Determining eruption ages and erosion rates of Quaternary basaltic volcanism from combined U-series disequilibria and cosmogenic exposure ages

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ABSTRACT

We present ^{238}U-^{230}Th -^{226}Ra disequilibria and cosmogenic ^{3}He and ^{36}Cl data for the Bluewater flow of the Zuni-Bandera volcanic field in western New Mexico. The ^{238}U-^{230}Th disequilibria measured on separated groundmass phases yield an internal isochron age of 68 ka (+24/–20 ka; 2σ). This value cannot be directly compared with surface exposure ages unless erosion rates are known. The apparent (zero erosion) ages determined from both the ^{3}He concentration (47.5 ± 5 ka; 2σ) and the ^{36}Cl concentration (41.2 ± 8.8 ka; 2σ) are significantly younger than the U-Th isochron age. When minimum estimates of surface erosion based on flow morphology are considered, the ^{3}He concentrations indicate a minimum exposure age of 60 ka, in good agreement with the U-Th isochron age, with a minimum erosion rate of 1.7 mm/k.y. and an erosion rate as high as 5 mm/k.y. in other locations. Correcting for erosion has little effect on the model ^{36}Cl age and, as a result, the ^{36}Cl age is significantly younger than the U-Th isochron age and erosion-corrected ^{3}He ages; this discordance is attributed to a lack of closed-system behavior in the ^{36}Cl system. These new ages have local significance for the geochronology of the Zuni-Bandera volcanic field; however, their larger significance is in their applicability to dating Quaternary basalts and quantifying erosion rates.

Keywords: dating Quaternary basalts, U-Th-Ra disequilibria, ^{3}He and ^{36}Cl cosmogenic ages, erosion rates.

INTRODUCTION

Accurate dating of Quaternary basaltic volcanism is an important but problematic issue with implications ranging from hazard assessment to evolution of magmatic systems. The half-lives of isotopic systems traditionally used for dating basalts, such as ^{147}Sm-^{143}Nd, ^{87}Rb-^{86}Sr, ^{238}U-^{206}Pb, and ^{176}Lu-^{176}Hf, are much too long to date Quaternary age volcanism. Recent refinements in mass spectrometric methods have enabled the development of dating methods for a number of new isotopic systems that are applicable to Quaternary and Holocene basalts. These methods include (1) ^{40}Ar/^{39}Ar, which under ideal conditions can now be used to date basalts as young as 20 ka (e.g., Renne, 2000; Singer et al., 2000); (2) surface exposure dating, which uses the in growth of cosmogenically produced nuclides (e.g., ^{3}He, ^{36}Cl) to delimit eruption ages ranging from as little as several hundred years to hundreds of thousands of years (Ackert et al., 2003; Kurz et al., 1990; Laughlin et al., 1994; Phillips et al., 1986, 2001; Dunbar and Phillips, 2004); and (3) U-series daughter nuclides, which have half-lives ranging from seconds to 75 k.y., and can date basalts from ~0.05 to 350,000 yr (Allègre and Condomines, 1976; Goldstein et al., 1994; Rubin et al., 1994; Peate et al., 1996; Sims et al., 2003; Condomines, 1997; Condomines et al., 2003, and references therein).

Each of these methods, however, has limitations. The ^{40}Ar/^{39}Ar dating requires the presence of suitable mineral phases to retain both K and Ar and to exclude excess Ar. Exposure ages are sensitive to individual exposure histories such as the erosion of the flow surface or burial history of the surface (e.g., cover by loess, younger volcanics, snow), both of which are difficult to quantify for older flows and result in young apparent ages when erosion is neglected. U-series isotopes are sensitive to addition or loss of parent and/or daughter nuclides, mixing processes, and long magma residence times.

We present new U-Th-Ra disequilibria, ^{3}He, and ^{36}Cl data for the Bluewater flow of the Zuni-Bandera volcanic field in western New Mexico. We consider the age estimates and sources of error for the different methods in the geologic context of the volcanic field to accurately delimit eruption age and erosion rate of the flow. These results demonstrate that the Bluewater flow is significantly older than previously reported (Laughlin et al., 1994; Dunbar and Phillips, 2004), and that U-Th disequilibrium ages can be used to quantify the influence of erosion on cosmogenic exposure ages. To our knowledge, this represents the first time that U-series and cosmogenic ages have been combined to define both the ages and erosion rates of volcanic flows.

GEOLOGICAL BACKGROUND AND AGE CONSTRAINTS

The Zuni-Bandera volcanic field (Fig. 1) is along the Jemez lineament, a northeast-trending zone of apparent crustal weakness defined by an alignment of Cenozoic volcanic fields extending across Arizona and New Mexico (Mayo, 1958). The Zuni-Bandera volcanic field is at the intersection of this Jemez lineament and the Rio Grande Rift, and is in the transition zone between thick crust (>40 km) associated with the Colorado Plateau and thin crust (<40 km) associated with the Rio Grande Rift.

The Zuni-Bandera volcanic field consists of numerous vents and mafic lava flows erupted over the past 0.7 m.y. (Laughlin et al., 1994). Three pulses of Quaternary basaltic volcanism within the Zuni-Bandera volcanic field have been identified: ca. 700 ka, ca. 150 ka, and the youngest, from ca. 80 to ca. 3 ka or younger. The Bluewater flow is part of this youngest pulse and originates from the El Tintero cinder cone (Fig. 1). The Bluewater flow is a silica-saturated, tholeiitic basalt with a holocrystalline texture. Its modal mineralogy consists of olivine and

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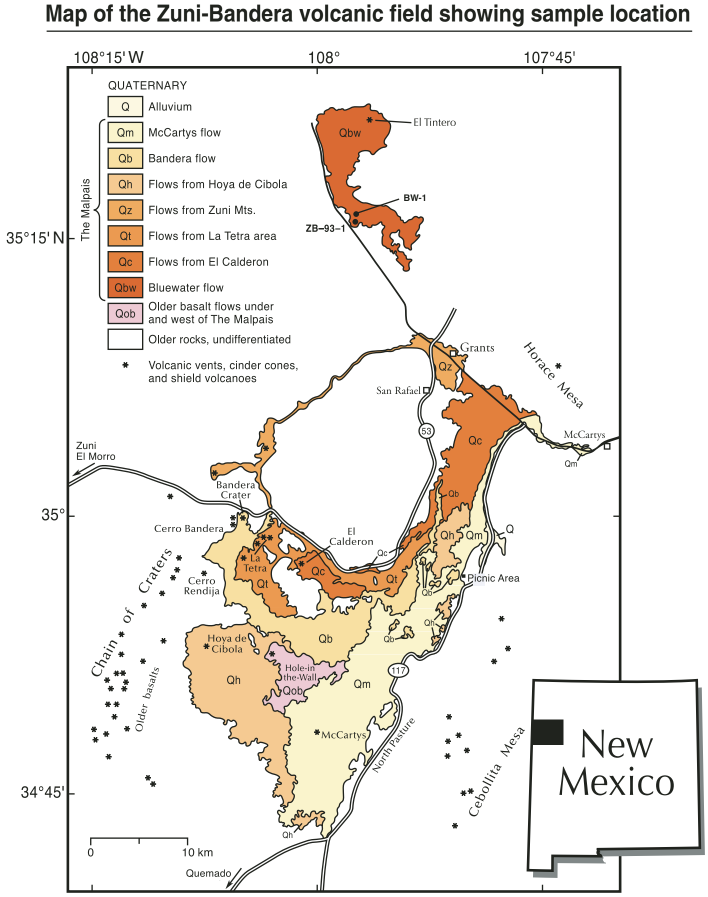

Figure 1. Location map of Zuni-Bandera volcanic field showing Bluewater flow and sample locations.

plagioclase phenocrysts, with a groundmass dominated by plagioclase and clinopyroxene microphenocrysts and subordinate opaque oxides and olivine. Original flow surface features such as glassy rinds and/or ropy pahoehoe are completely absent. Based on observations of nearby, younger dated flows with well-preserved surface features, Dunbar and Phillips (2004) inferred at least 10 cm of erosion. Comparison with other adjacent flows suggests that it is significantly older than the McCartys and Zuni-Bandera flows, which have concordant ^{14}C, ^{36}Cl, and ^{3}He ages of 3–4 ka and 10–12 ka, respectively, as well as the Paxton Springs and Twin Craters flows, which have ^{36}Cl ages of 15–20 ka (Dunbar and Phillips, 2004). The degree of surface weathering and other geomorphological data (e.g., topographic position) suggest that the Bluewater flow is younger than the El Calderon flow, dated by K-Ar as 110–128 ka (Laughlin et al., 1993).

Direct dating of the Bluewater flow by K-Ar yields ages of 5.69 and 2.23 Ma, indicating excess Ar (Laughlin et al., 1993, 1994). Laughlin et al. (1994) determined an apparent ^{3}He age of 56 ± 6 ka assuming no erosion. In contrast, Dunbar and Phillips (2004) determined a significantly younger ^{36}Cl age of 39.4 ± 7.0 on a single sample from a different location. The cause of this discrepancy, and thus the actual age of the flow, is unclear. In order to better define the age of the flow we have measured ^{3}He and ^{36}Cl on the same sample, thus eliminating any potential differences due to variable exposure rates of different samples. U-Th-Ra disequilibria were measured on the pristine interior of the flow, whereas the cosmogenic ^{36}Cl and ^{3}He ages were determined on the more weathered exterior.

U-Th-Ra DISEQUILIBRIA

The U-Th-Ra data for both whole rocks and minerals are reported in Table DR1 (see GSA Data Repository[1]). U-series dating of Quaternary basalts is accomplished by measuring radioactive disequilibria among the daughter isotopes of the ^{238}U decay chain [e.g., ^{238}U-^{230}Th ($t_{1/2}$ = 75 ka) and ^{230}Th-^{226}Ra ($t_{1/2}$ = 1.6 ka)]. Bluewater whole rocks have (^{230}Th)/(^{232}Th) of 1.14, (^{238}U/^{232}Th) of 1.09, and (^{230}Th/^{238}U) of 1.04, indicating that daughter ^{230}Th is in excess relative to parent ^{238}U. Assuming that this ^{238}U-^{230}Th disequilibrium was generated by partial melting, rather than secondary processes, the half-life of ^{230}Th (75,200 yr) delimits the age of the Bluewater flow to younger than 350 ka (i.e., <5 times the half-life of ^{230}Th). The (^{226}Ra/^{230}Th) of unity indicates that its age exceeds 8 ka (>5 times the half-life of ^{226}Ra).

The age of the Bluewater flow can be further determined through use of an internal isochron using Th isotopes and respective U and Th concentrations of minerals (see footnote 1 for mineral separation methodology). Application of the internal-isochron method requires closed-system behavior and assumes that at the time of crystallization all minerals have identical (^{230}Th/^{232}Th), but variable (^{238}U/^{232}Th). For the Bluewater flow, the whole rock, plagioclase (groundmass and phenocrysts), magnetite, olivine, and residual groundmass have a range of (^{238}U/^{232}Th) from 0.98 to 1.14, and (^{230}Th/^{232}Th) from 1.09 to 1.18, defining a linear trend interpreted as isochronous with eruption age significance (Fig. 2). We use a nonlinear, maximum-likelihood method to estimate the slope and intercept of the best-fit line through the whole rock, minerals, and groundmass data, and use Monte Carlo methods to estimate 95% confidence limits (Sohn and Menke, 2002). Regression of the whole rock, minerals, and groundmass, including phenocryst plagioclase and olivine, yields an age of 76 +36/–27 ka (95% confidence interval). The isochron slope is heavily weighted by the whole-rock and groundmass data that show wide dispersion and relatively small uncertainties.

Removing phenocryst plagioclase and olivine from the isochron calculation results in a tighter and more accurate estimate of the eruption age (Fig. 2). Removal is justified because these phenocrysts could have resided for an unknown but significant period of time during crustal magma storage or could be older phenocrysts from another magmatic system that were mixed into the magma prior to or during eruption. Regression of the remaining whole rock, microlite plagioclase, magnetite, and groundmass defines a younger age of 68 +24/–20 ka (95% confidence interval). While in principle the difference between the phenocryst and microlite-groundmass ages may provide constraints on magma storage times and/or remixing processes (e.g., Pyle et al., 1988), the large analytical uncertainties in the phenocrystic olivine and plagioclase do not provide the required resolution to accurately distinguish such effects on this isochron. It is important to note in the context of this study that any contamination effects or long magma residence times should not affect the microlite-groundmass isochron age, because these phases formed during and after eruption.

COSMOGENIC RESULTS

Surface exposure dating relies on the accumulation of cosmogenic nuclides in near-surface rocks due to interactions with cosmic rays. There are several detailed summaries of the technique (e.g., Gosse and Phillips, 2001), and only the most pertinent aspects are summarized here. Surface exposure dating is well suited for dating basaltic lava flows because (1) they cannot have been exposed to cosmic rays prior to eruption; and (2) samples with

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[1] GSA Data Repository item 2007109, Table DR1 (U-series disequilibria data), Table DR2 (helium isotopic data and exposure ages), Table DR3 (Cl concentration and isotopic data and ^{36}Cl exposure ages), Table DR4 (major and trace element abundances and Nd, Sr and Pb isotopic compositions), Appendix 1 (preparation of mineral separates), and Appendix 2 (photo of Bluewater Flow), is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

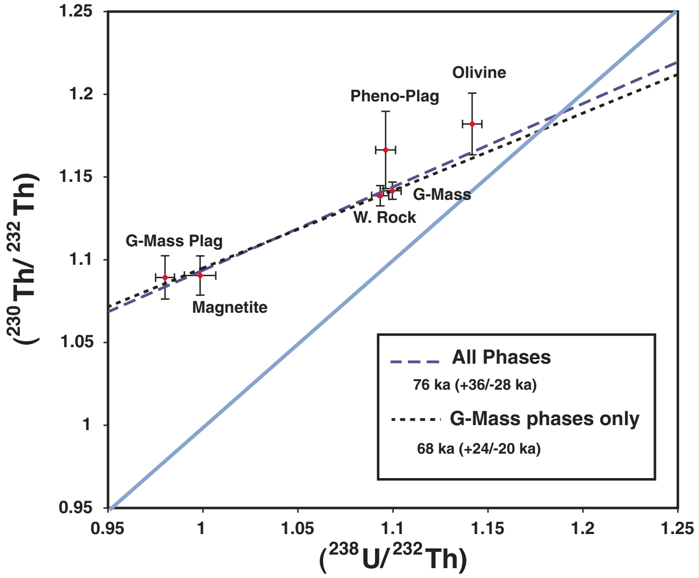

Figure 2. U-Th mineral isochrons for Bluewater flow calculated using (1) all groundmass (G-mass) and phenocryst (Pheno) phases; and (2) groundmass phases only. These isochrons are determined using nonlinear, maximum-likelihood method to estimate slope and intercept of best-fit line and Monte Carlo methods to estimate 95% confidence limits (Sohn and Menke, 2002). Error bars on data points represent 2σ analytical uncertainties. Larger uncertainties for olivine and plagioclase (Plag) phenocrysts are due to their much lower concentrations. Significant difference in (^{238}U/^{232}Th) of plagioclase phenocrysts and plagioclase groundmass suggests that either their magma sources were distinct, or that inclusions (mineral or melt) are causing difference. U and Th concentrations of olivine phenocrysts are also higher than expected from experimental partitioning (Blundy and Wood, 2003), suggesting that mineral or melt inclusions are controlling its U and Th budget. W. Rock—whole rock.

minimal surface erosion can often be selected based on preservation of surface flow features (Kurz, 1986). When lava flows undergo erosion or were covered, apparent exposure ages (ages calculated assuming no erosion or covering) will be minimum age estimates rather than actual eruption ages.

The ^{3}He technique is most suitable for dating basalt because olivine and clinopyroxene are common mineral phases that quantitatively retain He; the lack of quartz and the requirement for significantly larger sample sizes rules out applications of ^{10}Be or ^{26}Al in most cases. The ^{36}Cl technique is also well suited to dating basaltic lava flows because it can be applied to whole-rock (phenocryst poor) samples. Previous determinations of ^{3}He and ^{36}Cl concentrations in Bluewater samples (Dunbar and Phillips, 2004; Laughlin et al., 1994) yielded significantly different apparent ages. To evaluate the possibility of different exposure histories (erosion rates) at these different sample sites, new measurements of both nuclides were made. The magmatic ^{3}He/^{4}He isotope ratio (7.0 R/Ra; Table DR2 [see footnote 1]) is the same as the mean value obtained by Laughlin et al. (1994), but the cosmogenic ^{3}He concentration is slightly lower, resulting in a younger apparent exposure age of 47.5 ± 5.0 ka (2σ). Differences in cosmogenic ^{3}He concentrations exceed analytical uncertainties and most likely reflect a higher erosion rate at our sample site compared to the Laughlin et al. (1994) sites. The mean values of replicate analyses in Laughlin et al. (1994) are also significantly different, indicating measurable variation in the erosion rate at their two sample sites. Figure 3 shows calculated exposure ages as a function of erosion rate for the three ^{3}He sample sites.

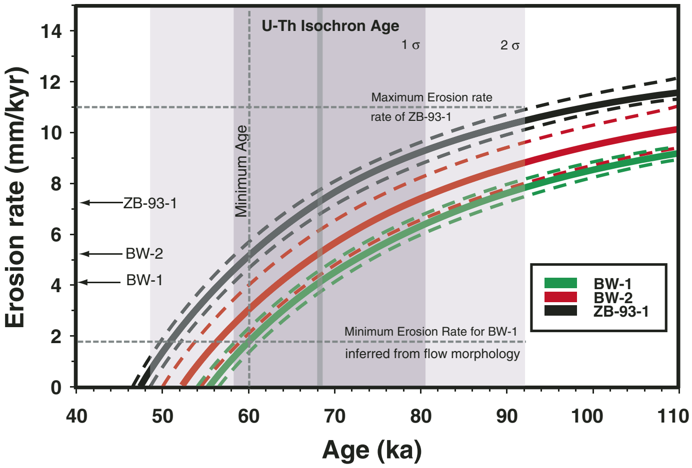

Figure 3. ^{3}He exposure age as function of erosion rate for three sites sampled for exposure age dating on Bluewater flow. Analytical uncertainties (2σ) are shown by dotted lines. Errors in production rate, scaling, and attenuation length will shift curves uniformly up or down but not change relative distance between them. Given that exposure age must equal eruption age at all sites, different curves indicate that different erosion rates must have affected each site. U-Th isochron age with 1σ (68% confidence level) and 2σ (95% confidence level) are shown. Extrapolation of U-Th ages to ^{3}He age curves provides estimate of erosion rates for different samples (indicated by arrows at left of figure). Minimum erosion rate for BW-1 is calculated using geomorphologic estimate of Dunbar and Phillips (2004), who inferred at least 10 cm of erosion. Maximum erosion rate of ZB-93-1 is determined by extrapolation of upper age limit (2σ) for U-Th groundmass phase mineral isochron.

Our new ^{36}Cl exposure age (Table DR3; see footnote 1) replicates that of Dunbar and Phillips (2004) within analytical uncertainties, ruling out laboratory errors in either processing or accelerator mass spectrometry measurements. While the mean apparent ^{36}Cl ages of 41.2 ± 8.8 ka (2σ) are just within 2σ error of our new ^{3}He age from the same sample, this interpretation is inconsistent with geological observations suggesting that this flow has been significantly eroded (Dunbar and Phillips, 2004) in that ^{3}He and ^{36}Cl ages diverge as erosion rate is increased. Correcting for erosion has little effect on the model ^{36}Cl age (because the productivity initially increases with depth) while increasing the ^{3}He age. In addition, the ^{36}Cl age is well outside the U-Th isochron age reported here. Thus, the cause of the apparently young ^{36}Cl ages remains unresolved. Generally, paired ^{3}He and ^{36}Cl measurements in the younger Zuni-Bandera volcanic field basalts (<20 ka) give concordant ages (Dunbar and Phillips, 2004). Because the McCartys and Bandera crater flows ^{3}He and ^{36}Cl ages agree well (Laughlin et al., 1994; Dunbar and Phillips, 2004), systematic errors in their respective production rates can be ruled out. Prolonged burial of at least several hundred thousand years would be required for decay of ^{36}Cl to be a factor, and is precluded by the relative ages and stratigraphic relationships with other flows in the Zuni-Bandera volcanic field as well as our new U-Th ages. Because neither erosion nor burial will account for the discrepancy in ^{36}Cl ages with the ^{3}He and U-Th isochron ages (which are essentially concordant), we treat the ^{36}Cl ages as only minimum ages. We note that the ^{36}Cl measurements were made on whole-rock samples that are primarily composed of fine-grained groundmass phases. Closed system assumptions for soluble species such as Cl, as well as K and Ca (the spallation targets for ^{36}Cl), may be violated for groundmass phases rich in these elements (i.e., glass) on old weathered surfaces. In contrast, ^{3}He was measured in mineral phases (olivine and clinopyroxene) that were significantly larger and hand-picked to exclude crystals with evidence of chemical weathering.

EROSION RATE

There is considerable geomorphological evidence to suggest that the Bluewater flow has been eroded. Based on the lack of a glassy rind and slabby vesicular layer typically seen on fresh pahoehoe flows, Dunbar and

Phillips (2004) inferred at least 10 cm of erosion. Using this estimate we obtain for BW1, the sample with the highest cosmogenic ^{3}He concentration, an erosion rate of 1.7 mm/k.y. and a minimum ^{3}He age of ca. 60 ka (Fig. 3), which is in agreement with the U-Th isochron age of 68 ka at the 68% confidence level (1σ). If one then accepts the minimum age of 60 ka for the Bluewater flow, then the erosion rates at the other two sites, which have lower ^{3}He concentrations, must be higher: 5.2 ± 0.5 mm/k.y. at ZB93-1 and 3.1 ± 0.8 mm/k.y. at BW-2. The observation that calculated erosion rates vary from sample to sample is consistent with geological observations that show considerable variability of the flow surface.

The U-Th isochron ages (which are not influenced by erosion) can also be used with cosmogenic nuclide concentrations to estimate erosion rates. Using the U-Th groundmass isochron age of 68 ka as the eruption age, we calculate an average erosion rate of 5.5 ± 1.6 mm/k.y. from the three individual sample erosion rates of 4.1 ± 0.2, 5.2 ± 0.9, and 7.2 ± 0.4 mm/k.y. for the BW-1, BW-2, and ZB-93-1 samples, respectively. These erosion rates correspond to total erosion estimates of ~27, ~34 and ~47 cm at the respective sites. These calculated erosion rates are larger, but of the same order of magnitude as the minimal erosion estimates of Dunbar and Phillips (2004), and indicate significant variability in the erosion rate of the flow surface. When the uncertainty in the U-Th isochron age is considered, the calculated erosion rates at the 68% confidence limit (1σ) range from 0.8 mm/k.y. to 9.5 mm/k.y., with total extents of erosion ranging from 5.8 to 76 cm. Similar extrapolations can be made at the 95% confidence level, which limits the erosion rate for ZB-93-1 as <11 mm/k.y.; however, the probability that the Bluewater flow is 92 ka or older is small (~2.5%).

SUMMARY

Cosmogenic nuclides and U-series disequilibria have different sources of geological uncertainty: cosmogenic nuclides are subject to uncertainties in the erosion rates, whereas U-Th disequilibria ages are subject to uncertainties in magma chamber residence time and magma mixing processes. Using only the groundmass phases of the flow, which in principle grew during and after eruption, eliminates the uncertainties in the U-Th isochron age associated with magma chamber residence time and mixing processes. Combining this U-series groundmass isochron age with the cosmogenic ^{3}He concentrations provides a self-consistent estimate of both the eruption age and erosion rate of the Bluewater flow. While these results have local significance for the geochronology of the Zuni-Bandera volcanic field, their larger significance is in their general applicability to dating Quaternary basalts and quantifying erosion rates. These results also demonstrate the utility of U-Th isochron method for dating young basalts, particularly for flows where (1) excess Ar or low K precludes use of ^{40}Ar/^{39}Ar dating; (2) there is no olivine or clinopyroxene for ^{3}He exposure dating; or (3) the extent of surface erosion is unknown.

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