Measuring the Age of the Lathrop Wells Volcanic Center at Yucca Mountain

B. Turrin *et al.* (*1*) argue that conventional K-Ar and $^{40}Ar/^{39}Ar$ age determinations and paleomagnetic data provide a definitive age assignment of approximately 136 ka (thousand years ago) to 141 ka for the Lathrop Wells volcanic center with an error of less than 10,000 years. This conclusion is tendered despite replicate age determinations that extend over almost three orders of magnitude. Turrin (*1*) and other also conclude (*2, 3*) that the Lathrop Wells volcanic center is a simple monogenetic center, and so revert to an earlier interpretation (*4, 5*) that was made before studies revealed the complexity of the volcanic stratigraphy (*6–9*).

The geologic map and stratigraphic nomenclature of the Lathrop Wells volcanic center presented by Turrin *et al.* (*1*) were extracted and modified without apparent reference to the original publication of these field studies (*10*). Stratigraphic units separated by soil-bounded unconformities were modified or not accounted for in their interpretation (*6, 8*). These unconformities indicate a hiatus in eruptive activity of significantly sustained time (at least 10^3 years) and allow the development of soil profiles that are similar to radiocarbon dated soil sequences within arid regions of the southwestern United States (*11–14*). Without complete stratigraphic sampling, statements regarding the complexity of Lathrop Wells eruptive history offer only an oversimplified stratigraphy. Turrin *et al.* state that their combined flow and scoria unit Ql_3/Qsu [(*1*), figure 1] is younger than the flows and scoria of Ql_5/Qs_5, but they report without any implications a weighted mean of 141 ± 9 ka for the younger rocks and an age of 136 ± 8 ka for the older rocks. In comparison, recently reported thermoluminescence age determination (*8*) of a buried soil between tephra deposits of their unit Qs_5 is 9.9 ± 0.7 ka. Cosmogenic ^3He age determinations (*8*) of surface-exposed volcanic bombs of unit Qs_5 yield ages of 23 ± 4 ka to 44 ± 13 ka. Flows that stratigraphically lie below these tephra and bomb deposits yield a thermoluminescence date of 24.5 ± 2.5 ka for baked soils that underly unit Ql_3 (*8*) and yield a cosmogenic ^3He date of 64 ± 6 ka on exposed bedrock of unit Ql_5 (*8*). The weighted means of the K-Ar and $^{39}Ar/^{40}Ar$ age determinations have insufficient precision to constrain the age of these late Quaternary volcanic flows and tephra separated by soil-bounded unconformites.

Our major criticism of the K-Ar and $^{40}Ar/^{39}Ar$ age determinations of the volcanic center made by Turrin *et al.* is of their method of averaging the age determinations, not of their analytical methods. If the data are compiled as a conventional mean, large 1-σ errors are obtained that overlap and are consistent with the results of every other chronology method used to assess the age of the Lathrop Wells center (*8*). The use of a weighted mean gives age assignments with unrealistically small errors, in that the group age dates range from 20 ka to 947 ka. Yet Turrin *et al.* do not explain why the weighted mean might be more reliable than the conventional mean, nor do they test the validity of the weighted mean method. Our specific concerns are as follows.

1) The age determinations are positively skewed with a mean larger than the median, which indicates influence of the mean by older ages.

2) Turrin *et al.* did not examine the data set with conventional tests for outliers. Evaluation of their data shows that outliers are present where outliers are defined to be more than 1.5 times the interquantile range. The data set is nongaussian, with inclusion of the outliers, and therefore is probably not suitable for description with a weighted mean.

3) Four age determinations were discarded by Turrin *et al.* in the weighted mean data reduction because of "contamination." No systematic criteria were presented for doing so, and recalculation of the data set (*1*) with these four age determinations yields significantly older values of the weighted mean with larger uncertainty.

4) The regression plots in [(*1*), figure 2] show the presence of influential cases which should have been identified to check for errors and suitability to the data set. The influential cases could strongly control the *y*-intercept, the values of which are used by Turrin *et al.* to argue against the presence of excess Ar.

5) There was no discussion of data errors other than analytical in (*1*). Because the $^{40}Ar/^{39}Ar$ analyses were of the matrix of fine-grained basalt (*15*), there is a possible problem of recoil of ^{39}Ar which could give anomalous older ages (*16, 17*).

6) Conventional, whole rock K-Ar data are averaged (*1*) with the $^{40}Ar/^{39}Ar$ to establish final values for the weighted means. However, the whole rock data are not listed in (*1*). Thus it is not clear whether the data set belongs to the same population as the $^{40}Ar/^{39}Ar$ data.

We conclude that the reduction of the data set of Turrin *et al.* with a weighted mean method is unsupported at best and may be invalid if all sources of variance in the data set are not analytical. Their conclusion that the soil and geomorphic studies of the Lathrop Wells center are miscalibrated is not supported by the data.

Turrin *et al.* argue that an angular difference of 4.7° between mean directions of remanent magnetization indicates that the dates of Lathrop Wells eruptive events differ by 100 years. However, angular differences between two paleomagnetic data sets can only be used at best to infer a *minimum* age between stratigraphic units. The geomagnetic field at Lathrop Wells could have occupied the observed directions numerous times during the Quaternary and thus could equally represent eruptions separated by 100, 10,000, 100,000 years, or 1 million years (Ma). For example, Champion (*3*) notes that the flow mean paleomagnetic directions from adjacent 3.7 Ma and 1.1 Ma flows in Crater Flat are "similar . . . but cannot be confused because they have different K-Ar ages and stratigraphic positions." Turrin *et al.* rely on these stratigraphic relations in neighboring Crater Flat, but not at Lathrop Wells (*6–8*).

The conclusion (*1*) that the paleomagnetic data of Qs_5 scoria and Ql_3 flows fall into only two statistically distinguishable groups is unfounded. First, Turrin *et al.* apparently did not sample or analyze several mapped units. Their paleomagnetic record is incomplete (*1–3, 18*), and thus their conclusions are premature. Second, the paleomagnetic data for the 27 sites with flows and spatter and for the 40 core samples from the scoria cone rim are not presented in (*1*) or in their supporting papers (*2, 3, 18*). These data are necessary to assess confidently the statistical validity of their proposed field magnetic groups. Third, on the basis of matching directions of remanent magnetization, Turrin *et al.* infer (*1*) that all scoria and spatter deposits of unit Qs_5 have the same direction as the main scoria cone, but do not note that this conclusion requires the rejection of paleomagnetic data. One-third of 16 reported samples from bombs of the main scoria cone unit (unit Qs_5) were rejected because discordant directions of remanent magnetization revealed apparent "cone slope slumping" (*18*). These rejected data contradict their statement (*1*) that 40 core samples from "bedded" bombs on the rim yield a direction "identical" to that of the flanking spatter cone. Fourth, the conclusion that the Lathrop Wells has a simple eruptive history (*1*) apparently contradicts an earlier interpretation by Turrin *et al.* that the center is polycyclic with "a more complex volcanic history than previously thought" (*18*). This interpretation is based on K-Ar data not presented in (*1*) and paleomagnetic data that indicate a *minimum* of 100 years between eruptions.

A simple eruptive history, together with an older age of the most recent volcanic activity in the region, could justify an assessment of decreased volcanic risk for Yucca Mountain. The polycyclic model, by contrast, requires the consideration of possible additional eruptions within the 10,000-year isolation period required for a potential radioactive waste repository. The latter model could lead to an assessment of increased potential of dispersal of such waste to the environment should a future volcanic eruption compromise the site.

Finally, the simplified volcanic history of Turrin *et al.* (*1*) apparently was not tested by geochemical studies. Recent studies by Perry and Crowe (*9, 19*) at Lathrop Wells center demonstrate that geochemical variations between the main scoria cone and flanking spatter deposits could not result from fractional crystallization of a single magma batch of mixing of separate batches. They conclude (*9, 19*) that the geochemical data are consistent with the interpretation that separate magma batches formed a complex polycyclic volcano characterized by scoria and spatter deposits that were separated in time by a prolonged hiatus in eruptive activity (*6*).

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Response: The comment by Wells *et al.* centers on three topics: the geologic map and stratigraphy, the K-Ar and $^{40}Ar/^{39}Ar$ data, and the paleomagnetic data.

The unit nomenclature of the geologic map in figure 1 of our report (*1*) is indeed modified from a map by Crowe *et al.* (*2*), of which two of us are co-authors, and we regret not having made that clear. The photomosaic map (*2*), however, is not on a controlled topographic base and has no latitude-longitude marks or north arrow. Most of the contacts on it are shown as either concealed or inferred. We therefore remapped, modified, and compiled the geologic map of Lathrop Wells on a topographic base, from which figure 1 of our report (*1*) was derived.

Wells *et al.* state that our composite unit Ql_5/Qs_5 (*1*), is oversimplified and does not "account for stratigraphic tephra" units separated by soil-bounded unconformities. The deposits in question were discussed in a paper by Turrin and Champion (*3*), which Wells *et al.* cite. These deposits of sand, silt, and lapilli-size tephra, supported in a matrix of eolian sand and silt, are immediately adjacent to the main cinder cone and overlie our unit Qs_5. We find no evidence (compositional, sedimentological, or granulometric) presented by Wells *et al.* (*4*) to support the volcanic origin of these lapilli-rich deposits. Turrin and Champion (*3*) have proposed that these deposits are cone-apron deposits derived from the nearby cone slope. Others (*5*) have also questioned the volcanic origin of these deposits.

Granulometry data on material from the basal portions of several of these deposits show that they contain 30 to 50% quartzofeldspathic eolian sand and silt (Fig. 1). This large proportion of eolian sand and silt, not mentioned by Wells *et al.* (*4*), cannot be accounted for by infiltration processes from overlying eolian units and indicates that these deposits are not volcanogenic in origin. Wells *et al.* and Crowe *et al.* (*6*) report without apparent documentation a thermoluminescence (TL) age of 9.9 ± 0.7 ka for these deposits and state that they can be traced continuously to the summit of the main cinder cone. This TL age is discordant with the ^3He exposure age [>51 ± 13 ka (*6, 7*)] for the cone rim. The paradox can be resolved if the "tephra" deposits (*4*) are not volcanic in origin, but are younger cone-apron deposits formed during subsequent erosion of the cinder cone. We conclude that the TL age of 9.9 ± 0.7 ka given (*6*) for these deposits is irrelevant to the age of volcanic activity at Lathrop Wells.

Wells *et al.* state that the ages we measured reverse the stratigraphic sequence of the volcanic events. Our analytical results—136 ± 8 ka for the older, composite units (Qs_5/Ql_5) and 141 ± 9 ka for the younger unit (Ql_3)—however, are statistically consistent with the stratigraphy within the stated analytical uncertainties. A difference of 5 ka between ages with σ uncertainties of 8 and 9 ka, respectively, is not statistically significant.

The ^3He cosmogenic exposure age dating method referred to by Wells *et al.* and Crowe *et al.* (*6*) is a developmental technique, and no analytical data for Lathrop Wells have been presented to our knowledge. Also, the ^3He-production rate as a function of latitude and time is in dispute (*8, 9, 10*). Exposure ages reflect time of exposure at the earth's surface and, as emphasized by Crowe *et al.* (*6*), always represent minimum ages for formation. Statistical comparison of the ^3He ages of the volcanic bombs from the cone rim yields a weighted mean of 31 ± 12 ka σ and a mean square of the weighted deviates (MSWD) (*11, 12*) of 39.7. This large MSWD indicates a high probability of a real difference in exposure ages for the volcanic bombs and supports our point about the danger of interpreting these ages as anything but minimum values. Because these ^3He age measurements are only minimums, they are consistent with our $^{40}Ar/^{39}Ar$ and K-Ar ages. Moreover, a U-Th disequilibrium age of 150 ± 40 ka for unit Ql_4 (our unit Ql_3) reported by Crowe *et al.* (*6*) supports our age determinations.

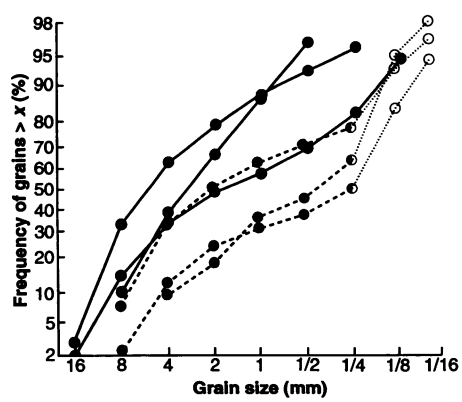

Fig. 1. Grain size distribution curve for scoria and cone-apron deposits from the Lathrop Wells volcanic center. Solid black lines and solid circles are grain size distribution curves of scoria and lapilli from the main cinder cone. Dashed and dotted lines show the grain-size distribution curves of the "tephra" deposits of Wells *et al.* (*4*). Dashed lines and solid circles indicate scoria and lapilli. Dotted lines and open circles indicate quartzofeldspathic eolian sand and silt.

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