Desert Pavement Evolution: An Example of the Role of Sheetflood[1]

Steven H. Williams[2] *and James R. Zimbelman*[3]
Department of Geology, Arizona State University, Tempe, AZ 85287

ABSTRACT

Patches of young, well-developed desert pavement were found atop bare rock on the Pisgah basalt flow, California. These particular stone mosaics formed directly atop the flow; no soil is present, or ever has been. Therefore, soil expansion and aeolian processes played no significant role in their creation or maintenance. The unusual setting at Pisgah allows sheetflood to be the sole agent responsible for the lateral movement of surface stones into these mosaics. The Pisgah mosaics thus represent an end-member case of desert pavement types, and they may represent a previously unrecognized initial substage of accretionary mantle formation.

Introduction and Background

"Desert pavement" is a general term for rocky surfaces common in regions of low rainfall and sparse vegetation. Pavements are characterized by a thin surficial layer of stone fragments, typically overlying a soil layer in which few fragments occur. The concentration, or surface spacing, of the stones comprising pavements can range from a simple lag deposit, where the concentration of the stones on the surface is only slightly greater than the horizontal spacing of stones in the soil beneath the surface, to stone mosaics, where the concentration is so great that the stone edges interlock and any underlying soil is not exposed to view from above (figure 1). The underlying soil is considered by many investigators to be an integral part of desert pavement, but Cooke and Warren (1973) point out the distinction between pavements underlain by soils and those that are not, suggesting that some pavements may form in place and some may form by the importation of stones from elsewhere (autochthonous and allochthonous pavements, respectively).

The traditional view of desert pavements is that they originate as an initially heterogeneous soil from which fines are removed by aeolian and/or sheetflood processes. Coarser rock fragments are forced to the surface by freeze/thaw action or the swelling of wetted clays, then rearranged by sheetflood (see Cooke and Warren 1973 and Dohrenwend 1987 for review). In this view, the four primary mechanisms known to affect the surface concentration of stones are: aeolian removal of fines, removal of fines by sheetflood, the upward migration of stones from within the soil, and the movement of stones by sheetflood.

A more recent view holds that desert pavements are part of an accretionary mantle, where aeolian deposition of salts, gypsum, and clays, along with some local weathering, assist mechanical weathering of local bedrock and soil formation beneath the stones on the surface, which undergo syndepositional lifting with the surface of the accreting soil layer (Wells et al. 1985, 1987; McFadden et al. 1984, 1987). The accretionary mantle model is attractive because none of the four primary mechanisms can, acting alone, produce all of the observed features of desert pavements.

Aeolian removal of fines is very important in the restoration of damaged pavements and was once thought to be the dominant process of desert of pavement (Greeley and Iversen 1985, p. 55), but though important (Symmons and Henning 1968), it is subject to three important limitations. First, a stone concentration much less than that shown in figure 1 tends to armor the underlying soil completely by shielding it from erosion by sand undergoing saltation transport (Chepil 1950; Cooke and

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[2] Now at: Dept. of Space Studies, Center for Aerospace Sciences, University of Tulane, Clifford Hall, Grand Forks, ND 58202-9008.

[3] National Air and Space Museum, Smithsonian Institution, Washington, D.C. 20560.

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Figure 1. A general view of the stone mosaics atop the Pisgah basalt flow. Examples of bedrock knobs in the process of weathering into detached stones are shown by arrows. A very small amount of silt has collected beneath the stones in the mosaic near the bottom of the image, but it is not visible without removing the stones because of the high degree of interlocking of their edges. The diameter of the lens cap is ~6 cm.

Warren 1973, p. 124); therefore, either the stone concentration was always as high as observed or some other process must have acted to increase it. Second, soil crusts tend to form that greatly increase resistance to aeolian erosion (Sharon 1962; Cooke and Warren 1973, p. 125–126). Third, the deflation mechanism cannot account for the stone-free zone immediately beneath most pavements; the zone would have to develop independently of the pavement. For these reasons, we consider aeolian activity to be more efficient in restoring damaged pavements than in creating them. The second mechanism, removal of fines by sheetflood, also cannot account for the stone-free zone and therefore cannot be solely responsible for pavement formation.

Upward migration of stones can produce the stone-free zone, and, in some cases, it is responsible for the restoration of pavements damaged by other processes, provided there are sufficient silts and clays (and stones) present in the soil. Data from experiments on sites atop alluvial and debris flow surfaces from which the pavement has been removed show that the timescale for pavement restoration by replacement from below to be on the order of several years to decades (Péwé 1978; Bales and Péwé 1979). Experiments show that wetting/drying-induced swelling of clays is very effective at heaving stones (Springer 1958; Anderson 1988), as is freezing and thawing of silts and the formation of needle ice (French 1976, p. 33; Bloom 1978; p. 351). However, none of these mechanisms is very effective in the Mojave Desert or in many other regions in which pavements occur because there are insufficient fines at depth to cause expansion, rainfall infiltration is limited by arid conditions and/or the presence of surface crusts, and/or the winter climate does not cause extensive soil freezing. Alluvial and debris deposits also have a greater number of stones at depth for heaving to the surface, unlike an accreting mantle on a basalt flow. For example, pavements developed on the Amboy, California basalt flow have not been restored from below over multi-year timescales (Williams and Greeley 1983; also unpublished data).

A fourth mechanism, the concentration and reorientation of stones by sheetflood, has been recognized as playing a role in pavement formation by some investigators (Jessup 1960; Cooke 1970), although Sharon (1962) discounts sheetflood-induced stone movement, even on slopes steeper than is typical for pavements, because stones are often sufficiently buried in the underlying soil that they will not move during a sheetflood event capable of moving fines from the surface. However, if stones are not imbedded and the surface is relatively impermeable, then simple calculations show that sheetflood is capable of moving them (see Discussion).

In this study, we examined the discontinuous patches of mosaicked stones lying atop a weathered pahoehoe flow at Pisgah, California to determine the mechanisms responsible for their formation and to see if they fit the accretionary model of Wells and McFadden.

The Study Site

The surfaces of young basalt flows in the Mojave Desert are particularly good places to study the evolution and development of desert pavements. Examples include the Cima (Kel-Baker) flows (Wells et al. 1984, 1985; McFadden et al. 1987), the Amboy flow (Williams and Greeley 1983; Greeley and Iversen 1978, 1985), and the site of the present study, the Pisgah flow, located at 34°45′N, 116°22′W, near highway I-40, approximately 55 km east of Barstow, California. The flow surface is very irregular, but there are numerous small, nearly level platforms. Mechanical weathering detaches many stones from the flow surface, but on much of the flow there has been virtually no soil development. Sheetflood events are likely because infiltration is limited mostly to fractures in the flow surface, and much of the sparse annual rainfall comes in one or a few summer thunderstorms, some of which may be very intense on a local scale.

We have found patches of well-developed stone mosaics lying directly atop a pahoehoe unit on the surface on the Pisgah basalt flow. The patches cover areas on the order of 1 m^2; some, if not all, are smaller than the surfaces most commonly considered as pavements. Details of the stone mosaics at Pisgah can be seen in figures 2 and 3, where a single site has parts of the basalt flow that are on the verge of detachment by mechanical weathering, isolated loose stones lying in small local depressions, well-interlocked mosaics in larger topographic lows, and a cone of debris apparently formed by the washing of stones and fines into a fissure. Small amounts of aeolian sand and dust has collected in some local sinks, but the stones in the mosaics on the platforms have virtually no dust or salt beneath them. Salt crystallization may aid in the mechanical weathering of the flow surface, but in this particular location, it appears that sheetflood flushes salts and dust from beneath the developing mosaic, preventing soil formation.

Discussion

There are few potential mechanisms that can explain all of the features of the Pisgah stone mosaic site. If the mosaic formation requires the presence of an accreting soil layer initially, it is illogical to invoke the presence of such a layer and then require its removal without disrupting the stone mosaic. This also precludes the action of any of the soil processes that affect desert pavement formation. Only wind and water are left as likely mechanisms. The Pisgah area has numerous features, such as wind streaks and ventifacts, indicative of active aeolian transport. However, wind speeds capable of moving surface stones (of 1 cm diameter) are ~three times those needed to entrain sand-sized material (Greeley and Iversen 1985). Such winds can and do occur (rarely); if they were common enough to produce the pavement, they would also produce aeolian erosion features more extreme than those observed. Further, the wind would not be capable of causing the slight movements of stones needed to produce interlocking.

Overland flow of water is the sole remaining plausible agent of pavement formation at Pisgah. No systematic meteorological data has been taken at or near the Pisgah area for many years; the only meteorological records in the region listed in the National Wind Data Index (Changery 1978) are for aviation-related observations taken at an unspecified location near Barstow, California for a brief time in 1931–1932. Daggett, California, immediately east of Barstow, has better records, but even there the only records in the Index are single daily observations taken during the period 1931–1976 and synoptic data (hard to access) for 1946–1948. More suitable for this study are some records taken around the turn of the century in the now-defunct town of Bagdad, approximately 20 km to the east of the Pisgah study site, from which 17 yr of weather records were summarized by Thompson (1929). Much (~50%) of the annual rainfall at Bagdad occurred during the three winter months, but it is the experience of the authors and of local residents that winter rains tend to be much less vigorous than summertime thunderstorms, when much of the rainfall can occur in a few tens of minutes or

Figure 2. A typical platform upon which the Pisgah mosaics develop. The local slope is ~5° toward the camera. Bedrock knobs almost detached from the flow body are at "A," stones whose downslope movement has been temporarily halted in small depressions are at "B," and a patch of stone mosaic is at "C." There is virtually no silt or salt beneath these stones.

less. Maximum monthly precipitation during the years reported were 1.29 inches for July and 2.20 inches for August, with the irregular nature of the rainfall attested to by the fact that the mean rainfalls for those same months are 0.16 and 0.31 inches, respectively. The annual rainfalls reported at Bagdad (2.28 inches average, 10.2 inches maximum) are similar to those reported for other regions in the Mojave, including the town of Barstow, 55 km west of the Pisgah site, for which 23 yr of records were available to Thompson (1929). Barstow had an average annual rainfall of 4.25 inches, with a maximum of 7.65 inches. The maximum July rainfall was 1.35 inches (0.24 inches average, 0.0 inches minimum); the maximum August rainfall was 2.20 inches (0.31 inches average, 0.0 inches minimum). Hence, intense rainfall in the Pisgah pahoehoe flows could be expected to produce a significant overland flow of water because infiltration is limited to vertical fractures and other irregularities in the surface. A simple calculation will suffice to show that a sheet of water moving down a smooth, shallow slope can exert enough pressure on a stone to overcome sliding friction, to cause rolling, and to cause the small movements needed to form a mosaic, provided that the stone is not imbedded or lodged in a small depression so that its movements are restricted. If the local catchment area for one of the Pisgah pavement sites covers ~1 m^2, and if the rainfall rate is ~1 mm/minute (both very reasonable assumptions), then ~20 cm^3 of water must exit the surface every second. That flow rate is not sufficient to move much material if the shape of the surface allows the sheetflood to remain unconcentrated. However, if variations in local topography force the flow through an exit with a cross-section of only a few square centimeters, then flow rates of tens of cm^3/sec and flow speeds in excess of 10 cm/sec are possible, both easily sufficient to cause motion (not entrainment).

Thus the atypical setting at Pisgah allows sheet-

Figure 3. If stones do not collect in a mosaic, they are liable to be eventually washed off the edge of the flow platform, as shown here. The cones of stones in the depression (arrows) contain a small amount of silt, but soil and soil processes have played a negligible role in the formation and evolution of the mosaics and cones shown here. The photographic dark slide is ~8 cm long.

flood to play the dominant, if not exclusive, role in the development of a tightly interlocked, well-developed stone mosaic without aeolian processes being involved. The Pisgah stone mosaics are an example of the allochthonous pavement of Cooke and Warren (1973), although the lateral distance the stones were transported is at most a few meters.

Conclusions

We believe that the Pisgah pavements represent an initial substage of accretionary mantle development, illustrated in figure 2, that can precede the initial stage described by Wells et al. (1985) and McFadden et al. (1987). In their model, aeolian deposition of clays and salts cause mechanical weathering of the basalt flow, with the fragments thus derived incorporated into a forming soil layer. Initial pavement formation is determined by colluvial, alluvial, and other mass wasting processes as the soil begins to develop. As additional aeolian deposition and local weathering add to the soil layer, the larger surface stones are maintained on top by processes that inhibit burial.

Our observations suggest that, in at least some cases, a well-developed stone mosaic can be formed prior to soil development, rather than contemporaneously with mantle accretion, as described in the Wells and McFadden model. This would not be true in most places, but the Pisgah mosaics are important because they demonstrate the potential importance of sheetflood in desert pavement formation.

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REFERENCES CITED

Anderson, S. P., 1988, The upfreezing process: Experiments with a single clast: Geol. Soc. America Bull., v. 100, p. 609–621.

Bales, J., and Péwé, T., 1979, Origin and rate of desert pavement: a progress report: Jour. Arizona and Nevada Acad. Sci., v. 14, p. 84.

Bloom, A. L., 1978, Geomorphology: a systematic Analysis of Late Cenozoic Landforms: Englewood Cliffs, N. J., Prentice-Hall, 510 p.

Changery, M. J., 1978, National Wind Data Index, Final Report: Document HC0/T1041-01, UC-60, Asheville, North Carolina, National Climatic Center, 243 p.

Chepil, W. S., 1950, Properties of soil which influence wind erosion: The governing principle of surface roughness: Soil Science, v. 69, p. 149–162.

Cooke, R. U., 1970, Stone pavements in deserts: Ann. Assoc. Am. Geog., v. 50, p. 560–570.

———, and Warren, A., 1973, Geomorphology in Deserts: Los Angeles, University of California Press, 374 p.

Dohrenwend, J. C., 1987, Basin and Range, *in* Graf, W. L., ed., Geomorphic systems of North America: Geol. Soc. America, Centennial Spec. Vol. 2, p. 303–342.

French, H. M., 1976, The Periglacial Environment: Essex, Longman Group Ltd., 309 p.

Greeley, R., and Iversen, J. D., 1978, Field Guide to Amboy Lava Flows, San Bernardino County, California, *in* Greeley, R.; Womer, M. B.; et al., eds., Aeolian Features of Southern California: A Comparative Geology Guidebook: NASA Office of Plenetary Geology, 264 p.

———, and ———, 1985, Wind as a Geologic Process: Cambridge, Cambridge University Press, 333 p.

Jessup, R. W., 1960, The Stony tableland soils of the southeastern portion of the Australian Arid Zone and their evolutionary history: Austral. Jour. Soil Sci., v. 11, p. 188–196.

McFadden, L. D.; Wells, S. G.; Dohrenwend, J. C.; and Turin, B. D., 1984, Cumulic soils formed in eolian parent materials on flows of the Cima volcanic field, Mojave Desert, California, *in* Lintz,. J., ed., Western Geological Excursion: Field Guidebook, Geol. Soc. America 1984 annual meeting, p. 208–222.

———; ———; and Jercinovich, M. J., 1987, Influences of eolian and pedogenic processes on the origin and evolution of desert pavements: Geology, v. 15, p. 504–508.

Péwé, T. L., 1978, Terraces of the lower Salt River valley in relation to the Late Cenozoic history of the Phoenix basin, *in* Burt, D. M., and Péwé, T. L., eds., Guidebook to the Geology of Central Arizona: Arizona Bur. Geology Mineral Tech. Spec. Paper 2, p. 1–13.

Sharon, D., 1962, On the nature of hammadas in Israel: Zeit. für Geomorph., v. 6, p. 129–147.

Springer, M. E., 1958, Desert pavement and vesicular layers of some desert soils in the desert of the Lahontan Basin, Nevada: Proc. Soil Soc. America, v. 22, p. 63–66.

Symmons, P. M., and Henning, C. F., 1968, A note on wind-stable stone-mantles in the southern Sahara: Geog. Jour., v. 134, p. 60–64.

Thompson, D. G., 1929, The Mohave Desert region, California: a geographic, geologic, and hydrologic reconnaissance: U.S. Geol. Survey Water Suppl. Paper 578, 759 p.

Wells, S. G.; Dohrenwend, J. C.; McFadden, L. D.; Turrin, B. D.; and Mahrer, K. D., 1984, Types and rates of Late Cenozoic geomorphic processes on lava flows of the Cima volcanic field, *in* Lintz, J., ed., Western Geologic Excursions: Field Guidebook, Geol. Soc. America 1984 annual meeting, p. 191–208.

———; ———; ———; ———; and ———, 1985, Late Cenozoic landscape evolution on lava flows of the Cima volcanic field, Mojave Desert, California: Geol. Soc. America Bull., v. 96, p. 1518–1529.

———; McFadden, L. D.; and Dohrenwend, J. C., 1987, Influence of Late Quaternary climatic changes on geomorphic and pedogenic processes on a desert piedmont, Eastern Mojave Desert, California: Quat. Res., v. 27, p. 130–146.

Williams, S. H., and Greeley, R., 1983, Desert pavement study at Amboy, California (abs.): NASA TMX-86246, p. 169–170.