CONF-940553--104

PRELIMINARY U-SERIES DISEQUILIBRIUM AND THERMOLUMINESCENCE AGES OF SURFICIAL DEPOSITS AND PALEOSOLS ASSOCIATED WITH QUATERNARY FAULTS, EASTERN YUCCA MOUNTAIN

J.B. Paces[1], C.M. Menges[1], B. Widmann[2], J.R. Wesling[3], C.A. Bush[1], K. Futa[1], H.T. Millard[1], P.B. Maat[1], J.W. Whitney[1]

[1]U.S. Geological Survey, Denver, CO
[2] Science Applications International, Corp., Golden, CO
[3]Geomatrix Consultants, Inc., San Francisco, CA

ABSTRACT

Geochronological control is an essential component of paleoseismic evaluation of faults in the Yucca Mountain region. New U-series disequilibrium and thermoluminescence age estimates for pedogenic deposits that bracket surface-rupture events are presented from four sites exposing the Paintbrush Canyon, Bow Ridge and Stagecoach Road faults. Ages show an internal consistency with stratigraphic relationships as well as an overall concordancy between the two independent geochronometers. Age estimates are therefore interpreted to date depositional events or episodes of pedogenic carbonate mobility that can be used to establish a paleoseismic fault chronology. Ultimately, this type of chronological information will be used to evaluate seismic hazards at Yucca Mountain.

INTRODUCTION

The likelihood and consequences of surface faulting and related seismicity near Yucca Mountain represent important issues of site suitability for long-term isolation of radioactive waste. A risk evaluation effort currently in progress is focused on the assessment of seismic hazards related to fault rupture and ground motions associated with earthquakes in the immediate vicinity of the potential repository. In addition, repeated tectonic fracturing may allow increased infiltration through the unsaturated zone via "fast" hydrologic pathways. Determination of the record of Quaternary fault displacements in the recent geologic past provides a means of estimating the probability that similar events might recur during the functional life span of the potential repository.

As part of the ongoing paleoseismic study, we report new ages obtained by both U-series disequilibrium and thermoluminescence (**TL**) dating techniques for surficial deposits and associated pedogenic materials from trenches and natural exposures associated with Quaternary faults along the east side of Yucca Mountain. Depositional units and associated soils are increasingly offset with depth at these sites documenting successive faulting events. Ages determined on these materials should provide numerical constraints for recurrence intervals and slip rates along faults that have been active throughout the late Quaternary. This paper focuses on geochronological data from sites which have been examined and logged by others.[1,2] Inherent limitations in some of the materials sampled preclude precise age resolution of depositional or soil-forming events. However, the two dating techniques used in this study do show an internal consistency with stratigraphic relationships, as well as an overall concordancy between ages determined by the two independent systems. Therefore, age estimates approximate depositional or pedogenic events which can be used to establish a paleoseismic chronology. This chronology is used to develop tectonic models for each of the faults in greater detail in a companion paper presented elsewhere in this volume.[1] Interpretation of best-age estimates for materials reported in this paper are considered preliminary, and may need to be revised somewhat in the future, pending collection of additional data.

Correspondence to: James B. Paces, U.S. Geological Survey, Mailstop 963, Box 25046, Denver Federal Center, Denver, CO 80225. (303)236-0533; FAX (303)236-4930.

DESCRIPTION OF WORK

Geological and structural mapping at four sites (Figure 1) along the Paintbrush Canyon, Stagecoach Road and Bow Ridge faults documents evidence for multiple (four to eight) Quaternary surface-rupturing events associated with normal to oblique-normal faulting.[1,2,3,4,5] We are investigating the timing of these events by dating displaced sediments and paleosols using a combination of two different geochronological systems. This approach allows a greater variety of fault-related materials to be dated and allows the reliability of dates to be assessed.

U-series disequilibrium utilizes natural radioactive decay of U and Th in authigenic carbonate cements associated with soil development following deposition. The fact that carbonate precipitation must post-date sedimentation, as well as the possibility of continued modification of early-formed carbonate by U leaching or by addition of a younger authigenic component, requires that U-series dates be considered minimum ages for the host lithologic unit. In some cases, sedimentation and carbonate precipitation events may not be separated significantly in time, however in other instances, tens of thousands of years may intervene.

Thermoluminescence dating utilizes the accumulation of luminescent properties within silt-sized minerals over time through the interactions of ionizing ratiation with the crystal latice. The technique assumes that the TL signal is reset by exposure to sunlight during transport to the depositional site. As such, a TL date provides an estimate of the time at which a silt-bearing unit, such as a scarp-related colluvial wedge or eolian layer, was buried. TL dating is particularly well-suited for younger deposits which lack sufficiently-developed pedogenic carbonate for U-series dating, although it may be applied to older deposits as well.

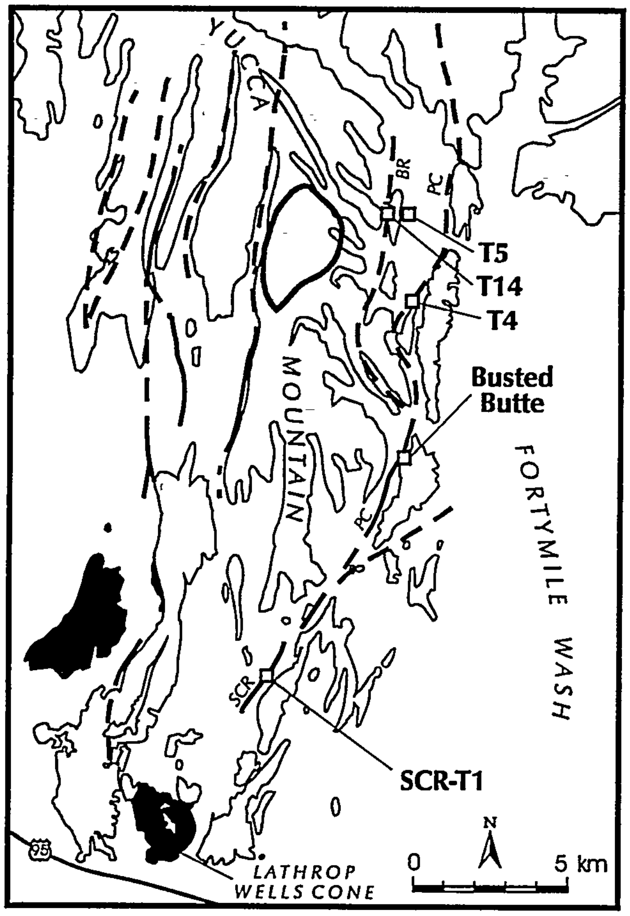

Figure 1: Geologic sketch map showing locations of sample sites. Light stippled area are felsic tuffs; dark stippled areas are basaltic rocks; unpatterned areas are Quaternary sedimentary deposits. T5, T14, and T4 = Midway Valley Trenches 5A, 14D, and 4, respectively; SCR-T1 = Stagecoach Road Trench 1. Faults with Quaternary movement are shown by solid and dashed bold lines (BR = Bow Ridge; PC = Paintbrush Canyon; SCR = Stagecoach Road). The perimeter drift of the potential repository is shown in outline.

ANALYTICAL TECHNIQUES

U-series disequilibrium dating

U-series disequilibrium geochronometers used in this study are based on the radioactive decay of the long-lived parent isotope, ^{238}U (half life of 4.46×10^9 years), through a series of short-lived daughter products including ^{234}U and ^{230}Th (half lives of 2.45×10^5 and 7.54×10^4 years, respectively). Because of the difference in half lives, the relative abundance of short-lived daughter isotopes will reach a state of secular equilibrium with the long-lived parent isotope (activity of $^{238}U = {}^{234}U = {}^{230}Th$) after which their rates of production become dependent only upon the rate of decay of the long-lived parent. The degree to which the daughter isotopes are in disequilibrium with the parent is a function of time, and provides the two clocks utilized below. The $^{230}Th/U$ geochronometer is based on the assumption that, initially, ^{230}Th is absent from carbonate cements, but gradually grows into secular equilibruim with time (maximum range of about 350 k.y.). The $^{234}U/^{238}U$ geochronometer is based on the presence of an initial excess of ^{234}U in most hydrogenic carbonate which decays more rapidly than ^{238}U until secular equilibruim $^{234}U/^{238}U$ values are re-established (maximum range of about 1 to 2 m.y. depending on initial $^{234}U/^{238}U$). The disadvantage of this latter clock is that an initial $^{234}U/^{238}U$ activity ratio must be assumed.

Unlike Th, which does not form water-soluble species under most natural conditions, U is oxidized to its hexavalent state in many near-surface environments and is readily transported in solution. Natural waters typically have an excess of ^{234}U relative to ^{238}U resulting in $^{234}U/^{238}U$ activity ratios greater than unity.[6] The elevated $^{234}U/^{238}U$ isotopic composition of a water is then imparted to calcite precipitated from solution. In deposits dominated by chemical precipitation, most ^{230}Th is produced by in situ decay of ^{234}U. However, in the pedogenic environment, detrital ^{230}Th constitutes a significant component and must be subtracted from the ^{230}Th derived from the authigenic carbonate. We use a series of leach, residue, and whole rock analyses from different size fractions of the same sample to produce mixing-lines which can be projected back to the detrital-Th-free component.[7,8,9,10,11,12,13] Evidence of the success of this technique is demonstrated, at least in part, by the fact that none of the detrital-Th-free components determined on samples in this study exhibited an excess of ^{230}Th

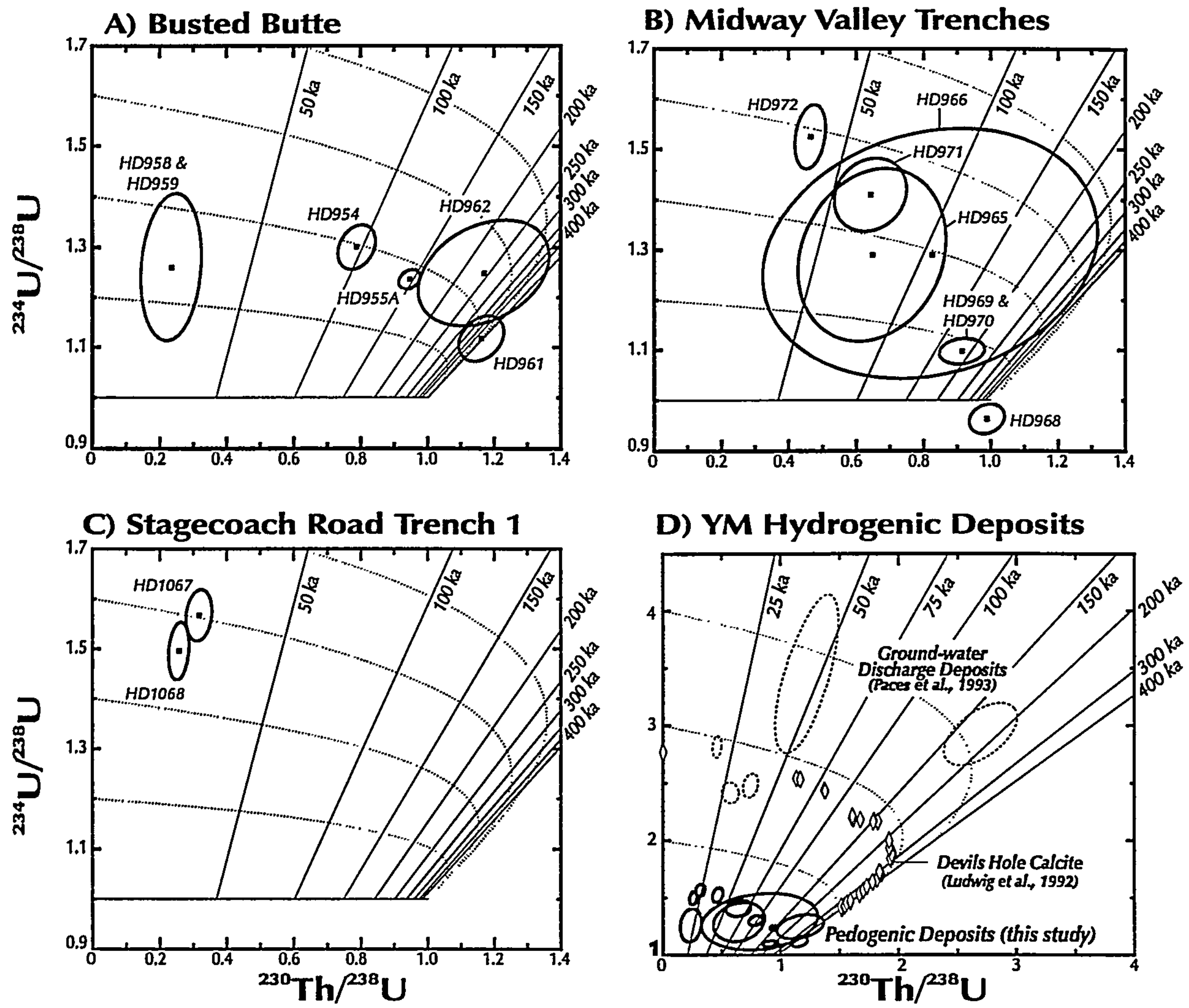

Figure 2: Results of uranium and thorium isotopic analysis of pedogenic carbonates. Dashed lines represent evolution paths for different initial 234U/238U ratios; straight lines labed with ages represent isochrons. Solid points and associated 95% confidence error elipses represent the projection of the 232Th-free mixing component ("pure" authigenic carbonate) onto the 234U/238U-230Th/238U plane. See text for further explanation of detrital Th corrections.

relative to ^{234}U or ^{238}U (that is, all ^{230}Th could be accounted for by the *in situ* decay of ^{238}U).

Samples used for U-series disequilibrium dating were collected from soils containing prominent laminar or massive carbonate (Stage III or greater)[14] or from calcite-replaced rhizoliths. Detrital material is physically removed, where possible, followed by gentle crushing and sieving to concentrate carbonate preferentially in the finer fractions. After heating at 900°C to remove organics and CO_2, samples are either leached in dilute (0.2 M) nitric acid to produce acid-soluble leach and insoluble residue pairs or totally digested in a combination of inorganic acids. After addition and equilibration of a mixed ^{236}U-^{229}Th tracer solution, chemical separations are performed following standard anion exchange procedures.[15] Purified U and Th are plated onto stainless steel disks for counting by alpha spectrometry for a minimum of 20,000 minutes (or 10,000 counts) on at least two different detectors. $^{234}U/^{238}U$ and $^{230}Th/^{238}U$ isotopic compositions of the ^{232}Th-free authigenic component (Figure 2) are obtained by simultaneous regression of $^{230}Th/^{238}U$, $^{234}U/^{238}U$, and $^{232}Th/^{238}U$ ratios from multiple aliquots of a single sample (or closely related samples) using maximum likelihood estimation techniques.[13,16] All uncertainties and error correlations are based on counting statistics and spike calibration uncertainties and are quoted at the 95% confidence level.

Thermoluminescence dating

Thermoluminescence dating is based on the property of some minerals (mostly feldspar and quartz) to accumulate trapped electrons in negative-ion vacancies within their

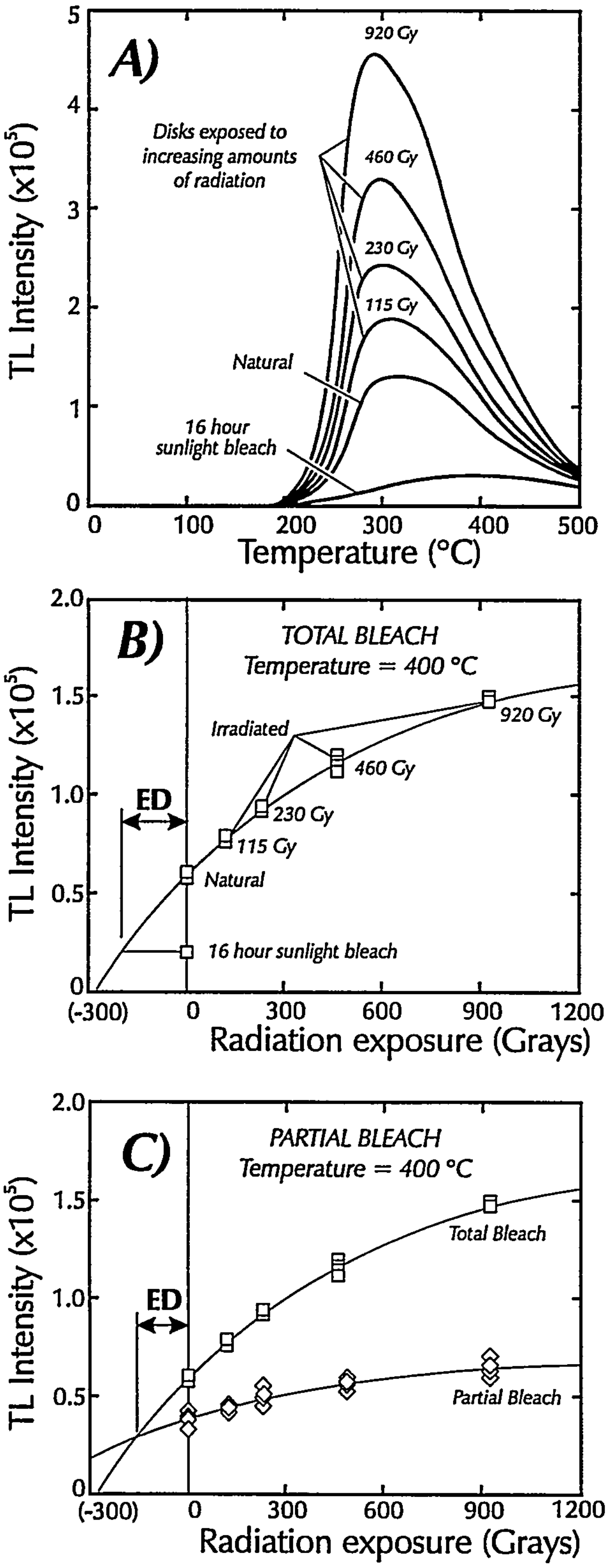

Figure 3: Example of TL data and techniques used to determine equivalent dose (ED). See text for further explanation. A) TL glow curves for irradiated, bleached, and natural disks from a single sample. B) TL growth curve at a single temperature showing determination of total bleach ED. C) Same sample showing partial bleach ED.

crystal lattices due to ionizing radiation.[17] Radiation sources include K, U and Th in the geologic material surrounding a mineral grain, as well as cosmic rays in the near-surface environment. Sufficient exposure of a mineral grain to heat or light increases lattice vibration, liberating the electrons trapped in defects, and resetting the TL signal to zero. Most temperatures in the near-surface environment are insufficient to affect the TL signal, however, exposure to sunlight for as little as 8 hours can reset the TL signal in fine-grained sediment.[18,19] Laboratory heating at 300 to 500 °C releases electrons from lattice traps in the form of light which can be measured by sensitive photomultipliers. The amount of light emitted (TL intensity) is proportional to the number of electrons released which, in turn, is a function of the cumulative amount of radiation that the sample has experienced. Therefore, the TL intensity of a sediment sample can be related to the age of most-recent burial if the radiation dose rate is also determined.

Materials collected for TL dating include eolian deposits (primary or reworked), pedogenic A horizons and distal portions of fault-related colluvial wedges. These materials generally contain an abundance of silt-sized material, are typically homogeneous, and have a high probability of being sufficiently bleached by sunlight prior to burial. Sampling and laboratory procedures are described elsewhere in more detail.[20] Samples are collected to avoid exposure to sunlight, and dose rates are measured in the field with a portable NaI gamma detector. Samples are processed in a dark room to remove organic material and carbonate cements and to separate out the four- to eleven-micron silt fraction. The silt slurry is plated onto aluminum disks (approximately 50) which are used in both total-bleach (TB) and partial-bleach (PB) experiments to estimate the equivalent dose (ED = the amount of radiation equivalent to the cumulative natural dose acquired by the sample after burial). For both experiments, disks are exposed to different radiation levels producing an array of artificially-enhanced TL signals (e.g., curves labeled 115, 230, 460 and 920 Gy in Figure 3A). Total-bleach experiments use a set of these disks plus a set of disks that were sunlight-bleached for 16 hours, and a set of "natural" disks that remained unmodified by bleaching or irradiation. Partial Bleach experiments use the remaining irradiated disks plus a set of "natural" disks, all of which are bleached in sunlight for one hour. Glow-curves (TL intensity versus temperature) are then measured for each disk the temperature is increased from 200 to 500 degrees centigrade (Figure 3A). Sections through the glow-curves at constant temperature define relationships between radiation exposure and TL signal accumulation. These relationships are used to estimate the equivalent dose (ED) for each heating step based on the radiation defined by a projection of the TL growth curve back to its initial value (defined by the 16 hour sunlight bleach) in the TB experiment (Figure 3B), and on the radiation defined by the intersection of

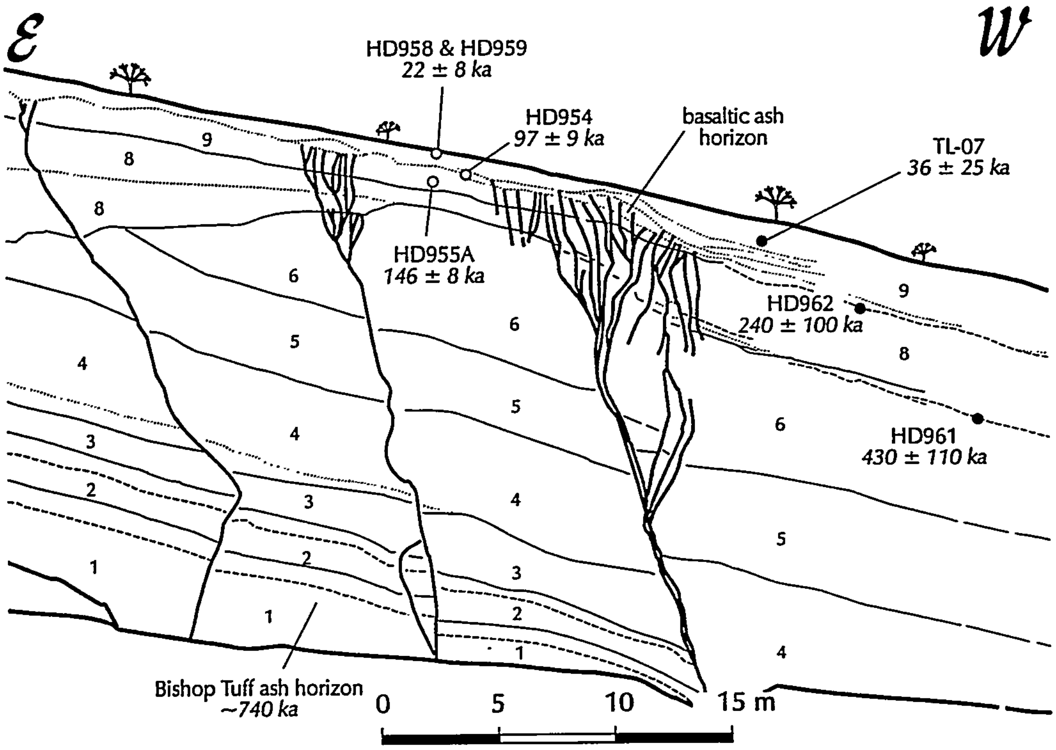

Figure 4: Simplified log of wall #4, Busted Butte sand ramp (after Menges et al., this volume)[1] showing location and resulting age estimates for U-series and TL samples (Tables 1 and 2, respectively). Light solid lines represent major lithologic boundaries (numbered sequentially); dotted lines represent depositional unit boundaries within major units; dashed lines represent soil unit boundaries. Bold lines represent faults or fractures. Ash horizons are discussed in text. Samples with open symbols are from wall #1 and are shown correlated with similar units in similar positions on wall #4.

projections of the TB and PB growth curves in the PB experiment (Figure 3C). The best estimate for the overall ED is then obtained by averaging the most stable individual ED values, typically between 340 and 420°C. Ages are then calculated by dividing the overall equivalent dose (ED in radiation units) by the measured dose rate (DR in radiation units per unit time). Uncertainties estimated for both experiments are quoted at the 95% confidence level and are typically greater for the PB experiment due to the shallower angle of intersection of the two curves. In samples where both experiments have been successfully completed, the best estimate of the age is given as an average of both TB and PB ages weighted by their respective uncertainties.

RESULTS

Paintbrush Canyon Fault: Busted Butte

The Paintbrush Canyon Fault is exposed in natural gullies incising sand ramps on the west side of Busted Butte. Two exposures (walls 1 and 4) have been cleaned and mapped.[1] The fault offsets a series of soils and stone lines recording some 700 k.y. of Pleistocene depositional, erosional and soil forming history (Figure 4). The lower age constraint is provided by the inferred presence of ash from the eruption of the Bishop Tuff (740 ka)[21] which occurs at the base of sand-ramp deposits at the south end of Busted Butte. This ash, although not yet identified in the mapped walls, is correlated with a stratigraphic position below the lowermost buried soil exposed at the base of wall 4 (unit 1, Figure 4).

In the upper portions of wall 4, two prominent buried laminar K soils (Stage III to IV) are preserved on the down-thrown block (near the tops of units 6 and 8 in Figure 4), but have been largely eroded on the up-thrown block. The lower of the two soils (HD961) yields a complex pattern of U-Th isotopic compositions. A leach-residue pair of the finest fraction yields a late Pleistocene two-point isochron age which is inconsistent with stratigraphic, geologic, structural data. In contrast, three whole rock analyses yield a $^{230}Th/U$ age of 590 ± 950 ka. Although scatter for the three-point isochron is low (M.S.W.D.[a] = 1.4), the large uncertainty reflects the fact that the sample is close to $^{230}Th/^{238}U$ secular equilibrium. However, it still exhibits a $^{234}U/^{238}U$ disequilibrium value of 1.117. This ratio results

[a]M.S.W.D. = Mean Square of Weighted Deviates representing a measure of the observed scatter for the points being regressed, divided by the scatter predicted by the assigned analytical errors. Values much greater than 2.5 typically indicate the presence of non-analytical scatter.[16]

Table 1: Best estimates for U-series disequilibrium ages of pedogenic carbonates. Each age estimate represents multiple aliquots that have been regressed to obtain ^{232}Th-free authigenic calcite compositions using maximum-likelihood techniques.[13,16] All errors are quoted at the 95% confidence limit.

Sample	# of Aliquots	$^{234}U/^{238}U$ activity ratio	$^{230}Th/^{238}U$ activity ratio	$^{230}Th/^{238}U$-$^{234}U/^{238}U$ error correlation	M.S.W.D.	$^{230}Th/^{238}U$ Age (ka)	Initial $^{234}U/^{238}U$
Busted Butte Sand Ramps, Walls #1 and #4: Paintbrush Canyon Fault							
HD958 & HD959	3	1.26 ± 0.12	0.234 ± 0.074	0.162	10.2	22 ± 8	1.28 ± 0.13
HD954	5	1.300 ± 0.036	0.788 ± 0.046	0.286	3.13	97 ± 9	1.40 ± 0.05
HD955A	5	1.236 ± 0.016	0.946 ± 0.026	0.298	1.13	146 ± 8	1.36 ± 0.02
HD962	4	1.248 ± 0.085	1.17 ± 0.16	0.317	6.08	240 ± 100	1.5 ± 0.3
HD961	3	1.117 ± 0.035	1.161 ± 0.059	0.332	1.41	430 ± 110✧	1.4✧
Midway Valley Trench 14D: Bow Ridge Fault							
HD971	4	1.409 ± 0.059	0.643 ± 0.088	0.162	2.7	64 ± 12	1.49 ± 0.07
HD969 & HD970	6	1.097 ± 0.021	0.914 ± 0.055	0.161	0.548	185 ± 28	1.16 ± 0.04
HD968	5	*0.963 ± 0.024	*0.988 ± 0.043			**>1000	
Midway Valley Trench 14C: Bow Ridge Fault							
HD965	3	1.29 ± 0.14	0.649 ± 0.19	0.159	2.27	74 ± 30	1.35 ± 0.17
HD966	5	1.29 ± 0.20	0.826 ± 0.41	0.174	12.6	105 ± 84	1.4 ± 0.3
Midway Valley Trench 5A							
HD972	2	1.524 ± 0.052	0.464 ± 0.037	0.259	n/a	39 ± 4	1.58 ± 0.06
Stagecoach Road Trench 1: Stagecoach Road Fault							
HD1068	5	1.496 ± 0.047	0.256 ± 0.025	0.207	7.27	20.2 ± 2.1	1.53 ± 0.05
HD1067	4	1.567 ± 0.042	0.317 ± 0.032	0.169	3.36	24.3 ± 2.7	1.61 ± 0.04

✧Age estimate based on the $^{234}U/^{238}U$ composition and an assumed initial U isotopic compositions of 1.4 (see text).
*Weighted average of individual aliquots. Not regressed to ^{232}Th-free component.
**Age estimate is based on $^{234}U/^{238}U$ compositions and an assumed initial U isotopic composition of 1.1 to 1.6.

in a $^{234}U/^{238}U$ age of 430 ± 110 ka (Table 1) if the sample had an initial activity ratio of 1.4; a value similar to other Busted Butte samples (in particular, HD954 and HD955A; Figure 2A). Ages of 330 to 580 ka for HD961 are obtained if the whole range (1.3 to 1.6, respectively) of observed Busted Butte initial $^{234}U/^{238}U$ activity ratios are used. The stratigraphic position of this soil relative to the Bishop Tuff ash horizon, lends support to the 430 ka estimate.

Four aliquots from a sample (HD962) of the overlying soil (Figure 4, unit 8) yield an age of 240 ± 100 ka (Table 1). The large uncertainty associated with this age estimate is the result of the small number of data points used in the regression, along with the presence of scatter not attributable to analytical errors (M.S.W.D. = 6.1). The latter result implies that the assumptions of either closed-system evolution of U-series isotopes or of an ideal two component mixture of homogeneous authigenic and detrital end members are not satisfied. The cause of the scatter is not known and could be the result of a variety of reasons including laboratory fractionation of U and Th, or mixing soil carbonates of several different generations. Additional analyses are currently in progress and should address this problem. Regardless, this age estimate is consistent with the stratigraphic position of the soil horizon near the top of the wall, and if approximately correct, suggests that most of the material in the sand ramp acculated prior to about 250 ka.

Three samples from wall 1 have been dated by U-series and are correlated to soils preserved in wall 4. A soil containing small, carbonate-replaced rhizoliths is developed in a distinct colluvial wedge adjacent to the fault trace at the top of the up-thrown block below the crest of the uppermost fault scarp. Both the wedge and associated rhizolith zone have been displaced across the main fault and related antithetic graben by at least two to three faulting events. Five aliquots of this sample (HD955A) yield an age of 146 ± 8 ka. This rhizolith-rich soil is correlated with a very similar soil that formed in a similar position on the up-thrown block of wall 4 below the uppermost fault scarp (base of unit 9 in Figure 4). On both walls this rhizolith-bearing unit is capped by a thin, laminar K soil, which, on wall 1, yields a U-series age estimate of 97 ± 9 ka. This laminar zone drapes into the fault plane and appears to be affected by only the most recent, small-displacement rupture. Directly overlying this laminar carbonate on both walls is a horizon containing reworked basaltic ash from one of the Lathrop Wells eruptions.[1] Ages for the two most widely-distributed eruptive events have been estimated at between 85 and 130 ka,[22] although recent TL and Ar/Ar age estimates indicate that the younger event (eruption number 2) may be as young as latest Pleistocene.[23] Attempts are currently underway to geochemically correlate the ashy deposits with specific tephra eruptions as well as to better constrain eruptive ages.

Table 2: Results of thermoluminescence analyses. All errors quoted at the 95% confidence level.

Location: MWV-T5a, -T4, -T14d = Midway Valley Trenches 5a, 4 and 14d; SCR-T1 = Stagecoach Road Trench 1; BBW4 = Busted Butte wall 4.

Experiment Type: TB = total bleach; PB = partial bleach.

K, U, Th: Elemental concentrations determined by portable gamma spectrometer.

CR: Cosmic ray dose rate corrected for elevation and depth in soil.

DR: Dose rate calculated from *in situ* radioactive decay and cosmic ray flux. Assumes an alpha radiation efficiency value of 0.10 ± 0.03 relative to beta and gamma. No correction for soil moisture has been applied.

ED: Equivalent dose estimate. n.a. indicates that data are not available for some of the partial bleach experiments.

TL Age: Ages based on equivalent dose and dose rate estimates.

Best Estimate Age: Weighted average of total bleach and partial bleach TL ages where both are available.

Sample	Location	Experiment Type	K (wt. %)	U (ppm)	Th (ppm)	CR (Gy/ka)	DR (Gy/ka)	ED (Gy)	TL Age (ka)	Best Estimate Age (ka)
TL-07	BBW4	TB	3.03	4.3	15.65	0.21	8.2±1.1	299 ± 205	36 ± 25	36 ± 25
		PB						n.a.	n.a.	
TL-03	MWV-T4	TB	3.04	3.94	14.89	0.21	7.94±1.05	598 ± 212	75 ± 28	75 ± 26
		PB						590 ± 500	74 ± 64	
TL-04	MWV-T4	TB	3.03	3.77	13.82	0.22	7.67±0.95	292 ± 51	38 ± 8	38 ± 8
		PB						250± 420	33 ± 55	
TL-05	MWV-T4	TB	3.04	3.94	14.89	0.21	7.94±0.99	48 ± 21	6.0 ± 2.7	6.0 ± 2.7
		PB						n.a.	n.a.	
TL-09	MWV-T14d	TB	2.72	5.07	15.32	0.17	8.2±1.2	1883 ± 811	230 ± 100	230 ± 100
		PB						n.a.	n.a.	
TL-06	MWV-T14d	TB	2.41	3.45	14.91	0.32	7.09±0.98	460 ± 280	65 ± 40	66 ± 34
		PB						500 ± 511	70 ± 73	
TL-02	SCR-T1	TB	3.17	4.91	16.69	0.27	8.9±1.2	96 ± 130	11 ± 15	12 ±11
		PB						115 ± 160	13 ± 18	
TL-01	MWV-T5a	TB	3.25	5.12	19.27	0.22	9.5±1.3	241 ± 76	25 ± 9	25.7 ± 8
		PB						261 ± 192	27 ± 21	

A TL date of 36 ± 25 ka was obtained for an orangish-brown oxidized sand layer overlying the ash-bearing unit and subjacent fault scarp at the top of wall 4 (sample TL-07, Table 2). Since this unit is not fractured, it provides a minimum age for the most-recent surface-rupturing event. Stage II soil carbonate (HD959) and small pedogenic ooids (HD958) in the uppermost carbonate soil on wall 1, when combined in the same regression, reflect a similarly youthful age of 22 ± 8 ka (Table 1) for the most recent episode of carbonate mobility at this locality.

Paintbrush Canyon Fault: Midway Valley Trench 4

The western splay of the Paintbrush Canyon Fault exposed in MWV-T4 (Figure 5) at the southern end of Midway Valley records four or five rupture events producing a cumulative displacement of the oldest exposed unit of about 2.2 m.[1,2] Samples of massive K horizons and carbonate-replaced rhizoliths from the older units have not yet been analyzed using U-series techniques. However, several TL age estimates are available for the younger units that bracket the two most-recent ruptures. Sample TL-03 is from a scarp-derived colluvial unit (Figure 5, unit IV) that was deposited following the penultimate rupture.[2] Since deposition of this unit shortly post-dates scarp-formation, the combined age estimate of 75 ± 26 ka (Table 2) from total- and partial- bleach experiments for this wedge provides a minimum age for this event. In the vicinity of the fault, unit IV is cut by a fluvial channel filled with a basal gravel and eolian/hillslope colluvium (unit V).[2] After deposition, a sufficient amount of time lapsed to develop a strong B horizon soil with Stage I carbonate prior to the most-recent rupture cutting the entire unit V package. Sample TL-04 was collected from this predominantly eolian unit below the soil and yields a best estimate age of deposition of 38 ± 8 ka (Table 2). Therefore, the most-recent displacement along this segment of the Paintbrush Canyon fault probably occurred after 30 ka (accounting for soil development). A sample of the modern A_v horizon soil was collected from within several centimeters of the surface as a test of the reliability of TL ages. The resulting age of 6.0 ± 2.7 ka (TL-05, Table 2) confirms the young age expected for this sample. The age estimate for this sample also agrees

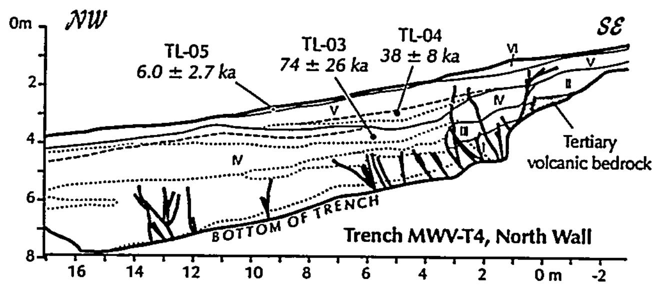

Figure 5: Simplified log of a portion of Midway Valley Trench 4 (after Wesling and others)[2] showing the stratigraphic positions and resulting ages of TL samples (Table 2). Unit boundaries are identified in Figure 4. Sample TL-05 is shown in the correct stratigraphic position, but is actually located further west (station 27 m horizontal and 4.7 m vertical).

with its position at the top of unfaulted unit 6 which exhibits a weak soil commonly associated with early to middle Holocene deposits in Midway Valley.[24]

Bow Ridge Fault: Midway Valley Trench 14D

Logging of the MWV-T14D box trench reveals four to six individual surface-rupture events along the Bow Ridge fault that offset all but the upper-most two of eleven colluvial and alluvial units in a stacked stratigraphic sequence (Figure 6).[1] The lower-most unit contains a strongly-developed, carbonate-rich paleosol that yields both $^{230}Th/^{238}U$ and $^{234}U/^{238}U$ ratios slightly less than unity (HD968; Figure 6, unit 1). These results imply an early Pleistocene or Pliocene age (1000 ka). $^{234}U/^{238}U$ activity ratios less than unity are common in material that is old enough to have reached secular equilibrium, followed by preferential leaching of ^{234}U relative to ^{238}U through interaction with fluids. The amount of cumulative displacement on this unit is unknown since it is only exposed on the footwall block. However, it must be equal to or exceed 45 cm, the amount of offset observed for the overlying unit.

Overlying this oldest paleosol is a sequence of several colluvial units and scarp-related wedges (units 2-4, Figure 6). Collectively, these lithologic units exhibit a well-developed soil profile with an argillic horizon (unit 4) overlying a Stage III to IV K horizon (including units 2 and 3). A sample from the sand-rich argillic horizon yields a total-bleach age estimate of 230 ± 100 ka (TL-09, Table 2); the oldest TL date obtained in this study. The partial-bleach experiment for this sample is currently being analyzed and will provide an additional test of the reliability of the TB age. We presently interpret this age estimate to represent the episode of deposition and burial of sediment in unit 4. This interpretation requires that subsequent pedogenesis affecting this and the underlying units be younger. A test of this hypothesis is provided by multiple aliquots of two samples of soil carbonate collected from the K horizon developed in units 2 (HD969) and 3 (HD970). When treated separately, aliqouts from both samples show insufficient dispersion of isotopic compositions to allow reliable regressions. However, whole-rock aliquots of both samples show linear ^{234}U-^{238}U-^{232}Th relationships which define an age of 185 ± 28 ka (Table 1). Analyses of leach-residue pairs typically do not lie on the same regression line and imply laboratory-induced fractionation of U and Th during leaching. A common age estimated for both units is consistent with soil-stratigraphic relationships and the depositional age presented above. Therefore, the 185 ka soil-carbonate age implies a maximum age for the E2 rupture event identified at the top of unit 4.[1]

A similar package of depositional and soil units occurs in the upper portions of the trench. The oldest lithologic unit not affected by fault rupture consists of a sandy colluvial layer (Figure 6, unit 10) exhibiting a moderately well-developed silica-rich argillic soil. A sample from this unit yields

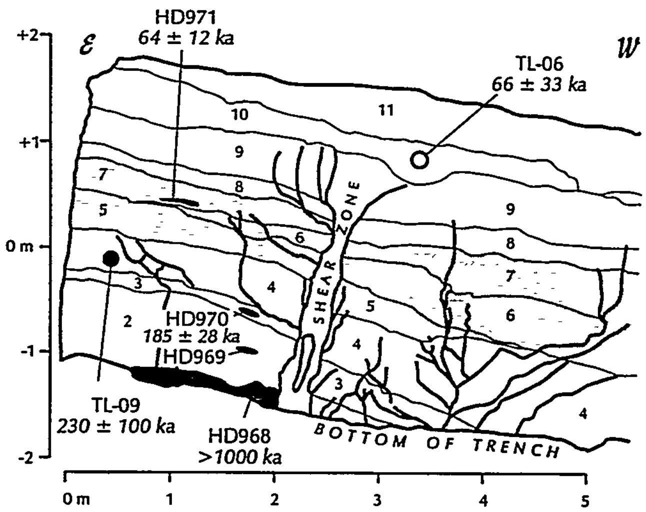

Figure 6: Simplified log of the south wall of the north box trench at MWV-T14D (after Menges et al., this volume)[1] showing sample locations and resulting U-series and TL age estimates (Tables 1 and 2, respectively). Boundaries between units are the same as those described in Figure 4. Patterned units are dominated by secondary carbonate (Stage III or IV); unpatterned units contain little (Stage I or II) or no secondary carbonate. Sample TL-06 was collected from the same stratigraphic position shown here, but from the north wall.

a TL age estimate of 66 ± 34 ka (Table 2, TL-06). This date is interpreted to represent the depositional age, however, pedogenesis in this horizon may be closely related to development of the upper petrocalcic horizon developed in the underlying units (Figure 6, shading in units 5-7). Four aliquots of a sample of a platy K horizon developed in unit 7 yield a U-series age of 64 ± 12 ka (Table 1, HD971). The position of this sample in the lowest portion of the laminar carbonate horizon, as well as the relatively low scatter associated with this regression (M.S.W.D. = 2.7), imply that the carbonate remained closed to U and its decay products, and that it is not the product of multiple generations of carbonate precipitation. Although the large error associated with the TL age estimate permits the most-recent rupture to be substantially younger, we provisionally interpret the two dates as being related to the same episode of pedogenesis which provides a minimum age bracket for the most-recent, major surface disruption event. Additional geochronological analyses of units five through nine are required to better constrain the timing of the two to four ruptures[1] inferred to have occurred in this stratigrahic interval.

Two preliminary U-series ages are available from the upper-most carbonate soil from trench MWV-T14C, located approximately 100 m north of MWV-T14D. An age estimate of 74 ± 30 ka (Table 1, HD965) was obtained from a sample of massive K horizon and age estimate of 105 ± 84 ka (Table 1, HD966) was obtained from a closely-associated sample (approximately 40 cm higher) in the overlying platy K hori-

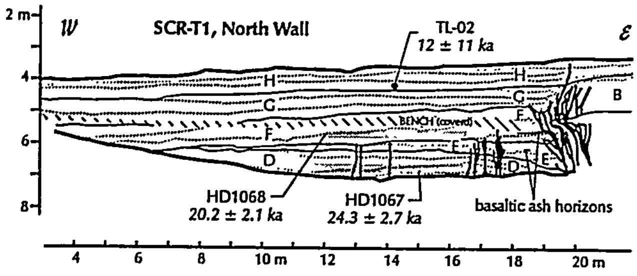

Figure 7: Simplified log of a portion of Stagecoach Road Trench 1 (after Menges and others, this volume)[1] showing positions and resulting age estimates for U-series and TL samples (Tables 1 and 2, respectively). Rhizoliths were collected within the stippled zones at two different levels in the lower trench. Ages and stratigraphic positions of rhizoliths and ash horizons are discussed in the text.

zon (Figure 2B). Both of these carbonate-rich units are in the same stratigraphic position as the upper calcrete observed in MWV-T14D, and although uncertainties are large, these age estimates are consistent with upper-most carbonate soil age reported from MWV-T14D (sample HD971). Both of these units are fractured by the most-recent rupture event on the Bow Ridge fault, however, offset is not apparent.

Stagecoach Road Fault: Trench 1 (SCR-T1)

The Stagecoach Road fault exposed in SCR-T1 juxtaposes unconsolidated sand-rich colluvium and alluvium in the down-thrown block in fault contact with massively carbonate-cemented sand and gravel in the up-thrown block (Figure 7). Stratigraphic relationships indicate from three to five small-displacement rupture events.[1] Paleosols in the down-thrown block lack well-developed pedogenic carbonate horizons, possibly due to the high porosity and permeability of the sandy parent material. However, a 1 m thick, rhizolith-rich zone is exposed in the lower portions of the trench at depths of two to three meters from the surface. Rhizoliths from the upper (HD1068) and lower (HD1067) portions of this horizon yield ages of 20.2 ± 2.1 and 24.3 ± 2.7 ka, respectively (Table 1). Data are also available from a single TL sample collected from near the top of the down-thrown block from a sandy unit that extends undisturbed across the most-recent event in the fault zone (TL-02, Figure 7). The resulting age estimate of 12 ± 11 ka (Table 2) provides a poorly-constrained minimum age for the youngest rupturing event. The youngest portion of this age range is unlikely since this horizon is overlain by deposits exhibiting weak soil development typical of early to middle Holocene units in the region.[24] Therefore, the last rupture event most-likely occurred between 5 and 20 ka. Further tectonic implications based on the rhizolith ages depend on whether the roots were established near the time of deposition of the unit or at a time during the last pluvial cycle that was significantly younger than the age of eolian deposition. Basaltic ash also is present in the same horizon, however until correlation and age uncertainties are resolved, it does not provide a definitive time marker. Additional TL samples from the same horizons are currently being analyzed to test these two hypotheses. If the rhizolith dates do reflect depositional ages, rates of eolian deposition, slip rates, and recurrence intervals are required to be substantially higher than those obtained for other faults in this study.[1]

Midway Valley Trench 5a:

Two additional dates are reported from trench MWV-T5a beneath what has now become the pad for the north Experimental Studies Facility (ESF) portal on the east side of Exile Hill. Although these samples are not related to known faulting or fracturing, they are being used to provide chronological control for the relative age assignments of surficial deposits mapped throughout the east side of Yucca Mountain.[24,25] A U-series date of 39 ± 4 ka, based on a single leach/residue pair, was obtained for carbonate from the platy K horizon of the upper-most calcrete layer that has been correlated with Qa3 soil elsewhere in Midway Valley.[24] Given the discrepancies between analytical results of leach/residue pairs versus those from whole rock aliquots observed in some samples analyzed in this study, this age must be view with considerable caution. However, it is grossly consistent with a TL date of 25.7 ± 8 ka obtained for a weakly silica-cemented, non-calcareous A horizon from a thin buried soil overlying the calcrete.

Conclusions

Most U-series and TL dates obtained in this study are consistent with relative stratigraphies observed at each sample site and are concordant, within error, between the two geochronological systems. However, present data also emphasize that geochronological results from Quaternary deposits are difficult to obtain and must be interpreted with great care using both analytical and soil-stratigraphic information. Nevertheless, new U-series and TL ages determined from Busted Butte, Midway Valley, and Stagecoach Road samples support and provide additional resolution to previous conclusions concerning recurrence intervals and vertical slip rates.[1,2,3] Geochronological data provided in this study are integrated with structural data and are interpreted in a paleoseismic context in a companion paper presented elsewhere in this volume[1] and are summarized below.

The preliminary results obtained from this study are inadequate to rigorously define the timing of most-recent rupture events and intervals of recurrence, but show promise for doing so with continued effort. Present geochronological relationships are interpreted to indicate that most-recent rupturing occurred between 30 and 100 ka at Busted Butte and MWV-T14D, and between 10 and 40 ka at MWV-T4. Large uncertainties for some of the present age estimates and the lack of materials that more-closely bracket rupture events disallow tighter constraints. A younger age estimate (5 to 23 ka) for the most-recent event is probable at Stagecoach Road. Recurrence intervals are difficult to quantify from older deposits, however, they imply a range of 30 to 100 ka for the Paintbrush Canyon and Bow Ridge faults. The long recurrence intervals inferred from the presently-available paleoseismic geochronology imply low slip rates for these faults.[1] Recurrence intervals and slip rates on the Stagecoach Road fault appear to be higher than other studied faults, and will be better quantified by additional dating efforts currently in progress. At the present level of investigation, age information is not sufficiently precise to uniquely correlate individual events between sites. Without this information, rupture lengths cannot be reliably determined and accurate estimates of earthquake magnitude are difficult to make. We hope that continued application of this type of integrated approach, combining multiple analytical techniques along with stratigraphic and pedogenic interpretations, will provide the geochronological constraints needed to accurately assess seismic hazards.

In addition to providing chronological brackets for faulting events, ages of eolian deposits and pedogenic carbonate provide information on past periods of eolian influx and carbonate mobility which are related to changes in past climate conditions. Although present data are insufficient to quantify specific periods of calcrete development, there appears to be a tendency for ages to cluster into discrete episodes linked to wetter regional climate periods rather than either forming and being modified continuously or being randomly distributed through time.[26] Pedogenic carbonate ages of about 20 to 40, 60 to 100, and 150 ka roughly correlate with glacial climate cycles observed on a global scale and probably reflect the need for a wetter climate at Yucca Mountain to allow significant dissolution and translocation of soil carbonate.

U isotopic compositions of the analyzed carbonates in this study also provide further support of the surficial hydrogenic origin of these deposits. Authigenic carbonate components (that is, the ^{232}Th-free mixing end member) for all samples have initial $^{234}U/^{238}U$ activity ratios between 1.1 and 1.6 (Table 1; Figure 2D). In contrast, ground waters and their associated surficial deposits in the vicinity of Yucca Mountain contain $^{234}U/^{238}U$ activity ratios of 2.5 and higher.[6,26,27,28,29] Therefore, ascending ground water cannot be a hydrogenic source for carbonates associated with these faults, particularly for those which exhibit finite disequilibrium ages.

ACKNOWLEDGMENTS

This study is supported by the Department of Energy as part of the Yucca Mountain Site Characterization Project under Interagency Agreement No. DE-AI08-92NV10874. The assistance of D. Craft, A. Walker and B. Boles in both field and laboratory aspects of this study is greatly appreciated. The comprehensive reviews of E.M. Taylor and S. Pezzopane helped to make this a more cohesive and comprehendable paper.

REFERENCES

1. C.M. MENGES, J.R. WESLING, J.W. WHITNEY, F.W. SWAN, J.A. COE, A.P. THOMAS and J.A. OSWALD, "Paleoseismic investigation of Quaternary faults on eastern Yucca Mountain, Nevada, *High-Level radioactive Waste Management Proceedings of the Fifth International Conference* (this volume)
2. J.R. WESLING, F.H. SWAN and A.P. THOMAS, "Preliminary report and map of trench MWV-T4 across the Paintbrush Canyon fault, Yucca Mountain area, Nye County, Nevada," Draft report (1994)
3. C.M. MENGES, G. VADURRO, R. CRESS, J. COE and F.W. SIMONDS, "Stratigraphic evidence for multiple small Quaternary displacements on the Bow Ridge fault at northeast Yucca Mountain, Nye County, Nevada," *Geol. Soc. Amer. Abst. with Prog. 25*, 120 (1993).
4. F.H. SWAN, J.R. WESLING and A.P. THOMAS, "Paleoseismic investigations of the Paintbrush Canyon fault in southern Midway Valley, Yucca Mountain, Nevada: preliminary results," *Geol. Soc. Amer. Abst. with Prog.* 25, 153. (1993)
5. J.R. WESLING, F.H. SWAN, A.P. THOMAS and M.M. ANGELL, "Preliminary results of trench mapping at the site of prospective surface facilities for the potential Yucca Mountain repository, Nevada," *Geol. Soc. Amer. Abst. with Prog. 25*, 162 (1993).
6. K.R. LUDWIG, Z.E. PETERMAN, K.R. SIMMONS, and E.D. GUTENTAG, "$^{234}U/^{238}U$ ratios as a ground water flow tracer, SW Nevada-SE California," *High-Level radioactive Waste Management Proceedings of the Fourth International Conference,* 1567 (1993).
7. J.K. OSMOND, J.P. MAY and W.F. TANNER, "Age of the Cape Kennedy barrier-and-lagoon complex," *J. Geophys. Res. 75*, 5459 (1970).
8. J.N. ROSHOLT, "$^{230}Th/^{234}U$ dating of travertine and caliche rinds," *Geol. Soc. Amer. Abstr. with Prog. 8*, 1076 (1976).
9. H.P. SCHWARCZ and A.G. LATHAM, "Dirty calcites 1. Uranium-series dating of contaminated carbonates using leachates alone," Chem. Geol. 80, 35-43 (1989).
10. S. LUO and T-L KU, "U-series isochron dating: A generalized method employing total-sample dissolution," *Geochim. Cosmochim. Acta 55*, 555 (1991).
11. J.L. BISCHOFF and J.A. FITZPATRICK, "U-series dating of impure carbonates: An isochron technique using total-sample dissolution," *Geochim. Cosmochim. Acta 55*, 543 (1991).
12. A. KAUFFMAN, "An evaluation of several methods for determining ^{230}Th-U ages in impure carbonates," *Geochim. Cosmochim. Acta 57*, 2303 (1993)
13. K.L. LUDWIG and D.M. TITTERINGTON, "Maximum likelihood estimation of U-Th errors," *Geochim. Cosmochim. Acta.* (in review)
14. M.N. MACHETTE, "Calcic soils of the southwestern United States," Geological Society of America Special Paper, 203 (1985).
15. B.J. SZABO, W.J. CARR, and W.C. GOTTSCHALL, "Uranium-thorium dating of Quaternary carbonate accumulations in the Nevada Test Site region, southern Nevada," *U.S. Geol. Survey Open-file Report 81-119*, (1981).
16. K.R. LUDWIG, "ISOPLOT: A plotting and regression program for radiogenic-isotope data; Version 2.70," *U.S. Geol. Surv. Open-File Report 91-445 (June 9, 1993 revision),* 42 p. (1993)

17. M.J. AITKEN, "Thermoluminescence Dating," Academic Press, N.Y. (1985).

18. A.K. SINGHVI and V. MEJDAHL, Thermoluminescence dating of sediments," Nuclear Tracks 10, 137-161 (1985).

19. S.L. FORMAN, "Thermoluminescence dating," Dating methods applicable to Quaternary geologic studies in the western United States (1989)

20. H.T. MILLARD, and P.B. MAAT, "Thermoluminescence dating procedures in use at the U.S. Geological Survey, Denver, CO," *U.S. Geol. Surv. Open File Report,* in review. (1994)

21. G.A. IZETT, J.D. OBRADOVICH and H.H. MEHNERT, "The Bishop ash bed (middle Pleistocene) and some older (Pliocene and Pleistocene) chemically and mineralogically similar ash beds in California, Nevada and Utah," *U.S. Geological Survey Bulletin* 1675, 37 p. (1988).

22. B. CROWE, F. PERRY, G. VALENTINE, S. WELLS, L. McFADDEN, J. GEISSMAN, S. POTHS, M. MURREL and S. FORMAN, "Status of volcanism studies for the Yucca Mountain Site Characterization Project," *Los Alamos National Laboratory Report LAMS-9325,* v. II (in press).

23. F. PERRY, personal communication, 1994

24. J.R. WESLING, F.H. SWAN, T.F. BULLARD, and A.P. THOMAS, "Surficial geologic map of Midway Valley, Yucca Mountain area, Nye County, Vevada," Draft report, Geomatrix Consultants, San Francisco, CA, 15 p. (1993).

25. S.C. LUNDSTROM, J.R. WESLING, F.H. SWAN, E.M. TAYLOR and J.W. WHITNEY, "Quaternary allostratigraphy of surficial depost map units at Yucca Mountain, Nevada: A progress report," *Geological Society of America Abstracts with Programs,* 25, 5, p. 112 (1993).

26. D.R. MUHS, J.W. WHITNEY, R.R. SHROBA, E.M. TAYLOR, and C.A. BUSH, "Uranium-series dating of secondary carbonates near Yucca Mountain, Nevada: Applications to tectonic, paleoclimatic and paleohydrologic problems," *High-Level radioactive Waste Management Proceedings of the First International Conference,* 924 (1990).

27. R.A. ZIELINSKI and J.N. ROSHOLT, "Uranium in waters and aquifer rocks at the Nevada Test Site, Nye County, Nevada," *Jour. Res. U.S. Geol. Survey* 6, 489 (1978).

28. K.R. LUDWIG, K.R. SIMMONS, B.J. SZABO, I.J. WINOGRAD, J.M. LANWEHR, A.C. RIGGS, and R.J. HOFFMAN, "Mass-spectrometeric ^{230}Th-^{234}U-^{238}U dating of the Devils Hole calcite vein," *Science 258,* 284 (1992).

29. J.B. PACES, E.M. TAYLOR and C.A. BUSH, "Late Quaternary history and uranium isotopic compositions of ground water discharge deposits, Crater Flat Nevada," *High-Level radioactive Waste Management Proceedings of the Fourth International Conference,* 1573 (1993)

HIGH LEVEL RADIOACTIVE WASTE MANAGEMENT

Proceedings of the Fifth Annual International Conference
Las Vegas, Nevada, May 22-26, 1994

VOLUME 4
1994

Sponsored by the
American Society of Civil Engineers
American Nuclear Society

In cooperation with:

American Association of Engineering Societies
American Chemical Society
American Institute of Chemical Engineers
American Medical Association
American Society for Testing and Materials
American Society for Quality Control
American Society of Mechanical Engineers
Center for Nuclear Waste Regulatory Analysis
Edison Electric Institute
Geological Society of America
Health Physics Society
Institute of Nuclear Materials Management
National Conference of State Legislatures
Society of Mining Engineers
U.S. Department of Energy
U.S. Geological Survey
U.S. Nuclear Regulatory Commission
University of Nevada Medical School
American Institute of Mining, Metallurgical and Petroleum Engineers
American Underground-Space Association
Atomic Energy Council Radwaste Administration
Atomic Energy of Canada Ltd.
British Nuclear Fuels Ltd.
Chinese Institute of Civil and Hydraulic Engineering
Commission of the European Communities
Conseil National des Ingenieurs et des Scientifiques de France
Electric Power Research Institute
Her Majesty's Inspectorate of Pollution
Hungarian Nuclear Society
Institution of Civil Engineers
Institution of Engineers-Australia
Institution of Engineers of Ireland
Japan Society of Civil Engineers
Korea Advanced Energy Research Institute
Korean Society of Civil Engineers
Ministerio de Industria y Energia-Uruguay
National Association of Corrosion Engineers
National Association of Regulatory Utility Commissioners
Nationale Genossenschaft fur die Lagerung Radioaktiver Abfalle (NAGRA)
National Society of Professional Engineers
Organization for Economic Cooperation and Development (OECD)- Nuclear Energy Agency
Power Reactor and Nuclear Fuel Development Corp.
Romanian Nuclear Energy Association
Swedish Nuclear Fuel and Waste Management Company
Swedish Nuclear Power Inspectorate
Swiss Society of Engineers and Architects
U.S. Council for Energy Awareness
Verein Deutscher Ingenieure

Hosted by
University of Nevada, Las Vegas
Howard R. Hughes College of Engineering

Published by the

American Nuclear Society, Inc.
La Grange Park, Illinois 60525, USA

American Society of Civil Engineers
345 East 47th Street
New York, New York 10017-2398, USA