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THE LATHROP WELLS VOLCANIC CENTER: STATUS OF FIELD AND GEOCHRONOLOGY STUDIES

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INTRODUCTION

The Lathrop Wells volcanic center is located 20 km south of the potential Yucca Mountain site, at the south end of the Yucca Mountain range. It has long been recognized as the youngest basalt center in the region.[1] However, determination of the age and eruptive history of the center has proven problematic. The Lathrop Wells center was interpreted originally as a monogenetic basalt center.[1-3] Its age was inferred to be about 300 ka.[4,5] However, during the earliest stages of study of the Yucca Mountain area (1980-1985), two perplexing questions emerged for the center. The first is the unmodified geomorphic appearance of the main scoria cone, which appeared inconsistent with a K-Ar age of 300 ka. The second is the markedly variable results of conventional K-Ar age determinations (whole rock) obtained for lava and bomb samples from the center. Age determinations obtained at separate laboratories ranged from negative ages to > 700 ka.[6]

Preliminary geomorphic and soils studies were completed at the Lathrop Wells center in 1986 to examine these questions.[7] The concern that the cone could be significantly younger than 300 ka was substantiated by this work. A second phase of field and laboratory studies were initiated at the center. Large scale (1:4000) color aerial photographs were obtained and the center was remapped.[8] A second group of samples was collected at selected sites that were judged to provide the best source material for K-Ar age determinations. Conventional, whole rock K-Ar age determinations were obtained for these samples. All analysis were completed at a single laboratory.[9] Additional geomorphic and soils data were obtained for volcanic landforms and soils at the Lathrop Wells center and other Quaternary volcanic centers in Crater Flat.[7]

The results of volcanic risk assessment for the Yucca Mountain site were reexamined, assuming a range of possible age assignments for the Lathrop Wells center.[10,11] The affects of the different age assignments were evaluated for calculations of the recurrence of volcanic events for the Yucca Mountain region. The impact of a possible late Pleistocene or Holocene age for all or parts of the center can be examined in terms of two hypotheses. If we assume the Lathrop Wells center is young (< 50 ka) and that hypothesis is incorrect, we have erred toward overestimating volcanic risk. Conversely if the hypothesis is that the center is older (> 100 ka), and that is incorrect, we have erred toward underestimating volcanic risk. The latter error is not acceptable for evaluating the suitability of the Yucca Mountain site. Therefore we assume that parts of the center could have formed during young eruptions, (< 50 ka) until conclusive proof is obtained to invalidate this assumption. The rationale for this is to maintain a conservative perspective in site suitability studies and because some data show that parts or much of the volcanic center could be younger than 50 ka.

A detailed Study Plan (8.3.1.8.5.1 Characterization of Volcanic Features)[11] was prepared describing planned geochronology and field studies to assess the chronology of the Lathrop Wells volcanic center and other Quaternary volcanic centers in the region. A paper was published discussing the geomorphic and soil evidence for a late Pleistocene or Holocene age for the main cone of the center.[12] The purpose of this paper was to expose the ideas concerning the age of the Lathrop Wells center to scientific scrutiny. Additionally, field evidence was described suggesting the Lathrop Wells center may have formed from multiple eruptive events with significant intervals of no activity between events.[12] This interpretation breaks with established convention in the volcanological literature that small volume basalt centers are monogenetic. They are inferred, based on historic analogues,[2,13] to have formed in a single eruptive event with a duration of months or years. The conclusion of multiple eruptions was based on the presence of basaltic fall deposits with interbedded soils.

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These deposits are exposed in quarry cliffs on the south flank of the main cone.[14]

Controversy has continued concerning the eruptive history and chronology of the Lathrop Wells volcanic center. Turrin and Champion[9] and Turrin et al.[15] argued that conventional K-Ar and $^{40}Ar/^{39}Ar$ age determinations provide definitive age assignments of about 136 to 141 ka for the volcanic center with an error of less than 10 ka. This conclusion was proffered despite replicate age determinations that range over almost three orders of magnitude. The basis for the conclusion is compilation of the data using a weighted mean ($1/\sigma$), a data reduction method that may not be applicable for this data set. Additionally, Champion[16] suggested, based on paleomagnetic data, that the Lathrop Wells volcanic center is a simple monogenetic center. This conclusion reverts to earlier interpretations of the volcanic center, made before recognition of the apparent complexity of the volcanic stratigraphy.[2,3] These interpretations represent an alternative and simplified approach to the chronology and stratigraphic problems of the center. However, a key point is that the K-Ar, $^{40}Ar/^{39}Ar$ and paleomagnetic interpretations,[9,15,16] are based on an incomplete data set. Not all volcanic units identified through detailed field studies[8] were sampled or analyzed. Additionally, alternative sources of data in disagreement with the radiometric and paleomagnetic data were not discussed or considered in the analysis.[9,15,16]

The purpose of this paper is to describe the status of field and geochronology studies of the Lathrop Wells center. Our perspective is that it is critical to assess all possible methods for obtaining cross-checking data to resolve chronology and field problems. It is equally important to consider application of the range of chronology methods available in Quaternary geologic research.[17] Such an approach seeks to increase the confidence in data interpretations through obtaining convergence among separate isotopic, radiogenic, and age-correlated methods.[18] Finally, the assumptions, strengths, and weaknesses of each dating method need to be carefully described to facilitate an impartial evaluation of results.

The paper is divided into two parts. The first part describes the status of continuing field studies for the volcanic center. We are attempting to establish the field and chronology relations of all the volcanic units. This work is supplemented by recently initiated trenching of contacts between lithostratigraphic units. The combined field and trenching studies represent one of the most detailed studies of a single small volume basalt center. The initial results of this work support the interpretation that the Lathrop Wells volcanic center is polycyclic; it formed during multiple, time separate eruptive events.

The second part presents an overview of the preliminary results of ongoing chronology studies and their constraints on the age and stratigraphy of the Lathrop Wells volcanic center. Along with the chronology data, the assumptions, strengths, and limitations of each method are discussed. The current status of studies leads to the conclusion that the age of the Lathrop Wells volcanic center remains unresolved. Some chronology data support an age assignment for the center of > 100 ka. Other chronology and age-calibrated methods indicate some eruptions at the center could be as young as Holocene. More work is required to resolve this issue.

GEOLOGY AND VOLCANIC STRATIGRAPHY

The Lathrop Wells volcanic center overlies alluvial deposits and faulted volcanic bedrock of the Paintbrush and Timber Mountain tuffs. It is located near the intersection of northwest-trending faults and the northeast-trending Stagecoach Road fault (Fig. 1).[19] The main cone of the center is elongate northwest. This elongation is probably controlled in part by the direction of prevailing winds during the pyroclastic eruptions that formed the cone. Additionally, the feeder dikes for the center are probably oriented northwest. This is indicated by two features. First, there is a zone of red scoria centered about the summit crater and extending to the southeast and northwest. The red scoria was probably formed by oxidization of the scoria deposits by rising volcanic gases emitted from an underlying northwest-trending dike. Second, there are two sets of northwest-trending, locally paired sets of spatter cones and scoria mounds that demarcate eruptive fissures. These are present along the east base of the main cone and at the northeast edge of the volcanic center. There is a third alignment of east-northeast trending spatter cones and scoria mounds that mark an additional fissure zone, north-northeast of the main cone.

A detailed preliminary geologic map of the Lathrop Wells volcanic center was completed in 1988.[8] The contacts of lithostratigraphic units on the map have remained largely unchanged. However, there have been several additional units recognized and existing map units modified or assigned to different stratigraphic intervals. Briefly, the significant new results include:

1. A lava flow, largely buried by eolian sand and silt on the north side of the cone, has been excavated through trenching. The lava flow is underlain and overlain by pyroclastic surge

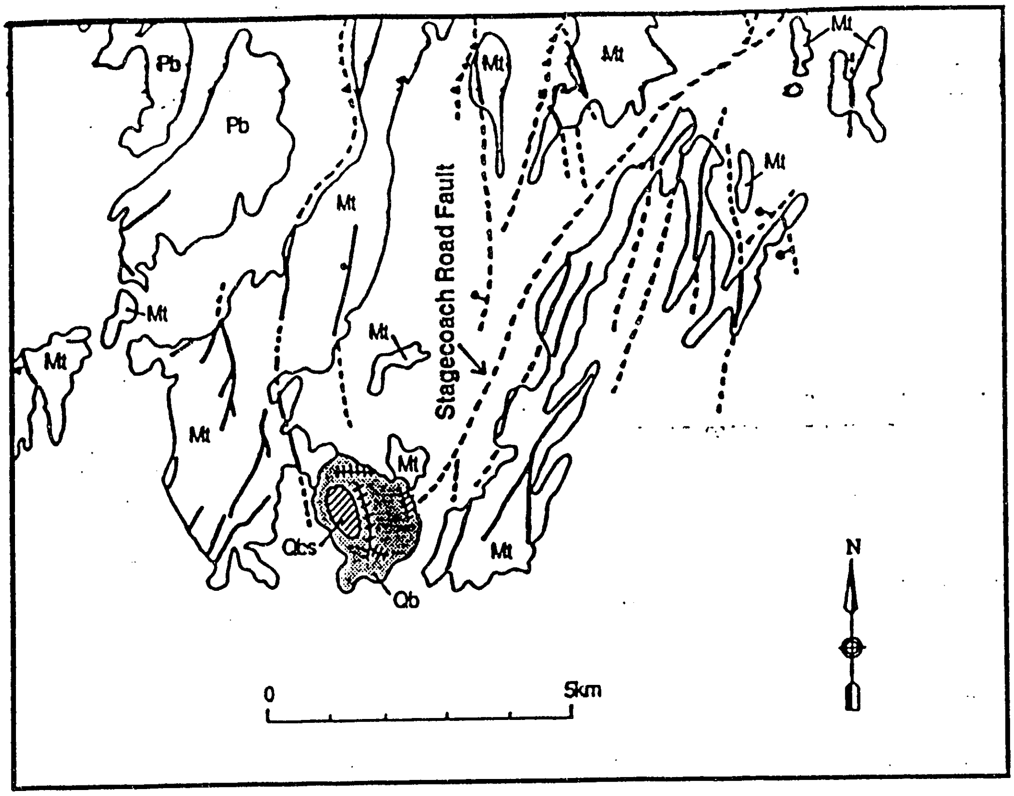

Fig. 1: Geologic setting of the Lathrop Wells volcanic center. Modified from Frizzell and Shulters.[20] The center is located at the south end of Yucca Mountain. It overlies Miocene tuff and alluvial deposits and is overlain by alluvium and eolian deposits. Mt: Miocene tuff undivided; Pb: Pliocene basalt of Crater Flat; Qb: Quaternary lava and scoria deposits of the Lathrop; Qbs: Main scoria cone of the center; Cross-hatched lines are eruptive fissures.

units and reworked scoria. The lava flow underlies a topographically high-standing lava flow (Ql_4). A soil with horizon development has been identified in the primary and reworked tephra section between the lava flows. This sequence requires a hiatus between eruption of the lavas.

2. Studies of soil horizon development on the eruptive units, now supplemented by trenching, continues to support a late Pleistocene or Holocene age of parts of the center.
3. Detailed petrographic, geochemical, and isotopic studies of the scoria and lava units have strengthened some unit assignments and revealed new field units.
4. We reassessed the results of paleomagnetic data, which were emphasized in establishing previous stratigraphic units. The uncertainty in the secular variation curve during the time of the Lathrop Wells eruptions has been neither established nor evaluated. Additionally, sufficient data have not been presented in publications to assess the validity or the uncertainty of correlations using paleomagnetic data. Existing paleomagnetic data must be applied with caution until more complete data sets have been published and the data verified.

The Lathrop Wells volcanic center formed from predominantly Hawaiian and Strombolian pyroclastic eruptions associated with outpouring of minor volumes of lava. The Hawaiian eruptions produced spatter cones, scoria mounds and lava flows from vents along several fissure systems. The Strombolian eruptions produced a relatively large scoria cone composed predominantly of non-agglutinated scoria. Pyroclastic surge deposits are interbedded with the lava and scoria deposits. However, the vents for these hydrovolcanic eruptions cannot, in most cases, be directly identified. Erupted lava flows were unusually viscous for basalt magma. They formed blocky aa flows directly at their vents. Flow lengths are generally < 1 km and some are no longer than a few tens of meters.

Special caution must be used in interpreting the vent configurations and geometry of basaltic volcanic centers. The pulsating dynamics of eruption columns and the variability in magma effusion rates can produce conspicuous unconformities and complexities in the stratigraphic relationships of volcanic centers. These complications can develop from eruptions over periods of hours, days, months or years. For example, eruptions of the Pu Oo vent on the flank of Kilauea opened first with a fountaining eruption along a fissure, then focused to a central vent. During the first few years of eruptive activity, a symmetrical spatter cone was formed, followed in time by an asymmetrical scoria cone, shaped by the prevailing trade winds.[21]

What we have discovered, through detailed multi-disciplinary studies, is that some volcanic units at the Lathrop Wells center are separated by soil-bounded unconformities. The degree of horizon development in the soils requires time between eruptions that far exceed the cooling times of small volumes of basalt magma in the shallow crust. It is these features that lead to the inference of eruption of spatially and temporally distinct batches of magma. We refer to these eruptions as polycyclic and consider them to be a subclass of polygenetic volcanoes. Polygenetic volcanoes typically are large volume volcanoes, often associated with shallow magma chambers. By contrast, we use the term polycyclic to refer to intermittent eruptions at small volume volcanoes (< 1 km^3) that are normally classified as monogenetic.[13]

New field and stratigraphic evidence described above suggests the original five lithostratigraphic units can now be separated into at least seven lithostratigraphic units (Fig. 2). These seven lithostratigraphic units can be grouped into three chronostratigraphic units. We infer that there is time significance to these units but cannot define their temporal boundaries with satisfactory confidence based on existing chronology data. We recognize that the chronostratigraphic units may change as additional geochronology and field data are obtained. The current (December, 1991) division of chronostratigraphic units for the Lathrop Wells volcanic center are described below, from oldest to youngest.

Chronostratigraphic Unit Three: The oldest identified chronostratigraphic unit at the Lathrop Wells center consists of three lavas, with minor vent scoria, exposed at separate localities. The first lava is buried largely by eolian sand and silt on the north flank of the center (Fig. 2). It was correlated tentatively with the Ql_5 lava.[8] However, geochemical studies have not confirmed this correlation.[22] Construction of shallow trenches revealed that the buried flow rests upon pyroclastic surge deposits. The flow, in turn, is overlain by primary and reworked surge and scoria-fall deposits containing a soil with distinct horizon development. This soil has been disturbed discontinuously by extensive bioturbation. Excavation of the buried flow and overlying tephra/soil units showed that this sequence underlies outcrops of the Ql_4 lava. We thus have identified an older lava of the center that is separated from the Ql_4 lava sequence by a soil-bounded unconformity. No age determinations or paleomagnetic data have been obtained for the flow. We recently drilled and sampled this unit and are now processing the samples for paleomagnetic determinations.

The second lava unit of chronostratigraphic unit 3 consists of blocky aa lava flows and local cone scoria. This unit was mapped originally as part of Ql_5. However, detailed petrology, and geochemical studies[22] have shown that one part of the Ql_5 unit is petrographically, geochemically, and isotopically distinct. This unit has been labeled Ql_6 on the revised geologic map (Fig. 2). Unmodified exposures of the unit are exposed along a narrow band at the southwest edge of the center. Here the Ql_6 unit consists of aa lava flows and cone scoria. However, much of the original distribution of the unit has been either removed or covered by scoria excavation at the commercial quarry site. The basal contact of the Ql_6 lava is elevated above the modern pavement surface and base level. It is the only volcanic unit in the Lathrop Wells volcanic center that shows this relation. Additionally, exposure edges for this unit are not flow margins. There has been sufficient erosional stripping of the lava margin to expose the massive aa flow interior which is underlain and overlain by flow breccia and clinker. No K-Ar or paleomagnetic data have been published for this unit. We have sampled the unit for isotopic dating using the U-Th disequilibrium method. Paleomagnetic studies of this unit are in progress.

The third lava unit of chronostratigraphic unit 3 is Ql_5, a series of lavas that crop out along the southern part of the Lathrop Wells center (Fig 2). These lavas were inferred to be derived from a fissure (Qs_5) that extends northwestward, along the east base of the main cone.[8] This interpretation was based on the reported uniformity of the field magnetic directions for these units.[9] Several new observations indicate that this conclusion may be only partly correct. First, careful examination of the paleomagnetic sample sites has shown that the Ql_5 lavas were not sampled or analyzed for the paleomagnetic studies.[9] The basis for their correlation with the northwest-trending fissure cannot be confirmed. Second, petrologic studies suggest that the Ql_5 lavas are distinct compositionally from most of the northwest-trending fissure.[22] Finally, we have

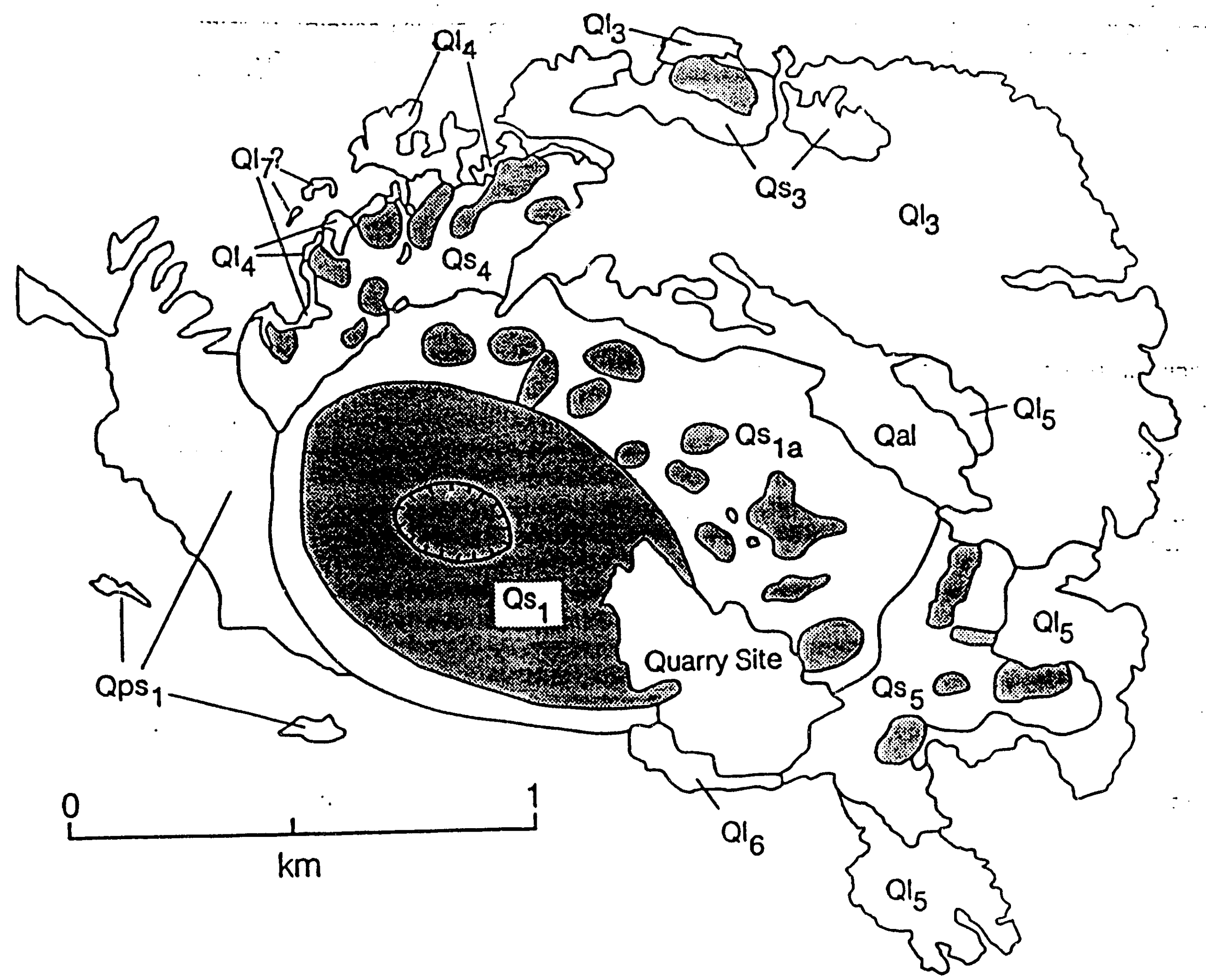

Fig. 2: Geologic map of the lithostratigraphic units of the Lathrop Wells volcanic center. Modified from Crowe et al.[8] Shaded patterns outline the scoria mounds and cones that are the primary eruptive sites of the center. Chronostratigraphic unit 3 includes aa lava flow units (Ql_7, Ql_6, Ql_5), vent spatter, agglutinate, and scoria-fall deposits (Qs_5). Chronostratigraphic unit 2 includes aa lava flow units (Ql_4, Ql_3), pyroclastic-surge deposits and vent spatter, agglutinate, and scoria-fall deposits ($Q3_4$, Qs_3 and Qs_{1a}). At least two pyroclastic surge units may be associated with this unit. Chronostratigraphic unit 1 includes cone scoria (Q_{s1}), and tephra-fall deposits derived from the scoria cone (not shown on the map). Parts of the scoria-fall sheet are included with Qs_{1a}.

tentatively reassigned the southern parts of the main northwest-trending fissure system (Qs_{1a} on Fig. 2) to a revised Qs_5 unit. This is based on an increased degree of erosional modification of the spatter and scoria mounds at the south end of the fissure, proximate to outcrop lobes of the Ql_5 lavas. There are two concerns with this assignment. First, systematic data have not been obtained on erosion patterns of degradation of vent spatter and agglutinate through time. We cannot evaluate with confidence whether the geomorphic differences are temporally significant. Second, Champion,[16] and Turrin and Champion,[9] have reported paleomagnetic data for the southern part of the fissure that match the rest of the fissure. However, the number of sites in the newly identified Qs_5 unit (Fig. 2) are insufficient to evaluate all vent zones. Further, paleomagnetic data for individual sites were not published so the correlations could not be evaluated.

Chronostratigraphic Unit Two: The second chronostratigraphic unit forms the major volume of the Lathrop Wells center. This sequence includes part of the main cone (outer parts of the scoria-fall sheet), the Ql_4 and Qs_4 lavas and scoria/fissure system, the Ql_3 and Qs_3 lava and scoria/fissure system, and most of the main northwest-trending fissure system (Qs_{1a} on Fig. 2; previously assigned to Qs_5). The following stratigraphic relations for these units have been established through field mapping and trenching studies. Pyroclastic surge deposits that appear to have been derived from the main cone (Qps_1) underlie the Ql_4 lavas. The Ql_4 lavas are overlain by the Ql_3 lavas. Tephra from the main cone overlies the Ql_4/Qs_4 and Ql_3/Qs_3 units. This last observation is based primarily on field mapping and has been verified by trenching at a few locations. Turrin et al.[15] lump the Ql_4/Qs_4 and Ql_3/Qs_3 units together based on identification of a similar field magnetic direction for these units. They separate the main northwest-trending rift zone and the main cone from the Ql_4/Qs_4 and Ql_3/Qs_3 unit on the basis of a 4.7 degree angular difference in measured field magnetic directions. This may be a valid observation and we are attempting to verify it through additional paleomagnetic studies. Existing stratigraphic and trenching data neither refutes nor collaborates their assignments. Petrographic, geochemical, and isotopic studies suggest the units could all be closely related.[22] Some chronology data described below supports an age division between the Ql_4 and Ql_3 lavas.

Chronostratigraphic Unit One: The youngest chronostratigraphic unit is not shown in Fig. 2 because it consists of small volume tephra units and it occurs largely in the area of active quarrying. This group consists of tephra units separated by soils that are exposed in quarry cliffs south of the main cone.[12,14] These tephra units are correlated with a distinctive sequence of plane-parallel bedded scoria-fall and hydrovolcanic deposits identified in the south quarry wall of the main cone. These deposits can be traced continuously in the upper quarry walls to the summit of the main cone. Because of the presence of the soil deposits beneath and between the tephras, they are separated as a distinct chronostratigraphic unit.

Discussion: One unit of the Lathrop Wells center remains problematic. A cluster of vent agglutinate and related scoria deposits forming satellitic scoria cones are exposed on the south flank of the main scoria cone. These cones have been extensively modified by commercial quarrying. They are overlain by a lithologically and geochemically distinct scoria-fall and pyroclastic surge unit that underlies the tephra beds of chronostratigraphic unit 1. These deposits may be part of the third, or second ~~chrono-stratigraphic units.~~ Champion[16] and Turrin and Champion[9] assigned this unit to what would be equivalent to our second chronostratigraphic unit based on paleomagnetic data. However, they show only one sample site[9] and did not publish the data for this site. Trace-element geochemical data shows that at least part of this sequence is unique.[22] Currently this unit is unassigned until further data are obtained.

GEOCHRONOLOGY STUDIES

A range of geochronology methods have been used to establish the age of the Lathrop Wells volcanic center. We describe the results of these studies, below, by individual method. The nomenclature used to describe the chronology methods is after Colman et al.[18] The methods used include the conventional K-Ar, $^{40}Ar/^{39}Ar$, the U-Th disequilibrium method using solid source mass spectrometry, surface exposure dating using cosmogenic ^3He, and the thermoluminescence method. Additional age determinations using the ^{36}Cl method have been reported by other workers. Cross-checking methods used to evaluate the isotopic and radiogenic data include field, geomorphic, soils and paleomagnetic studies, and major and trace element geochemistry.

Conventional K-Ar method: Potassium-argon age determinations of whole rock samples of basalt from the Lathrop Wells volcanic center have been dated by a variety of laboratories.[6,9] The most comprehensive summary of the results of the whole rock dating is by Turrin and Champion.[9] They obtained K-Ar ages of samples, some replicate, for separate sites from the Ql_5, Ql_4, Ql_3, and Qs_1 units. They reported a weighted mean of 116±13 ka for the Ql_5 unit and 133±10 ka for the Ql_3 unit (a combined Ql_3/Qs_3 and Ql_4/Qs_4 unit). The arithmetic mean is 185±190 for their Ql_3 unit and 214±86 for their Ql_5 unit; the arithmetic mean for all samples is 220±162 ka. Turrin and Champion[9] site stratigraphic constraints and U-Th ages on alluvium deposits that contain primary and reworked cinders 4 km northwest of the Lathrop Wells center. They suggest the tephra was deposited between 240±30 and 145±25 ka. This is based on an inferred correlation of tephra with Quaternary stratigraphic units dated by the U-trend method. We have examined these ash beds and note the following uncertainties with the suggested correlation. First, neither petrographic nor geochemical data have been obtained for the tephra. While the fall deposits probably were derived from the Lathrop Wells center, no correlation has been established with specific eruptive units. The most likely correlation for the tephra are with one or several of the pyroclastic surge units at the center. However, because there are multiple surge units, the stratigraphic significance of this correlation is uncertain. Second, insufficient mapping and stratigraphy studies have been completed on the alluvial units associated with the tephra to establish either the number of tephra units, or the stratigraphic relations with the alluvial deposits dated by the U-trend method.

The strengths of the conventional K-Ar data set are that this is the best tested and proven of chronology methods applied to the Lathrop Wells center. The ages are derived from a large number of age determinations. Additionally, the ages are consistent with the age obtained using the U-Th disequilibrium method (see discussion below).

The weaknesses of the conventional K-Ar age determinations are several. First, the range of measured ages for the conventional K-Ar age determinations is from 37±29 to 571±360 ka -- an unacceptably large range to attempt to use the data to resolve the chronology of volcanic units with a precision of about 10 to 100 ka. This range is also too large to explain as analytical error. Second, the age determinations are based on whole rock analysis, not mineral separates. Third, the age determinations do not show a normal distribution.[15] Thus, averages of the data set may not be meaningful. Finally, averaging of the data using a weighted mean is not valid if the sources of error are not analytical.

$^{40}Ar/^{39}Ar$ Age Determinations: Turrin and Champion[9] cite weighted means of 183±21 ka for unit Ql_3, 138±54 ka for unit Ql_5 and 149±45 ka for unit Qs_5 using the $^{40}Ar/^{39}Ar$ method. The age determinations range from 42±185 to 947±24 ka. The arithmetic mean of the Ql_3 samples is 171±87 if samples identified as contaminated are removed from the data set. However, no criteria are presented for identifying contaminated samples.[9] The authors appear to have rejected selectively, any age determinations > 400 ka.[9] If the rejected samples are included in calculations, the arithmetic mean for the sample set is 252±220 ka. The age determinations range from -20±263 to 368±644 for the combined Ql_5 and Qs_5 data set. The arithmetic mean of these samples is 150±90 ka.

Turrin et al[15] use the same data set but average (weighted mean) the conventional K-Ar data set with the $^{40}Ar/^{39}Ar$ age determinations. They obtain an age of 136±8 ka for the Ql_5/Qs_5 data set and 141±9 ka for the Ql_3/Qs_3 units. They do not list the conventional K-Ar data used in their calculations so an arithmetic mean cannot be calculated from their paper. These weighted ages are not in agreement with the weighted averages of the $^{40}Ar/^{39}Ar$ and conventional K-Ar age determinations reported in their earlier paper.[9]

The limitations of the $^{40}Ar/^{39}Ar$ data set are several. Most important, analysis of fine-grained basalt using a laser fusion method is recognized to yield anomalously old ages because of recoil effects of ^{39}Ar during neutron activation.[23] This limitation was not discussed.[15] Second, the extreme spread in the age determinations cannot readily be explained as analytical error. It may result from a systematic error term that has not been identified. Third, the $^{40}Ar/^{39}Ar$ ages of individual units are systematically older than the conventional K-Ar age determinations. Averaging of both data sets may not be appropriate. At the least, justification needs to be presented for the treatment of the data. Finally, examination of the isochron and inverse-isochron plots (Turrin et al.[15]; their figure 2), show that the slope is controlled strongly by two points that are divergent from the main data set. These points are not identified. If removed from the data set, the regression parameters and slope of the plots would be dramatically changed.

Summary of K-Ar Methods: Evaluation of the conventional K-Ar and $^{40}Ar/^{39}Ar$ age determinations for the Lathrop Wells center show the measurements are of high quality and provide one approximation of the age of the center. Controversy concerning the age of the center is with **the method of averaging the age** determinations, not the analytical methods or results. If the data sets are compiled using conventional arithmetic means, large errors (one σ) are obtained. These errors overlap with and are consistent with the results of virtually all other methods used to assess the age of the Lathrop Wells center. Moreover, the errors suggest that the K-Ar methods, as applied to the basaltic rocks of the Lathrop Wells center, may have insufficient precision to successfully resolve the chronology problems.

The use of a weighted mean leads to age assignments with small errors. These data do conflict with results of other chronology methods and soils and geomorphic studies.[12] Three questions must be asked. First, is a weighted mean a proper statistical method to use with data sets where the range in replicate analysis exceeds considerably the expected analytical errors? Second, can cross-checking data be obtained to test the validity of applying a weighted mean for replicate age determinations with poor reproducibility? Are there other explanations for the large age range of replicate analyses such as excess Ar, or contamination of the basalt with Cenozoic tuff? These questions can only be answered by further chronology studies.

Uranium-Series Dating

Magmatic processes, such as melting or crystallization, can produce radioactive disequilibrium between members of the uranium decay series.[24] Such disequilibria can be used to estimate the time since eruption for a volcanic event. To do so, however, requires that certain conditions be met. The following requirements and assumptions must be verified before any meaning should be attached to such a date:

1. **Closed System Behavior.** This is a necessary condition both for magma chamber processes as well as during and after eruption.
2. **Short Residence Time.** The residence time of minerals in the magma chamber after crystallization or in ascent to the surface must be short relative to the radioactive half-lives of interest.
3. **Measurable parent-daughter fractionation.** This condition has become somewhat easier to meet with the application of mass spectrometry to these measurements.
4. **Pure Mineral Separates.** An efficient separation of minerals and phases containing the U and Th is required in order to differentiate between a true isochron and the case of a mixing line which could result from a mixture of minerals from different sources and/or of different ages.

Samples from three flow units at Lathrop Wells have been analyzed for ^{238}U-^{230}Th disequilibrium. The pair ^{238}U-^{230}Th was selected because it is well-suited for providing chronology data over the age range of interest (< 200 ka). Initially a whole rock isochron method was attempted. This approach sometimes can be applied to a sequence of volcanic flows that are closely spaced in time and have measurable ^{238}U-^{230}Th disequilibrium and different $^{238}U/^{232}Th$ ratios.[25] However, this approach was unsuccessful at the Lathrop Well center because the whole rock samples appear to be in radioactive equilibrium (within ±0.5%). Mineral phases were then separated from a sample of the Ql_4 lavas in order to obtain an internal isochron (Fig. 3). The apparent isochron age of this sample is 150 ±40 ka. The precision of the isochron is limited by

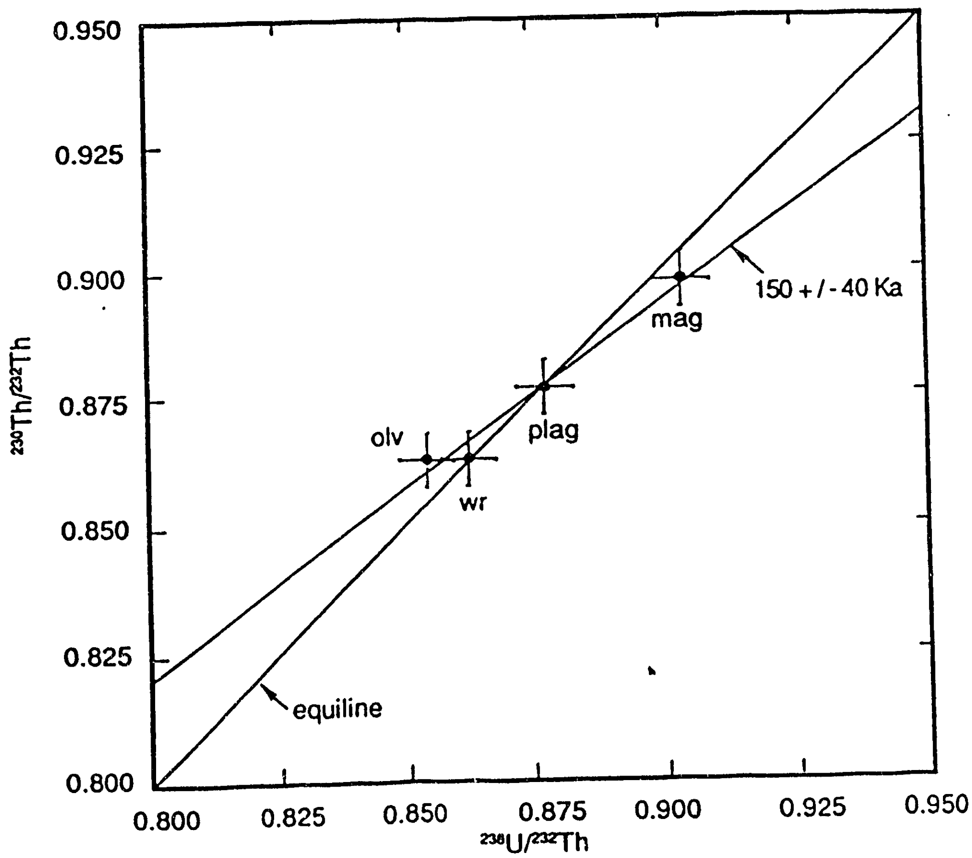

Figure 3: Plot of $^{230}Th/^{232}Th$ versus $^{238}U/^{232}Th$ for the Ql_4 lava of the Lathrop Wells center.

the small degree of Th/U fractionation observed for the separated phases (Table 1). The accuracy of the isochron for defining an eruption age is dependent on how well the criteria listed above have been met. While the extremely fine-grained size of the basalt sample argues against prolonged magma storage, it makes clean mineral separates difficult to obtain. Without pure mineral separates, there is always the possibility that the apparent isochron for the Ql_4 unit is produced by mixing of components of different age. With additional work, it should be possible to better evaluate the accuracy of the ^{238}U-^{230}Th dates by analyzing other volcanic units from the center. Samples of the Ql_6 lava are currently being processed.

The uranium-series method provides very high precision in the age range of interest. Given that the assumptions of an analysis are met, the measured age should represent the crystallization age of the lava flows. We have no reason to discount the U-Th age other than noting the small degree of Th/U fractionation of the analyzed phases and the possibility of a mixing age. Because this is a development method, we evaluate the results with caution until additional age determinations using the uranium-series method are obtained.

COSMOGENIC ^{3}HE AGE DETERMINATIONS

We have estimated the ages of lithostratigraphic units at the Lathrop Wells volcanic center by measuring the accumulation of cosmogenic ^3He in volcanic rocks exposed at the surface. The calculation of ^3He surface exposure ages follow standard techniques.[26] After field collection of samples, an olivine fraction separated from a sample is first crushed in vacuum, releasing the magmatic noble gases. These gases are analyzed by static noble gas mass spectrometry.[27] The crushed sample is then melted, releasing cosmogenic helium plus any residual magmatic helium. The concentration of cosmogenic ^3He is equal to total ^3He released in the melt step minus residual magmatic ^3He. We assume that magmatic ^3He is equal to the ^4He component released by melting, times the $^3He/^4He$ ratio released in the crushing step.

Table II lists the age estimates from the measured concentrations of cosmogenic ^3He from surface samples of the Lathrop Wells center. The data have been corrected for mass discrimination, processing blank, and sample thickness. To allow comparison of relative ages, the uncertainties in the ages only include analytical uncertainties (one σ). The production rates used in

Table I: Thorium and Uranium Concentrations for Lathrop Wells Samples

Sample/Fraction	Thorium (ppm)	Uranium (ppm)	232Th/238U
LW-89-3-21-1			
whole rock	6.89	2.11	3.38±0.01
non-magnetic	7.06	2.16	3.37±0.02
magnetic	5.50	1.71	3.33±0.01
LW-89-3-21-2 (Ql_4)			
whole rock	7.97	2.26	3.63±0.02
olivine	0.32	0.09	3.67±0.02
plag/glass	7.36	2.13	3.57±0.02
magnetite	3.45	1.03	3.47±0.02
LW-89-3-21-3			
non-magnetic	7.20	2.02	3.69±0.02
magnetic	6.50	1.84	3.65±0.02

Table II are from Cerling.[28] They are adjusted for latitude and altitude using the corrections of Lal.[29] These production rates are correlated to the ^{14}C time scales. If they are correlated to the Uranium series time scale using the data of Bard et al.[30] the ages would increase by about 17%. The production rates for the helium data used in Table II are probably accurate to ±30% or better.

The samples from Qs_1 were collected at the summit of the main cone of the Lathrop Wells. The samples were selected from a flat part (several meters wide) of the cone rim to avoid erosional loss of overlying scoria down the steep cone slopes or the crater interior. All samples collected are volcanic bombs. Selection criteria included parallelism of the direction of aerodynamic elongation of the bombs to the layering of the scoria deposits, flattening (impact-induced) of the bomb parallel to layering of the scoria deposits, preservation of a well developed rock varnish upper surface, and the presence of calcite-silica coatings on the bottom surface of bombs indicating no movement of the clast. The spread in ages of the bomb samples may indicate that they do not all share a similar surface exposure history. A particular process of concern is the eolian erosion of ash from the exposed rim of the crater. There is also the possibility of an inherited exposure history for some bombs if the Lathrop Wells center is polycyclic. This possibility is discounted, however, because of the careful selection criteria used to collect the samples. We are relatively confident all collected bombs showed evidence of aerodynamic shaping indicating aerial ejection in a molten state. The cosmogenic ^{3}He ages are minimum surface-exposure ages. Therefore the oldest age of the bomb from the summit may provide the best approximation of the minimum age of the cone (44±13 ka).

The lava samples were collected from well preserved, primary flow tops of the aa lava flows. Because there has been a history of intermittent deposition of eolian sands on the lobes of the Ql_4 lava, we attempted to collect samples from aa spines that projected above the height of active sand deposition. Eolian sands are thinner at the Ql_5 locality and were judged not to be a problem. At both lava flow localities, we collected spiny, vesicular flow material that appears to represent undisturbed clinker from the top of an aa flow. The preliminary data suggest that there may be a difference in age between the Ql_4 and Ql_5 lavas, consistent with a polycyclic interpretation of the center. However, we interpret these results cautiously until experiments are completed on the reproducibility of analysis of multiple samples from the same lava flow surface. Such an experiment is in progress.

There are two concerns with the cosmogenic ^{3}He method. First, is the surface exposure history of the dated surface. Minimum ages will be obtained if there has been erosional removal of material or previous cover of the surface. Second, the calibration of the ^{3}He surface production rates are uncertain and vary with altitude and latitude. Most of the cited helium ages in the western United States are calibrated to one locality.[28]

Zerda et al.[31] have attempted to date the volcanic units from the Lathrop Wells volcanic center using the cosmogenic ^{36}Cl method. They initially reported dates of about 75 ka for the Ql_5 unit and the main cone rim and 110 ka for a surface bomb of unknown stratigraphic position. These ages have recently been revised (downward) because of surface ^{36}Cl contamination. Their age for the Ql_5 lava now appears consistent with the ^{3}He age. However, their revised ages have not been reported in the literature. Moreover, cosmogenic production rates for the ^{36}Cl and ^{3}He methods have not been cross-calibrated.

Table II: Cosmogenic ^{3}He Ages for the Lathrop Wells Center

Sampled Unit	Sample Type	Production Rate (^{3}He/g-a)	Age (ka)
Qs_1	Bomb	288	44±5
Qs_1	Bomb	288	28±4
Qs_1	Bomb	288	23±4
Ql_4	Lava	257	48±5
Ql_5	Lava	257	64±6

THERMOLUMINESCENCE AGE DETERMINATIONS

Seven analysis of four different samples have been obtained using the thermoluminescence (TL) method (Table III). These results are judged to be analytically reliable and reproducible, but preliminary. The TL method has not been used previously in attempting to date soil units for a volcanic center. All soil samples were collected from the Av horizon. The TL age estimates were determined by the total and partial bleach methods. All samples were preheated at 100 degrees C for two days to isolate the most time sensitive TL signal and to obviate any effects of anomalous fading. These samples were tested for anomalous fading for over 60 days and exhibited no fading within 5% analytical resolution. Three samples were collected from buried soils associated with tephra deposits in the quarry wall south of the main cone. The soil samples are interbedded with basaltic fall deposits from chronostratigraphic unit one. The resulting age estimates are in their correct stratigraphic sequence. Sample F89-LA3 provides the best approximation of the age of the lower tephra deposits (9 ka; Table III). The upper two samples date the age of the upper tephra units (4 ka; Table III).

The sample from the sediment sequence was collected several tens of centimeters from the basal contact of an overlying aa flow lobe. Preliminary modeling of the temperature rise of the sample from emplacement of the overlying lava flow, shows it to be well above 300 degrees C. These temperatures are sufficient, as shown through laboratory experiments, to remove any previously acquired TL signal within 15 minutes. The indicated TL age estimate of the Ql_3 lava is 24.5±2.5 ka. We are in the process of obtaining TL ages for lava flows overlying sediments that have been dated by the ^{14}C-method for multiple localities in the Snake River Plains. These results will be used to test the reproducibility of TL ages of lava-baked sediments.

Table III: Thermoluminescence Age Estimates For the Lathrop Wells Volcanic Center

Litho-stratigraphic unit	Sample Unit	Field Number	Lab Number	TL Age (ka)
Quarry Qs_1	Buried Av Soil 1*	F89-LA3	ITL-Y1	8.9±0.7 9.9±0.7 8.7±1.0
Quarry Qs_1	Buried Av Soil 2	F89-LA4	ITL-Y6	3.7±0.4
Quarry Qs_1	Buried Av Soil 4	F89-LA6	ITY-Y4	3.7±0.4 4.5±0.4
Ql_3	Baked sed under lava	F89-LA-1	ITL-Y5	24.5±2.5

* Soil description and unit assignments from Wells et al.[12]

GEOMORPHIC STUDIES

Geomorphic studies of the Lathrop Wells volcanic center have been described previously by Wells et al.[12] They equated the geomorphic and pedogenic features of the Lathrop Wells center with a 15 to 20 ka cone in the Cima volcanic field. The close comparison of the centers suggested, by inference, that the Lathrop Wells center is no older than 20 ka. The weaknesses of this correlation are primarily twofold. First, the age relations for the Cima scoria cone are only partially constrained. Second, the correlation is dependent on the assumption of the similar operation of rates of processes of erosion and soil formation. The first weakness has been addressed by Wells et al.[32] They have obtained new cosmogenic ^3He, and thermoluminescene ages for the Black Tank center in the Cima volcanic field. These data support an age of between 9 and 14 ka for the main cone sequences at the Black Tank center. In addition, recent trenching has demonstrated that the base of the main scoria cone at Lathrop Wells is flanked by a sand ramp which displays little evidence of mass wasting or colluviation from the cone slopes. This supports the original inference of Wells et al.[12] that the cone slope is virtually unmodified by erosional processes. The second weakness is discussed in the following section on soil processes.

SOIL STUDIES

Studies of soils on volcanic landforms associated with the Lathrop Wells center show that weakly developed calcic soils have formed in scoria deposits that flank the north and south side of the main cone and on the cone slope.[12] The surfaces of the lavas flows are almost completely mantled by eolian deposits or by pyroclastic deposits. These deposits have only incipient soil development in the upper several decimeters. The primary pedogenic features exhibited by the soils include weakly developed "vesicular A" (Avk) horizons[33] and weakly developed B horizons in which fine sand, silt clay, calcium carbonate (exhibiting stage I morphology of Gile et al.)[34] and trace amounts of soluble salts have accumulated. The presence of substantial amounts of quartz and other pedogenic materials (calcium carbonate and sulfates or chloride salts) that are rare or absent in the basaltic tephra unequivocally demonstrate the eolian origin of most of these pedogenic materials.

At the Lathrop Wells volcanic center, the most strongly developed soils have been observed on the summit of a scoria mound (Qs_4) located northeast of the main cone and in the scoria-fall sheet of the main cone.* These soils have the thickest, most well developed vesicular A horizons in soils observed to date, ranging from 5 to 8 centimeters thick and possessing strong, coarse platy structure with subordinate subangular blocky to prismatic structure. The subjacent Bwk horizons are approximately 8 to 17 centimeters thick, with subangular to blocky structure. These horizons do not, however, exhibit color hues or chromas substantially redder than those of the least altered loamy sandy parent materials or the most recently accumulated materials above the vesicular A horizon. Pedogenesis in the lowest 1 meter of the profile exposed in pits is characterized by the accumulation of moderately thick to thin, largely discontinuous coatings of carbonate, gypsum and soluble salts. A small amount of pedogenic silica may also have accumulated, although this requires confirmation by chemical analysis. The content of these materials diminishes progressively with depth. Only the most incipient coatings can be observed at depths of 1.3 to 1.5 m in the parent scoria materials. A soil observed on the steeper part of the cone slope has a similarly thick, calcareous B horizon, but lacks the well developed vesicular A horizon.

Soils observed in the sequence of buried scoria units exposed in the quarry on the south side of the center,[12] are more weakly developed. They exhibit 2 to 4 cm thick vesicular horizons and very incipient, calcareous cambic B horizons. The scoria parent materials have carbonates, salts and perhaps silica accumulated primarily on the bottoms of scoria fragments. As noted above, pedogenic materials are observed to depths that exceed 1 m. Fresh scoria lacking any pedogenic materials are only present at depths of 1.5 m or more.

In contrast, soils formed in sand ramps that flank the cone are very weakly developed. Pedogenesis is indicated primarily by the slight increases in disseminated carbonate with depth and the accumulation of very thin, discontinuous coatings of carbonates and perhaps salts on the bottoms of many of the larger coarse fragments. Scoria fragments in such deposits commonly exhibit thicker and nearly continuous coatings of carbonate. However, the nonsystematic spatial location of the coatings on the fragments as a function of depth show that only a minor volume of material has been derived from higher positions on the cone slope by gravitational forces. Soils on the cone slope, as noted previously, have Bk horizons with carbonate coated fragments. They provide a source for most of the fragments with thick carbonate coatings observed in the sand ramp deposits and distal cone slope sediments and soils.

The medium-and fine-grained sandy deposits of eolian origin are inferred to bury previously formed vesicular horizons of soils in the scoria deposits. These deposits range from 2 cm to over 1.3 m thick in the sand ramps. They are present below the weakly developed scoria pavement and have little or no soil development. These soil-stratigraphic relations suggest an increase in eolian activity during the late Holocene, resulting in the deposition of locally thick accumulations of sand. Subsequent to deposition of the sand, geomorphic conditions were presumable sufficiently different to enable the development of cumulic soils. These soils incorporated much finer grained desert loess and formed accretionary cambic B and vesicular A horizons.

Soil profile development similar to the Lathrop Wells center is associated with landforms and deposits of late Pleistocene age in the Cima volcanic field.[33,35,36] Soils that possess Avk, weakly reddened Bw or weak Bt horizons and Bky horizons with stage I morphology, are associated with flows with K-Ar age determinations[37] of about 60 to 140 ka. Similarly developed soils are also present on lava flows in the Cima volcanic field, which may be as young as 15 ka.[12] Soils with these characteristics are referred to as phase I soils.[33] The most detailed studies of soils in the Cima volcanic field have focused on soils developed on the lava flow surfaces. Here, soils have formed primarily in eolian deposits that locally mantle the surface. Soil development also extends into flow rubble and commonly into fractures that penetrate the dense, interior parts of the flows. The predominant process that influences the development of these soils is cumulic. That is, eolian materials (desert loess) entrapped on the flow surface are continuously translocated below an evolving stone pavement and progressively altered by pedogenic processes. This results in the development of an increasingly thick, predominantly stone-free Av and B horizon above the flow surface/rubble.[33,36,38]

Morphologically and textually, these soils strongly resemble soils that have formed on alluvial fan and eolian deposits that post-date the highest lake shoreline observed above the playa of Silver Lake, located 15 km north of the Cima volcanic field. This shoreline, formed during the highest stand of pluvial Lake Mojave, approximately 13 to 16 ka.[39,40,41,42] The soils on the latest Pleistocene and Holocene alluvial fans and eolian deposits in this area have been the subject of several studies.[40,43,44,45,46] These studies show that these soils have also formed by processes similar to the described soils in the Cima volcanic field. Soils on deposits in the Silver Lake area that are considerably older than the latest Pleistocene fan deposits are associated with strongly developed desert pavements and have reddened, relatively thick clayey Bt horizons and strongly developed calcic with stage II morphology. These soils resemble phase 2 soils that occur on older Pleistocene flows in the Cima volcanic field which also have strongly developed desert pavements and thick, reddened Bt horizons. Most importantly, the age constraints for latest Pleistocene and Holocene deposits and soils in the Silver Lake area enable calibration of rates of soil-forming processes during the latest Pleistocene and Holocene in the arid regions o he Mojave Desert. This in turn provides a basis for estimation of ages of soils in this region, where no other age information is available.

Soils formed in scoria deposits or in aprons that flank flows at the Cima volcanic field have also been examined.[36,47,48] These soils are generally similar to soils on the flow surface. However, the soils formed in scoria deposits associated with the youngest scoria cones in the Cima volcanic field possess relatively weak development of Avk horizons. They do not have B horizons that are as red or thick as those typically observed in the phase 1 soils on associated lavas. This indicates that much of the eolian material entrapped on surfaces associated with scoria is readily translocated through the highly permeable, open framework scoria to depths of more than a meter by infiltrating soil water. In the lower part of the soil profiles, the initially fragile, glass-coated irregularities and edges of scoria fragments are altered by infiltrating water, as shown by the presence of reddish, brown coatings on the tops of the fragments, the destruction of vesicle edges and spines, and the chemical alteration of glass. Pedogenic accumulation of calcium carbonate, salts and perhaps some amorphous silica primarily on the bottoms of the fragments is a major attribute of these soils. Soil development in cone aprons resembles that observed on flows. Equally, soil development on scoria-cone aprons of older cones is closely similar to observed phase 2 soils, demonstrating the primary role of cumulic pedogenesis on this volcanic landform.

Soils on flows and volcanic aprons associated with the Red and Black cones at Crater Flat exhibit the morphologic and textural features of phase 2 soils in the Cima volcanic field.[12] Soils on volcanic units of the Lathrop Wells center are similar to phase 1 soils of the Cima volcanic field. These consistencies suggest that similar soil-forming factors influence pedogenesis in these areas. Similar landforms, closely analogous climate and similar biota have been conducive to the operation of similar pedogenic processes which formed morphologically and textually similar profiles. These generalizations are probably especially applicable for latest Pleistocene and Holocene soils of much of the Great Basin and other parts of the arid southwestern United States. This is controlled primarily by the overwhelming influence of accelerated eolian activity coupled with aridification on pedogenesis that has characterized the geologic record over the last 15 ka.[33,36,38,40,45,46,49-56]

We do not currently propose that pedogenic processes at the Lathrop Wells center are identical to those at the Cima volcanic field. However, there are no indications that the rates or processes of soil formation are substantially different. If eolian influx rates have been higher at the Lathrop Wells center, thick deposits of desert loess would mantle stable Pleistocene and Holocene landforms and soils throughout the area. This has not been observed. Equally, eolian activity in the Yucca Mountain region cannot be substantially lower than the Cima volcanic field because of the presence in the former, of active sand dunes on flows and the nearby Armagosa dune field. Abundant sources of eolian materials, including desert loess are provided by the numerous basins, many of which contain large playas. Accordingly, we conclude that the weakly developed soils of the Lathrop Wells center closely resemble the Holocene soils in the Silver Lake area and the Cima volcanic field. We infer that the soils must have formed over a similar time span. We conclude that the Lathrop Wells soils have formed largely during the late Pleistocene and Holocene. They probably cannot be older than 20 ka and almost certainly cannot be older than 50 ka.

PALEOMAGNETIC STUDIES

Considerable paleomagnetic data have been obtained for the Lathrop Wells volcanic center in order to discriminate among different eruptive events, Turrin et al.[15] report that the paleomagnetic data from the eruptive units fall into two statistically distinguishable populations, correlated to their revised definition of units Qs_5 and Ql_3. They use the angular difference between the means of the two populations to infer an age difference between the two events of no more than 100 years. At some localities in the western United States and Hawaii, a sufficient amount of paleomagnetic data from recent, radiocarbon dated lavas suggests that the average rate of directional secular variation of the geomagnetic field is on the order of 4 to 6 degrees per century.[57] Use of the angular distance between the estimated mean directions of two populations of magnetization data to constrain the amount of time separating the eruptive events, is not well founded. The angular difference between two paleomagnetic data sets can at best constrain the minimum age difference between the rocks sampled, not the absolute difference, as only two, totally independent records of the field have been obtained.

Additional paleomagnetic data are presently being obtained from three volcanic flows at Lathrop Wells (Ql_6, four sites, LW1-4; Ql_5, four sites, LW5-8, and Ql_7, two sites, LW9-10). Directions of natural remanent magnetization (NRM) have been measured for all samples from the 10 sites. In addition, anisotropy of magnetic susceptibility measurements have been obtained for all samples prior to progressive demagnetization of the NRM. Either alternating field or thermal demagnetization will be carried out on all samples to determine the direction and relative intensity of all components of the magnetization comprising the NRM. Dispersion of NRM directions varies considerably from site to site. Some of the sites are contaminated to some extent by a lightning induced isothermal remanent magnetization (IRM) which typically leads to considerable dispersion of the NRM. Detailed progressive alternating field demagnetization is necessary to adequately remove the IRM component and resolve the direction of the pre-existing, well-grouped thermoremanent magnetization (TRM). Those sites in Ql_6 and Ql_5 that give well-grouped NRM directions have directions that do not differ significantly from those reported by Turrin et al.[15] Although sites LW9 and LW 10, in the buried lava, give NRM directions which also are similar to those reported by Turrin et al.,[15] these results cannot be interpreted to indicate that the flow is essentially identical in age to, for example, Ql_5. Rigorous statistical comparison of results obtained in the present study and those reported by Turrin et al.[16] will follow when directions of TRM are carefully determined through progressive demagnetization.

SUMMARY

Field studies of the Lathrop Wells volcanic center are in progress. Revisions of the lithostratigraphic units have been greatly enhanced by systematic trenching, which is in the initial phases. Current data provide compelling evidence (soil-bounded unconformities) that the volcanic center is polycyclic. Eruptive deposits are divided into three soil-bounded chronostratigraphic units. The chronology of these units has not been established firmly. The results of conventional K-Ar and $^{40}Ar/^{39}Ar$ studies appear to have insufficient precision to constrain the age of the chronostratigraphic units. The results of U-Th series, cosmogenic ^3He and thermoluminescence age determinations are somewhat inconsistent. Individual methods give ages that vary from older (> 100 ka; U-Th) to intermediate (25 to 65 ka; ^3He) to younger (5 to 25 ka; thermoluminescence). These methods are development and we are using new applications of the methods. Therefore it is not surprising that data are inconsistent at an early stage of research. Resolution of the chronology data will require more data at the Lathrop Wells center. Additionally, it may be prudent to test the chronology methods at other localities in the western United States where there are independent controls on the age of volcanic units. Data from geomorphic and soils studies, supplemented by trenching, continue to support a late Pleistocene or Holocene age assignment for the volcanic center. The uncertainties and assumptions of paleomagnetic studies are just now being examined. More data are required to assess the significance of using the method to establish stratigraphic and chronology constraints.

ACKNOWLEDGMENTS

We have welcomed the opportunity to develop and test stratigraphic and chronology models of the Lathrop Wells volcanic center through systematic trenching of lithostratigraphic units. Initial progress has been gratifying. We have progressed in model testing and are increasingly confident that the stratigraphic problems and even some of the chronology issues show hope of resolution, or at least reduction. We are indebted to Al Pratt, Los Alamos National Laboratory. Without his determination, we would still be awaiting possession of our now field tested, truck-mounted backhoe. We acknowledge the useful and timely review comments of Chris Fridrich, Department of Energy. The work was supported by the Yucca Mountain Site Characterization Project Office as part of the Civilian Radioactive Waste Management Project. This Project is managed by the U.S. Department of Energy.

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6/23/93