Cosmogenic ^{36}Cl dating of a young basaltic eruption complex, Lathrop Wells, Nevada

Marek G. Zreda
Fred M. Phillips } Geoscience Department, New Mexico Tech, Socorro, New Mexico 87801
Peter W. Kubik*
Pankaj Sharma } Nuclear Structure Research Laboratory, University of Rochester, Rochester, New York 14627
David Elmore Department of Physics, Purdue University, West Lafayette, Indiana 47907

ABSTRACT

It has been proposed that the Lathrop Wells volcanic center, a late Quaternary basaltic complex in southern Nevada, has erupted more than once. In common with most Quaternary basalts, this volcanic center has proved difficult to date by K/Ar and other commonly employed methods. We have measured the accumulation of ^{36}Cl in 11 samples from lava flows and volcanic bombs and obtained a combined average age of 81 ± 7.9 ka, with no systematic differences between sample subsets collected from different volcanic features. The ^{36}Cl dates do not support a history of multiple eruptions, but neither do they completely preclude the possibility.

INTRODUCTION

Quaternary basalts are common in many parts of the world and provide important information on tectonic activity, crust and mantle geochemistry, and geomorphic history. Although volcanic rocks have commonly been dated by K/Ar and ^{40}Ar/^{39}Ar methods, young basaltic rocks can be difficult to date by these methods because of low K content, unsuitable mineral content, and contamination by atmospheric Ar. The development of alternative methods for dating young basalts would, therefore, aid several branches of the earth sciences.

In this paper, we report results from ^{36}Cl dating at the Lathrop Wells volcanic center in southern Nevada. The Lathrop Wells center is a typical late Quaternary basaltic cinder cone complex. The proximity of the cinder cone to the proposed high-level nuclear waste repository at Yucca Mountain, Nevada, has stimulated interest in the chronology of its activity. As a result, numerous K/Ar and ^{40}Ar/^{39}Ar measurements have been performed there (Turrin et al., 1991). Many other dating approaches either have been attempted or are in progress. The variety of methods employed at the Lathrop Wells center make it a valuable site for the intercomparison of dating methods.

The approach described herein is fundamentally different from conventional radiometric dating methods. The underlying assumption for both the K/Ar and ^{40}Ar/^{39}Ar methods is that the system is closed chemically and isotopically at the time of crystallization, and the concentrations of relevant isotopes change with time owing to radioactive decay of the parent and formation of daughter nuclides. In contrast, the dating method based on accumulation of cosmic-ray–induced ^{36}Cl assumes negligible initial concentration of ^{36}Cl and an "open" system with respect to accumulation of cosmic-ray–induced ^{36}Cl. This assumption is valid because energetic cosmic-ray particles easily penetrate crystal lattices of minerals in surficial rocks, interact with certain target nuclides, and produce cosmogenic ^{36}Cl, even though no chemical transfer of species occurs. While open to cosmogenic ^{36}Cl, the system is closed chemically and isotopically with respect to other, noncosmogenic sources of ^{36}Cl. The concentration of cosmogenic ^{36}Cl, after accounting for decay of ^{36}Cl to ^{36}Ar, is thus a predictable function of time and is the basis of this geochronometer.

Eruptive Deposits of the Lathrop Wells Volcanic Area

The Lathrop Wells cone belongs to a group of five isolated late Cenozoic basaltic eruptions in the Crater Flat, Nevada, volcanic field (Wells et al., 1990). At Lathrop Wells, the volcanic eruption are represented by aa and block lava flows, scoria deposits, and volcanic bombs (Vaniman et al., 1982; Crowe et al., 1983; Turrin et al., 1991). The lava flows, located south and east of the rim, are composed of vesicular basalts with olivine and plagioclase phenocrysts in a finely crystalline matrix. They are usually only slightly weathered and exhibit original flow structures at the surface. The scoria deposits are found in the area immediately around the cone and in isolated patches southeast of the rim. The bombs are present in the rim area and immediately to the northwest of the rim, as well as in several isolated locations on a small alluvial plateau west of the rim (Fig. 1).

The oldest of the Crater Flat cones was dated by K/Ar at ~1.5 Ma (Vaniman et al., 1982), whereas the age of the youngest, the Lathrop Wells cone, is uncertain. It has been intensively studied in connection with the proposed high-level radioactive waste reposi-

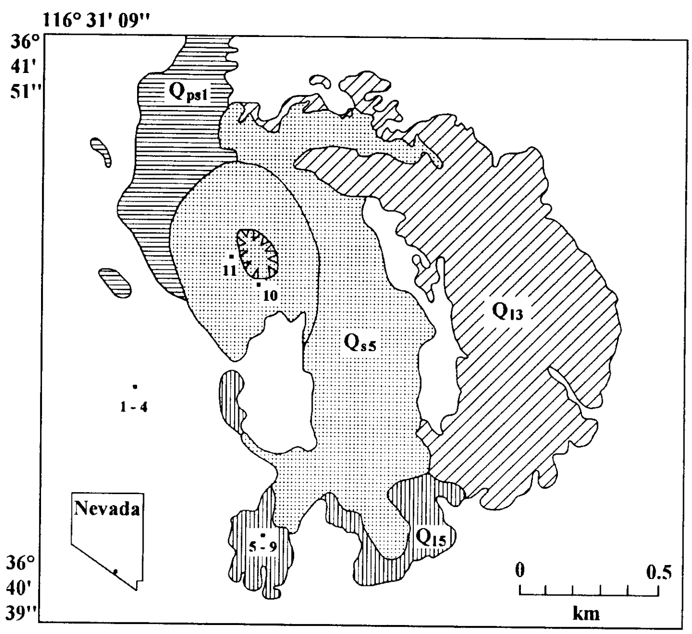

Figure 1. Geologic map of Lathrop Wells volcanic center (modified from Turrin et al., 1991) and locations of samples for ^{36}Cl. Numbers correspond to those in Table 1. Patterns and letter designations indicate major stratigraphic units: Q_{l5}—stratigraphically older lava flow; Q_{s5}—scoria deposits contemporary with Q_{l5}; Q_{l3}—stratigraphically younger lava flow; Q_{ps1}—pyroclastic deposits. Blank space indicates undifferentiated alluvial deposits surrounding volcanic center. Toothed pattern indicates rim area.

*Present address: Institut für Mittelenergiephysik, ETH-Hönggerberg, CH-8093 Zürich, Switzerland.

tory at the southwest margin of the Nevada Test Site. The eruption age was bracketed by U/Th ages of 345 and 25 ka obtained for underlying and overlying carbonate sedimentary units (Szabo et al., 1981). U-trend dates of 240 and 145 ka were obtained for associated Quaternary deposits in the nearby Yucca Mountain area (Swadley et al., 1984). Initial studies based on K/Ar analysis reported an age "much younger" than 270 ka, which was later reduced to <100 and possibly <50 ka (Crowe et al., 1988) on the basis of new K/Ar dates and soil studies. This conclusion was supported by Wells et al. (1990), who used surface modification criteria to compare the Lathrop Wells cinder cone with K/Ar–dated cinder cones from the Cima volcanic field, California, and found evidence for polycyclic volcanic activity at Lathrop Wells, with the youngest episode as recent as 20 ka. A contrasting view was proposed by Turrin et al. (1991), who reported whole-rock $^{40}Ar/^{39}Ar$ ages of several lava flows and scoria units and combined these results with the existing K/Ar dates to obtain weighted means of 136 ± 8 ka for the older unit and 141 ± 9 ka for the younger one. Although several age determinations have been attempted, the existing age estimates are discordant, and the problem of the eruption history at Lathrop Wells remains controversial.

Surface-Exposure Dating by Cosmogenic ^{36}Cl Accumulation

The cosmogenic ^{36}Cl method (Davis and Schaeffer, 1955; Phillips et al., 1986) is based on the fundamental difference between high surface (cosmogenic) and low subsurface (radiogenic or background) production rates of ^{36}Cl. In the subsurface, ^{36}Cl forms almost exclusively by thermal-neutron activation of ^{35}Cl by slow neutrons associated with radioactive decay of U and Th (Bentley et al., 1986). In rocks exposed at the surface, ^{36}Cl is produced primarily by spallation reactions on ^{39}K and ^{40}Ca due to fast secondary neutrons and by thermal-neutron activation of ^{35}Cl (Phillips et al., 1986; Zreda et al., 1990, 1991). The subsurface ^{36}Cl concentration is in secular equilibrium between radiogenic production and decay; i.e., it is constant over time. The radiogenic ^{36}Cl can thus be subtracted from the measured ^{36}Cl to yield the cosmogenic component, which is subsequently used to calculate surface-exposure ages. In this study, we used the dating equations, scaling factors for latitude and altitude, and ^{36}Cl production parameters presented in Zreda et al. (1991).

Evaluation of the accuracy and precision of ^{36}Cl age determinations is based on the following considerations. (1) Accuracy of the method is primarily dependent on uncertainty in the production rates estimated to be less than 10% (Zreda et al., 1991) in the Great Basin area. These production rates have already been applied to date Meteor Crater, Arizona (Phillips et al., 1991), and yielded an average age within 2% of that from independent age estimates. Potential problems with temporal variations in cosmogenic nuclide production rates that affect young samples (~10 ka) are probably negligible for older samples because these variations are averaged over time. (2) Analytical errors associated with determination of major and trace elements, stable Cl, and ^{36}Cl are on the order of a few percent and lead to similar uncertainties in ^{36}Cl ages. Precision of ^{36}Cl ages depends mainly on rates of postdepositional processes occurring on sampled surfaces. Erosional removal of <80 cm of soil (since the surface formation) results in a small overestimation of the age, whereas removal of thicker material will have an opposite result. These two effects can be recognized from statistical analysis of ^{36}Cl data sets. The cosmogenic ^{36}Cl method has been shown to yield accurate and precise ages for surfaces with negligible erosion (Phillips et al., 1986, 1991; Zreda et al., 1991), but its applicability to fast-eroding landforms remains to be confirmed. In this study, we therefore concentrated our sampling on relatively stable surfaces, such as basalt flows.

EXPERIMENTAL METHODS

Using a hammer and a chisel we collected samples from the top 5 cm of carefully selected rocks. We then extracted Cl from all samples and measured ^{36}Cl by accelerator mass spectrometry.

Sample Collection

Samples LWC88-1, YM88-5, YM88-6L, YM88-6M, and YM88-8 were taken from pressure ridges on the tops of the lava flow south of the cone (unit Q_{l5} of Turrin et al., 1991), which is stratigraphically the oldest unit in the volcanic center (Turrin et al., 1991). Field observations indicated a possibility that parts of the lava flow were covered by eolian sand deposits, which would have provided shielding from cosmic rays and temporarily decreased the cosmic-ray flux reaching the rock surface if the sand dunes had migrated over the rocks sampled. This would result in underestimation of the calculated eruption age. To minimize this possibility, we selected the highest pressure ridges we could find for sample collection. We also explored deep fractures in the higher parts of the lava flow for remnants of eolian deposits but could not find any. We consider it unlikely that the high points on the floor that we sampled were ever covered by sand.

A small alluvial plateau west of the cone contains isolated pyroclastic deposits (unit Q_{ps1} of Turrin et al., 1991), which are considered the youngest volcanic units in this area. Bombs were sampled from this relatively flat alluvial surface because we considered it less subject to erosional modification than the loose and steeply sloping cone surfaces. We collected four small volcanic bombs (LWC88-3 through LWC88-6) lying on top of the soil. The sampled bombs are ellipsoidal and range from 40 to 80 cm in length. The rocks are dense, contain no vesicles, and are lightly weathered. The bombs did not have the thick weathering rinds that are typical of buried basaltic cobbles.

Finally, we analyzed two samples (LWC89-S and LWC89-W) of volcanic bombs from the top of the very rim of the cinder cone (unit Q_{s5} of Turrin et al., 1991). Although sample LWC89-W was relatively fresh looking, sample LWC89-S was brick red and clearly was strongly chemically altered. Although the rim area is geomorphically less stable and thus less suitable for dating than the other two locations, we analyzed these two samples for comparison with the other samples.

Sample Preparation and Analyses

The samples were cleaned of any organic material present at the surfaces, ground, and leached in 5% nitric acid to remove any meteoric Cl from the grain boundaries and to dissolve any secondary carbonates present in the vesicles and micropores within the rock matrix. Samples for ^{36}Cl were obtained by dissolution of powdered rocks in a hot mixture of concentrated nitric and hydrofluoric acids and precipitation of Cl as AgCl (Zreda et al., 1990, 1991). The samples were measured by accelerator mass spectrometry (Elmore et al., 1979) at either the University of Rochester or Purdue University. Major element composition was determined by X-ray fluorescence on fused disks, B and Gd (gadolinium) by prompt gamma emission spectrometry, and Cl by combination ion-selective electrode.

DETERMINATION OF ^{36}Cl AGES

The lava-flow samples (LWC88-1 and YM88-5 through YM88-8; Table 1) collected from the tops of pressure ridges required correction for surface geometry. The thermal-neutron absorption rate calculated by Zreda et al. (1990, 1991) is valid for smooth, flat, and broad surfaces where thermal neutrons are lost from the rock only in the vertical direction. If the surface geometry is rough (e.g., basalt flows with pressure ridges), thermal neutrons will leak out of the rock not only upward, but also sideways. This added outflux of thermal neu-

TABLE 1. TARGET ELEMENT CONCENTRATIONS, MACROSCOPIC CROSS SECTIONS (Σ), $^{36}Cl/Cl$ RATIOS, AND ^{36}Cl SURFACE-EXPOSURE AGES FOR SAMPLES FROM LATHROP WELLS, NEVADA

Map no.	Sample ID	K_2O (%)	CaO (%)	Cl (ppm)	Σ* (cm²/kg)	$^{36}Cl/Cl$† (10^{-15})	Sample age (ka)	Surface age (ka)	Eruption age (ka)
1	LWC88-3	1.67	7.48	268	7.54	344 ±15	79 ±3.4		
2	LWC88-4	1.44	7.41	255	7.49	417 ±19	96 ±4.5	84 ±8.1	
3	LWC88-5	1.64	7.57	272	7.44	371 ±20	85 ±4.6		
4	LWC88-6	1.67	7.40	105	7.39	600 ±35	78 ±4.6		
5	LWC88-1	1.75	7.33	270	7.53	335 ±26	93§ ±7.2		
6	YM88-5	1.72	7.14	268	7.43	270 ±25	73§ ±6.8		81 ±7.9
7	YM88-6L	1.84	7.06	308	7.07	281 ±19	81§ ±5.4	81 ±7.3	
8	YM88-6M	1.88	7.19	292	7.67	270 ±21	77§ ±6.0		
9	YM88-8	1.98	7.48	217	6.96	352 ±27	79§ ±6.1		
10	LWC89-S	1.59	7.51	1164	8.45	263 ±29	83# ±9.2	76 ±10	
11	LWC89-W	1.61	7.32	233	7.27	326 ±27	68 ±5.7		

Note: The sample ages are for single rock samples, the surface ages are arithmetic averages of the sample ages, and the eruption age is the overall arithmetic mean. All samples are from the surface, at elevation 914 m above sea level, lat 36.4°N, long 243.4°E; the elevation-latitude-depth (ELD) scaling factor (equation 1 in Zreda et al., 1991) for all samples is 1.89.

* Macroscopic absorption cross section of the rock (Zreda et al., 1991).

† After subtraction of the radiogenic $^{36}Cl/Cl$ of 11×10^{-15}.

§ Corrected for surface geometry (see text for details). Uncorrected surface age is 66.7 ±6.1 ka.

\# Corrected for meteoric $^{36}Cl/Cl$ (see text for details).

trons reduces the thermal-neutron capture rate and lowers the production rate of ^{36}Cl from ^{35}Cl, thus leading to underestimation of the apparent ^{36}Cl ages.

The required correction depends on the surface geometry, particularly on the height of those parts that protrude above the base level, and calculating it on the basis of principles of cosmic-ray physics is rather difficult. Fortunately, experimental data for thermal-neutron behavior at and below the solid-air interface have recently been made available for various geometries (Fabryka-Martin et al., 1990). Specifically, for a pyramidlike construction above a base-level surface, which was geometrically closest to pressure ridges on lava flows, Fabryka-Martin et al. (1990) observed a 30% decrease in the thermal-neutron flux, relative to the flux at the flat surface. Therefore, for the samples from the lava flow, we reduced by 30% the production rate of ^{36}Cl due to thermal-neutron absorption by ^{35}Cl. We note that this correction is simply empirical and probably represents a maximum estimate of neutron leakage. The production rates due to spallation reactions remain unchanged because the energetic neutrons that are responsible for these reactions are relatively unaffected by the rock-air interface.

The five lava-flow samples yielded corrected cosmogenic ^{36}Cl ages ranging from 73 to 93 ka, with the mean of 81 ±7.3 ka (Table 1, Fig. 2). The ages are approximately uniformly distributed in this interval. Their scatter can be attributed to analytical errors of ^{36}Cl determination, which range from 6.8% to 10.7%, and to errors associated with the other geochemical parameters. The standard deviation of the sample mean is similar to the individual standard deviations, which indicates that there are probably not any random factors, other than analytical uncertainties, that significantly affect these dates.

The group of four "alluvial" volcanic bombs (samples LWC88-3 through LWC88-6) yielded surface-exposure ages ranging from 78 to 96 ka, with an average value of 84 ±8.1 ka (Table 1, Fig. 2). The sample standard deviation of 9.6% is somewhat higher than the individual analytical errors, which range from 4.3% to 5.8%. This discrepancy may result from erosional processes occurring on the surface where the samples are collected. Because of the distribution of thermal neutrons below the surface, erosion may result in apparent ages that are either too old or too young, depending on erosion rates. In this case, since the spread of the data points is very small and the number of samples is very limited, the sample mean is the best estimate of the eruption time. Furthermore, these dates are in very good agreement with those calculated above for the lava flow.

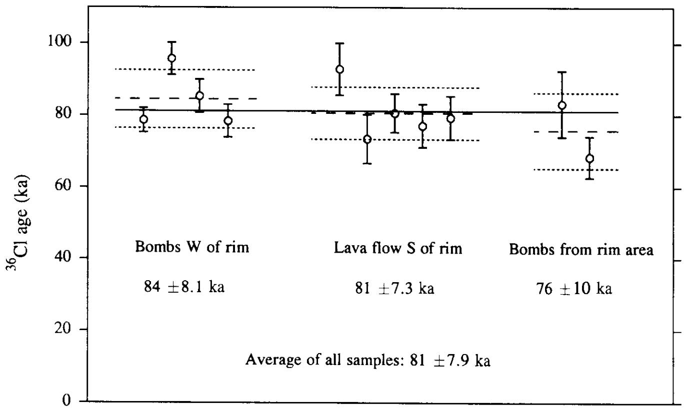

Figure 2. ^{36}Cl ages of samples from Lathrop Wells. Error bars represent ^{36}Cl measurement errors. Long dashes are means of three groups of samples; short dashes represent intervals within one standard deviation calculated for each group; solid line is mean of all 11 samples.

The last two samples we measured (LWC89-S and LWC89-W) are less suitable for dating than the other nine because of their location in the rim area and because of the presence of inseparable secondary minerals in one of them. They were collected from the geomorphically unstable rim area, where the effects of erosion are particularly profound. We consider it likely that both of them could have been initially covered by some loose volcanic material and then gradually exposed by erosion. Full evaluation of this hypothesis would require a much more complete data set and is not attempted here.

In addition to its possibly complex exposure history, sample LWC89-S has undergone extensive chemical and mineral changes; olivines have been replaced by iddingsite, and micropores have been filled with secondary carbonates. The carbonates are easily separable from the rock matrix by leaching in nitric acid. However, iddingsite is not separable from the rest of the rock, and, therefore, the measured ^{36}Cl content and total concentration of Cl in the weathered sample are essentially composite components that make these samples unsuitable for dating in a straightforward fashion. However, it is possible to decompose this combined information into two parts, cosmogenic and meteoric, if one of them is known beforehand. We discuss the procedure in a separate paper (in preparation) and focus here on the dating.

The calculated age for sample LWC89-S is 83 $\pm$9.2 ka, which is in acceptable agreement with the age of 68 $\pm$5.7 ka obtained for the second sample from the rim area. The average value of 76 $\pm$10 ka is slightly below the average values for the lava flow and the four volcanic bombs described above. This small discrepancy may be explained by faster erosion on the cone rim than in other areas, but it may also be a result of analytical uncertainty.

Comparison of the ^{36}Cl data from the three surfaces studied indicates that the three average ages are statistically indistinguishable. We therefore combine them to obtain an overall average of 81 $\pm$7.9 ka as our best estimate of the eruption time (Table 1, Fig. 2). Our age estimate appears to be in reasonable agreement with independent methods. It falls between the bracketing U/Th dates of 345 and 25 ka from Szabo et al. (1981). In Figure 3, we compare the cumulative distribution of the ^{36}Cl dates with the distribution of $^{40}Ar/^{39}Ar$ dates reported by Turrin et al. (1991). Although the medians of the two distributions differ by about 60 ka, the two distributions do overlap. The younger median age by the ^{36}Cl method could possibly be attributed to the effects of erosion, which would bias cosmogenic nuclide methods toward younger (in this case) than actual apparent ages. However, erosion should produce a wide scatter in apparent ages from samples collected from different locations, and the close grouping of the ^{36}Cl dates argues strongly that the effects of erosion have been minimal.

Turrin et al. (1992) presented a result of incremental-heating $^{40}Ar/^{39}Ar$ analysis. The sample from unit Q_{13} yielded a plateau age of 142 $\pm$19 ka, which agrees with the earlier total fusion estimates and is statistically different from the ^{36}Cl ages reported herein. However, the same sample gave an isochron age of 107 $\pm$31 ka (Turrin et al., 1992) that appears to be in better agreement, within 1σ, with our estimates. Additional analyses will be required to compare adequately the results of the two methods.

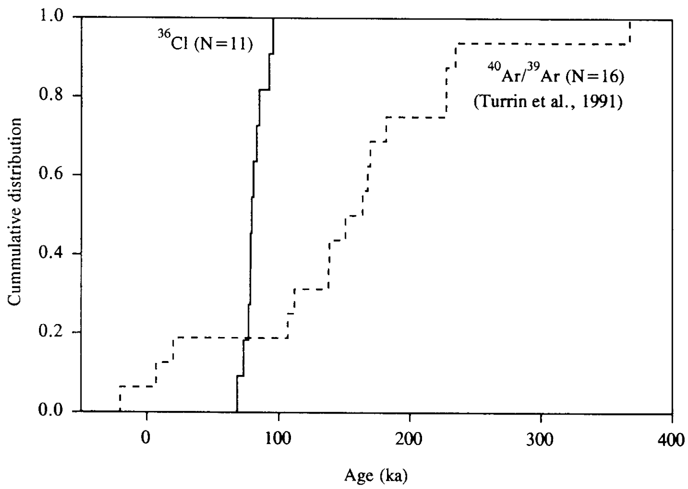

Figure 3. Cumulative distributions of ^{36}Cl ages and total fusion $^{40}Ar/^{39}Ar$ and K/Ar ages of Turrin et al. (1991). Two distributions overlap, but respective means differ by ~60 ka. For comparison, recently reported incremental-heating $^{40}Ar/^{39}Ar$ plateau age is 142 $\pm$19 ka, and isochron age is 107 $\pm$31 ka (Turrin et al., 1992).

As demonstrated by Figure 2, there are no statistically significant differences between the ^{36}Cl dates from the various sample groups. Our data, therefore, do not support a hypothesis of multiple eruptions at the Lathrop Wells center. However, neither do the data preclude multiple eruptions. The following considerations must be acknowledged when evaluating the possibility of multiple eruptions. (1) Not all mapped eruptive units have been dated. (2) The 1σ statistics of the combined data would permit a 16 ka interval within which the center could have erupted more than once. (3) The empirical neutron-leakage correction for samples from flow Q_{15} could be too large. The limiting minimum case would be no excess neutron leakage, in which case the mean age for the Q_{15} samples would be 67 $\pm$6.1 ka. This age differs at the 1σ level from the age of the four bombs and would support the possibility of multiple eruptions. This possibility might be evaluated by sampling Q_{15} at other, flatter locations. (4) There is some possibility that a recent, minor, scoria eruption could have deposited only a thin layer of cinders on the cone rim. If such a thin layer were then rapidly eroded off the rim, the ^{36}Cl dates on previously erupted bombs might possibly be little affected and thus still agree with the dates from the flow and bombs away from the cone. This possibility could readily be evaluated by measuring profiles of cosmogenic nuclide accumulation with depth through the scoria near the base of the cone.

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