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) contributes 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 28 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, or 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; Silemon, 1978; Christensen 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 (Gorn and Borden, 1981; Dorn et al., 1986; Harrington, 1986; Dreyer 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; Jepsen, 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. Some pavements on colluvial-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 cumulative 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 pedogenetic 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 5 cm vertically by adjacent flow.

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topographic highs also result in the development of colluvial wedges of rubble and the consequent infilling of topographic depressions with the colluvial material. These clasts move laterally by colluvial and alluvial processes into the topographic lows where abundant silt has accumulated, and they form a surface layer of armor of stones (Fig. 2; Wells et al., 1985). On progressively older flows, the extent of bedrock highs (pahoehoe) as the eolian mantles and stone pavements fill in the lows andconnect. Thus, the surface area for basalt clasts is significantly reduced on flows older than 0.4 Ma (Wells et al., 1985). Pavements on flow younger than 0.4 Ma have mixtures of clasts that were derived specifically from topographic highs, presumably due to a decrease in the rate of supply of increasing subdued topographic highs. In contrast, relatively large clasts for clasts in pavements on flows older than 0.4 Ma indicate lower densities in the residence time of clasts in the pavement. This is supported by the data on the reddening (fire-exhaustion) that underlies only 10-20% of clast underclays in pavements on flows younger than 0.4 Ma, whereas all reddenings on flows older than 0.4 Ma are all reddenings to 5YR and 2.5YR tones. This suggests that the reddenings on the topographic highs are reddened by weathering and burned by eolian sedimentation, and that these clasts are typical of the surface processes that inhibit burial.

SOILS DEVELOPED IN THE EOLIAN MANTLE BENEATH THE PAVEMENT Soils exhibiting a wide variation in the degree of development in deposits underlying the pavement. These deposits are quartz-rich, well-drained tuffs that have been transported to the flow surfaces largely by windblown suspended load (Wells et al., 1985) where they are trapped by the rough surfaces of the flow (Gegyik and Bosen, 1981). Between major periods of eolian deposition, a lower eolian fines are present development of soils in the eolian deposits. Moderate eolian depositional rates are apparently critical for maintaining clasts at the soil surface. In the Cima volcanic field, these distinct phases of soil development are recognized on flows younger than 1.1 Ma (Hawkesworth et al., 1984). A critical aspect of soil and pavement development on flow surfaces is the formation of the vescicular A (Av) horizon. Such horizons, observed in many desert soils, are typically clay- and silt-rich, which may impair their physical properties. The vescicular horizons are probably due to entrapped soil air that expands as soil temperature rapidly increases after summer rainfall. Some of the sand and silt fractions of the Av horizon of desert soils may be attributed to comminution of gravel lithology, susceptible to mechanical weathering (McBirney, 1977). However, the paucity of parental material in the Av horizon emphasizes the largely eolian origin of these soils. Significant amounts of trapped eolian silt and fine sand and solutes are more readily transported below the surficial through these cracks. The walls of the Av pedons are typically coated with loose ten and are almost noncalcareous due to this process. In contrast to the shrinkage of the cracks, infiltration through cracks is very slow and eventually causes alteration of the interior, reflected by the reddened and carbonate-enriched mantles of the ped interior. Moderate accretion of calcium carbonate ferro-silicate into Av pedons and drying of pedons during the summer results in drying of the soil and vertical displacement of overlying clasts (Fig. 3). During the winter, soil moisture is retained and the dome collapses, causing fresh eolian fines on red walls and in cracks between pedons to be incorporated in the Av horizon. With continued Av-horizon development, the interior of Av pedons becomes crenulate and form a continuous B horizon (McFadden et al., 1986). Significant amounts of trapped eolian silt and fine sand and solutes are more readily transported below the surficial pavements that might sometimes be mantled at the surface as eolian material is slowly incorporated beneath the pavement. The results of our studies...
show that the development of an Av horizon and ultimately a cambic soil are critical as-
pects 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 rela-
tively high loess 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 loess event and the
accumulation of large quantities of carbonates
and soluble salts in these soils strongly suggest
that alkaline plays, formed after the disappear-
ance of late Pleistocene pluvial lakes in the Mo-
jave Desert, are a major source of these eolian
materials (McFadden et al., 1986). Smooth
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 pave-
ment on each surface can only have been de-
ivered from a preexisting pavement formed on
a now buried soil. On flows with rough surfaces,
however, high rates of loess deposition pre-
cluded development of a soil, and the preexisting
pavement was buried (Wells et al., 1985). Re-
maining topographic highs on these flows pro-
vided 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 (Turpin et al., 1986). We hypothesize, therefore, that
crystalline weathering of basalt in the pavement and in the rubble produces authigenic minerals
whose chemical compositions reflect contrasting weathering environments rather than composi-
tional differences. To test this hypothesis, sample
clasts were collected from the pavement and un-
derlying soil on selected flow surfaces of various
ages and were examined by using optical petro-
graphic techniques, scanning electron micro-
copy, and electron microscope analysis (Fig. 4;
Table 1).

**Table 1.**

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*Note:* Data for the latest Pleistocene - 0.13 to 0.06 Ma; middle Pleistocene - 0.06 to 0.16 Ma (Turpin et al., 1986). Structural formula on basis of the stoichiometry of 20 (O) and (OH).

![Figure 4. Scanning electron microscope photomicrograph showing oomolite, interlocking authigenic clay crystals forming chemical alteration of latest Pleistocene basaltic flow rubble in Cima volcanic field.](image)

**Figure 4.** Scanning electron microscope photomicrograph showing oomolite, interlocking authigenic clay crystals forming chemical alteration of latest Pleistocene basaltic flow rubble in Cima volcanic field. Electron microscope analysis and structural formula calculations of authigenic clay indicate that mixed-layer clay consists of illite and smectite.

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**DISCUSSION**

We hypothesize that stone pavements on alluvial fans of desert pediments 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 basaltic and lava topography inherited from the braced piedmonts of ephemeral streams in and enervicous (Ball, 1974). Fan surfaces of early Holocene age, however, exhibit partial pavement development, and stone pavements are ubiquitous on fan surfaces of late Pleistocene age. Vegetation A horizon that are nearly identical to those observed in the Cima volcanic field constitute the initially developed horizon of soils on surfaces 0.2 Ma in the Cima field (McFadden et al., 1986).

The paragenesis of authigenic minerals indicated in strongly altered pillow basalt is clay - zeolite - calcite - celadonite. This sequence suggests that the most recent authigenic occurred in a strongly saline environment and is consistent with the hypothesis that much of the incipient pedogenic carbonate and sulfide are defined by authigenic authigenic phases (McFadden et al., 1986).

Many processes have significantly influenced soil development on alluvial deposits in deserts. Much of the silt, clay, iron oxides, and soluble albit that have accumulated in soils formed in arid environments are attributable to incorporation ofolian materials rather than to chemical weathering of soil parent materials (Peters, 1954; Atkinson, 1961; Littman, 1973; Marchetti, 1985; McFadden and Tilley, 1985). As discussed previously, however,olian 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 late Pleistocene to early Holocene. A major increase in eolian activity during the Holocene has also been documented in the desert of southern Nevada (Whitby 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 determination of the silt. We propose that a eolian horizon is authigenic and potentially much of the uppermost B horizon of Pleistocene soils on fan surfaces of the Mojave Desert must have been eolianogenic activity that began as early as the late Pleistocene and has continued into the Holocene. The outcrop exposure of eolian materials has been slow enough to permit development of cumulative strata and concomitant uplift of pedogenic soils. Thus, although in some cases accumulation of a superficial gravel layer may be attributed to eolian or fluvial removal of fines, we believe that such processes can contribute very little to the evolution of pavement formation on pediments.

The results of analysis of the chemical composition of the varnish on clasts of desert pavement also strongly support the proposed process of pavement development. Dres and Oberlander (1981) showed that varnish-forming microorganisms require the near neutral pH conditions that are present only in a subaerial environment. Cation ratios of varnish form on pavements on late Pleistocene fan surfaces are significantly lower than the ratios of varnish from early or middle Holocene pavements (Dres, 1982, 1984; Dres et al., 1986) imply, instead, that varnish development has occurred on surfaces exposed continuously since the development of the fan surface. Pavements in the Mojave Desert that we investigated in middle Pleistocene (Ball, 1974; Wells et al., 1985; McFadden et al., 1996) must therefore consist of materials that have formed largely in eolian deposits of Holocene age. Thus, we believe that sediments in the Cima volcanic field, we conclude that deserts pavements (1) are formed at the land surface and (2) remain at the land surface via eolian deposition and continuous development of cumulative sediments beneath the pavements.