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K-Ar Ages and Paleomagnetic Directions from the Lathrop Wells Volcanic Center, Southwestern Nevada: An Evaluation of Polycyclic Volcanism

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Abstract

Paleomagnetic data suggest that there may be two eruptive units at the Lathrop Wells volcanic center, Nevada. The measured directions of remanent magnetization for the two units are 51.5° inclination, 2.2° declination, and 51.4° inclination, 354.5° declination. The difference in the paleomagnetic field directions of 4.7°, is significant at the 99.98 percent confidence level. The observed angular difference between the two mean directions suggests a minimum age difference between the eruptive events of about 100 years. Weighted means of K-Ar ages on these two units (Ql_3 = 131 ± 10 ka; Ql_5 = 115 ± 12 ka), though reversed from the mapped stratigraphic succession, are not significantly different at the 95 percent confidence level. Based on statistical analysis, the difference in age between the flows is less than or equal to approximately 30 k.y. Moreover, the K-Ar ages from the flow units Ql_3 and Ql_5 are consistent with the reported uranium series dating, uranium-trend chronology, and ^{36}Cl and ^{3}He exposure ages of the surficial units in the Yucca Mountain region.

INTRODUCTION

Yucca Mountain, located near the southwest boundary of the Nevada Test Site (NTS), is being evaluated to determine its suitability for a high-level radioactive-waste repository. One aspect of the site characterization studies at the potential radioactive waste repository at Yucca Mountain is an evaluation of the hazards associated with possible future volcanic activity (Crowe and Carr, 1980; Crowe et al., 1983). The most recent nearby volcanic activity occurred 10 to 20 km southwest of Yucca Mountain, in the Crater Flat area (Fig. 1). The youngest volcanic edifice in the Yucca Mountain area is the Lathrop Wells cone.

The chronology of these volcanic events and the estimates of eruptive volumes through time are essential to assessing the volcanic hazard probability and making a consequence analysis for the potential repository at Yucca Mountain. Moreover, an important part of assessing the volcanic hazards during the required isolation period (10^4 yr) of the high-level radioactive waste is understanding the past behavior of the volcanic activity of the Yucca Mountain area.

The chronology of the Lathrop Wells cinder-cone complex, the youngest volcanic center in the Crater Flat-Yucca Mountain region is being evaluated as part of the site characterization studies of Yucca Mountain. Recent studies indicate that some cinder cone complexes in the southwest United States are polycyclic (the products of multiple eruptive cycles) with recurrence intervals of 10^3 to 10^5 years (Turrin and Renne, 1987; Renault et al., 1988). The Lathrop Wells cinder-cone complex and the Crater Flat volcanic field are being examined for polycyclic behavior. This evaluation includes paleomagnetic studies, soil and geomorphic studies, and isotopic dating (K-Ar, ^{40}Ar/^{39}Ar, ^{3}He/^{4}He surface exposure dating, and uranium disequilibrium dating). The purpose of this paper is to present and summarize the results of K-Ar studies of samples collected from lava flows of the Lathrop Wells volcanic center.

GEOLOGIC SETTING

The Lathrop Wells volcanic center is located in the southern part of the Great Basin in Nevada, approximately 140 km northwest of Las Vegas, Nev. (Fig. 1). The Great Basin has been the site of extensive Cenozoic igneous activity that reflects the spatial and temporal changes in the tectonic setting of western North America (Armstrong et al., 1969; McKee, 1971; Christiansen and Lipman, 1972; Lipman et al., 1972; Noble, 1972; Lipman, 1980). The most recent volcanism within the Great Basin has been dominated by transitional subalkaline (hypersthene normative) to alkaline undersaturated (nepheline normative) mafic lavas associated with crustal rifting (Leeman and Rodgers, 1970; Luedke and Smith 1978a, 1978b, 1981, 1982, 1983; Lipman, 1980; McKee and Noble, 1986). K-Ar ages from these basaltic volcanic fields indicate that there has been intermittent basaltic volcanism for the last 8 million years (Crowe and Carr, 1980; Turrin and Dohrenwend, 1984; Turrin et al., 1985a; Turrin et al., 1985b; and Turrin and Gillespie, 1986).

Locally, the Nevada Test Site area consists of a number of coalesced caldera complexes that were active during the Miocene (14 to 8 Ma) (Byers et al., 1976; Christiansen et al., 1977). Since then volcanism has continued in the form of small isolated subalkaline (hypersthene normative) to alkaline undersaturated (nepheline normative) basaltic volcanic fields (Vaniman and Crowe, 1981; Vaniman et al., 1982).

Geology of the Lathrop Wells Volcanic Center

The Lathrop Wells cone and flow complex overlies Quaternary alluvial sediments and the Topopah Spring Tuff (?), Miocene ash-flow and air-fall tuff units. Generally, the flows are dense basalt with vesicular tops and bottoms, and exhibit block flow and aa flow morphologies. The basalt is mostly holocrystaline and sparsely porphyritic with phenocrysts of olivine and microphenocrysts (?) of plagioclase in a medium- to fine-grained pilotaxitic groundmass of plagioclase, olivine, clinopyroxene (Ti-augite), opaque minerals (Fe-Ti oxides), interstitial glass, and apatite (Vaniman and Crowe, 1981; Vaniman et al., 1982). Olivine phenocrysts may exhibit thin rims of iddingsite (?), and the plagioclase and clinopyroxene phenocrysts appear unaltered. Xenoliths of the underlying Topopah Spring Tuff are commonly found in the lava flows and scoria deposits. A calculated mean volume of 0.03 percent of tuff fragments from scoria deposits at four localities in the Lathrop Wells scoria cone was reported by Crowe et al. (1983).

Based on paleomagnetic and field data, we have divided the eruptive events at the Lathrop Wells volcanic center into two separate periods of activity. The sequence of volcanic events is as follows, from oldest to youngest:

1. The development of a northwest-southeast-trending fissure complex composed of local vents of irregular scoria mounds and agglutinate (unit Qs_5, Fig. 2) accompanied by eruption of small block and aa flows (unit Ql_5, Fig. 2). The last phases of this eruption produced the main scoria cone. These units have similar directions of remanent magnetization which are statistically different from the directions obtained from geologic units of the next event.
2. Subsequent volcanic activity occurred along a small, poorly-exposed vent system, producing a lava flow unit (Ql_3, Fig. 2). The main body of this Ql_3 lava flow flowed to the east and south around the older flow and vent complex.

A third period of volcanic activity was suggested by Renault et al., (1988) and Wells et al. (1988, 1990), who described a complex sequence of buried soils and air-fall tephra (?), eolian and cone apron deposits, exposed in the quarry area. Wells et al. (1990) suggested that the lapilli-size tephra deposits in the soil profiles represent air-fall units that have been modified by the filling of the voids by eolian material. Wells et al. (1992) and Crowe et al. (1992) reported a thermoluminescence (TL) age of 9.9 ± 0.7 ka for these deposits. However, the volcanic origin of these deposits has been questioned (Turrin et al., 1991, 1992; Turrin and Champion, 1991; Champion, 1991; Whitney and Shroba, 1991).

An alternative interpretation (Turrin and Champion, 1991 and Turrin et al. 1991, 1992) is that these deposits are derived from the adjacent cone slope. These deposits of sand, silt, and lapilli-size tephra supported in a matrix of eolian sand and silt occur immediately adjacent to the main cinder cone and overlie the scoria unit (Qs_5). Granulometry data on material from the basal portions of several of these "tephra" deposits show that they contain 30 to 50 percent quartzofeldspathic eolian sand and silt (Turrin et al., 1992). This large proportion of eolian sand and silt cannot be explained by infiltration processes from overlying eolian units and argues against a volcanogenic origin.

Age Constraints on the Lathrop Wells Volcanic Center

Uranium-thorium and uranium-trend ages provide some constraints on the age of the Lathrop Wells volcanic center. Uranium-thorium dates, on massive laminated stalactitic calcrete from beneath the lava flow (unit Ql_3), and one on a thin, soft, porous carbonate layer from the base of a loess deposit that overlies scoria deposits (unit Qs_5) near the quarry, yield ages of 345 (+180, -70) ka , 345 (+180, -71) ka, and 25 ± 10 ka, respectively (Szabo et al., 1981). Szabo et al. (1981) considered the age on the loess layer to be a minimum age, because soil carbonates generally are not isotopically closed systems with respect to uranium. In addition, there is some time interval between eruption of a lava flow, and the accumulation of eolian material on the flow surface. Likewise, the stalactitic calcrete reflects a minimum age, but given favorable conditions can be considered an age for the cementation of the deposit.

The principal source of error in uranium-thorium dating lies in the assumption of a closed system (Curtis, 1981). In fact, it has been shown that uranium-thorium ages are almost always too young when compared to other isotopic dating systems. Slate (1985) and Slate et al. (1991) compared uranium-thorium ages on soil carbonates from soils formed on K-Ar dated basaltic lava flows that range in age from 140 to 870 ka in the Pinacate volcanic field, northwestern Sonora, Mexico. Uranium-thorium ages were consistently younger than the K-Ar ages by as much as an order of magnitude.

Uranium-trend dating does not require the isotopic system to be closed (Rosholt, 1977, 1980). This method consists of determining an isochron from a given alluvial unit by analyzing four to nine samples covering various soil horizons. The results ideally define a linear isochron in which the slope increases with increasing age of the alluvium for a given half-period of the flux controlling the migration of uranium in the alluvial deposits (Rosholt, 1977, 1980). An empirical model, calibrated by several horizons dated by other methods, compensates for different climatic and environmental conditions.

Uranium-trend ages on Quaternary stratigraphic units in the Yucca Mountain region provide additional constraints on the Lathrop Wells volcanic center (Fig. 3). Middle and upper Pleistocene alluvial, fluvial, and eolian deposits, the upper part of unit Q2c of Swadley et al. (1984), locally overlie and contain reworked cinders from the Lathrop Wells volcanic center. Swadley et al. (1984) reported;

1. Uranium-trend ages from the upper part of unit Q2c were 270 ± 30 ka and 240 ± 50 ka.
2. Stratigraphic relationships, however, indicate that unit Q2c is time-transgressive and the upper part of Q2c is equivalent to unit Q2s, which yields uranium-trend ages from 480 ± 90 ka to 160 ± 90 ka.
3. Unit Q2s is older than unit Q2b, which yields uranium-trend ages that range from 145 ± 25 ka to 160 ± 18 ka.

The uranium-thorium age on the calcrete from beneath the lava flow unit (Ql$_3$) requires that the unit be younger than 345 (+180, -70) ka. Moreover, if the uranium-trend ages and correlations between the Quaternary stratigraphic units in the Yucca Mountain region as proposed by Swadley et al. (1984) are correct, then the age of the major eruptive phase of the Lathrop Wells volcanic center is bracketed between 145 ± 25 and 270 ± 30 ka.

Cosmogenic ^{3}He and ^{36}Cl exposure ages provide minimum ages for the Lathrop Wells volcanic center. Volcanic bombs from the cinder cone rim (unit Qs$_5$, Fig. 2) yield cosmogenic ^{3}He exposure ages of 22 ± 4 to 57 ± 7 ka (Poths and Crowe, 1992; Crowe et al., 1992; Poths et al., 1994) and ^{36}Cl exposure ages of 68 ±5.7 ka to 83 ±9.2 ka (Zreda et al., 1993). In addition, Zreda et al. (1993) also report ^{36}Cl exposure ages of 78 ±4.6 to 96 ±4.5 ka form volcanic bombs found on alluvial surfaces adjacent to the Lathrop Well volcanic center. Cosmogenic exposure ages from the lava flows yield similar ages as the volcanic bomb data. The ^{3}He exposure ages from both lava flow units (Ql_3 and Ql_5) yield overlapping ages that range from 61 ±6 ka to 100 ±9 ka (Poths et al., 1994). ^{36}Cl exposure ages from the lava flow unit Ql_5 are concordant with the ^{3}He ages and range from 73 ±6.8 ka to 93 ±7.2 ka. The cosmogenic exposure age data do not provide any evidence for multiple eruptions nor do they support a Holocene age for the Lathrop Wells volcanic center.

PALEOMAGNETIC STUDIES

Directions of remanent magnetization have been obtained from outcrops of the Lathrop Wells cinder cone and flow complex to investigate the possibility that the complex was formed by multiple eruptive events. The geomagnetic field is not constant in direction or intensity at any given location through time, but instead undergoes a secular variation at a rate of about 4° per century (Champion and Shoemaker, 1977). Thus, in any given area, volcanic rocks produced by two or more eruptive events that are different in age by more than a few decades usually do not record the same direction of magnetization. If units have the same directions of remanent magnetization, then the hypothesis that they were formed at the same time may not be precluded. If they have significantly different directions of remanent magnetization, they cannot have erupted at the same time. Given the rate of secular variation, it is possible to suggest the minimum time required to produce the observed directional differences. Therefore, paleomagnetic studies of eruptive units offer a simple and direct means of determining the number of eruptive events within a given volcanic field.

Methods

Methods used in the paleomagnetic studies largely followed established procedures (McElhinny, 1973), except that a suncompass was used exclusively for core orientation. Core samples were taken in the field using a hand-held, gasoline-powered, diamond coring drill. Lava flows are generally sampled in cross section in paleomagnetic studies, but a young lava flow and cone, such as Lathrop Wells, has few cross-sectional exposures. Exposures of massive flow interiors along the eroded eastern margin of the lava flow (unit Ql_3) provided the best sampling opportunity for that unit (Fig. 2). The older(?) scoria unit (Qs_5) was sampled in part from quarried exposures of rootless flow and spatter layers, but also in some cases from the tops and margins of naturally eroded volcanic constructs.

All specimens were progressively demagnetized in an alternating field to remove secondary remanent magnetizations due to viscous magnetic (VRM) and lightning-derived (IRM) components. Ideally, samples treated in this way should show a univectoral decay toward the origin on a vector-component diagram. Even with this treatment some specimens had unremovable secondary magnetic components probably due to lightning strikes. The stable endpoint remanent directions were averaged by site using conventional Fisherian statistical techniques.

Results

Generally, well-grouped site mean directions were obtained after modest levels of alternating field demagnetization. With the exception of site B8179, which had severe lightning problems, most sites have a low percentage of rejected cores (see Table 1). The mean directions are well defined and present a coherent pattern on an equal-area net (Fig. 4A). Figure 4A shows all site means, with enclosing circles of 95 percent confidence for the lava and scoria units (Ql_3 and Qs_5). The directions group in two masses close to one another. At first glance, these data seem nearly identical; however, the mean of site mean directions for each of the two geologic units define two separate directions of magnetization that differ by 4.7° (Fig. (4B). A statistical comparison of these mean directions shows them to be different at the 99.98 percent confidence level (see McFadden and Jones, 1981). At least two eruptive events are thus demonstrated for the Lathrop Wells volcanic center.

It is not possible to uniquely establish the time interval between these two directions of magnetization from paleomagnetic data alone. However, based on paleomagnetic studies of Sunset Crater in Arizona (Champion, 1980), the angular difference of 4.7° suggests that the time difference between the eruptive events is approximately 100 years.

K-Ar STUDIES

Methods

All argon analyses in this report are by isotope dilution using procedures described by Dalrymple and Lanphere (1969). Potassium analyses are by flame photometry using a lithium internal standard following procedures described by Carmichael et al. (1968) or Ingamells (1970). The estimated analytical precision of the data is calculated using standard methods of error propagation, as described in Taylor (1982). Reported analytical precision is one standard deviation (1σ).

Results

The data (Tables 2-5) exhibit significant variability between both individual rock samples and splits of the same rock sample. The error estimates given with each individual analysis consider only sources of analytical error. They do not address sample inhomogeneity, thus the dispersion in the data set (standard deviation) does not necessarily represent the analytical precision. A more reliable estimate of precision is probably derived from the standard error of the mean (SEM) of replicate ages. Weighted means (x_{best}), in the tables, are calculated by multiplying the individual analysis (X_i) by its weighting factor, the reciprocal of the variance ($1/\sigma_i^2$), using the following equation:

$$x_{best} = \frac{\sum_{i=1}^{n} (1/\sigma_i^2) \times X_i}{\sum_{i=1}^{n} (1/\sigma_i^2)}$$

The uncertainty of the weighted average is obtained by pooling the variances and is calculated using the following equation:

$$s_{x_{best}} = \left(\sum_{i=1}^{n} (1/\sigma_i^2) \right)^{-1/2}$$

The value obtained from pooling the variance essentially equates to the standard error of the mean. See Taylor (1982) for a more complete description of using weighted means to obtain a single "best" estimated average and uncertainty for a data set. Generally, the preferred age given for any set of data is the weighted average because the more precise analyses are given more weight in the determination of the average age.

The data presented in Table 2 were obtained in 1978 as part of the initial volcanic hazard studies for the Yucca Mountain Project. Three separate analyses of sample TSV-1, from the lava flow unit (Ql_3), collected from the stream-eroded eastern flow margin (Fig. 2), yielded ages of 336 ± 28, 38 ± 19, and 3 ± 75 ka. The arithmetic mean and standard deviation of sample TSV-1 is 126 ± 183 ka with a SEM of 106 ka. The weighted average obtained from the sample TSV-1 is 127 ± 15 ka. Sample TSV-129, a welded spatter collected from the summit crater of the cinder cone at Lathrop Wells, yielded an age of 670 ± 400 ka. A K-Ar age of 300 ± 100 ka was reported for this same sample (TSV-129) by Marvin et al. (1989) who also reported an age of 230 ± 40 ka for sample TSV-283, from the interior of a volcanic bomb collected on the west side of the summit of the Lathrop Wells cone.

In 1979 samples were again collected from the Lathrop Wells volcanic center as part of a test to evaluate the overall precision of K-Ar dating of late Cenozoic basalts by different laboratories (Sinnock and Easterling, 1983). Six samples from the Lathrop Wells center were collected from the block flow unit (Ql_5, Fig. 2) (Scott Sinnock, Sandia National Laboratory, oral commun., 1989). In that study, no attempt was made to minimize the sample heterogeneity. The six samples were collected from one site within a radius of 20 to 30 m. The samples were physically split into three nominally equal pieces and sent to three separate K-Ar laboratories for analyses -- University of California, Berkeley; Laboratory of Isotope Geochemistry, Department of Geosciences, University of Arizona; and Geochron Laboratories Division, Kruger Enterprises Inc., Cambridge, Mass. Although the results are not identified with the laboratory, the Berkeley laboratory chooses to identify its results as laboratory B in Table 3.

The K-Ar ages on the Lathrop Wells volcanic center in the Sinnock and Easterling (1983) report ranged from 1.1 Ma to -30 ka (table 2.3). The arithmetic means, standard deviation, and standard error of the mean, calculated from the data in Sinnock and Easterling (1983), are

Laboratory A: 730 ± 190 ka, SEM = ±80 ka

Laboratory B: 80 ± 80 ka, SEM = ±30 ka (Berkeley);

Laboratory C: 570 ± 90 ka, SEM = ±40 ka .

The weighted averages of these data are 660 ± 30 ka, 100 ± 20 ka, and 530 ± 40 ka, respectively. The results from laboratory B (Berkeley) are statistically younger (at the 95 percent confidence level) than both laboratory A and laboratory C. However, the original Berkeley data (Table 4) show slight discrepancies with those reported in the Sinnock and Easterling (1983) report in that:

1. Sample 1 should have an arithmetic mean of 80 ka, not 120 ka.
2. Sample 5 should have an arithmetic mean of 115 ka, not 125 ka.

In addition, the standard deviations reported by Sinnock and Easterling (1983) were apparently obtained by arithmetically averaging those reported for the individual measurements. We feel that is not the correct way to have handled these data. Granted, calculating a standard deviation for a sample number of two ($n = 2$) is also not the correct way to handle the data either, because it is possible to underestimate the standard deviation. For example, sample 4 (Table 4) yields ages of 90 ± 30 ka and 70 ± 30 ka. The arithmetic mean of these numbers is 80 ka, with a standard deviation of ± 10 ka. The correct way to calculate a standard deviation for these data would be to pool the variances using the equation of Taylor (1982). The pooled standard deviation for sample 4 is ± 21 ka.

The corrected results from the Berkeley data, given in Table 4, yield an arithmetic mean and standard deviation of 68 ± 106 ka for all analyses, with a SEM of ± 31 ka. The weighted mean of the data is 97 ± 13 ka.

In 1986, samples were collected at five different sites from the lava flows at the Lathrop Wells volcanic center (Fig. 2). Argon extractions and isotopic analyses were performed at the Berkeley Geochronology Center, Berkeley, Calif. (BGC). Samples 1-86 through 4-86 are from the lava flow unit (Ql_3). Sample 5-86 is from block flow unit (Ql_5) and is inferred to underlie or laterally merge into the scoria unit (Qs_5).

The K-Ar analytical data for both flow units (Ql_3 and Ql_5) are presented in Table 5. The data for the two units range from 37 ka to 571 ka and from 110 ka to 337 ka, respectively. The arithmetic mean, weighted average, standard deviations, and the SEM for each site is given for three replicate analyses in Table 5. For the lava flow unit Ql_3, however, sample number NNTS #3-86 appears to be consistently and anomalously old relative to the other 3 sites. This sample has a profound effect on the arithmetic mean, standard deviation and SEM. If sample NNTS #3-86 is included, the arithmetic mean is 214 ± 170 ka with a SEM of ± 49 ka. If NNTS #3-86 is rejected the values drop to 125 ± 53 ka, SEM of ± 18 ka, respectively. Because the 3 individual determinations for sample NNTS #3-86 each have large uncertainties, they have little effect on the weighted average. The weighted average age of unit (Ql_3) including sample NNTS #3-86 is 137 ± 13 ka; excluding sample NNTS #3-86, the weighted average is 135 ± 13 ka. There are no obvious outliers in the data set for the block flow unit (Ql_5). The arithmetic mean for this unit is 188 ± 80 ka with a SEM of ± 33 ka (Table 5). The weighted mean for the block flow from this data set is 176 ± 60 ka.

DISCUSSION

K-Ar ages for the Lathrop Wells cinder cone and flow complex range from -170 ka to 1.1 Ma (Tables 2-5). The dispersions in the K-Ar data are in part due to two factors:

1. Large atmospheric argon corrections. The ^{40}Ar extracted from a sample consists primarily of two components, atmospheric ^{40}Ar and radiogenic ^{40}Ar (^{40}Ar*). The atmospheric ^{40}Ar, equal to 295.5 times the ^{36}Ar, is subtracted from the total ^{40}Ar by measuring the ^{36}Ar component which is all from atmospheric contamination. The errors introduced by subtracting the large atmospheric ^{40}Ar from the total measured ^{40}Ar increase exponentially as the residuals between the two numbers diminish. Therefore, errors can be quite large when the percent ^{40}Ar* is small (see Dalrymple and Lanphere, 1969, p. 104, for a more complete discussion).
2. The fact that some bias toward anomalously old ages *may* be introduced by the occurrence of extraneous ^{40}Ar incorporated into rocks and minerals by several means. As defined in Dalrymple and Lanphere, (1969, p. 121), argon (^{40}Ar) incorporated into the material being dated by any process other than *in situ* radioactive decay of ^{40}K is

called *excess* ^{40}Ar. Radiogenic ^{40}Ar* produced within the rock or mineral grains by ^{40}K before the event being dated is referred to as *inherited* ^{40}Ar. Radiogenic ^{40}Ar that was produced before a metamorphic or thermal event and that has remained in the rock/mineral system is called *inherited metamorphic* ^{40}Ar. Argon can also be inherited by incorporating older contaminating material into the sample being dated, either by natural processes or during the laboratory processing of the sample. This is referred to as *inherited contamination* ^{40}Ar.

The possible effects of excess argon from contaminating xenoliths from the underlying tuffs, not addressed by either the Environmental Assessment (U.S. Department of Energy, 1986) or Sinnock and Easterling (1983), are discussed below and also by Turrin and Champion (1991) and Turrin et al. (1991, 1992). Crowe et al. (1983) report the occurrence of 0.032 percent tuff fragments, by volume, in the Lathrop Wells scoria deposits. This equates to 0.06 percent tuff xenoliths by volume (0.054 percent by weight; tuff density = 2.7 g/cm^3; basalt density = 3.0 g/cm^3) in the Lathrop Wells lava flows, assuming densities of 1.5 gm/cm^3 and 3.0 g/cm^3 for the scoria and lava flows, respectively. The tuff xenoliths are most likely from the Topopah Spring Member of the Paintbrush Tuff. The Topopah Spring Member was K-Ar dated by Marvin et al. (1970) at 13.2 Ma. Potassium analyses from the Topopah Spring Member range from 4.7 to 6.0 percent K_2O (Lipman et al., 1966). The effect of contaminating grains can be estimated using the formula

$$t_1 = t_3 + ft_2 \times K_2/K_1;$$

where t_1 is the apparent age of sample, t_2 is the apparent age of the contaminant, t_3 is the true age of sample, f is the fraction of contaminant, K_1 is the potassium content of the uncontaminated sample, and K_2 is the potassium content of the contaminant (Dalrymple and Lanphere, 1969, p. 142). A conceptual uniform 0.06 percent tuff contamination would add an additional 22 ka to the K-Ar ages of the lava flows, provided that none of the radiogenic ^{40}Ar released from the xenoliths escaped out of the lava flow, an unlikely scenario. Even though the samples were screened for obvious visible contamination, such contamination was retrospectively seen in sample NNTS #3-

86 (Table 4). The contamination of this sample by tuff xenoliths is identified by the atomic K/Ca ratios (K/Ca = 0.49 x $^{39}Ar_K/^{37}Ar_{Ca}$ see Dalrymple et al., [1981]) and by their analytically distinct older ages (Turrin et al. 1991, 1992; Turrin and Champion, 1991).

Zero age residuals for the two Berkeley argon-extraction/mass spectrometer systems (Table 6) are obtained by fusing sealed capillary pipettes that contain 0.2 to 1 microliters of air in the argon-extraction system. The air samples are processed and the Ar isotopic ratios are measured in the exact same manner as unknown samples. An age is calculated from these data based on an approximate potassium content and the average weight of basalt sample used for a typical analysis. By definition these calculated ages should be zero, because the air pipette samples do not contain any radiogenic $^{40}Ar^*$.

Age resolution for an unknown basalt sample is given by these residual data. Residual ages for the two argon-extraction/mass spectrometer systems used (BC and GORT) have an arithmetic mean of 15 ± 70 ka and -34 ± 117 ka, with a SEM of 31 ka and 52 ka, respectively. However, the weighted average of the residual ages of 22 ± 15 ka for the BC system and 8 ± 13 ka for the GORT system, is the more significant value because the better analyses are given more weight in the determination of the average zero age residuals. The zero-age residual data indicate that there is no statistically significant bias in the atmospheric ^{40}Ar corrections for either of the extraction/mass spectrometer systems. In fact, the combined zero age residual data from the two systems (arithmetic mean -10 ± 94 ka; SEM 30 ka; weighted average 14 ± 10 ka) indicate that any sample randomly analyzed several times (n> 5) with approximately 1.5 percent K^+ and using about 7.4 g of material would have an instrumental standard error of about 10 to 20 ka.

Combining the reported analytical precision of the weighted averages for the two flow units and the zero-age residuals, a 95 percent confidence interval of 30 ka can be obtained using the following equation from Dalrymple and Lanphere (1969, p. 120):

$$C.V. = 1.960x(\sigma^2/n_1+\sigma^2/n_2)^{1/2}$$

This value (30 ka) is the minimum difference in age between the two flows that would be detectable at the 95 percent confidence level, provided that each sample is measured at least five times.

As previously noted, the uranium-trend ages and the proposed correlations between the Quaternary stratigraphic units in the Yucca Mountain region bracket the age of the eruptive phases of the Lathrop Wells volcanic center between 145 ± 25 ka and 270 ± 30 ka (Swadley et al., 1984). These results and the $^{40}Ar/^{39}Ar$ age data reported by Turrin and coworkers (Turrin and Champion, 1991; Turrin et al. 1991, 1992), indicating a potential for contamination from the underlying tuff, suggest that the K-Ar ages obtained from laboratory A (660 ± 30 ka) and laboratory C (530 ± 40 ka) must be rejected. In addition, because zero-age residuals are not reported in either the Sinnock and Easterling (1983) or U.S. Department of Energy (1986) report, the reported K-Ar data from laboratory A and laboratory C cannot be tested for any possible systematic errors originating from the atmospheric ^{40}Ar corrections. For these reasons the data from these laboratories are excluded in the subsequent analysis.

The accepted K-Ar data are (Table 7) 21 analyses from the block flow unit (Ql_5) and cinder complex that yield an arithmetic mean age of 150 ± 165 ka and a SEM of ± 39 ka. The weighted average of the flow unit (Ql_5) sample set is 115 ± 12 ka. All 15 samples from the lava flow unit (Ql_3) yield an arithmetic mean of 196 ± 170 ka, a SEM of ± 44 ka, and a weighted average of 133 ± 10 ka. If the 3 age determinations of the contaminated sample (NNTS #3-86) are deleted from the data set, the arithmetic mean is 126 ± 90 ka and the SEM is ± 26 ka. Again, because the 3 individual determinations for sample NNTS #3-86 have large uncertainties, they have little effect on the weighted average. The weighted average without sample NNTS #3-86 is 131 ± 10 ka. None of the ages just discussed are statistically different at the 95 percent confidence level. The K-Ar ages from the two flow units Ql_3 are entirely consistent with the uranium-trend chronology and stratigraphy of the surficial units in the Yucca Mountain region (Swadley et al. 1984).

SUMMARY

We believe the data presented in Table 7 to be the best synthesis of the numerous conventional K-Ar age determinations from the Lathrop Wells volcanic center. Possible effects of contamination by the tuff xenoliths and the possibility of systematic errors in the atmospheric argon correction have been considered. The weighted averages of the K-Ar ages from the block flow unit (Ql_5) and lava flow unit (Ql_3) (115 ± 12 ka and 133 ± 10 ka, respectively) indicate an older age for the most recent period of volcanic activity at Lathrop Wells than suggested by Wells et al. (1990). These ages are concordant at the 95 percent confidence level with the $^{40}Ar/^{39}Ar$ results presented in Turrin and Champion (1991) and Turrin et al. 1991, 1992). Moreover, these K-Ar ages are consistent with the geochronology (Szabo et al., 1981) and stratigraphy (Swadley et al., 1984) of the surficial units in the Yucca Mountain region.

Paleomagnetic data indicate that there may be two statistically differentiable eruptive units, block flow unit (Ql_5) and the lava flow unit (Ql_3), occurring at the Lathrop Wells volcanic center. Their mean directions of remanent magnetization are 51.5° inclination 2.2° declination, and 51.4° inclination 354.5° declination, respectively. The angular difference in the directions of 4.7° is significant at the 99.98 percent confidence level. The angular difference between the two mean paleomagnetic directions suggests a minimum age difference between the eruptive events of about 100 years. Given the reported analytical precision of the weighted average K-Ar ages of the two units and the zero-age residuals of the spectrometers of approximately ± 10 ka, the statistical difference in age between Ql5 and Ql3 is less than or equal to approximately 30 ka.

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FIGURE CAPTIONS

Figure 1. Location map of the Crater Flat/Yucca Mountain area. Brick pattern delineates Paleozoic limestones; stippled pattern represents Tertiary ash-flow tuffs; chevron patterns are Tertiary basalt flows; light shaded areas are Tertiary and Quaternary scoria cones and pyroclastic deposits; dark shaded areas are Quaternary basalt flows; white area is Quaternary alluvium. Sawtooth line is a detachment fault, teeth toward upper plate. On the inset LV indicates Las Vegas, NV.

Figure 2. Generalized geologic map of the Lathrop Wells cinder cone and flow complex, showing locations of sampling sites of K-Ar and paleomagnetic samples. Numbers correspond to samples listed in Tables 1 through 5. Areas enclosed with hachured outlines are scoria mounds composed of welded agglutinate and volcanic bombs; area enclosed with sawtoothed outline is crater at top of main scoria cone. Units: Ql_5, early basaltic lava flows; Ql_3, later basaltic lava flows; Qs_5, early scoria deposits; Qps_1, pyroclastic base-surge deposits; Qsu, undifferentiated scoria deposits, with some scoria mounds contemporaneaous with unit Ql_3. Unpatterned areas, Quaternary alluvium.

Figure 3. Correlations between the regional Quaternary stratigraphic units and corresponding radiometric ages in the Yucca Mountain region as reported by Swadley et al. (1984). If these correlations are correct, then the age of the major eruptive phase of the Lathrop Wells volcanic center is bracketed between 145±25ka and 270±30ka.

Figure 4. Equal-area plots of (A) mean directions of remanent magnetization with circles of 95% confidence for paleomagnetic sites taken in Lathrop Wells volcanic units, and (B) mean directions of remanent magnetization with circles of 95% confidence for units Ql_3 and Qs_5 at Lathrop Wells. Unit means differ at the 99.98% confidence level.

Table 1 Lathrop Wells Paleomagnetic Data

	Location			Peak Cleaning	Direction					VGP	
Site	Lat °N	Long °E	N/No	Field (mT)	I	D	α95	k	R	Lat °N	Long °E
						Unit Ql$_3$					
B8017	36.696°	243.495°	23/24	20	47.0°	355.8°	1.8°	286	22.92319	80.8	87.4
B8119	36.694°	243.502°	12/12	10+	53.4°	356.2°	2.6°	292	11.96229	85.5	112.7
B8131	36.694°	243.502°	12/12	10+	52.1°	353.6°	2.7°	266	11.95857	83.4	118.1
B8143	36.693°	243.503°	12/12	10+	52.4°	351.9°	2.8°	245	11.95517	82.4	126.8
B8155	36.693°	243.503°	12/12	5+	50.6°	355.8°	3.1°	196	11.94380	83.6	97.6
B8167	36.689°	243.506°	12/12	10+	51.9°	356.3°	2.9°	222	11.95041	84.9	101.0
B8179	36.684°	243.505°	6/12	20+	52.6°	351.5°	2.7°	634	5.99211	82.2	129.2
Mean			**7/7**		**51.4°**	**354.5°**	**1.9°**	**1060**	**6.99434**	**83.5**	**109.9**
						Unit Qs$_5$					
B8041	36.684°	243.492°	20/20	20+	51.8°	2.2°	1.3°	595	19.96791	85.4	40.2
B8061	36.688°	243.494°	11/12	30+	53.9°	2.0°	3.1°	222	10.95486	87.2	26.8
B8191	36.683°	243.497°	12/12	10	49.6°	0.4°	2.2°	402	11.97266	83.8	60.3
B8203	36.683°	243.497°	9/12	25+	51.4°	1.7°	2.8°	331	8.97581	85.1	46.5
B8215	36.684°	243.497°	13/15	10+	50.6°	4.7°	1.6°	656	12.98171	83.4	25.9
Mean			**5/5**		**51.5°**	**2.2°**	**1.8°**	**1855**	**4.99784**	**85.1**	**41.2**

[N/No is number of cores averaged in site mean direction over number of cores taken at site. I and D are mean remanent inclination and declination values, α95 is radius of the cone of 95 percent confidence about the mean direction, *k* is Fisherian precision parameter, R is length of site resultant vector, and VGP is virtual geomagnetic pole calculated from site location and mean remanent direction.]

Table 2. Lathrop Wells K-Ar, U.S. Geological Survey, 1978

Flow unit	Sample number	K^+ (wt. percent)	$^{40}Ar^*$ (mol/g x 10^{-12})	Percent $^{40}Ar^*$	Age ± 1σ (ka)	Material
Ql_3	TSV-1	1.509±0.005	0.907	2.4	336 ± 28	Basaltic lava flow
			0.100	0.4	38 ± 19	
			0.012	0.1	3 ± 75	
				Arith. mean ±1σ is 126 ± 183ka [SEM ± 106ka] Weighted average is 127 ± 15 ka		
Best age for Ql_3:		**Arith. mean ± SEM 126 ± 106 ka**				
Ql_5	TSV-129	1.500±0.006	1.727	3.8	670 ± 400	Basaltic welded spatter
	TSV-129[a]	1.552±0.012	0.7552	1.7	300 ± 100	
				Arith. mean ±1σ is 485 ± 261ka [SEM ± 185ka] Weighted average is 322 ± 97ka		
	TSV-283[a]	1.498±0.006	0.5861	3.0	230 ± 40	Basaltic volcanic bomb interior
Best age for Ql_5:		**Weighted average 243 ± 37 ka**				

[Decay constants: $\lambda_\varepsilon + \lambda_\varepsilon' = 0.581 \times 10^{-10}\ yr^{-1}$; $\lambda_\beta = 4.962 \times 10^{-10}\ yr^{-1}$; and $^{40}K/K_{total} = 1.167 \times 10^{-4}$; see Steiger and Jager (1977)]

[a] Data from Marvin et al. (1989)

Table 3. Lathrop Wells K-Ar Data as reported in Sinnock and Easterling (1983)

Sample	K^{+}%	$^{40}Ar^{*}$ (mol/g x 10^{-12})	Percent $^{40}Ar^{*}$	Age ± 1σ (ka)
		Laboratory A		
1	1.389	1.75	3.5	700 ± 70
2	1.5281	1.78	1.5	650 ± 70
3	1.518	2.10	2.8	770 ± 80
4	1.611	1.70	1.6	590 ± 60
5	1.586	3.25	2.4	1100 ± 300
6	1.503	1.58	2.3	580 ± 80
		Laboratory B		
1	1.633	0.23	1.6	120 ± 30
2	1.606	0.10	0.1	-10 ± 290
3	1.628	-0.08	0.0	-30 ± 140
4	1.545	0.21	1.1	80 ± 30
5	1.577	0.30	0.4	125 ± 180
6	1.558	0.48	0.9	175 ± 90
		Laboratory C		
1	1.625	1.69	7.9	600 ± 90
2	1.643	1.74	4.0	610 ± 160
3	1.580	1.80	6.5	660 ± 100
4	1.597	1.54	7.2	560 ± 90
5	1.607	1.64	3.4	590 ± 210
6	1.566	1.05	6.6	390 ± 70

[Isotope abundances for potassium were not given, and decay constants were not specified in the Sinnock and Easterling (1983) report. It was reported, however, that one of the laboratories used $\lambda_{\varepsilon} + \lambda_{\varepsilon'} = 0.585 \times 10^{-10} yr^{-1}$; $\lambda_{\beta} = 4.72 \times 10^{-10} yr^{-1}$ for decay constants; the other two used the accepted decay constants of Steiger and Jager (1977) of ($\lambda_{\varepsilon} + \lambda_{\varepsilon'} = 0.581 \times 10^{-10} yr^{-1}$; $\lambda_{\beta} = 4.962 \times 10^{-10} yr^{-1}$)]

Table 4. U.C. Berkeley K-Ar data used in Sinnock and Easterling (1983)

Flow unit	Sample	Lab number	Sample weight (g)	%K^{+}	^{40}Ar* (mol/gm x 10^{-11})	%Ar*	Age ± 1σ (ka)
Ql5	1	3667	7.2064	1.633 ± 0.03	0.035	2.8	120 ± 20
		3668	8.5813	1.633 ± 0.03	0.011	0.5	40 ± 40
							Arith. mean ± 1σ is 80 ± 18 ka **Weighted average is 104 ± 18 ka)**
Ql5	2	3697	7.6553	1.577 ± 0.02	-0.006	-0.7	-80 ± 420
		3706	10.4419	1.635 ± 0.03	0.16	0.2	60 ± 160
							Arith. mean ± 1σ is -10 ± 41 ka **Weighted average is 42 ± 150 ka)**
Ql5	3	3665	7.7166	1.626 ± 0.01	0.032	0.5	110 ± 110
		3787	9.8831	1.630 ± 0.01	-0.047	-0.5	-170 ± 160
							Arith. mean ± 1σ is -30 ± 91 ka **Weighted average is 20 ± 91 ka)**
Ql5	4	3655	8.5546	1.547 ± 0.01	0.023	1.3	90 ± 30
		3721	8.995	1.542 ± 0.01	0.018	1	70 ± 30
							Arith. mean ± 1σ is 80 ± 21 ka **Weighted average is 80 ± 21 ka)**
Ql5	5	3662	9.4878	1.557 ± 0.01	0.01	0.1	40 ± 230
		3663	9.2694	1.577 ± 0.01	0.05	0.8	190 ± 130
							Arith. mean ± 1σ is 115 ± 113 ka **Weighted average is 154 ± 113 ka)**
Ql5	6	3659	8.6201	1.558 ± 0.04	0.04	0.7	150 ± 100
		3728	11.7424	1.558 ± 0.04	0.055	1.1	200 ± 80
							Arith. mean ± 1σ is 175 ± 62 ka **Weighted average is 180 ± 62 ka)**

Arith. mean of ±1σ is 68 ± 106 ka [SEM ± 31 ka]
Weighted average of all analyses is 97 ± 13 ka

[Decay constants: $\lambda_{\varepsilon} + \lambda_{\varepsilon'} = 0.581 \times 10^{-10}\ \mathrm{yr}^{-1}$; $\lambda_{\beta} = 4.962 \times 10^{-10}\ \mathrm{yr}^{-1}$; and $^{40}\mathrm{K}/\mathrm{K}_{\mathrm{total}} = 1.167 \times 10^{-4}$; see Steiger and Jager (1977)]

Table 5 Lathrop Wells K-Ar Data, 1986

Flow unit	Sample	Lab number	Material	Sample weight (g)	%K+	^{40}Ar* (mol/gm x 10^{-13})	%Ar*	Age ±1σ (ka)
Ql3	NNTS #1-86	5429	WR AOB	8.10876	1.556 ± 0.013	5.356	2.4	199 ± 23
		5258		8.12395		4.115	1.3	153 ± 96
		5259		8.30009		1.741	0.7	65 ± 88
						Arith. mean ±1σ is 139 ± 68 [SEM ±39 ka]		
						Weighted average is 189 ± 22 ka		
Ql3	NNTS #2-86	5264	WR AOB	7.6488	1.496 ± 0.018	3.107	1.1	120 ± 66
		5430		7.38628		4.774	1.0	184 ± 110
		5263		7.13162		2.387	0.8	92 ± 85
						Arith. mean ±1σ is 132 ± 47 [SEM ±27 ka]		
						Weighted average is 123 ± 47 ka		
Ql3	NNTS #3-86	5266	WR AOB	7.81638	1.459 ± 0.03	10.58	2.1	418 ± 240
		5267		7.44786		11.41	2.1	451 ± 240
		5265		7.92347		14.44	3.3	571 ± 360
						Arith. mean ±1σ is 480 ± 81 [SEM ±81 ka]		
						Weighted average is 459 ± 154 ka		
Ql3	NNTS #4-86	5378	WR AOB	7.27209	1.531 ± 0.017	0.9759	0.3	37 ± 29
		5431		6.34199		3.7630	1.1	142 ± 33
		5269		9.11042		3.6310	1.3	137 ± 35
						Arith. mean ±1σ is 105 ± 59 [SEM ±34 ka]		
						Weighted average is 98 ± 18 ka		
Ql5	NNTS #5-86	5432	WR AOB	7.15661	1.565 ± 0.016	4.124	0.5	152 ± 110
		5272		7.65629		4.225	0.5	156 ± 290
		5273		9.38816	1.576 ± 0.04	5.763	0.7	211 ± 340
		5605		7.01987	1.565 ± 0.016	9.149	0.7	337 ± 150
		5941-1		5.98324		3.137, 2.800	0.3, 0.3	110 ± 124
		5928-1		6.21759	1.565 + 0.016	3.913, 5,404	0.5, 0.7	159 ± 127
						Arith. mean ±1σ is 188 ± 80 [SEM ±33 ka]		
						Weighted average is 176 ± 60 ka		

Ql3 lava flow: Arith. mean ±1σ is 214 ± 170 ka; [SEM ± 49 ka]; weighted average is 137 ± 13 ka

Ql3 lava flow (less NNTS #3-86): Arith. mean ±1σ is 125 ± 53 ka; [SEM ± 18 ka]; weighted average is 135 ± 13 ka

Best age of Lathrop Wells Ql3 lava flow: Weighted average of 137 ± 13 ka

Best age of Lathrop Wells Ql5 lava flow: Weighted average of 176 ± 60 ka

[Decay constants: $\lambda_\epsilon + \lambda_{\epsilon'} = 0.581 \times 10^{-10}\ yr^{-1}$; $\lambda_\beta = 4.962 \times 10^{-10}\ yr^{-1}$; and $^{40}K/K_{total} = 1.167 \times 10^{-4}$; see Steiger and Jager (1977)]

Table 6. Zero-age residual data from Berkeley argon extraction systems

Sample number	Extraction system	Material	%K$^+$	^{40}Ar* (mol/gm x 10^{-14})	Percent ^{40}Ar*	Age ±1σ (ka)
5761-3	BC	Air	1.52	3.258	0.3	12 ± 22
5758-2	BC	Air	1.52	8.887	1.11	34 ± 25
5720-2	BC	Air	1.52	-4.670	-0.3	18 ± 70
5723-3	BC	Air	1.52	26.860	0.7	102 ± 53
5716-2	BC	Air	1.52	-24.350	-0.5	-92 ± 64
				Arith. mean ±1σ is 15 ± 70 ka [SEM ± 31 ka]		
				Weighted average is 22 ± 15 ka		
5713B	GORT	Air	1.52	15.440	1.1	59 ± 98
5721	GORT	Air	1.52	-48.900	-1.9	-186 ± 68
5717	GORT	Air	1.52	-0.0002	-0.0	0 ± 20
5713A	GORT	Air	1.52	51.660	1.3	82 ± 20
5713D	GORT	Air	1.52	-32.970	-1.9	-125 ± 32
				Arith. mean ±1σ is -34 ± 117 ka [SEM ± 52 ka]		
				Weighted average is 8 ± 13 ka		
Arith. mean of all samples ± 1σ is -10 ± 94 ka [SEM ± 30 ka]						
Weighted average of all samples ±1σ is 14 ± 10 ka						

[Decay constants: $\lambda_{\varepsilon} + \lambda_{\varepsilon}' = 0.581 \times 10^{-10} yr^{-1}$; $\lambda_{\beta} = 4.962 \times 10^{-10} yr^{-1}$; and $^{40}K/K_{total} = 1.167 \times 10^{-4}$; see Steiger and Jager (1977)]

Table 7. Compilation of K-Ar data from tables 2-5 for the Lathrop Wells cinder cone and flow complex.

Lava flow unit (Ql$_3$)		Block flow unit (Ql$_5$)	
Sample	Age ±1σ (ka)	Sample	Age ±1σ (ka)
NNTS #1-86	199 ± 23	KA3667	120 ± 20
	153 ± 96	KA3668	40 ± 40
	65 ± 88		
		KA3687	-80 ± 420
NNTS #2-86	120 ± 66	KA3706	60 ± 160
	184 ± 110		
	92 ± 85	KA3665	110 ± 110
		KA3787	-170 ± 160
NNTS #3-86	418 ± 240	KA3655	90 ± 30
	451 ± 240	KA3721	70 ± 30
	571 ± 360		
		KA3662	40 ± 230
		KA3663	190 ± 130
NNTS #4-86	37 ± 29		
	142 ± 33	KA3659	150 ± 100
	137 ± 35	KA3728	200 ± 80
TSV-1	336 ± 28	NNTS #5	152 ± 110
	38 ± 19		156 ± 290
	3 ± 75		221 ± 340
			337 ± 150
			110 ± 124
			159 ± 127
		TVS 129	670 ± 400
			300 ± 100
		TVS 283	230 ± 40
Arithmetic mean ±1σ [SEM]	196 ± 170 [44 ka]		150 ± 165 [39 ka]
Arithmetic mean ±1σ:	126 ± 90 [26 ka]*		
Weighted average:	**133 ± 10 ka**		**115 ± 12 ka**
	131 ± 10 ka*		

*(not including NNTS #3-86)

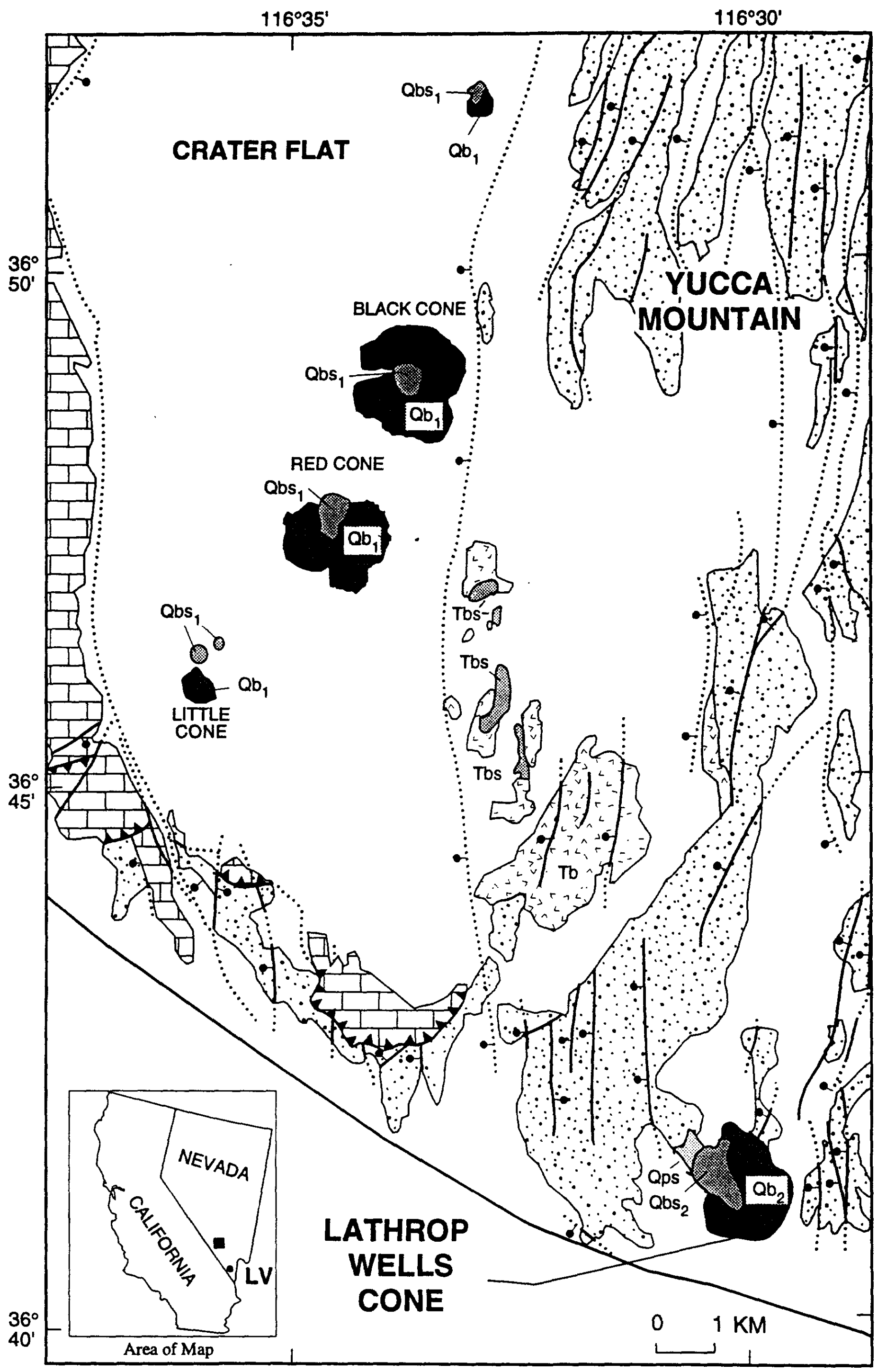
116°35'
116°30'
CRATER FLAT
Qbs$_1$
Qb$_1$
36° 50'
YUCCA MOUNTAIN
BLACK CONE
Qbs$_1$
Qb$_1$
RED CONE
Qbs$_1$
Qb$_1$
Qbs$_1$
Tbs
Qb$_1$
Tbs
LITTLE CONE
Tbs
36° 45'
Tb
Qps
Qbs$_2$
Qb$_2$
NEVADA
CALIFORNIA
LV
LATHROP WELLS CONE
0 1 KM
36° 40'
Area of Map

FIGURE 1.

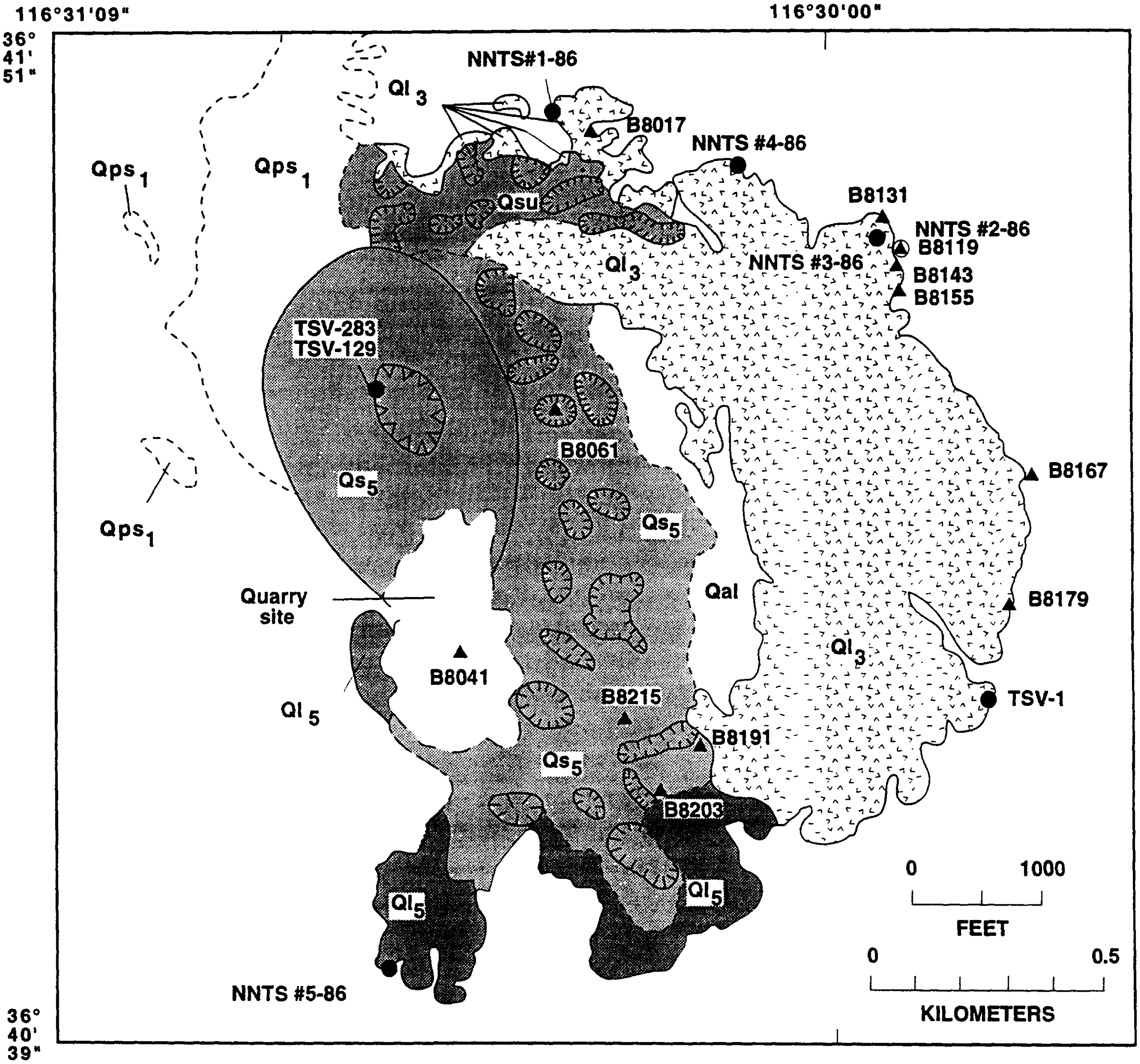
116°31'09"
116°30'00"
36° 41' 51"
36° 40' 39"
NNTS#1-86
Ql3
Qps1
Qps1
Qps1
B8017
NNTS #4-86
Qsu
B8131
NNTS #2-86
B8119
NNTS #3-86
Ql3
B8143
B8155
TSV-283
TSV-129
B8061
Qs5
Qs5
B8167
Quarry site
Qal
B8179
Ql3
B8041
Ql5
B8215
TSV-1
B8191
Qs5
B8203
Ql5
Ql5
0
1000
FEET
0
0.5
KILOMETERS
NNTS #5-86

FIGURE 2.

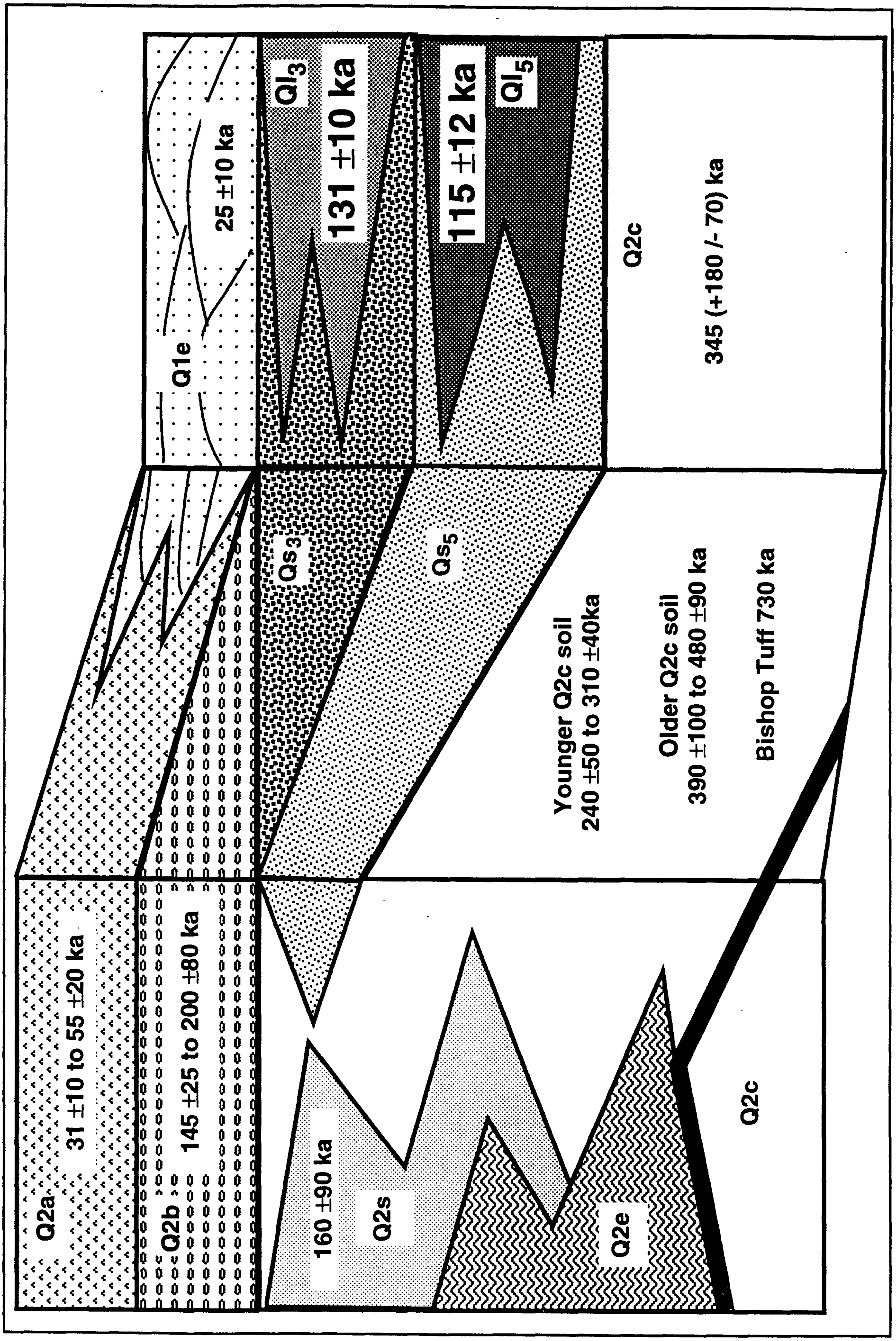
Q2a
31 ±10 to 55 ±20 ka
Q2b
145 ±25 to 200 ±80 ka
160 ±90 ka
Q2s
Q2e
Q2c
Q1e
25 ±10 ka
Ql$_3$
131 ±10 ka
Qs$_3$
Ql$_5$
115 ±12 ka
Qs$_5$
Q2c
345 (+180 /- 70) ka
Younger Q2c soil
240 ±50 to 310 ±40ka
Older Q2c soil
390 ±100 to 480 ±90 ka
Bishop Tuff 730 ka

FIGURE 3.

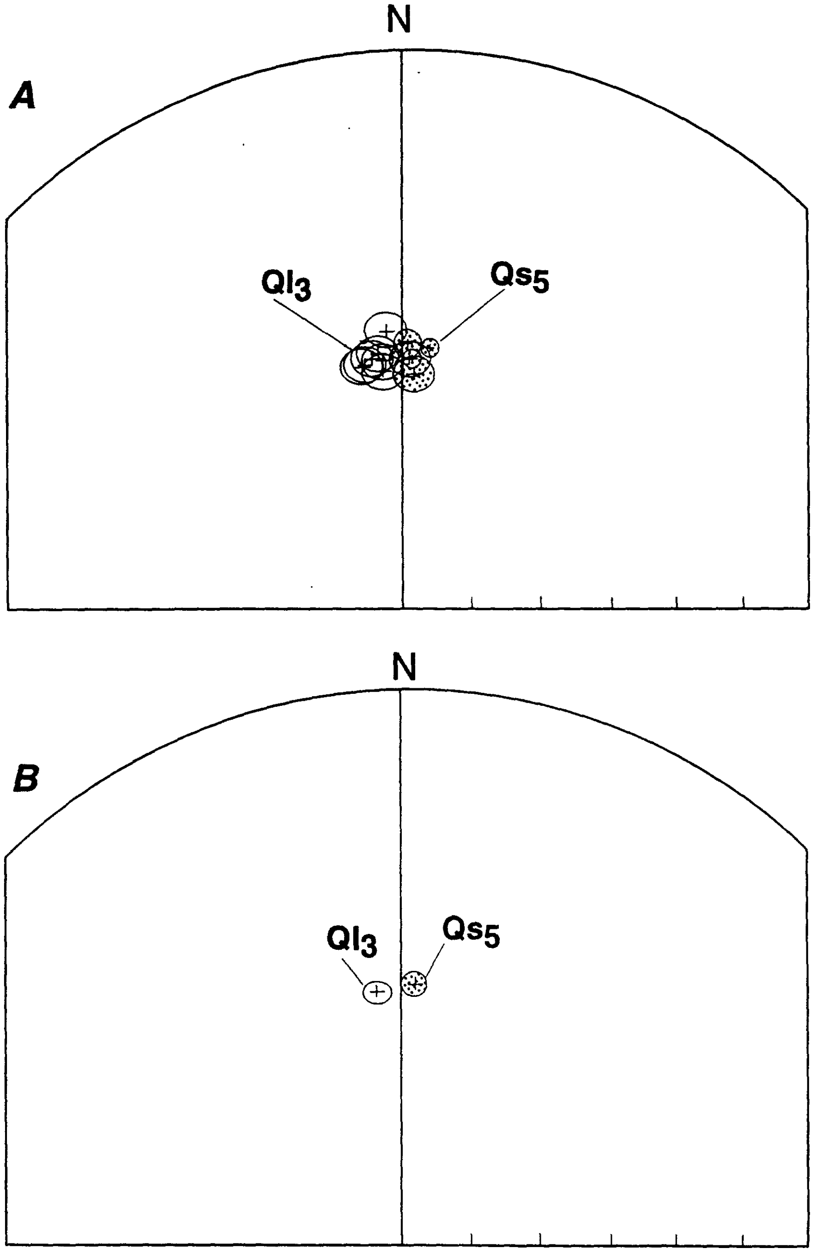

FIGURE 4.