Desert pavements and associated rock varnish in the Mojave Desert: How old can they be?

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ABSTRACT

Desert pavements are common features of arid landscapes and have been widely used as a relative age indicator of the geomorphic surfaces upon which they are developed. In this study I examined the patterns of pavement development as a function of elevation in the Mojave Desert as well as the causes for the gradual disappearance of pavement at high elevations. Pavement density, as measured by percentage of pebble coverage, decreases systematically with elevation gain by ~3% per 100 m, from 95% coverage below 500 m to less than 60% at 1700 m. Plants appear to be the main agent of pavement disruption; plant density decreases as pavement density increases. Burrowing by rodents and crusting by cryptobiota also disrupt pavement development at higher elevation. During the last glacial maximum, plant communities were displaced 1000–1400 m downward in the Mojave Desert. Pavements today generally do not survive above the blackbush (*Coleogyne ramossisma*)-sagebrush (*Artemisia tridentata*) zone. Evidence from packrat middens shows that these and other plants typical of high elevations today grew as low as 300–400 m during the last glacial maximum. I suggest that during the last glacial maximum, desert pavements were confined to the lowest alluvial fans of Death Valley and adjoining low valleys. No alluvial desert pavements above ~400 m in the region are older than the latest Pleistocene. By the same reasoning, desert varnish on desert pavements above 400 m may all be Holocene in age, except where developed on stable boulders.

Keywords: desert pavement, rock varnish, Mojave Desert, Death Valley, packrats.

INTRODUCTION

Desert pavements are conspicuous features of many deserts, and in the Mojave Desert they have long attracted the attention of geologists (Blake, 1858; Gilbert, 1875). Desert pavements are distinguished by several unique surface and subsurface features. Where best developed, desert pavement is composed of a continuous mantle of flat-lying, densely packed, partially overlapping pebbles, typically overlying a soft, silty layer filled with gas vesicles, termed a vesicular horizon. Desert pavements and vesicular horizons occur together so consistently that they probably formed as a part of the same process, although the exact mode of formation is the subject of much debate (Blake, 1904; Cooke, 1970; Williams and Zimbelman, 1994; McFadden et al., 1998). For geomorphologists, desert pavements have additional practical importance, because their degree of development is widely used as a means of determining relative age of surfaces.

Another feature found on clasts in most desert pavements is rock varnish, which has been used to date desert landforms (Dorn, 1983; Dorn et al., 1989). In this paper, I examine desert pavements in the Mojave Desert with the aim of determining limits on the rates of pavement and associated rock-varnish formation. I will argue that desert pavements and much of the associated varnish at all but the lowest elevations in the Mojave Desert are Holocene in age and that desert pavements older than the very latest (post–15 ka) Pleistocene are confined to elevations under ~400 m.

MEASUREMENTS

My students and I performed pebble- and plant-density counts[1] and described underlying soil profiles at 16 sites spanning 240–2300 m in elevation. Only the best-developed desert pavement at a given elevation was selected, often by using aerial photographs. To measure pebble density, we used the wire intercept method in a 1 m^2 wire (see footnote 1) mesh at 5 m intervals along a 30 m transect. Approximately 1500–1700 observations were made per site. Differences in this measurement were ±2% between pairs of operators. We quantified plant density along 200–300 m of tape per site, and we confined our counts to perennial plants, because annuals never exceeded 5% of total cover at the time of measurement.

RESULTS OF TRANSECT SURVEY

Sites included in this survey are mainly in the Spring Mountains near Las Vegas, Nevada (Fig. 1), which are composed largely of limestone and dolostone. To assess the influence of lithology on pavement development and distribution, we also surveyed sites in the Amargosa Desert and Death Valley (Fig. 1) underlain by the alluvial derivatives of Precambrian quartzite and metasedimentary rocks, and of volcanic rocks.

Pebble density falls off quite uniformly (r^2 = 0.84) with elevation increase, at a rate of ~3% per 100 m (Fig. 2). Pebble densities typically exceed 90% at sites at or below 500 m, irrespective of rock type. Pavements persist as long as pebble density remains above ~60%. At 60%, substantial pebble cover is still pre-

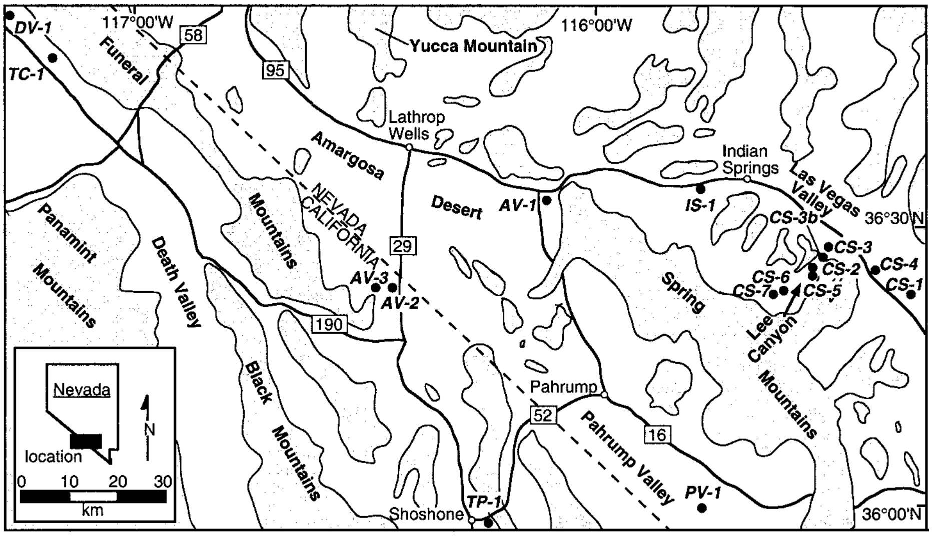

Figure 1. Map of study area with locations of desert-pavement study sites (black circles). Shaded areas denote main mountain ranges.

[1]GSA Data Repository item 2001095, Plant and pavement density measurements, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301–9140, editing@geosociety.org, or at www.geosociety.org/pubs/ft2001.htm.

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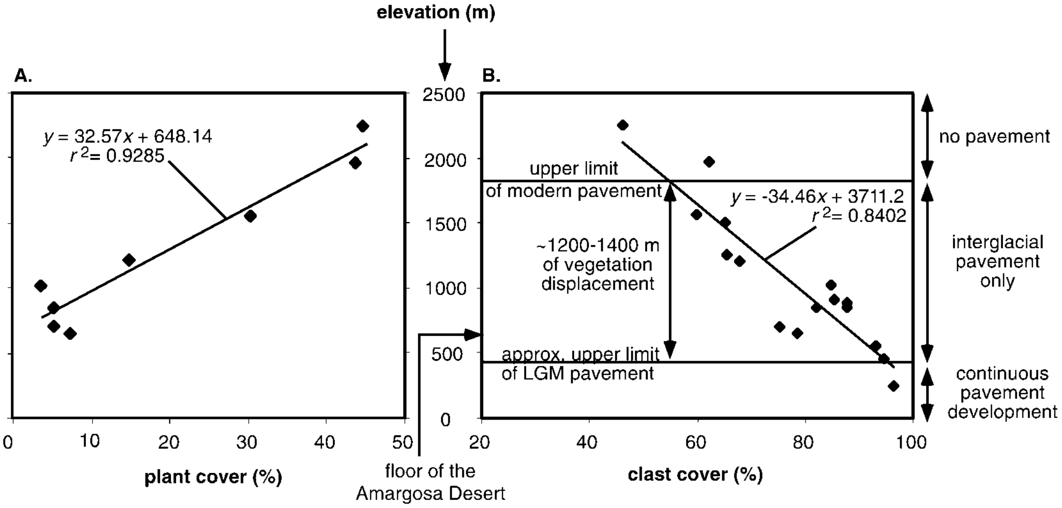

Figure 2. A: Percentage of plant (tree and shrubs) cover versus elevation for selected sites. B: Percentage of clast cover versus elevation for all sites. LGM—last glacial maximum.

sent, but above ~1800–1900 m, the surface features unique to desert pavements, such as surface smoothness (Fig. 3A) and interlocking of pebbles (Fig. 3E), disappear.

Other soil and surface features that accompany desert pavements also diminish with elevation increase. On siliceous clasts, varnish gradually disappears at higher elevation on small- to medium-size (<~15 cm) clasts. The key pedogenic feature associated with desert pavement is vesicular horizons. Vesicular horizons are dominated by eolian silt, contain abundant tiny gas vesicles, and vary between 0 and 10 cm thick in study soils. Well-developed Av horizons persist to ~1560 m, although silty surface textures and some vesicles persist in surface horizons to almost 2000 m.

Floristically, the Mojave Desert is divided into several widely recognized zones. Mojave desert scrub covers the low elevations below about 1800 m, and Great Basin steppe–pygmy conifer forest is dominant above 1800 m, followed by pine and fir forest. In the lower part of the desert scrub zone, creosote (*Larrea divaricata*) and several types of saltbush (*Atriplex* sp.) dominate the sparse shrub cover. Creosote, white bursage (*Ambrosia dumosa*), and Joshua tree (*Yucca brevifolia)* typify the middle part of the zone as plant density increases. This assemblage is replaced by shrubs and succulents such as blackbush (*Coleogyne ramosissma*) and joshua tree between 1300 and 1500 m. By 1800 m, blackbush begins to give way to sagebrush (*Artemisia tridentata*) and scattered juniper (*Juniperus osteosperma*), which in turn is joined by pinyon (*Pinus monophylla*) and ponderosa pine (*Pinus ponderosa*) above 2100 m. An increase of ~3% per 100 m ($r^2 = 0.93$) in plant density accompanies this progression of plant zones (Fig. 2A). The demise of desert pavements with elevation gain is gradual. The highest elevation to which pavements persist varies slightly from range to range, probably in response to differences in rainfall. In the Spring Mountains

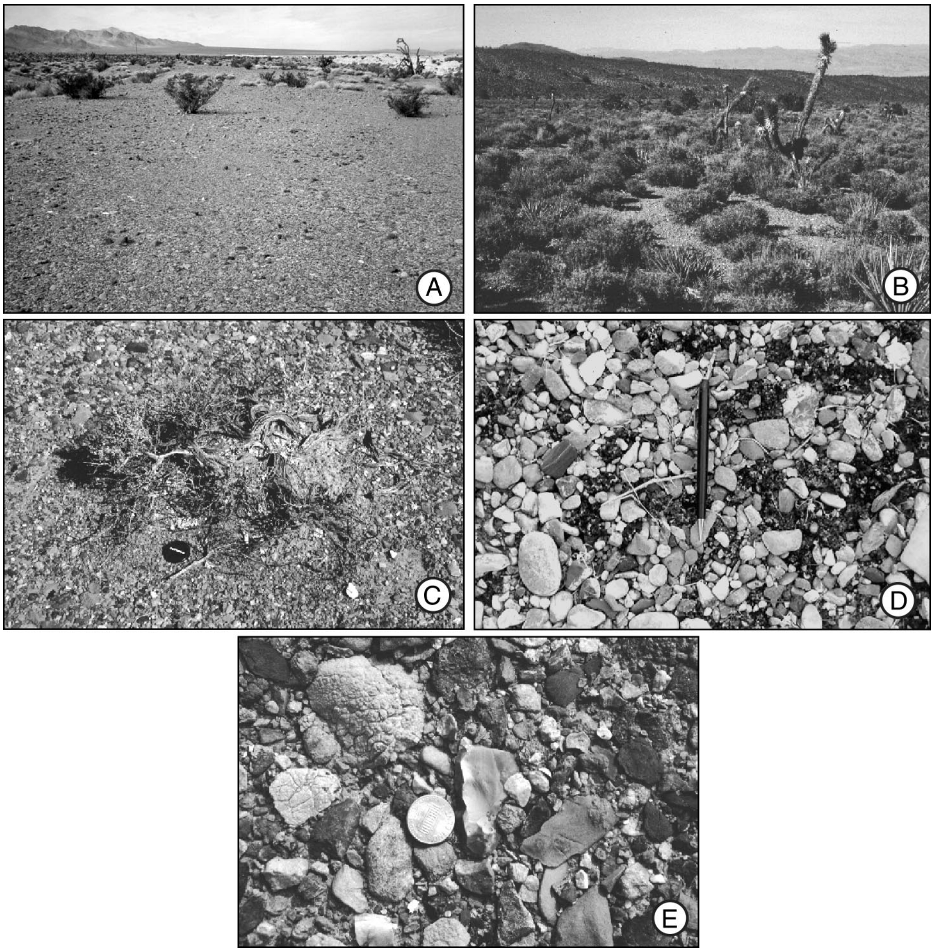

Figure 3. A: Desert pavement at site CS-1 (elevation 844 m). Gravel underlying this surface is inset into (and therefore younger than) light-colored spring deposits of latest Pleistocene age (see text) in right background. Smooth, interlocking pavement with 88% pebble cover has therefore developed at this site during Holocene time. B: Site CS-6 (elevation 1970 m) covered by mixed blackbush, sagebrush, and Joshua tree. Desert pavements do not develop in presence of these plants and juniper at 1800–1900 m. C: Disruption of pavements by shrub of *Atriplex canescens,* site AM-2 (elevation 648 m). Lens cap is ~6 cm diameter. D: Disruption of pavements by cryptobiotic crusts (dark areas) at site CS-3b (elevation 1210 m). Pencil is ~12 cm long. E: Artifact (to immediate right of ~2-cm-wide coin) interlocked into desert pavement, near site AM-2 (elevation 648 m).

outside Las Vegas (Fig. 1), the highest ecotone where we observed the last vestiges of pavement is within the middle to upper blackbush zone, between 1800 and 1900 m (Fig. 3B). In Fish Lake Valley (Fig. 1, ~160 km northwest of Lathrop Wells), pavements persist to 1900 and 1950 m, within the lower sagebrush zone. This instance appears to be an extreme; in most areas, pavements don't extend far, if at all, into the sagebrush zone.

Several processes appear to disrupt pavement development. The chief agent is plants, mainly shrubs, which create a local mound of soil around the plant crown, in which clasts and silt are thoroughly churned (Fig. 3C). This effect diminishes with distance from the stem, but it typically extends nearly as far as the foliage radius of most shrubs except creosote. Other pavement-disrupting processes include rodent burrowing and crusting by cryptobiotic crusts. The disruptive effect of burrowing, as single holes or clusters of holes, is conspicuous by 1200 m. Cryptobiotic crusts also become abundant within the blackbush zone, and their growth is clearly disruptive to pavement at this and higher elevations (Fig. 3D).

PALEOVEGETATION CHANGES AND PAVEMENT DESTRUCTION

The distribution of vegetation changed dramatically in the Mojave Desert during the shifts from glacial to interglacial climates. The most detailed evidence for these changes comes from the many pack rat middens preserved in dry caves in the region (e.g., Spaulding, 1983, 1990). In general, vegetation zones in the Mojave Desert shifted downward on the order of 1000–1400 m during the last glacial maximum (LGM), depending on the taxa involved. In the modern Mojave, even weakly developed pavements do not develop above the lower sagebrush zone, at or just below where juniper begin to appear. Today this boundary is no higher than 1900 m at the sites in this study. In the past, juniper and sagebrush were common, as shown by their macrofossils in many middens between 400 and ~1600 m. Juniper does tend to favor rocky substrates, whereas sagebrush thrives on the finer-grained soils of the valleys (where desert pavements develop) and very likely covered valley bottoms during glacial periods (Mehringer, 1967; Thompson and Mead, 1982). During the LGM, pack rat midden records from Death Valley show that juniper extended at least as low as ~425 m elevation (Wells and Woodcock, 1985), to the very margins of the alluvium-covered basins. Farther south in the Whipple Mountains, juniper is recorded as low as 320–360 m (Wells and Hunziker, 1976; Bull, 1991), and sagebrush is recorded as low as 365 m (King and Van Devender, 1977). Vegetation such as creosote, typically associated with well-developed pavements in the Mojave today, was confined to elevations below 300 m during the LGM, along the lowest reaches of the Colorado River (Cole, 1990).

I therefore argue that during the LGM, well-developed desert pavements were confined to all but the lowest elevations in the Mojave Desert, in line with a similar suggestion by McFadden et al. (1998) for vesicular horizons. A key assumption underlying this conclusion is that the relationship between vegetation zonation and plant density found today also held in the past. If that assumption is correct, then pavements now found no higher than ~400 m are largely Holocene in age. Even this low elevation probably represents a conservative upper limit, inasmuch as pavements today tend to be poorly developed down into the blackbush zone–uppermost creosote zone. On the other hand, the shift from full-glacial to interglacial vegetation was a gradual one, and at lower-elevation sites (<1000 m), elements of desert-scrub vegetation arrived in terminal Wisconsin time (post–15 000 yr B.P.) (Spaulding, 1983). This lag could mean that pavements at low-elevation sites began to develop just before the end of the late Pleistocene. Thermophile desert-scrub assemblages did not completely ''modernize'' in most areas until the early Holocene (Spaulding, 1990).

The impact of vegetation changes, if repeated through other glacial-interglacial cycles, would produce a threefold division of the Mojave Desert relative to desert-pavement development (Fig. 2B). Surfaces at elevations exceeding ~1900 m never host desert pavements; surfaces between 1900 and perhaps 400 m undergo strong pavement development only during interglacial periods but undergo pavement obliteration in intervening glacial periods; and surfaces below ~400 m undergo continuous pavement development.

Desert pavements have been used in a variety of studies in the Mojave Desert as a relative indicator of the age of geomorphic surfaces. References to stronger pavement development on Pleistocene surfaces than Holocene surfaces in the Mojave abound in the literature (e.g., Shlemon, 1978; Taylor, 1986; Hoover, 1989; Bull, 1991; Peterson et al., 1995). The results of this study suggest that such ''Pleistocene'' (older than 15 000 yr B.P.) pavements will be found only below ~400 m (e.g., Bull, 1991) and that all alluvial pavements found above ~400 m formed in the past 15 000 yr.

EVIDENCE FOR RAPID FORMATION OF PAVEMENTS

My students and I examined four localities (Fig. 1: IS-1, PV-1, CS-1, CS-4) between 840 and 1020 m elevation, where the ages of well-developed desert pavements are securely defined by radiocarbon dates from the underlying deposits. Pavements at these localities are developed on alluvial gravel that is inset into or caps well-dated spring deposits (Fig. 3A). Thirty dates place the age of the top of the spring deposits between 10 410 ± 110 (A-5305) to 8760 ± 60 (Beta-73963) ^{14}C yr B.P. (Quade et al., 1998) and provide a maximum age constraint for the beginning of desert-pavement formation at each locality. Therefore, the pavements formed during the Holocene. All the sites are underlain by a 4–9-cm-thick vesicular horizon capping ≥1 m of gravel. The pavement at these sites is smooth and interlocking and has little preserved bar-and-swale topography. Clasts mantle 85%–88% of the surface, as strongly developed as pavement from two other sites at about this elevation (Fig. 1, sites AM-1, TC-1; clast cover 83%–93%) underlain by alluvial deposits of middle Pleistocene age. These results—if representative of pavement-forming processes regionally—support my suggestion that the well-varnished, interlocking pavements so widespread in the Mojave Desert below ~1600 m (but above ~400 m) have developed since the end of the Pleistocene.

Most previous research supports the idea that well-developed desert pavements can form quickly. On time scales of 10^2 to 10^3 yr, desert pavements show significant recovery along abandoned historic roads or from prehistoric scraping to make pavement pictograms (Rogers, 1939; Setzler, 1952; reviewed by Elvidge and Iverson, 1983). Moreover, the presence of numerous lithic artifacts of probable early to middle Holocene age interlocked into pavements at some of the study sites (Fig. 3E; see also Cooke, 1970; Brakenridge and Schuster, 1986) suggests that interlocking pavements can develop over those time spans.

Wells et al. (1995) used evidence from cosmogenic ^3He in basaltic pavement clasts to argue that the clasts have remained at the surface of the silt-filled depressions for as long as 85 ka in the Cima volcanic field (~100 km southeast of Shoshone; see Fig. 1). At an elevation of 900–1200 m, pavements on these surfaces should have been disrupted during the LGM. In my view, the ^3He evidence only shows that pebbles have been at or near the surface for long periods, not that stone pavement has been continuously present. It is not surprising that most clasts might remain at or near the surface despite bioturbation during glacial periods. The very young (Holocene) thermoluminescence ages obtained from vesicular horizons in the Cima field support this view (McFadden et al., 1998). These young ages imply that the vesicular horizons, and their associated pavements, form quickly, probably assisted by the generally higher rates of eolian dust fall during interglacial periods (Wells et al., 1985; McFadden et al., 1998).

IMPLICATIONS FOR ROCK VARNISH DATING

The Mojave Desert has served as a proving ground for two controversial dating methods, cation ratio and ^{14}C dating of rock varnish (e.g., Dorn, 1983; Dorn et al., 1989; Reneau and Raymond, 1991; Beck et al., 1998). In many rock-varnish studies, bedrock or colluvial clasts were sampled (e.g., Whitney and Harrington, 1993); these substrates are not subject to the sorts of destructive processes that affected alluvial desert pavements during glacial periods. On the other hand, the results of this study demonstrate that much caution must be exercised during sample selection where rock varnish from desert pavements is involved.

Our observations from the transect sites show that varnish preservation diminishes with increase in elevation, in concert with gradual pavement destruction. At low elevations (e.g., $<$1500 m), where pavement clasts can be interlocking and stable, varnish develops on all but the smallest clast sizes of most rock types except limestone and some quartzites. With elevation increase, smaller clasts are turned over regularly enough that varnish is not preserved. There is a clast-size limit to this destructive process that varies with lithology and local slope. In this study, unquantified observations from surfaces above 2000 m suggest that clast sizes under 10 cm are unstable and do not preserve strong varnish coats, whereas clasts over 20 cm often do, where not spalled by physical weathering and range fire, or abraded by wind action (Reneau, 1993). Some published papers on rock varnish mention some of these issues (e.g., Dorn et al., 1989; Liu and Broecker, 2000) but are not always specific about the clast sizes sampled (e.g., Dorn, 1983; Peterson et al., 1995). My conclusion is that varnish on clasts in pavements from below 400 m elevation should, in principal, preserve multiple glacial-interglacial varnish-forming events, regardless of clast size. For higher elevations, only the larger clast sizes in pavements have the potential of preserving episodes of varnish formation of pre-Holocene age.

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