Cosmogenic ^{3}He surface-exposure dating of stone pavements: Implications for landscape evolution in deserts

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ABSTRACT

The formation of stone pavements, a ubiquitous gravel armor mantling landforms in arid regions of the world, has been previously attributed to erosion by wind and water or alternating shrinking and swelling of soil horizons, implying that gravel is concentrated at the land surface in a time-transgressive manner. A newly proposed model for pavement evolution differs from these models in that pavement clasts are continuously maintained at the land surface in response to deposition and pedogenic modification of windblown dust. In-situ cosmogenic ^{3}He surface-exposure ages on volcanic and alluvial landforms in the Mojave Desert of California are used to understand pavement evolution over geologic time scales and to test this new model. These exposure ages are stratigraphically consistent, show internal consistency at each site, and, for stone pavements adjacent to pristine, continuously exposed volcanic bedrock, are indistinguishable at the 1σ level. We conclude that stone pavements are born at the surface and that pavements may provide one of the longest-term records of geologic, hydrologic, and climatic processes operating on desert surfaces.

INTRODUCTION

Surface-exposure ages of landforms, as determined from in-situ–produced cosmogenic isotopes, are currently used to determine the timing and rates of geologic and hydrologic events during the Quaternary (reviewed in Cerling and Craig, 1994). In this paper, we apply the method of cosmogenic ^{3}He exposure dating to elucidate the formation of stone (desert) pavements, one of the most prevalent features mantling almost all types of desert surfaces (Cooke et al., 1993; Mabbutt, 1977). Although a stone pavement is only a one- to two-clast-thick layer of closely packed angular to subrounded gravels that armor low-relief surfaces (Fig. 1), stone pavements control surface stability and hydrology, record activities of chemical and physical processes on desert surfaces, serve as a source and storage site for archaeological materials, and serve as a mappable feature for relative age control (Cooke et al., 1993). An understanding of the geomorphic processes that concentrate clasts at the land surface and the time scales of these processes is important to any land-management application or scientific interpretation of pavement attributes.

Pavement-forming processes have been evaluated primarily by experimental observations at time scales of years to decades. Pavement formation has been attributed to (1) wind deflation of fine particles, creating a coarse-grained lag; (2) surface runoff and lateral transport by creep, resulting in a winnowing of fine clasts; and (3) shrink-swell processes of soils, causing upward migration of clasts to the land surface (Cooke et al., 1993; Thomas, 1989). In all of these hypotheses, clasts are concentrated at the land surface at significantly different times and, thus, are not necessarily related to the time of formation of the landform. None of these hypotheses, however, has been quantitatively evaluated at scales of 10^3 to 10^4 yr.

A new model of desert-pavement formation (McFadden et al., 1986, 1987; Wells et al., 1984, 1985) proposes that deposition of windblown sediments, not deflation or water erosion, is the major agent of pavement evolution. According to this model, the stone pavement remains at the land surface on an accretionary (i.e., vertically growing) mantle of soil-modified dust (Fig. 1). This hypothesis implies (1) that pavement clasts have been continuously exposed since the formation of the underlying landform and associated deposits and (2) that the properties of clasts in pavements (e.g., Wells et al., 1985, 1987) reflect the types of surficial processes operative since the underlying landform or deposit was created. Thus, we refer to this model as pavement formation by being "born at the surface."

Surface-exposure dating using cosmogenic isotopes provides a quantitative approach to understanding pavement evolution beyond the time scale of experimental observations. We compare in-situ cosmogenic ^{3}He exposure ages of clasts from pavements with exposure ages of their bedrock source, late Quaternary basaltic flows. This method tests whether pavement clasts remain continuously at the surface or are concentrated at the surface randomly over time. Young basaltic lava flows provide a unique opportunity to test the various models of pavement formation since they can be readily dated using cosmogenic ^{3}He (Kurz, 1986; Cerling, 1990; Laughlin et al., 1994), which is quantitatively retained in olivine and pyroxene. Such flows have uneroded bedrock highs surrounded by topographically lower stone pavements, thus allowing a comparison of the exposure age of the lava flow (i.e., time of emplacement of flow) with the surface-exposure ages of stone-pavement clasts derived from the flows.

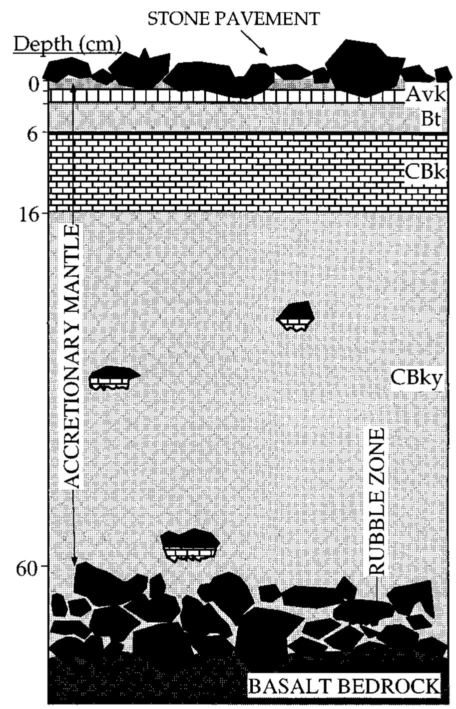
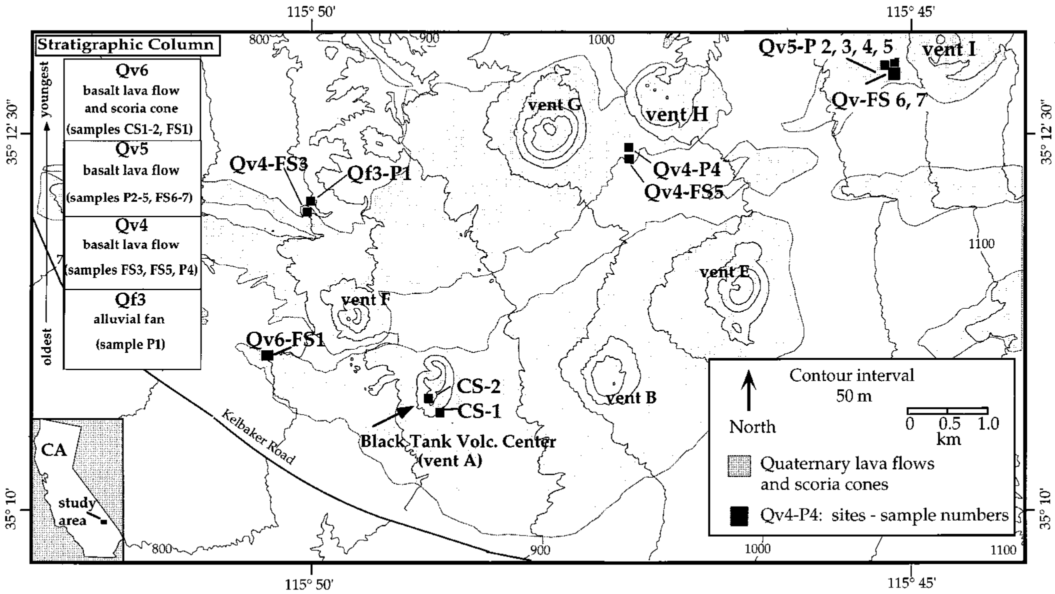


Figure 1. Stratigraphic section and corresponding pavement and soil-profile description for accretionary mantle developed on basalt flow derived from vent I (CVF-Qv5). See Wells et al. (1985) and McFadden et al. (1987) for processes of accretionary-mantle formation. For morphological properties of soil profile and properties of stone pavement, see Dohrenwend et al. (1984), Wells et al. (1984, 1985), and McFadden et al. (1986, 1987); over geologic time, pavement surfaces are characterized by reduction in original constructional relief of a landform, concentration of coarse interlocking gravel, relatively gravel-free layer, and weakly to moderately developed soil.

Figure 2. Location map of cosmogenic ³He surface-exposure samples on volcanic and alluvial-fan landforms, southwestern Cima volcanic field. Stratigraphic relations of landforms shown in upper left corner along with their associated sample numbers (see Table 1 for sample data).



Cosmic rays penetrate the upper few metres of the Earth's surface, creating detectable amounts of rare nuclides (Lal, 1991). The production of cosmogenic nuclides declines by a factor of two for every 75 cm below the surface in a sediment with a density of 1.58 g/cm^3. Previous pavement studies (Mabbutt, 1977) suggest clasts in pavements were buried in excess of 50 cm and, in some cases, in excess of 100 cm prior to their exposure at the surface. If clasts currently within a desert pavement were buried below the surface at such depths for a significant amount of time prior to their concentration at the land surface, a stone pavement developed over a basaltic flow will have (1) an apparent surface-exposure age that is less than the age of constructional topographic highs continuously exposed since the lava solidified and (2) considerable scatter in the ages as clasts arrive at the surface at different times. In contrast, stone pavements with surface-exposure ages similar to the age of the continuously exposed bedrock highs indicate that the pavements are born at the surface.

SAMPLING STRATEGY AND METHODOLOGY

This study area is the Cima volcanic field in the Mojave Desert of eastern California that contains ~40 basaltic scoria cones and >60 associated lava flows, ranging in age from late Tertiary to latest Pleistocene (Dohrenwend et al., 1984; Turrin et al., 1985) Stone pavements are present on pedogenically altered accretionary mantles (Fig. 1) developed over topographic lows and highs on these lava flows (McFadden et al., 1986; Wells et al., 1985). Three late Pleistocene basalt flows (from oldest to youngest: Qv4, Qv5, and Qv6) with distinct stratigraphic and geographic positions were sampled to evaluate whether the cosmogenic ^{3}He surface-exposure dates would reflect the relative chronology of the volcanic eruptions (Fig. 2). The topographically higher areas of these flows were carefully sampled in locations where original volcanic textures (e.g., pahoehoe) were well preserved and where it appeared that erosion had been minimal (<10 cm). Such locations provided the continuously exposed bedrock samples in this study, including the flows from vent I (Qv5) and vent H (Qv4) (Fig. 2). We also collected individual large pavement clasts derived from and adjacent to these two flows. In the first case, two samples each (CVF-Qv5-P2 through -P4) were taken from two geographically distinct desert pavements separated by a few metres horizontally and ~1 m vertically. Bedrock samples were taken from a nearby and isolated volcanic tumuli (CVF-Qv5b-FS6 and -FS7). On the older lava flow (Qv4), samples were collected from a stone pavement (CVF-Qv4-P4), and another from an adjacent bedrock high (CVF-Qv4-FS5) (Fig. 3). At a second sample site on flow Qv4, a sample was collected from the distal end of a flow that buried a stone pavement developed on a late Pleistocene alluvial fan surface (Qf3) (Harden et al., 1991) (Fig. 2). Near the terminus of flow Qv4, the sample CVF-Qf3-P1 was collected from the exposed portion of a stone pavement developed on an alluvial fan that had been partially buried by flow Qv4. From stratigraphic relations, the sample CVF-Qf3-P1 from the alluvial fan should predate samples from Qv4, yielding an older exposure age. Samples CVF-Qv6-CS1 and -CS2 were taken from volcanic bombs on the scoria cone rim of Black Tank (vent A) volcanic center, and sample CVF-Qv6-FS1 was taken from the surface of a basalt flow that breaches and thus postdates the scoria

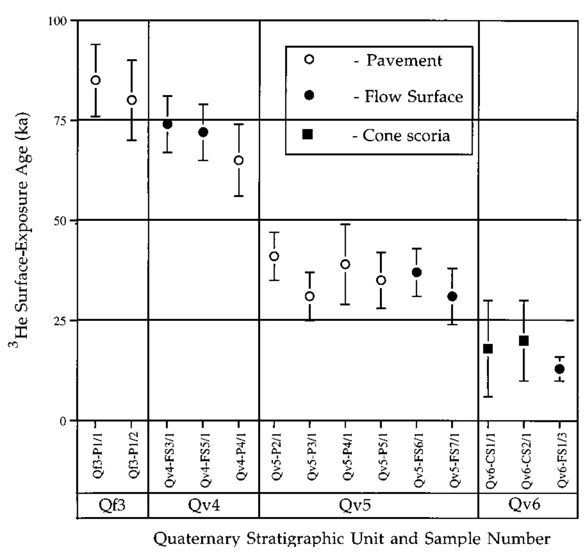


Figure 3. Cosmogenic ³He surface-exposure ages for selected stratigraphic samples of desert pavement, basalt-flow surfaces, and bombs in scoria cones, southwestern Cima volcanic field (see Table 1 for details and Fig. 2 for locations).

TABLE 1. HELIUM ISOTOPIC ANALYSES AND SURFACE EXPOSURE AGES

Sample Number*	CRUSH		HEAT					
	^4He† (10^{10} atom/g)	$^3He/^4He$ ($\times10^{-6}$)	^4He† (10^{10} atom/g)	$^3He/^4He$ ($\times10^{-6}$)	^3He_c§ (10^6 atom/g)	Elevation (km)	^3He prod. rate (g/yr)	Surface-exposure age (ka)
CVF-Qf3 - P1/1	16.	12.5 ± 3.1	35	63.2 ± 4.4	17.7 ± 1.9	0.795	208	85 ± 9
- P1/2	2.4	2.5 ± 17.0	40	51.8 ± 3.6	16.7 ± 2.0	0.795	208	80 ± 10
CVF-Qv4 - FS5/1	48.	9.8 ± 1.3	38	53.5 ± 3.9	17.3 ± 1.7	0.980	240	72 ± 7
- P4/1	62.	10.6 ± 1.2	97	26.2 ± 1.6	15.5 ± 2.2	0.980	240	65 ± 9
- FS3/1	35.	14.3 ± 1.7	19	87.4 ± 6.6	15.4 ± 1.4	0.795	208	74 ± 7
CVF-Qv5 - P2/1	35.	12.4 ± 1.9	21	59. ± 7.	10.6 ± 1.6	1.088	260	41 ± 6
- P3/1	32.	15.1 ± 2.1	19	52. ± 7.	8.1 ± 1.6	1.088	260	31 ± 6
- P4/1	38.	10.5 ± 2.1	21	56. ±11.	10.0 ± 2.6	1.088	260	39 ± 10
- P5/1	51.	11.2 ± 1.8	16	66. ±10.	9.2 ± 1.7	1.088	260	35 ± 7
- FS6/1	20.	14.1 ± 3.0	19	62. ± 8.	9.5 ± 1.6	1.088	260	37 ± 6
- FS7/1	51.	11.0 ± 1.5	40	31.8 ± 3.8	8.1 ± 1.7	1.088	260	31 ± 7
CVF-Qv6 - FS1/1	15.	12.4 ± 2.5	13	34.1 ± 3.3	2.8 ± 0.5	0.790	207	13 ± 3
- CS1/1	137.	11.4 ± 1.0	148	13.6 ± 1.3	4.3 ± 2.8	0.964	239	18 ± 12
- CS2/1	78.	9.1 ± 1.5	129	14.4 ± 1.2	4.8 ± 2.4	0.964	239	20 ± 10

*P = Stone pavement, FS = flow surface, CS = cone scoria; CS2/1 indicates sample 2, aliquot 1 of cone scoria.
† Accuracy of ±10%.
§^3He_c denotes cosmogenic ^3He, corrected for sample thickness.

cone (Fig. 2). The Qv6 samples are stratigraphically younger than all the other samples (Wells et al., 1994). Thus, our sampling strategy has a built-in check from stratigraphic relations, allowing us to assess the resolution of the chronologic concurrence yielded by the surface-exposure dates.

The concentrations of cosmogenic ^3He were determined on olivine and pyroxene separates by means of a standard, two-step process (Kurz, 1986; Cerling, 1990; Laughlin et al., 1994). Mineral separates were first crushed in a vacuum, allowing us to analyze the magmatic He released from inclusions. We then extracted and analyzed the remaining mixture of cosmogenic and magmatic He, released by a fusion step. The amount of cosmogenic ^3He is determined by the equation

$$^3He_c = {}^3He_f - {}^4He_f(^3He/^4He)_{cr}, \quad (1)$$

where the subscripts c, f, and cr denote cosmogenic, fusion, and crush, respectively. This deconvolution assumes that only two He components are present: cosmogenic ^3He and magmatic He. The magmatic He is characterized by the $^3He/^4He$ ratio that results from the crushing step. The $^3He/^4He$ ratios released by crushing were averaged for samples that were duplicates or from a given flow (e.g., all of the samples for flow Qv5, Fig. 2). The averaged $(^3He/^4He)_{cr}$ value used for the members of those sample sets has an uncertainty that reflects the scatter of the individual values. Concentrations of cosmogenic He were then corrected by 2% to 5% for the sample thickness (Cerling and Craig, 1994), giving the values listed in Table 1. We calculated the surface-exposure ages by using the production rate of Cerling (1990), corrected for altitude, latitude, and the recalibration of the ^{14}C time scale (Cerling and Craig, 1994). Stated errors are 1σ and include the uncertainties in these assumptions as well as the analytical assumptions. We omit the ~20% uncertainty associated with the absolute calibration of the production rate in that this factor will bias all ages equally.

SURFACE-EXPOSURE AGES: EVALUATING STRATIGRAPHIC RELATIONS AND MODELS OF PAVEMENT FORMATION

The 14 surface-exposure ages are concordant with the chronology of volcanic eruptions established in the field by stratigraphic relations (Table 1; Figs. 2 and 3). Samples from Qf3 (85 ± 9 and 80 ± 10 ka) are approximately the same age or slightly older than Qv4 (74 ± 7 and 72 ± 7 ka), which, in turn, are older than Qv5 (37 ± 6 and 31 ± 7 ka). Flow Qv6 yields the youngest ages (18 ± 12 ka and 20 ± 10 ka for the volcanic bombs and 13.2 ± 3 ka for the lava flow), in agreement with an independent surface-exposure age (J. Stone, 1989, personal commun.) and thermoluminescence dates (Wells et al., 1994).

The pavement and bedrock data also show internal agreement at each site where multiple samples were analyzed. Stone-pavement samples CVF-Qv5-P2 through -P5 are indistinguishable at the 1σ level, ranging from 41 ± 6 to 31 ± 6 ka. Likewise, the ages of the stone-pavement samples are statistically identical with the bedrock sample ages of 31 ± 7 and 37 ± 6 ka (CVF-Qv5-FS6 and -FS7). Bedrock samples from the stratigraphically older flow, Qv4, have concordant values of cosmogenic ^3He ages, 72 ± 7 and 74 ± 7 ka, as well as a slightly younger but overlapping value (65 ± 9 ka) on its associated stone pavement. The agreement between surface-exposure ages of well-preserved pahoehoe surfaces on basaltic flows and those of their associated stone pavements developed over accretionary mantles indicates that clasts forming stone pavements have been exposed continuously since the emplacement of the basalt flows.

At vent I (Fig. 2), two samples (CVF-Qv5-P4 and -P5) were collected from a pavement overlying a 20- and 30-cm-thick accretionary mantle on a slight bedrock high. Two additional samples (CVF-Qv5-P2 and -P3) were collected from a pavement in a topographic depression (i.e., created during emplacement of lava and not by deflation) in which the accretionary mantle (Fig. 1) exceeds 50 cm thickness. Both sample sets from pavements in differing geomorphic positions yield similar ages (Fig. 3, Table 1). These results substantiate the model that stone pavements remain at the land surface in response to vertically accreting eolian fines and their pedogenic alteration (McFadden et al., 1987; Wells et al., 1985). These results also demonstrate that different regions of stone pavements on the same underlying rock unit yield the same surface-exposure ages.

If clasts comprising a stone pavement arrive at the land surface by shrinking and swelling of soils, wind deflation, or winnowing by water, the surface-exposure ages in these two different geomorphic positions should not be the same. Soil-profile properties, including shrink-swell conditions, differ between topographic lows and highs on basalt flows because of the trapping efficiency of fine sediments in the internally drained basins (McFadden et al., 1986). Also, the accretionary mantle overlying flow Qv5 has 2–3-cm-thick, weakly developed Bt horizons overlying decimetre-thick CBk horizons (Fig. 1). This degree of soil-profile development is incapable of creating shrink-swell conditions that would allow clasts to migrate 0.5 to 0.7 m upward to the land surface. The lack of winnowing by water at these sites is demonstrated by field observations showing that boundaries of many pavement clasts fit together like a jigsaw puzzle. Significant alteration of the surface by running water would eliminate the compatible geographic position with adjoining pavement clasts.

On the basis of similar stone-free eolian accretionary layers and pedogenic features, McFadden et al. (1987) and McDonald (1994) proposed that stone pavements on alluvial fans evolve in a manner similar to that on the basalt flows. Testing this hypothesis by cosmogenic exposure ages is difficult because clasts on alluvial landforms have transport histories with the potential for long-term exposure (Nishiizumi et al., 1993). In our study, exposure ages of the alluvial-fan (Qf3) pavement are estimated to be 85 ± 9 and 80 ± 10 ka (QVF-Qf3-P1/1 and -P1/2). The only independent age determinations on the Qf3 deposits are given, in part, by a series of K-Ar dates (Turrin et al., 1985) that bracket the exposure ages derived from the alluvial-fan pavement. No independent isotopic date exists to support the surface-exposure age of alluvial fan Qf3.

CONCLUSIONS

The similarity of cosmogenic ^3He surface-exposure ages for relatively uneroded basaltic-flow surfaces and adjacent stone pavements substantiates that individual clasts within stone pavements have been continuously exposed at the land surface since the emplacement of the underlying volcanic flow (i.e., up to 10^5 yr) and that clasts are not concentrated at the surface randomly over geologic time (Fig. 3; Table 1). Rather, stone pavements remain at the surface because of vertical inflation caused by deposition of windblown dust and its subsequent pedogenic modification. Gravel-free layers underlying stone pavements (Fig. 1) serve as a criterion for distinguishing born-at-the-surface pavements from those resulting from wind and water erosion (Williams and Zimbelman, 1994).

Pavement clasts prevent erosion of eolian accretionary mantles for hundreds of thousands of years and, consequently, preserve a long-term record of dust influx and soil formation. Over geologic time, the properties of pavements change systematically (see Fig. 1; Wells et al., 1985, 1987), reflecting the history of surficial processes operative since the formation of the landform and its underlying deposit. On pavement surfaces, the degree of soil-profile development, the amount of varnish cover, and Mn accumulations in varnish have been used in discriminating among deposits of Holocene and Pleistocene age (McFadden et al., 1989; Reneau, 1993). These properties are strongly dependent upon dust influx and relatively independent of the depositional character of the landform, such as lithology (McDonald, 1994). The genetic bond among dust influx, soil formation, and pavement evolution explains why some pavement properties provide consistent age estimates for the landform and/or deposits that they overlie. On basaltic lava flows, the duration of geologic, hydrologic, and climatic activities operating on the pavement can be evaluated because of the long exposure histories. Exposure ages for pavements mantling fluvial, lacustrine, or colluvial deposits will most likely contain an inherited exposure owing to the transport path (Nishiizumi et al., 1993). For those pavement clasts that have been continually exposed on alluvial landforms, the exposure ages may not be consistent with the deposition and/or construction of the underlying landform.

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