Influences of eolian and pedogenic processes on the origin and evolution of desert pavements

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ABSTRACT

Well-developed desert pavements are present above eolian deposits that mantle flows of the Cima volcanic field, located in the Mojave Desert, California. Soil-stratigraphic data and geochemical data demonstrate that eolian and pedogenic processes play major roles in the evolution of these pavements. Eolian dust (1) accelerates mechanical fragmentation of flow rock, providing the source material for pavements, and (2) accumulates slowly below basaltic colluvium in flow depressions, eventually promoting development of cumulate soils below the evolving stone pavement. An increase in dust flux during the Holocene has raised ancient Pleistocene pavements as much as 20 cm above the former land surface. The results of our studies demonstrate for the first time that most desert pavements do not form by deflation, by overland flow, or by upward migration of stones through a slowly formed, clayey argillic horizon. Desert pavements are born and maintained at the surface.

INTRODUCTION

Desert pavements, consisting of a one- to two-particle-thick layer of closely packed, angular to subrounded gravel, are one of the more prominent landforms of hot and arid regions (Cooke and Warren, 1973; Mabbutt, 1977; Ritter, 1986). Desert pavements on surfaces of alluvial fans usually exhibit very little relief, are darkly varnished, and occur above a relatively gravel-free layer in which a moderately to strongly developed soil has formed. Characteristics of desert pavements have been used to map Quaternary surficial deposits (Denny, 1965; Bull, 1974; Shlemon, 1978; Christenson and Purcell, 1985), and changes in the chemical composition of varnish and the presence of organic carbon in varnish coating gravel of pavements have proved to be useful for estimating the age of the underlying materials on which the pavement formed (Dorn and Oberlander, 1981; Dorn et al., 1986; Harrington, 1986; Dethier and Harrington, 1986).

Development of desert pavements is usually attributed to deflation, erosion of fine-grained material (Cooke and Warren, 1973; Ritter, 1986), or upward migration of gravel through an increasingly clay-rich, gravel-depleted B horizon via alternating shrinking and swelling (Springer, 1958; Jessup, 1960; Cooke, 1970; Mabbutt, 1977; Dan et al., 1982). On the basis of recent studies of pavement, soil, and landscape development in the Cima volcanic field, we conclude, instead, that pavements are born at the land surface and that pavement clasts are never deeply buried in the underlying soil. Stone pavements on eolian-mantled lava flows in this area form at the surface by two major processes: (1) colluviation of basaltic clasts from topographic highs into topographic depressions filled with eolian silt and (2) detachment and uplifting of clasts from bedrock surfaces as eolian fines accumulate in fractures and along flow surfaces. The pavements are maintained at the surface as cumulate soils develop beneath the pavements in response to the incorporation of eolian silts and clays deposited on the land surface.

PAVEMENT EVOLUTION

The origin and evolution of stone pavements on the basalt flows are directly linked to two fundamental processes: (1) deposition and pedogenic alteration of the eolian mantle and (2) mechanical weathering to form the rubble zone. The source of the clasts in the pavements is mechanically weathered basaltic bedrock derived from topographic highs. Salt-rich eolian fines accumulate in fractures of the basalt (McFadden et al., 1986), and wetting and drying of the fines result in volumetric changes related to crystal growth or shrinking and swelling of clay (Cooke and Warren, 1973). This volumetric change enhances fracturing and displaces the basaltic clasts vertically and laterally (Fig. 1). As displacement occurs, additional eolian fines and salts are deposited between the clasts, further enhancing separation of clasts from the underlying bedrock. Mechanical weathering of

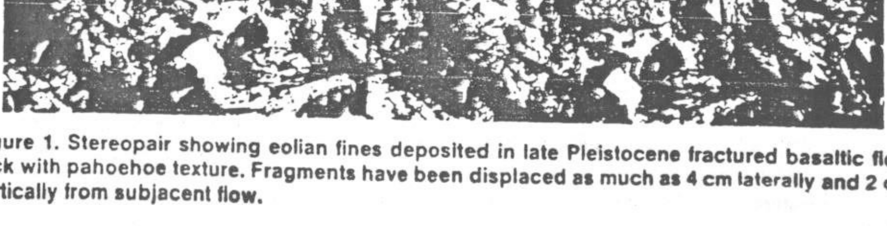

Figure 1. Stereopair showing eolian fines deposited in late Pleistocene fractured basaltic flow rock with pahoehoe texture. Fragments have been displaced as much as 4 cm laterally and 2 cm vertically from subjacent flow.

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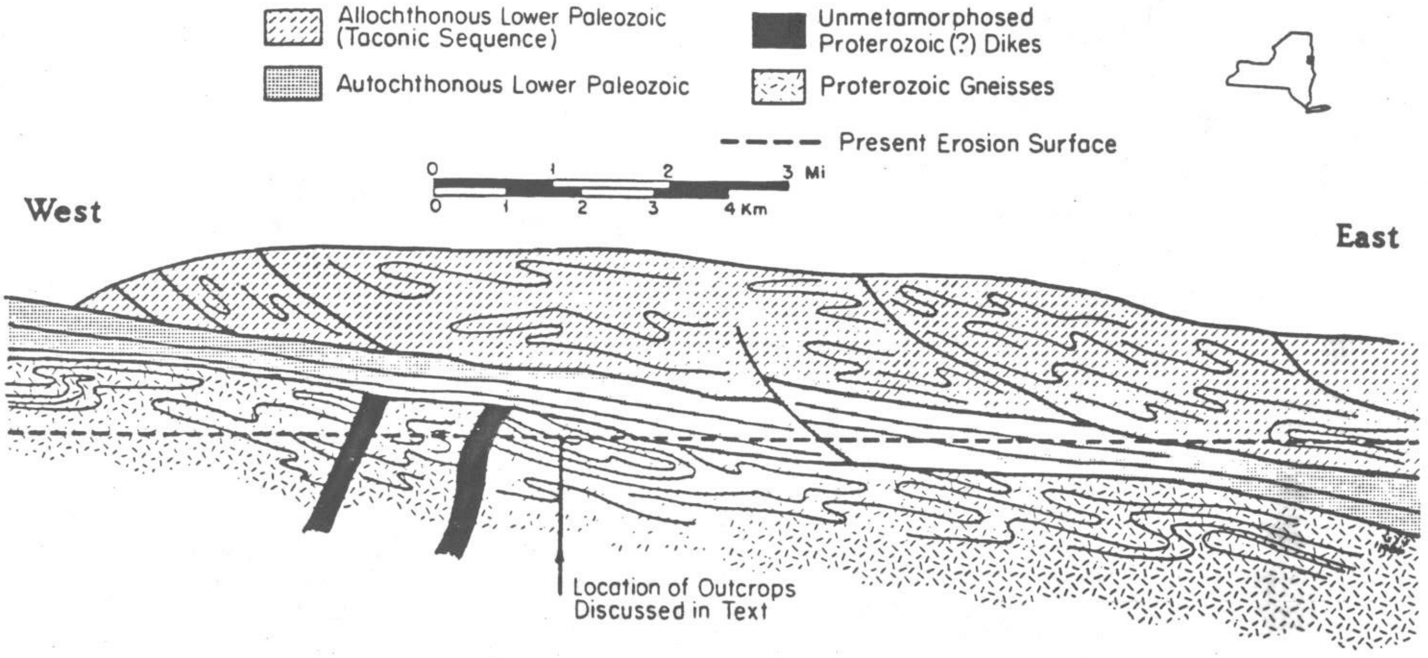

Figure 4. Schematic cross section of Fort Ann-Whitehall area during Taconic orogeny. Arrow shows location of outcrops discussed in text.

beyond the contact now exposed, as illustrated schematically in Figure 4. During thrusting, stresses transmitted through the autochthonous lower Paleozoic rocks caused minor east-over-west displacement along favorably oriented foliation planes in the underlying Proterozoic gneiss. The preponderance of north-northeast-striking planes that dip gently to moderately east-southeast would be nearly optimum for such movement. This displacement produced the observed foliation-parallel slickensides and minor offset of vertical dikes. In addition, minor cataclasis occurred along contacts between rocks of contrasting mechanical properties, such as gneiss and marble, and thus provided access for fluids. Similar features have not been reported in the overlying Paleozoic rocks, possibly because planar surfaces in the latter are less well defined.

Simultaneously, tectonic overpressures created by the overriding thrust slice(s) expelled connate brines from the autochthonous Paleozoic rocks and forced these brines into the underlying crystalline rocks along foliation planes, lithologic contacts, and faults. These fluids are likely to have been enriched in Mg, in view of the evidence for hypersaline depositional environments in the Paleozoic rocks. The overpressures were sufficient to create and maintain open spaces, which then were filled by K-feldspar, dolomite, and celadonite. The brines also caused dolomitization of the marbles, serpentinization of calc-silicate minerals, and precipitation of cherty silica. The mineral assemblages are consistent with an origin at temperatures not over 420 °C in the presence of an aqueous fluid; the actual temperatures may have been much lower in view of the presence and purity of the K-feldspar.

Potential large-scale effects of pressurized fluids expelled from sedimentary rocks as a result of overthrust tectonics have been described recently by Hearn and Sutter (1985) and Oliver (1986). We believe that these rocks display evidence of the same phenomenon on a more local scale.

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topographic highs also results in the development of colluvial wedges of rubble and the concomitant infilling of topographic depressions with the colluvial material. These clasts move laterally by colluvial and alluvial processes into the topographic lows in which abundant silt has accumulated, and they form a surface layer or armor of stones (Fig. 2; Wells et al., 1985). On progressively older flows, the extent of bedrock highs decreases as the eolian mantle and stone pavement fill in the lows and coalesce; thus, the source area for basalt clasts is significantly reduced on flows older than 0.4 Ma (Wells et al., 1985). Pavements on flows younger than 0.4 Ma have mixtures of clasts that were derived episodically from topographic highs, presumably due to a decrease in the rate of supply from increasingly subdued topographic highs. In contrast, relative-age data for clasts in pavements on flows older than 0.4 Ma indicate fewer differences in the residence time of clasts in the pavement. This is supported by the data on the reddening (iron oxidation) clast undersides: only 10%–20% of clast undersides in pavements on flows younger than 0.4 Ma have weakly reddened, oxidized coatings, whereas clast undersides on flows older than 0.4 Ma are all reddened to 5YR and 2.5YR hues. This suggests that no new clasts are added to pavements once the bedrock topographic highs are reduced by erosion and buried by eolian sediments, and once stones are added to the pavements, they are typically maintained at the surface by processes that inhibit burial.

SOILS DEVELOPED IN THE EOLIAN MANTLE BENEATH THE PAVEMENT

Soils exhibiting a wide variation in the degree of development occur in deposits underlying the pavement. These deposits are quartz-rich, well-sorted sandy silts that have been transported to the flow surfaces largely as windblown suspended load (Wells et al., 1985) where they are trapped by the rough surfaces of the flow (Greeley and Iversen, 1981). Between major periods of eolian deposition, a lower eolian flux rate permits development of soils in the eolian deposits. Moderate eolian depositional rates are apparently critical for maintaining clasts at the land surface. In the Cima volcanic field, three distinct phases of soil development are recognized on flows younger than 1.1 Ma: weakly developed soils on flows younger than 0.18 Ma (Fig. 2); strongly developed soils containing thick argillic horizons on flows that are 0.18 to 0.7 Ma (Fig. 2); and strongly developed soils containing truncated argillic horizons that are massively impregnated by pedogenic $CaCO_3$ on flows that are 0.7 to 1.1 Ma (Dohrenwend et al., 1984).

A critical aspect of soil and pavement development on flow surfaces is the formation of the vesicular A (Av) horizon. Such horizons, observed in many desert soils, are typically more clay- and silt-rich than the underlying soil parent materials. The spherical vesicles are probably due to entrapped soil air that expands as soil temperature rapidly increases after summer rainfall events (Evenari et al., 1974). Some of the sand and silt fractions of the Av horizons of desert soils may be attributed to comminution of gravel lithologies susceptible to mechanical weathering (Mabbutt, 1977; Ritter, 1986); however, the paucity of basaltic material in the Av horizon emphasizes the largely eolian origin of material that composes this horizon. Vesicular horizons in the study area have a pronounced columnar structure (Fig. 2) that is attributed to alternating shrinking and swelling of the clays in the increasingly clay-enriched Av horizon (McFadden et al., 1986). Significant amounts of trapped eolian silt and fine sand and solutes are more readily transported below the surface through these cracks. The walls of the Av peds are typically coated with loose silt and are almost noncalcareous due to this process. In contrast to rapid infiltration through the cracks, infiltration through peds is very slow and eventually causes alteration of the interior, reflected by the reddened and carbonate-enriched nature of the ped interior. Moderate accretion of eolian fines into Av peds and drying of peds during the summer result in doming of the ped tops and vertical displacement of overlying clasts (Fig. 3). During the winter, soil moisture is retained and the domes collapse, causing fresh eolian fines on ped walls and in cracks between peds to be incorporated in the Av horizon. With continued Av-horizon development, the interiors of Av eventually coalesce and form a continuous B horizon.

Mabbutt (1977) suggested that some pavements might somehow be maintained at the surface as eolian material is slowly incorporated beneath the pavement. The results of our studies

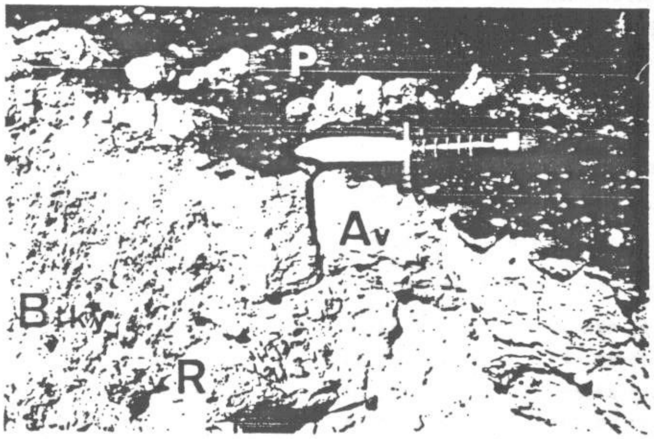

Figure 2. Stone pavement (P) formed over accretionary mantle in topographic depression on late Pleistocene flow in Cima volcanic field. Development of vesicular A (Av) horizons of phase 1 soils, carbonate- and gypsum-bearing argillic horizons (Btky) of phase 2 soils, and origin of basalt rubble (R) are discussed in text.

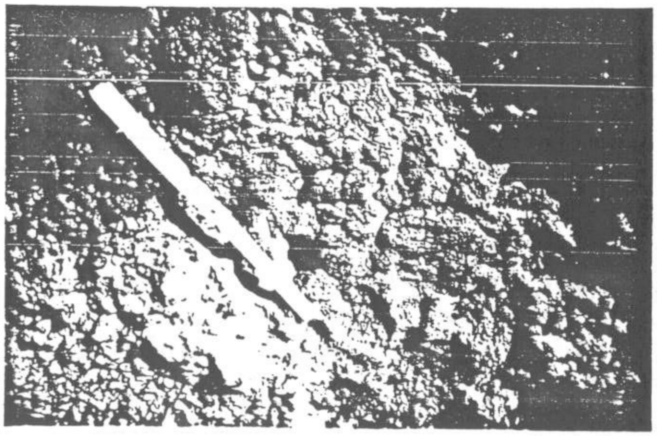

Figure 3. Domed surface of vesicular A horizon exposed after careful removal of stone pavement. Note strongly developed, nonorthogonal crack system.

show that the development of an Av horizon and ultimately a cumulate soil are critical aspects of pavement formation. Moreover, these results demonstrate that the presence of clay-enriched and virtually gravel-free B horizons that often occur below desert pavements does not require the often-invoked process of upward migration of gravel through the B horizon.

Age data for the flows and soil-stratigraphic data support the hypothesized mechanism of pavement evolution. The presence of similarly developed soils in loess beneath pavements on flows younger than 0.18 Ma and as young as 16 ka indicates that the most recent period of relatively high eolian influx rates occurred during the latest Pleistocene to early Holocene (Wells et al., 1985; McFadden et al., 1986). The apparent timing of the most recent eolian event and the accumulation of large quantities of carbonates and soluble salts in these soils strongly suggest that alkaline playas, formed after the disappearance of late Pleistocene pluvial lakes in the Mojave Desert, are a major source of these eolian materials (McFadden et al., 1986). Smoother surfaces of older volcanic flows where bedrock crops out are rare and trap loess less efficiently. The most recent loess is typically present as a thin veneer that buries an older loess deposit in which a very strongly developed soil is present (Fig. 2). The source of clasts in the desert pavement on such surfaces can only have been derived from a preexisting pavement formed on a now buried soil. On flows with rough surfaces, however, high rates of loess deposition precluded development of a soil, and the preexisting pavement was buried (Wells et al., 1985). Remaining topographic highs on these flows provided materials for development of the present desert pavement.

CHEMICAL ALTERATION OF THE STONE PAVEMENT

X-ray fluorescence analysis of volcanic rocks of a variety of ages in the Cima field shows that their composition is quite similar (Turrin et al., 1986). We hypothesize, therefore, that chemical weathering of basalt in the pavement and in the rubble produces authigenic minerals whose chemical compositions reflect contrasting weathering environments rather than compositional differences. To test this hypothesis, sample clasts were collected from the pavement and underlying soil on selected flow surfaces of various ages and were examined by using optical petrographic techniques, scanning electron microscopy, and electron microprobe analysis (Fig. 4; Table 1).

Decomposition of the basalt has occurred mainly by alteration of the glass–iron ox mesostasis. Olivine is the primary sili mineral that is chemically altered in both pa ment and rubble. Olivine alteration is characterized by uptake of H_2O, TiO_2, Al_2O_3, C Na_2O, K_2O, and P_2O_5. SiO_2, MgO, and M however, are generally depleted relative to fres olivine. The primary products of alteration i pavement and rubble samples include authig clay (Fig. 4) and ferric oxyhydroxides that f layers 10 to 50 μm thick on fracture and vesicl walls. Microprobe analyses indicate that the au thigenic clay is a mixed-layer clay, prob consisting of illite and smectite or illite and miculite (Table 1; Fig. 4).

Alteration of the rocks in the pavement di from alteration of rubble in several major spects. Authigenic clay in pavement samples ap pears to be significantly enriched in Al_2O_3 an depleted in CaO relative to authigenic cla rubble. Also, structural formula calculation dicate that there is a greater percentage of F and Mg relative to Al in octahedral sites in au thigenic clay of rubble than in octahedral sit authigenic clay of pavement clasts (Table Additionally, rubble clays are more Na and K rich (i.e., higher illite component) than sur pavement clays. In general, porosity due to p ence of fractures and vesicles is greater in ro of the rubble compared to rocks in th pavement.

TABLE 1. MICROPROBE ANALYSES OF AUTHIGENIC CLAY MINERALS IN BASALT CLASTS FROM LATE PLEISTOCENE AND MIDDLE PLEISTOCENE PAVEMENTS AND RUBBLE

	Late Pleistocene flow pavement* (wt %)	Rubble+ (wt %)	Middle Pleistocene flow pavement§ (wt %)	Rubble# (wt %)
SiO_2	43.65 ±3.45	44.14 ±2.32	46.02 ±1.57	36.71 ±3.09
TiO_2	0.75 ±0.47	0.73 ±0.19	0.37 ±0.15	7.72 ±0.91
Al_2O_3	24.20 ±3.32	14.82 ±1.28	23.44 ±0.95	13.52 ±1.27
Fe_2O_3**	8.14 ±1.92	7.05 ±0.95	5.37 ±0.59	15.27 ±3.86
MnO	0.43 ±0.47	0.11 ±0.06	0.05 ±0.03++	0.23 ±0.15
MgO	3.18 ±0.60	4.31 ±0.66	4.26 ±0.57	3.59 ±1.71
CaO	1.76 ±1.32	2.04 ±0.57	1.39 ±0.55	6.27 ±2.17
Na_2O	0.19 ±0.31	0.63 ±0.22	0.14 ±0.07	1.14 ±0.35
K_2O	2.06 ±0.32	2.61 ±0.35	2.22 ±0.34	1.19 ±0.32
P_2O_5	0.80 ±0.93	0.53 ±0.48	0.35 ±0.33	1.10 ±1.10
Total	84.31	76.26	83.07	82.21

Note: Flow ages: late Pleistocene—0.13 ±0.06 Ma; middle Pleistocene—0.56 ±0.16 Ma (Turrin et al., 1986). Structural formula on basis of 20 (O) and (OH).

* $(Si_{6.38}Al_{1.62})(Al_{2.55}Ti_{.08}Fe_{.90}Mn_{.05}Mg_{.69})Ca_{.28}Na_{.05}K_{.38}P_{.10}$

\+ $(Si_{7.16}Al_{.84})(Al_{1.99}Ti_{.09}Fe_{.86}Mn_{.02}Mg_{1.04})Ca_{.35}Na_{.20}K_{.54}P_{.07}$

§ $(Si_{6.74}Al_{1.26})(Al_{2.78}Ti_{.04}Fe_{.59}Mn_{.01}Mg_{.93})Ca_{.22}Na_{.04}K_{.41}P_{.04}$

\# $(Si_{5.85}Al_{2.15})(Al_{.39}Ti_{.57}Fe_{1.83}Mn_{.03}Mg_{.85})Ca_{1.07}Na_{.35}K_{.24}P_{.15}$

** All Fe calculated as Fe_2O_3.

++ Below detection limit.

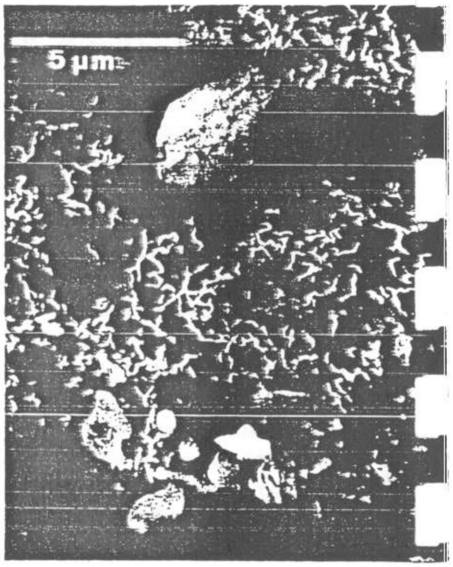

Figure 4. Scanning electron microscope p tomicrograph showing crenulate, interloc authigenic clay crystals formed during ch cal alteration of latest Pleistocene basalti flow rubble in Cima volcanic field. Electro microprobe analysis and structural for calculations of authigenic clay indicate mixed-layer clay consists of illite and sme

These differences in character of chemical weathering of pavement and rubble samples imply that alteration has taken place in contrasting geochemical environments. Precipitation of alkaline clays in rubble samples may be favored by alteration of basalt under alkaline soil conditions, whereas alteration under less alkaline to neutral conditions in a largely subaerial pavement environment may favor development of more Al-rich clay. However, a more severe alteration of rubble should occur in the relatively well insulated subsoil environment; thus, the magnitude of chemical weathering is ultimately greater in rubble samples than in pavement samples. Accordingly, a rubble sample from an early Pleistocene flow displays the greatest magnitude of chemical and physical weathering. This sample also contains abundant zeolite and rare celestite, authigenic minerals that have precipitated in fractures (Fig. 5, A and B). Chemical alteration of the rubble parallels the significant chemical alteration of the loess parent materials of well-developed soils underlying pavements on surfaces older than 0.2 Ma in the Cima field (McFadden et al., 1986).

The paragenesis of authigenic minerals indicated in strongly altered rubble is clay → zeolites + calcite(?) → celestite. This sequence suggests that the most recent authigenesis occurred in a strongly alkaline environment and is consistent with the hypothesis that much of the accumulated pedogenic carbonates and sulfates are derived by deflation of Holocene alkaline playas (McFadden et al., 1986).

DISCUSSION

We hypothesize that stone pavements on alluvial fans of desert piedmonts have probably evolved in a manner similar to that proposed for the stone pavements in the Cima volcanic field. Surfaces of alluvial fans in the deserts of the southwestern United States initially have a bar-and-swale topography inherited from the braided pattern of ephemeral streams in arid environments (Bull, 1974). Fan surfaces of early Holocene age, however, exhibit partial pavement development, and stone pavements are ubiquitous on fan surfaces of late Pleistocene age. Vesicular A horizons that are nearly identical to those observed in the Cima volcanic field constitute the initially developed horizon of soils on such fan deposits. Weakly developed color B horizons are present below the vesicular A horizon of middle to early Holocene soils, but a weak to moderately strong and usually nongravelly argillic horizon is present below the vesicular A horizon of late Pleistocene and older soils on these fans (McFadden, 1982; McFadden and Bull, 1987; Wells et al., 1987).

Eolian processes have significantly influenced soil development on alluvial deposits in deserts. Much of the silt, clay, carbonates, and soluble salts that have accumulated in soils formed in arid environments are attributable to incorporation of eolian materials rather than to chemical weathering of soil parent materials (Brown, 1956; Gile et al., 1966, 1981; Lattman, 1973; Machette, 1985; McFadden and Tinsley, 1985). As discussed previously, however, eolian activity during the Quaternary has been strongly episodic in the Mojave Desert, the most recent period of relatively high eolian influx rates having occurred during the latest Pleistocene to early Holocene. A major increase in eolian activity during the Holocene has also been documented in the desert of southern Nevada. Whitney et al. (1986) reported that eolian silt overlying a sequence of early through late Pleistocene alluvial units was deposited between 6.5 and 3 ka, on the basis of thermoluminescence age determinations of the silt.

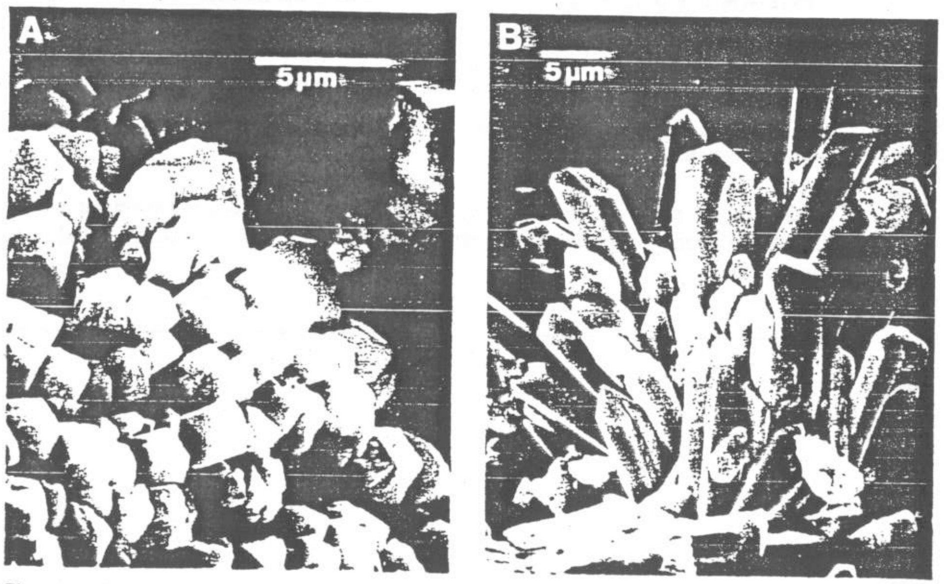

Figure 5. Scanning electron microscope photomicrographs showing authigenic minerals present in basaltic rubble in well-developed, phase 3 soil on early Pleistocene flow in Cima volcanic field. A: Spherulitic zeolite crystals. Electron microprobe data indicate that zeolite is probably phillipsite. B. Spherulitic celestite ($SrSO_4$) crystals.

We propose that the vesicular A horizon and potentially much of the uppermost B horizon of Pleistocene soils on fan surfaces of the Mojave Desert record the significant increase in eolian activity that began as early as the latest Pleistocene and has continued into the Holocene. The rate of incorporation of eolian material has been slow enough to permit development of cumulate soils and concomitant uplift of preexisting stone pavements. Thus, although in some cases accumulation of a surficial gravel lag may be attributed to eolian or fluvial removal of fines, we believe that such processes can contribute very little to the evolution of pavements formed on piedmonts.

The results of analysis of the chemical composition of the varnish on clasts of desert pavements also strongly support the proposed process of pavement development. Dorn and Oberlander (1981) showed that varnish-forming, mixotrophic microorganisms require the near neutral pH conditions that are present only in a subaerial environment. Cation ratios of varnish from pavements on late Pleistocene fan surfaces are significantly lower than the cation ratios of varnish from clasts of early or middle Holocene pavements (Dorn, 1983, 1984; Dorn et al., 1986). If well-developed pavements can form only after a clay-rich B horizon develops and causes upward migration of gravel, a significant number of clasts in late Pleistocene pavements should have relatively high cation-ratio values that would reflect the emergence of these clasts sometime during the Holocene. Cation-ratio and varnish micromorphologic data from a variety of study areas (Dorn, 1983, 1984; Dorn et al., 1986) imply, instead, that varnish development has occurred on stones exposed continuously since abandonment of the fan surface. Pavements in the Mojave Desert that are probably as old as middle Pleistocene (Bull, 1974; Wells et al., 1985; McFadden et al., 1986) must therefore coexist with soils that have formed largely in eolian deposits of Holocene age. Thus, on the basis of our studies in the Cima volcanic field, we conclude that desert pavements (1) are born at the land surface and (2) remain at the land surface via eolian deposition and simultaneous development of cumulate soils beneath the pavements.

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Reviewer's comment

The ideas in this paper are *great!* I grew up BELIEVING that desert pavements were forme either (a) deflation or (b) upward movement of rocks. This paper has the potential to dispel all those old ideas.

David W