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Uranium-Series Dating of Pedogenic Carbonates from the Livermore Valley, California

Kevin G. Knauss

January 7, 1981

Lawrence
Livermore
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Laboratory

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URANIUM-SERIES DATING OF PEDOGENIC
CARBONATES FROM THE
LIVERMORE VALLEY, CALIFORNIA

ABSTRACT

A uranium-series dating technique has been applied to pedogenic carbonates from the Livermore Valley in California. The results from geomorphologically distinct Quaternary alluvial units are internally consistent and for one alluvial unit are corroborated by a concordant ^{14}C age for an associated wood fragment. In appropriate situations, age dates for pedogenic carbonates derived using this technique may provide a time stratigraphy for alluvial units and hence provide some limits (minimum age) for last fault movement.

INTRODUCTION

Detailed knowledge concerning geology is of great importance in assuring safe operation of nuclear and other facilities at the Lawrence Livermore National Laboratory (LLNL). Particularly important is the knowledge of the location of faults and the timing of their most recent activity. For this reason, a Site Investigation has been initiated to evaluate site and local geology at the LLNL.

As part of the Site Investigation being undertaken by the Geoscience staff at LLNL, seven exploratory trenches, a roadcut, a basement excavation, an outcrop, and two storm sewer trenches have been mapped. Within these exposures a variety of pedogenic carbonates were encountered including finely disseminated caliche from near surface sandy layers, caliche-filled desiccation cracks (in some cases up to 1/2 in. thick) at the base of argillic (clay-enriched) "B" soil horizons within buried paleosols, root casts, massive nodular caliche, and caliche cements from clayey gouge zones along faults. Age dates for these materials (1) may provide a time stratigraphy for the alluvial units mapped, and hence (2) may provide some limits (minimum age) for last fault movement, and (3) may establish the degree of tectonic stability.

Recently, a technique was developed to age-date pedogenic carbonates in gravelly desert soils (Ku et al., 1979) using uranium-series disequilibrium methods and involving a combined chemical leaching and correction procedure to cope with the detrital contamination problem. The results presented here are an attempt to extend the uranium-series method to the dating of semiarid region pedogenic carbonates from the Livermore Valley.

The nine samples studied thus far include six specimens taken from argillic B horizons. The B horizon within a paleosol is generally thought of as a zone of accumulation or illuviation, and in alkaline environments the B horizon has been considered a chemically closed system (Hunt, 1972). However, during pluvial periods within the Pleistocene epoch, this concept of the B horizon may not have been correct. The age-dating implications of an "open-system" will be discussed later. The remaining three samples were taken from silty sand or mudstones which contained abundant disseminated caliche and which at one time either served as conduits for ground-water flow or were saturated with water due to ground-water ponding. In addition, one of three wood fragment samples collected from the trenches contained enough material to be age-dated by the ^{14}C method.

URANIUM-SERIES DISEQUILIBRIUM DATING

The ^{230}Th - ^{234}U method is a modification of the geochronometer first applied to coralline material by Potratz et al. (1955). It assumes (1) carbonate when formed incorporates in it a few parts per million (ppm) of uranium, but negligible amounts of thorium isotopes, and (2) subsequent to its formation, the carbonate acts as a closed system with respect to the uranium and thorium isotopes. With these assumptions, the age (t) of the carbonate can be derived from the relationship:

$$^{230}\text{Th} = ^{238}\text{U} [1 - \exp(-\lambda_0 t)] \quad (1)$$

where λ_0 is the decay constant of ^{230}Th , and the notation of nuclides refers to their activities. Because in most surficial waters ^{234}U is often

found to be in excess of ^{238}U (i.e., activity ratio (AR) $^{234}\text{U}/^{238}\text{U} \geq 1.0$), the decay of this excess ^{234}U requires that Eq. (1) be modified to:

$$^{230}\text{Th} = ^{238}\text{U} [1 - \exp(-\lambda_0 t)] + [^{234}\text{U} - ^{238}\text{U}] [\lambda_0 / (\lambda_0 - \lambda_4)] [1 - \exp(\lambda_4 t - \lambda_0 t)] \quad (2)$$

where λ_4 is the decay constant of ^{234}U . The modification necessitates measurement of ^{238}U , ^{234}U , and ^{230}Th to age-date the carbonate.

In applying this technique to pedogenic carbonates, one must also consider the fact that these carbonates may contain a significant amount of detrital material, mostly aluminosilicates. Because these minerals are much older than the carbonate, elimination or correction for this "detrital contamination" is necessary. A combined chemical leaching and correction procedure described later has been applied.

GEOLOGIC SETTING

The LLNL is located in the southeastern portion of the Livermore Valley (Fig. 1). The Livermore Valley is an east-west trending topographic and structural depression oriented perpendicular to the structural grain of the Central California Diablo Range within which it is located. The Diablo Range consists dominantly of highly deformed metamorphic and igneous rocks of the Jurassic-Cretaceous Franciscan assemblage. The range is generally bounded on the west by the active San Andreas Fault system and on the east by the ancestral Coast Range Thrust Fault system.

The Livermore Valley itself is underlain by up to 4000 ft of predominantly continental alluvium of late Tertiary and Quaternary age. The Quaternary alluvial deposits have been mapped by several investigators and differentiated based on soil types, stratigraphic position, and geomorphology. None of these investigators was able to assign absolute ages to the Quaternary alluvial units. Herd (1977) noted that soils developed on "older" alluvial units have argillic B horizons and hence considers them of Pleistocene age.

FIG. 1. Major fault zones of the San Francisco Bay Area according to Carpenter et al. (1931)—(LLNL is shown).

He cites Birkeland (1974) as having established that in the nearby Sacramento Valley, some 40,000 years of soil formation appear to be required to form a minimal B horizon.

Within the Livermore Valley and adjacent areas there is evidence of recent activity along the Calaveras, Las Positas, and Greenville Faults as well as Quaternary movement of several other faults (Figs. 2 and 3). Three of these faults, the Corral Hollow, the Tesla, and the Doutherty, have been postulated to cross the LLNL Site.

In those areas where faults have been postulated or where tonal lineations interpretable as fault-related have been identified, exploratory trenches have been excavated and logged to evaluate near surface conditions in the Quaternary alluvium. In addition, a roadcut on Greenville Road immediately south of LLNL and a basement excavation on the site have been examined for evidence of faulting. During these investigations caliche was often encountered and, whenever possible, samples were acquired for age-dating. In three trenches wood fragments were encountered and sampled. Only one of these, however, provided enough carbon to allow a ^{14}C age determination to be made.

The locations of the trenches and exposures are shown in Fig. 4. A brief description of the samples follows in Table 1.

FIG. 2. Faulting in the eastern Livermore Valley according to Herd (1977).

FIG. 3. Faulting in the eastern Livermore Valley according to Blume (1978).

FIG. 4a. Trench locations on the LLNL site according to Carpenter et al. (1981).

FIG. 4b. Trench locations near the SLNL site according to Carpenter et al. (1981).

TABLE 1. Sample descriptions.

Identification	Type
<u>Part A. Dated samples</u>	
<u>Carbonates</u>	
E-1 C1a	Caliche filling vertical shrinkage fractures up to 8 in. long and 1/2 in. thick. Taken from argilllic B horizon in soil profile (unit 9) approximately 11 ft below present surface at station 1+67.
E-1 C2a	Caliche taken in position stratigraphically equivalent to E-1 C1a at station 1+72.
Greenville Rd. #1	Grey-white mudstone (unit 9) containing abundant disseminated caliche. Unit associated with Las Positas Fault zone and present only south of the zone.
Greenville Rd. #2	Sample taken on revisit to Greenville Rd. cut, equivalent to Greenville Rd. #1.
E-5 #1	Caliche filling vertical shrinkage fractures in clayey members of unit 5 approximately 10 ft below present surface at station 234.
E-6 #3	Caliche filling vertical fractures in silty clay (unit 5) approximately 10 ft below present surface at station 1+40 on west wall of trench.
<u>Wood</u>	
E-3	Wood fragment in unit 46 north of Las Positas Fault zone approximately 11-1/2 ft below present surface at station 0+232.
<u>Part B. Undated samples</u>	
E-2 #2	Caliche filling vertical fractures in silty clay (unit 3a) approximately 5-1/2 ft below present surface at station 215.
E-6 #1	Composite sample taken from caliche filling vertical fractures in silty clay (unit 2) approximately 5 ft below present surface between stations 0-5 and 0-15.
Nova #2	Traces of caliche filling narrow fractures coated with reddish brown clay in large lens of sandy silt (unit 3), approximately 8 ft below the present surface at station 1+56.

ANALYTICAL TECHNIQUE

The carbonate material was carefully scraped off the enclosing soil matrix and cleaned of any obvious noncarbonate grains by hand-picking with tweezers. About 5 g of the dried sample was leached with 500 ml of cold, 0.2 N HCl. The final pH of the leachate was found to vary from 0.8 to 1.5, depending on the amount of carbonate present. This is a weaker leach than that applied by Ku et al. (1979) because these samples contained a higher clay content than encountered by the previous authors. The HCl-insoluble residue was separated by centrifugation, dried, and weighed. It was then totally dissolved in HF-HClO₄.

Radiochemical analyses were made on both the leachate and the residue solutions after spiking with ²³²U and ²²⁸Th yield tracers to allow isotope dilution. Procedures for the isolation and purification of the uranium isotopes generally followed Ku et al. (1979); i.e., separation from 8 N HCl medium using Dowex 1X8 anion exchange resin, elution with 0.1 N HCl, removal of iron by extraction from 8 N HCl into isopropyl ether, extraction of uranium from 4 N HNO₃ saturated in Al(NO₃)₃ into ethyl acetate, back-extraction into deionized water, and wet-ashing. The thorium isotope isolation was made using the first eluant from the uranium anion-exchange column. By repeated ferric hydroxide precipitations followed by washes with 0.05 N NH₄OH, chloride was removed and the solution was made 8 N in HNO₃. Thorium was separated from this solution onto Dowex 1X8 anion-exchange resin, eluted with 8 N HCl, and then wet-ashed. Thin sources of purified uranium and thorium were prepared by electroplating from NH₄Cl solution at pH 3 onto platinum discs using a current of 0.8 A for 1.5 hr. These plates were counted on an alpha spectrometer equipped with silicon surface-barrier detectors having overall system plus source resolution (FWHM) consistently better than 60 keV at 5.5 MeV.

RESULTS

The results of the radiochemical analyses of leach and residue fractions are listed in Table 2. The errors quoted in the results are standard deviation (1 σ) derived from counting statistics.

TABLE 2. Results of radiochemical analyses of leach and residue fractions.

Sample		Activity (dpm/g)				Concentration (ppm)		Activity ratio			Weight fraction soluble in 0.2 N HCl
		^{232}Th	^{238}U	^{234}U	^{230}Th	U	Th	$\frac{^{234}\text{U}}{^{238}\text{U}}$	$\frac{^{230}\text{Th}}{^{232}\text{Th}}$	$\frac{^{230}\text{Th}}{^{234}\text{U}}$	
E-1 C1a	Leach	0.236 ±.011	1.343 ±.032	1.486 ±.034	0.879 ±.024	1.799 ±.042	0.974 ±.046	1.107 ±.030	3.717 ±.189	0.591 ±.021	0.712
	Residue	1.054 ±.042	1.343 ±.031	1.212 ±.029	1.814 ±.057	1.799 ±.041	4.347 ±.172	0.903 ±.028	1.720 ±.078	1.496 ±.059	
E-1 C2a	Leach	0.168 ±.006	1.745 ±.045	1.961 ±.049	1.385 .020	2.338 ±.060	0.695 ±.024	1.124 ±.031	8.210 ±.298	0.706 ±.021	0.663
	Residue	0.640 ±.023	1.599 ±.034	1.639 ±.036	1.982 ±.046	2.143 ±.045	2.636 ±.096	1.024 ±.027	3.100 ±.123	1.209 ±.038	
Greenville Rd. #1	Leach	0.123 ±.006	0.669 ±.029	0.897 ±.029	0.440 ±.011	0.897 ±.038	0.508 ±.023	1.339 ±.058	3.572 ±.184	0.491 ±.020	0.666
	Residue	1.295 ±.045	1.373 ±.040	1.162 ±.033	1.526 ±.049	1.840 ±.054	5.337 ±.184	0.846 ±.033	1.178 ±.049	1.313 ±.059	
Greenville Rd. #2	Leach	0.117 ±.007	0.768 ±.026	0.951 ±.030	0.410 ±.014	1.029 ±.034	0.481 ±.029	1.239 ±.049	3.511 ±.237	0.431 ±.020	0.760
	Residue	1.393 ±.034	1.332 ±.035	1.208 ±.033	1.654 ±.039	1.785 ±.047	5.741 ±.144	0.907 ±.032	1.187 ±.037	1.368 ±.049	

TABLE 2. (Continued.)

E-2 #2	Leach	0.223 ±.011	1.235 ±.055	1.359 ±.058	0.273 ±.013	1.654 ±.073	0.921 ±.046	1.101 ±.058	1.211 ±.080	0.201 ±.013	0.541
	Residue	1.397 ±.054	1.278 ±.040	1.194 ±.039	1.589 ±.059	1.713 ±.054	5.759 ±.223	0.934 ±.037	1.137 ±.049	1.331 ±.066	
E-5 #1	Leach	0.171 ±.009	2.016 ±.047	2.331 ±.052	0.527 ±.017	2.702 ±.063	0.703 ±.038	1.156 ±.028	3.089 ±.186	0.226 ±.009	0.604
	Residue	1.211 ±.037	1.406 ±.048	1.390 ±.048	1.816 ±.048	1.884 ±.064	4.992 ±.151	0.998 ±.041	1.499 ±.050	1.307 ±.056	
E-6 #1	Leach	0.198 ±.011	1.262 ±.037	1.458 ±.041	0.265 ±.013	1.691 ±.051	0.816 ±.045	1.155 ±.043	1.338 ±.097	0.182 ±.010	0.421
	Residue	1.533 ±.056	1.214 ±.038	1.150 ±.037	1.914 ±.065	1.628 ±.051	6.318 ±.233	0.947 ±.038	1.248 ±.051	1.664 ±.078	
E-6 #3	Leach	0.378 ±.017	2.259 ±.055	2.727 ±.064	0.557 ±.021	3.027 ±.074	1.561 ±.070	1.207 ±.031	1.470 ±.081	0.204 ±.009	0.586
	Residue	1.899 ±.082	1.364 ±.037	1.325 ±.037	2.239 ±.092	1.829 ±.050	7.825 ±.339	0.971 ±.033	1.179 ±.054	1.689 ±.084	
Nova #2	Leach	0.540 ±.024	1.359 ±.045	1.510 ±.048	0.592 ±.026	1.821 ±.059	2.225 ±.101	1.111 ±.045	1.097 ±.066	0.392 ±.021	0.286
	Residue	1.681 ±.072	1.479 ±.031	1.409 ±.029	1.607 ±.071	1.982 ±.041	6.929 ±.296	0.953 ±.023	0.956 ±.041	1.140 ±.056	

CARBONATE AGE ESTIMATE

In the discussion to follow, the symbol of a nuclide (e.g., ^{230}Th) denotes specific activity (dpm/g). Subscripts C, D, L, and R refer to carbonate, detrital mineral, leachate, and 0.2 N HCl-insoluble residue, respectively. The letter F denotes weight fraction (hence $F_L + F_R = F_C + F_D = 1$). Presumably, $F_C \sim F_L$ and $F_D \sim F_R$.

As a first approximation, the leach raw data can be taken to represent data for the carbonate phase; i.e., $^{230}\text{Th}_L = ^{230}\text{Th}_C$, etc. Ages for the samples, calculated via Eq. (2) from leach data, are listed in Table 3 as Age¹. These ages should be amenable to refinement, as shown below.

Consider the following possibilities:

(1) Differential solubilization of ^{234}U and ^{230}Th could occur during the acid treatment; ^{234}U may be preferentially leached from the detrital minerals relative to ^{230}Th , as suggested by the excess ^{230}Th activities (e.g., $\text{AR } ^{230}\text{Th}/^{234}\text{U} \geq 1$) in residues. This effect tends to render the ages too young.

(2) The presence of measurable amounts of ^{232}Th in leachates indicates that not all the leachable ^{230}Th is produced in situ in the carbonate; some of it must have accompanied the observed ^{232}Th as part of the "common" ^{230}Th ; i.e., ^{230}Th originally incorporated in the carbonate as well as present in the detrital phases. Its presence would have the effect of rendering too old the ages calculated on the basis of leachates.

To deal with these possibilities, a correction scheme is proposed based on the following assumptions (Ku et al., 1979):

- (1) Initially, the carbonate contains negligible amounts of ^{232}Th and ^{230}Th , or it has a $^{230}\text{Th}/^{232}\text{Th}$ ratio similar to that in the detrital phase.
- (2) Secular equilibrium exists in the detrital phase.
- (3) Upon the acid leaching of detrital minerals, no fractionation of the thorium isotopes occurs; i.e., $^{230}\text{Th}_R / ^{232}\text{Th}_R = ^{230}\text{Th}_D / ^{232}\text{Th}_D$.

These assumptions lead to the relationships:

$$^{230}\text{Th}_C = ^{230}\text{Th}_L - ^{232}\text{Th}_L \left(^{230}\text{Th}_R / ^{232}\text{Th}_R \right) \quad (3)$$

$$^{234}\text{U}_C = ^{234}\text{U}_L - ^{232}\text{Th}_L \left(^{230}\text{Th}_R / ^{232}\text{Th}_R \right) - (F_R/F_L) \left(^{230}\text{Th}_R - ^{234}\text{U}_R \right) \quad (4)$$

$$^{238}\text{U}_C = ^{238}\text{U}_L - ^{232}\text{Th}_L \left(^{230}\text{Th}_R / ^{232}\text{Th}_R \right) - (F_R/F_L) \left(^{230}\text{Th}_R - ^{238}\text{U}_R \right) \quad (5)$$

The correction term $^{232}\text{Th}_L (^{230}\text{Th}_R / ^{232}\text{Th}_R)$ refers to that amount of ^{230}Th , or its equivalent ^{234}U and ^{238}U , leached from the detrital phase. The correction terms $(F_R/F_L) (^{230}\text{Th}_R - ^{234}\text{U}_R)$ and $(F_R/F_L) (^{230}\text{Th}_R - ^{238}\text{U}_R)$, respectively, refer to the amount of ^{234}U and ^{238}U leached from the detritals in excess (or deficit) relative to ^{230}Th . Both terms, therefore, are correcting for the effect of differential acid-extraction of ^{230}Th and the two uranium isotopes from the detrital phase.

These calculated values for $^{230}\text{Th}_C$, $^{234}\text{U}_C$, and $^{238}\text{U}_C$ can then be used to solve Eq. (2) to provide a corrected Age² listed in Table 3.

An additional method has been proposed to calculate the carbonate age of caliche. Szabo et al. (1978) used a graphical isochron-plot for this purpose. Ages are calculated by means of isochron-plots of the respective acid-soluble and acidinsoluble residue pairs. The slope of the $^{230}\text{Th}/^{232}\text{Th}$ vs $^{234}\text{U}/^{232}\text{Th}$ plot yields the $^{230}\text{Th}/^{234}\text{U}$ activity ratio of the pure carbonate component. Similarly, the slope of the $^{234}\text{U}/^{232}\text{Th}$ vs $^{238}\text{U}/^{232}\text{Th}$ yields the $^{234}\text{U}/^{238}\text{U}$ activity ratio of the pure carbonate component. From these isotopic ratios isochron-plot ages of the caliche are calculated using Eq. (?) to provide a corrected Age³ listed in Table 3.

Table 3 also contains the ^{14}C age date determined for the wood fragment uncovered in trench E-3. This sample was dated by S. Robinson of the United States Geological Survey, Menlo Park, California.

AGE DATE RELIABILITY

Most of the samples dated thus far consist of relatively thick caliche-filled desiccation cracks in argillized B soil horizons. The samples are in

TABLE 3. Ages for samples--calculated using Eq. (2).

Sample	Type	Unit ^a	Age in years $\times 10^3$			
			Age ¹	Age ²	Age ³	¹⁴ C age
E-1 C1a	Caliche	Qoa ₃	96	89	57	--
E-1 C2a	Caliche	Qoa ₃	128	119	88	--
Greenville Rd. #1	Caliche	QT ₁	71	77	52	--
Greenville Rd. #2	Caliche	QT ₁	60	55	42	--
E-3	Wood	Qoa ₂	--	--	--	17
E-5 #1	Caliche	Qoa ₂	28	18	16	--
E-6 #3	Caliche	Qoa ₂	26	8	7	--

^aAs mapped by Herd (1977).

contrast to the relatively massive, impermeable pebble coatings dated by Ku et al. (1979), although they are similar to carbonate cementations of an arid-zone pediment gravel dated by Szabo et al. (1978). There are intuitive concerns dealing with the "closed system" nature of the Livermore Valley pedogenic carbonates. Although the B soil horizon is generally considered a zone of accumulation in alkaline environments, conceivably during wetter periods it may have been subject to leaching and material transport. Directly confirming the "closed system" nature of these pedogenic carbonates would require concordia between these ²³⁰Th/²³⁴U dates and ages obtained from other radiometric dating methods. Such methods are not available in this instance; therefore, evaluations will have to be made on the internal consistency of the data as well as their conformity with any relative age estimates of the alluvial units based on geomorphic evidence. The combinations of young and old potential C sources for these pedogenic carbonates preclude the use of ¹⁴C methods. In addition, this technique is limited to approximately a 40,000-year range whereas many of the buried paleosols encountered are clearly older than that, as estimated from geomorphic evidence.

The individual caliche dates represent average ages of the entire thickness of carbonate included in each analysis. The time elapsed in accreting this carbonate is unknown. In addition, the rates of accretion may have been more rapid during pluvial times in the Pleistocene.

The reliability (precision) of the ages may be inferred by a consideration of the two pairs of coeval samples analyzed: E-1 C1a + E-1 C2a and Greenville Rd. #1 + Greenville Rd. #2. The data have been summarized in Table 4 and include the mean and standard deviation in the various model ages. The precision of approximately ± 10 to 20% is comparable to that observed in analyses of presumed coeval pedogenic carbonates by Ku et al. (1979). Because of the difficulty in assessing the initial ^{230}Th activities, dating impure carbonates by these methods will probably have inherent uncertainties of this magnitude. Nevertheless, as there are no other absolute dating tools for these deposits, limitations of precision of such magnitude can certainly be tolerated at this time.

In this preliminary effort it is important to consider the radiochemical nature of the noncarbonate detrital minerals because they are important to the assumptions used in correcting the leachate data. Some knowledge can be

TABLE 4. Age of coeval pedogenic carbonates.

Sample	Age in years $\times 10^3$					
	Age ¹	Mean ¹	Age ²	Mean ²	Age ³	Mean ³
E-1 C1a	96		89		57	
		112 $\pm$ 23		104 $\pm$ 21		73 $\pm$ 22
E-1 C2a	128		119		98	
Greenville Rd. #1	71		77		52	
		66 $\pm$ 8		66 $\pm$ 15		47 $\pm$ 7
Greenville Rd. #2	60		55		42	

gathered by inference from the data on residues. As seen from Table 2, the uranium and thorium concentrations in the residues are in the range 1 to 8 ppm, with an average Th/U weight ratio of 3.1. These values are generally expected from an average shale. The $^{234}\text{U}/^{238}\text{U}$ activity ratios are near the secular equilibrium value (average 0.94). Ku et al. (1979) have determined that criteria can be specified by which large deviations from these norms can be used to identify samples that are unsuitable for dating by these methods.

Analyses of several of the samples did not give reliable age estimates. Three samples all had carbonate contents less than 60% by weight, whereas more reliably dated samples are above this amount. Furthermore, these three samples all had low leachate $^{230}\text{Th}/^{232}\text{Th}$ ratios compared to other samples, indicating that they contain a significant detrital or common thorium component in the leachate (carbonate) fraction. Because of the uncertainty in initial ^{230}Th content of the carbonate, the ages were less reliable and ranged widely. Ages for these samples (E-2 #2, E-6 #1, and Nova #2) will not be included in the interpretive discussion to follow.

DISCUSSION

The caliche formed as a soil profile develops on alluvial materials obviously postdates the alluvium. Hence, the age dates derived for these pedogenic carbonates provide minimum ages for the alluvium. These minimum ages can yield some information about the Quaternary seismicity of the Livermore Valley.

Exploratory trench E-1 was located where vague photo lineaments were noted subparallel to the mapped trace of the Las Positas Fault and where a strand of the Corral Hollow Fault (Blume, 1971) crosses the southeast corner of the laboratory site. The trench was excavated in Pleistocene alluvial deposits (Qoa₃ or older) as mapped by Herd (1977). A mature soil profile was observed beneath the present ground surface. Furthermore, another buried soil profile was observed at greater depth in the eastern end of the trench. Samples E-1 C1a and E-1 C2a were acquired from this lower soil profile. No evidence of faulting was observed in this trench. The average age of the lowest soil was approximately 100×10^3 years or greater; hence, one can assume

that if in fact a strand of the Corral Hollow Fault or sympathetic faults subparallel to the Las Positas Fault do intersect trench E-1, they have not been active since late Pleistocene times. The presence of multiple buried paleosols may be due to a sequence of soil-forming intervals during past, more favorable soil-forming climates or they may represent soil formation during periods of tectonic and geomorphic stability possibly within the same climatic period.

Exploratory trench E-6 was also located to intersect photolineaments reported as branching from the Las Positas Fault. This trench, however, was excavated in younger Pleistocene alluvial deposits mapped as Qoa₂ by Herd (1977). There was no evidence of faulting observed in this trench. The age of approximately 14×10^3 years or older for the buried paleosol (sample E-6 #3) is consistent with its assignment to relatively younger Pleistocene alluvial material (Qoa₂) than that encountered in trench E-1 (Qoa₃).

The Greenville Roadcut site intersects the trace of the Las Positas Fault as mapped by Herd (1977); however, numerous small faults present striking N35°-73°W have been interpreted as evidence for the location of the Corral Hollow Fault zone by others (Blume, 1972). A gravel horizon in colluvium is terminated along a line which strikes N35°E; i.e., coincident with the strike of the Las Positas Fault. The situation is relatively ambiguous. The two Greenville Road samples consisted of caliche disseminated in mudstone. This mudstone unit is present only south of the fracture zone described in the text. This unit has been inferred as part of the Pleistocene (Pliocene?) Livermore Formation. The average age for the caliche, however, is approximately 60×10^3 years which would indicate that it is secondary in nature. One interpretation might be that the Las Positas Fault acted as a ground-water barrier, and northward flowing ground water rose up against the fault barrier into the brecciated mudstone and was evaporatively precipitated within it. The ability of the Las Positas Fault to act as a ground-water barrier has been observed elsewhere, for example, within trench E-4 and at the Christmas Tree Farm located on south Vasco Road. The relationship between the average age of this secondary caliche and last movement on the Las Positas Fault is unclear.

Exploratory trench E-3 was located to cross the mapped trace of the Las Positas Fault just northeast of Arroyo Seco. The trench did in fact encounter a 20-ft-wide zone of faulting at the hill front near the south end of the

trench. To the north of this fault zone displacement of alluvium (probably Qoa₂) against steeply dipping Livermore Formation beds was observed. Within this alluvium, a wood fragment was collected and age-dated by the ¹⁴C method. Its age of 17×10^3 years agrees with the age of pedogenic carbonate from presumed Qoa₂ alluvium in trench E-6. The fault terminates this and overlying units indicating that movement has occurred more recently than 17×10^3 years ago.

Exploratory trench E-5 was excavated across the trace of the Corral Hollow Fault as projected by previous investigators and across vague linear tonal contrasts in aerial photographs. The trench exposed alluvial deposits mapped as Qoa₂ by Herd (1977). No evidence of faulting was observed in this trench. The age of pedogenic carbonate in a buried paleosol within the Pleistocene alluvial material was approximately 20×10^3 years. This age for presumed Qoa₂ material agrees with that determined for similar material in trenches E-6 and E-3.

It is not reasonable to derive accumulation rates for alluvium in the east end of the Livermore Valley using these age dates. There is abundant evidence that at any point conditions have fluctuated between erosional and depositional regimes.

CONCLUSIONS

Although trench E-3 contained no caliche, which would provide direct concordancy check with the wood fragment acquired, concordancy can be indirectly inferred. The wood fragment in trench E-3 was taken from Qoa₂ material. Two carbonate samples from other trenches also taken from Qoa₂ material corroborate the date. Preliminary results indicate that uranium-series disequilibrium dating may be extended to semiarid region pedogenic carbonate, as well as to other nonpedogenic carbonate cementations resulting from the actions of ground and surface waters. Secondary carbonates may provide useful information about stratigraphic relationships between various alluvial units within the Livermore Valley. Under appropriate conditions, absolute ages may be obtainable with better than $\pm 20\%$ precision, which is a tolerable level when one considers that no other absolute dating techniques are available. In appropriate situations relationships between disturbed and undisturbed units

allow one to deduce a minimum age for fault movement, or potentially a bracket of ages.

The results obtained indicate no evidence of faulting on the LLNL work site since at least Late Pleistocene time. However, the Las Positas Fault immediately south of the LLNL site was active during Late Pleistocene (and possibly Holocene) time.

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