is Black Mountain (21T, 21B, 27), which belongs to a series of cinder cones in the eastern part of the field (Fig. 1). The samples represent the extremes of trace element fractionation for this cinder cone.

ANALYTICAL METHODS

Mineral separations on the 250 to 420 micron fraction are performed by methylene iodide followed by hand magnet. We use only the upper 3 cm of flow surfaces (except for 21B), and only those samples with primary flow features, such as spatter, flow lineation, and cooling rinds. Mineral separates are a mixture of olivine (Fo_{80}) and clinopyroxene. Olivine is approximately 90% of the mixture for most samples, except sample 21T which is approximately 50% olivine and 50% pyroxene.

Samples are analyzed on a static mass spectrometer equipped with ion counting detection, built at the University of Minnesota (NIER and SCHLUTTER, 1985). The mineral separate is first crushed in vacuum, and the inherited (magmatic) component released is analyzed for its amount and isotopic composition of helium and neon. The same sample is then heated in a double-walled, all-metal vacuum furnace. The helium and neon released in this step is a combination of cosmogenic and residual magmatic components (CRAIG and POREDA, 1986; KURZ, 1986a,b). Both crushing and melting take place on-line to the mass spectrometer. For both steps the heavy noble gases are removed by sorption on charcoal at liquid nitrogen temperatures, and the remaining gas is admitted to the mass spectrometer. Neon is analyzed on the same gas after the completion of the helium analysis.

Our detection limit for ^{3}He is roughly 1×10^5 atoms. The blanks for ^{3}He for both crushing and melting, which are measured before and/or after each sample, are approximately at the detection limit and remain constant to within a factor of two uncertainty. ^{4}He blanks are about 3×10^{-12} cm^3 STP for crushing and 5×10^{-11} cm^3 STP for furnace heating. Neon blanks are atmospheric in isotopic composition and are about 8×10^{-12} and 1.2×10^{-10} cm^3 STP for ^{20}Ne in crusher and furnace runs, respectively. Cosmogenic ^{21}Ne concentrations are calculated by assuming that all ^{20}Ne in the melt fraction is due to a component with atmospheric isotopic composition and subtracting the corresponding amount of ^{21}Ne. What remains is the cosmogenic ^{21}Ne (usually between 10 and 50% of total ^{21}Ne). Known amounts of air noble gases serve as our standard. Experience with our low-sensitivity ion source has shown that the presence of air neon does not affect our sensitivity calibration for helium.

ANALYTICAL RESULTS

The helium data reported in Table 1 have been corrected for blank and mass fractionation. The ages and ^3He_c reflect uncertainties due

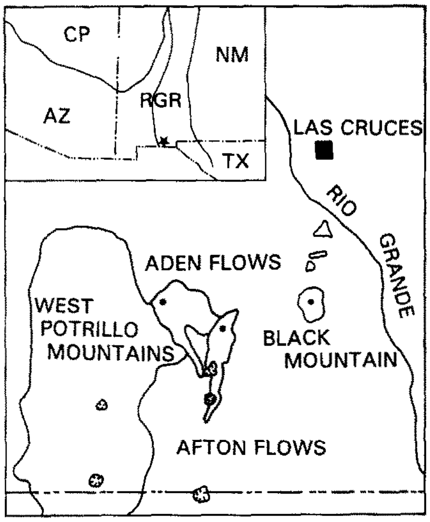

FIG. 1. Location map of the Potrillo volcanic field (star in inset). Abbreviations in the inset are as follows: CP, Colorado Plateau; AZ, Arizona; NM, New Mexico; TX, Texas; RGR, Rio Grande rift. The Potrillo volcanic field includes three spatially distinct areas: a western expanse of flows and cinder cones not included in this study, the Afton and overlying Aden volcanic centers in the central part of the field, and an eastern alignment of cinder cones (HOFFER, 1976; ANTHONY et al., 1991). The horizontal dimension of the figure is approximately 75 km.

to these factors and to uncertainty in the correction for magmatic ^3He. The cosmogenic ^3He is calculated by subtracting from the total ^3He a magmatic component equal to the total ^4He released in the heating step times the $^3He/^4He$ ratio released in the crush step. This method assumes that all of the ^4He released by heating is due to a magmatic component with a helium isotopic composition identical to that released in the crushing step. This is a reasonable assumption for a young, low-uranium phase like olivine.

Our yield from the crush step is often small, creating large uncertainties in the inherited or magmatic $^3He/^4He$ (Table 1). In calculating the correction for the residual magmatic ^3He in the melt step, we therefore assume that the magmatic $^3He/^4He$ is constant within a single flow and base the corrections on analyses with the greater precision. We use the value for 21B for both samples from that flow and the value for 22B for both samples of the Afton flow. Average values are used for samples 23 and 24. The analytical uncertainties in the ages shown in the final column of Table 1 reflect error propagation of these uncertainties in the $^3He/^4He$ of the crush step. The overall errors and the effect of this averaging remain small because of the large proportion of cosmogenic helium in the melt step (Table 1).

We note also that the inherited $^3He/^4He$ for all samples is similar to MORB ($\approx$8 times the atmospheric ratio, R_a), within their analytical uncertainties, and that the measurements with the lowest errors are most consistent with a MORB signature. There seems at this point little evidence for a non-MORB signature for the inherited component in these lavas, a conclusion which agrees with published ϵ_{Nd} values of +6 and $^{87}Sr/^{86}Sr$ of 0.7035 for lavas from the field (RODEN et al., 1988). This tentative conclusion reinforces the idea of a depleted mantle source for the magmas from this southern portion of the Rio Grande rift (PERRY et al., 1988).

We use neon concentrations to monitor the assumption that all ^4He in the melt step belongs to the magmatic component. Neon has three isotopes—^{20}Ne, ^{21}Ne, and ^{22}Ne. ^{20}Ne and ^{22}Ne are dominated by the magmatic component; only the low-abundance ^{21}Ne has a significant cosmogenic contribution. Thus, in the absence of radiogenic ^4He, $^4He/^{20}Ne$ should be similar in crush and melt steps. For sample 21T the $^4He/^{20}Ne$ released in the melt step was substantially higher (68 ± 26) than that released in the crush step (3.0 ± 0.4). We do not know the source of the radiogenic component in this sample; possible explanations are a U-rich accessory phase in the mineral separate or contamination of the sample during processing. We use the measured $^4He/^{20}Ne$ to partition ^4He in the melt step between magmatic and radiogenic components. The validity of this correction is suggested by the agreement in age between 21T and 21B, the duplicate sample from this same flow that did not show high $^4He/^{20}Ne$.

Neon data also suggest that there has not been serious diffusive loss of cosmogenic helium from our olivine samples. Cosmogenic $^3He/^{21}Ne$ in our samples is approximately 2.3 (Table 1), which agrees within error with a predicted value of 2.0 (LAL, 1991) and a measured value for olivine from Hawaii of 2.1 (MARTI and CRAIG, 1987).

^3He surface exposure ages are calculated using standard techniques (KURZ, 1986a,b; KURZ et al., 1990; CERLING, 1990). The ages (Table 1) are based on a ^3He production rate of 434 atom/g/yr at 39 N latitude and 1445 m elevation (CERLING, 1990) and are corrected (LAL, 1991) for latitude (32.2°N), elevation (1284–1387 m), and sample thickness (3–6 cm). The constancy and accuracy of the production rate of cosmogenic ^3He is still a subject of debate (CERLING,

Table 1. Surface exposure ages of samples from the Potrillo volcanic field.

	Description	Crush		Melt					
		$^3He/^4He$ (R/R_a)	$[^4He]^1$ 10^{-10} cc/g	$[^3He]$ 10^{-12} cc/g	$[^4He]$ 10^{-10} cc/g	$[^3He_c]$ 10^6 atom/g	$^3He/^{21}Ne_c$	%[2] $[^3He_c]$	"Age"[3] ka
Black Mountain									
21T	Upper flow associated	15 ± 12	5.5	0.97 ± 0.05	180 ± 18	25.7 ± 1.3	2.6±0.6	98.6	77 ± 4
21B	with cinder cone[4]	13 ± 7	10.3	1.10 ± 0.06	54 ± 10	26.9 ± 2.3	3.0±0.5	91.0	85 ± 7
27	Lower flow	12 ± 4	20.2	0.94 ± 0.06	36 ± 6	23.8 ± 1.7	2.6±0.5	94.2	69 ± 5
Afton volcanic center									
22B	Flow resting on La Mesa	12.8 ± 4.1	22	0.92 ± 0.05	30 ± 7	23.3 ± 1.34	2.4±0.3	94.2	72 ± 4
22D	surface[5]	14 ± 15	4.2	1.03 ± 0.05	27 ± 9	26.4 ± 1.35	2.3±0.3	95.4	81 ± 4
Aden volcanic center									
23C1	Flow collected 5 km	12.7 ± 5.7	16.7	0.240 ± 0.035	23 ± 9	5.5 ± 1.1	2.5±1.2	85.3	16.9± 3
23C2	from Aden Crater[6]	8.9 ± 5.	16.8	0.228 ± 0.028	23 ± 6	5.2 ± 0.9	--	84.9	15.9± 2
24B	Spatter cone in Aden	7.2 ± 1.6	57	0.252 ± 0.025	46 ± 7	5.5 ± 0.7	--	81.2	15.7± 2
24C	Crater[7]	7.8 ± 1.4	109	0.307 ± 0.3	71 ± 10	6.3 ± 0.9	1.5±0.5	76.4	17.9± 2
25A	Lava lake within crater	8.2 ± 1.5	62	0.317 ± 0.039	77 ± 10	6.2 ± 1.1	--	72.8	18.2± 3

1. Uncertainty ± 10%.
2. Percent of ^3He in melt step of cosmogenic origin.
3. Analytical uncertainties with error propagation from inherited component.
4. 6 cm thick sample cut parallel to flow surface, 21T = top 3 cm, 21B= bottom 3 cm.
5. Two separate samples from the same flow surface, collected 15 m apart.
6. 23C1 and 23C2 represent two fractions of olivine from the same hand sample.
7. 24B and 24C represent two separate samples from the same spatter cone.

1990; KURZ et al., 1990; LAL, 1991). A reasonable uncertainty, however, is approximately ±30%, and we use this value in comparing results from surface exposure dating with other techniques in Fig. 2. These uncertainties are greater than the analytical uncertainties given in Table 1, which represent full error propagation for our experiments.

The uncertainty in production rate stems from a number of factors: the production rate has been precisely calibrated at only one age (≈15 ka) and may vary by 10 to 20% due to changes in the intensity of cosmic ray flux. Also, the production rate is tied to the ^{14}C timescale, and all ages would increase approximately 17% if adjusted to proposed revisions in that timescale (BARD et al., 1990). Ages would also be systematically low if the surfaces had been eroded or covered since eruption. Based on the preservation of primary surface features, we estimate that erosion has been 1 to 5 cm maximum. This amount of erosion would result in not more than 10% underestimation of age for the oldest flows.

The analytical results show good reproducibility, with all sample splits similar within 1σ error. As the footnotes in Table 1 summarize, there are different types of duplicates reported in this study, some of which reflect laboratory uncertainties and some preservation of surfaces. 23C1 and 23C2 are two fractions of olivine from the same hand sample. 21T and 21B are the top and bottom of a single sample, with different methods of correction for the magmatic component (see previous text). 22B and 22D are two separate samples from the same flow, as are 24B and 24C. Reproducibility for different samples of the same surface (e.g., samples 22 and 24) is approximately 14%. This is currently our best estimate of precision of the ^3He surface exposure ages.

In addition to showing reasonable precision, the ages make geologic sense in that results from the two samples within Aden Crater (23 and 24) are similar and are younger than the underlying Afton flows. We note here that the samples from Aden Crater had the highest quality surfaces, with delicate spatter structures intact, and thus do not suffer from underestimation of age by erosion.

DISCUSSION

Our results agree with previous dates (Fig. 2) based on development of calcium carbonate in soils (GILE, 1987, 1990) and with one set of K/Ar analyses (SEAGER et al., 1984). There is a discrepancy with a second set of K/Ar analyses (SEAGER et al., 1984) that give ages of ≈500 ka for all three eruptive centers. The following geologic arguments support the surface exposure dates. Lavas emanating from the eastern cones flow down the erosional scarp of La Mesa to the current Rio Grande valley, entrenchment of which may have required an interval of time greater than the 200 to 400 Ka implied by the older K/Ar dates (cf. SEAGER et al., 1984). Also, the surfaces of Aden Crater appear considerably fresher than those of Black Mountain and the Afton flows, in contradiction to the synchronous ages given by the second set of K/Ar analyses.

The precise relative chronology of flows yields important information concerning magmatic evolution, allowing us to attach a time sequence to the compositional trends of Fig. 3. The Potrillo volcanic field, with its overall high concentrations of the rare-earth and alkali elements, shows the correlation between silica undersaturation and enrichment of rare earth elements typical of some continental rift and oceanic island lavas (see, e.g., ANTHONY et al., 1989; LUHR et al., 1989). In addition, we have previously documented for this field a correlation between increasing concentration of incompatible elements and decreasing Mg number from the lowermost flows to the uppermost within individual eruptive centers (ANTHONY et al., 1992; CHEN, 1991). This evolution is interpreted as resulting from shallow-level fractionation of an assemblage including olivine, which is the predominant phenocrystic phase. The indistinguishable ages for the two flows from Black Mountain, which are at opposite ends of the trend

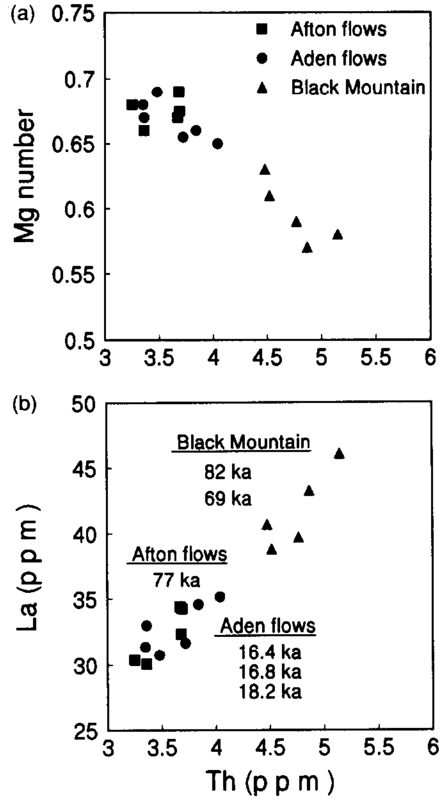

FIG. 3. (a) Th in ppm vs. Mg# (molar $Mg/(Mg + Fe^{2+})$). Decreasing Mg# is interpreted to result from olivine fractionation. (b) Th in ppm vs La in ppm. Magnesium and iron determined by X-ray fluorescence, La and Th by instrumental neutron activation analysis. Typical analytical uncertainties are 2 ppm for La and 0.1 ppm for Th.

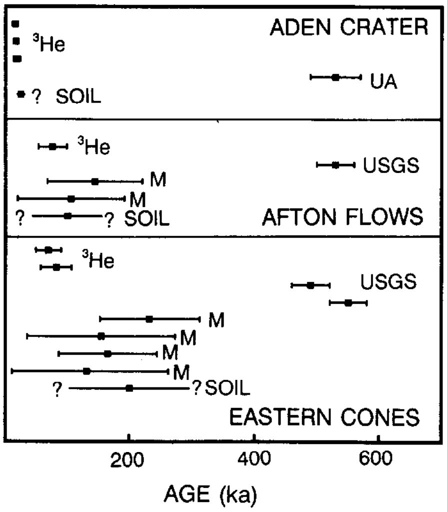

FIG. 2. Summary of chronology available for the Potrillo volcanic field. ^3He indicates data from this study, "soil" indicates age estimates derived from accumulation of pedogenic calcium carbonate (GILE, 1987, 1990). "M" indicates K/Ar analyses made by Mobil Oil Company and reported by SEAGER et al. (1984). "UA" and "USGS" indicate flows that were re-sampled by W. R. Seager and analysed at the University of Arizona and the United States Geological Survey.

for that eruptive center, and also for the three samples from the Aden Complex suggest that this shallow-level fractionation occurs fairly rapidly.

Although the same correlation between increasing incompatible elements and decreasing Mg number applies to the volcanic field as a whole, age does not correlate with position in the fractionation trend. Volcanic activity appears to have come in bursts, with simultaneous activity in the central and eastern portions of the field, followed by a period of quiescence, and then re-initiation of activity in the central portion of the field. Although they are synchronous, the lavas at Black Mountain are more evolved than the Afton flows (Fig. 3), and the compositions of lavas from the central portion of the field are similar, although of varying age. Thus, the volcanic centers are not related by simple periodic tapping of a continuously evolving magma chamber but rather seem to be fed by a complex system of magma chambers, with their final chemical evolution taking place in shallow, individual chambers.

CONCLUSIONS

1) ^{3}He surface exposure dates obtained on samples from a Quaternary lava field show good reproducibility. Duplicate samples from the same flow surface agree in all cases within analytical error. Further, samples from flow surfaces which, based on geologic evidence, should be approximately synchronous, i.e., a spatter cone and a lava lake from one of the craters, also agree within analytical error.
2) Uncertainty in the ages of the lavas is greater than analytical error because of insufficient knowledge of the production rate of cosmogenic ^{3}He through time. The ages are, however, geologically reasonable in that they conform to known stratigraphy. Further, the ages agree with estimates based on build-up of pedogenic carbonate and some K-Ar determinations. The ^{3}He surface exposure dating technique appears to hold substantial promise for the dating of young lavas.
3) The relative ages of the samples yield insight into the processes of magma genesis. Each eruptive center shows correlation between decreasing Mg number and increasing concentration of incompatible elements upsection. This same chemical correlation characterizes the volcanic field overall, but age does not correspond to position in the fractionation trend. Thus, processes are more complex than simple periodic tapping of a fractionating magma chamber.

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