Late Quaternary geomorphology and soils in Crater Flat, Yucca Mountain area, southern Nevada

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ABSTRACT

Soil-geomorphic studies indicate that six major allostratigraphic units occur in Crater Flat, Nevada, adjacent to Yucca Mountain. These units are, from youngest to oldest, Crater Flat, Little Cones, Late Black Cone, Early Black Cone, Yucca, and Solitario. Presence and degree of differentiation of Av, Ak, Bw, Bt, Btk, Btkq, and Bqkm genetic soil horizons characterize units, confirm relative ages, and aid in estimating numerical ages. Stratigraphic order and soils allow correlation with similar alluvial sequences in adjacent Basin and Range areas. Minimum-limiting ages—by ^{14}C accelerator mass spectrometry (AMS) and cation-ratio dating of rock varnish and by ^{230}Th/^{234}U dating of pedogenic carbonate—support allostratigraphic order and are in reasonable agreement with numerical ages estimated for correlative regional units. Consistent, clustered, ^{14}C AMS varnish ages from widely separated, same-age surfaces suggest that the ages, although minima, do not significantly underestimate true ages. Rock-varnish ^{14}C AMS ages on Late Black Cone and younger units, and K-Ar ages from volcanic lava cones, provide calibration points for a Crater Flat cation-leaching curve. This curve differs somewhat from a previous Yucca Mountain curve and yields calculated cation-ratio ages younger by factors of two to three for the younger units.

If the ^{14}C AMS varnish ages provide reasonably close minimum ages, as we believe they do, the Little Cones and Late Black Cone units collectively form an extensive late Wisconsin–early Holocene deposit not previously described in Crater Flat. The Late Black Cone unit (>17 to >30 ka) correlates with units in the Lower Colorado River, Death Valley, Mojave Desert, and Las Vegas areas—all likely products of climatically induced, late Wisconsin pluvial alluviation. Similarly, the Little Cones unit (>6 to >11 ka) correlates with regional units thought related to alluviation during climatic transition from the late Wisconsin maximum pluvial to the arid Holocene. The areal distribution of late Pleistocene units demonstrates that the Crater Flat piedmont and valley floor were extensively alluviated during the last glacial episode.

Ages of three older, mid-Quaternary units are uncertain, but they are largely younger than Bishop ash (730 ka). The Early Black Cone and Yucca units are estimated from rock-varnish cation-ratio dating to be from >159 to >201 ka and >375 ka, respectively, and the Solitario unit, which contains the Bishop ash, is from >433 to >659, but <730 ka.

Our allostratigraphic units differ in age by factors of 2–10 from a previous "surficial deposits" stratigraphy used in the Yucca Mountain area. Although the earlier stratigraphy has some units numerically equivalent in age to our allostratigraphic units, we found soil features in deposits of these ages different from those previously described.

INTRODUCTION

Crater Flat is an alluvium-filled structural basin on the west side of Yucca Mountain, Nevada—the site under consideration for a high-level nuclear waste repository. The Quaternary alluvium of the Nevada Test Site region was first described by Hoover et al. (1981). Their "surficial deposits" chronology was the principal stratigraphic framework for most surficial geologic studies in the Yucca Mountain area, and geologic quadrangle maps of the Yucca Mountain and Crater Flat region used their chronology (Swadley, 1983; Swadley and Carr, 1987; Swadley and Parrish, 1988; Swadley and Hoover, 1989a, 1989b). Numerical ages for the units were estimated by Swadley et al. (1984) and Rosholt et al. (1985). Taylor (1985) and Harden et al. (1991) described soils associated with surficial deposits on the east side of Yucca Mountain.

North-trending, late Quaternary faults offset alluvium in Crater Flat both along the canyons of the western flanks of Yucca Mountain and out on the piedmont slope (Fig. 1). The Hoover et al. (1981) stratigraphic framework was used in some previous paleoseismic studies near Yucca Mountain. Swadley and Hoover (1983) found no evidence of young faulting in exploratory trenches in Crater Flat. Swadley et al. (1984) concluded that none of 32 identified faults in the Yucca Mountain area have offsets younger than 40 ka and noted that no Holocene faulting had been recognized. However, subsequent fault studies (Whitney et al., 1986; Ramelli et al., 1988, 1989) identified late Pleistocene and Holocene faults in Crater Flat. Reheis (1986) found that late Quaternary soils had experienced faulting in deposits along the Bare Mountain fault bounding the west side of Crater Flat, im-

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plying these deposits to be generally younger than suggested by the "surficial deposits" stratigraphy.

We believe the initial lack of recognition of young fault offsets at Yucca Mountain was in part due to unrecognized late Quaternary stratigraphy. Regional Quaternary chronologies in other, similar alluvial-geomorphic settings of the arid Basin and Range Province (cf. Wells et al., 1990a; Bull, 1991) suggest that many basins were extensively alluviated during the late Quaternary, particularly during the Wisconsin glacial-pluvial episode (ca. 12–75 ka). We hypothesize that alluviation in the Yucca Mountain region was more active during the late Quaternary than previously thought and that earlier stratigraphic studies may not be detailed enough to allow identification of late Quaternary deposits.

Because detailed Quaternary stratigraphic relationships are required for characterizing seismic hazards at the proposed repository site (U.S. Department of Energy, 1988), we tested our hypothesis in several ways. We collected geomorphic and soil data that allowed us to compare and test the previous work while developing a refined late Quaternary chronology for Crater Flat. In contrast to previous work, we used allostratigraphic relationships and experimental rock-varnish and uranium-series dating techniques to define and scale stratigraphic relationships. We compare our results with previous soils and surface-exposure dating studies, correlate our stratigraphy with other late Quaternary units in the southern Nevada, Death Valley, and Mojave Desert areas, and provide new stratigraphic data relevant to understanding climatic-alluvial processes in the Basin and Range Province during the late Quaternary.

DEFINITION OF STRATIGRAPHIC UNITS

We mapped geomorphic surfaces using topographic relations and soils to establish boundaries and characterize the units (cf. Peterson, 1981). These Quaternary units are termed *allostratigraphic units*, defined by the North American Commission on Stratigraphic Nomenclature (1983) as mappable stratiform bodies of sedimentary rock defined and identified by bounding discontinuities—geomorphic surfaces and soils in this case. Allostratigraphic units are analogous to the alluvial-geomorphic units of Ku et al. (1979) and Bull (1991). We contrast our units with the "surficial deposits" units of previous workers (Table 1), which are hybrids of time-stratigraphic and rock-stratigraphic units, not allostratigraphic units. Using geomorphic surfaces and related soils, we produced a map delineating allostratigraphic units for interpreting the Quaternary history of the Crater Flat piedmont (Fig. 1).

ALLOSTRATIGRAPHIC UNITS IN CRATER FLAT

Six major units comprise the piedmont slopes of Crater Flat; from youngest to oldest, they are the Crater Flat, Little Cones, Late Black Cone, Early Black Cone, Yucca, and Solitario units. At one or more locations, a surface remnant of each unit is topographically clearly above or below a physically adjacent, next-younger or next-older fan remnant—an inset relationship that is a clear demonstration of relative age. Also, surface remnants of each unit have characteristic and distinctively different soils from those of the physically adjacent remnant of a younger or older unit. At some locations,

TABLE 1. SURFICIAL-DEPOSITS STRATIGRAPHY

Unit	Age (ka)*	Distinguishing soil characteristics
Q1a Q1b	0–0.15 0.15–4.0	Soils developed on oldest subunit (Q1c) are incipiently developed with only minimal A and stage I carbonate (Bk) horizons.
Q1c	7.0–9.0	
Q2a	~40	Soils have Av, Bw, and stage I Bk horizons. Unit is only recognized in 3 locations on Nevada Test Site where it appears to be a single debris flow.
Q2b	160–250	Soils have Av, Bw, and stage I Bk horizons; 1–3 mm carbonate coatings on clast bottoms. Recognized only as strath terraces in Q2c and QTa.
Q2c	270–800	Contains 3 different soils: Oldest soil contains 30- to 70-cm-thick Bt and 1–2 m thick stage IV Bk horizons; intermediate-age soil contains 50-cm-thick Bt and 1-m-thick stage III–IV Bk horizons; youngest soil contains 50-cm-thick Bw and 0.5- to 1-m-thick stage II–III Bk horizons. Bishop ash (~730 ka) occurs in lower part of unit.
QTa	110–2000	Deeply dissected; soils are stripped with 3-m-thick stage IV+ Bk horizon remaining.

Note: From Hoover et al. (1981) and other subsequent papers.
*From Swadley et al. (1984) and Rosholt et al. (1985).

TABLE 2. COMPARISON OF CRATER FLAT ALLOSTRATIGRAPHIC UNITS WITH SURFICIAL-DEPOSITS UNITS

Allostratigraphic unit*	Age (ka)	Surficial-deposits unit†	Age (ka)
Modern	0	Q1a	0–0.15
Crater Flat	>0.3 to >1.3	Q1a	0–0.15
		Q1b	0.15–4
		Q1c	7–9
Little Cones	>6 to >11	Not mapped	n.i.§
Late Black Cone	>17 to >30	Q2b (as part of Q2bc)	160–250
Early Black Cone	>159 to >201	Q2c	270–800
Yucca	>375	Not mapped	n.i.
Solitario	>433 to >659 but <730	QTa	1100–2000

*This study.
†Hoover et al. (1981) unit as mapped by Swadley and Parrish (1988).
§n.i. = no information.

units that are fan aprons are thin (<1 m thick) and veneer over, and feather into, older units. Soil examination is required to map such areas. Table 2 shows the correlation of units with the "surficial deposits" units used by Swadley and Parrish (1988) to map Crater Flat. Table 3 describes illustrative pedons for each of our allostratigraphic units. Additional representative pedon descriptions from Crater Flat are available in Appendix 1.

In Crater Flat, presence or absence and degree of differentiation of the following six genetic soil horizons help identify geomorphic surfaces: the vesicular A horizon (Av), a recarbonated lower-A subhorizon (Ak), a cambic or cambic-like horizon (Bw), various argillic horizons (Bt, Btk, Btkq), a strongly opalized argillic subhorizon (Btkq), and duripans (Bqkm). The first two soil horizons are not defined in *Soil Taxonomy* (Soil Survey Staff, 1975) but are characteristic of many desert soils (cf. Eckert et al., 1978; Nettleton and Peterson, 1983).

Crater Flat Unit

The Crater Flat unit consists of active and recently active washes, inset fans, fan skirts, and fan aprons (landform terms are from Peterson, 1981). The unit is erosionally inset below all older surfaces in Crater Flat and contains one or more geomorphic subunits not differentiated here because of the scale of the study.

The soils of the Crater Flat unit are coarse textured, thermic, Typic Torriorthents (pedon CFP-41; Table 3) without any organized desert pavement. They have neither significant genetic soil horizons (i.e., no Av, cambic, or argillic horizons) nor any differentiated horizon of carbonate or opal accu-

TABLE 3. ILLUSTRATIVE PEDONS FOR CRATER FLAT ALLOSTRATIGRAPHIC UNITS

Horizon	Depth (cm)	Color		Texture	Size (% vol)			Size (% wt)			Argillans	Structure	Consistency			Cementation	$CaCO_3$, effervescence & morphology	pH	Pores	Roots	Lower boundary
		Dry	Moist		Gravel	Cobble	Stone	Sand	Silt	Clay			Dry	Moist	Wet						
CRATER FLAT UNIT (SITE CFP-41)																					
AC	0–19	10YR 6/2	10YR 4/2	EGS	65	0	0	95	3	2	none	SG	LO	LO	SO/PO	none	EO & E	8.6	no V's	1VF	GW
Ck	19–100	10YR 6/2	10YR 4/2	EGS	65	3	0	95	3	2	none	SG	LO	LO	SO/PO	none	E	8.6	N.D.	1VF-F, v1M	N
LITTLE CONES UNIT (SITE CFP-26)																					
Av	0–5	10YR 7/3	10YR 4/3	GVFSL	20	0	0	58	35	7	none	2VCOPR	SH	VFR	SO/PS	none	ES	8.6	3VF-MV	none	AS
Ak	5–19	10YR 7/3	10YR 5/3	GSL	30	0	0	68	24	7	none	1FSBK	VSH	VFR	SO/PO	none	ES-CISF&SPB	8.8	N.D.	v1VF	CS
Bwk	19–29	10YR 7/3	10YR 5/3	GSL	30	0	0	74	20	6	none	M	SO	VFR	SO/PO	none	EV-CISF&SPB	9.0	N.D.	1VF	GS
Bk	29–54	10YR 7/3	10YR 5/3	VGSL	50	0	0	76	19	5	none	M	SO	VFR	SO/PO	none	EV-CSPB	9.0	N.D.	1VFv1F	CW
2Bk1	54–78	10YR 7/3	10YR 5/3	EGSL	65	0	0	80	15	5	none	M	SO	VFR	SO/PO	none	EV-CSPB	8.4	N.D.	1VFv1F	CW
2Bk2	78–100	2.5Y 7/1	2.5Y 5/2	VGCOS	50	5	0	95	3	2	none	SG	LO	LO	SO/LO	none	ES-CSPB	8.2	N.D.	none	N
LATE BLACK CONE UNIT (SITE CFP-32)																					
Av	0–6	10YR 7/2	10YR 4/3	L	13	0	0	48	40	12	none	2VCOPR	SH	VFR	SS/PS	none	EO	8.6	3VF-FV,2MV	none	AS
Ak	6–15	10YR 6.5/2	10YR 4.5/3	GSL	20	0	0	64	28	8	none	1FPL & 1VFSBK	VSH-SO	VFR	SO/PO	none	ES&EV-D,SPB,SF	9.4	N.D.	1VF-F	CW-I
Bt	15–33	10YR 6/3	8YR 4.5/3	VGSL	50	0	0	60	25	15	INPBC & PO	1VF-FSBK	SH	FR	VSS/VPS	none	EO&E	8.4	N.D.	1VF	CW
Btk	33–51	7.5YR 6/3	7.5YR 4/4	EGSL	68	0	0	70	20	10	NPBCC	1VFSBK	VSH	VFR	VSSPO	none	ES&EV & EO-D,SP	8.4	N.D.	none	AW-I
Bqkm	51–71+	10YR 8/1 & 10YR 6/2	10YR 7/2 & 10YR 4/3	EGLS	65	0	0	N.D.	N.D.	N.D.	none	2VCOPL	EH	EFI	n.a.	CS	EV-D,SP	N.D.	N.D.	none	N
EARLY BLACK CONE UNIT (SITE CFP-37)																					
Av	0–5	10YR 7/2	10YR 4/2	L	10	0	0	45	40	15	none	3COPR	SH	VFR	SS/PS	none	EO & EV	8.4	3FV	none	AS
AB	5–11	10YR 6/2	10YR 4.5/3	GCL	15	0	0	36	35	29	none	3COPR & IMPL	SH	VFR	S/P	none	EO & EV	8.4	1VFV	v1VF	AW
Btk1	11–35	7.5YR 6/4	7.5YR 4/4	VGCL	50	0	0	37	25	38	2NCO	3VFABK	SH	FR	VS/P	none	EO & ES	8.6	N.D.	1VF,v1F	CW
Btk2	35–48	7.5YR 6/4	7.5YR 5/4	EGLCOS	65	2	0	80	15	5	none	1VFSBK	LO	VFR	SO/PO	none	EO & EV	8.8	N.D.	1VF	VAW
Bqkm	48–130	10YR 8/1	10YR 7/3	N.D.	70	5	0	N.D.	N.D.	N.D.	none	M	SH-VH	LO-VFI	n.a.	none-CS	EV	N.D.	N.D.	v1VF-M	N
EARLY BLACK CONE UNIT (SITE CFP-29)																					
Av	0–5	10YR 7/2	10YR 4.5/2	GL	20	0	0	48	40	12	none	2COPR	SH	VFR	SS/SP	none	EO & E	8.8	3VF-MV	none	AS
Ak	5–12	10YR 6.5/3	10YR 4.5/3	SL	10	0	0	74	18	8	none	1VFSBK	SO	VFR	SO/PO	none	ES	8.4	N.D.	1VF	AW
Btqy	12–24	7.5YR 6/3	7.5YR 4/4	GCL	20	2	0	27	35	38	2MKPF & PO	2VFGR-ABK	SO-SH	VFR	S/P	none	EO & ES	8.2	N.D.	none?	AS
Btq	24–47	7.5YR 6/3	7.5YR 4/4	"SL"	50	5	0	n.a.	n.a.	n.a.	INPO & PBC	1COPL & 3FABK	H-VH	VFI	SO/PO	CW	EO	8.2	N.D.	none	CW
Bqkm	47–55+	10YR 8/1 & 10YR 7/2	10YR 7/3 & 10YR 4.5/3	n.a.	60	10	0	n.a.	n.a.	n.a.		M	VH-EH	VFI-EFI	brittle	CS	ES-D,SP,SF	8.2	N.D.	none	N
YUCCA UNIT (SITE CFP-39)																					
Av	0–8	10YR 7/2	10YR 4/2	L	5	0	0	53	35	18	none	3COPR & 1MPL	SH	VFR	SS/P	none	EO & E	8.8	3F-MV	none	AW
Ak	8–17	10YR 6.5/3	10YR 5/3	L	10	0	0	50	35	15	none	1MPL & 2VFSBK	SH	VFR	SS/PS	none	ES-SPB	9.0	N.D.	1VF-F	CW
Bt	17–38	7.5YR 5/4	7.5YR 4/6	VGC	30	10	0	28	30	42	4KPF	3VF-FABK	SH	FR	VS/VP	none	E	8.8	N.D.	v1VF	CS
Btk	38–57	10YR 6/6	10YR 4.5/6	VGC	45	2	0	22	38	40	4KPF & CO	2FSBK	H	FI	VS/VP	none	EO & E-SPB	8.6	N.D.	none	VAW
Bqkm	57–61+	10YR 8/1 & 10YR 7/4	10YR 7/4 & 9YR 5/4.5	n.a.	50	N.D.	0	N.D.	N.D.	N.D.	N.D.	M	EH	EFI	brittle	CS	ES	N.D.	N.D.	none	N
YUCCA UNIT (SITE CFP-38)																					
Av	0–7	10YR 6.5/1	10YR 4.5/2	GL	20	0	0	50	35	15	none	3COPR	H-SH	VFR	S/P	none	EO & E	8.6	3F-MV	v1VF	AW
Ak	7–17	10YR 6/2	10YR 4.5/2	GL	20	0	0	42	40	18	none	1MPF & 2VFSBK	SH	VFR	SS/PS	none	ES-SPB	9.0	N.D.	1VF,v1M	AW
Bt	17–28	7.5YR 6/4	7.5YR 4/6	FG"L"	20	0	0	n.a.	n.a.	n.a.	4KPF,BR,CO	1MPL & 3VFABK	H	FI	SS/P	VCW peds	EO	8.4	N.D.	2VF,1M	VAW
Btqkm	28–72	7.5YR 6/4	7.5YR 4/4	G"LS"	15	0	0	n.a.	n.a.	n.a.	3KPF	3MPL	H	FI	SO/PO	CW	EO & EV	8.4	N.D.	none	VAW
Bqkm	72–77+	10YR 8/1 & 10YR 7/2	10YR 7/3 & 10YR 7/3	n.a.	30	0	0	n.a.	n.a.	n.a.	N.D.	M	VH	EFI	n.a.	CS	EV	N.D.	N.D.	none	N
SOLITARIO UNIT (SITE CFP-40)																					
Av	0–5	10YR 7/2	10YR 4.5/3	VFSL	10	0	0	67	25	8	none	3COPR	SH	VFR	SO/PS	none	E & EO	8.8	3F-MV	none	AS
Ak	5–9	10YR 7/3	10YR 5/3	L	8	0	0	42	35	23	none	3COPR	SH	FR	S/P	none	EV	8.8	N.D.	none	AW-B
Btk	9–19	7.5YR 6.5/4	7.5YR 5/4	VGCL	50	0	0	30	35	35	?	1VFSBK	SH	FR	S/P	none	EO & EV	8.8	N.D.	1VF-F	VAW
Bqkm	19–21+	10YR 8/2-3	10YR 7/3	n.a.	50	0	0	n.a.	n.a.	n.a.	N.D.	M	EH	EFI	brittle	CI	EV	N.D.	N.D.	3VF-F	N

Note: Abbreviations refer to terminology of Soil Survey Staff (1975). N.D. = not determined; n.a. = not applicable.

mulation. The alluvium forming these soils is ubiquitously a very gravelly to extremely gravelly sand or loamy sand, so the soils are in sandy-skeletal soil families. At most, microtopographic muting of the surface is accompanied by very slight accumulations of pedogenic carbonate as filaments on pebble bottoms at 20–50 cm depths—that is, Stage I carbonate accumulation (Gile et al., 1966).

Little Cones Unit

The Little Cones unit consists primarily of a large fan-piedmont remnant surrounding the Little Cones basalt cones in southwestern Crater Flat and several other large remnants around Black and Red Cones. These surface remnants are freshly eroded by the younger, expanding Crater Flat surfaces and are themselves erosionally inset below Black Cone remnants. Compared with the raw, rough, bar-and-swale microtopography of the Crater Flat surface, the Little Cones surface typically is fully smoothed, with abstracted drainageways and a slightly varnished desert pavement on a clearly differentiated soil.

Little Cones soils have minimal but distinct desert pavements and sandy loam Av horizons. Calcareous cambic horizons (Bwk), with some pedogenic carbonate on pebble bottoms, and late Stage I Bk horizons occur under the Av horizons; the Bk does not contain enough pedogenic carbonate to be a calcic horizon, in the sense the term *calcic horizon* is used in *Soil Taxonomy* (Soil Survey Staff, 1975). In some pedons, the bottom of the Bwk horizon is too shallow to meet the Soil Survey Staff's (1975) arbitrary 50 cm depth requirement for a cambic horizon; hence, the soils may be identified as either Camborthids (with a cambic horizon) or Torriorthents (without a cambic horizon), depending on where they are examined.

Pedon CFP-26 (Table 3) illustrates soil features in a pavette[1] near the Little Cones basalt cones, where the parent material is mixed volcanic and limestone alluvium.

The Av horizon is only 5 cm thick and barely exhibits the dilatancy[2] of common Av horizons, but is coherent, is cracked into polygons, and is coarsely vesicular.

There is a prominent but noncemented, late Stage I, 2Bk horizon that has relatively thick pebble-bottom carbonate coatings. A few, very thin carbonate laminae occur on the bottoms of a few of the Av horizon's coarse prisms; these laminae and the Ak horizon are interpreted as evidence of shallow carbonate accumulation during late Holocene time. High pH values (pH > 8.5) just below the Ak horizon are evidence of eolian addition of soluble sodium salts and their accumulation just below the current depth of carbonate accumulation. The relatively thick carbonate coatings on the pebbles in the 2Bk horizon are considered earlier Holocene additions.

Black Cone Unit

The Black Cone unit consists of small- to medium-sized, fan-piedmont remnants ranging in size from tens of square meters to tens of square kilometers, and in aggregate about as extensive as the Crater Flat surface. This unit has been more closely and more deeply dissected than the Little Cones surface, but less so than the Yucca or Solitario surfaces. Its ubiquitous remnants are broad, flat, microtopographically muted interfluves covered by darkly varnished, closely spaced desert pavement. Boundaries with younger units are evident because they commonly are at erosional scarps. However, boundaries between the Black Cone unit and the older Yucca or Solitario unit remnants are generally less evident, because the darkness of the rock varnish and the closeness, extensiveness, and sorting of the desert pavements are not observably different.

Soil differences are demonstrable where Black Cone remnants are inset below Yucca or Solitario surfaces (Fig. 2), but there are also noticeable differences in soil development between various remnants of the Black Cone unit that are related to surface-age differences confirmable by inset relations in the field. Differences in soil development between certain Black Cone remnants are distinct enough that, together with the numerical age relationships discussed later, they allow subdivision and mapping of the Black Cone unit as Late and Early Black Cone subunits.

Late Black Cone Subunit. Soils of the Late Black Cone subunit have prominent, loam-textured Av horizons under moderately well-varnished desert pavement, have either argillic or cambic horizons, and have haplic (weak or discontinuous) duripans or calcic horizons. The argillic horizons are less clayey than those of Early Black Cone age soils. Pedon CFP-32 (Table 3) is a Haplic Durargid formed in volcanic alluvium from Yucca Mountain, and is located between Red and Black Cones on an elongate, low, fan-piedmont remnant (Fig. 1). It has a minimal, very gravelly, sandy-loam argillic horizon and a haplic duripan. Its desert pavement is well sorted, closely spaced, and moderately darkly varnished. The underlying loam-textured Av horizon is moderately thick, dilatant, leached of carbonates, and has a prominent crust when dry. This soil is one of the younger, less-differentiated Durargids of the later part of the Black Cone unit. Its argillic horizon has clay skins but a relatively low clay content (~15%). Noncalcareous parts in the Av and Bt horizons are evidence that these horizons were previously leached free of carbonates and have been recarbonated. The soil's haplic duripan has only a single thin lamina on top, and although quite coherent in situ, it is only weakly cemented.

Near the Bare Mountain piedmont (Fig. 1), alluvium of the Late Black Cone subunit contains limestone resulting in the formation of Typic Camborthids rather than Durargids. An illustrative Calciorthid has a 10-cm-thick, coarsely vesicular Av horizon and a calcareous cambic (Bwk) horizon. Its 2Bk horizon contains ~20% by volume Stage II–III, weakly carbonate-cemented gravel lenses in a Stage I matrix. Because the Late Black Cone Durargids and Calciorthids occur on same-age geomorphic surfaces, they confirm previous work (Nettleton and Peterson, 1983) suggesting that moderate amounts of limestone parent material will prevent the formation of an argillic horizon.

Early Black Cone Subunit. Soils of the Early Black Cone subunit, where formed in volcanic alluvium, have prominent, loam-textured Av horizons under darkly var-

[1]Desert pavement commonly is most closely spaced and prominent between coppice dunes and biocoppices on barren, flat to slightly depressed areas or along the barren crests of old, rounded, fan-piedmont remnants. These most-prominent patches of desert pavement are called pavettes here, and are where Av horizons and underlying B horizons are best examined. Coppice dunes are low, sandy, eolian accumulations around the base of desert shrubs. Biocoppices are microtopographic aggregates of several coppice dunes that are joined together by a thin, sandy, eolian sheet. Desert pavement is absent from coppice dunes and biocoppices where burrowing rodents concentrate and bioturbate (i.e., mix) the soils.

[2]Dilatancy is the tendency of a crushed and worked mass of wet soil material to flow when it is jarred. The greater the flow and the lower the water content, the higher the content of silt and very fine sand and the lower the content of clay and humus.

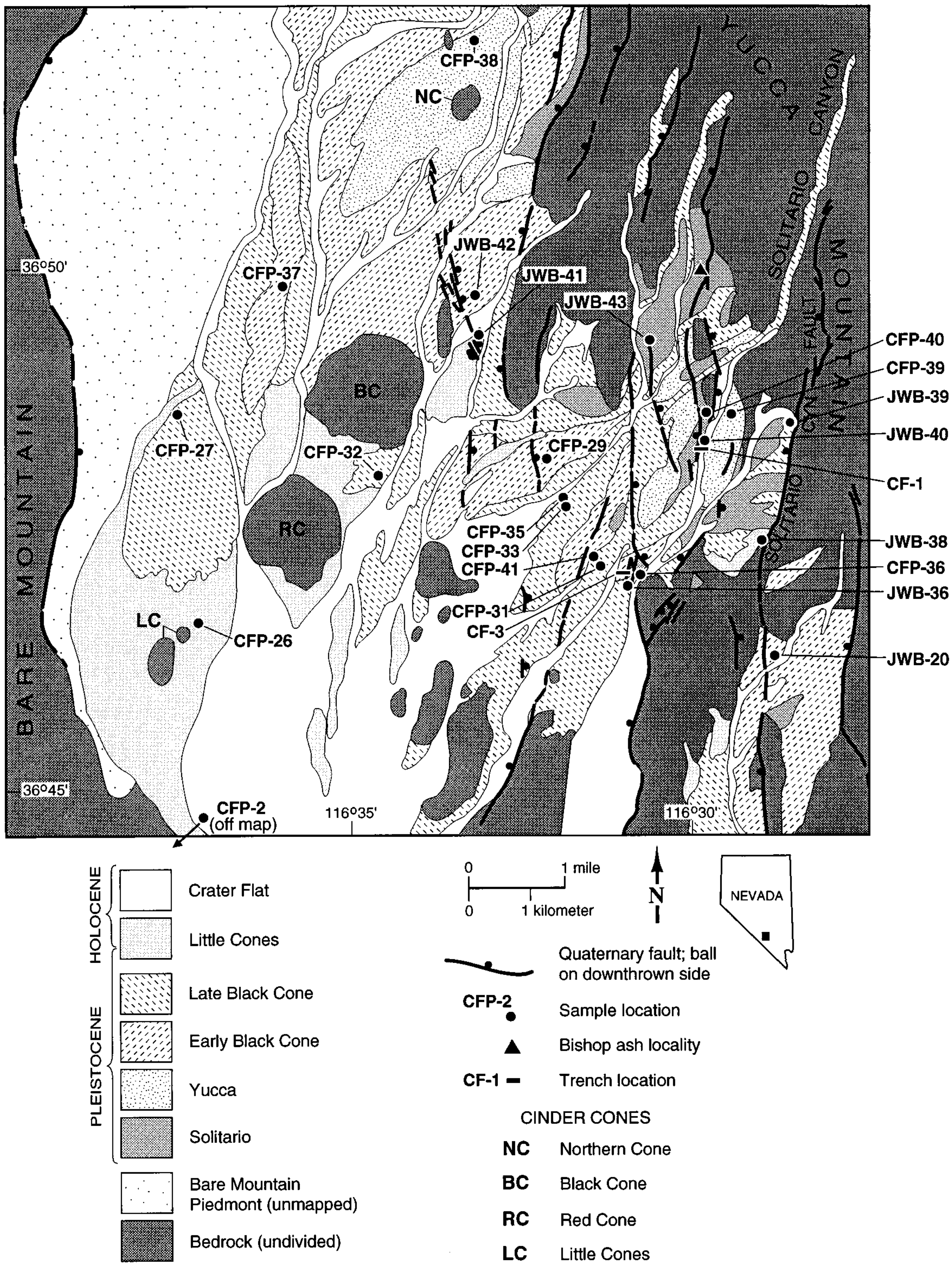

Figure 1. Allostratigraphic map of the central portion of Crater Flat.

nished desert pavement, argillic horizons that generally are clay loams, and typic or haplic duripans. The argillic horizons may or may not be opalized in their lower part. Pedon CFP-37 (Table 3), on the summit of an elongate fan-piedmont remnant prominently inset below large Yucca-age fan-piedmont remnants in northern Crater Flat, is an example of a Typic Durargid with an argillic horizon only minimally opalized. The very gravelly clay loam texture of the argillic horizon suggests that it is older than the very gravelly sandy loam Bt horizons of the Late Black Cone Durargids. Noncalcareous parts in the Av and Bt horizons are evidence that the A and Bt were previously leached free of carbonate and have been recarbonated. Other than a few thin opal coatings on peb-

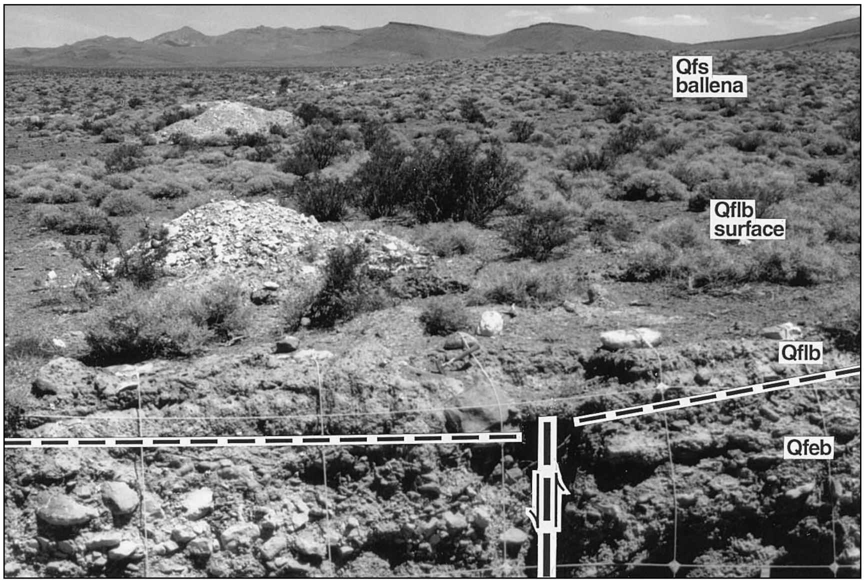

Figure 2. Late Black Cone surface offset by the Windy Wash fault at U.S. Geological Survey trench CF-3. The surface is inset below a Solitario-age ballena, the site of trench CF-2, seen in the middle ground; Yucca Mountain lies in the background. The trench exposes thick A and Av horizons and polygenetic Bk and Bqkm horizons. A rock-varnish ^{14}C AMS age of 28 920 ± 400 yr B.P. was obtained for the surface at this location.

ble bottoms, there is no morphological suggestion that the Bt horizon has been opalized. The duripan has only a single lamina on top, but strongly to weakly cemented lenses are imbricated closely enough below it to allow the pan to be called typic.

Pedon CFP-29 (Table 3) is an example of an Early Black Cone Typic Durargid that has a prominently opalized argillic horizon above its duripan. The distinctly reddish-hued (7.5YR), sticky, plastic, argillic horizon has at least a clay-loam texture. Its lower, platy part (Btq) reflects an intermediate stage of the progressive accumulation of pedogenic opal that can convert an argillic horizon into a duripan (cf. Flach et al., 1969).

Yucca Unit

The Yucca unit consists of several fairly extensive fan-piedmont remnants that are deeply dissected and narrow but flat-topped. It can be distinguished from the Black Cone, Little Cones, and Crater Flat units by aerial photograph patterns, topographic separation, and soil differences. On both color and black-and-white aerial photographs, transverse bands of darkly varnished desert pavement on low, Av-horizon slump-steps contrast with bands of light-colored biocoppice areas on step-risers to give a distinctively banded photographic pattern for many remnants. These contrast with the photographic pattern for both Late and Early Black Cone fan-piedmont remnants, where dark patches of desert pavement are irregularly shaped, or longitudinally elongated, and light-colored biocoppices are semicircular spots, creating a mottled photographic appearance.

Yucca-age soils are Typic Durargids that have darkly varnished desert pavements and loam-textured, strongly crusting Av horizons; Ak horizons are somewhat thicker than those of younger soils. Their argillic horizons are thicker and more clayey than those of the younger soils, and some have been so strongly opalized (microcemented) that the apparent field texture is a loam or loamy sand. Where exposed in wash cuts, the duripans are strongly cemented and thick.

Pedon CFP-39 (Table 3) illustrates a Yucca-age Typic Durargid that has minimal opalization of a 40-cm-thick argillic horizon. This soil is on a Yucca fan remnant inset below a Solitario-age remnant near the mouth of Solitario Canyon. Pedon CFP-38 (Table 3) illustrates a Yucca-age Typic Durargid that has a 55-cm-thick argillic horizon so strongly opalized that the material, originally clay textured, now has the texture of a loam in its upper part and a loamy sand in its platy lower part. Both soils have as much as 0.5 m of strongly cemented duripan. Although duripans on well-preserved Yucca surface remnants could not be adequately examined in soil pits because of their strongly cemented nature, wash exposures suggest that they are in general thicker and more strongly cemented than duripans on Black Cone remnants. Pedon CFP-38 has several opaline surficial laminae on its duripan, whereas pedon CFP-39 has only a single surficial opal lamina on its equally cemented duripan.

Solitario Unit

A few ballenas (fully rounded ridge-line fan remnants; cf. Peterson, 1981) comprise the Solitario unit. One at the mouth of Solitario Canyon (Fig. 1) is 1.5 m higher than an adjacent, flat-topped, Yucca-age fan remnant that is clearly inset below the Solitario remnant, demonstrating their relative ages. Bedrock spurs in Solitario Canyon—and in other canyons northeast of Crater Flat—appear to be bedrock-pediment remnants of a Solitario-age surface that was once much more extensive. A Solitario remnant in the northeast corner of Crater Flat (Fig. 1) contains reworked Bishop ash (ca. 730 ka) at 5–7 m depth (Marith Reheis, 1991, written commun.).

No well-preserved Solitario-age soils were found. Rather, there is a complex of Typic Durorthids with small areas of Typic Durargids on the rounded crests of the ballenas studied. Ballenas form by erosional rounding of formerly flat-topped fan remnants, with stripping of A and Bt horizons from the soil of the original fan-remnant summit. Apparently the original soil was a Durargid; subsequent stripping shattered the upper part of the duripan and mixed the detritus with later dust accumulations, leaving a Typic Durorthid.

Pedon CFP-40 (Table 3) is a Typic Durargid on a ballena summit that represents the truncated remnants of the original soil. The ballena is littered with chips of duripan laminae from the Bqkm horizon, indicating that the shattered top of the duripan has been extensively bioturbated. The ballena is distinctively light colored on aerial photographs, apparently due to the chips of duripan laminae strewn across its surface. In a second, adjacent pavette location, there is a Typic Durorthid that has only an Av (0–5 cm) and an Ak (5–19 cm) over the duripan. In a third pavette location, the Durorthid has only an Av (0–7 cm) over the duripan.

The duripans commonly have 1–3 cm of thick, strongly opalized laminae on their tops. Fault trenches dug into the sides of ballenas show that the duripans extend from the crest on over the sides of the ballenas. The strongly cemented, laminar part of the duripan, however, is thickest (~0.5 m) at the ballena crest and thinner on the younger sideslopes. The shallow sola (Av, Ak, Btk) likely do not represent the original Solitario-age soil; rather, they probably represent dust fall and soil formation on top of a stripped duripan since about Late Black Cone time. The strongly cemented, thickly laminae-covered duripans at the ballena crests are some measure of the original Solitario soil.

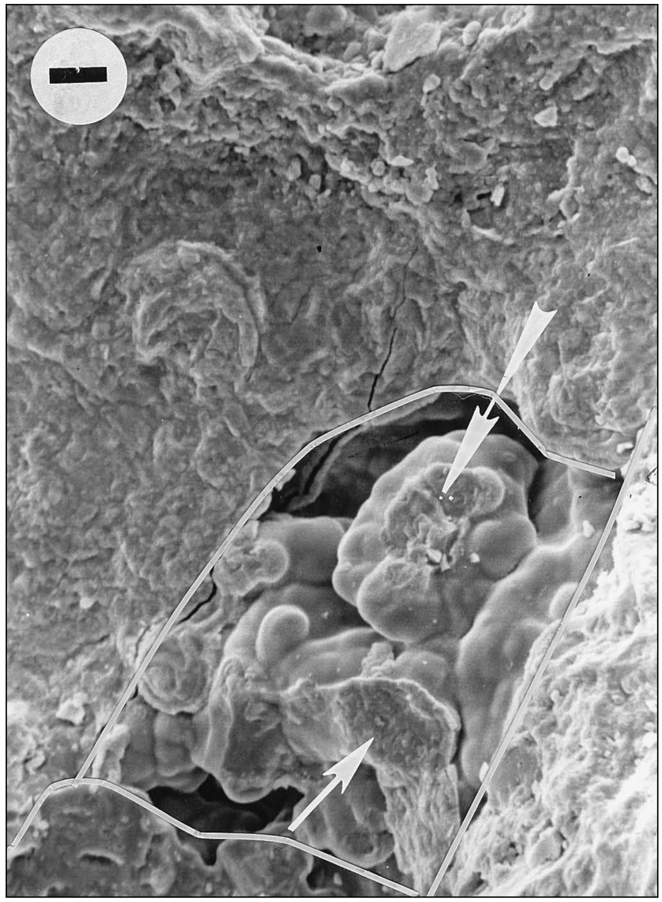

Figure 3. Examples of pockets of organic matter beneath rock varnish. (A) Secondary electron microscope view of organic matter beneath rock varnish at CFP-26 (Table 4). The upper line separates varnish from subvarnish organic matter. The lower line shows the varnish/rock boundary. White arrows identify broken edges where spot energy-dispersive analysis of X-rays (EDAX) was taken. Bar scale = 10 μm.

AGES OF ALLOSTRATIGRAPHIC UNITS

The lack of radiometrically datable stratigraphic horizons in the Yucca Mountain region, apart from the Bishop ash, requires the application of less-conventional dating techniques. Previous numerical age estimates (Table 1) are almost exclusively from uranium-trend dating of soils and sediments from the Nevada Test Site area (Swadley et al., 1984; Rosholt et al., 1985). The open-system uranium-trend technique estimates time of initial sediment deposition (Rosholt, 1980; Muhs et al., 1989) rather than merely the time of secondary deposition of the pedogenic carbonates in the sediment, which is measured by the closed-system uranium-series ($^{230}Th/^{234}U$ disequilibrium) method (Ku, 1976). Harrington and Whitney (1987) used some uranium-trend dates for the Hoover et al. (1981) Q2b and Q2c units to calibrate a rock-varnish cation-leaching curve for the Yucca Mountain area. Whitney and Harrington (1993) dated colluvial slope deposits at Yucca Mountain using the rock-varnish cation-ratio curve and ^{36}Cl analyses. Harden et al. (1991) used uranium-trend ages from Rosholt et al. (1985) to calibrate soils in Fortymile Wash on the east flank of Yucca Mountain. For this study, we used four different rock-varnish and uranium-series methods to test our soil-geomorphic relations and to scale and correlate our units.

Rock-Varnish Dating Methods

Rock varnish is a dark Fe- and Mn-rich layering that accretes on subaerial rock surfaces in arid and semiarid environments. Three separate rock-varnish methods—accelerator mass spectrometry radiocarbon (^{14}C AMS) dating, cation-ratio (CR) analysis, and varnish microlamination layering—were used to estimate ages for clasts lying on unit surfaces. As a surface-exposure dating technique, rock-varnish age estimation provides only a minimum age for the geomorphic surface and soil that characterize a unit, because varnish forms only after the clasts are exposed by erosion or the surface is depositionally stabilized. In this study, varnish fragments were collected from multiple clasts at each sampling site to assess the potential for disparate ages.

We believe our most accurate estimates of minimum surface-exposure age are from the ^{14}C AMS varnish-dating technique. Sampling of rock varnish for this procedure requires a layered, microstratigraphic context, where varnish encapsulates organic material (Fig. 3). The first step is mechanical removal of the outer layers of varnish under 10–45× magnification. The remaining organic material includes that at the varnish/rock interface and that in the weathering rind under the varnish. The second step is removal of the basal layer of varnish and the rock immediately underneath. The third step is pretreatment of the subvarnish organic material with HF, hydroxylamine hydrochloride, dithionite, and HCl.

The two most important aspects in the ^{14}C AMS varnish-dating method are the use of layered varnishes and the pretreatment with HF. If the varnish is not layered, it yields ^{14}C ages far younger than corresponding independent ^{14}C age control (Dorn et al., 1989, 1992; Nobbs and Dorn, 1993). If the HF pretreatment is not used, younger organic material adsorbed onto clays is not removed, and the ^{14}C AMS ages are again far younger than independent age controls (Dorn et al., 1989).

Dorn et al. (1989) tested ^{14}C AMS dating of varnish by comparing varnish ages in a variety of settings with independent ^{14}C age controls. Harden et al. (1991) used rock-varnish ^{14}C AMS and shell ^{14}C dates to calibrate soils at Silver Lake, California. In central Nevada, varnish ^{14}C AMS dates on alluvial-fan surfaces are consistent with the ages of underlying late Quaternary tephra and with conventional ^{14}C dates (Yount et al., 1993; J. W. Bell, unpubl. data). A discussion of uncertainties associated with rock-varnish ^{14}C AMS dating is presented below.

CR dating is based on the observation that concentrations of Ca and K in rock var-

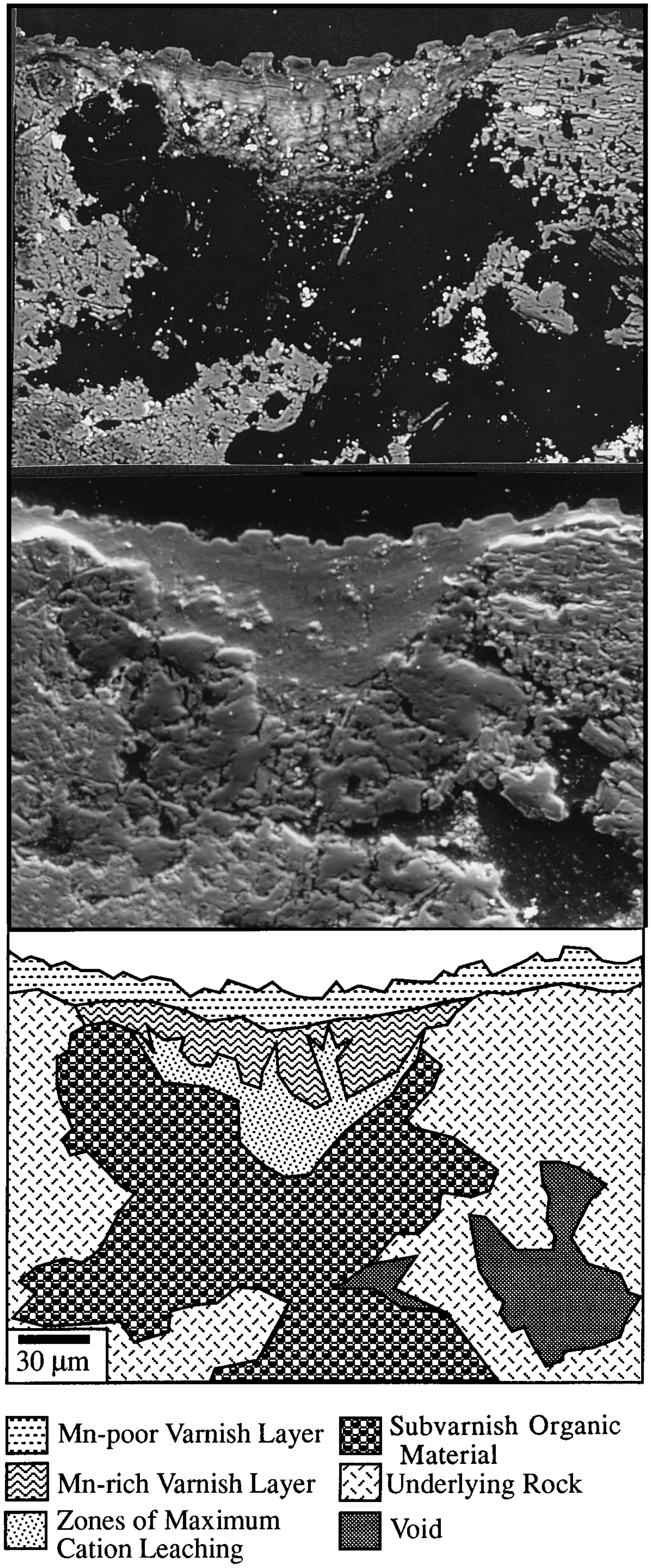

Figure 3. (*Continued*). (B) Comparison of backscatter view (upper) and secondary view (lower) of a polished thin section of varnish at CFP-32 (Table 4). The backscatter image reflects the average atomic number, so the Mn-rich layer is brightest, the Mn-poor layer is darker, and the organic matter is black. In contrast, the secondary electrons (lower) image shows topography; the mapped organic matter is also indicated by a strong carbon signal in wavelength dispersive electron microprobe measurements. Note also the presence of areas of cation leaching and the layering of Mn-poor on Mn-rich varnish.

nish decrease over time with respect to Ti (Dorn, 1983). Cation ratios for all samples were measured by wavelength-dispersive electron microprobe. Current CR practice is summarized in Dorn (in press); Dorn (1988a, 1989) and Dorn et al. (1990) described the CR procedure used for this study. A smaller duplicate sample set was analyzed in 1988 by proton-induced X-ray emission (PIXE) at Crocker Nuclear Laboratory, University of California, Davis. These samples were also analyzed by wavelength-dispersive electron microprobe, and no significant disparities were found in the cation ratios between the two data sets.

We use here only the wavelength-dispersive microprobe data. We note that this analysis discriminates all elements used in the CR dating, and it is thus not affected by the Ba and Ti problem encountered in other methods (Dorn et al., 1990; Whitney and Harrington, 1993). The microprobe and PIXE data sets are available in Appendix 2.

CR dating is still experimental, and its greatest uncertainties are the environmental variables other than time. More than two dozen non-time-dependent variables have been isolated (Dorn, 1989, 1992; Krinsley et al., 1990; Dorn and Krinsley, 1991). Reneau and Raymond (1991) argued that there is no systematic cation-leaching process and that observed CR change is an artifact of sampling rock substrate. However, Dorn and Krinsley (1991) provided textural, chemical, and laboratory-simulation evidence for cation leaching in rock varnishes. A more complete discussion of the controversies associated with cation-ratio dating and reasons why certain samples were rejected is available in Appendix 2.

TABLE 4. RESULTS OF ROCK VARNISH ANALYSES

Allostratigraphic unit (this study)	Sample	^{14}C AMS date (yr B.P.; AMS lab #)	(K+Ca)/Ti (ave. ± 1σ)	Cation-ratio age (yr) −2σ (ave.) +2σ
Crater Flat	CFP-41		9.17 ± 0.25	150 (300) 600*
	JWB-36	1 320 ± 70 (ETH 5264)	7.95 ± 0.17	800 (1100) 1600†
Little Cones	CFP-2	6 645 ± 245 (ETH 3197)	6.47 ± 0.13	§
	JWB-38	8 425 ± 70 (ETH 5268)	6.37 ± 0.13	§
	CFP-26	10 180 ± 270 (ETH 3187)	6.13 ± 0.13	§
	JWB-41	11 135 ± 105 (ETH 5270)	5.99 ± 0.13	§
Late Black Cone	CFP-33	17 280 ± 370 (ETH 3191)	5.75 ± 0.05	§
	CFP-31		5.67 ± 0.15	14 000 (19 000) 27 000
	JWB-39	19 660 ± 240 (ETH 4483)	5.68 ± 0.15	§
	CFP-27	25 700 ± 360 (ETH 3188)	5.42 ± 0.12	§
	CFP-35	26 970 ± 375 (ETH 3192)	5.34 ± 0.15	§
	CFP-36	28 920 ± 400 (ETH 3190)	5.32 ± 0.07	§
	CFP-32	30 320 ± 460 (ETH 3189)	5.14 ± 0.07	§
Early Black Cone	CFP-37		3.98 ± 0.19	110 000 (159 000) 218 000
	CFP-29	>40 120 (ETH 5259)	3.98 ± 0.32	116 000 (167 000) 229 000
	JWB-42		3.90 ± 0.11	122,000 (176 000) 241 000
	JWB-20		3.79 ± 0.12	139 000 (201 000) 275 000
Yucca	CFP-39		3.29 ± 0.11	254 000 (375 000) 508 000
	CFP-38		3.29 ± 0.11	253 000 (373 000) 505 000
Solitario	JWB-43		3.17 ± 0.10	293 000 (433 000) 585 000
	CFP-40		2.95 ± 0.10	383 000 (572 000) 769 000
	JWB-40		2.84 ± 0.09	440 000 (659 000) 885 000

Allostratigraphic unit (this study)	Sample	K-Ar age (yr B.P.)	(K+Ca)/Ti (ave. ± 1 σ)	Cation-ratio age (yr) −2 σ (ave.) +2 σ
Little Cones basalt	#	770 000 ± 40 000	2.63 ± 0.08	§
Red Cone basalt	#	950 000 ± 80 000	2.63 ± 0.12	§
Black Cone basalt	#	1 090 000 ± 120 000	2.53 ± 0.06	§

*Error are asymmetric due to the semilog nature of the 2σ error curves.
†Samples were collected from two localities at JWB-36. One was used for calibration; the other was assigned the CR age.
§Varnish cation ratio used in calibration.
#K-Ar ages from Smith et al. (1990).

Manganese:iron ratios in rock-varnish microlaminations reflect the alkalinity of the varnish-forming environment. High ratios develop in less alkaline (more humid) environments, whereas low ratios develop in more alkaline (arid) environments (Dorn, 1988b, 1990; Jones, 1991). By calculating Mn:Fe ratios for successive varnish layers and by correlating sequences of varnish layers, it is possible to construct a relative-age sequence.

Rock-Varnish Dating Results

Rock-varnish samples were collected from 22 widely separated sites on Crater Flat allostratigraphic units (Fig. 1, Table 4). Samples from 12 sites were analyzed in 1988 (Dorn, 1988a), and an additional 10 were analyzed in 1989 (Bell et al., 1989). Twelve of the 22 varnish sites were dated by ^{14}C AMS. Eleven finite ^{14}C AMS ages were obtained on the Crater Flat, Little Cones, and Late Black Cone units. One infinite age of >40,120 yr B.P. was obtained on an Early Black Cone surface, providing an internal check of the method.

Rock-varnish ^{14}C AMS ages and K-Ar ages on basalt cones in Crater Flat are used to calibrate the Crater Flat cation-leaching curve (Fig. 4). Since first presented by Dorn (1988a), the Crater Flat cation-leaching curve has evolved as new ^{14}C AMS calibration points became available. Earlier CR ages (Dorn, 1988a) were recalculated using individual CR measurements, as described in Dorn et al. (1990). In addition, the Lathrop Wells basalt flow calibration point included on the original curve was dropped, because recent studies (Wells et al., 1990b, 1992; Turrin et al., 1991; Zreda et al., 1993) indicate that the history of the Lathrop Wells center is still unresolved. The CR calibration values listed in Table 4 are averages of four or more individual measurements, and are used to construct the following least-squares semilog regression in Figure 4:

$$CR = 13.52 - 1.83 \log_{10} \text{age}. \quad (1)$$

The 2σ error envelope shown in Figure 4 was constructed to account for errors in cation ratios and calibrated ages. The upper line is a least-squares semilog regression of the +2σ cation-ratio and age errors:

$$CR = 13.93 - 1.87 \log_{10} \text{age}. \quad (2)$$

The lower line is a least-squares semilog regression of the −2σ cation-ratio and age errors:

$$CR = 13.49 - 1.89 \log_{10} \text{age}. \quad (3)$$

Calibrated CR ages are assigned for each separate cation ratio using equation (1). By

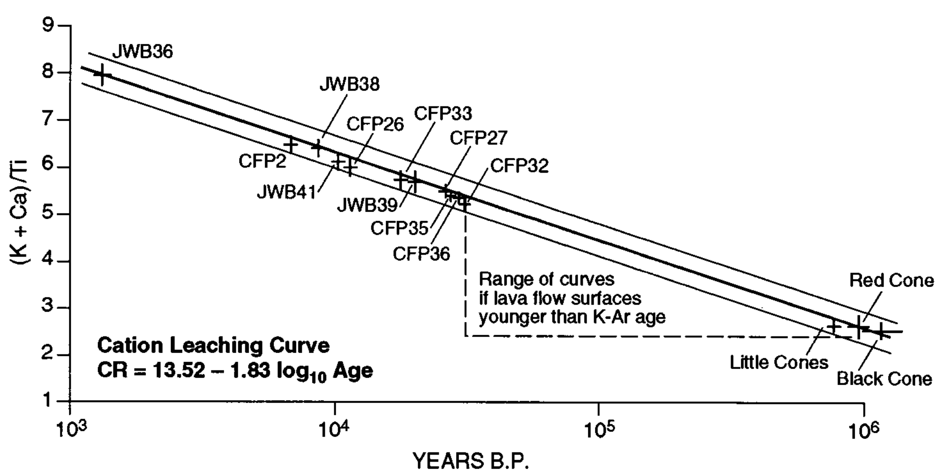

Figure 4. Rock-varnish cation-leaching curve for Crater Flat. Calibration based on ^{14}C rock-varnish dates for geomorphic surfaces (this study) and on K/Ar dates for basaltic lava flows (Smith et al., 1990). Error bars indicate uncertainty for each data point used to construct the least-squares semilog regression. The error envelope accounts for ±2σ errors in both cation ratios and calibration ages. The triangular area below the regression encloses a possible range of curves extending from CFP-32 if the sampled lava flow surfaces are actually younger than the K-Ar ages.

treating each CR as a separate time indicator, intersample variability will thus be indicative of the time-transgressive growth of the varnish. The mean of each calibrated age is presented in Table 4 as the average age; the 2σ errors are derived from equations (2) and (3) and the microprobe measurements contained in Appendix 2. It should be noted that although CR averages may be identical (e.g., samples CFP-29 and CFP-37), the average of the separate age calculations can differ due to the semilog nature of the regressions.

To define the older end of the curve, we used recent K-Ar dates for basalt flows in Crater Flat (Smith et al., 1990; Table 4). For the younger end of the curve, a ^{14}C AMS age of ca. 1300 yr B.P. is available (sample JWB-36; Table 4) for calibrating all but the youngest site. Sample CFP-41, which has the highest CR, is <<1300 yr B.P. and has a provisional age of ca. 300 ± 200 yr B.P. based on an extension of the curve. We note that CR values for the Early Black Cone, Yucca, and Solitario units fall between the ^{14}C AMS and K-Ar calibration points; hence, these ages are "hybrids" between the two time scales.

The CR values for the Black Cone, Red Cone, and Little Cones basalts are important calibration points on Figure 4, because they establish the older end of the curve. We assume that the samples collected from the broad constructional lava surfaces are close to the original flow surfaces. Detailed mapping of flow patterns indicates that although the lava flows have been locally eroded, the original flow surfaces are still well preserved with <1–2 m of erosion (Faulds et al., 1994; E. I. Smith, 1993, personal commun.). Although we attempted to sample varnishes from areas on each flow that were felt to be closest to an original texture, we cannot completely exclude the possibility that some of the sampled surfaces have been eroded. If so, a range of curves could exist; these would fall within the area indicated on Figure 4. Nonetheless, our basic conclusions would remain unchanged, while details may vary slightly; that is: (1) the cation ratios could only be used to define relative clusters of statistically distinct populations for the Early Black Cone, Yucca, and Solitario units, and (2) the true ages of the samples dependent on the K-Ar ages would have to be even younger than those calculated here (Table 4).

Selected varnish alkalinity ratios were measured by wavelength-dispersive microprobe, and several trends are evident (Figs. 5 and 6) when evenly layered subaerial varnishes are used (cf. Dorn, 1990; Krinsley et al., 1990). Younger varnishes have fewer Mn:Fe layers than older varnishes. Crater Flat and Little Cones varnishes are only Mn poor, reflecting a period of enhanced alkalinity during the Holocene (Dorn, 1990). Late Black Cone varnishes have a basal layer of reduced alkalinity, possibly corresponding with a more moist late Pleistocene period in the Nevada Test Site area (Spaulding, 1985; Claassen, 1986; Szabo et al., 1994). Early Black Cone, Yucca, and Solitario varnishes have progressively more complex sequences.

Based on the rock-varnish results, we estimate approximate minimum ages for the allostratigraphic units. Rock-varnish ^{14}C AMS ages suggest the Crater Flat unit is late Holocene (>0.3 to >1.3 ka), the Little Cones unit is latest Pleistocene to earliest Holocene (>6 to >11 ka), and the Late Black Cone unit is late Wisconsin (>17 to >30 ka). Because the CR dating method has significant analytical uncertainties, we use broad CR age ranges for grouping the older units. The Early Black Cone unit is estimated to be from >159 to >201 ka. The Yucca and Solitario units are taken to be mid-Pleistocene, with approximate minimum ages of >375 ka and >433 to >659 (but <730 ka), respectively.

Reliability of Rock-Varnish ^{14}C Ages. Rock-varnish ^{14}C AMS ages date the onset of varnish formation and thus are interpreted as minima for the subaerial exposure of clasts on the sampled units. Although we do not know precisely how much the rock-varnish ^{14}C AMS ages underestimate the true numerical ages, we infer that the results provide reasonably close minimum ages for the following reasons: (1) Dorn et al. (1989) found that ^{14}C AMS varnish ages underestimate true exposure ages of control samples by ~10% due to the lag between exposure and varnish accretion. Other studies based on independent controls and stratigraphic associations have produced similar results (Moore and Clague, 1991; Benson et al., 1992). (2) We sampled widely separated localities from each unit to stratigraphically test the consistency of the method. Relative consistency and clustering of both ^{14}C AMS ages and cation ratios from the same allostratigraphic units suggest that either a systematic bias influences the ages, that the ages closely approximate true ages, or both. (3) All eleven ^{14}C AMS varnish ages from Late Black Cone and younger units are finite, suggesting these units are young enough to be within the range of ^{14}C dating (<35–40 ka). This is consistent with the microchemical signals (Figs. 5 and 6) suggesting that the Late Black Cone and Little Cones varnishes were deposited in the late Wisconsin and Holocene. (4) Uranium-series ages are consistent with the varnish results. Three ^{230}Th/^{234}U ages on pedogenic carbonate from a Late Black Cone soil range between 17.1 and 39.4 ka (discussed below); at the same locality, surface clasts yielded a ^{14}C AMS varnish age of 28.9 ka (Table 5; Fig. 7).

Uncertainties associated with the ^{14}C AMS varnish ages include the nature of the organic material and replication. Organic matter encapsulated beneath rock varnish includes lichen, charcoal, fungal mats, bacteria, microcolonial fungi, algae, pollen, plant remains, and unidentified organic material (Dorn and DeNiro, 1985; Dorn et al., 1989; Nagy et al., 1991; Watchman, 1992; Nobbs and Dorn, 1993; Dragovich, 1993). The samples dated in this study included endolithic algae, lichen remains, and unidentified organic material. Future tests are needed to resolve what types of material yield the most reliable ages.

Replicate ^{14}C AMS varnish measurements overlap within 2σ errors about half of the time (Dorn et al., 1989, 1992; Nobbs and Dorn, 1993; Whitley and Dorn, 1993). Watchman (1992) was unable to obtain overlapping measurements on two replicate varnish samples from different locations. The lack of overlap in ages is not surprising, however, because the organic material was likely encapsulated at different times as the varnish accreted. This further argues that the ages are minima.

Cation-Leaching Curve. The Crater Flat cation-leaching curve (Fig. 4) differs somewhat from a previous cation-leaching curve for Yucca Mountain (Harrington and Whitney, 1987; Whitney and Harrington, 1993). Although both curves have similar cation ratios for the older Red and Black Cones basalt calibration points, they deviate substantially at their younger ends. For Early Black Cone and younger units, the Crater Flat curve yields calculated CR ages younger by factors of two to three than those of Harrington and Whitney (1987).

We sampled varnish from the 40 ka Crater Flat locality used in the Harrington and Whitney (1987) calibration. Our varnish analysis yielded a ^{14}C AMS age of 28.9 ± 0.4 ka and a mean cation ratio of 5.32 ± 0.07 (sample CFP-36, Table 4). The cation ratio of 6.0 ± 1.0 reported by Harrington and

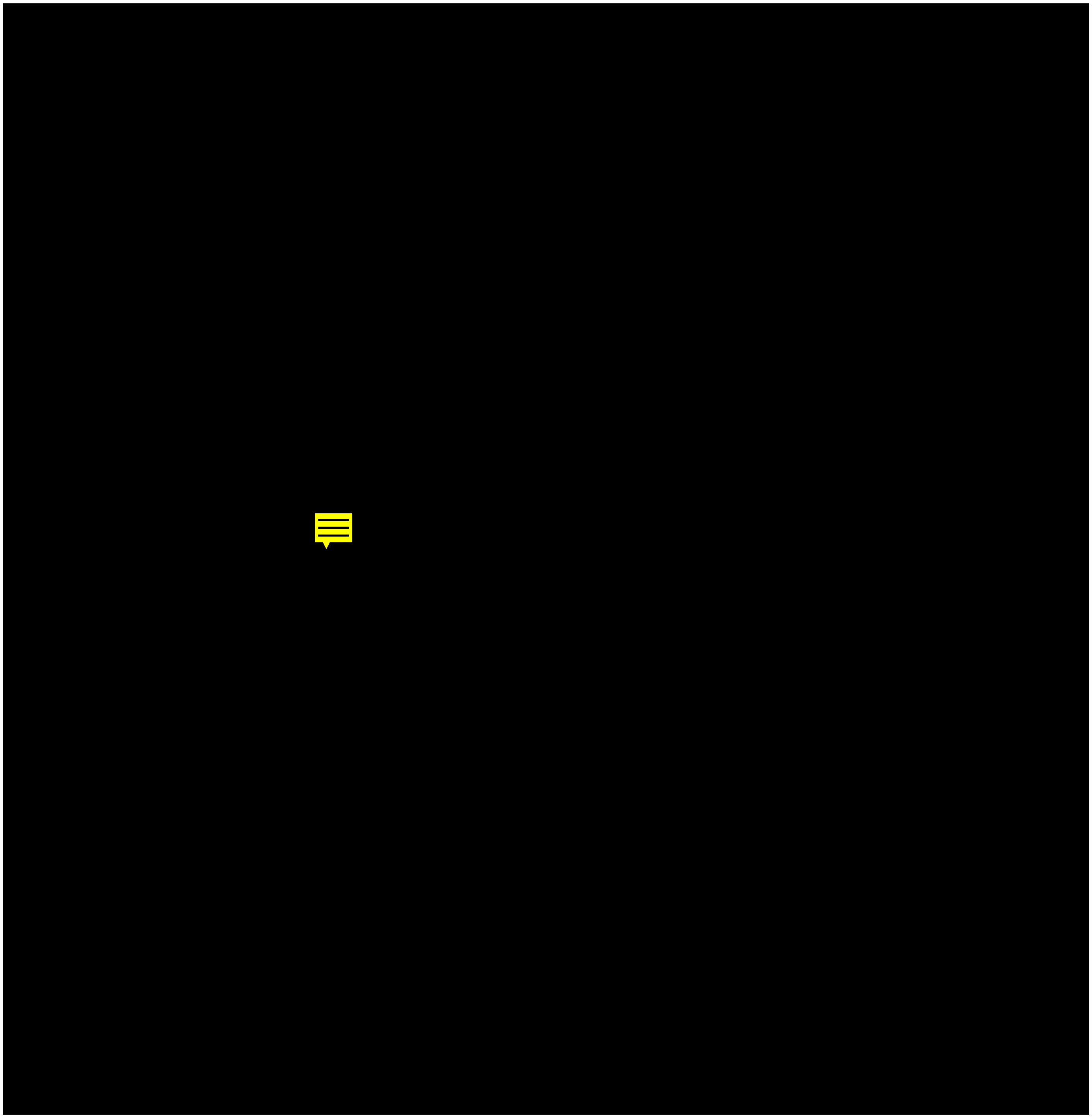

Figure 5. Visual microlaminations revealing black (Mn-rich, less alkaline) and orange (Mn-poor, more alkaline) layers from five geomorphic surfaces. (Top left) CFP-2, varnish thickness is ~10 μm. (Middle left) CFP-33, thickness is ~25 μm. (Bottom left) CFP-32, thickness is 35 μm. (Top right) CFP-29, thickness is ~60 μm. (Middle right) CFP-29, second microbasin, thickness is ~60 μm. (Bottom right) CFP-40, thickness is ~100 μm. Although colors do not reveal precise chemical values, the images show trends with more complex laminae in progressively older morphostratigraphic positions. A section from CFP-40 (bottom right) reveals two problems found in varnish sedimentology: an unconformity (at the top of the varnish, perhaps from aeolian abrasion) and interruption of layers (at the right, perhaps from microcolonial fungi secreting acids and "boring a hole" into layers).

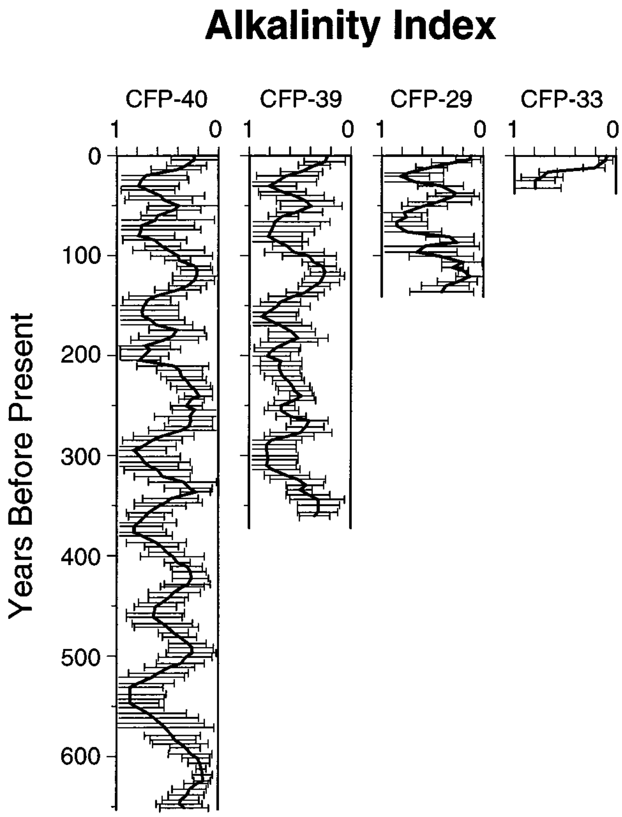

Figure 6. Averaged electron-microprobe analyses (wavelength dispersive mode) of Mn:Fe microlaminations from different allostratigraphic units. As in Dorn (1990), the alkalinity index represents normalized Mn:Fe values. Zero is the lowest ratio (higher alkalinity), and 1 is the highest ratio (less alkalinity). Years before present (in 10^3) were derived by normalizing depth to the ^{14}C or cation-ratio age. Alkalinity index values were then regressed for every 5000 yr. The central line indicates the average alkalinity-index values for 20 transects across layered varnishes from five different rocks, and bars represent 2σ.

Whitney (1987) for varnish at this locality would correspond to a calculated CR age of ca. 12–13 ka based on the Crater Flat curve, and is a ratio we found more closely related with the Little Cones unit.

We do not know the reasons for this disparity, but speculate that it may be related to one or more of the following factors: (1) curve calibration methods (^{14}C versus uranium trend); (2) cation-ratio measurement methods (scraping electron microprobe versus in situ scanning electron microscope); (3) field sampling and laboratory preparation techniques; or (4) stratigraphic uncertainties.

Uranium-Series Dating of Pedogenic Carbonate

Six samples of pedogenic carbonate were collected from trenches CF-1 and CF-3 in Crater Flat (Figs. 1 and 7) and analyzed by the uranium-series dating method of Luo and Ku (1991). Trench CF-1 crosses a fault displacing a Solitario-age ballena veneered by a Late Black Cone–age slope deposit; trench CF-3 crosses a fault displacing a Late Black Cone alluvial surface (Fig. 2). Samples U1, U3, and U6 are from the uppermost Bqkm laminae and are assumed to be the most recent layers added to the petrocalcic horizons at these locations. Samples U2, U4, and U5 were collected from carbonate rinds on clasts located 20–75 cm below the laminar horizons and were analyzed for a stratigraphic test of the dating method.

The isochron method of Luo and Ku (1991) is based on the concept that ^{230}Th in the samples has two components. One component is that part of the ^{230}Th initially present when the deposit formed; this component is associated with all phases bearing ^{232}Th. The other component is that part of the ^{230}Th produced by in situ decay of ^{234}U since the sample formed. It is this latter component, called the authigenic component, that is used in the age estimation. This authigenic ^{230}Th will grow with time in phases such as carbonate and opal, which coprecipitate some uranium as they form. In essence, the ages derived estimate the time of uranium coprecipitation. It should be noted that the sampled pedogenic carbonate material was as much as 5 mm in thickness. The ages reported here, therefore, represent means for the periods over which the carbonate accumulated. They are minimum

TABLE 5A. RADIOCHEMICAL AND UNCORRECTED AGE DATA ON PEDOGENIC CARBONATE SAMPLES FROM CRATER FLAT

Sample no.*	^{238}U (ppm)	^{234}U/^{238}U (ppm)	^{230}Th/^{234}U (ppm)	^{230}Th/^{232}Th (ppm)	Uncorrected age (ka)
U1					
(a)	7.86 ± 0.31	1.61 ± 0.06	0.307 ± 0.014	1.99 ± 0.10	38.9 ± 3.6
(b)	6.78 ± 0.17	1.55 ± 0.04	0.331 ± 0.012	2.13 ± 0.13	42.6 ± 2.7
(c)	5.67 ± 0.12	1.51 ± 0.03	0.291 ± 0.009	1.81 ± 0.09	36.6 ± 2.1
U2					
(a)	5.24 ± 0.17	1.60 ± 0.05	0.588 ± 0.022	6.19 ± 0.54	89.9 ± 6.0
(b)	4.76 ± 0.13	1.68 ± 0.04	0.644 ± 0.022	4.41 ± 0.31	102.4 ± 6.2
(c)	3.52 ± 0.11	1.41 ± 0.04	0.716 ± 0.032	1.61 ± 0.10	125.0 ± 11.0
U3					
(a)	7.75 ± 0.25	1.57 ± 0.07	0.164 ± 0.029	2.98 ± 0.18	19.2 ± 4.8
(b)	8.13 ± 0.19	1.48 ± 0.03	0.186 ± 0.007	2.23 ± 0.13	22.1 ± 1.6
(c)	6.98 ± 0.21	1.59 ± 0.04	0.193 ± 0.009	1.27 ± 0.08	22.9 ± 2.1
U4					
(a)	10.15 ± 0.20	1.48 ± 0.02	0.357 ± 0.012	3.17 ± 0.20	46.7 ± 2.4
(b)	5.45 ± 0.17	1.44 ± 0.05	0.419 ± 0.018	1.50 ± 0.09	57.2 ± 4.5
(c)	4.95 ± 0.19	1.44 ± 0.05	0.479 ± 0.022	1.41 ± 0.08	68.1 ± 5.9
U5					
(a)	18.98 ± 0.48	1.46 ± 0.02	0.321 ± 0.006	19.5 ± 1.3	41.1 ± 1.6
(b)	6.82 ± 0.16	1.29 ± 0.03	0.568 ± 0.015	4.10 ± 0.20	87.5 ± 4.7
(c)	6.82 ± 0.18	1.28 ± 0.02	0.522 ± 0.012	4.52 ± 0.19	77.5 ± 3.6
U6					
(a)	14.17 ± 0.36	1.48 ± 0.03	0.448 ± 0.009	17.8 ± 1.2	62.1 ± 2.5
(b)	13.77 ± 0.25	1.42 ± 0.02	0.454 ± 0.006	12.0 ± 0.4	63.5 ± 1.8
(c)	12.10 ± 0.31	1.42 ± 0.02	0.462 ± 0.006	8.76 ± 0.24	64.9 ± 2.2

*(a), (b), and (c) denote subsamples.

TABLE 5B. ISOCHRON-DERIVED AUTHIGENIC RATIOS OF ^{234}U/^{238}U AND ^{230}Th/^{234}U, AND AGES CALCULATED THEREFROM

Sample no.	(^{234}U/^{238}U)a	(^{230}Th/^{234}U)a	Age (ka)
U1	N.D.	N.D.	39.4 ± 3.0*
U2	1.66 ± 0.03	0.555 ± 0.044	82.4 ± 9.4
U3	1.56 ± 0.03	0.147 ± 0.017	17.1 ± 2.5
U4	1.50 ± 0.02	0.302 ± 0.018	38.2 ± 2.9
U5	1.49 ± 0.02	0.288 ± 0.009	36.2 ± 1.7
U6	1.53 ± 0.01	0.434 ± 0.004	59.5 ± 0.9

*From the uncorrected ages of three subsamples (see Table 5A). It represents a maximum age for the sample. N.D. = not determined.

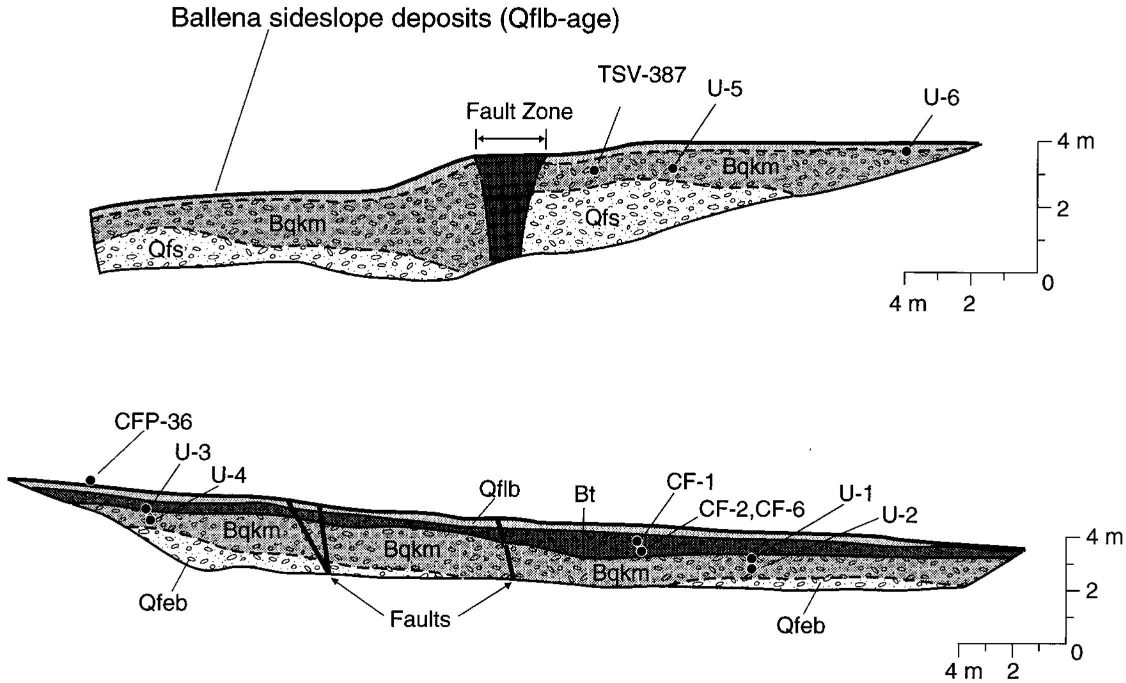

Figure 7. Reinterpretation of Swadley et al. (1984) logs from trenches CF-1 (upper) and CF-3 (lower). Uranium-series ages are (Table 5B) U-1 (39.4 ± 3.0 ka), U-2 (82.4 ± 9.4 ka), U-3 (17.1 ± 2.5 ka), U-4 (38.2 ± 2.9 ka), U-5 (36.2 ± 1.7 ka), and U-6 (59.5 ± 0.9 ka). Sample TSV-387 is 33 ± 4 ka (Szabo and O'Malley, 1985). Uranium-trend ages are CF-1 (40 ± 10 ka), CF-2 (270 ± 20 ka), and CF-6 (190 ± 50 ka) (Rosholt et al., 1985). A rock-varnish ^{14}C AMS age (CFP-36) of 28.9 ± 0.4 ka was obtained for clasts on the surface overlying samples U-3 and U-4. Qflb = Late Black Cone, Qfeb = Early Black Cone, and Qfs = Solitario.

ages with respect to the initiation of the pedogenic process at the sampling sites.

Each of the six samples was divided into three subsamples with different U/Th ratios. After total dissolution of the subsamples, measurements of their ^{238}U, ^{234}U, ^{232}Th, and ^{230}Th were made using isotope-dilution alpha spectrometry. Besides the assumption of a closed system, the age calculations assume that, for a given sample, the subsamples are the same age and had a common $^{230}Th/^{232}Th$ ratio when the sample formed.

The analytical results with uncertainties (1σ) based on the counting statistics are listed in Table 5A, together with the uncorrected ages calculated without considering the ^{230}Th initially present in the deposit. The results were used to construct isochron plots from which the authigenic $^{234}U/^{238}U$ and $^{230}Th/^{234}U$ activity ratios were derived for each sample from the slopes of the plot. These ratios and calculated ages are listed in Table 5B; isochron plots are available in Appendix 3. The uncertainties for the isochron-derived ages include both the counting error and errors associated with the linearity of the isochron plots (Luo and Ku, 1991).

With the exception of sample U1, the samples all gave isochron plots with good linearity. For sample U1, separation into subsamples with sufficiently different $^{238}U/^{232}Th$ ratios was unsuccessful, and no meaningful isochron was obtained. The age of sample U1 (Table 5B) is an average of the uncorrected ages for its three subsamples, and it represents the maximum age for the sample.

The calculated ages for the six samples range from 17.1 ± 2.5 to 82.4 ± 9.4 ka (Table 5B). At trench CF-1, the Bqkm horizon is polygenetic, with a Late Black Cone soil developed on a truncated Solitario soil. The uranium-series ages of 36.2 ± 1.7 and 59.5 ± 0.9 ka are interpreted to date the carbonate added during Late Black Cone time, although we note that sample ages are reversed with respect to stratigraphic position. The younger age of sample U-5 is, however, close to a $^{230}Th/^{234}U$ date of 33 ± 4 ka previously obtained from this trench by Szabo and O'Malley (1985) (Sample TSV-387, Fig. 7).

The best results are from trench CF-3, where the carbonate horizon is polygenetic, with a Late Black Cone Bk horizon superimposed on an Early Black Cone Bqkm horizon. Uranium-series ages of 17.1 ± 2.5, 38.2 ± 2.9, and 39.4 ± 3.0 ka from the uppermost laminae and the underlying rind carbonate are consistent with a Late Black Cone age for the geomorphic surface. A fourth older age of 82.4 ± 9.4 ka on rind carbonate may in part be dating the Bqkm horizon of the older Early Black Cone soil. Rosholt et al. (1985) reported three uranium-trend ages from sediments in this trench (Fig. 7); their date of 40 ± 10 ka (Sample CF-1) is in reasonable agreement with our results. We interpret their older ages of 190 ± 50 ka (Sample CF-6) and 270 ± 20 ka (Sample CF-2) to be dating the Early Black Cone horizons.

A rock-varnish ^{14}C AMS age of 28.9 ± 0.4 ka was obtained for clasts on the upthrown side of the Late Black Cone surface above samples U-3 and U-4 at trench CF-3 (Sample CFP-36; Table 4).

DISCUSSION

Age-Related Soil Features

Based on consistent field relations and pedon characteristics (Table 3), the following age-related soil features are good criteria for identifying and mapping surficial stratigraphic units in Crater Flat: (1) Vesicular surface horizons (Av) form in coarse, sand-textured alluvium by dust fall on the surface and infiltration of very fine sand, silt, and clay which lends coherence to the original, loose sand and creates a material in which bubble-like, vesicular pores can form by wetting and drying. Minimal, sandy, loam-textured Av horizons have formed in coarse-textured alluvium only since early Holocene or latest Pleistocene time. Prominent, loam-textured Av horizons occur in soils of at least late Pleistocene age. In soils older than late Pleistocene, Av horizon morphology is not an adequate criterion for establishing yet greater age, because the morphology does not change and erosion might prevent progressive thickening of the Av horizon on many sites. (2) There has been shallow, limited accumulation of eolian calcium carbonate and introduction of significant amounts of eolian sodium salts in all soils since early Holocene. Thus, older soil horizons that had been leached under moister pluvial conditions have been recarbonated and alkalized. (3) Presence of an organized desert pavement is indicative of at least early Holocene age. If darkly varnished, the pavement is no younger than late Pleistocene age and possibly much older. (4) Calcic horizons and duripans form in mixed limestone-volcanic and purely volcanic alluvium, respectively. Neither horizon occurs in soils younger than late Pleistocene age. (5) In volcanic alluvium, minimally typic duripans are found only in the younger of the mid-Pleistocene-age soils, whereas fully typic duripans are found in the older of the mid-Pleistocene soils. (6) Obvious opalization of an argillic horizon occurs only in mid-Pleistocene-age soils, but it may occur in soils of widely differing ages, and it does not occur consistently in soils of equivalent age. Opalization is an indicator of considerable age, but whether or not it occurs probably depends on the local soil-forming environment.

TABLE 6. COMPARISON OF CRATER FLAT ALLUVIAL CHRONOLOGY WITH OTHER CHRONOLOGIES IN THE REGION

Crater Flat (this study)	Lower Colorado River (Bull, 1991)	Las Vegas and Indian Springs Valleys (Quade, 1986; Quade and Pratt, 1989)	S. Death Valley (Dorn, 1988b; Hooke and Dorn, 1992)	East-central Mojave (Wells et al., 1990a)
Modern (0)	Q4b (0)	Modern (0)	Modern (0)	Modern (Qf9) (0)
Crater Flat (>0.3 to >1.3)	Q4a (0.1–2) Q3c (2–4) Q3b (4–8)	Unit G (0–4.0) Unit F (4.0–8.0)	Q4c (0.5–2.5) Q4b (2.0–4.5)	Qf8 (<0.3 to >0.7) Qf6,7 (2–8)
Little Cones (>6 to >11)	Q3a (8–12)	Unit E (8.6–14.0)	Q4a(6–11)	Qf5 (8–15)
Late Black Cone (>17 to >30)	Q2c (12–70)	Unit D (15–30)	Q3 (13–50)	Qf4 (<34 to >45)
Early Black Cone (>159 to >201)	Q2b (70–200)	Unit C (>30) Unit B (>40 to >60)	Q2a, Q2b (110–190)	Qf3 (>47 to >130) Qf2 (<160 to >320)
Yucca (>375)	Q2a (400–730)	Unit A	Qla, Qlb (>500 to >800)	
Solitario (>433 to >659 but <730)	Q1 (<1200)	Unit A	Q1a, Q1b (>500 to >800)	Qf1 (<3800)

Note: Listed ages (in ka) are in parentheses.

Comparison of Allostratigraphic Units with Previous Work

When comparing the results of our allostratigraphic study with previous work, we noted several important differences. Our Crater Flat unit generally is included within the Q1 delineations mapped by Swadley and Parrish (1988). Three subdivisions of the Crater Flat unit that might be made based on microtopography are (1) raw, active channels; (2) raw, rough, bar-and-swales with little smoothing; and (3) inset fans with rounded or muted bar-and-swales and proto-desert pavement. The last subdivision would correspond to unit Q1c of Hoover et al. (1981), estimated to be 7–9 ka (Table 2)—that is, about the age of the Little Cones unit.

No unit correlative to the Little Cones unit was included in the Hoover et al. (1981) chronology or mapped by Swadley and Parrish (1988). Apparently, it is contained within their unit Q1c, but that was described as having a substantially less-developed soil (Table 1). Little Cones soils have minimal but distinct desert pavements and sandy loam Av horizons—characteristics not previously described.

In comparison with the Swadley and Parrish (1988) map, the Black Cone unit most closely corresponds to their unit Q2bc (undifferentiated Q2b and Q2c), but the Q2b and Q2c soil characteristics and numerical ages are different from those for the Black Cone unit (Tables 1 and 2). Unit Q2b was mapped only as minor strath terraces, with soils having Bw and Stage I Bk horizons. Unit Q2c soils have morphologies comparable to the Early Black Cone subunit (Tables 1 and 3), but unit Q2c was inferred by Hoover et al. (1981) to contain Bishop ash (ca. 730 ka). We found Bishop ash in the older Solitario unit. The Late Black Cone subunit probably corresponds most closely to unit Q2a of Hoover et al. (1981) (Table 2), which was not mapped by Swadley and Parrish (1988) in Crater Flat. The Q2a unit, however, lacks the well-developed Bt horizon and haplic duripan of the Late Black Cone subunit.

Both the Yucca and Solitario units are included, for the most part, in the Swadley and Parrish (1988) QTa delineations (ca. 1.1–2.0 Ma; Table 1). Our mapping and the occurrence of Bishop ash in the Solitario unit indicate, however, that QTa is younger than this.

Regional Correlation and Climatic-Alluvial Implications

Our Quaternary stratigraphy for Crater Flat correlates well with similar sequences described for the southern Nevada, lower Colorado River, Death Valley, and Mojave Desert regions (Table 6). Though more limited in areal extent, our units are additional evidence for regional climatic control of alluvial deposition in these dry landscapes. Bull (1991) proposed that regional fan alluviation occurred during the mid- to late Wisconsin (10–75 ka) and during the transition from the late Wisconsin maximum (ca. 18 ka) to the arid Holocene.

The Late Black Cone subunit is similar in stratigraphic position and soil morphology to unit Q2c (12–70 ka) of Bull (1991) in the lower Colorado River region; both units have the youngest Bt (argillic) and Bk (stage II–II) horizons, generally indicative of soil formation under more moist conditions of the late Wisconsin period (Nettleton et al., 1975). Estimated minimum ages for the Late Black Cone subunit are also consistent with estimated ages of other regional units, many of which are similarly dated by minimum-limiting techniques. The Late Black Cone unit also is time correlative with the 13–50 ka unit Q3 of Dorn (1988b) in southern Death Valley and with the <34 to >45 ka unit Qf4 of Wells et al. (1990a) in the east-central Mojave Desert; it may also be correlative with the 75 ka unit of Sowers et al. (1989) in the Kyle Canyon, Nevada, area. In nearby Las Vegas and Indian Springs Valleys, Haynes (1967), Quade (1983, 1986), and Quade and Pratt (1989) described a well-dated late Wisconsin unit D that was deposited under paludal-alluvial conditions between 15 and 30 ka, an age close to that estimated for the Late Black Cone subunit.

If the rock-varnish ^{14}C AMS ages reasonably approximate true numerical ages, as we believe they do, the Late Black Cone subunit was largely deposited during the late Wisconsin (>10 and <35 ka). This late Wisconsin alluviation may have been related to pluvial conditions, or it may have been related to a pulse of warming during otherwise average glacial-pluvial conditions (Bull, 1991). Paleoclimatic evidence from packrat middens in the Nevada Test Site region (Spaulding, 1985) indicates that average annual precipitation during the 10–38 ka period was between 10% and 40% greater than at present. Full-glacial conditions existed in the southern Nevada region at ca. 18 ka, gradually declining during the next few thousand years (Spaulding, 1985; Claassen, 1986). Although the estimated age of the Late Black Cone unit best fits a late Wisconsin age, the radiometric ages are nevertheless minima, and we cannot completely exclude the possibility that this unit is somewhat older. Some other regionally correlative units may also be of mid-Wisconsin age, and Bull (1991) suggested that alluviation also occurred during the mid-Wisconsin interstadial (ca. 30–60 ka).

The Little Cones unit apparently correlates with unit Q3a (8–12 ka) of the lower Colorado River region (Bull, 1991). Its Bw horizon (and lack of a Bt) and stage I Bk suggest an early to mid-Holocene age (Gile, 1975; Nettleton et al., 1975). The Little Cones unit is time correlative with unit E of Haynes (1967), Quade (1983, 1986), and Quade and Pratt (1989) in Las Vegas and Indian Springs Valleys. Numerous ^{14}C ages ranging between ca. 8 and 14 ka were reported by Quade (1986) from the fine-grained, valley-bottom facies of unit E, which grades upslope into extensive alluvial fan complexes (Quade, 1983). Although unit E is not tied clearly to climatic control (Quade and Pratt, 1989), its deposition is close to the Pleistocene-Holocene temperature-precipitation transition (Spaulding, 1985; Claassen, 1986). Early Holocene alluviation may have been associated with monsoonal conditions during the transition from full-pluvial to interpluvial climate (Bull, 1991).

Whitney and Harrington (1993) used varnish cation ratios to estimate a mid-Pleistocene glacial age (170 ka) for some colluvial boulder deposits on the eastern flank of Yucca Mountain and to infer paleoclimatic conditions. This age is close to the minimum we estimate for the Early Black Cone unit, but the cation ratios are different. Their cation ratio of 4.52 ± 0.55 is greater (i.e., younger) than those we measured on Early Black Cone varnishes (Table 4) and would correspond to a calculated CR age of ca. 80 ka based on the Crater Flat cation-leaching curve (Fig. 4). If correct, this younger age may indicate that the colluvial boulder deposits formed during the early Wisconsin.

Whitney and Harrington (1993) also concluded that the late Wisconsin was a time of sediment storage on Yucca Mountain hillslopes, with relatively little sediment being deposited on the valley floors. Our results, however, suggest that the late Wisconsin was a time of widespread piedmont and valley-floor fan alluviation. Based on the areal distribution of the Late Black Cone and Little Cones remnants (Fig. 1), we infer that most of Crater Flat was alluviated during the late Wisconsin. The principal drainages originating on the western flank of Yucca Mountain (e.g., Solitario Canyon) were sources of debris- and flood-flow deposits that covered most of the preexisting alluvial landscape. Although these deposits may be thin, they are areally extensive and therefore comprise a significant volume. This alluvial debris was derived from deposits stored within the canyons and on the slopes of Yucca Mountain, which may account for the absence of slope deposits of this age noted by Whitney and Harrington (1993).

Harden et al. (1991) compared four late Quaternary soil chronosequences from the southern Great Basin, including a set of soils from Fortymile Wash near Yucca Mountain. They calibrated soil ages and development rates in Fortymile Wash based on the Hoover et al. (1981) stratigraphy and on the uranium-trend ages of Rosholt et al. (1985). Comparing the soil-development rate in Fortymile Wash with that at Silver Lake, California, they concluded that Pleistocene soils in Fortymile Wash developed at a rate lower by as much as a factor of 10 than the Holocene soils at Silver Lake. Our results suggest that soil ages in Crater Flat are younger by factors of 2–10 than the calibration ages used by Harden et al. (1991) at Fortymile Wash, and that soil-development rates are in closer agreement with the Silver Lake rates.

CONCLUSIONS AND IMPLICATIONS FOR FUTURE STUDIES

Six major allostratigraphic units were identified and mapped in Crater Flat using geomorphic surfaces and soils. Rock-varnish ^{14}C AMS and cation-ratio dating together with uranium-series dating provide minimum age estimates in good agreement with relative stratigraphic relations and soil morphology. Although ^{14}C AMS varnish ages are minima, the relative consistency in ages and cation ratios from equivalent allostratigraphic surfaces together with varnish alkalinity ratios, uranium-series dates on pedogenic carbonate, and regional correlations suggest that these minimum ages do not significantly underestimate true ages.

Our three youngest units—the Crater Flat, Little Cones, and Late Black Cone units—correlate well by stratigraphic order, soils, and estimated numerical age with other regionally recognized, alluvial-stratigraphic sequences, but the latter two were not included in earlier studies of the Nevada Test Site region. The Little Cones and the Late Black Cone units collectively form an extensive late Quaternary stratigraphic sequence, which was not recognized in previous mapping of Crater Flat. Although the "surficial deposits" stratigraphy has units numerically equivalent in age (Q1c, 7–9 ka, and Q2a, ca. 40 ka; Table 1), soil features described in this previous work do not fit those we found in deposits of these ages. Q1c soils were described as only minimally developed, whereas the Av, Bw, and Bk horizons of the Little Cones unit are readily visible and differentiated. Q2a soils were said to have only Bw and stage I Bk horizons, morphologies characteristic of a Holocene age (Gile, 1975), whereas the Late Black Cone soils display distinct Bt and stage II–II Bk horizons typical of pre-Holocene soils (Nettleton et al., 1975).

We conclude that the Late Black Cone unit best fits a late Wisconsin age and is contained within map units Q2b and Q2bc of Swadley and Parrish (1988) based on similarities in map delineations and surficial characteristics such as desert pavement. However, previously reported pre-Wisconsin uranium-trend ages of 160–250 ka and post-Wisconsin–type soil (Bw) morphologies for Q2b deposits (Table 1) are inconsistent with soils and ages found for the Late Black Cone subunit.

Stratigraphic position, soil development, and estimated rock-varnish cation-ratio age (>159 to >201 ka) indicate that the Early Black Cone unit is at least oxygen-isotope stage 5 age (≥125 ka), but the true age is uncertain. It is likely correlative with Bull's (1991) unit Q2b (70–200 ka) for which a climatic origin was inferred. The correlative "surficial deposits" unit is Q2c (Table 2), which was estimated to range in age from 270 to 800 ka. From map delineations and soil descriptions, we infer that most parts of Q2c mapped by Swadley and Parrish (1988) include the Early Black Cone unit. We conclude that their correlation of the lower part of unit Q2c with Bishop-age and older deposits is in error. Rather, the Bishop ash occurs in the Solitario unit, which is stratigraphically older and likely includes the QTa unit of Hoover et al. (1981). We believe that the uranium-trend ages of 300–500 ka reported by Rosholt et al. (1985) for Q2c deposits are too old for the stage III–V Bk and haplic duripan horizons we found in Early Black Cone soils, morphologies that are more indicative of a younger Pleistocene age (Gile et al., 1966; Bull, 1991).

As elsewhere in the now arid Basin and Range Province, Crater Flat was likely alluviated during the late Wisconsin and during the transition from a full glacial to the arid Holocene climate. In contrast to previous work indicating that alluvial inactivity characterized the late Wisconsin at Yucca Mountain (Whitney and Harrington, 1993), we conclude that much of the preexisting Crater Flat alluvial landscape was covered by deposits originating in the drainages on the west flank of Yucca Mountain, suggesting that debris- and flood-flow processes were quite active during full and late glacial time.

The extent of late Pleistocene and early Holocene stratigraphy found in this study may be significant for assessment of seismic hazards at the proposed Yucca Mountain high-level nuclear waste facility. Based on our allostratigraphy, several faults in Crater Flat displace Late Black Cone and younger deposits, indicating that tectonic activity has been more recent than previously estimated. In comparison with previous work, our allostratigraphic units are younger by factors of 2–10. Such age differences can result in seismic slip-rate calculations that significantly underestimate seismic hazard. If faulted deposits inferred to be of Q2c age (270–800 ka) are offset 1 m, an average slip rate of 0.001–0.004 mm/yr would be calculated, a rate that is indicative of relatively low tectonic activity (cf. Slemmons and dePolo, 1986). In contrast, if the offset unit were actually of Late Black Cone or Little Cones age (ca. 10–30 ka) an average slip rate of ~0.03–0.1 mm/yr would be calculated, a rate indicative of a more active tectonic setting.

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APPENDIX 1. PEDON DESCRIPTIONS[3]

APPENDIX 2. CHEMICAL ANALYSES OF ROCK VARNISH[3]

APPENDIX 3. U-SERIES ISOCHRON PLOTS[3]

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