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Dynamical Processes on Desert Pavements and the Healing of Surficial Disturbances

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Mature desert pavements are traditionally regarded as hallmarks of stability, but their stability is dynamic, not static. In a study aimed at documenting this dynamic stability and its role in healing surface disturbances, experiments were performed over a 5-yr period on small cleared patches, or plats, on pavement surfaces in Panamint Valley, California. These experiments show that stones from plat edges begin to resurface the clearing at rates of about 1% per year on 40-cm-square plats and 10% per year on 10-cm-square plats. Stones contributing to the regenerated pavement have smaller average diameters than stones on the surrounding pavement. Cavities 5–10 cm deep, formed in mature pavement by removal of embedded boulders, fill by ravel and slope failure. After five years, cavity depth has been reduced by as much as 60%. Forty-year-old boulder cavities are nearly completely refilled and have been repaved by smaller than average pavement stones. Gaps caused by removal of small stones (2–3 cm) have completely healed in 5 yr. Displacement of surface stones by small animals is a major component of the healing process.

INTRODUCTION

Desert pavements are nearly flat, stony expanses found on abandoned alluvial surfaces in desert country. Pavement stones coated with desert varnish form a mosaic approximately one clast-diameter thick. This stone cover rests upon a fine-grained substrate composed of clay, silt and fine sand that is mostly stone-free. Well-varnished and tightly mosaicked stone pavements on surfaces of late Pleistocene age (Bull, 1991) are commonly considered to be hallmarks of stability. Field evidence presented here, however, shows that desert pavements remain dynamic even in maturity. Some of the surface stones on desert pavement are incrementally mobile on time scales of 1 yr or less as indicated by observations described below. Evidence is presented below suggesting that animal activity is one important cause of stone displacement.

The implications of pavement clast mobility are several. The commonly occurring small scars and defects in the pavement surface caused by biogenic activity or other agencies are rapidly resurfaced with stones from the surrounding pavement. The present work documents the healing of surface scars showing that clast displacement is an essential element of pavement integrity and longevity. Human disturbance to the pavement cover, if not too extensive, can also be repaired by this mechanism. The cross-surface flux of stones also represents a powerful smoothing agent, lowering topographic highs and filling topographic depressions. In this manner clast displacement contributes to the development of the nearly flat modern pavement surface. In addition, pavement clast mobility provides a mechanism by which clasts are able to “float” on top of a layer of accumulating aeolian sediment. The results presented here support a recent model of pavement formation on volcanic flow surfaces that emphasizes the importance of dust-accretion over deflation in pavement genesis (Wells *et al.,* 1985; McFadden *et al.,* 1987).

SETTING AND EXPERIMENTAL APPROACH

The present study focuses on desert pavement in Panamint Valley, a broad north–south trending valley just west of Death Valley, California (Fig. 1). Panamint Valley was chosen as a pavement-dynamics study site on the basis of its mature desert pavement. Where channelization or local topography has isolated piedmont surfaces from upslope runoff, and where tough, platy stone fragments are abundant owing to clast lithology, well-mosaicked and darkly varnished carpets of stone have developed. The hot summers, dry climate, and relative impermeability of the tightly packed, stony surfaces are responsible for a near lack of pavement vegetation. While dark coatings of desert varnish and good mosaicking of stones attest to overall pavement stability, only the largest pavement clasts are firmly fixed in the fine-grained substrate. Pavement surfaces are, consequently, easily scuffed and disrupted by man, animals, and machines. Small (2–5 cm) scars are commonly seen on otherwise undisturbed pavements; fecal pellets and claw, beak, or hoof marks attest to a faunal origin. Human impact includes tire impressions from slowly driven vehicles and denuded areas resulting from spinning wheels, bulldozer blade scrapes, ordnance impact craters, and prospects.

The mechanisms and rates of pavement recovery have been studied by documenting the changes to experimental plots fol-

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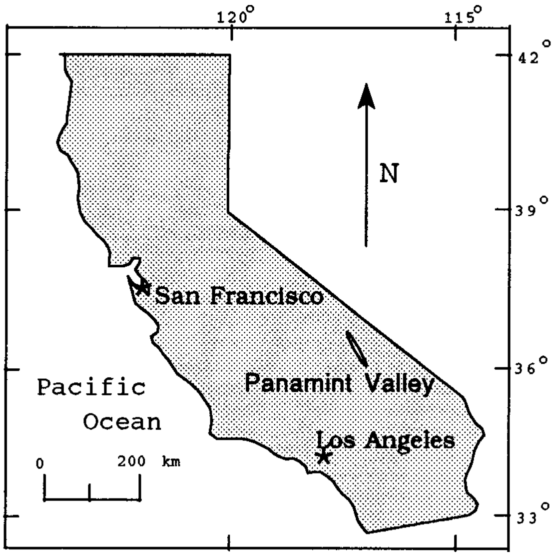

FIG. 1. Map of California showing location of Panamint Valley field area. Experimental sites are located on extensive tracts of desert pavement east of the main Panamint Valley road, near its intersection with Nadeau Road.

lowing localized controlled disturbances. We have found that the natural lateral mobility of stones of sizes commonly found in desert pavements is a powerful mechanism by which a pavement area denuded of surface stones by one or more of the above mechanisms can spontaneously begin to heal. Stone mobility thus plays an important role in the maintenance of pavement stability against both natural and anthropogenic disturbances. The origin of the observed motion of individual clasts lies in a variety of mechanisms, including biological agitation.

In February 1985 four experimental plots of 30 m^2 each were established on representative pavement surfaces located at an average elevation of about 500 m on the west side of the valley. Pavement clasts at this site comprise a heterogeneous mixture of lithologies, including volcanics, carbonates, quartz and quartzites, and gneisses and granite. Locally, embedded boulders protrude up to several decimeters above the pavement surface, and shallow gullies peripherally indent pavement margins. Faint depressions or swales also occur irregularly. Otherwise, the pavement surfaces at these sites are smooth to within several centimeters. The slope of the surface at the plots on which regeneration experiments were performed ranges from 1.3° to 3.0°.

The microstratigraphy underlying the pavement at the study site resembles that reported by other students of desert pavement (Engel and Sharp, 1958; Denny, 1965; Hunt and Maybe, 1966; Cooke, 1970; Evenari *et al.,* 1974). The surficial layer of stones at the Panamint site is composed principally of angular fragments with mean diameter a little greater than 1 cm, but ranging in size from granules to boulders. Beneath this layer is a cumulate horizon of nearly stone-free, grayish to brown, vesicular clay, silt and fine sand ranging at this site from 1 to occasionally 15 cm in thickness, most commonly from 5 to 10 cm. The gray/brown soil horizon grades downward into a more reddish, indurated and stone-poor lower unit perhaps 10 cm thick that in turn rests upon original weathered and carbonate-coated gravels. The relatively unweathered appearance of the fine-grained, stone-free horizon, especially its upper portion, suggests an aeolian origin. Dust traps deployed on the pavement surface captured fine material similar in appearance to that in the stone-free horizon. In a windy, dry environment like Panamint Valley, with its large playa dust source, deposition of aeolian fines is not surprising. Capture and subsurface-sequestering of aeolian material has been documented elsewhere in the California desert (Wells *et al.,* 1985; McFadden *et al.,* 1987).

Within each plot, experiments were performed to measure the magnitude of individual stone displacements and rates of recovery for a range of artificial disturbances made in the surficial stone layer. The recovery of the stony layer was documented by repeat photography, conducted over a period of about 5 yr. Disturbances that were monitored included cleared plats as well as scars resulting from removal or displacement of individual surface stones. Some observations of historical disturbances were also made. These studies provide information on the nature and current rates of processes by which pavements heal when their stony skin is disrupted.

Studies of undisturbed pavement were also carried out. Most mobile stones on undisturbed pavement have a somewhat smaller diameter (0.9 cm on one uncleared patch) than the average pavement stone (1.3 cm on the same patch) (Fig. 2). Because of the smaller size of stones in the mobile population, disturbed areas healed by stone displacement are often readily recognizable to the eye.

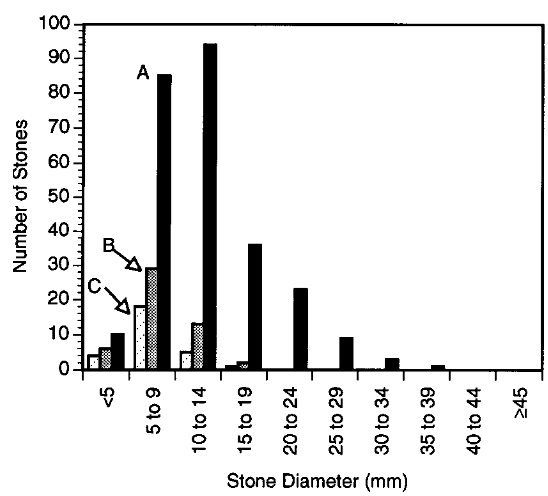

FIG. 2. Distribution of stone diameters on a patch of uncleared pavement. The bars labeled “A” indicate the population in December 1987 of all stones on this patch having diameters exceeding about 0.3 cm. The bars marked “B” represent stones that were found to have moved detectably within a subsequent period of 11 months (19% of all stones). The bars marked “C” represent that part (51%) of the mobile population “B” that had moved into its December 1987 position sometime within the preceding 10 months. Thus, a stone that was mobile within about a year after December 1987 (B) was likely also to have been mobile in the preceding year (C).

Larger clasts (5–15 cm) that have been overturned and exhumed are common on some pavement surfaces. These clasts, identified by the exposure of reddened undersides and carbonate coatings, are typically reincorporated back into the pavement mosaic, an indication that their origin is not recent. The origin of these stones is not known, but may reflect infrequent bioturbation by large animals such as coyote.

REGENERATION EXPERIMENTS ON CLEARED PLATS

Twelve cleared plats, each square, were prepared in three of our experimental plots. Six of these measured 40 cm on a side, two measured 20 cm, three measured 10 cm, and one 5 cm. Interior stones were either pushed into a berm surrounding and adjacent to the cleared surface, or removed entirely. The bermed plats mimic natural and anthropogenic disturbances that are likely to leave disturbed stones nearby. Plats were photographed at intervals over a period of about five years to measure stone displacements. Examples of localized disturbances, consistent with animal activity, can be seen in several of the frames. The following chronology records some of these observations.

February 1985 (0 months elapsed). This was the set-up date for most of the cleared plats. Figure 3a shows a 40-cm plat with berm, cleared on this date.

May 1985 (4 months elapsed). Accumulated stone displacement for all plats corresponds to one stone about 1 cm in diameter moving a distance of about 2 cm onto a plat for every 40 cm of plat perimeter. None of the 40-cm plats lacking a berm shows measurable stone movement onto the cleared area.

February 1986 (13 elapsed months). Stones originating on berms with diameters of 1–2 cm have moved distances of 1–2 cm. In several places depressions in the fine-grained matrix hold small tubular droppings.

May 1986 (16 elapsed months). In one 40-cm plat shallow claw marks were visible, accompanied by the displacement into the plat of two stones, each 1 cm in diameter, a distance of about 1 cm each.

February 1987 (24 months elapsed). A total of seven additional stones, with diameters greater than or equal to 1 cm, have moved onto the 40-cm plats. In some plats fines and granules have been swept or washed against the downslope edge of the plat. At essentially all sites there are uncountable but widespread displacements of clasts less than 1 cm in diameter onto and within the plats.

December 1987 (34 months elapsed). One stone (only), with a diameter of about 1 cm, has moved detectably into a cleared plat. Rabbit droppings have appeared and then disappeared in some of the plats over the last 34 months. Several of the smaller plats are estimated to be $\sim$20% covered by granules and larger debris. Some of this coverage comes from small incremental displacements (encroachment) of stones immediately adjacent to the cleared area. For the 10- and 5-cm plats, this edge encroachment is more effective on a percentage basis at covering exposed substrate than it is in the larger plats. Typical coverage of a 40-cm bermed plat by displaced and encroaching stones is 3-5% after nearly 3 yr.

February 1990 (61 months elapsed). Partial repairing of the cleared 40-cm plat (Fig. 3a) is shown in Figure 3b, after an elapsed time of 5 yr. The total number of countable displacements of stones with diameters greater than about 1 cm onto all cleared plats since December 1987 is 140. The average estimated displacement is 3 cm; this is probably a minimum value for the actual displacement, since the point of origin of many of the stones cannot be determined. The greatest displacement documented is 10 cm. No stone bigger than 6 cm has moved detectably. The loci of stone disturbances are not distributed evenly among the plats, nor within a given plat. Two of the 40-cm plats show together only 28 measurable stone displacements for stones with diameter greater than 1 cm. A total of only two or three distinct displacements are detectable in two of the 10-cm plats and the 5-cm plat. But one 40-cm plat contains at least 50 new displacements and another 40-cm plat at least 37.

The results of the above studies show that, as on the uncleared pavement surface, stones that moved onto cleared plats are mostly smaller in diameter than the average pavement stone. Figure 4 shows the results of a point count of stones on and adjacent to a 40-cm plat.

Within a given plat, stone motion is often highly localized. In the 40-cm plat of Figure 3b, many displacements appear to have originated along the left and upper edges of the plat (arrow). In another 40-cm plat with ten displacements, about half originated along one edge and the other half in an adjacent corner of the plat. The positions of stones with diameters greater than about 1 cm in these plats were essentially unchanged. Similar localized activity in a 10-cm plat is shown in Figure 5 (arrow). The presence of localized and apparently random bursts of activity, some of which are effective at moving stones up to 3 cm in diameter a distance of several centimeters while adjacent areas are undisturbed, suggests that animals play a role in pavement dynamics. This interpretation is supported by the occurrence of claw marks and droppings near or within cleared plats.

ADDITIONAL OBSERVATIONS

Not all motion in the cleared plats is resolvable into large displacements of individual stones. In one 20-cm plat there was a general encroachment affecting all four sides of the plat, with numerous stones shifting into the plat a distance of up to 1 cm; here and elsewhere encroachment tends to round plat corners. There does not appear to be a correlation of encroachment magnitude or direction with the slope of the plat itself.

The recovery rates of plats lacking a berm are significantly less than for bermed plats. Of the 140 stones with diameters greater than about 1 cm that were displaced onto cleared plats

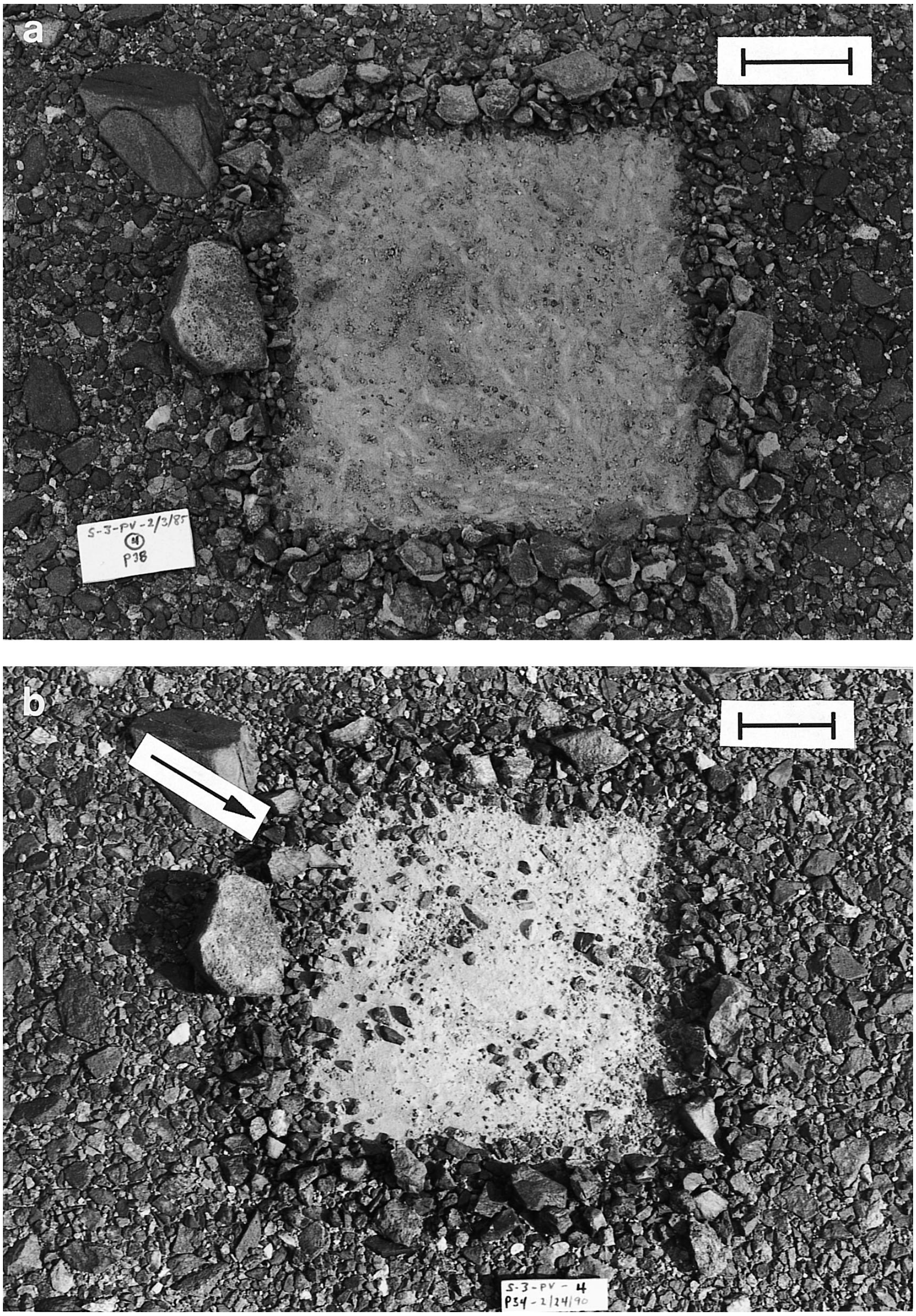

FIG. 3. Cleared plat area, 40 cm by 40 cm. Scale bars are 10-cm long. (a) February 1985 (0 months elapsed), immediately after clearing. (b) February 1990 (61 months elapsed). Surface partially repaved. Stone displacements are frequently localized (arrow).

between December 1987 and February 1990, only 28 are in plats lacking berms. While one bermed 40-cm plat contains only two displaced stones in this size range, two others contain 87 displacements.

Displacement of stones is episodic in time. Figure 6 shows the percentage of the original cleared area covered by displaced stones and granules versus time for each of three 40-cm plats with berms. In two of the plats, most recovery occurred during the last two years of the 5-yr observation period, while in the third plat, essentially no recovery occurred during the last three years. Abundant signs of animal traffic together with the sporadic occurrence of clast displacement point to an important biomechanical contribution to pavement dynamics.

Not unexpectedly, small cleared plats begin to heal more quickly than large plats. Figure 7 shows the projected resurfacing time as a function of clearing size if the measured 5-yr

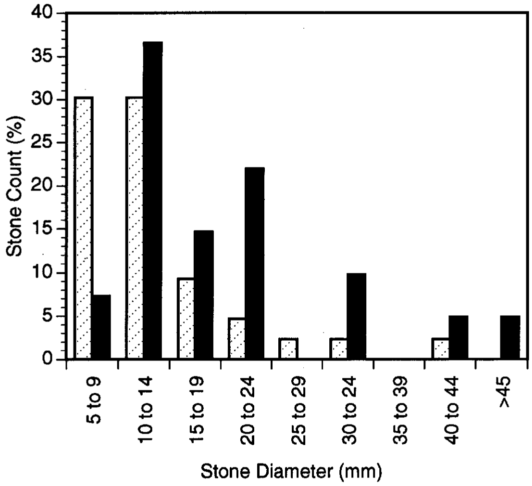

FIG. 4. Area-weighted distribution of stone diameters (>0.5 cm) on and adjacent to 40 cm by 40 cm cleared plat. Hatched bars represent population of stones that had moved into the central 30 cm by 30 cm region of cleared plat. Solid bars represent area-weighted population of stones on adjacent ambient pavement. Mean area-weighted stone diameters for these populations are 1.2 and 2.0 cm, respectively.

average resurfacing rates remain constant. On this basis, a 5-cm plat would become resurfaced in approximately a decade and a 40-cm plat in about 80 yr.

REMOVAL OF SMALL STONES

A series of experiments was carried out to monitor the healing of scars formed by the removal of selected stones from an otherwise intact pavement surface. Twelve stones were removed, leaving gaps in the pavement with plan-view areas ranging from about 9 cm^2 to greater than 500 cm^2. In vertical section the smaller gaps represent essentially just a missing pavement stone with no significant indentation of the silty substrate. The larger cavities, representing the removal of small boulders, penetrated as much as 10 cm into the substrate. In the former case, lateral motion of stony pavement material was able to heal the pavement in 5 yr or less. After this period of time, the stone originally removed to create the scar still rests near where it was placed on top of the pavement, showing that integration of a foreign object into undisturbed pavement is a slower process than healing of a scar of the same size.

REMOVAL OF BOULDERS

For the larger scars resulting from boulder removal, failure of the steep silty slopes and ravel of unstable pavement material from the edge of the scar rapidly reduce the depth of the cavity, but pavement regeneration, as well as smoothing of the cavity, remain incomplete after 5 yr. Figure 8 shows the evolution of a boulder scar. Figure 8a shows the original scar; part of the wall has collapsed and a handful of stones measuring about 1 cm in diameter has fallen in during boulder removal. After 4 months there is some unlocking of clasts along the upper edge of the scar; areal coverage in the cavity by stones with diameters greater than 1 cm is estimated to be about 12%. As long as cavity walls remain steep, repaving can be temporarily halted or reversed as colluvial infilling of fine material buries the partially repaved cavity bottom. Thus by 34 months, areal coverage has decreased by 9%. After 5 yr, coverage of original scar area by pavement stones is about 11% (Fig. 8b).

From information furnished by the National Cartographic Information Center, Menlo Park, California, it is known that boulders were removed from mature pavement to build a large cairn near the experimental sites. Approximately 40 yr later (1990) the scars created by the boulder removal were still visible (Fig. 9). Judging from the size of boulders in the cairn and the location of varnish ground-line markings on them, holes left by removed boulders were up to 10–15 cm deep. By 1990 all holes were filled with clay, silt, sand, granules, and pebbles, although many still made a shallow depression in the ambient paved surface. Many of the scars exhibit mosaicked pavements of clasts with diameters averaging about 1 cm, which is smaller than the mean size of clasts in the surrounding mature pavement (1.9 cm at this location). Clasts on the scar are also less darkly varnished, and the larger 5–6 cm stones of the mature pavement are lacking. Excavation of the soil beneath the boulder-scar pavement shows that the stone-free layer has been replaced with an irregularly layered mixture of fines, granules and pavement stones representing colluvial fill.

The size distributions for stones resurfacing one of these boulder-removal scars, for colluvial stones buried within the cavity, and for stones on the adjacent ambient pavement surface are shown in Figure 10. The distributions show how the population of stones resurfacing the scar is depleted in sizes greater than about 1.5 cm, suggesting that the average excursion distance of stones larger than 1.5 cm over a 40-yr period is less than the 20-cm radius of the scar. Mean diameters of clasts larger than about 0.5 cm are 1.0 cm for buried stones, 1.0 cm for stones on the surface of the scar, and 1.9 cm for stones on the nearby ambient pavement.

The rates of cavity infilling and pavement regeneration observed over shorter periods in the experiments described earlier, and the size-populations of stones involved in those processes, are consistent with these observations.

SUMMARY AND DISCUSSION

Desert pavements are dynamic, not static. Mobility of surficial clasts enables desert pavements to heal following local disruption of their surficial stone cover. Stone mobility also contributes to lifting of pavement clasts over a layer of accumulating aeolian sediment. The smoothness of desert pavement, its stability (and hence its longevity), and the peculiar stratigraphic pattern of older clasts resting on top of younger stone-free sediment are all aided by the occurrence of vigorous clast displacement.

Much of the stone mobility is probably due to biological activity. Biogenic mechanisms are suggested by the clustered

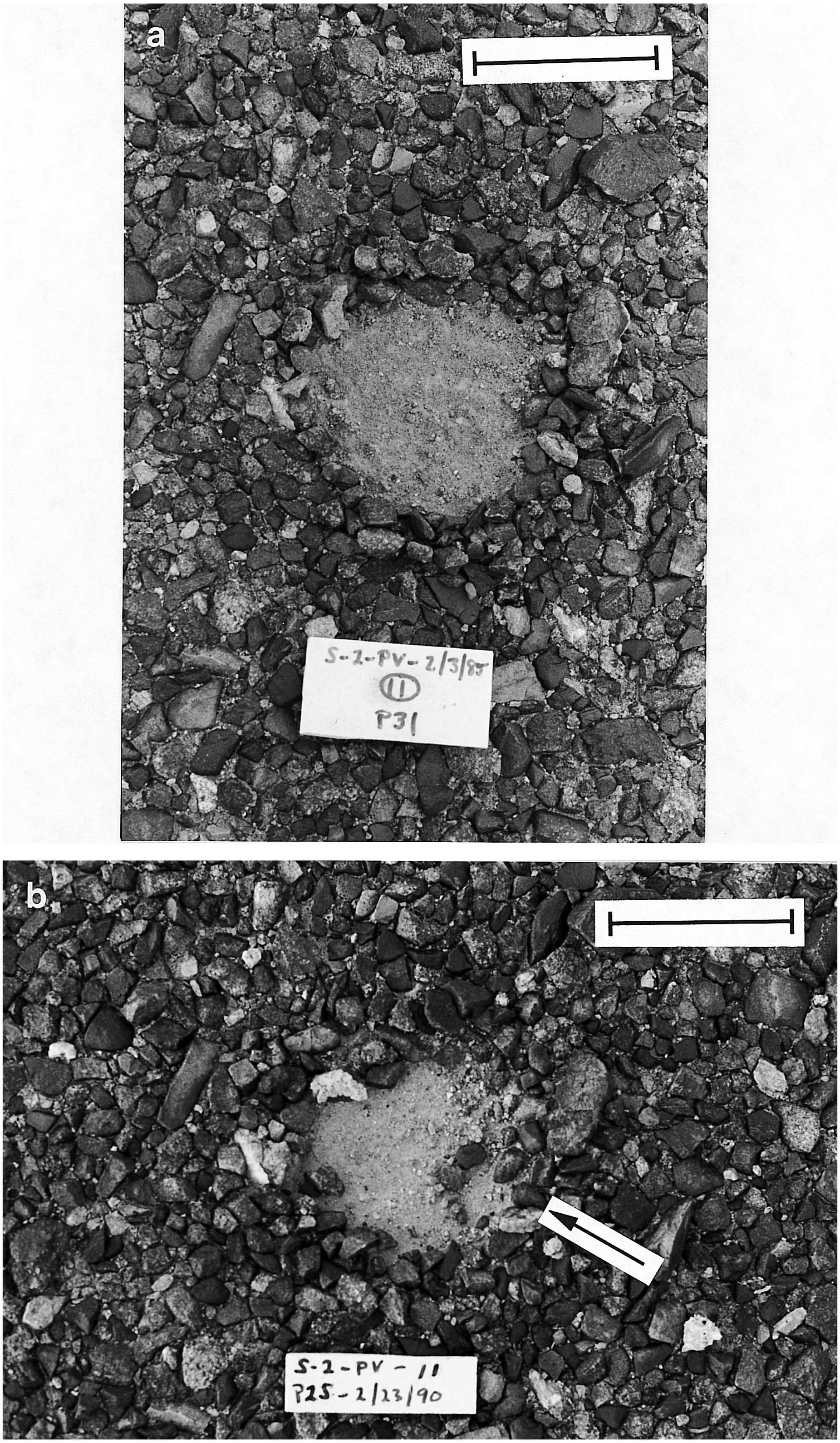

FIG. 5. Cleared plat, 10 cm by 10 cm (a) in February 1985 (0 elapsed months) and (b) February 1990 (61 elapsed months). Six of the seven displacements monitored over this period originated in a pod of activity along one edge of the plat (arrow). Scale bars are 10 cm long. This particular plat shows less recovery than the average 10-cm plat (which is about 33% resurfaced after 5 yr).

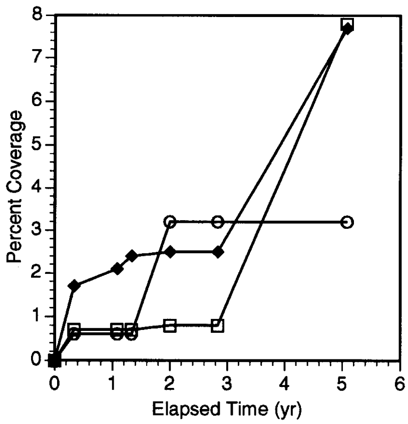

FIG. 6. Percent areal coverage by displaced stones is plotted versus time for three 40 cm by 40 cm cleared plats with berms. Displacement of stones is episodic in time and space. In two plats most of the resurfacing occurred during the final two years of the experiment, while in the third plat essentially no resurfacing occurred during the last three years. If the average 5-yr recovery rate (6.2%) for these plats is taken to be constant, the approximate resurfacing time will be about 80 yr.

nature of many clast displacements. However, direct observation of clast motion via natural mechanisms is sparse and anecdotal. We saw centimeter-sized stones moved by a jackrabbit accelerating from rest and by feral burros ambling across a stretch of pavement. (Burros, however, can have been a factor only since the mid-nineteenth century.) Raindrop impact (Ellison, 1945) is no doubt important as a more uniformly distributed background mechanism, especially for displacement of smaller stones. We have seen pavement pebbles up to 1 cm in size moved by raindrop impact. We infer that violent action, such as animal pawing, creates a small disturbance exposing the fine-grained substrate, and that stone movement by small or slowly moving animals and by other agents, such as raindrops, aids in healing and smoothing disturbed pavement.

Other agents that could act either to damage or to heal a pavement surface include earthquakes, wind, hail, running water, freezing and thawing or wetting and drying, plant growth, and people and their machines. In Panamint Valley, large scarps along the valley boundaries and smaller scarps and lineations criss-crossing the valley alluvium attest to widespread surface disruption resulting from seismic activity. While the overall role of earthquakes in pavement dynamics is unclear, pavement is damaged or destroyed locally where scarps are generated.

Observation shows that winds gusting to 50–60 km h^{-1} are insufficient to move any pavement material, except granules and smaller material where a disturbance has recently been made. Even granules and sand are nearly immovable on undisturbed surfaces, remaining securely protected in the gaps between larger pavement stones. Higher velocity winds or dust devils could possibly move 1–2 cm pavement stones, although we recognized no evidence for such movement. The ineffectiveness of wind is underscored by lack of abrasion of the high-quality varnish that covers many pavement stones. Large hailstones can no doubt move pavement stones up to several centimeters in diameter, but the incidence of hail in Panamint Valley is not known.

Running water is potentially a powerful agent for transport of material across pavement surfaces. The penetration of shallow peripheral gullies into otherwise intact zones of pavement confirms the occurrence of surface flow. On cleared-plat experiments, granules and sand from the plats were in several cases observed to have been deposited against the downslope berm. After sustained (12 hr) rainfall, slow flow between 1–2 cm clasts was observed. Storm precipitation would generate more intense flow. However, we recognized no evidence that running water had displaced stones greater than 1 cm in diameter, either in the experimental plats or on a natural pavement. Additionally, stone displacement around cleared plats was often localized, and stones moved upslope as well as downslope.

Experiments and observations on areas of cleared desert pavement significantly larger than our plats have indicated that, in the presence of enough subsurface stones, erosion of finer material by wind or running water can eventually lead to a lag deposit formed from such buried clasts (Sharon, 1962; Symmons and Hemming, 1968; Cooke, 1970; Péwé, 1978). This mechanism, which differs from the surface stone mobility mechanisms discussed above, probably does not apply to the small clearings investigated in this study, nor is it likely to have contributed to the dynamical pavement maintenance that we have inferred. The pavements we have studied have nearly stone-free substrates that would require erosion to depths of 5–15 cm to expose significant numbers of large clasts.

Changes in subpavement soil driven by climatic or weather cycles might help to generate new pavement or to seat existing pavement stones. Wetting and drying (Springer, 1958; Jessup, 1960) and freezing and thawing (Corte, 1963; Inglis, 1965) of soil have been discussed as mechanisms capable of heaving buried stones to the surface and contributing to pavement formation or regeneration. Low infiltration rates are common in

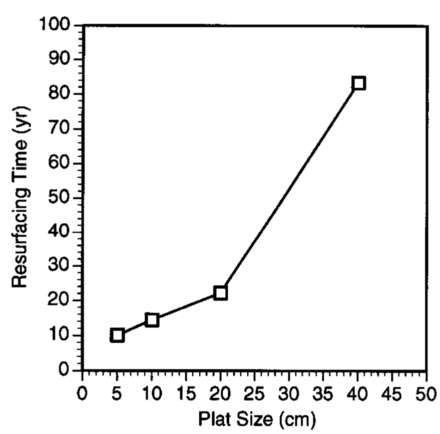

FIG. 7. Estimated resurfacing times for 5 cm by 5 cm, 10 cm by 10 cm, 20 cm by 20 cm, and 40 cm by 40 cm plats are shown, based upon measured 5-yr resurfacing rates. For small plats, extrapolated recovery times do not increase as fast as plat area. The 40-cm plats, however, are estimated to take about four times as long to recover as the 20-cm plats.

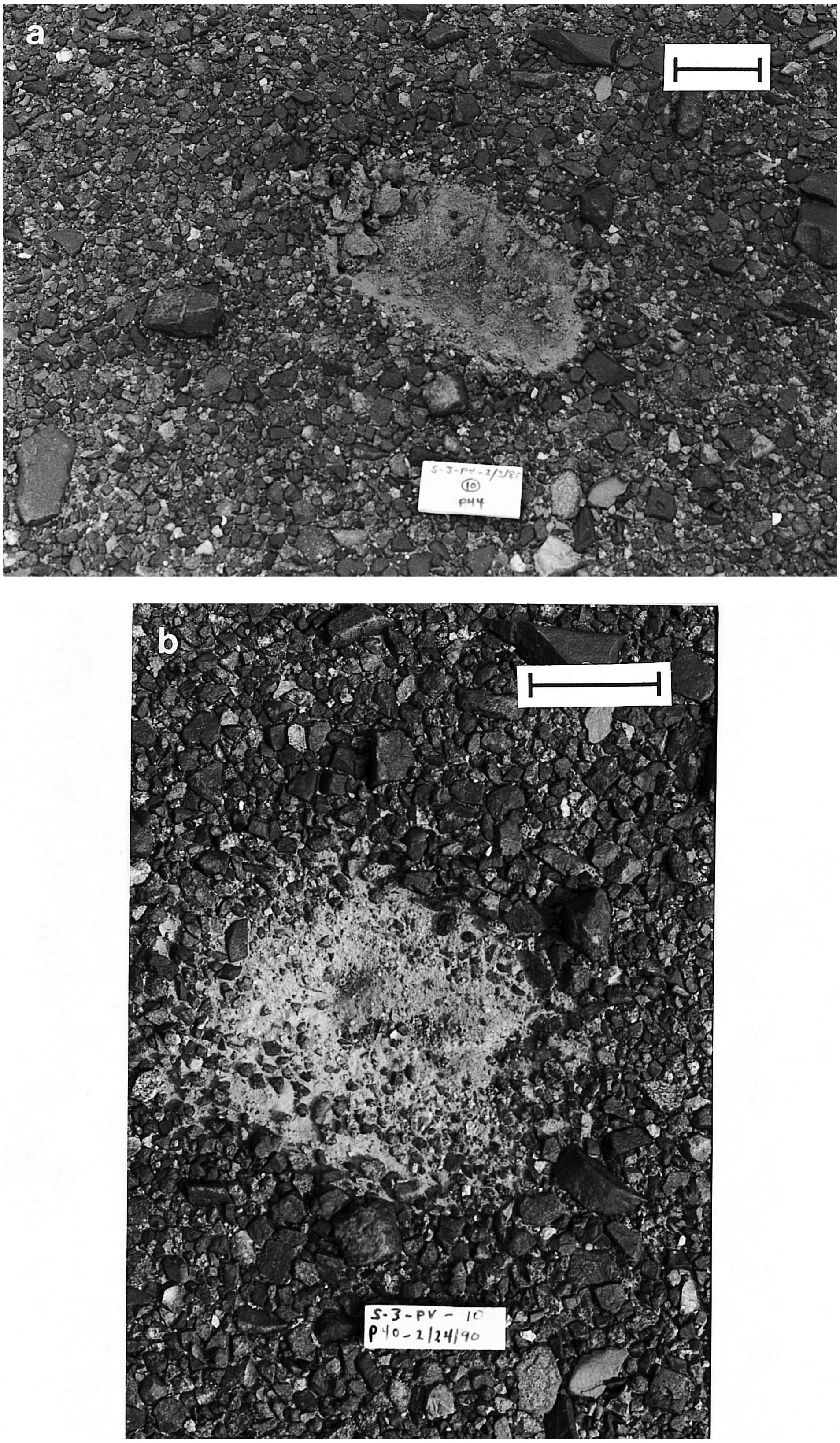

FIG. 8. (a) A boulder was removed from the pavement, creating a scar measuring 544 cm^2 in cross-sectional area and 5.5 cm in depth. (b) After 61 months the plan-area scar exposure measured 782 cm^2. The maximum cavity depth had decreased to 3.5 cm. Stone coverage of the scar was about 11%. Scale bars are 10 cm long.

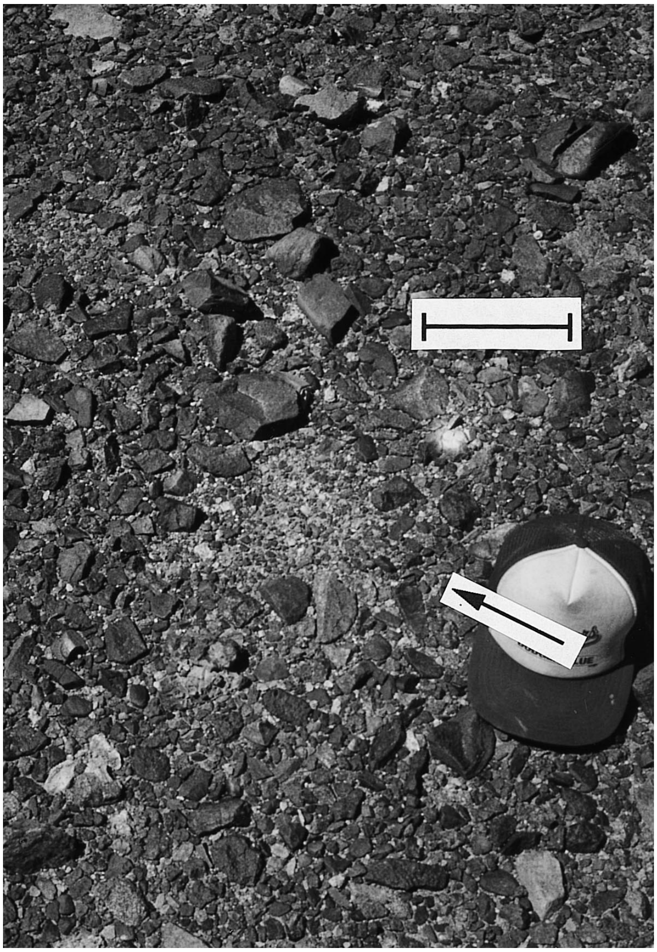

FIG. 9. A 40-yr-old boulder removal scar (arrow). White spot is dab of spray paint. Stones on the scar have smaller mean diameter than stones on surrounding pavement and are less well varnished. Scale bar is about 15 cm long.

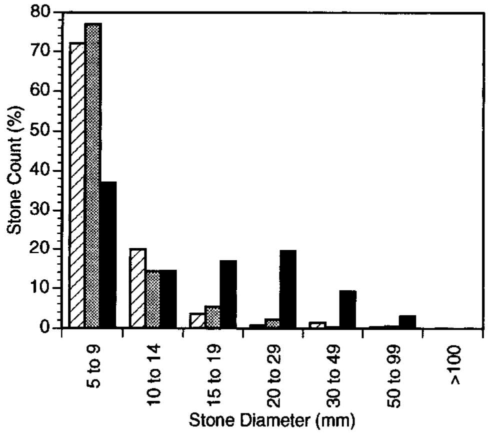

FIG. 10. Distribution of diameters of colluvial stones filling a 40-yr-old boulder removal cavity (hatched bars), of stones on the surface of the boulder scar (shaded bars), and of stones from surrounding undisturbed pavement (solid bars).

desert pavements (Musick, 1975), making wetting beyond a few centimeters in depth infrequent. After one 12-hr rain, the pavement substrate was saturated to a depth of about 2 cm. Under present climatic conditions in settings such as Panamint Valley, periods of subfreezing temperatures are brief and soil penetration by a freezing front correspondingly shallow. At our pavement sites there are not enough buried rock fragments near the surface to refurbish a pavement even if wetting and drying or freezing and thawing were to occur frequently. All of these mechanisms, however, plus thermal expansion and contraction, no doubt contribute to the excellent seating and mosaicking of mature pavement.

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