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SURFICIAL MATERIALS AND STRUCTURE AT PAJARITO MESA

by

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ABSTRACT

Geologic surface mapping and exploratory trenching were conducted at Pajarito Mesa to evaluate the potential for surface faulting at the proposed Los Alamos National Laboratory Mixed Waste Disposal Facility (MWDF). Previous studies had indicated that southern extensions of the north-south trending Rendija Canyon and Guaje Mountain fault zones may cross Pajarito Mesa, near the site of the proposed MWDF, and that displacement had occurred on at least one and possibly both faults to the north during the last 11,000 years. Thus, an evaluation of their southern projections was required to evaluate whether the site met federal regulations pertaining to the siting of hazardous waste disposal facilities.

Exploratory trenches totaling 1340 m in length were excavated on Pajarito Mesa, exposing deposits that range in age from over 1 million years to less than 1000 years. Surficial deposits above the 1.2 million year old Bandelier Tuff include: (1) pumice-rich alluvium of early Pleistocene age that was deposited prior to incision of Pajarito Canyon; (2) buried soils up to 2 m in thickness that include well-developed argillic B horizons; (3) the ca. 50-60,000 year old El Cajete pumice; and (4) variably developed soils in deposits that range in age from at least 30,000 years to less than 1000 years. Variations in the thickness and characteristics of surficial materials along the length of the trenches provide evidence for temporal and spatial variations in surface erosion, and also for distinct periods of net deposition on the mesa top. Deposits both above and below the El Cajete pumice contain significant amounts of fine sand and silt, suggesting that substantial amounts of wind-blown sediment have been episodically deposited on the Pajarito Plateau; this eolian sediment may provide much of the fine-grained material incorporated into the mesa-top soils. The uppermost deposits also bury possible 10,000 to 11,000 year old fire pits and younger Anasazi archaeological sites that were excavated into the mesa-top soils, recording multiple periods of net surface deposition in the Holocene that may represent regional periods of accelerated wind erosion.

A variety of approaches was used to evaluate possible faulting on Pajarito Mesa, including: surface geologic mapping; detailed logging of stratigraphic contacts exposed within the trenches; surveying of a stratigraphic contact within the

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Bandelier Tuff; examination of variations in fracture characteristics both in the trenches and along cliffs; and an examination of mesa-top topographic profiles.

Faulting was recognized in the trenches only in the area of the early Pleistocene alluvium, 70 m east of the Rendija Canyon fault projection, where at least seven faults with a total of at least 1.2 m of down-to-the-west offset were exposed in a 20 m wide zone. A detailed survey of a stratigraphic contact in the Bandelier Tuff suggests a total of 7 to 9 m of down-to-the-west offset in a 100 to 200 m wide zone in the same area, with the alluvial deposits apparently preserved on down-dropped blocks. The survey also provided evidence for several additional areas of faulting to the west. No offset of the buried soil beneath the El Cajete pumice was observed anywhere in the trenches, demonstrating the absence of faulting on this part of Pajarito Mesa for at least the last 50-60,000 years; the site therefore meets regulatory requirements that facilities such as the proposed MWDF be located more than 60 m from Holocene faults. The absence of young faulting at this site indicates that the youngest surface ruptures that were previously documented on the Rendija Canyon and Guaje Mountain faults to the north terminated north of Pajarito Mesa or perhaps were transferred to other faults to the east or west.

Many uncertainties remain concerning the location, orientation, and timing of faulting at Pajarito Mesa, including the age of the most recent movement, due to the apparently dispersed nature of faulting on this part of the Pajarito Plateau and the common absence of well-defined stratigraphic contacts older than the El Cajete pumice. Fracture characteristics by themselves appear to be unreliable in defining the presence or absence of faulting at Pajarito Mesa, and the area of recognized faulting near the Rendija Canyon fault projection shows no increases in fracture density or fracture width either in the adjacent cliffs or within the trenches. In fact, this fault zone displays a relatively low fracture density in the trenches, and individual fractures that experienced movement are no wider than average. Variations in fracture density and fracture width at Pajarito Mesa may in part reflect variations in welding of the Bandelier Tuff, with wider fractures typically occurring in areas where the tuff is most welded, and the lowest fracture densities occurring where the tuff is nonwelded. However, the local concurrence of variations in the mesa-top topographic profile and relatively high fracture density and fracture width in the trenches suggests the possibility of Quaternary faulting in several areas, including part of the projected Guaje Mountain fault zone, although these inferences cannot be verified at present.

INTRODUCTION

Pajarito Mesa is the candidate site for the proposed Los Alamos National Laboratory (LANL) Mixed Waste Disposal Facility (MWDF). Previous studies which examined subsurface data, aerial photograph lineaments, and bedrock fracture characteristics had suggested that southern extensions of the north-south trending Rendija Canyon and Guaje Mountain fault zones cross Pajarito Mesa (Fig. 1) (Dransfield and Gardner, 1985; Vaniman and Wohletz, 1990; Wong et al., 1995). At least one and perhaps both of these faults had Holocene surface rupture (< 11 ka (ka = 1000 years ago)) to the north (Gardner et al., 1990; Kelson et al., 1993; Wong et al., 1993, 1995), and an evaluation of their southern projections is thus critical for understanding potential surface rupture hazards to the MWDF.

Federal regulations pertaining to the citing of hazardous waste disposal facilities require that such facilities not be located within 200 ft (61 m) of faults displaying Holocene offset (40 CFR 264.18). They further require that if faults or lineaments are present within 3000 ft (915 m) of a proposed facility and if site analyses are otherwise inconclusive as to the exact location and age of faulting, then detailed subsurface exploration involving trenching is required (40 CFR 270.14). Surface geologic mapping and fracture studies at Pajarito Mesa were inconclusive as to the exact location and age of faulting (Vaniman and Chipera, this report). Thus, exploratory trenching activities were initiated.

Exploratory trenches totaling 1340 m in length were excavated on Pajarito Mesa in the summer and fall of 1993 (Figs. 1 and 2), and detailed geologic logs of the trench walls were prepared (Kolbe et al., 1994). The trenches were sited to include both the proposed MWDF disposal pits and the southern projections of the Rendija Canyon and Guaje Mountain fault zones, as mapped by Vaniman and Wohletz (1990) and Wong et al. (1995), to more thoroughly evaluate the history of faulting on Pajarito Mesa. The trenches were excavated deep enough to expose 0.5 to 1.0 m of intact Bandelier Tuff bedrock beneath the surficial deposits, where possible, and they ranged in depth from 1.5 to 4 m. In addition to the constraints they provided for faulting, the trench exposures displayed a unique cross section of mesa-top soils in the central part of LANL. These exposures provided an opportunity to examine the characteristics and variability of surficial materials on a relatively undisturbed mesa, and to evaluate the mesa-top history of erosion, deposition, and soil development.

This report summarizes the characteristics of surficial materials and the structure of Pajarito Mesa, as determined in the trench exposures (Kolbe et al., 1994) and from complementary surface studies. Data from similar trenching activities on a nearby mesa in the TA-63 area, 1 km north of Pajarito Mesa, (Fig. 1; Kolbe et al., 1995) are also discussed as they pertain to evaluating faulting and surficial materials. Finally, some interpretations of the characteristics of faulting in the central part of LANL are made based on these studies and on other work in the area.

SETTING

Pajarito Mesa is a roughly east-west trending mesa bounded by Pajarito Canyon to the north and Threemile Canyon to the south (Fig. 1). The mesa top elevation at the trenches decreases from 7300 ft (2226 m) at the west to 7180 ft (2189 m) at the east. The width of the mesa varies from about 200 to 400 m at the trenches, being narrowest to the east adjacent to a small tributary canyon of Threemile Canyon. The trenches are all located within 40 m of the mesa-top drainage divide, typically within less than 15 m. The mesa-top gradient averages about 3% (1.7° slope), although it shows significant local variations (Fig. 3). The western and eastern trenches are located on relatively gentle parts of Pajarito Mesa, with average gradients of about 2.3% and 2.1% (1.3° and 1.2°), respectively, with a steeper area in between that averages about 4.6% (2.6°).

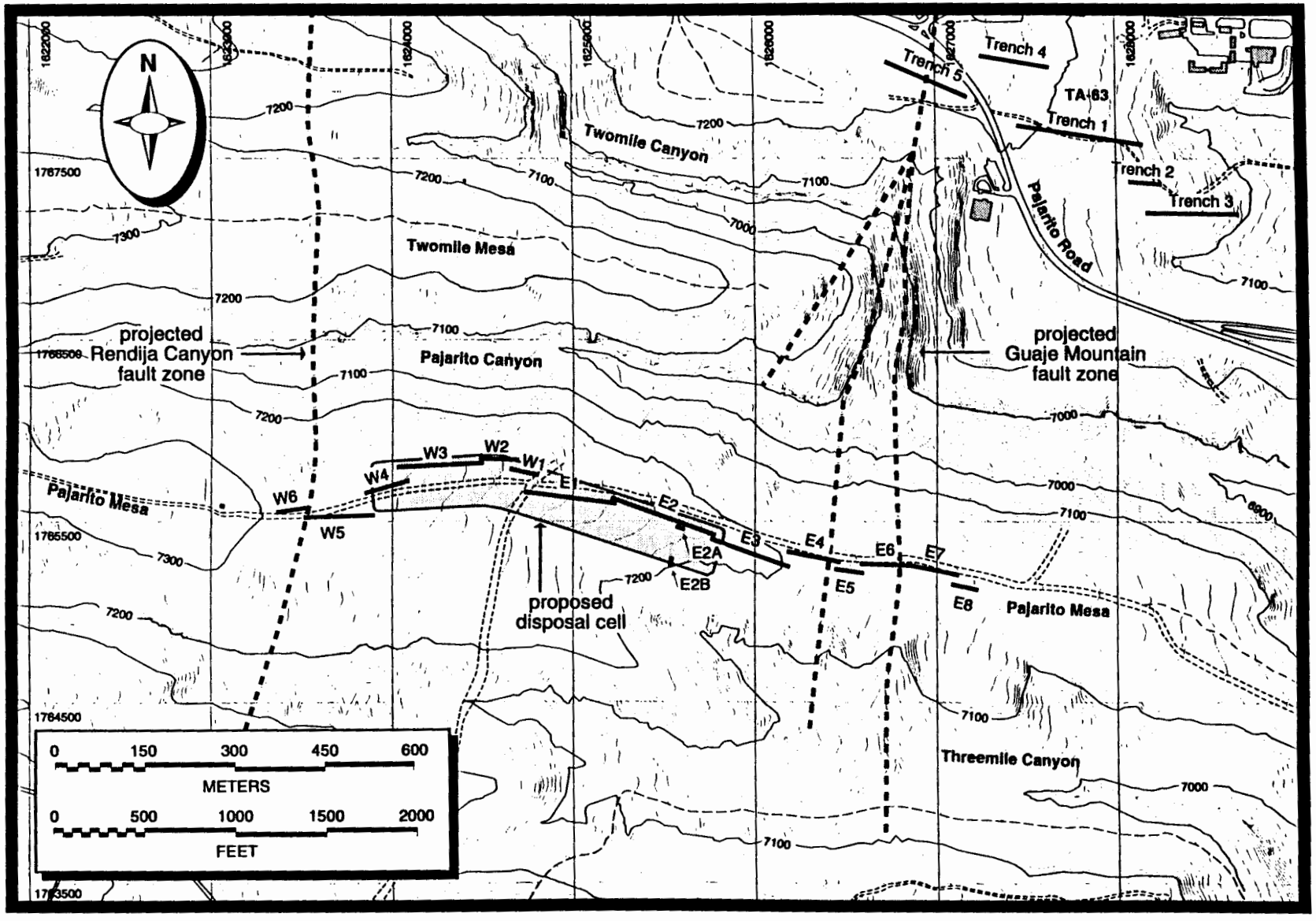

Fig. 1. Map showing trench locations on Pajarito Mesa and at TA-63 (thick solid lines), proposed MWDF disposal cell (shaded area), and projected fault traces (thick dashed lines). Projected fault traces from Vaniman and Wohletz (1990); note that fault projections east of the proposed disposal cell are eliminated in this report (see section by Vaniman and Chipera). Topographic base from FIMAD, showing NAD 83 coordinates and 10-ft contour intervals.

Fig. 2. Photograph of trench during excavation.

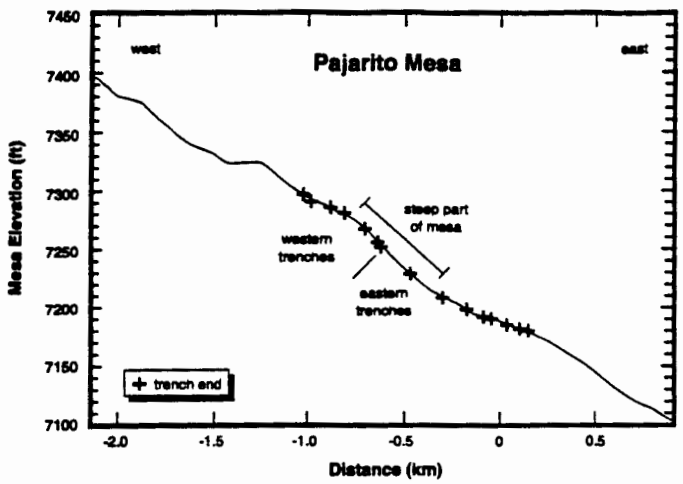

Fig. 3. Longitudinal topographic profile of Pajarito Mesa. Crosses indicate location of end-points of each trench. Profile trends N85W, with the topographic crest of the mesa projected to the profile line. Topography from FIMAD maps with 2-ft contour intervals. Distance is relative to the confluence of Pajarito and Twomile Canyons.

Bedrock at Pajarito Mesa consists of several units of the Tshirege Member of the Bandelier Tuff that were erupted from the Jemez Mountains about 1.22 Ma (million years ago) (Izett and Obradovich, 1994). Tshirege Member unit 4 is exposed in trenches W1 to W6 and part of E1, and the underlying unit 3 is exposed in the eastern trenches (bedrock units from Vaniman and Wohletz, 1990, and Broxton et al., this report). Units 3 and 4 are separated by volcanic surge beds which are best exposed on Pajarito Mesa to the south of the mesa-top drainage divide. The surge beds are also exposed in trench E1 at the base of unit 4, and are present over short distances in trenches E2 and E6 as clasts within a basal soil layer that is composed largely of disrupted tuff.

The climate at Pajarito Mesa is semi-arid, with estimated average annual precipitation of about 43 cm (17 in.). About 40% of the precipitation occurs in July and August during summer thunderstorms. Average annual snowfall is about 125 cm (50 in.) (Bowen, 1990). The vegetation is dominated by Ponderosa pine forest to the west, west of trench E1, and piñon-juniper woodland to the east.

SURFICIAL MATERIALS

Surficial deposits that range in age from early Quaternary (> 1 Ma?) to latest Holocene (< 1 ka) overlie the Tshirege Member of the Bandelier Tuff in the Pajarito Mesa trenches. The stratigraphic units as logged by Kolbe et al. (1994) are shown schematically in Fig. 4. Units 5a, 5c, and 5b of Kolbe et al. (Fig. 4) correspond to Tshirege Member unit 4, unit 3, and the intervening surge beds, respectively. Units 4a to 4f of Fig. 4 includes early Quaternary alluvium and associated pumice beds. Units 3a to 3e are divisions of soils that underlie the ca. 50-60 ka El Cajete pumice. Unit 2c is undisturbed El Cajete pumice, unit 2b is disrupted (bioturbated) El Cajete pumice, and unit 2a is a soil B horizon that is developed within the disrupted pumice and in overlying deposits.

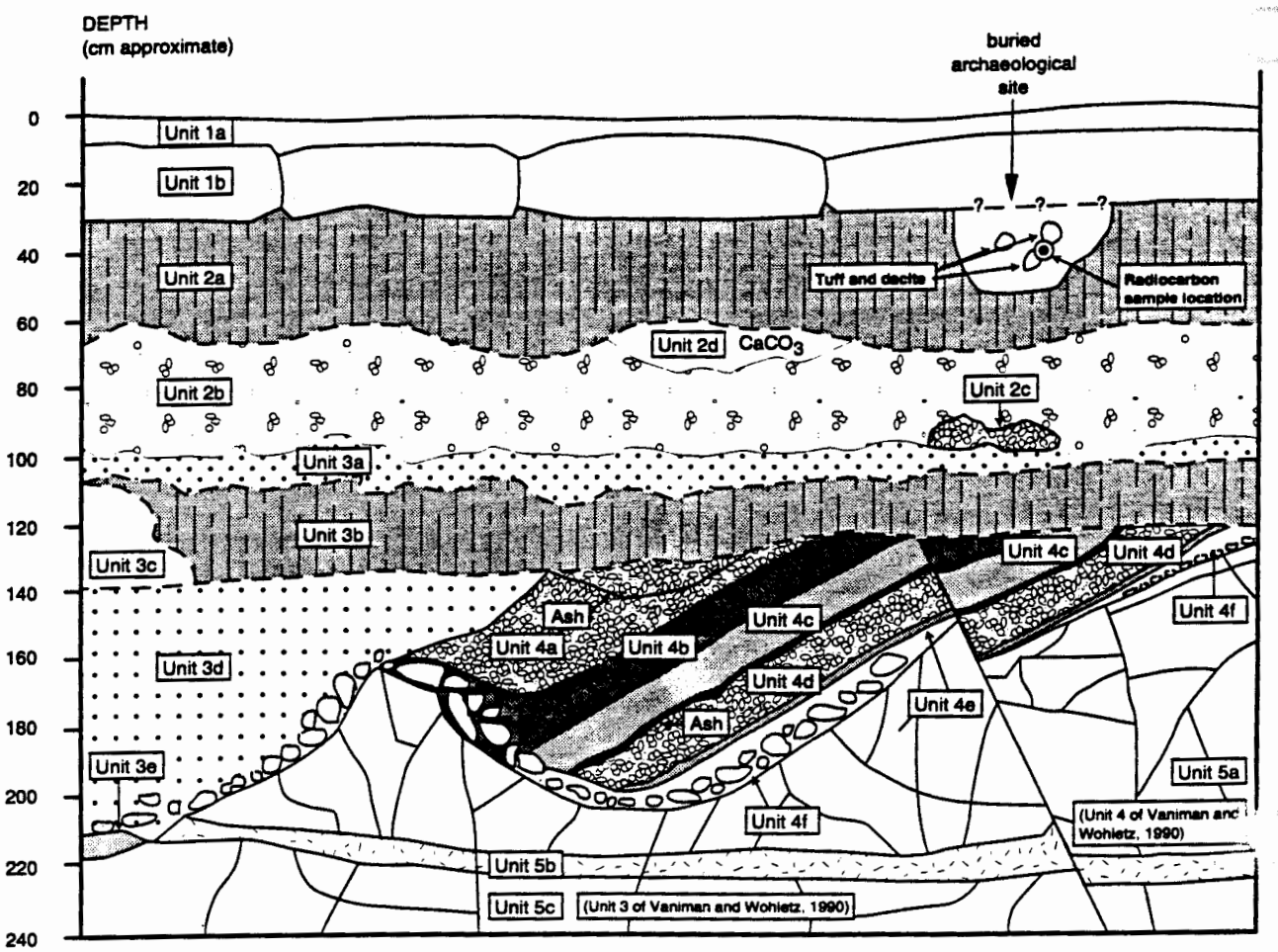

Fig. 4. Schematic composite log showing relations of units exposed in Pajarito Mesa trenches, modified from Kolbe et al. (1994). Unit designations discussed in text.

Units 1a and 1b of Kolbe et al. (1994) are the uppermost units at Pajarito Mesa, and are locally associated with or overlie buried archaeological sites. The soil units at Pajarito Mesa (units 1 to 3 of Fig. 4) display significant lateral variability in thickness and degree of soil development, as discussed below.

Radiocarbon Age Control

Age control for the soil units younger than the El Cajete pumice is provided by radiocarbon dating of charcoal contained within these units. Radiocarbon dates in this study were converted to calibrated calendar ages using the computer program of Stuiver and Reimer (1993) to correct for the effects of fluctuations in the $^{14}C/^{12}C$ ratio in the atmosphere. Calibrated ages are most useful when comparing radiocarbon ages with ages obtained from other methods, such as archaeological sites dated by dendrochronology. As part of the calibration, corrections to the reported ^{14}C dates were made for isotope fractionation (if this correction was not made by the dating laboratory), and an "error multiplier" was used to account for possible sources of laboratory error that were not included in the reported uncertainties. The correction for isotope fractionation used in this report assumes an average $\delta^{13}C$ value of -23.7 ± 1.3‰ based on analyses of 57 samples from the Pajarito Plateau. Eighteen analyses from Pajarito Mesa (Tables 1 and 2), included within the larger data set, provide a similar average $\delta^{13}C$ value of -24.2 ± 0.8‰.

TABLE 1. Radiocarbon Dates For El Cajete Pumice and Related Units

Field Number	Laboratory Number *	^{14}C Date (yr B.P.)	$\delta^{13}C$ (‰)	Pretreated Sample Weight (g or mg)	Ref **
Samples from El Cajete Pumice, Jemez Mountains					
-	W-1553	> 42,000	-	-	1
RP-1	QL-4629	> 58,000	-22.3	16.5 g	2
RP-25	QL-4645	50,100 ± 1300 #	-22.1	17.2 g	2
RP-47	QL-4727	57,200 + 4100/ -2700	-21.7	19.2 g	2
RP-51	QL-4728	> 54,100	-22.1	19.8 g	2
RP-47	Beta-68851/CAMS-10505	26,370 ± 270 #	-23.9	0.7 mg	2
RP-47c	Beta-70684/CAMS-11759	> 47,640	-22.4	10.7 mg	2
Samples from underlying stratigraphic units, Pajarito Plateau					
WTT1-1D	Beta-55313/CAMS-3715	> 47,500	-24.0	66.8 mg	3
WTT1-5	TO-3413	19,070 ± 160 #	-	37.0 mg	3
WTT2-1	Beta-60220	22,420 ± 690 #	-	350 mg	3
E3 RCS 5	Beta-68838	> 46,570	-	4.4 g	4
E7 RCS 1	Beta-68839/CAMS-10497	10,030 ± 50 #	-23.0	286.5 mg	4
E8 RCS 2	Beta-68841/CAMS-10498	> 45,400	-23.7	2.9 mg	4

* Laboratory designation: Beta = Beta Analytic Inc., Miami, Florida; CAMS = Lawrence Livermore National Laboratory, Livermore, California; QL = Quaternary Isotope Laboratory, Seattle, Washington; TO = IsoTrace Radiocarbon Laboratory, Toronto; W = U. S. Geological Survey, Reston, Virginia.
**References: 1 = Bailey et al., 1969; 2 = S. L. Reneau and J. N. Gardner, previously unpublished data 3 = Wong et al., 1995; 4 = Kolbe et al., 1994.
Date believed to be too young due to contamination of sample or of stratigraphic unit with young carbon.

Inclusion of an "error multiplier" in the calibration of radiocarbon dates is recommended by some radiocarbon dating laboratories to incorporate uncertainties not included in the reported laboratory uncertainty (e.g., Stuiver and Reimer, 1993). The uncertainties in ^{14}C dates reported by the analytical laboratories (Tables 1 and 2) are based solely on counting statistics and may not accurately reflect the ability of a single lab or multiple labs to reproduce a ^{14}C age on a single sample. A recent international interlaboratory comparison indicated that an error multiplier of about 2 was typical for laboratories that participated in the study (Scott et al., 1990), and an error multiplier of 2 is therefore used in this study, although the study of Scott et al. (1990) showed that even this relatively conservative value may not encompass all sources of laboratory error. Although there is not yet a consensus on the most appropriate error multiplier, other recent studies have similarly chosen a value of 2 (e.g., Nelson, 1992, Plafker et al., 1992).

Mesa-Top Alluvium

Deposits of stratified pumice-rich alluvium, consolidated fluvial sand beds, and thin ash layers (unit 4 of Fig. 4) were exposed in trenches W3, W4, and W5, immediately overlying Tshirege Member unit 4 . The pumice beds (units 4a and 4d of Fig. 4) are often pure, and may in part represent fluvial reworking of fallout deposits soon after their eruption. Scattered rounded cobbles of Tschicoma Formation dacite are present in the sand beds, particularly in the trench W3 deposits. These alluvial deposits are up to at least 1.4 m thick, but their tops have been eroded and the original thickness is thus unknown. The alluvial layers in trench W5 dip 5° to 20° to the east, much steeper than the mesa top or Bandelier Tuff stratigraphic contacts (1° to 3°), suggesting that they have been tectonically tilted. Erosional unconformities also exist within the alluvium, and east of the 33 m point in trench W5 units 4c to 4f had been eroded prior to deposition of unit 4b (Fig. 5).

TABLE 2. Radiocarbon Dates From Post El Cajete Units, Pajarito Mesa

Field Number	Laboratory Number *	^{14}C Date (yr B.P.)	$\delta^{13}C$ (‰)	Calibrated Age ***	Pretreated Sample Weight (g or mg)	Depth (m)	Trench Location (m)
Unit 1b Soils							
E1 RCS1a-b	Beta-69121	modern	-24.9	post-1955 A.D. #	0.32 g	0.15	17-27
W3 RCS1a-d	Beta-69123	70 ± 90	-23.6	0 # cal BP (0-500 #) 1955 # cal AD (1450-1955 #)	0.37 g	0.18	143
E3 RCS4	Beta-68837 CAMS-10496	540 ± 60	-23.9	540 cal BP (310-680) 1410 cal AD (1270-1640)	14.2 mg	0.22	142
E5 RCS3	Beta-72977 CAMS-13705	600 ± 60	-23.5	620-560 cal BP (330-730) 1330-1400 cal AD (1220-1620)	114.6 mg	0.14	25
W2 RCS3a-c	Beta-69122 CAMS-10753	710 ± 50	-23.4	660 cal BP (520-780) 1290 cal AD (1160-1430)	263.4 mg	0.18	54-61
Potential Archaeological Sites							
W4 RCS5	Beta-70683	420 ± 70	**	500 cal BP (660-0 #) 1450 cal AD (1290-1954)	3.2 g	0.35	28
E8 RCS1	Beta-68840	760 ± 50	**	680 cal BP (550-920) 1280 cal AD (1030-1400)	1.8 g	0.5	7
W4 RCS1	Beta-68844 ETH-11894	895 ± 55	-23.7	784 cal BP (651-1051) 1166 cal AD (899-1299)	481 mg	0.8	6
W4 RCS3a	Beta-70682	920 ± 50	**	900-800 cal BP (1060-670) 1050-1150 cal AD (900-1290)	13.9 g	0.8	17
W4 RCS4	Beta-68846	970 ± 70	**	930 cal BP (660-1230) 1030 cal AD (720-1290)	1.1 g	0.35	57
W4 RCS6	Beta-72978	1020 ± 70	**	940 cal BP (1270-670) 1010 cal AD (680-1280)	1.6 g	0.5	16
W5 RCS1	Beta-72979	2750 ± 70	**	2860 cal BP (3260-2500) 900 cal BC (1310-550)	2.0 g	0.4	84
W3 RCS4	Beta-69124 CAMS-10754	8770 ± 50	-24.9	9840-9680 cal BP(9980-9490) 7890-7740 cal BC (8030-7540)	31.1 g	0.34	144
E5 RCS2a	Beta-72976 CAMS-13704	9270 ± 50	-25.2	10290-10210 cal BP (10540-10010) 8340-8270 cal BC (8590-8060)	24.2 mg	0.4	51
E1 RCS2	Beta-68833 CAMS-13704	9490 ± 90	**	10490-10770 cal BP (10040-11000) 8540-8820 cal BC (9050-8090)	1.4 g	0.46	92
E1 RCS2a	Beta-70681 CAMS-11758	9470 ± 60	-23.9	10470 cal BP (10960-10150) 8520 cal BC (9000-8200)	61.1 mg	0.46	92

TABLE 2. Radiocarbon Dates From Post El Cajete Units, Pajarito Mesa (cont.)

Field Number	Laboratory Number *	^{14}C Date (yr B.P.)	$\delta^{13}C$ (‰)	Calibrated Age ***	Pretreated Sample Weight (g or mg)	Depth (m)	Trench Location (m)
Unit 2a Soils							
W2 RCS2	Beta-68842	1870 ± 60	-23.7	1820 cal BP (1530-2060)	20.0 mg	0.4	23
	CAMS-10499			140 cal AD (114BC-424AD)			
W2 RCS4	Beta-68843	3090 ± 60	-23.8	3270-3340 cal BP (2950-3560)	1.8 mg	0.5	50
	CAMS-10500			1390-1330 cal BC (1610-1000)			
E2 RCS9	Beta-68836	9400 ± 60	-24.4	10370 cal BP (10040-10910)	16.7 mg	0.5	169
	CAMS-10495			8420 cal BC (8960-8090)			
E4 RCS2	Beta-72975	11,590 ± 60	-24.9	13520 cal BP (13860-13230)	2.1 mg	0.5	68
	CAMS-13703			11570 cal BC (11910-11280)			
W1 RCS2	Beta-70139	25,920 ± 230	-25.0	too old for calibration	1.9 mg	0.75	48
	CAMS-11247						
E2 RCS6	Beta-68835	28,330 ± 170	-26.0	too old for calibration	7.0 mg	0.46	43
	CAMS-10494						
E2 RCS4&7	Beta-68834	30,070 ± 210	-24.5	too old for calibration	2.6 mg	0.47	69
	CAMS-10493						

* Laboratory designation: Beta = Beta Analytic Inc.; CAMS = Lawrence Livermore National Laboratory; ETH = Die Eidgenossische Technische Hochschule University, Zurich.

** Radiocarbon date was not corrected for $\delta^{13}C$.

*** Calibrated ages obtained using computer program CALIB 3.03 of Stuiver and Reimer (1993), which correct for long-term variations in the $^{14}C/^{12}C$ ratios in the atmosphere. These calibrated age ranges incorporate an error multiplier of 2.0 and 2σ uncertainty. Ages in ( ) are 2σ range. For samples that were not corrected for $\delta^{13}C$, the $\delta^{13}C$ value was assumed to be -23.7 ± 1.3 ‰ based on $\delta^{13}C$ values of 57 samples collected from the Pajarito Plateau.

# Denotes possible influence of ^{14}C resulting from atmospheric nuclear tests.

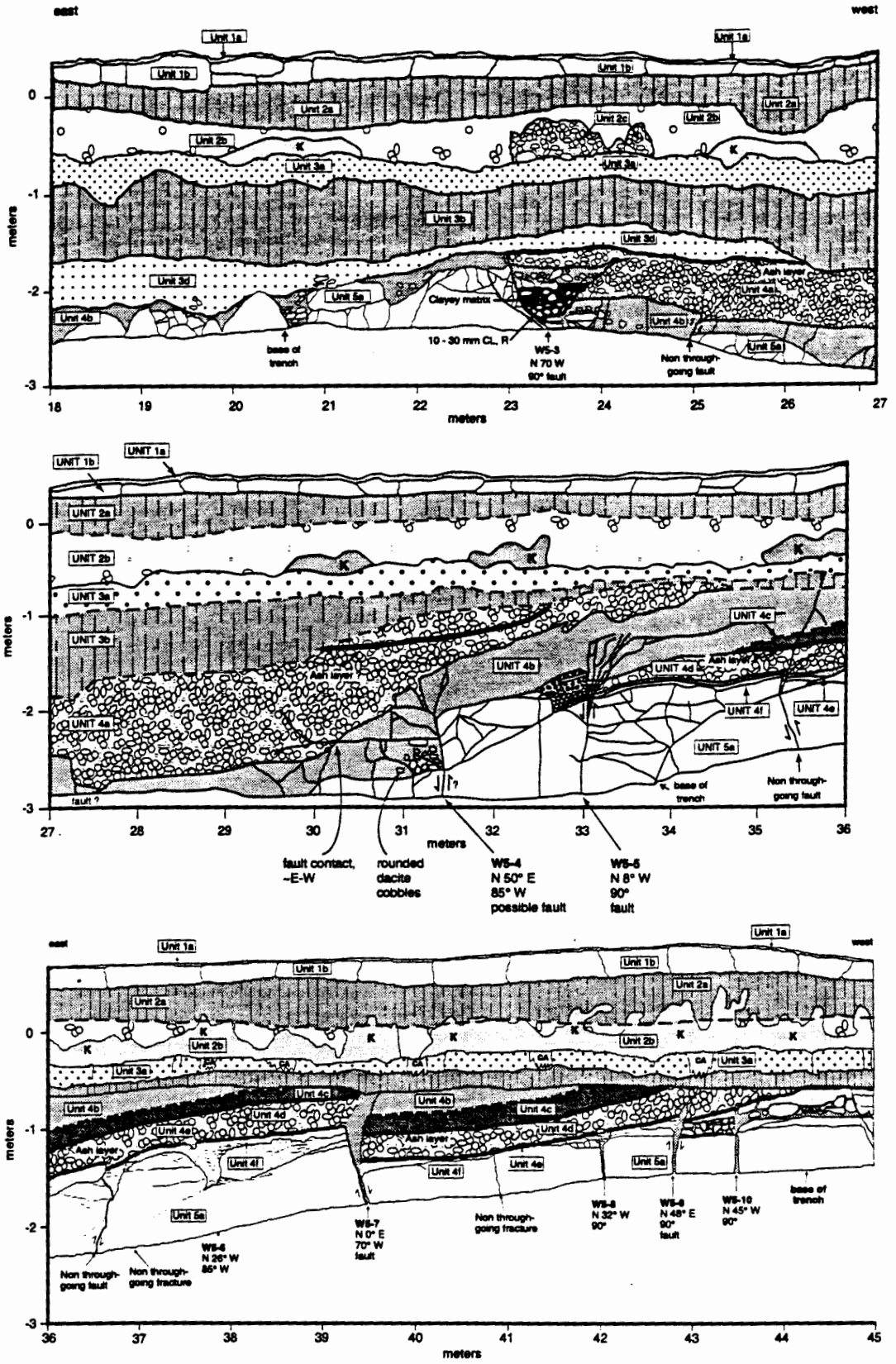

Fig. 5. Log of part of trench W5 from 18 to 45 m, showing alluvial stratigraphy and faults."K" indicates krotovina (animal burrow or root hole). Modified from Kolbe et al., 1994.

A paleochannel trending N75W was clearly exposed in trench W3, and other paleochannels trending obliquely to trenches W4 and W5 were recognized by contrasting stratigraphy between the opposite trench walls (Fig. 6). The paleochannels in trenches W4 and W5 have similar estimated orientations of N80W ± 10° and N60W ± 30°, respectively (Fig. 7).

The pumices in the alluvium are part of a series of pre-El Cajete, post-Bandelier pumice fall deposits that have been recently recognized at other locations on the Pajarito Plateau. These pumices may have originated from eruptions in the Valles caldera that closely post-dated caldera formation. A $^{40}Ar/^{39}Ar$ date of 1.25 ± 0.01 Ma from pumices overlying the Bandelier Tuff near the Guaje Pines Cemetery, 6 km north of Pajarito Mesa (Laughlin et al., 1993), is very similar to a revised $^{40}Ar/^{39}Ar$ date of 1.22 ± 0.02 Ma for the Tshirege Member of the Bandelier Tuff (Izett and Obradovich, 1994), and supports this interpretation. The mineralogy and chemical composition of the Pajarito Mesa pumices indicate that they represent several different eruptions, and stratigraphic relations elsewhere on the Pajarito Plateau indicate that the pumice beds at Pajarito Mesa are younger than the dated Guaje Pines beds (D. E. Broxton, personnel communication, 1994), although the range in age of the pumices is presently unknown. Because of the local abundance of the pumice in the alluvium, the alluvium is believed to be similar in age to the pumice and probably older than 1 Ma.

Patches of stream-rounded cobbles and boulders also occur along both the north and south sides of Pajarito Mesa (Qoal; Fig. 7). The clasts range up to at least 0.9 m in size and are primarily composed of Tschicoma Formation dacite, derived from the Sierra de los Valles, and a small percentage (about 5%) of Bandelier Tuff. Similar gravels are now being deposited only in the major canyons, such as Pajarito Canyon, that originate in the Sierra de los Valles. The dacite gravels occur both on top of Tshirege Member unit 4 to the west, and on top of the resistant part of unit 3 to the east, at a height of 60 to 75 m above the bottom of Pajarito Canyon. The gravels are typically found on the sloping edges of the mesa, resting on Bandelier Tuff bedrock (Figs. 7 and 8).

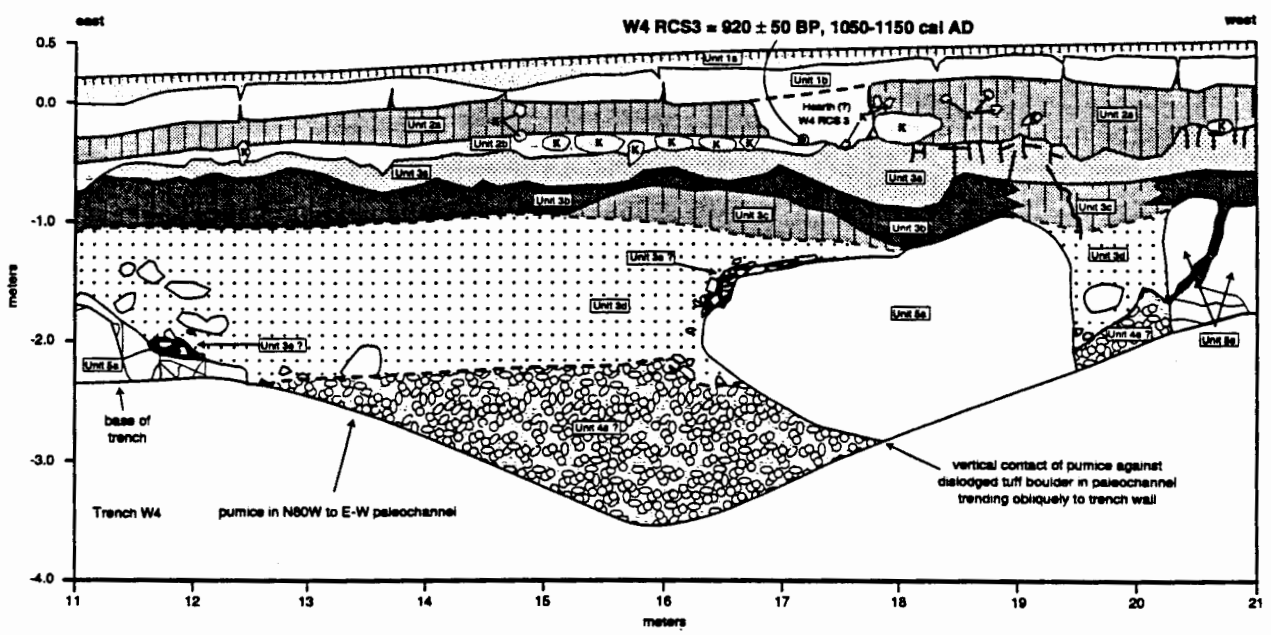

Fig. 6. Log of part of trench W4, showing early Quaternary pumice-rich alluvium (unit 4a?) within a paleochannel. The unit 5a (Tshirege Member unit 4) block at 16.5 to 19.5 m apparently partially collapsed from the west wall of the paleochannel. The eastern contact of this block with the unit 4a pumice trends N80W. Also shown in this sketch is the W4 RCS3 sample site, an inferred archaeological site that contained charcoal dated at 1050 to 1150 A.D. "K" indicates krotovina (animanl burrow or root hole). Modified from Kolbe et al. (1994).

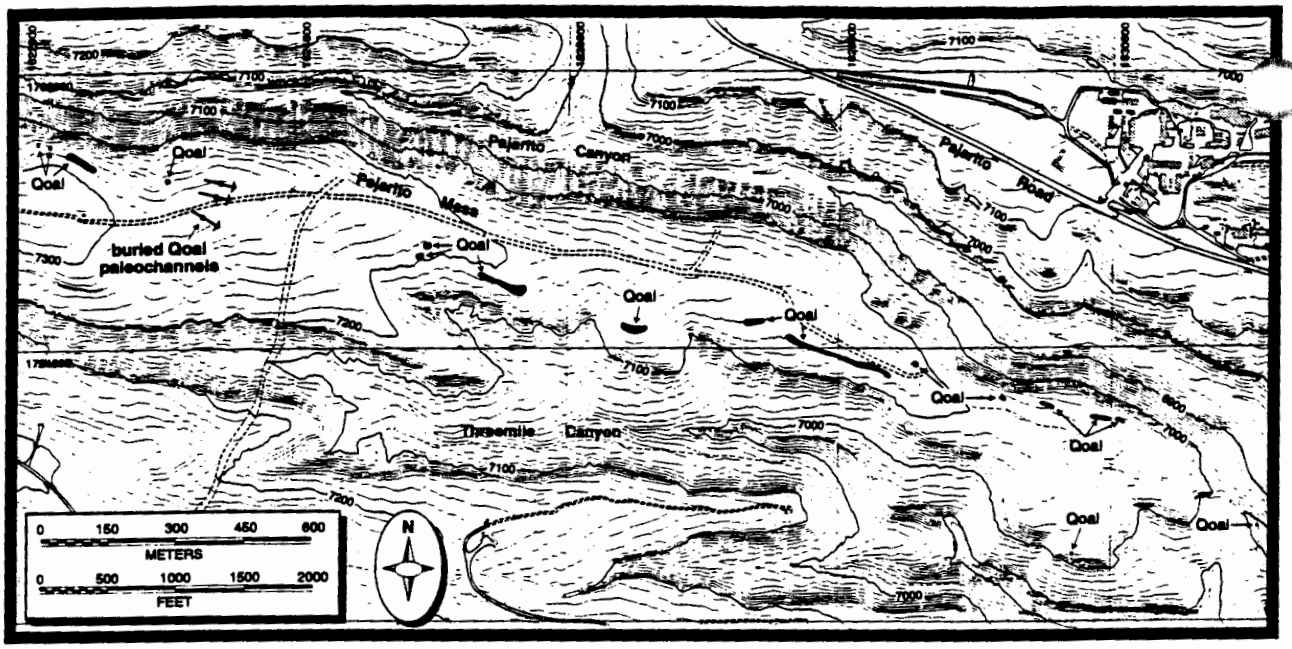

Fig. 7. Map showing location of mesa-top alluvial gravels on Pajarito Mesa (black areas labeled Qoal) and estimated orientations of paleochannels (arrows) exposed in trenches W3, W4, and W5. Topographic base from FIMAD, showing NAD 83 coordinates and 10-ft contour intervals.

The thickness of these deposits was not determined, but may range up to 0.5 m or more. It is notable that the gravel patches are aligned along a general trend of about N70W to N75W that is similar to the orientations of the paleochannels which were exposed in trenches W3, W4, and W5 This similarity suggests that most of the gravel patches may record the location of a discrete paleochannel or closely-spaced paleochannels.

The absence of rounded dacite gravels in most of the trenches was unexpected, given their abundance on the mesa edges, and a short exploratory trench (trench E2B, Fig. 1) was excavated through one of the gravel patches to investigate their stratigraphic context. The dacite clasts exposed in trench E2B are scattered within both a lower clay-rich soil and an unconformably overlying upper soil that is correlative with the Holocene soils exposed in the main trenches (Fig. 9). Notably, the highest concentration of dacite clasts observed in this trench occur within the upper soil, and supports the interpretation that they represent a lag deposit left after extensive erosion of an older alluvial deposit.

The dacite-bearing alluvial deposits on Pajarito Mesa are interpreted as deposits from the Pajarito Canyon drainage basin that pre-date incision of the canyon on this part of the Pajarito Plateau, during which time stream channels spread out over the top of the Bandelier Tuff. A source in the present Pajarito Canyon basin is inferred from the mapped distribution of these gravels, with their western outcrops on the north side of Pajarito Mesa, adjacent to the rim of Pajarito Canyon. A source in the Pajarito Canyon basin is also suggested by the paleochannel orientations of N60W to N80W in trenches W3, W4, and W5 (Fig. 7). Abandonment of the old stream channels probably resulted from the headward erosion of Pajarito Canyon from its mouth at the Rio Grande, consolidating a diffuse drainage system, as interpreted for Los Alamos Canyon (Reneau, 1995).

Alluvial deposits and associated lag gravels similar to those present at Pajarito Mesa are widespread on the western Pajarito Plateau. Other localities include DP Mesa (Reneau, 1995), the Los Alamos County landfill (Wong et al., 1995), Los Alamos townsite (S. Reneau and J. Gardner, unpublished data), and Twomile Mesa (Longmire et al., 1995). Alluvial gravels have also been

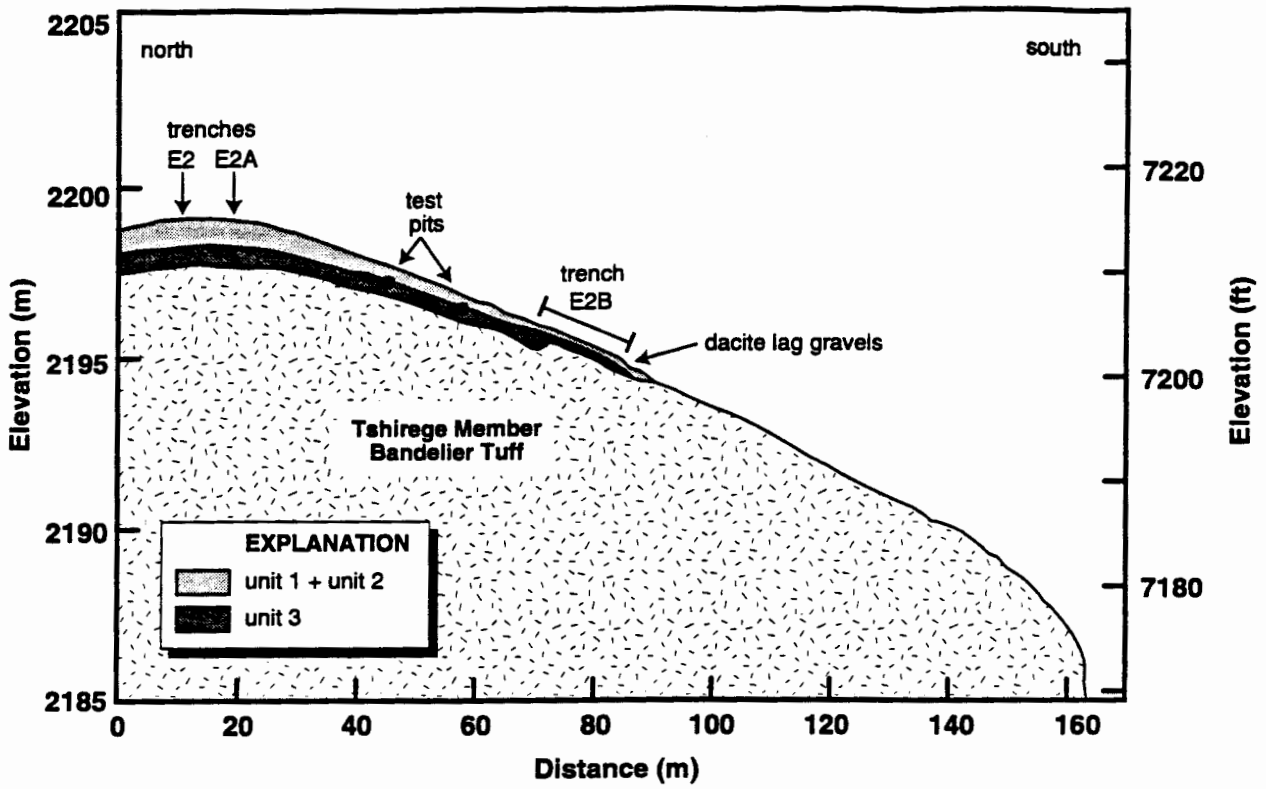

Fig. 8. North-south cross section across south side of Pajarito Mesa at trenches E2, E2A, and E2B, showing general variations in soil thickness.

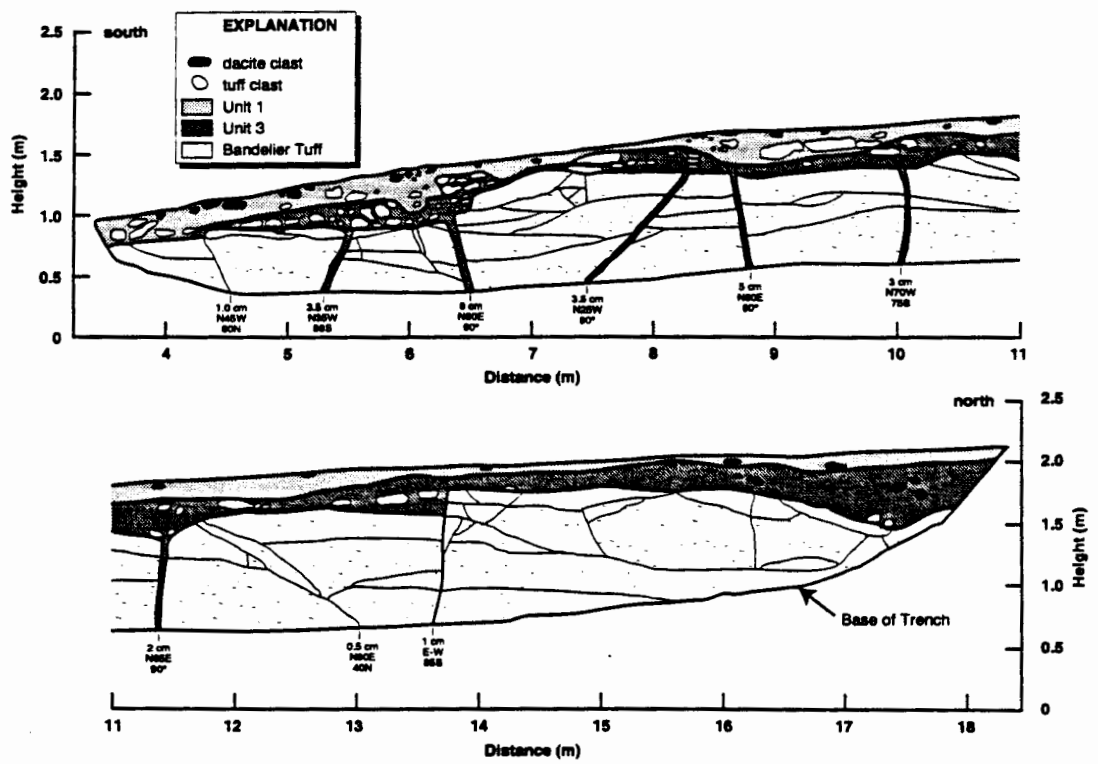

Fig. 9. Log of exploratory trench E2B excavated on south side of Pajarito Mesa, showing context of stream-rounded dacite cobbles as erosional lag deposits mixed into younger deposits. Units 1 and 3 in this trench are inferred to be correlative with units 1 and 3 of Kolbe et al. (1994).

found on the eastern Plateau, including Mesita del Buey at TA-54 (S. Reneau, unpublished mapping, 1994). These deposits were probably much more extensive at one time, and have been largely removed by erosion. For example, rounded dacite pebbles and coarse sand were found in fractures in a trench at TA-63, north of Pajarito Canyon (trench 1 of Kolbe et al., 1995; Fig. 1), indicating the former presence of a stream at that location, although no other evidence of alluvial deposits was found on that mesa.

Pre-El Cajete Soils

The lowermost soil units at Pajarito Mesa (units 3a to 3e of Fig. 4), occurring beneath the El Cajete pumice, show considerable variability in thickness and degree of soil development. The base of these units typically consists of a rubble zone of Bandelier Tuff clasts within a clay-rich matrix, although unit 3 locally overlies the mesa-top alluvium. Average thickness of pre-El Cajete soils exposed in the trenches ranges from 0.3 m in trenches W2 and W3 to 1.0 m in the east half of E1, and the maximum thickness exceeds 2.0 m in part of trench E1 (Fig. 10). The soils are composed of varying mixtures of weathered Bandelier Tuff, post-Bandelier alluvium and associated pumices, and eolian fine sand, silt, and clay. A significant component of wind-blown sediment is suggested by the textural similarity of much of unit 3 to overlying units 1 and 2, where the fine-grained fraction of deposits above the El Cajete pumice clearly have an eolian source. The local abundance of coarse sand-size quartz crystals also demonstrates that these soils include significant amounts of weathered Bandelier Tuff, and secondary silt and clay produced by *in situ* weathering of the tuff may also contribute to the fine-grained component of these soils. The relative contributions of eolian additions and *in situ* weathering to the fine fractions of the pre-El Cajete soils have not yet been determined.

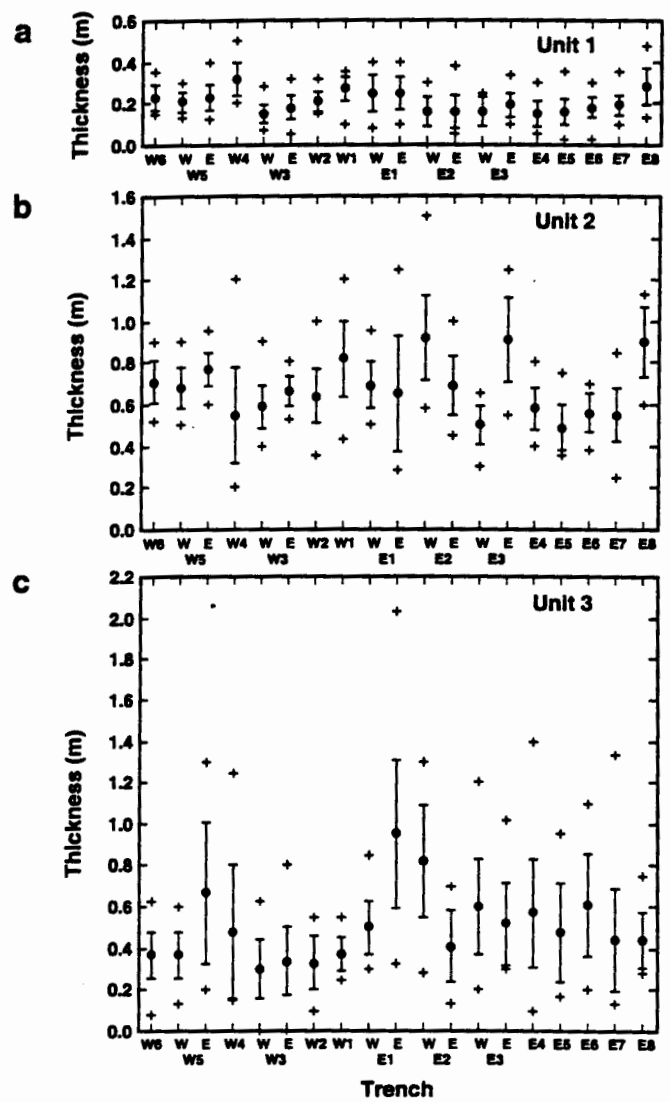

Fig. 10. Variations in thickness of a) unit 1, b) unit 2, and c) unit 3, in Pajarito Mesa trenches. Long trenches are divided in half. Measurements made from trench logs of Kolbe et al. (1994). Solid circles indicate mean values, bars indicate one standard deviation, and crosses indicate minimum and maximum values.

The pre-El Cajete soils typically include a well-developed soil B horizon (unit 3b of Fig. 4). This horizon is a reddish-brown clay or clay loam with coarse subangular blocky to prismatic soil structure (Kolbe et al., 1994). The degree of soil development in unit 3b, as shown by its color, clay content, and structure, is generally much greater than that present in the B horizon overlying the El Cajete pumice (unit 2a of Fig. 4), and suggests an extended period of stability of the mesa-top soils prior to deposition of the pumice. In places, including the area of

thickest pre-El Cajete soils in trench E1, an additional buried B horizon is locally present (unit 3e of Fig. 4).

The soil unit immediately beneath the El Cajete pumice (unit 3a of Fig. 4) is extremely well indurated and has an upper boundary that is typically very distinct in the trench exposures. Unit 3a locally has a distinctly hummocky upper surface, with these hummocks typically spaced about 0.4-0.5 m apart and with local relief of about 0.1-0.2 m. This unit is interpreted to constitute the soil A horizon that was buried by the El Cajete pumice. The induration may represent partial cementation with silica derived from weathering of the pumice, although this hypothesis has not yet been confirmed with laboratory analyses. A possibly correlative unit, which has a similar degree of induration, was observed in trenches 1 and 4 at TA-63 (unit 4 of Kolbe et al., 1995). However, no overlying pumice was present at TA-63 and this correlation has not been confirmed.

The cause of the significant variations in thickness of the pre-El Cajete soils (Fig. 10c) is not clear. Although surface erosion is generally expected to be greater on steeper slopes, where other factors are equal, the variations in thickness of the pre-El Cajete soils on Pajarito Mesa do not seem to be related to the variations in slope gradient on the mesa top (Fig. 3). For example, unit 3 on the steeper area, from the middle of trench W3 to the west end of trench E3, is typically similar in thickness to unit 3 in the gentler areas east and west (Fig. 10c). The area of thickest soils, in trench E1, may be at a site where a shallow mesa-top drainage, associated with the shallow mesa-top valley to the south, was completely filled with sediment. An analogous buried drainage was exposed in trench 1 at TA-63 to the north (Kolbe et al., 1995). Alternatively, the thicker unit 3 soils are in part associated with known or suspected areas of pre-El Cajete faulting, including the eastern parts of trenches W5 and E1, suggesting a local structural control. The evidence for faulting is discussed in a later section.

El Cajete Pumice

The El Cajete pumice, produced by the most recent volcanic eruptions from the Jemez Mountains, occurs along most of the length of the Pajarito Mesa trenches and constitutes an important stratigraphic marker. Deposits of undisturbed El Cajete pumice (unit 2c of Fig. 4) are up to 0.85 m thick in trench E8 (Fig. 11), but the tops of the deposits are probably eroded and the original thickness is unknown. The absence of outcrop-scale sorting or obvious stratigraphic layers in these deposits suggests that they represent primary volcanic fallout. Translocation of clay into the pumice beds has resulted in post-depositional development of horizontal to sub-horizontal banding ("Bt lamellae", Fig. 11), a feature that is commonly observed in deposits of the El Cajete pumice on the Pajarito Plateau (for example, see Frijoles and Seaby series descriptions of Nyhan et al., 1978, p. 24 and 29).

The pumice in trench E8 is the thickest deposit of El Cajete pumice yet found in the central part of LANL, although deposits up to 1.2 m thick were exposed 6 km west in a trench along West Jemez Road south of Cañon de Valle (Wong et al., 1995), and 2.2 m of primary fallout pumice occurs 6 km south on Frijoles Mesa, in TA-49 (Longmire et al., 1995). The axis of the El Cajete dispersal plume was towards the southeast, south of Pajarito Mesa (Self et al., 1988, 1991), and deposits of pumice should thus become thicker to the south.

The El Cajete pumice has been extensively disturbed at Pajarito Mesa. In most trenches only small scattered patches of undisturbed pumice remain (e.g., 23-25 m in trench W5, Fig. 5), although clasts of pumice are generally abundant in the overlying soils. The disturbed pumice was designated as unit 2b (Fig. 4). The percentage of the length of each trench that contains undisturbed pumice is typically 1% to 8%, although several trenches contain no undisturbed pumice and one trench, E8, has pumice along almost 90% of its length (Fig. 12). The disturbance and incomplete preservation probably reflects a combination of bioturbation of the deposits by burrowing animals,

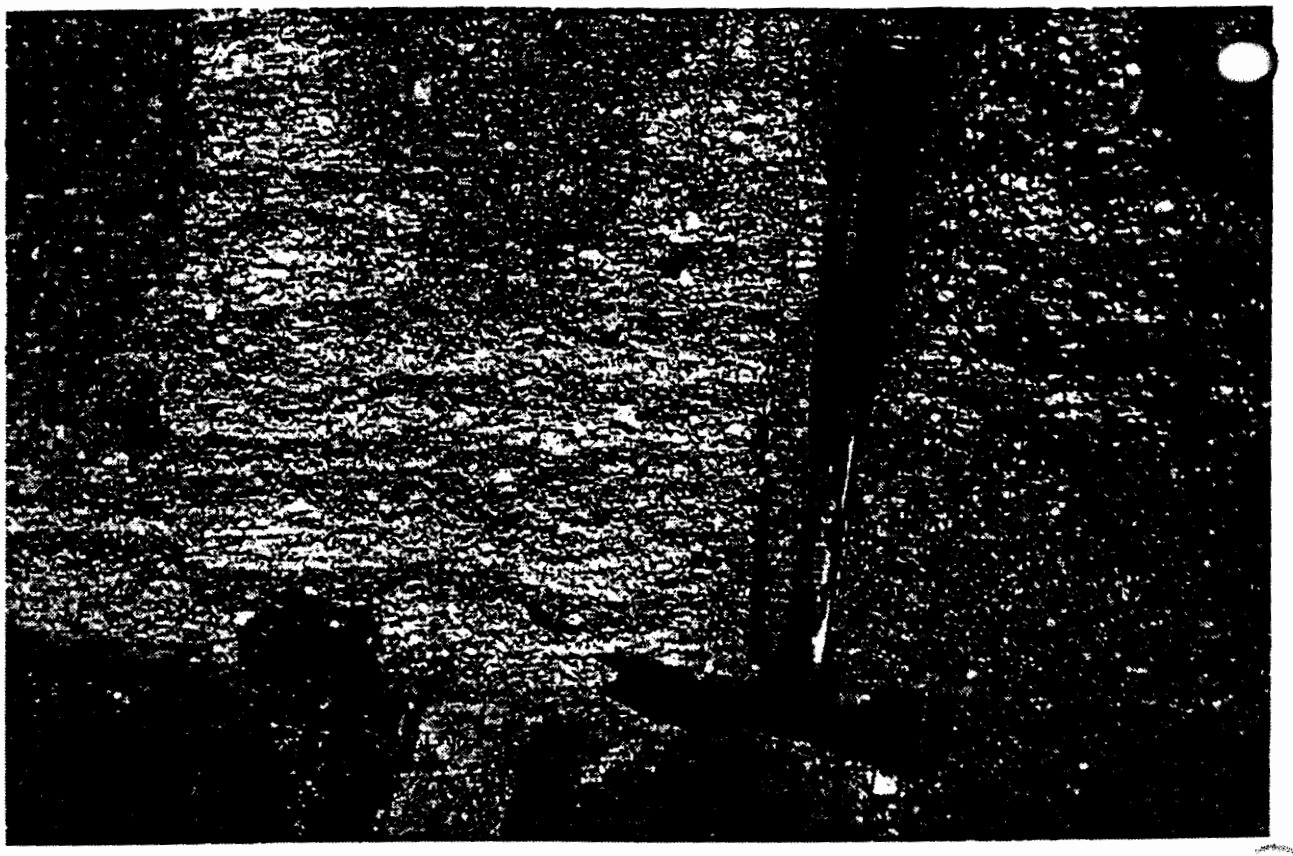

Fig. 11. Photograph of El Cajete pumice in trench E8. Sub-horizontal bands ("Bt lamellae") reflect post-depositio. translocation of clay into the pumice beds. Hammer rests on top of buried unit 3a soil horizon.

root growth and decay since deposition, and erosion by surface runoff. The reason for the anomalously great extent of El Cajete pumice in trench E8 is not certain, but its preservation may be related to reduced surface erosion on a relatively gently sloping part of Pajarito Mesa.

Age of Pumice

Conflicting ages have been obtained for the El Cajete pumice. Fission-track ages on zircon crystals from the pumice and related volcanic units in the Jemez Mountains range from 130 to 180 ka (Marvin and Dobson, 1979; Miyachi et al., 1985), with a weighted average of 146 ± 27 ka. $^{40}Ar/^{39}Ar$ analyses on biotite crystals from the pumice and related units have yielded ages of 205 to 1300 ka (Self et al., 1991), but these probably reflect xenocrystic contamination and all of these ages are apparently too old. Recent electron spin resonance (ESR) analyses suggest significantly younger ages of 45 to 73 ka (Toyoda et al., 1995). These younger ages are generally consistent with thermoluminescence (TL) age estimates of 57 ± 5 and 61 ± 5 ka (1σ uncertainty) for a colluvial deposit buried beneath the pumice along West Jemez Road, and 48 ± 5 to 52 ± 5 ka from the unit 3a soil immediately beneath the pumice in trench E8 (Table 3; S. Forman, written communication, 1995). Additional age constraints are provided by radiocarbon analyses of charcoal that was entrained within the pumice beds in the Jemez Mountains. Four analyses of material from the same bed by the Quaternary Isotope Laboratory, University of Washington, yielded ages ranging from 50.1 ± 1.3 to > 58 ka (Table 1). Because these ages are very close to the limit of conventional radiocarbon dating, and contamination with very small amounts of modern carbon would yield erroneous "finite" ages, these analyses probably indicate an age of > 58 ^{14}C ka, although there is the possibility of a finite age (M. Stuiver, personnel communication, 1993). At

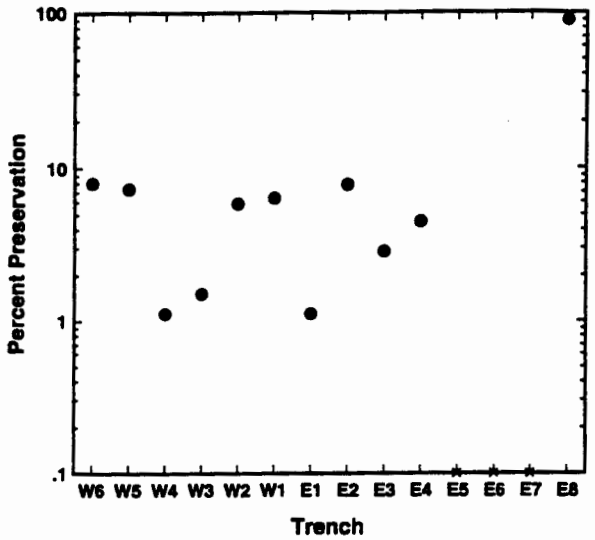

Fig. 12. Variation in preservation of primary fallout El Cajete pumice deposit (unit 2c of Fig. 4) along trenches. Vertical scale indicates percent of each trench length that contains any primary deposit; note logarithmic scale. No primary pumice was present in trenches E5, E6, or E7. Measurements made from trench logs of Kolbe et al. (1994).

present, we consider the best estimate of the age of the El Cajete pumice to be 50-60 ka based on the similarity of the ESR and TL age estimates and the ^{14}C age constraints.

Other analyses of charcoal from the El Cajete pumice and underlying stratigraphic units from the Jemez Mountains and the Pajarito Plateau have yielded ages of 10 to > 46 ka (Table 1). Four anomalously young ages of 10 to 26 ka indicate the presence of young carbon in these samples, introduced either in the field or in the laboratory, and illustrate some of the uncertainties that accompany radiocarbon dating. One of the anomalously young analyses, 26.37 ka, was on a very small split of a sample that had previously yielded a 57.2 ka age (Table 1), suggesting that laboratory contamination may in some cases be significant and that such small samples are particularly suspect. Some of the other young dates were from much larger samples, including a 10.03 ka date from trench E7 at Pajarito Mesa (Table 1), and contamination of these deposits with young carbon prior to sampling seems to have occurred. Possible sources of field contamination include younger roots that penetrated old charcoal fragments; the burning of roots that penetrated old deposits during surface fires, producing charcoal that is much younger than the deposit; and the transport of young charcoal into old deposits within animal burrows.

Post-El Cajete Soils

Soil units occurring above the El Cajete pumice (units 2b, 2a, 1b, and 1a of Fig. 4) vary significantly in texture, morphology, and age along the trenches. As logged by Kolbe et al. (1994),

TABLE 3. Thermoluminescence Data and Age Estimates Constraining the Age of the El Cajete Pumice *

Laboratory Sample Number	Equivalent Dose Method[1]	Light Exposure (Hours)[2]	Temperature Range (°C)[3]	Equivalent Dose (grays)	Estimated Water Content (wt %)	Dose Rate (grays/ka)[4]	TL Age Estimate (ka)[5]
West Jemez Road, Water Tanks Trench 1							
OTL-464	Total Bleach	16h sun	250-400	253.30 ± 5.02	25 ± 10	4.47 ± 0.34	57 ± 5
	Partial Bleach	1h sun	250-400	272.40 ± 3.39	25 ± 10	4.47 ± 0.34	61 ± 5
Pajarito Mesa, Trench E8							
OTL-528	Total Bleach	8h UV	250-360	197.24 ± 3.89	25 ± 10	4.10 ± 0.33	48 ± 5
OTL-516	Total Bleach	8h UV	250-360	242.90 ± 5.58	25 ± 10	4.76 ± 0.36	51 ± 5
OTL-515	Total Bleach	8h UV	250-360	217.50 ± 4.18	25 ± 10	4.18 ± 0.33	52 ± 5

* Thermoluminescence analyses provided by Steven Forman, Ohio State University. See Forman et al. (1993) for discussion of dating method.

[1] All TL measurements were made with a Corning 5/58 and HA-3 filters in front of the photomultiplier tube. Samples were preheated to 124°C for 48 hrs prior to analysis.

[2] Hours of light exposure to define residual level. "Sun" is natural sunlight in Columbus, Ohio. UV is light exposure from 275 watt General Electric ultraviolet "sunlamp".

[3] Temperature range used to calculate equivalent dose.

[4] Dose rates were calculated using values of K, Th, and U analyzed at the Ohio State University and the estimated water content. For samples from major stratigraphic contacts, the radionuclide contents from the overlying pumice and underlying soil were averaged.

[5] All errors are at one sigma and calculated by averaging the errors across the temperature range.

unit 2b generally consists of El Cajete pumice that has been disturbed by bioturbation (burrowing animals, root growth, etc.); unit 2a consists of a buried soil B horizon developed within the disturbed pumice or on overlying deposits; unit 1b consists of material deposited unconformably on top of unit 2a, which locally contains cultural material near Anasazi ruins; and unit 1a consists of the uppermost silty soils, largely deposited since Anasazi occupation. Unit 1 averages 0.1 to 0.3 m thick in the trenches, with a maximum thickness of 0.5 m (Fig. 10a), and unit 2 averages 0.5 to 0.9 m thick, with a minimum and maximum thickness of 0.2 and 1.5 m, respectively (Fig. 10b). Units 2a, 1b, and 1a are typically much finer grained than unit 2b, with high concentrations of fine sand and silt, and they record the deposition of substantial amounts of wind-blown sediment on Pajarito Mesa since the El Cajete eruptions.

Field observations and radiocarbon ages indicate that unit 2a varies significantly along the trench exposures, and contains a complex history of sediment deposition, soil development, and erosion. Ages obtained from unit 2a are 26 to 30 ka in trenches E2 and W1, 11.6 ka in trench E4, 8.8 to 9.5 ka in trenches E1, E2, E5, and W3, and 1.8 to 3.1 ka in trench W2 (Table 2). Sketches of some of the radiocarbon sample sites are shown in Fig. 13, and possible stratigraphic relations between unit 2a deposits in different parts of the trenches are shown in Fig. 14. Although it is possible that some of the younger dates reflect contamination of the deposits with young carbon, the variations in apparent ages are associated with lateral variations in soil characteristics, and none of the unit 2a dates can be clearly rejected. The available data suggest that incorporation of some wind-blown sediment into disturbed El Cajete pumice deposits prior to 26 to 30 ka was followed by a period of relative stability of the mesa top, during which time soil development progressed. Soil development may also have been in part concurrent with eolian deposition, resulting in a cumulative soil profile. These older unit 2a deposits had been locally eroded prior to deposition of younger fine-textured unit 2a deposits in trenches E1 and E2 at about 9.5 ka. Significant erosion of mesa-top soils after 9.5 ka has also probably occurred, although it is not possible to determine the total amount of erosion.

The early Holocene unit 2a deposits (9-10 ka) may represent either a separate period of eolian influx or, less likely, extensive local reworking of older deposits. A time of major climatic transition began about 11 ka in the southwestern United States, when vegetation associated with wetter Pleistocene climates was replaced by plants more typical of modern climates (Spaulding et al., 1983; Van Devender et al., 1987). These climatic changes probably affected the depositional history on Pajarito Mesa. Specifically, the transition to a drier climate and accompanying vegetation changes may have increased the susceptibility of both the Pajarito Plateau and lower elevation areas to the south and southwest to wind erosion, and thereby increased eolian input to mesas on the Plateau. The unit 1 deposits may similarly reflect either additional eolian input in the last 1000 years, or else significant erosion and redeposition of older sediments, perhaps associated with disturbance of the mesa top by Anasazi cultivation or historic grazing. More data on the age and characteristics of the post-El Cajete soils are needed to evaluate these hypotheses.

All of the unit 2a deposits have probably been affected by local disturbances since deposition, such as by burrowing animals, root growth, and tree toppling, which would contribute to heterogeneity within each unit 2a depositional unit. For example, within an area of generally poorly-developed unit 2a soils in trench W1, field examination indicated the local occurrence of deposits that appeared much more indurated, presumably reflecting stronger soil development. One of these more indurated sites yielded an age of about 26 ka (Table 2), suggesting that small patches of older deposits can locally exist within younger soils after extensive bioturbation of these horizons.

The combined thickness of units 1 and 2 on Pajarito Mesa averages 0.6 to 1.2 m along the trenches, with minimum and maximum thicknesses of 0.4 and 1.6 m, respectively (Fig. 15a). Because Pajarito Mesa was probably buried by an approximately uniform thickness of pumice at about 50-60 ka, significant spatial variations in net erosion since that time would presumably be

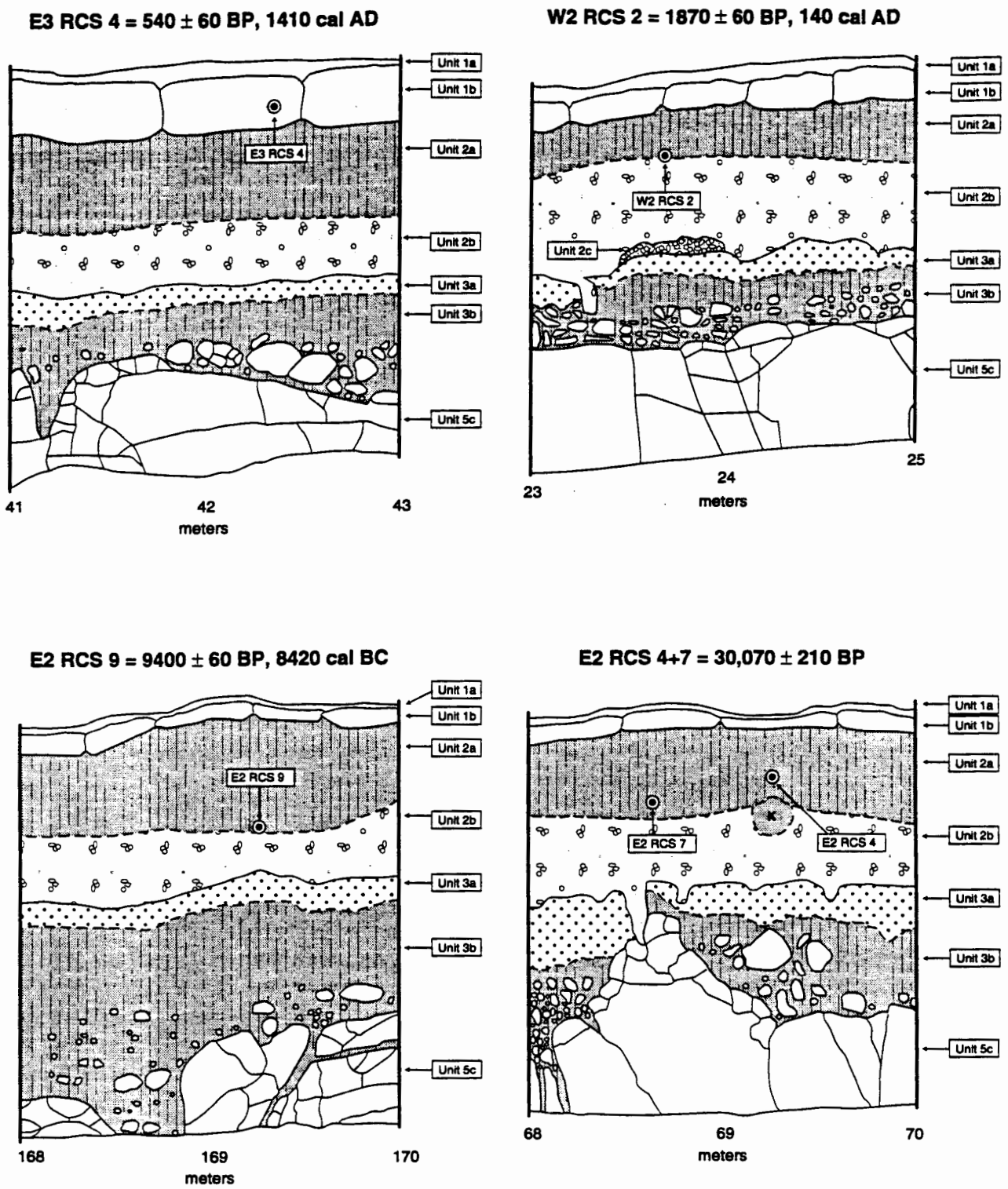

Fig. 13. Sketches of selected radiocarbon sample locations, from Kolbe et al. (1994). No vertical exaggeration.

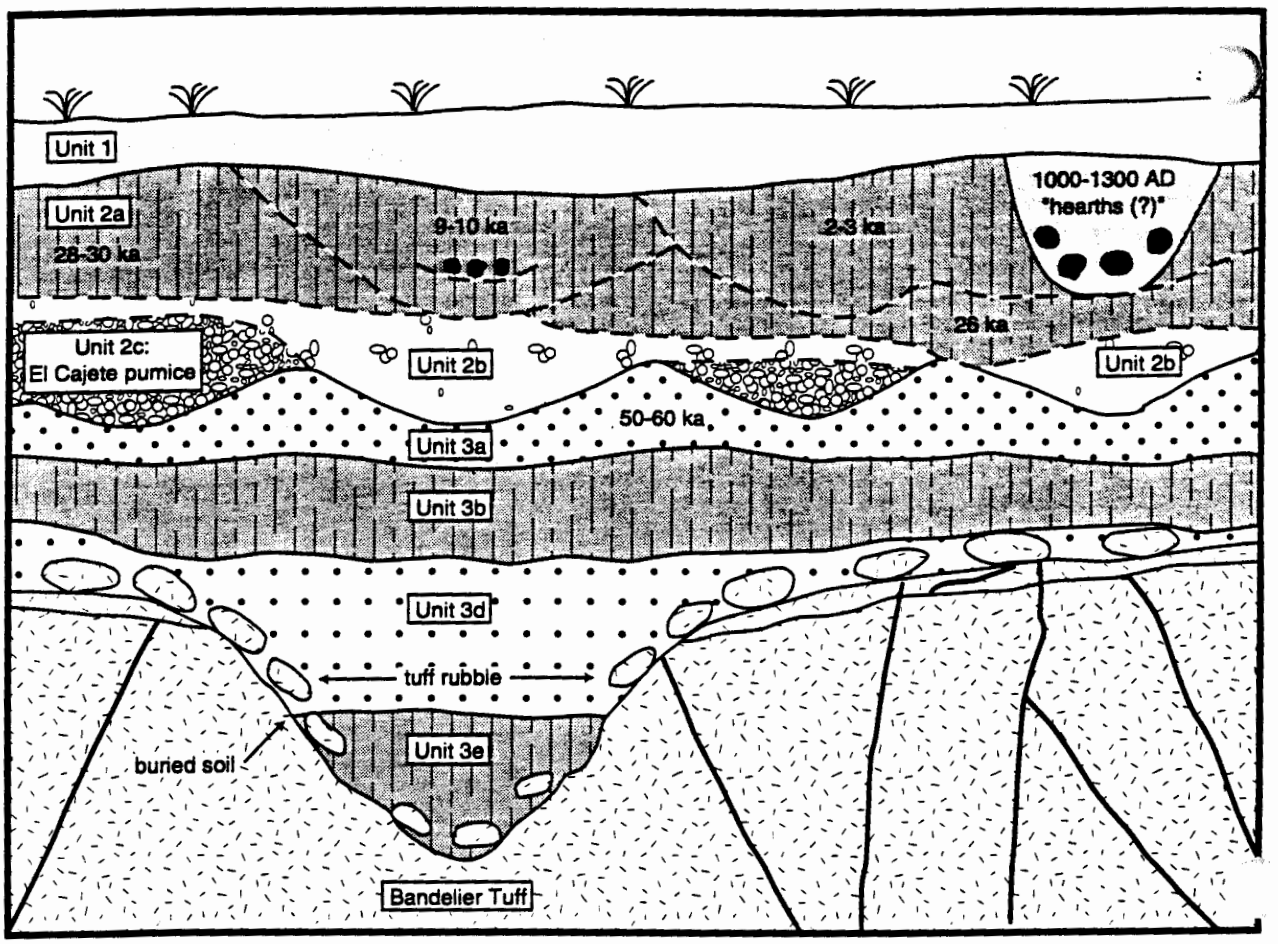

Fig. 14. Schematic sketch showing inferred stratigraphic relations of unit 2a packets in different parts of the Pajarito Mesa trenches.

recorded by variations in the total thickness of the pumice and younger units. Notably, no systematic variations in thickness occur related to the variations in the gradient of the mesa top, although slope gradient is an important variable in models developed to predict soil erosion rates (such as the Universal Soil Loss Equation, Wischmeier and Smith, 1978). Some of the thicker post-El Cajete soils, in trenches E1 and E2 (Fig. 15a), actually occur on a steep part of the mesa.

Proximity to the mesa edges seems to be a more important factor affecting net erosion than mesa-top gradient. The areas of thinnest soils occur along the eastern trenches where the mesa is narrowest (Fig. 1), although local areas of thicker soils are also present to the east (e.g., trench E8) (Fig. 15a). Clasts of El Cajete pumice are very rare in trenches E6 and E7, and presumably this reflects extensive local erosion prior to deposition of the finer-grained unit 2 sediments. Greater erosion towards the mesa edge, resulting in thinner soils, is also seen in a north-south transect across Pajarito Mesa that includes trenches E2, E2A, and E2B (Fig. 8). Unfortunately, because the original thickness of the pumice and younger eolian deposits on Pajarito Mesa is unknown, no calculations can be made of average long-term mesa-top erosion rates at this time.

It is significant that the last 700 to 1000 yr have been characterized by net deposition, not erosion, on the crest of Pajarito Mesa. Using the average thickness of unit 1 of about 0.2 m (Fig. 10) and the ages of 1290 A.D. or younger for the unit 1b deposits (Table 2), indicates an average deposition rate of about 0.3 mm/yr for the last 700 yr. There clearly has been great spatial anc

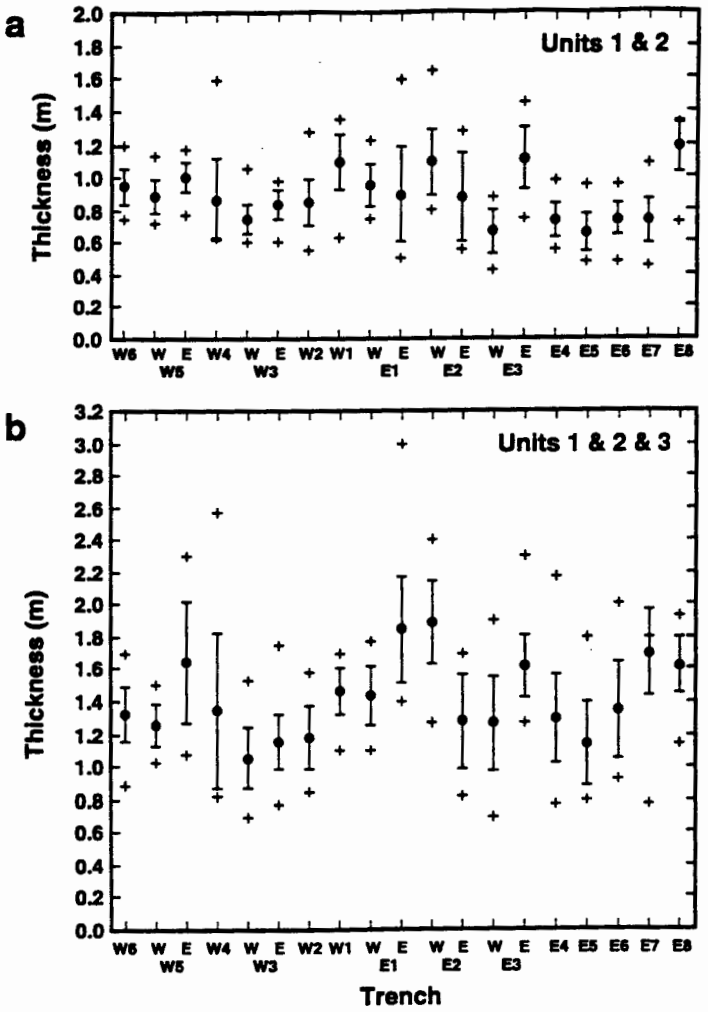

Fig. 15. Variations in total thickness of a) unit 1 plus unit 2, and b) units 1, 2, and 3, in Pajarito Mesa trenches. Long trenches are divided in half. Measurements made from trench logs of Kolbe et al. (1994). Solid circles indicate mean values, bars indicate one standard deviation, and crosses indicate minimum and maximum values.

temporal variability in surface processes on Pajarito Mesa, and the cause of this variability is not fully understood.

The history of mesa-top disturbance and erosion since deposition of the El Cajete pumice has apparently varied greatly between mesas on the Pajarito Plateau. For example, despite the ubiquitous presence of El Cajete pumice in the Pajarito Mesa soils (except for trenches E6 and E7), pumice clasts were completely absent in soils exposed by trenches at TA-63 only 0.8 km north, on a mesa top with similar slope gradients. However, El Cajete pumice was observed within a few fractures at TA-63 (Kolbe et al., 1995), demonstrating that it was once present there, and in addition the pumice has been found up to 2 km farther north. The lack of pumice in the TA-63 soils documents significantly greater net erosion there than on Pajarito Mesa since 50-60 ka, although the reasons for these variations in relative erosion rate are unknown.

Archaeological Sites

The Pajarito Mesa trenches exposed at least ten inferred archaeological sites that had no surface expression and were therefore not identified during archaeological surveys undertaken prior to trenching. These sites were generally recognized in the trench walls by the occurrence of dacite or tuff clasts in units otherwise barren of clasts (Figs. 6, 16, and 17). These clasts were commonly oxidized, and were typically associated with charcoal. Oxidized soil, providing further evidence of prehistoric fires, was seen in some sites, and baked clay was found at one site (W4 RCS4 sample site). Textural and structural differences between material within the sites and adjacent soils also helped delineate many of the sites. The archaeological sites exposed in the Pajarito Mesa trenches appear to cluster into two general temporal groups: a younger group associated with Anasazi occupation of the mesa and an older less distinct group dating to the pre-Anasazi Paleo-Indian period.

As logged by Kolbe et al. (1994), the younger sites were interpreted to be typically excavated into the unit 2 soils and to be overlain by unit 1b, although at least one site was logged as excavated through unit 1b and into unit 2 (W4 RCS1 site, Fig. 16). These younger sites are located within 100 m of small mesa-top ruins that have been assigned to the Coalition period (1100 to 1325 A.D.) and the Classic period (1325 to 1600 A.D.) of the Rio Grande Anasazi (Hoagland et al., 1994). Regional surveys have indicated that usage of mesas at this relatively high elevation peaked in the Late

Coalition period, 1250 to 1325 A.D., although it continued into the Late Classic period (1550 to 1600 A.D.) (Stuart and Gauthier, 1981; Orcutt, 1991). The calibrated calendar ages of charco collected from six sites in trenches W4 and E8 range from 1010 to 1450 A.D. (Table 2), and include dates that are in part older than expected from the surface archaeological survey. Although this may suggest previously unrecognized occupation of Pajarito Mesa during the Late Developmental period (900 to 1100 A.D.), the apparent discrepancy may instead reflect either the burning of relatively old wood by the Anasazi or the analytical uncertainties inherent in radiocarbon dating.

Radiocarbon ages obtained from unit 1b throughout the trenches are similar to or younger than the ages obtained from the Anasazi sites, with calibrated calendar ages from 1290 A.D. to post-1955 A.D. (Table 2). This supports the interpretation of Kolbe et al. (1994) from the trench logging that unit 1 is generally contemporaneous with or younger than the Anasazi occupation. A comparison of the calibrated radiocarbon data from the archaeological sites and from unit 1b is shown in Fig. 18. The data in Fig. 18 are calculated probabilities of the calibrated sample ages,

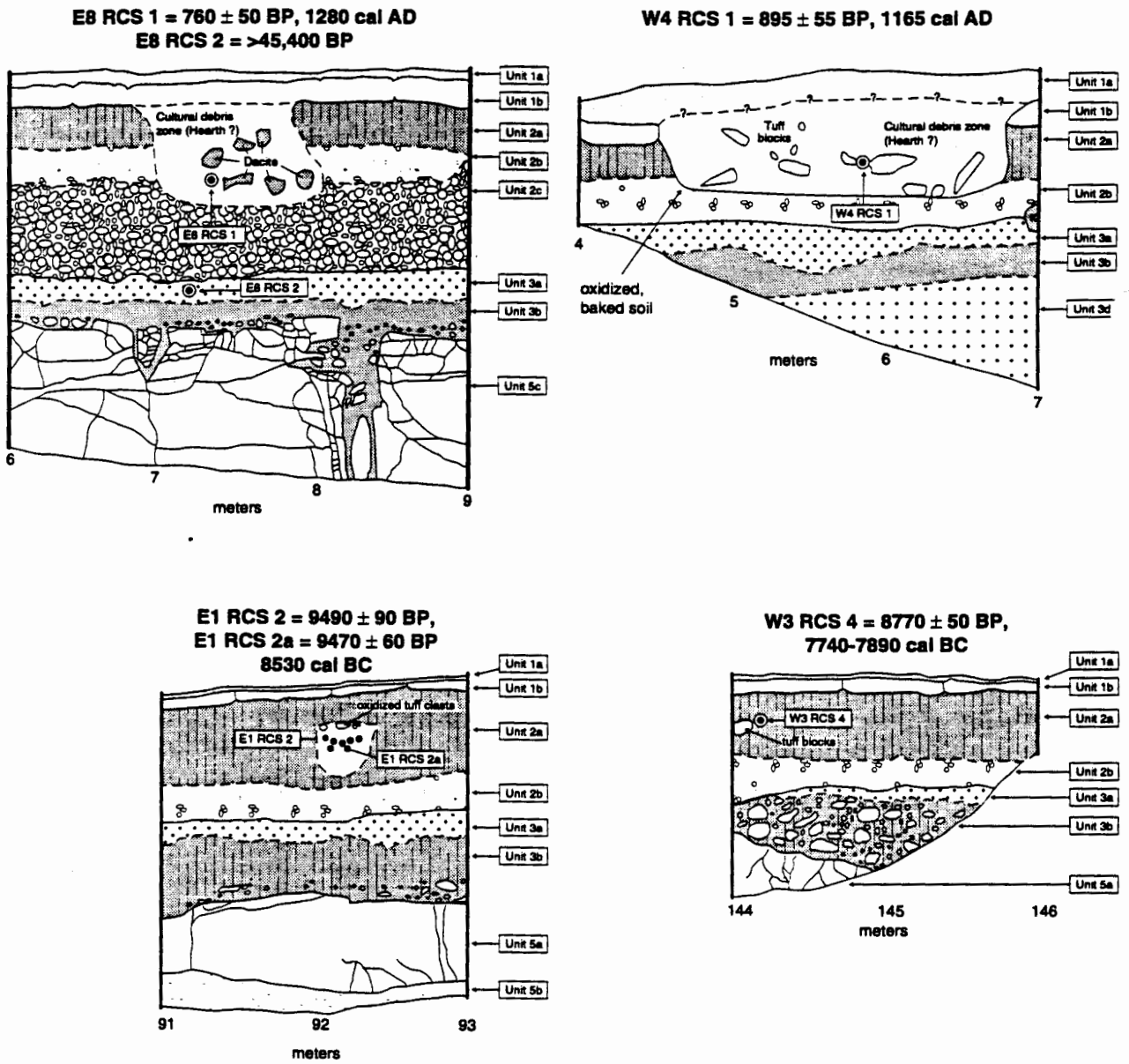

Fig. 16. Sketches of inferred archaeological sites exposed in Pajarito Mesa trenches, from Kolbe et al. (1994). No vertical exaggeration.

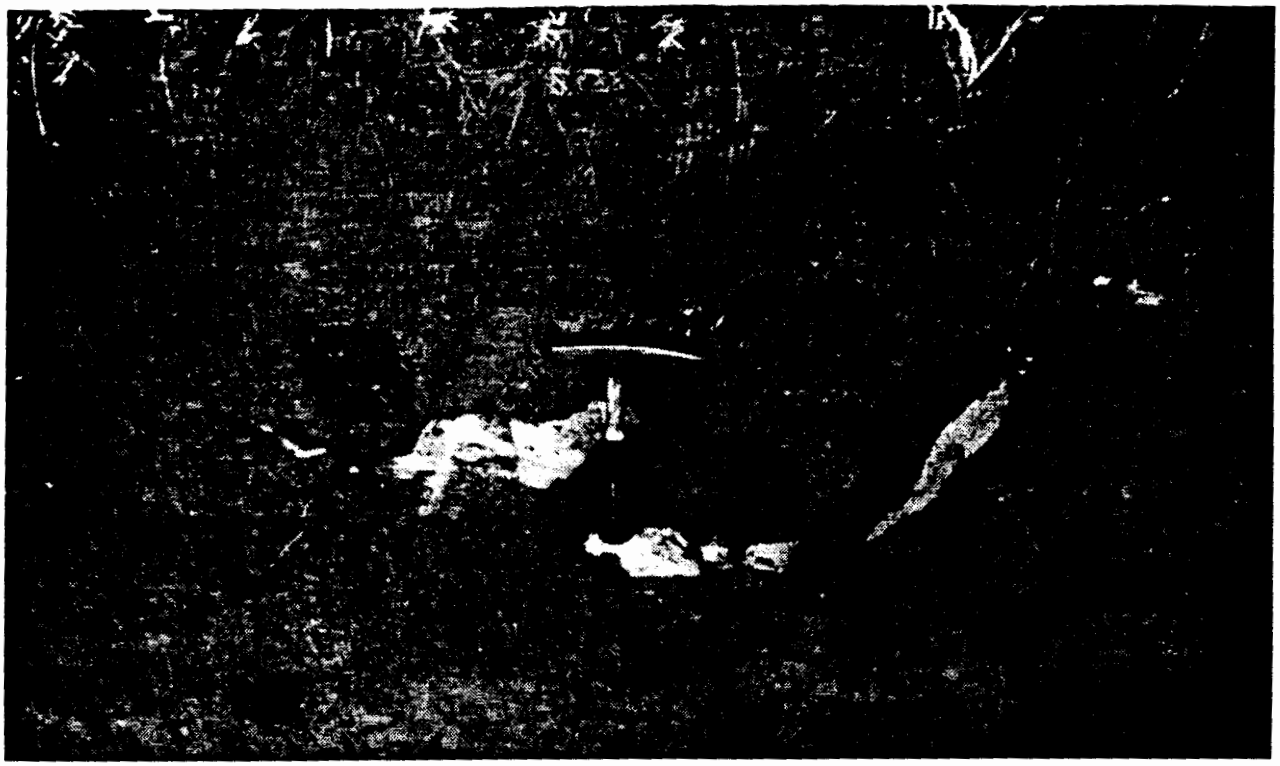

Fig. 17. Photograph of tuff blocks in buried archaeological site at trench W4 RCS1 sample site (1165 cal A.D.).

which show the relative probability that the true sample age is represented by specific calendar years. These data include the laboratory uncertainty of the true age of each sample and an error multiplier of 2.0, as discussed earlier. Other uncertainties, including the age of the wood when it was burned and possible contamination with younger carbon, are not included in these probabilities. Figure 18 shows that the typical unit 1b ages of 1300 to 1400 A.D. post date the typical ages of 1000 to 1300 A.D. from the archaeological sites. The 1300 to 1400 A.D. unit 1b ages suggest that much of this unit was deposited during the Classic period of the Rio Grande Anasazi, although it is not known whether deposition was directly related to Anasazi disturbances.

Three of the inferred sites, exposed in trenches E1, E5, and W3, at sites generally farther from ruins, yielded surprisingly old ages of about 8.8 to 9.5 ka (7740 to 8820 B.C.; Table 2). These ages correspond to the Paleo-Indian period in New Mexico (10,000 B.C. to 5500-4000 B.C.; ages from Cordell, 1979, 1984; Stuart and Gauthier, 1981; Hoagland et al., 1994), and would represent the oldest buried sites found on the Pajarito Plateau, although older Folsom points (ca. 10 to 11 ka) have been previously found on the Plateau (Steen, 1977, 1982). The trench E1 and E5 sites display the strongest evidence for pre-Anasazi occupation, with scattered heavily oxidized tuff clasts occurring within unit 2a, about 1 m higher than other tuff clasts in the soil (Fig. 16). Because of its potential archaeological significance, charcoal was re-collected from the E1 site after the first radiocarbon analysis had been completed, and a second analysis confirmed the accuracy of the 9.5 ka age (Table 2). The stratigraphy exposed in the trench walls at both the E1 and E5 sites suggests that the dated material represents shallow fire pits that were constructed during a period of early Holocene mesa-top aggradation, with the sites buried and preserved by continued deposition of fine-grained sediment. It is also possible that the fire pits were excavated into older deposits,

and that subsequent soil development has masked differences in deposit age. However, a similar radiocarbon age of 9.4 ka from a very similar deposit in trench E2 (E2 RCS9, Table 2) provides supporting evidence for an extensive period of aggradation at this time.

The 8.8 ka trench W3 site is more problematic, with non-oxidized tuff clasts occurring about 0.5 m above other clasts in the unit 3 rubble zone (Fig. 16). Biological disruption of this soil profile by a toppling tree, bringing tuff blocks up to the surface, cannot be ruled out. No artifacts were seen at the sites in trenches E1, E5, and W3, and a better understanding of their significance will require archaeological excavation.

One inferred archaeological site in trench W5, identified by the occurrence of oxidized tuff clasts in unit 2a, in association with abundant charcoal, yielded an intermediate radiocarbon date of 2.75 ka (900 B.C., Table 2). This date suggests an association with the Archaic period (6000-4000 B.C to 600 A.D.; ages from Cordell, 1979, 1984; Hoagland et al., 1994). However, although the tuff clasts indicate the presence of an archaeological site, the dated charcoal was unusually abundant and could conceivably represent a root burned in the soil either before or after occupation. The context of this date is therefore uncertain.

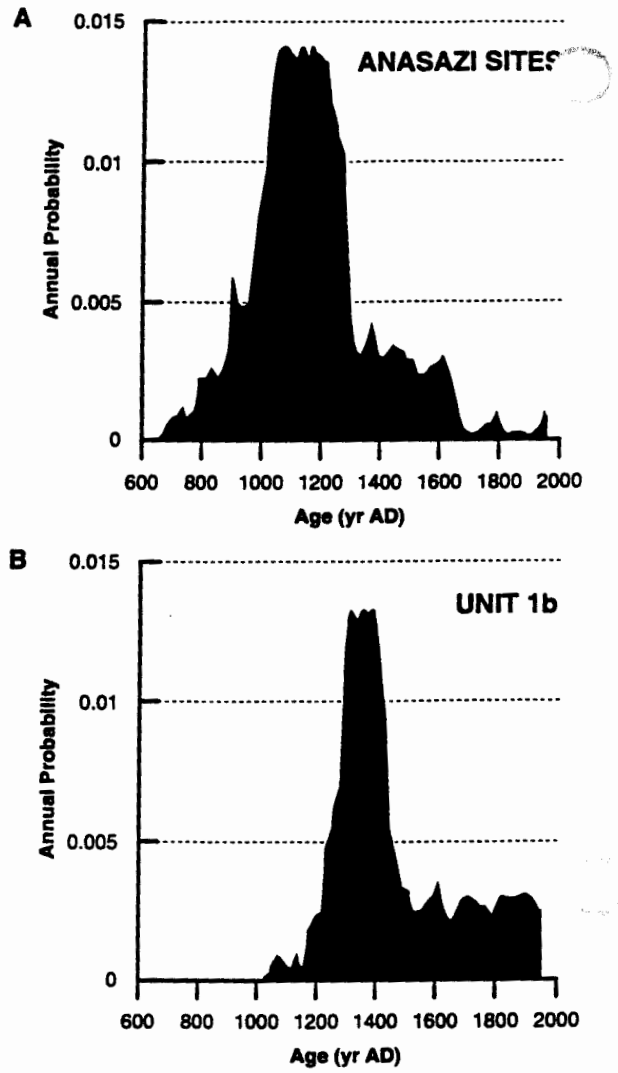

Fig. 18. Probability plots showing radiocarbon analyses from A) Anasazi sites in trenches E8 and W4, and B) unit 1b deposits in trenches W2, W3, E3, and E5. The probability data were obtained using the computer program CALIB 3.03 of Stuiver and Reimer (1993), and indicate the relative probabilities that the calibrated ages represent the actual sample ages. The plots represent the sum of the annual probabilities for each sample. The probabilities include both analytical uncertainties and uncertainties in calibrated ages due to variations in the $^{14}C/^{12}C$ ratio in the atmosphere over time.

Relation to Los Alamos County Soil Survey

The extensive transects of soils exposed in trenches at Pajarito Mesa (Kolbe et al., 1994), and also in the TA-63 area to the north (Fig. 1, Kolbe et al., 1995), provide an opportunity to check the general mapping units employed in the soil survey of Los Alamos County (Nyhan et al., 1978), and to place these mapping units in the context of the depositional history of the mesas.

The predominant soil series mapped along the crest of Pajarito Mesa, and also at the TA-63 trenches 1 and 4, is the Nyjack loam. As described: "Typically, the surface layer is a brown loam, very fine sandy loam, or sandy loam about 5 cm thick, and the subsoil is a brown clay loam about 50 cm thick. The substratum is a gravelly sandy loam about 40 cm thick, which may contain as much as 30% pumice. Depth to tuff bedrock and the effective rooting depth range from 50 to 102 cm" (Nyhan et al., 1978, p. 25). The surface layer, subsoil, and substratum as described by Nyhan et al. (1978) generally seem to correspond well to units 1, 2a, and 2b of Kolbe et al. (1994) at Pajarito Mesa, with the pumice referred to by Nyhan et al. (1978) being the El Cajete pumice. The main difference between the descriptions of Nyhan et al. (1978) and the trench data are in the depth to tuff bedrock, which at Pajarito Mesa ranges from

0.7 to 2.6 m and averages 1.0 to 1.9 m in the trenches (Fig. 15b), and in the occurrence of buried soils (unit 3 of Kolbe et al., 1994) which were not described by Nyhan et al. (1978). Notably, the soils at TA-63 trenches 1 and 4 are also mapped as part of the Nyjack series by Nyhan et al. (1978), yet the TA-63 soils (Kolbe et al., 1995) are strikingly different from the typical soils at Pajarito Mesa, with the complete absence of El Cajete pumice. The TA-63 soils thus either seem most similar to the Pajarito Mesa trench E6 and E7 soils, where El Cajete pumice clasts were rare, or with the Pajarito Mesa unit 3, which may have been exposed by erosion of the pumice and younger deposits.

Also mapped by Nyhan et al. (1978) at the Pajarito Mesa trench sites are Frijoles very fine sandy loam on the mesa top and Hackroy sandy loam on the southern mesa margins. The Frijoles series, as described by Nyhan et al. (1978), is similar to the Nyjack series in that it contains abundant pumice, but differs in "having formed in thick pumice beds" (Nyhan et al., 1978, p. 24), presumably in extensive areas of undisturbed El Cajete pumice such as were exposed in trench E8. In contrast, the description of the Hackroy series does not mention pumice and instead indicates a higher clay content. "The surface layer of the Hackroy soils is a brown sandy loam, or loam, about 10 cm thick. The subsoil is a reddish brown clay, gravelly clay, or clay loam, about 20 cm thick. The depth to tuff bedrock and the effective rooting depth are 20 to 50 cm" (Nyhan et al., 1978, p. 25). This description seems to agree well with the lower soils exposed in trench E2B on the south side of Pajarito Mesa (Fig. 9), and with the typical TA-63 soils of Kolbe et al. (1995).

As interpreted from the Pajarito Mesa trench exposures, the Frijoles series and Nyjack series constitute soils developed in eolian-deposited sediments above the El Cajete pumice during the last 50-60 ka. The original pumice deposits have been largely disturbed by bioturbation or stripped by erosion in the Nyjack soils, whereas more extensive areas of undisturbed pumice underlie typical Frijoles soils, although the soil mapping boundaries may not correspond to the actual boundaries of the pumice deposits. Frijoles soils are not mapped north of Pajarito Mesa (Nyhan et al., 1978), and this reflects the greater original thickness of El Cajete pumice on the southern Pajarito Plateau, closer to the axis of the dispersal plume (Self et al., 1988, 1991). Pumice, presumably the El Cajete, is also noted in the Seaby series (Nyhan et al., 1978), and may occur in other series as well. The Hackroy series is interpreted to typically constitute older clay-rich soils that were once buried by the pumice, with the pumice having been subsequently eroded. The thick deposits of post-El Cajete eolian-derived sediments have also apparently been eroded from areas mapped as the Hackroy series, in turn suggesting that these areas have a higher susceptibility to surface erosion.

These observations illustrate the general relationship of the mapped soil series to the geomorphic history of deposition and erosion on Pajarito Plateau mesas, and the utility of the soil survey in examining gross spatial variations in the geomorphic history of the mesas. However, it is clear that substantial variation in soil characteristics and soil thickness can occur within the mapping units of Nyhan et al. (1978), and that site-specific data are required to confirm the accuracy of the mapping units at any location.

STRUCTURE

Data on faulting at Pajarito Mesa have been obtained by several methods, including geologic mapping, logging of fractures and surficial units in the exploratory trenches, detailed surveying of a stratigraphic contact within the Bandelier Tuff, and examining bedrock and topographic profiles. Fault zones on this part of the Pajarito Plateau have been difficult to map and characterize because they seem to display relatively little post-Bandelier displacement (< 10 m) and because the fault offset may be dispersed along many fractures in zones hundreds of meters wide (Vaniman and Wohletz, 1990). In addition, the boundaries of most mapping units within the Bandelier Tuff are not

sharply defined, such as between welded and nonwelded tuff, making recognition of small offsets problematic. Fault offsets can be most precisely measured where distinct stratigraphic boundaries such as post-Bandelier alluvial layers or surge beds within the Bandelier Tuff, are exposed. In these cases offsets of 10 cm or less can be recognized and measured. However, exposures of the surge beds between Tshirege Member unit 3 and unit 4 at Pajarito Mesa are very discontinuous, with this contact being typically covered by colluvium, obscuring the stratigraphic evidence for or against faulting. In addition, the mesa-top alluvium was only exposed along a small fraction of the total trench length (45 m, or 3.4%), and faults that pre-dated the soil units may have been unrecognizable in most trench exposures. Because of these difficulties, data from geologic mapping and from the trench exposures were supplemented with km-long surveys of the surge beds along the south margins of both Pajarito Mesa and Twomile Mesa to the north, in order to evaluate possible dispersed deformation of the Bandelier Tuff. In addition, longitudinal profiles of bedrock in the trenches and of the mesa top were examined to further constrain possible deformation in areas where the surge beds are not present. Together, these methods allow a more complete evaluation of the location and amount of faulting at Pajarito Mesa, although many details remain unresolved.

Faulting of Surficial Units

The buried soil beneath the El Cajete pumice is generally continuous along the 1340 m of trench exposure, constituting an outstanding stratigraphic marker to constrain possible faulting over the last 50-60 ka. Although this soil has been locally disturbed, probably by burrowing animals and root growth, no tectonic deformation of the soil was recognized, documenting the lack of faulting during the past 50-60 ka on this part of Pajarito Mesa (Kolbe et al., 1994). Notably, this indicates that the most recent surface ruptures that were previously documented along the Guaje Mountain and Rendija Canyon faults to the north (Gardner et al., 1990; Kelson et al., 1993; Wong et al., 1993, 1995) either terminated somewhere north of Pajarito Mesa or were accommodated on other unrecognized fault traces to the east or west. This is consistent with the conclusion of Kolbe et al. (1995) that no Holocene faulting had occurred along the southern projection of the Guaje Mountain fault zone at the TA-63 trench sites north of Pajarito Mesa.

Faulting of post-Bandelier deposits on Pajarito Mesa has only been identified in trench W5, where seven discrete faults with at least 1.2 m of cumulative down-to-the-west offset were recognized over a distance of 20 m (Kolbe et al., 1994). These faults offset the pumice-rich alluvium (Figs. 5 and 19), which is presumably greater than 1 Ma in age. The faults typically were truncated upward at the base of unit 3, although one fault with 5 cm of offset could be traced as a clay-filled fracture into unit 3b (35.5 m, Fig. 5). The possible continuation of a fault into unit 3b indicates that multiple episodes of faulting may be recorded in the trench W5 fault zone, although the evidence for post-unit 3b faulting at that location is inconclusive. Additional evidence for possible recurrent movement in this fault zone is provided by the observation that offset on fault W5-5 may have occurred during deposition of unit 4b, whereas movement on other faults post-dated deposition of unit 4a (Fig. 5, Kolbe et al., 1994).

The faults are steeply dipping and show evidence of both normal and reverse movement. They typically branch upward within the alluvium into multiple splays. No slickensides were observed. Only four of the fractures displaying offset could be traced to the opposite trench wall, suggesting that the others transferred movement to intersecting fractures with different orientations, although the north trench wall was not logged and this inference was not tested. Strikes of the four continuous faults range from N70W to N-S to N48E, also suggesting a locally complex pattern of faulting.

Eastward tectonic tilting of the trench W5 alluvium is indicated by its relatively high dips of 5° to 20°, which is possibly associated with rotation of blocks west of a larger fault that was not recognized in the trenches. As discussed above, the mesa-top alluvium only occurs along a small

part of the total trench length, and pre-El Cajete faulting of similar magnitude to that documented in trench W5, if it was present, may not be recognizable elsewhere in the trenches because of the absence of suitable pre-El Cajete, post-Bandelier stratigraphic markers. The available trench data are thus insufficient to eliminate the possibility of faulting between 1.22 Ma and 50-60 ka elsewhere.

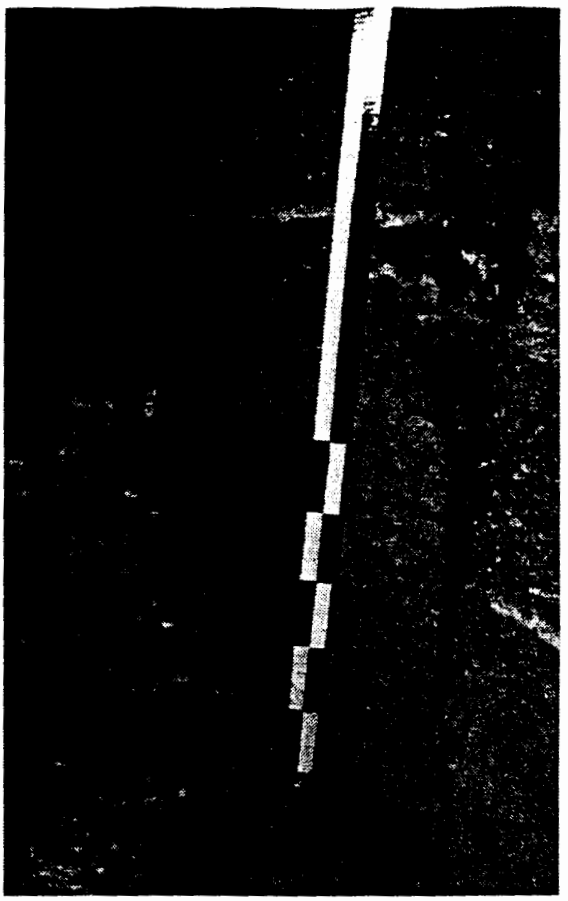

Fig. 19. Photograph of trench W5 fault W5-7. Trench location is 39.5 m. White layer is volcanic ash, unit 4e of Figs. 4 and 5. Small divisions on scale are 10 cm in length.

Faulting of Bandelier Tuff

Mapping and surveying of stratigraphic contacts within the Bandelier Tuff provides evidence for Quaternary faulting at Pajarito Mesa that supplements the evidence reported by Kolbe et al. (1994) for offsets of the mesa-top alluvium. Vaniman and Chipera (this report) reported the possibility of about 4 m of down-to-the-east faulting of the top of Tshirege Member unit 2 in a 335 m wide zone in Threemile Canyon, south of trenches W5 to W2. In addition, Vaniman and Chipera (this report) reported three small faults in the surge beds separating Tshirege Member units 3 and 4 on the south side of Pajarito Mesa, with about 23 to 30 cm of offset both down to the southeast and down to the southwest.

To supplement these data on post-Bandelier faulting, a detailed survey of the surge beds at the contact between Tshirege Member units 3 and 4 was made with a total station (computerized theodolite). All locations where this contact was located in the trenches and along the south sides of Pajarito Mesa and Twomile Mesa were surveyed, and in addition approximate locations of this contact were also surveyed in areas where the contact was obscured by colluvium. The Pajarito Mesa and Twomile Mesa surveys extended about 1.2 and 1.0 km, respectively, and the survey data are shown in Figs. 20 and 21. Interpretations of faulting, based on these surveys, assume that the surge beds originally had a relatively smooth eastward slope, and that prior deposition of > 100 m of Tshirege Member units 1, 2, and 3 had erased the small-scale irregularities that existed in the pre-Tshirege topography, particularly any west-facing features.

Of these two mesas, Pajarito Mesa has the most abundant exposure of the contact between Tshirege Member units 3 and 4, and areas of potential faulting are thus best constrained on Pajarito Mesa. The most striking structural feature is a 100 to 200 m wide zone of apparent down-to-the-west steps at the eastern end of the transect (Fig. 21a), in the same area as the faulting observed in trench W5 and the exposures of mesa-top alluvium in trenches W3 and W4. Apparent offset of the contact across this zone is about 7 to 9 m, significantly greater than observed in trench W5. In addition, because this zone extends to the easternmost area surveyed, it is possible that more faults are present to the east. The survey data suggest that only part of this fault zone was recognizable in the trenches, and that the mesa-top alluvium is preserved on down-dropped blocks.

The zone of faulting begins about 30 to 130 m east of the projected Rendija Canyon fault of Vaniman and Wohletz (1990), but no offset was recognized along the projected trace itself.

Additional evidence of faulting was found at several areas to the west. The most significant is a down-to-the-west step of at least 3 to 4 m at the western end of the Pajarito Mesa transect (Fig. 21a), where no fault had been previously recognized. Two shallow grabens are also suggested by the survey data, about 50 to 70 m wide and 2 m deep.

The survey along the south side of Twomile Mesa also revealed evidence of down-to-the-west faulting in several areas, with estimated offsets of 1 to 4 m, and a possible 1 to 2 m high horst (Fig. 21b). However, exposures of the contact between Tshirege Member units 3 and 4 are less common than on Pajarito Mesa, and the location and amount of possible offset is therefore less well constrained. No down-to-the-west steps of the magnitude present near Pajarito Mesa trench W5 were observed on Twomile Mesa, suggesting that the zone of faulting identified on Pajarito Mesa occurs east of the surveyed area on Twomile Mesa, east of the Rendija Canyon fault projection of Vaniman and Wohletz (1990).

Small-scale offsets of 0.1 to 0.5 m were observed along the surge beds at several locations on Pajarito and Twomile Mesas, including the three sites described by Vaniman and Chipera (this report). The locations of the small faults are shown on Fig. 21. Most of these faults were not at the

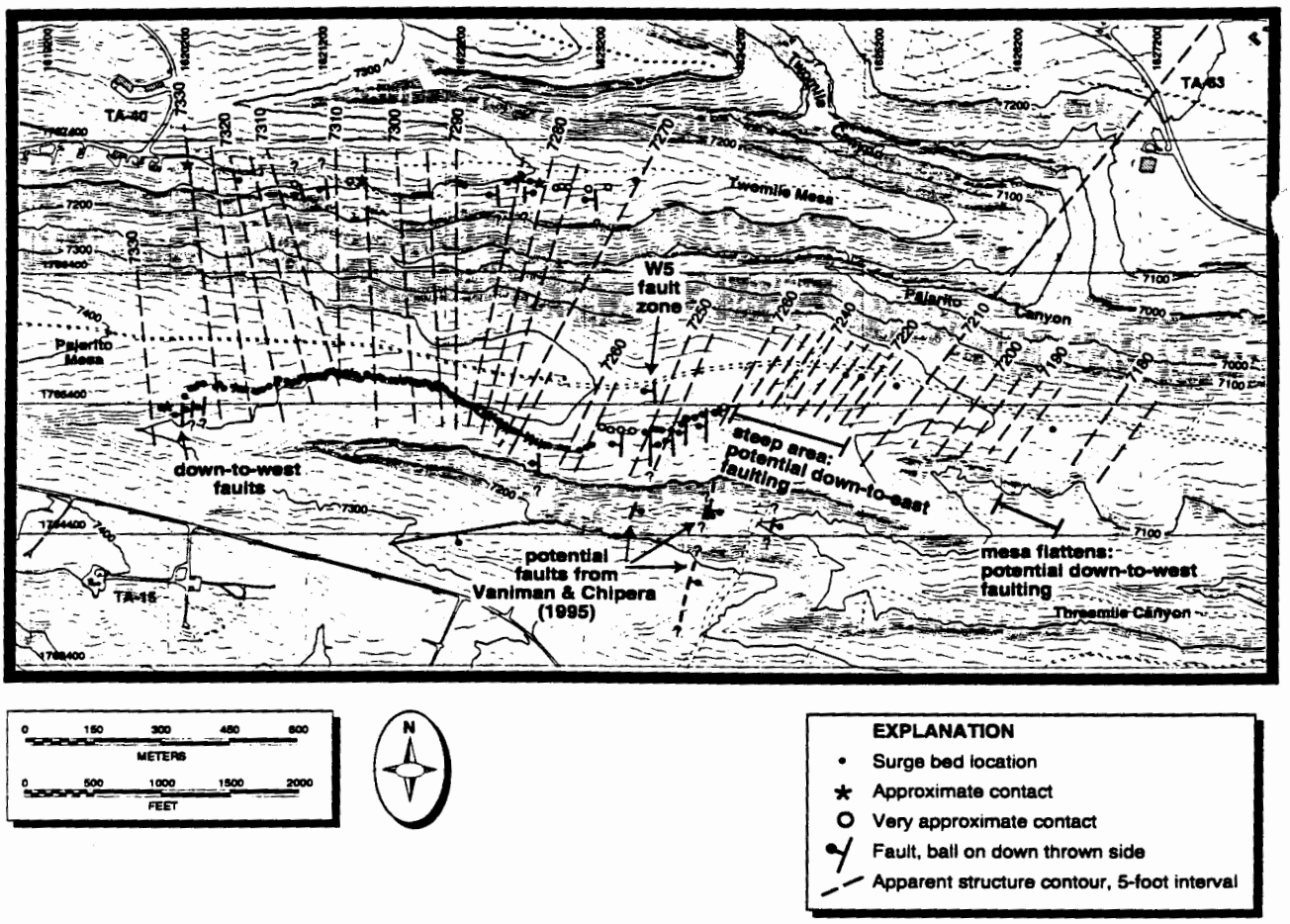

Fig. 20. Map showing surveyed data points on surge bed on Pajarito Mesa and Twomile Mesa, apparent structure contours on top of Tshirege Member unit 3, and inferred fault zones. Most faults are shown schematically with north-south orientations, although their true orientations are unknown. The structure contours were drawn assuming that there is no significant offset along the contours, and they will thus need revision when fault orientations and offsets are better constrained. Topographic base from FIMAD, showing NAD 83 coordinates and 10-ft contour intervals.

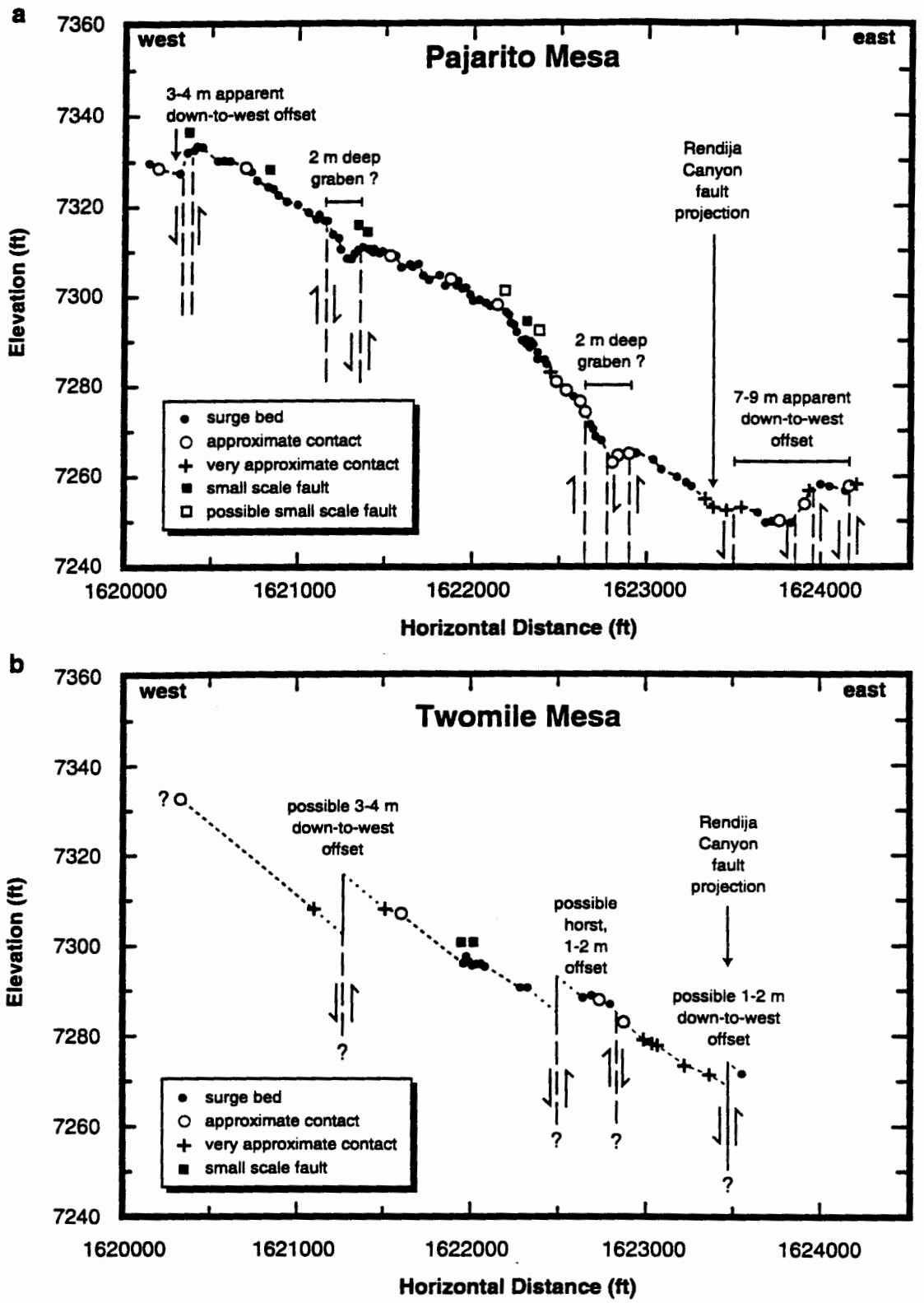

Fig. 21. Elevation of surge beds at the contact of Tshirege Member units 3 and 4, measured along east-west transects on the south sides of a) Pajarito Mesa and b) Twomile Mesa, showing inferred faults with greater than 1 m displacement and locations of small-scale faults (0.1-0.5 m) visible in outcrop. Surveyed with total station. Horizontal scale shows NAD 83 coordinates. Projected Rendija Canyon fault from Vaniman and Wohletz (1990). Possible faults on Twomile Mesa are poorly constrained due to limited exposures of surge beds.

sites where larger-scale faulting was identified or inferred. This suggests that the small-scale faults may simply reflect minor secondary faulting between more pronounced fault traces. Similar distributed small-scale faulting has been identified at many sites along Mesita del Buey at TA-54 (D. E. Broxton, J. S. Carney, S. L. Reneau, unpublished data, 1993).

The presence of down-to-the-east faulting, as inferred by Vaniman and Chipera (this report) nearby in Threemile Canyon (Fig. 20), is suggested by an examination of variations in the top of bedrock as exposed in the trenches. Surge beds are exposed at three locations in trenches E1, E2, and E6, indicating that the top of bedrock in the eastern trenches probably approximately marks the top of Tshirege Member unit 3. For a distance of over 400 m between the E2 and E6 surge locations, including part of the southern projection of the Guaje Mountain fault zone (Vaniman and Wohletz, 1990), the top of bedrock displays very little variation in slope, suggesting no vertical offset of the top of unit 3 (Fig. 22). However, immediately west the bedrock surface steepens, and the reappearance of surge beds 80 m to the west suggests the possibility of down-to-the-east faulting with about 2 to 3 m of offset (Fig. 22). Additional down-to-the-east faulting of 1 to 3 m within the next 150 m to the west is suggested by projections of the surveyed surge beds south of the trenches to the trench line (Fig. 23a), although these projections are based on estimated strikes of the Bandelier Tuff and the accuracy of these estimates is unknown, as discussed in the next section.

Although significant uncertainties are inherent in using bedrock profiles to constrain faulting, including the assumption that the original slope of the Bandelier Tuff did not change abruptly over short distances, the data on bedrock slopes presented here are consistent with the down-to-the-east faulting inferred by Vaniman and Chipera (this report) in Threemile Canyon. The estimates of possible down-to-the-east faulting based on bedrock profiles from the trenches are similar to the estimate of 4 m of cumulative down-to-east offset made by Vaniman and Chipera (this report) Assuming a correlation of the area of steep bedrock exposed from trench E2 to trench W3 with the Threemile Canyon fault zone inferred by Vaniman and Chipera (this report) (Fig. 20) provides an estimated fault zone orientation of N35E to N45E. An apparent N75E fault with about 1 m of down-to-the-south offset was located during reconnaissance mapping on the north margin of Threemile Mesa (Fig. 20), also suggesting a strong easterly component to the inferred faults in Threemile Canyon.

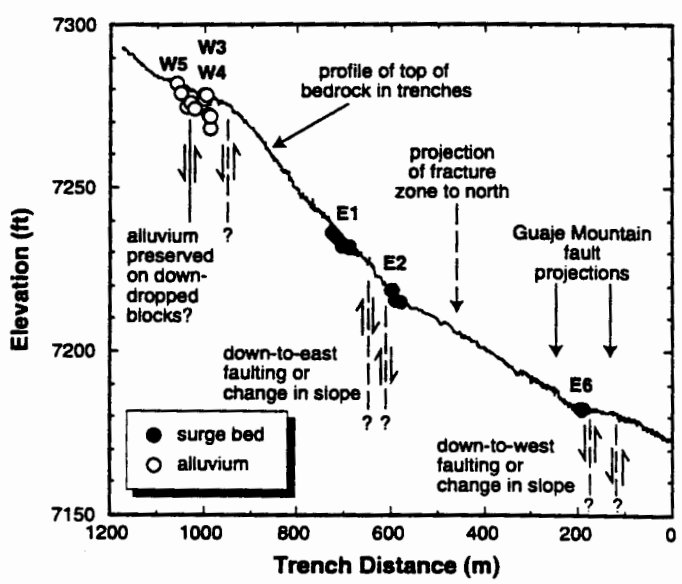

Fig. 22. Profile of top of bedrock in trenches, showing locations of surge beds in trenches E1, E2, and E6, mesa-top alluvium in trenches W3, W4, and W5, and possible faults. Data from trench logs and original survey data of Kolbe et al. (1994). Trench distance measured from east end of trench E8, with adjustments to total length made to remove overlapping sections. Guaje Mountain fault projections from Vaniman and Wohletz (1990).

Structure Contours

Structure contours of geologic contacts provide data on the strike and dip of bedrock units, which are useful for evaluating possible subsurface groundwater flow directions and tectonic deformation. The surveyed locations of the surge beds between units 3 and 4 of the Tshirege Member, discussed above, allow structure contours to be estimated for this geologic contact in the vicinity of Pajarito Mesa.

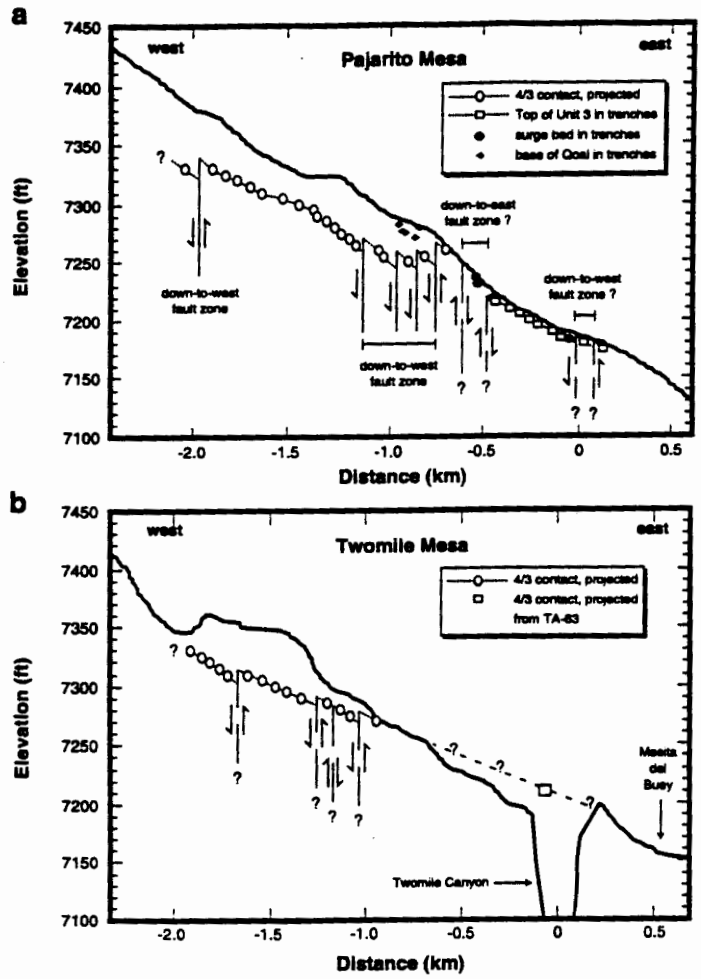

Fig. 23. Profiles of a) Pajarito Mesa and b) Twomile Mesa, with elevations of surge beds projected to center of mesa, showing inferred zones of faulting. Projections assume strikes of Bandelier Tuff as shown in Fig. 20.

These structure contours are shown on Fig. 20, and incorporate data on locations of the surge beds on the south sides of Pajarito Mesa and Twomile Mesa, surge locations within the trenches at Pajarito Mesa (Kolbe et al., 1994) and TA-63 to the north (Kolbe et al., 1995), and bedrock elevations in the trenches. They suggest that the strike of the Bandelier Tuff varies from about N10W on the western part of Pajarito Mesa to N35E to the east, and that the dip typically varies from about 1° to 3° to the east or southeast. However, because the exact location, orientation, and magnitude of fault offset in this area are not certain, no estimates of offset of the contours were made and they are thus considered here as "apparent" structure contours. Some of the apparent changes in strike and dip of the contact in Fig. 20 probably reflect the presence of faulting between measurement points, whereas others may reflect variations in the original depositional slope of the Bandelier Tuff. These contours will thus need revision as more data become available.

Mesa Profiles

Variations in the gradient of mesas on the Pajarito Plateau have been used to help recognize the location of distributed fault zones which are not clearly expressed by large offsets of Bandelier Tuff stratigraphic units (Vaniman and Wohletz, 1990). Profiles of Pajarito and Twomile Mesas, obtained from FIMAD maps with 2-ft contour intervals, were examined in this study to test the reliability of this use of topographic data and to provide additional constraints on faulting.

Pronounced variations in the slope of Pajarito Mesa occur in the vicinity of the trenches (Fig. 3), and these variations correspond in part to areas of recognized or potential faulting. The area of down-to-the-west faulting seen both in trench W5 and along the south side of Pajarito Mesa corresponds to a relatively gentle part of the mesa (Fig. 23a). Similarly, the steeper part of the mesa top, in the central part of the trenched area, may reflect the apparent down-to-the-east faults within the Bandelier Tuff mapped by Vaniman and Chipera (this report) in Threemile Canyon. However, this steep part of Pajarito Mesa also coincides with the eastern end of Tshirege Member unit 4, and the variations in slope gradient here may partially reflect the unit 4 flow front.

Variations in the gradient of Pajarito Mesa also suggest additional constraints on the location of the Guaje Mountain fault zone. The slope of the bedrock surface exposed in the trenches is gentlest east of the eastern exposure of surge beds, in trenches E6 and E7 (Fig. 22). By analogy with the gentle mesa top gradient at the trench W5 fault zone, this suggests the presence of additional down-to-the-west faulting of about 2 to 3 m or more over a 100 m wide zone. This area

includes the eastern trace of the Guaje Mountain fault projection of Vaniman and Wohletz (1990) (Fig. 1), and the slope change may provide evidence for the existence of one of their fault trace. However, we cannot exclude the possibility that this slope change instead represents origin. variations in the slope of the Bandelier Tuff or another previously unrecognized fault that does not connect with the Guaje Mountain fault.

The data obtained from Pajarito and Twomile Mesas indicate that although variations in mesa top gradient can provide evidence for the location and magnitude of faulting, mesa top profiles need to be used cautiously. Prominent steps occur on both mesas in the areas underlain by Tshirege Member unit 4 that do not relate to comparable steps in the underlying surge beds (Fig. 23). These steps apparently represent variations in the original thickness and subsequent erosion of unit 4. At present, we can also not evaluate possible variations in the original slope of the Bandelier Tuff flow units that relate to the underlying paleotopography. However, an examination of variations in mesa top gradient, when combined with mapping of geologic contacts, can still be useful in indicating the most likely sites for faulting and in providing evidence against faulting in other areas.

Fracture Characteristics

Variations in fracture density and fracture width in roadcuts and on cliffs have been used to infer the location of distributed fault zones on the Pajarito Plateau (Vaniman and Wohletz, 1990; Wohletz, 1995), and similar analyses of fractures exposed in the Pajarito Mesa and TA-63 trenches were made by Kolbe et al. (1994, 1995). Measurements of fracture orientation and aperture in the trenches focused on steeply dipping (> 45°) "through-going" fractures (those that could be traced from the south to the north trench walls), because these were judged to be the fractures most likely to be produced by faulting or to accommodate tectonic extension. However, the occurrence of small-scale offset on some non through-going fractures in trench W5 (Fig. 5) indicates that this criterion is not entirely valid. All fractures were drawn on the trench logs, allowing an examination of the density of both through-going and non through-going fractures.

At Pajarito Mesa, the average spacing of through-going fractures ranges from 2.2 m in trenches E4 to E8, to 3.2 m in trenches E1 to W4 (density of 9.4 to 13.9 fractures per 30 m (100 ft) of trench, Fig. 24). The average spacing of all steeply-dipping fractures ranges from 0.9 to 1.2 m (density of 26.4 to 34.5 fractures per 30 m (100 ft), Fig. 24). For both through-going and non through-going fractures, the average spacing generally increases from west to east. Although there is significant local variation in the density of both through-going and non through-going fractures (Fig. 24), much of this variation does not appear to be related to faulting. For example, the areas of highest fracture density in the eastern trenches, where Tshirege Member unit 3 is exposed, occur in trenches E2 to E5 (Fig. 24) where the uniformity of the bedrock surface gradient (Fig. 22) argues for no vertical offset. In addition, the area of faulting exposed in trench W5 shows a relatively low density of fractures (Fig. 24), suggesting that faulting of the magnitude documented there (1.2 m) is insufficient to increase the fracture density significantly. The area of possible down-to-the-east faulting between the trench E1 and E2 surge beds also has a low fracture density. At trench W5, the specific fractures that accommodated faulting also are no wider than average, arguing that the presence or absence of fault movement along specific fractures may be indeterminate in the absence of distinct stratigraphic markers.

The strongest suggestion of a relation between fracture density and faulting is present in trench W3, where high densities of both through-going and non through-going fractures occur in an area where the mesa-top gradient steepens to the east. As discussed above, the presence of old alluvium in the trenches only in the more gently-sloping part of the mesa to the west suggests that these deposits were preferentially preserved on down-dropped blocks associated with a down-

to-the-west fault zone. The zones of higher fracture density could thus conceivably indicate the location of previously unrecognized faulting, although the available data remain inconclusive. An alternative explanation for the variations in fracture density is that they primarily reflect variations in welding of the tuff. The low fracture density where the contact between Tshirege Member unit 3 and unit 4 is exposed in trench E1, and also where clasts of the surge beds are present in a rubble zone in trenches E2 and E6 (Fig. 24), may be due to a reduced fracture density at the nonwelded top of unit 3. This in turn suggests that most fractures within unit 3 do not continue upward into unit 4, but instead die out within the uppermost part of unit 3. The relatively low fracture density in trench W5 in the vicinity of the fault zone may similarly reflect exposure of a higher, less-welded level of unit 4, protected from erosion where it was preserved on a down-faulted block (e.g., Fig. 23a).

The fracture data from the Pajarito Mesa trenches are generally consistent with the data of Vaniman and Chipera (this report) from mesa-penetrating fractures at the base of Tshirege Member unit 3, in that average fracture spacing increases from west to east and no zones of significantly higher fracture density were identified. However, the average spacing of mesa-penetrating fractures varies from 4.1 to 6.1 m from the west to the east along Pajarito Mesa (Vaniman and Chipera, this report), or about 40% to 60% greater than the values obtained by Kolbe et al. (1994) for through-going fractures. This suggests that about one third of the through-going fractures do not penetrate completely through the more welded tuff units and into the underlying nonwelded tuff.

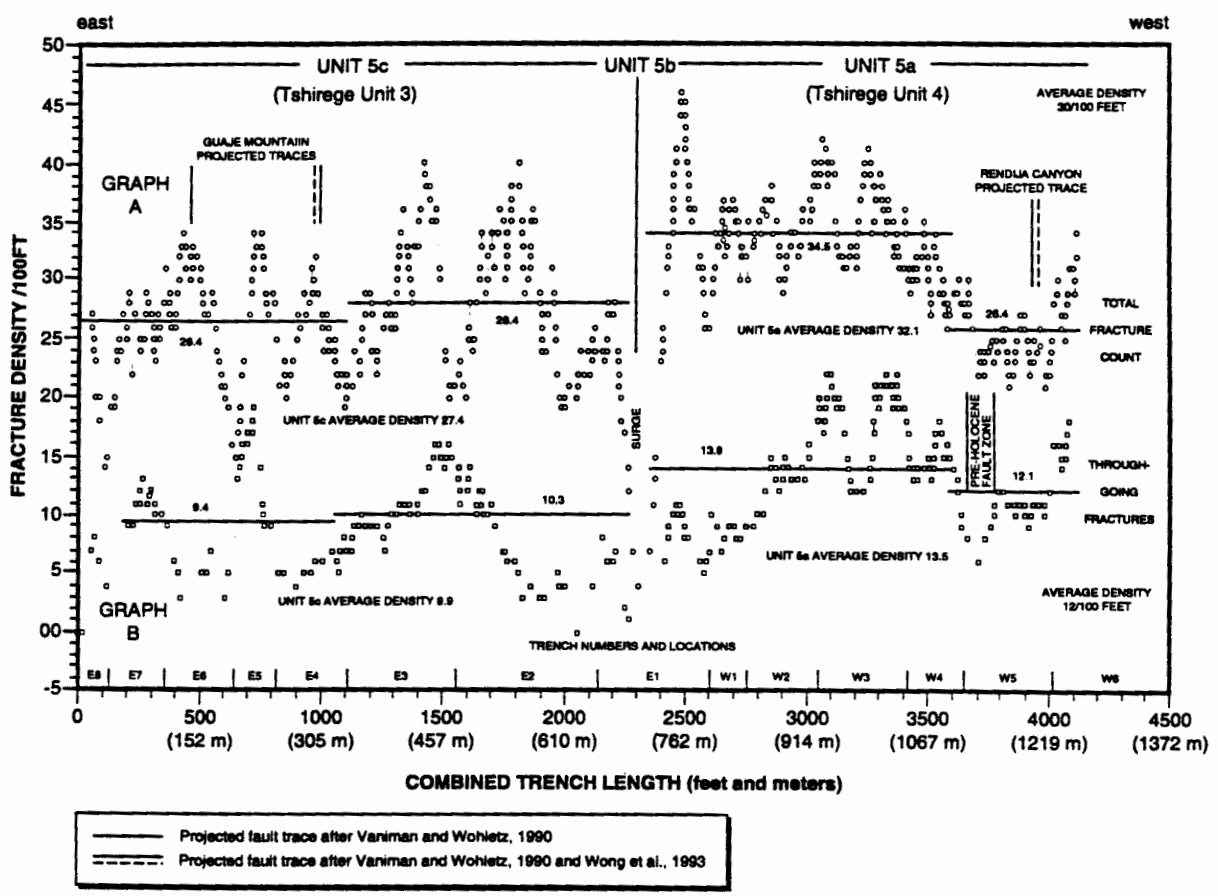

Fig. 24. Fracture density variations in trenches; from Kolbe et al. (1994).

The average width of through-going fractures in the Pajarito Mesa trenches is about 2 cm (Kolbe et al., 1994), and is similar to average fracture widths of about 1 to 2 cm in the TA trenches (Kolbe et al., 1995). Average fracture widths in the Pajarito Mesa trenches are generally slightly higher to the east, in Tshirege Member unit 3, although the measurements of Vaniman and Chipera (this report) indicated that fracture width at the base of Tshirege unit 3 was instead higher to the west. This difference between fracture width measured in the trenches and along cliffs, in combination with the variations seen within the cliff survey, suggests that fracture width may in part vary with welding of the tuff. Specifically, the easterly decrease in fracture width observed by Vaniman and Chipera (this report) may be related to the easterly decrease in welding within Tshirege Member unit 3, and the westerly decrease in fracture width observed by Kolbe et al. (1994) may similarly be related to the fact that Tshirege unit 4 is less welded than unit 3 at Pajarito Mesa (Broxton et al., this report).

It is also notable that the trend of increasing fracture widths to the east, as measured in the trenches, is opposite the general trend of increasing fracture density to the west that was discussed above (Kolbe et al., 1994). These data can be combined into a cumulative fracture opening per length of trench (fracture density multiplied by average opening), to show the total percentage of the tuff occupied by through-going fractures and to allow an examination of spatial variations in these percentages (Fig. 25). As measured over 15 m sections of trench, such percentages show great local variability, ranging from 0% to 2.6% and averaging about 0.6% (Fig. 25a). Much of this variability may be an artifact of the size of the measurement interval, and general patterns can be more easily seen by averaging the data over longer sections of trench (Fig. 25b).

As averaged over 60 m sections, fracture percentages range up to 1.4% and show significant gross variability that in part reflects the fracture density variations shown in Fig. 24 (Fig. 25b). The lowest fracture percentages occur in trenches E1, E2, and E6 in the vicinity of the surge beds again suggesting that fractures have generally not propagated through this stratigraphic contact. The highest fracture percentages occur in trenches W3, E7, and where trenches E2 and E3 overlap (Fig. 25b). These areas of high fracture percentages may in part reflect tectonic extension associated with fault zones, but natural stratigraphic variability in fracture characteristics cannot be ruled out. Specifically, the trench W3 area in part includes the fault zone surveyed on the south side of the mesa (Fig. 21a), and the trench E7 area includes the gentle part of Pajarito Mesa near the Guaje Mountain fault projection where possible down-to-the-west faulting is indicated (Figs. 22 and 23a). In contrast, the higher percentage of the trench walls occupied by through-going fractures at the ends of trenches E2 and E3 (Fig. 25b) are in an area of relatively uniform bedrock slope where no evidence for faulting has been recognized (Figs. 22 and 23a). The causes of these variations in fractures are thus not completely clear.

Evaluation of Fault Projections at Pajarito Mesa

An interpretation of subsurface data beneath the Pajarito Plateau by Dransfield and Gardner (1985) suggested that southern projections of the north-south trending Guaje Mountain and Rendija Canyon faults occurred in the pre-Bandelier rocks beneath Pajarito Mesa. Later work by Vaniman and Wohletz (1990), involving reconnaissance mapping, measurements of fracture density in roadcuts, and interpretation of geomorphic features such as canyon-wall embayments, projected both faults across Pajarito Mesa within the Bandelier Tuff. Vaniman and Wohletz (1990) interpreted that these faults were expressed as zones of intense fracturing 300 m or more wide in roadcuts to the north, with small-scale offset occurring on many individual fractures. More recently, interpretation

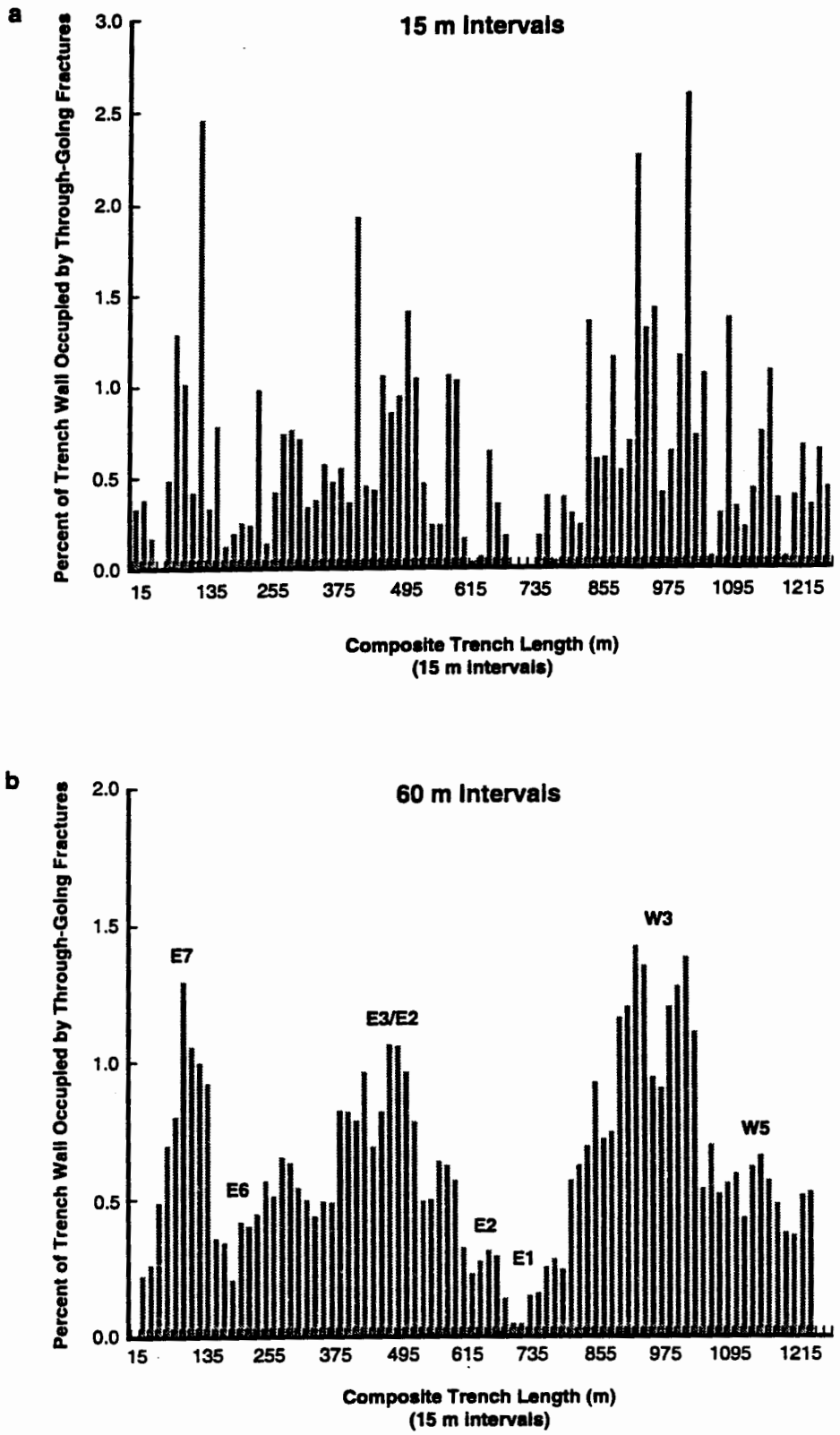

Fig. 25. Variations in percentage of trench walls occupied by through-going fractures, plotted for 15-m intervals. Values represent average fracture width multiplied by fracture density and divided by interval length. a) Percentage for each 15-m interval. b) Percentage for 60-m intervals, calculated as a running average with 15-m increments. Data from Kolbe et al. (1994).

of aerial photograph lineaments by Wong et al. (1993, 1995) concurred with the possible southern projection of these faults across Pajarito Mesa, although conclusive evidence for faulting had not been recognized this far south prior to this study.

The geologic mapping and exploratory trenching conducted as part of MWDF site characterization activities (Kolbe et al., 1994; Vaniman and Chipera, this report; this study) suggest revisions to the previous interpretations of faulting in the vicinity of Pajarito Mesa. No increase in fracture density across the projections of the fault zones was seen (Fig. 24), and surveying of surge beds revealed no offset of the Bandelier Tuff along the Rendija Canyon fault projection (Fig. 21). Faulting is present in the vicinity of the Rendija Canyon fault projection, shown by both trench logging and surface mapping, but may be more complicated than previously inferred. Specifically, both down-to-the-west and down-to-the-east faulting is suggested (Figs. 22 and 23). These fault zones may intersect along the south margin of Pajarito Mesa, bounding a wedge-shaped horst block, although their relation to each other is not certain. The relation of these fault zones to the north-south trending Rendija Canyon fault is also uncertain. Although the down-to-the-west fault zone exposed in trench W5 could be a southern continuation of the Rendija Canyon fault (Kolbe et al., 1994; Wong et al., 1995), it is also possible that it is part of a previously unrecognized fault zone. The northern and southern extents of the faults that cross Pajarito Mesa near the western part of the proposed MWDF and their paleoseismic history have not been determined, although the trench studies demonstrate that they have not moved in the last 50-60 ka.

The question of whether a southern projection of the Guaje Mountain fault crosses Pajarito Mesa within the Bandelier Tuff is also unresolved. Although no significant increases in fracture density occur across its projection either at Pajarito Mesa or north at TA-63 (Kolbe et al., 1994, 1995), the lack of increases in fracture density at areas of recognized faulting in trench W5 indicates that fracture characteristics alone can be inconclusive. A decrease in bedrock gradient in the eastern area trenched on Pajarito Mesa (Fig. 22), in an area with a high percentage of fractures (Fig. 25b) suggests the possibility of down-to-the-west faulting in the Bandelier Tuff, perhaps associated with the Guaje Mountain fault zone. Alternatively, the apparent decrease in gradient could reflect primary variations in the dip of the Bandelier Tuff, and the southern extent of the Guaje Mountain fault thus remains uncertain.

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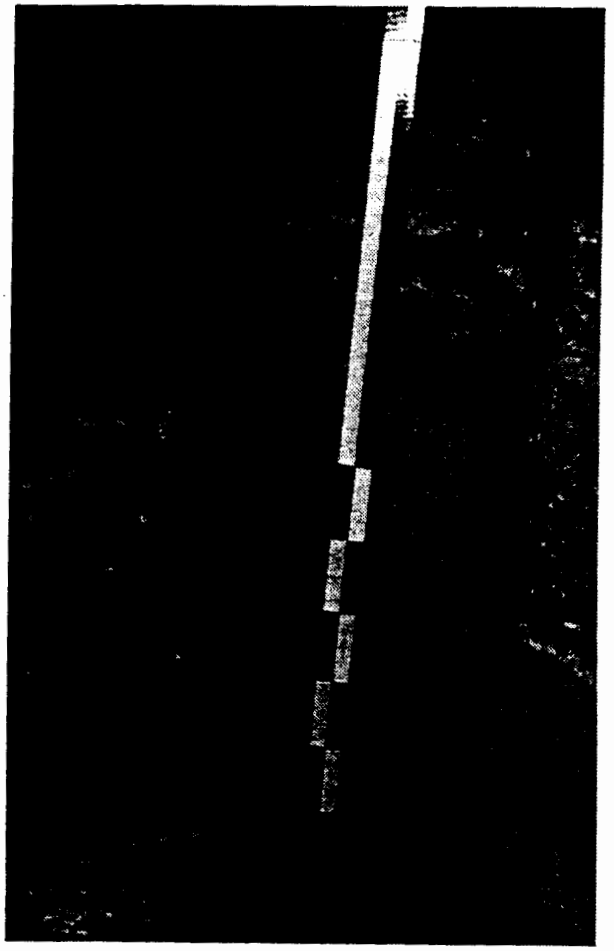

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