DIVISION S-5—PEDOLOGY

Pedogenesis of Vesicular Horizons, Cima Volcanic Field, Mojave Desert, California

K. Anderson,* S. Wells, and R. Graham

ABSTRACT

An existing model of desert pavement formation suggests desert pavement clasts rise vertically on an accreting eolian mantle and the underlying vesicular horizon coevolves with pavement formation. Results presented here support this model and provide a mechanism whereby eolian material is transported from the ground surface to ped interiors, thereby increasing the thickness of the vesicular horizon underlying desert pavements. Basaltic desert pavements in the Cima Volcanic Field are underlain by a vesicular horizon with strong coarse columnar and strong medium platy soil structure. Peds collected from three sites along a topographic gradient were subsampled into seven ped domains to quantify physical, chemical, and micromorphological properties within peds and along the topographic transect. Ped interiors have up to 40% clay and 12% $CaCO_3$ whereas sediments adhering to ped sides have <7% clay and 2% $CaCO_3$. Argillans and siltans lining platy surfaces in ped centers and bottoms indicate desert dust is translocated vertically along the macropores between peds and horizontally along platy boundaries to ped interiors. Once soils develop a strong columnar and platy structure, translocation to ped interiors is enhanced. Calibrated radiocarbon ages between 5440 and 5045 BP for Av ped centers suggest enhanced dust flux and pedogenesis occurred during the drier middle Holocene, an inference supported by luminescence dating and correlations with regional eolian chronologies.

Vesicular soil horizons commonly underlie desert pavements in the southwestern USA. The hypothesis that vesicular soils and associated desert pavements coevolve is supported by soil and stratigraphic field studies (McFadden et al., 1984, 1986; Wells et al., 1985, 1987; McDonald, 1994), geochemical and mineralogical investigations (McFadden et al., 1987), and cosmogenic dating procedures (Wells et al., 1995; Anderson and Wells, 1997). Fine-textured eolian material accumulating below surface clasts is pedogenically altered into a vesicular horizon. Continued eolian accumulation and pedogenesis leads to cumulic soil development below accretionary desert pavements. In the California Cima Volcanic Field, fine-textured desert dust is deposited on rubbly, basalt flow surfaces (Fig. 1). Through processes such as rain splash, surface wash, and translocation, dust continually accumulates below basaltic clasts, developing underlying vesicular horizons. Thus, pavement clasts have never been buried as was once assumed, but rather they rise upwards on a vertically accreting eolian mantle (Wells et al., 1987, 1995; McFadden et al., 1987). The processes by which dust is incorporated into vesicular horizons that underlie desert pavements are poorly understood. Chemical, physical, and micromorphological data on vesicular soil peds are presented here that help identify the processes of dust translocation and $CaCO_3$ accumulation within vesicular soil peds. Combining such data with age estimates of vesicular horizons provides insights into the mechanisms and timing of accretionary desert pavement formation.

The designation of vesicular horizons as Av does not easily conform to established criteria for horizon nomenclature. For example, although vesicular horizons have been designated Av since at least 1958 (Springer, 1958) and are presently designated as such in the soils literature (Peterson, 1980; McFadden et al., 1984, 1998), the Soil Survey Manual (Soil Survey Staff, 1993) reserves v for plinthite soil horizons. In addition, Av horizons exhibit complex properties commonly attributed to B horizons, such as enrichment in salts, $CaCO_3$, and translocated clay, but they also continuously incorporate new parent material from eolian additions, so might be designated as surface C horizons. Nevertheless, to avoid confusion and maintain convention, the Av designation is used here.

Early models of pavement formation focused on the exhumation of clasts by deflation (Springer, 1958; Jessup, 1960; Sharon, 1962; Symmons and Hemming, 1968; Cooke, 1970; Cooke and Warren, 1973; Mabbutt, 1977) or the shrink and swell heave of clasts to the ground surface (Springer, 1958; Johnson and Hester, 1972; Mabbutt, 1977). More recently, the association of vesicular soils with desert pavements on many landforms in the Southwest has been shown to support an accretionary mechanism of pavement development (McFadden et al., 1986; McDonald, 1994). The shift from assuming that desert pavements are zones of erosion to the realization that they can be zones of deposition has caused studies of landscape development in the Mojave Desert to refocus on dust accumulation and soil formation (McFadden et al., 1987; McDonald et al., 1994; Reheis and Kihl, 1995). Examples of accretionary desert pavements on basalt flows of the Cima Volcanic Field include up to 2 m of relatively clast-free, quartz-rich eolian sands between basalt flows and the overlying desert pavements. The uppermost horizon, generally an Av, represents an actively accreting physically and chemically complex layer.

K. Anderson, Box 6013, Bilby Research Center, Northern Arizona University, Flagstaff, AZ 86011; S.G. Wells, Desert Research Institute, 2215 Raggio Parkway, Reno, NV 89512; R.C. Graham, Dep. of Environmental Science, University of California, Riverside, CA 92521. Received 9 Feb. 2001. *Corresponding author (kirk.anderson@nau.edu).

Published in Soil Sci. Soc. Am. J. 66:878–887 (2002).

Abbreviations: AMS, accelerated mass spectrometry; BP, before present; EC, electrical conductivity; MRT, mean residence time; TL, thermoluminescence.

Vesicular horizons were recognized by Marbut (1935) to be common in arid environments. Recently, because of the unique properties and stratigraphic position of Av horizons at the ground surface, investigations are focusing on their effects on decreasing infiltration and increasing runoff, thereby influencing plant-water relationships, soil development, surficial processes, and landscape evolution (Musick, 1973; Wells et al., 1984, 1987; McDonald, 1994). Many researchers have investigated the processes of vesicle formation. Springer (1958) reproduced vesicles from sieved Av material after only five wet and dry cycles. The original Av properties of sieved soils return after 20 to 30 wetting and drying cycles; additional cycles increase the number, size, surface area, sphericity, and continuity of pores (Miller, 1971; Figueira and Stoops, 1983; Figueira, 1984). Evenari et al. (1974) determined that vesicle formation was influenced by the following: texture, wetting front displacement of soil air, surface sealing by crusts or clasts, air trapped when wet, and thermal expansion of air bubbles. Bouza et al. (1993) found that a high exchangeable Na percentage (>15) is an important vesicle formation factor for Patagonian soils. Vesicle stability is aided by $CaCO_3$ (Evenari et al., 1971) and clay coatings (Sullivan and Koppi, 1991). Observations of Av horizons in the Cima Volcanic Field reveal strong columnar and platy soil structure, with individual peds exhibiting textural and chemical zonation from ped exterior to ped interior locations. Qualitative field properties include sandy, low-$CaCO_3$ ped exteriors, and clayey $CaCO_3$-rich ped interiors (McFadden et al., 1984). Using micromorphic, physical, and chemical analyses, Anderson et al. (1994; this study) observed that vertical and horizontal translocation of fines and solute transport within the Av horizon increase the clay and $CaCO_3$ content of ped interiors.

Radiocarbon Age Estimates

Radiocarbon age estimates based on soil organic matter can be difficult to interpret, although interpretations can be enhanced using supporting independent data. Some researchers suggest that reliable radiocarbon dating of soils is possible (Scharpenseel, 1979; Goh et al., 1977), whereas others rely on the concept of mean residence time (MRT), where a radiocarbon age on soil organic matter is the mean age of all the organic C components added to the soil over time. The MRT concept assumes that younger C is continuously added to the soil, and that older C is lost by processes of decay, translocation, and mineralization. Mean residence time dates are minimum age estimates; soils are actually older than MRT ages suggest (Birkeland, 1999).

Because of the importance of determining soil age in geomorphic, pedogenic, and archeological settings, radiocarbon dating of soils continues to be used by many researchers. Wang et al. (1996) obtained model ages based on the ^{14}C activity and rates of younger C additions. Scharpenseel (1979) determined that careful consideration of sample selection and analysis of specific organic matter fractions (humic, fulvic, humin, humic-clay, etc.) could greatly improve interpretation of the radiocarbon age. However, because of the physical and chemical variability of soil processes, it remains unclear which humus fraction is the most representative of the initiation of soil genesis for any particular soil (Stout et al., 1981). Anderson and Wells (1997) reported consistent stratigraphic trends in accelerator mass spectrometry (AMS) radiocarbon ages of vesicular soils on an alluvial fan sequence in the Mojave Desert, suggesting that an age-dependent signature may be preserved in Av soils. Because of the uncertainties of AMS ages on soil organic matter, conservative interpretations using minimum mean residence times are useful within the context of supporting data, as discussed below.

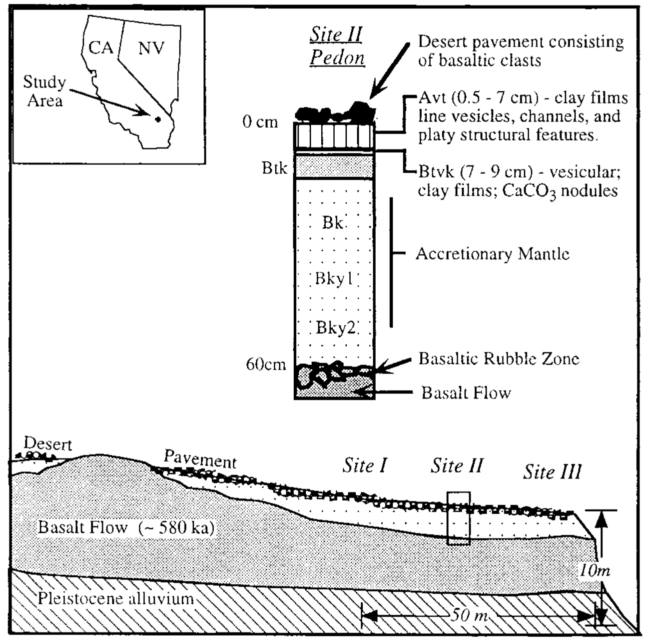

Fig. 1. Diagram showing stratigraphic and topographic relationships of Sites I, II, and III discussed in the text. Soil stratigraphy and brief descriptions of vesicular horizons show desert pavements overlying the accretionary eolian mantle. Note the location of the Cima Volcanic Field within the Mojave Desert.

The objectives of the research presented in this paper are to (i) identify the physical and chemical properties of Av peds underlying desert pavements and to (ii) determine the processes active within the Av horizon that may affect desert pavement formation. Detailed physical, chemical, and micromorphological analyses of Av peds enhance understanding of vesicular ped formation and the influence of Av horizon genesis on the development of accretionary desert pavements. Radiocarbon age estimates provide preliminary chronologic control in understanding the timing and rate of Av soil genesis for (i) comparisons with other dated soils, (ii) correlation with potentially important climatic periods, and (iii) determining whether Av horizons form during discrete periods of the geologic past, e.g., Pleistocene or Holocene.

MATERIALS AND METHODS

Site Characteristics

The study area is on a basalt flow in the Cima Volcanic Field, in the eastern Mojave Desert, that has been K-Ar dated

Table 1. Soil physical properties of Pedon II.

		Color			Consistence§							
Horizon	Depth	Dry	Text.†	Structure‡	dry	moist	wet	HCl reaction¶	Clay films#	Pores††	Boundary‡‡	Other§§
	cm											
Typic Natrargid												
A	0–0.5	10YR 7/3	ls	m	lo	lo	sp,po	eo	na	na	as	na
Avt	0.5–7	10YR 7/3	l	3,c,cpr-2,f,pl	h	fr	s,p	e-es pin eo pex	4,n,po	3,vf-m,v+t,in	as	10YR 5/3, cl ped int.
Btvk	7–9	7.5YR 5/4	sicl	3,c,cpr-2,f,pl	sh-h	fr	s,p	es	2,n,po,br,co	3,vf-m,v,in	cs	na
Btk	9–16	7.5YR 5/4	l	1,f-m,abk	so	fr	ss,p	e mat.; ev nod.	1,n,pf	na	cw	7.5YR 8/4, vh, ev nodule
Bk	16–27	7.5YR 5/4	sl	1,f,abk	so	fr	ss,p	es mat. ev nod.	na	na	aw	7.5YR 8/4, vh, ev nodule
Bky1	27–40	7.5YR 5/6	sl	l,f,abk	lo	fr	ss,ps	eo-e	na	na	cw	asicular gypsum
Bky2	40–60	7.5YR 5/6	sl	m	lo	fr	ss,ps	ve mat. e nod.	na	na	cw	asicular gypsum

† ls, loamy sand; l, loam; sicl, silty clay loam; sl, sandy loam.
‡ m, massive; 3, strong; c, coarse; cpr, columnar; 2, moderate; f, fine; pl, platy; 1, weak; abk, angular blocky.
§ lo, loose; h, hard; sh, slightly hard; so, soft; fr, friable; so, non-sticky; po, non-plastic; s, sticky; p, plastic; ss, slightly sticky; ps, slightly plastic.
¶ eo, no reaction; ve, very slightly effervescent; e, slightly effervescent; es, strongly effervescent; ev, violently effervescent; pin, ped interior; pex, ped exterior; mat, matrix; nod, nodules.
# na, data not available; 4, many, n, thin; po, in pores; 2, few; br, bridges; co, coatings; pf, ped faces.
†† 3, many; vg, very fine; m, medium; v, vesicular; t, tubular; in, inped.
‡‡ a, abrupt; s, smooth; c, clear; w, wavy.
§§ c, common; 1, fine; int, interior; vh, very hard; ev, violent effervescent.

to 580 000 ± 160 000 yr old (Turrin et al., 1984). This flow was chosen for the following reasons:

1. Previous work provides a reliable pedologic framework (McFadden et al., 1987).
2. The thick (up to 2 m) eolian sheet and strongly developed columnar-structured vesicular horizon underlying the desert pavement provides a spectacular example of the accretionary model of desert pavement formation.
3. Age control for the underlying bedrock provides a maximum age for soil formation.

The basalt flow is 700 m above sea level and grades <2° to the west. The flow surface lies 10 m above the local base level as an erosional remnant (Fig. 1). Vegetation includes creosote bush [*Larrea tridentada* (Sessé & Moc. ex DC.) Coville], brittle bush (*Encelia farinosa*), mormon tea (*Ephedra trifurca*), and joshua tree (*Yucca brevifolia* Engelm.). Mean annual precipitation is between 12 and 25 cm and the mean annual temperature is 16 to 18°C (National Oceanic and Atomspheiric Administration [NOAA], 1978, p. 570). The basalt flow overlies Pleistocene alluvial fan gravels. A mantle of desert dust overlies the basalt flow (Fig. 1, Tables 1 and 2). Overlying the soil is a tightly interlocking desert pavement mosaic with millimeter-scale distances between well-varnished basaltic boulders and cobbles (McFadden et al., 1989). The <5-mm interclast spaces consist of basaltic fragments derived from local salt weathering of larger clasts and loose quartz-rich sand, silt, and clay eolian deposits. In some locations a thin, cohesive crust has formed. Pebble to small cobble-size clasts generally rest on the surface, whereas larger cobbles can be embedded in the Av horizon up to several centimeters. Poorly preserved pavement fabric occurs in areas where plant growth and animal activity are high. Relief across the surface is generally low, except where bedrock highs are exposed or where drainages have incised.

Sampling and Analysis

The Av horizon exhibits strong columnar parting to platy soil structure, allowing cohesive, columnar peds to be sampled individually. Three sample sites were chosen 25-m apart along a 50-m transect. Site II is downslope from Site I and upslope from Site III (Fig. 1). After pavement characteristics were described, pavement clasts were removed, which allowed collection of surface eolian material. Removal of surficial material revealed polygonal ped tops (Hunt et al., 1966; McFadden et al., 1987), ranging in both diameter and thickness from <1 to >10 cm. The soil at Site II, judged to be similar to the soils at Sites I and III, was described in detail (Soil Survey Staff, 1992, 1993); it is a Typic Natrargid consisting of Avt-Btvk-Btk-Bk-Bky1-Bky2 horizons (Fig. 1, Tables 1 and 2). The Av horizon has the following characteristics: 10YR hue, high value, and low chroma, reflecting the low organic matter content and slight oxidation; high silt and clay content; columnar and platy soil structure; horizon thickness between 5 and 10 cm; and numerous vesicular and channel pores. Ten to 12 peds from each site were collected and stored separately.

In the laboratory, ped domains were defined according to macroscopic characteristics such as Munsell color, texture, carbonate nodules, and soil structure. Peds were subsampled according to the defined domains to quantify physical and chemical variations within peds (Fig. 2). Based on variations in soil properties, the following seven distinct ped domains were identified and sampled: (1) material adhering to ped

Table 2. Soil chemical and physical properties of Pedon II.

Horizon	Depth	pH	EC†	$CaCO_3$	Sand	Silt	Clay	Silt + Clay	Texture‡
	cm		dS m^{-1}	%					
Typic Natrargid									
A	0–0.5	9.6	2.0	0.6	64	33	2	36	sl
Avt	0.5–7	10.1	3.7	6.4	33	38	30	67	cl
Btvk	7–9	9.7	10.1	5.3	na	na	na	na	na
Btk	9–16	9.1	17.2	12.7	42	37	20	58	l
Bk	16–27	8.9	18.4	5.6	53	36	11	47	sl
Bky1	27–40	8.3	24.1	8.8	53	44	3	48	sl
Bky2	40–60	8.3	23.2	16.3	na	na	na	na	na

† Electrical Conductivity.
‡ ls, loamy sand; l, loam; sicl, silty clay loam; sl, sandy loam; na, data not available.

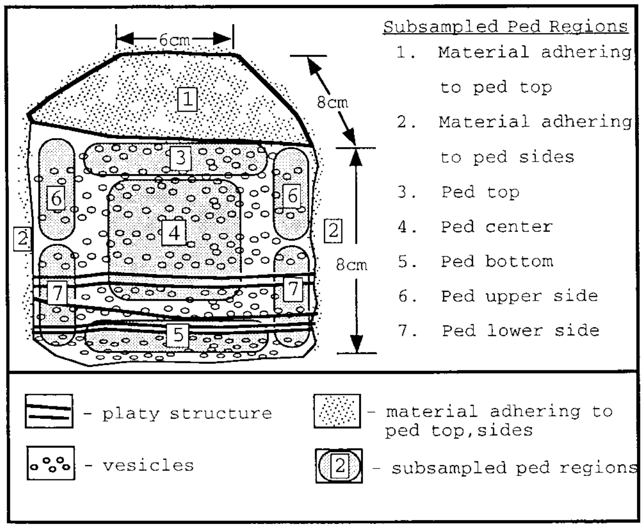

Fig. 2. Cross-section of ped interior showing vesicles, platy structure, and sampling strategy for Av peds, including subsampled Domains 1 through 7.

tops, (2) material adhering to ped sides, (3) ped top, (4) ped center, (5) ped bottom, (6) ped upper side, and (7) ped lower side (Fig. 2). Material adhering to ped surfaces (Domains 1 and 2) is generally <3 mm thick. Other sampled domains are generally between 1 and 3 cm thick, according to ped size. Subsampled ped domains from single peds provided too little material for subsequent laboratory analysis. Therefore, analyzed samples consisted of combined material from subsampled domains of several peds from each separate site. The exception to this was subsampling for the accelerator mass spectrometry radiocarbon analysis, which was performed on the center domain of two individual peds.

Particle size was determined by pipette analysis, after removal of salts and carbonate by sodium acetate digestion (Gee and Bauder, 1982). Calcium carbonate weight percentage was determined by the manometric method (Nelson, 1982). Electrical conductivity was measured on saturation extracts following Rhoades (1982). Soil pH was measured using a 1:1 ratio of soil/water paste. Large-format thin-sections (2 by 3 cm) were made on vertical sections of Av peds.

Bulk soil samples for AMS radiocarbon age determination were collected from ped centers at Sites I and II. Ped centers were sampled after trimming ped tops and sides until the center domain remained. Pretreatment for both samples included four steps: removal of macroscopic roots, acid washes in hot HCl to remove inorganic carbonates, alkali washes in NaOH to remove secondary organic acids, and final acid wash to neutralize the sample. These treatments were designed to remove the acid and alkali-soluble fraction, leaving the alkali-insoluble organic fraction for age determination. Pretreatment and analysis were performed by Beta Analytic, Inc. (Florida).

RESULTS

Micromorphology

Micromorphic analysis focused on properties of vesicles and channel pores, cutans, and carbonate accumulations. Evidence of plant and animal activity can be seen in thin sections, although rootlets, obvious animal burrows, and identifiable plant and animal remains are rare. Spherical vesicles occur in the sandy loam material that occupies exterior positions of ped tops and sides. Vesicles are not lined with clay or carbonate but are bounded by sand grains. Interior positions of ped tops, ped sides, and ped centers are dominated by irregularly shaped vesicles, compressed vertically and elongated horizontally. Many vesicles in these domains have subrounded to angular borders.

Channel pores are absent from exterior positions of ped tops and ped sides. Interior positions of ped tops, sides, and centers have interconnected channel pores, but they are commonly filled with sediment. In the lower positions of ped centers, ped lower sides, and ped bottoms, channel pores are common. Channel pores are often connected to the macropores between ped faces, forming a continuous conduit from the ground surface to interior ped domains. Channel pores in ped bottoms can be interconnected to a great extent, forming platy soil structure. Argillans and siltans commonly line the lower surfaces of platy structure, whereas the upper surfaces may have a coating of $CaCO_3$, called calcitans (Fig. 3).

Physical and Chemical Analysis

Macroscopically delineated domains within peds provide a basis for interpreting genetic processes from measured physical and chemical properties. General trends in particle-size distribution show that materials adhering to ped tops and sides have the lowest clay content, whereas ped centers have the highest (Table 3). Material adhering to ped tops and ped faces (Domains 1 and 2) consistently have the coarsest texture, sandy loam, with 2 to 7% clay. Ped top (Domain 3) textures range from silt loam to loam, having 19% clay and 45 to 50% silt, the highest silt concentration within the ped. Ped center textures range from loam to clay, with the highest clay (27 to 40%) and silt plus clay (70 to 71%) concentrations. Ped bottom textures are loam to clay loam, with generally the second highest clay concentrations. Upper-side textures are loam, with consistently low clay and high silt concentrations. Lower-side textures are clay loam and loam, illustrating an increase in clay concentration compared with upper sides.

The $CaCO_3$ content was determined for 18 subsamples, although this was not determined for material adhering to ped faces (Domain 2) because of small sample recovery (Table 3). The general trend is that material adhering to ped tops has the lowest $CaCO_3$ content and ped centers have the highest. Materials adhering to ped tops (Domain 1) have a $CaCO_3$ content ranging from 0.4 to 1.5%, and ped tops (Domain 3) range from 3.0 to 5.5%. Ped centers have a $CaCO_3$ content ranging from 6.0 to 12.1%, and those of ped bottoms are nearly as high, ranging from 6.1 to 8.6%. Upper and lower ped sides have similar $CaCO_3$ contents, with the lowest being 1.1% and the highest 3.3%.

Trends in particle-size distribution and $CaCO_3$ content also occur along the topographic transect, from Site I to Site III. The silt + clay content for material adhering to ped tops increases from 34% at the upper site (Site I) to 40% at the lower site (Site III). Similarly, the silt + clay content of material adhering to ped faces increases from 40 to 45% and the clay content for ped centers

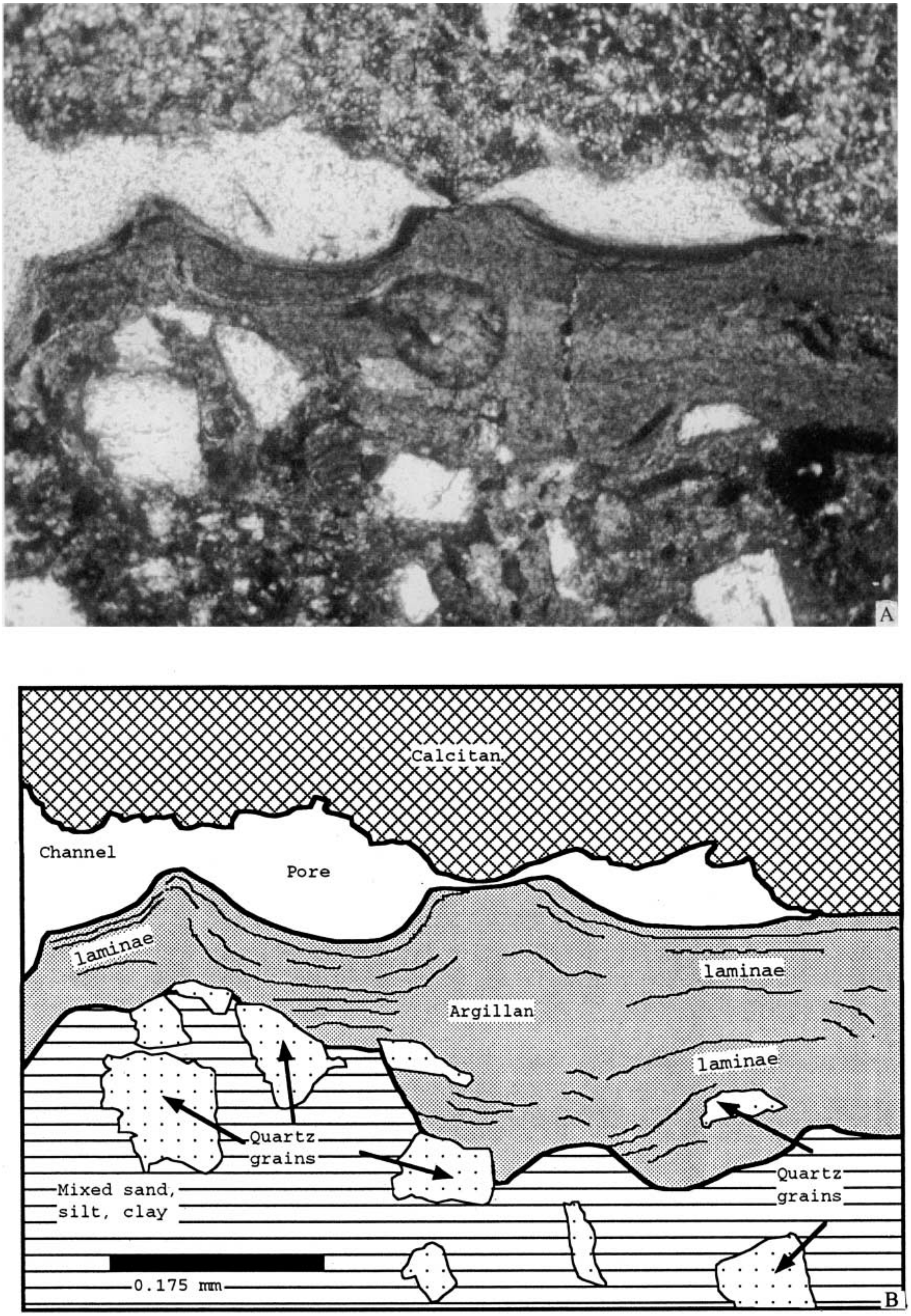

Fig. 3. (a) Photomicrograph of Av ped, with argillans indicating lateral translocation of dust to ped interiors. (b) Line drawing identifying major micromorphological features seen in Fig. 4a. See text for details.

increases from 27 to 40% between Site I and Site III. An increase in $CaCO_3$ content in downslope positions is noted for some peds in Domains 1, 3, and 4.

The results of pH and electrical conductivity (EC) analysis indicate alkaline and saline conditions (Table 3); the pH values are 9.2 or greater. No noticeable pat-

Table 3. Properties of subsampled vesicular horizon peds, Cima Volcanic Field.

Description	Domain	pH	EC†	$CaCO_3$	Sand	Silt	Slay	Silt + Clay	Texture‡
			dS cm^{-1}	%					
				Site I					
on ped top	1	9.2	1.3	0.4	66	40	4	34	sl
on ped face	2	na	na	na	60	33	7	40	sl
ped top	3	9.7	0.9	3.0	31	50	19	69	l
ped center	4	9.7	1.2	6.0	30	43	27	70	cl
ped bottom	5	9.6	1.9	6.1	34	44	22	66	l
upper side	6	9.6	2.2	2.1	31	47	21	69	l
lower side	7	9.5	1.1	3.3	32	38	29	68	cl
				Site II					
on ped top	1	9.6	2.0	0.6	64	33	2	36	sl
on ped face	2	na	na	na	58	35	7	42	sl
ped top	3	9.8	4.1	4.1	36	45	19	64	l
ped center	4	9.8	2.7	9.4	29	35	36	71	cl
ped bottom	5	9.8	2.5	8.6	33	34	33	67	cl
upper side	6	9.7	4.9	1.2	33	44	23	67	l
lower side	7	9.6	4.5	1.1	34	37	28	66	cl
				Site III					
on ped top	1	9.5	1.0	1.5	60	35	6	40	sl
on ped face	2	na	na	na	55	41	4	45	sl
ped top	3	9.8	2.1	5.5	34	48	19	66	l
ped center	4	9.3	9.4	12.1	29	31	40	71	c
ped bottom	5	9.4	7.7	7.4	32	37	32	68	cl
upper side	6	9.8	2.6	2.5	39	41	19	61	l
lower side	7	9.5	6.2	3.1	41	37	22	59	l

† Electrical conductivity.
‡ ls, loamy sand; l, loam; sicl, silty clay loam; sl, sandy loam.

tern in pH values occurred within peds or along the topographic transect. The EC values indicate saline conditions (EC $>$ 4 dS m^{-1}) for many of the subsampled domains. Electrical conductivity of $<$2 dS m^{-1} occurs at all sites for material adhering to ped tops. The highest EC, 9.4 dS m^{-1}, is in the ped center of the lowest topographic position, Site III.

Radiocarbon Ages

Accelerator mass spectrometry radiocarbon analysis of fine-grained bulk soil samples from two subsampled ped centers provides similar age determinations. Conventional, uncalibrated radiocarbon ages are 4530 $\pm$ 50 BP (Beta-93902) at Site I, and 4570 $\pm$ 50 BP (Beta-91527) at Site II, 25 m apart. The two sigma (95% probability) tree-ring calibrated radiocarbon age estimate from Site I ranges from 5315 to 4995 years before present (BP), whereas the age from Site II ranges from 5440 to 5045 years BP. The calibrated radiocarbon ages, interpreted as MRTs, are comparable with a 5000 $\pm$ 1000 BP thermoluminescence age obtained from an Av horizon from a similar-aged basalt flow nearby (McFadden et al., 1998). They are also useful for discussing relationships with regional climatic (Spaulding, 1991) and eolian chronologies (Clarke, 1994).

DISCUSSION

Interpretation of Processes

The micromorphic characteristics of Av peds suggest that pore shape and continuity control the movement of material to ped interiors. Pore shapes include a variety of nonmatrix and interstructural pores (Soil Survey Staff, 1993). Nonmatrix pores occur as many very fine to medium ($<$0.5–5 mm) and occasionally coarse to very coarse (5–10 mm) elliptical and channel shapes. Elliptical pores may coalesce to form interconnected channels, which in turn may coalesce laterally to create platy soil structure. Platy structure in the center and bottom of columnar peds forms conduits connected to interstructural macropores between the columnar peds (Sullivan and Koppi, 1991). Interstructural pores are generally $<$0.5 cm wide and $<$10 cm long. Continuous conduits between interstructural macropores, and the channels and platy structure within the columnar peds, allow movement of sediment and water from the ground surface to ped interiors (Anderson et al., 1994). Incorporation of fine material within the ped probably occurs in two ways: transport in suspension by flowing water and matric suction. Flowing water transports the fines down vertical boundaries between peds and inward along the horizontal platy boundaries where clays accumulate as layered argillans. Further evidence for the transport of coarser material occurs in the form of microbedding, where millimeter-size channels contain deposits fining upward from sand to silt size. Matric suction draws water, solutes, and colloids to ped interiors and, as evapotranspiration dries the soil, $CaCO_3$ precipitates and clay remains. Anderson et al. (1994) indicated that sediment movement may be enhanced by the dispersive properties at the soil surface under high Na concentrations, and the flocculating properties of ped interiors and bottoms because of higher $CaCO_3$ concentrations.

Peds contain two domains of low clay and $CaCO_3$ content and five domains of higher clay and $CaCO_3$. Domains 1 and 2 have consistently lower clay and $CaCO_3$, and higher sand and silt content than the other domains. Ped centers have higher clay and $CaCO_3$ contents than all other ped domains, with up to 15 times the $CaCO_3$ concentration of exterior domains. Also, micromorphic investigations show argillans and calcitans lining horizontal channels and platy structural features in the lower portions of ped centers. Numerous irregular argillaceous and skeletal glaebules, and sand-filled granotubules in the upper portions of ped centers, indicate that this domain is relatively inactive with regard to the lateral translocation of sediment. Pedotubules filled with sandy material suggest that as upper ped centers become filled with sediment, the active zone of translocation shifts to lower ped domains, such as ped bottoms, where platy structures dominate.

Ped bottom domains have calcitans and layered argillans that represent distinct episodes of lateral clay translocation. Fining upward microbedding of silt and sand in ped bottoms indicates lateral sediment transport by suspension along the platy structure, which represents the active domain of lateral clay, silt, and sand translocation (see Fig. 3). Particle-size distribution, $CaCO_3$ content, and micromorphology of Av peds indicate that soluble and easily translocated constituents are preferentially removed from the outer two domains, consequently accumulating in the ped center, upper-side, lower-side, and bottom domains.

From a landscape-scale perspective, the $CaCO_3$ and clay data may provide insights into processes involved in the progressive reduction of relief on desert pavement surfaces. Incipient desert pavement landscapes have high constructional relief because of irregular topography inherited during initial emplacement, whereas mature pavement landscapes (middle to early Holocene and late Pleistocene) have reduced constructional relief (Wells et al., 1984; Bull, 1991). As pavements develop, topographic highs are reduced by salt weathering, rain splash, and colluviation, and topographic lows are filled with slopewash colluvial and eolian material. A measurable increase in both fines and $CaCO_3$ occurs from Site I to Site III (see Fig. 1). Site III, at the topographically lowest position, has consistently higher silt and clay contents for many ped domains, and clayey, $CaCO_3$-rich ped centers. Processes related to eolian deposition, surface transport of fines via overland flow, and subsurface transport of solutes to lower topographic positions may be responsible for the observed increases. The amount of clay and $CaCO_3$ incorporated into the topographically lower soils may increase the volume of material in these positions at a greater rate than slightly higher positions, thereby aiding in relief reduction of increasingly older desert pavement surfaces.

Ages of Av Peds

The processes of soil organic matter turnover and the subsequent addition of younger C to the soil system do not conform to the basic assumption that "carbon isotopic ratios have not been altered except by ^{14}C decay since the sampled material ceased to be an active part of the carbon reservoir" (Taylor, 1987). Because surface soils are an active part of the C reservoir, that is, younger C continues to be added to the soil during pedogenesis, they are very difficult to interpret. Radiocarbon ages on soils result from a mixture of material being added daily to fractions already in the soil, perhaps for thousands of years (Birkeland, 1999). Ages determined by bulk soil radiocarbon analysis are the average ages of all organic constituents in the soil, excluding those removed through pretreatment processes. In this context, MRTs do not represent steady-state systems because (i) the rates of additions and removals from the soil system may exhibit considerable temporal variation, and (ii) organic matter steady states are not attained in desert soils for a very long time (perhaps 300 000 yr) because of the relatively slow rates of organic matter additions and removals (Wang et al., 1996). Although such age determinations can be problematic (Stout et al., 1981), limited interpretations can be made using MRTs as minimum ages (Martel and Paul, 1974; Goh et al., 1977; Scharpenseel, 1979). Some researchers think that specific organic fractions can provide reliable oldest ages, and therefore the closest to the inception of soil genesis (Goh et al., 1977; Holliday et al., 1985), while others have determined that results are neither repeatable nor predictable from one soil to another (Gilet-Blein et al., 1980).

Most studies of soil radiocarbon ages identify the potential source of young organic C as continued growth and decay of in situ organic matter; few studies have attempted to account for organic matter additions from eolian sources, even though Reheis and Kihl (1995) measured up to 23.5% organic matter from dust traps in the Cima Volcanic Field and 45% in other portions of the Mojave Desert. Given that Av soils in the Cima Volcanic Field have eolian origins (McFadden et al., 1984, 1987, 1998), and that >20% of desert dust consists of organic matter, it must be assumed that a significant portion of organic matter added to desert soils is from eolian sources. Therefore, radiocarbon ages determined on any soil fraction must take this into account. Although the origin of organic C for bulk AMS analysis of the sampled Av peds remains unclear and only speculative, the possible sources, and interpretations, must attempt to explain the contributions from both in situ organic matter production and eolian additions.

A conservative interpretation of the AMS ages of Av peds can be made by comparing them with (i) an independent thermoluminescence (TL) age on Av soils, (ii) regional eolian activity, and (iii) periods of regional aridity. Preliminary inferences can thus be made regarding increased aridity, eolian activity, and enhanced vesicular soil formation during the middle Holocene.

Because the radiocarbon ages are interpreted as minimum age estimates, Av soil genesis probably began sometime prior to the 5440 to 4995 BP period. The 5000 $\pm$ 1000 BP TL age on quartz sands from an Av soil ped on a nearby 560 ka basalt flow (McFadden et al., 1998) supports these ages. The TL age on eolian quartz sand suggests an influx of eolian material onto the basalt flows in the Cima Volcanic Field during the middle Holocene, influencing vesicular soil formation by adding eolian fines to the developing Av horizon. Considering the organic matter data from Reheis et al. (1995) discussed above, it is possible that increased amounts of eolian organic matter were also added to the soil system during this time. This might explain the correspondence between AMS and TL dating methods. Resulting ages from both methods could be interpreted as MRTs, given the dynamic processes active in the Av horizons, where organic matter and quartz grains are introduced to ped centers by the processes described earlier. Perhaps enough eolian organic matter was added during this time to lower the MRT age towards the ~5000-BP period.

The AMS and TL ages correspond to middle Holocene eolian activity at Silver Lake playa, 20 km upwind from the Cima Volcanic Field, where an eolian deposit is bracketed by 8350- and 3620-BP radiocarbon ages (Wells et al., 1989). Eolian deposits at the Kelso sand dunes, 10 km south of the project area, have been dated using optically stimulated luminescence to between 8420 and 3500 BP (Clarke, 1994). Spaulding (1991), using packrat midden data, suggested that a period of increased aridity occurred between ~8000 and 4000 BP in portions of the Mojave Desert.

The correspondence between AMS and TL dated Av horizons, with periods of increased eolian activity and regional aridity, suggests that the Av horizons investigated in this study may, in part, be influenced by a middle Holocene increase in eolian sediment and organic matter mobilization, deposition, and incorporation into surface Av soils. Wells et al. (1984, 1987) and McFadden et al. (1984, 1986) have suggested that desiccation of Silver Lake at the end of the Pleistocene dramatically increased the supply of dust to the Cima Volcanic Field, greatly affecting soil genesis and clast fracturing by increasing the amount of salt-rich eolian fines. They postulated that Av horizon development on the basalt flows in the Cima Volcanic Field may have been initiated or enhanced during the Pleistocene to Holocene transition and its increased eolian activity. The results from chemical, physical, and chronologic analyses presented above suggest that the middle Holocene may also have been a time of increased eolian deposition, affecting pedogenic development of the already formed Av horizon, with a corresponding influence on desert pavement formation.

Implications for Desert Pavement Formation

The processes of sediment incorporation below desert pavement on well-developed soils include clay and $CaCO_3$ accumulation in the upper several centimeters of the vesicular soil, causing horizon thickening and vertical accretion. Pavement clasts above this accreting Av horizon ride upward as material below continues to accumulate. Translocation and subsequent storage of eolian fines and salts in ped interiors provides a mechanism for cumulic soil development below pavement clasts, whereby material is added to the soil via lateral macropore conduits.

The initial phase of the process of eolian accumulation and pavement development remains speculative, but is probably influenced by adhesion and surface tension forces as water and sediment act to form laminar surface crusts that adhere to clast bottoms (Fig. 4). A second phase includes continued eolian influx and $CaCO_3$ accumulation, allowing formation of incipient vesicles

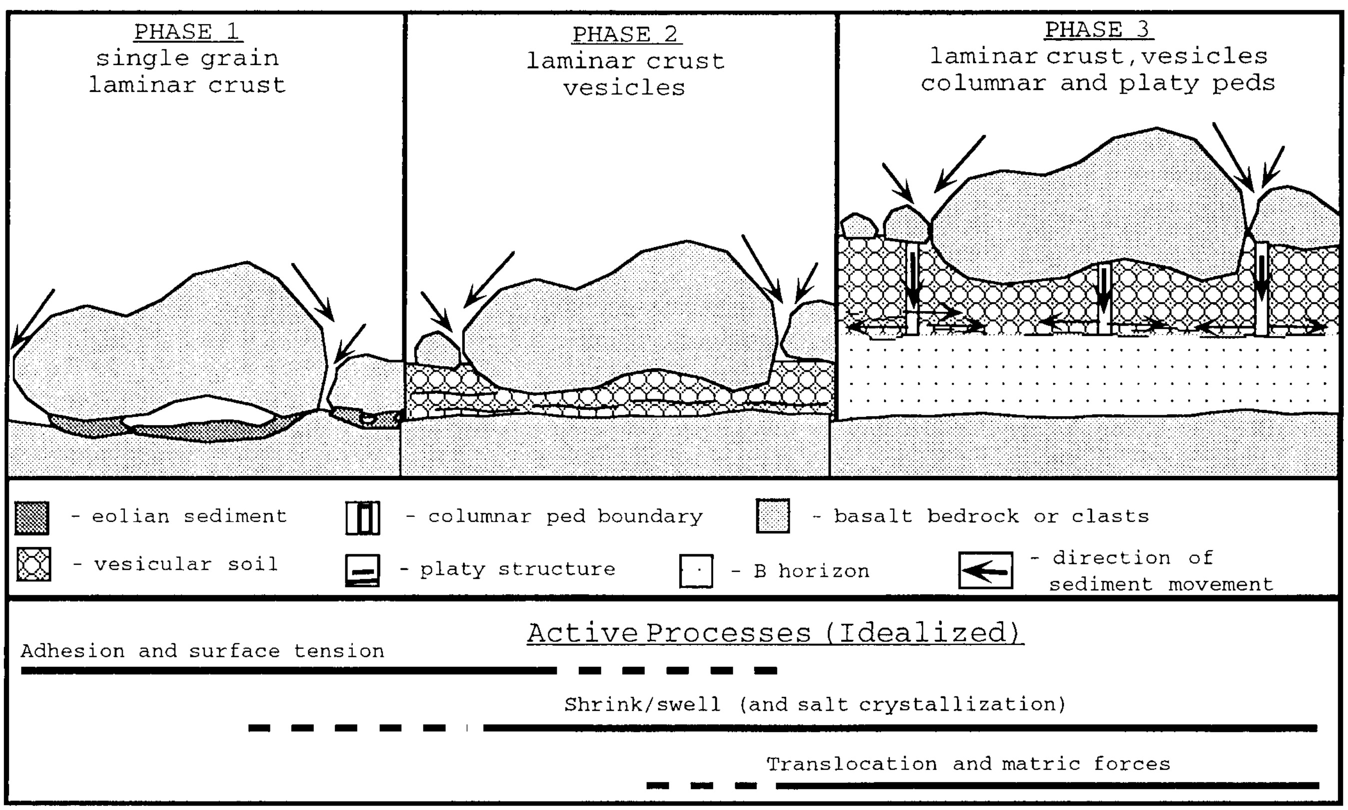

Fig. 4. Hypothesized phases of eolian accumulation and vesicular soil formation emphasizing the influence of pedogenic processes on lifting clasts and consequent formation of accretionary desert pavements. Size of largest clast shown is ~20 cm.

and pedogenic alteration. When soil properties reach certain physical and chemical thresholds—based largely on clay type and amount, and salt and Na concentration—shrinking and swelling processes may enhance clast lifting. A critical third phase of development is related to the formation of well-defined soil structure by shrink-swell activity, where vertical pores between columnar peds are connected to platy structure at ped bottoms. When this phase is attained, further eolian material can be added to both the ped tops and ped interior positions.

An increase in clay and $CaCO_3$ in Av horizons in topographic lows suggests that rates of cumulic soil development and associated pavement-clast lifting are accelerated in lower topographic positions, increasing the rate of relief reduction. In addition, as Av horizons continue to accumulate material, underlying soil horizons continue to develop as well, although the relations between Av genesis and subsoil development remain poorly understood. McFadden et al. (1987) found evidence that subsoil Btvk morphologies support the idea of the transformation of Av's to B horizons. However, increasing Av thickness with time on alluvial fan chronosequences seem to indicate rather long periods of Av stability and continued development (Anderson, 1999; McDonald, 1994). McDonald (1994) finds evidence that the Av horizon may, in fact, also rise vertically as material accumulates below both the pavement clasts and the existing Av layer.

Organic matter is continuously added to the soil by both in situ processes and eolian deposition. Preliminary interpretations of radiocarbon age estimates, and correlation with regional chronologies, suggest that the middle Holocene was a period of increased additions of datable material to the soil, notably quartz sand and organic C. Such an increase may provide enough material to cause a decrease of the mean residence time AMS and TL age-estimates, moving towards concordant chronologies. These concordant AMS and TL ages on Av peds correspond to a period of increased aridity and eolian activity throughout the Mojave Desert during the middle Holocene, with important influences on Av soil genesis and desert pavement development.

ACKNOWLEDGMENTS

This project was supported in part by National Science Foundation grant EAR-9205696, Geological Society of America student research grant, Institutional Proposal Assistance grant from the Desert Research Institute, Reno; Los Alamos National Laboratory, University of California Riverside, California State University Desert Studies Center, Zzyzx. I thank Diana Anderson and Yvonne Wood for field assistance; Eric McDonald and Les McFadden for very helpful discussions on desert pavement formation processes; and Louella Holter, Bilby Research Center, Northern Arizona University for assistance in preparing this manuscript. We also thank two anonymous reviewers for their helpful comments.

REFERENCES

Anderson, K.C., S.G. Wells, R.C. Graham, and L.D. McFadden. 1994. Processes of vertical accretion in the stone-free zone below desert pavements. p. 87. *In* GSA Abstracts with Programs 26, 7, Seattle, WA. Geological Society of America, Boulder, CO.

Anderson, K.C., and S.G. Wells. 1997. Processes responsible for the development of accretionary desert pavements in the southwestern USA. Fourth International Conf. on Geomorphology. University of Bologna, Bologna, Italy.

Birkeland, P.W. 1999. Soils and geomorphology. Oxford Univ. Press, New York.

Bouza, P., H.F. Del Valle, and P.A. Imbellone. 1993. Micromorphological, physical, and chemical characteristics of soil crust types of the Central Patagonia Region, Argentina. Arid Soil Res. Rehabil. 7:355–368.

Bull, W.B. 1991. Geomorphic responses to climatic change. Oxford Univ. Press, New York.

Clarke, M.L. 1994. Infra-red stimulated luminescence ages from aeolian sand and alluvial fan deposits from the eastern Mojave Desert, California. Quat. Geochron. 13:533–538.

Cooke, R.U. 1970. Stone pavements in deserts. Assoc. Am. Geog. 60:560–577.

Cooke, R.U., and A. Warren. 1973. Geomorphology in deserts. UCLA Press, Los Angeles, CA.

Evenari, M.L., L. Shannon, and N. Tadmor. 1971. The Negev: The challenge of the desert. Harvard Univ. Press, Cambridge, MA.

Evenari, M., D.H. Yaalon, and Y. Gutterman. 1974. Notes on soils with vesicular structure in deserts. Z. Geomorph. N.F. 18:1162–1172.

Figueira, H., and G. Stoops. 1983. Application of micromorphometric techniques to the experimental study of vesicular layer formation. Pedology 33:77–89.

Figueira, H. 1984. Horizonte vesicular: Morfologia y genesis en un aridisol del norte de la Patagonia. (In Spanish.) Cienci del Suelos 2:121–129.

Gee, G.W., and J.W. Bauder. 1982. Particle-size analysis. p. 383–411. *In* A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA, Madison, WI.

Gilet-Blein, N., G. Marien, and J. Evin. 1980. Unreliability of 14C dates from organic matter of soils. Radiocarbon 22:919–929.

Goh, K.M., B.P.J. Molloy, and T.A. Rafter. 1977. Radiocarbon dating of Quaternary loess deposits, Banks Peninsula, Canterbury, New Zealand. Quat. Res. 7:177–196.

Holliday, V.T., E. Johnson, H. Haas, and R. Stuckenrath. 1985. Radiocarbon ages from the Lubbock Lake Site: 1981–1984. Part 1. J. Plains Anthropological Soc. 30:277–291.

Hunt, C.B., T.W. Robinson, W.A. Bowles, and A.L. Washburn. 1966. Hydrologic basin, Death Valley California. USGS Prof. Paper 494-B. U.S. Gov. Print. Office, Washington, DC.

Jessup, R.W. 1960. The stoney tableland soils of the southeastern portion of the Australian arid zone and their evolutionary history. J. Soil Sci. 11:188–196.

Johnson, D.L., and N.C. Hester. 1972. Origin of stone pavements on Pleistocene marine terraces in California. Assoc. Am. Geog. Proc. 4:50–53.

Mabbutt, J.A. 1977. Desert landforms. MIT Press, Cambridge, MA.

Marbut, C.F. 1935. Soils of the United States. *In* Atlas of American agriculture. Part 3. USDA Bureau of Soils, Washington, DC.

Martel, Y.A., and E.A. Paul. 1974. The use of radiocarbon dating of organic matter in the study of soil genesis. Soil Sci. Soc. Am. Proc. 38:501–506.

McDonald, E.V. 1994. The relative influences of climatic change, desert dust, and lithologic control on soil-geomorphic processes and soil hydrology of calcic soils formed on Quaternary alluvial-fan deposits in the Mojave Desert, California. Ph.D. diss. Univ. of New Mexico.

McDonald, E.V., L.D. McFadden, and S.G. Wells. 1994. Quaternary stratigraphy of the Providence Mountains piedmont and preliminary age estimates and regional stratigraphic correlations of Quaternary deposits in the eastern Mojave Desert, California. p. 205–210. *In* S.F. McGill and T.M. Ross (ed.) Geological investigations of an active margin. GSA Cordilleran Section Guidebook, San Bernardino, CA.

McFadden, L.D., S.G. Wells, J.C. Dohrenwend, and B.D. Turrin. 1984. Cumulic soils formed in eolian parent materials on flows of the Cima volcanic field, Mojave Desert, California. p. 134–149. *In* J.C. Dohrenwend (ed.) Surficial geology of the eastern Mojave Desert, CA. GSA Guidebook, Reno, NV.

McFadden, L.D., S.G. Wells, and J.C. Dohrenwend. 1986. Influences of Quaternary climatic changes on processes of soil development

on desert loess deposits of the Cima volcanic field, CA. Catena 13:361–389.
McFadden, L.D., S.G. Wells, and M.J. Jercinovich. 1987. Influences of eolian and pedogenic processes on the origin and evolution of desert pavements. Geology 15:504–508.
McFadden, L.D., J.B. Ritter, and S.G. Wells. 1989. Use of multiparameter relative-age methods for age estimation and correlation of alluvial fan surfaces on a desert piedmont, eastern Mojave Desert, California. Quat. Res. 32:267–290.
McFadden, L.D., E.V. McDonald, S.G. Wells, K.C. Anderson, J. Quade, and S.L. Forman. 1998. The vesicular layer and carbonate collar of desert soils and pavements: Formation, age and relation to climate change. Geomorphology 24:101–145.
Miller, D.E. 1971. Formation of vesicular structure in soil. Soil Sci. Soc. Am. Proc. 35:635–637.
Musick, B.H. 1973. Barrenness of desert pavement in Yuma County, AZ. Arizona Academy of Sciences 10, Tucson, AZ.
Nelson, D.W. 1982. Carbonate and gypsum. p. 181–197. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA, Madison, WI.
National Oceanic and Atmospheric Administration. 1978. Climatologic data annual summary: Environmental data and information service. Vol. 82, No. 13. United States Department of Commerce, Washington, DC.
Peterson, F.F. 1980. Holocene desert soil formation under sodium, salt influence in a playa-margin environment. Quat. Res. 13:172–186.
Reheis, M.C., and R. Kihl. 1995. Dust deposition in southern Nevada and California, 1984–1989: Relations to climate, source area, and lithology. J. Geophys. Res. 100(D5):8893–8918.
Reheis, M.C., J.C. Goodmacher, J.W. Harden, L.D. McFadden, T.K. Rockwell, R.R. Shroba, J.M. Sowers, and E.M. Taylor. 1995. Quaternary soils and dust deposition in southern Nevada and California. GSA Bull. 107:1003–1022.
Rhoades, J.D. 1982. Soluble salts. p. 167–179. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA, Madison, WI.
Scharpenseel, W.H. 1979. Soil fraction dating. p. 277–305. *In* R. Berger and H. Suess (ed.) Radiocarbon dating. Proceedings of the Ninth International Conf., Univ. of Calif. Press, Berkeley, CA.
Sharon, D. 1962. On the nature of hamadas in Israel. Z. Geom. 6:129–147.
Soil Survey Staff. 1992. Keys to soil taxonomy. USDA Tech. Monogr. 19. USDA, Blacksburg, VA.
Soil Survey Staff. 1993. Soil survey manual. USDA Agric. Handb. 18. U.S. Gov. Print. Office, Washington, DC.
Spaulding, W.G. 1991. A middle Holocene vegetation record from the Mojave Desert of North America and its paleoclimatic significance. Quat. Res. 35:427–437.
Springer, M.E. 1958. Desert pavement and vesicular layer of some soils of the desert of the Lahontan Basin, Nevada. Soil Sci. Soc. Am. Proc. 22:63–66.
Stout, J.D., K.M. Goh, and T.A. Rafter. 1981. Chemistry and turnover of naturally occurring resistant organic compounds in soil. p. 1–73. *In* E.A. Paul and J.N. Ladd (ed.) Soil biochemistry, Vol. 5. Marcel Dekker, New York.
Sullivan, L.A., and A.J. Koppi. 1991. Morphology and genesis of silt and clay coatings in the vesicular layer of a desert loam soil. Aust. J. Soil Res. 29:579–586.
Symmons, P.M., and C.F. Hemming. 1968. A note on wind-stable stone mantles in the southern Sahara. Geog. J. 134:60–64.
Taylor, R.E. 1987. Radiocarbon dating: An archaeological perspective. Academic Press, Orlando, FL.
Turrin, B.D., J.C. Dohrenwend, S.G. Wells, and L.D. McFadden. 1984. Geochronology and eruptive history of the Cima volcanic field, eastern Mojave Desert, California. p. 88–100. *In* J.C. Dohrenwend (ed.) Surficial geology of the eastern Mojave Desert, California. GSA Guidebook, Reno, NV.
Wang, Y., R. Amundson, and S. Trumbore. 1996. Radiocarbon dating of soil organic matter. Quat. Res. 45:282–288.
Wells, S.G., J.C. Dohrenwend, L.D. McFadden, B.D. Turrin, and K.D. Mahrer. 1984. Types and rates of late Cenozoic geomorphic processes on lava flows of the Cima volcanic field, Mojave Desert. p. 116–133. *In* J.C. Dohrenwend (ed.) Surficial geology of the eastern Mojave Desert, California. GSA Guidebook, Reno, NV.
Wells, S.G., J.C. Dohrenwend, L.D. McFadden, B.D. Turrin, and K. Mahrer. 1985. Late Cenozoic landscape evolution on lava flow surfaces of the Cima volcanic field, Mojave Desert, California. GSA Bull. 96:1518–1529.
Wells, S.G., L.D. McFadden, and J.C. Dohrenwend. 1987. Influence of Late Quaternary climatic change on geomorphic and pedogenic processes on a desert piedmont, eastern Mojave Desert, California. Quat. Res. 27:130–146.
Wells, S.G., R.Y. Anderson, L.D. McFadden, W.J. Brown, Y. Enzel, and J.L. Miossec. 1989. Late Quaternary paleohydrology of the eastern Mojave River drainage basin, southern California: Quantitative assessment of the late Quaternary hydrologic cycle on a large arid watershed. p. 242–250. New Mexico Water Resour. Res. Inst. Tech. Comp. Report, Albuquerque, NM.
Wells, S.G., L.D. McFadden, J. Poths, and C.T. Olinger. 1995. Cosmogenic ^{3}He surface-exposure dating of stone pavements: Implications for landscape evolution in deserts. Geology 23:613–616.