Tracking painted pebbles: Short-term rates of sediment movement on four Mojave Desert piedmont surfaces

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[1] To quantify short-term sediment movement rates across Mojave Desert piedmonts, 1600 painted and numbered pebbles were laid out in paired, orthogonal, 20 m lines at 4 sites and resurveyed five times over 2 years and revisited 2 years later. Pebble lines cross shallow (5–15 cm), ephemeral channels and adjacent unconsolidated interfluvies, the latter being the dominant landform at all sites. Two sites are located on surfaces that have been or are impacted by military training activities, including the use of tracked vehicles. The two other sites have not been disturbed by human impact. Three different processes transport pebbles. Episodic streamflow in ephemeral channels transports a few pebbles long distances (decimeters to meters) down gradient. Bioturbation moves many pebbles small distances (centimeters) in any direction, and vehicular disturbance transports pebbles varying distances (centimeters to meters) in any direction. Significant down-gradient sediment movement occurred dominantly in channels where flowing water was concentrated. Interfluvies were stable surfaces where little transport occurred. Off-road vehicle use is coincident with accelerated pebble movement. Pebbles moved further and faster down gradient at the disturbed Iron Mountain and East Range Road sites (mean speeds of 0.18 and 0.34 m yr\(^{-1}\), respectively) than at the undisturbed Chemehuevi and Goldstone sites, (mean speeds of 0.17 and 0.02 m yr\(^{-1}\), respectively). Mean pebble movement is highly and negatively correlated with vegetation density. Short-term pebble movement rates are several times lower than long-term (10\(^3\) to 10\(^4\) year) rates, suggesting the importance of rare, extreme precipitation events for sediment transport such as those of fall and winter 2004.


1. Introduction

[2] Desert piedmonts, the long, low-gradient slopes that extend up to 20 km from steep mountain fronts down to flat basin centers, remain an enigma after many years of research [Denny, 1967; Oberlander, 1974; Leece, 1990]. Piedmonts can be primarily depositional features (alluvial fans) or erosional landforms (pediments), encompassing a wide variety of different morphologies. Processes that form and change piedmont surfaces are so episodic and occur on such long timescales that only rarely can they be observed directly [McGee, 1897; Schick, 1986]. Thus sediment movement rates, on piedmonts and on other desert landforms, have rarely been quantified [Abrahams et al., 1984]. The rarity of run off and the paucity of vegetation allow disturbance of desert soils by wheeled and tracked vehicles to persist for more than a hundred years implying very slow rates of surface change [Iverson, 1980; Iverson et al., 1981; Webb et al., 1986; Nichols and Bierman, 2001].

[3] This study quantifies short-term sediment transport rates across four sandy, unconsolidated desert piedmonts in order to describe and quantify fundamental geomorphic processes. Because of their large size, broad distribution, and low gradient, piedmonts have been extensively altered by humans. Such impacts range from building roads and structures to driving off-road vehicles across piedmont surfaces [Sheridan, 1979]. Understanding how, where, and with what frequency piedmont sediment will move is important for making informed land and hazard management decisions [National Research Council, 2000]. For example, piedmonts in arid regions have been contaminated by mining wastes [Baker, 1993] and low-level radioactive waste disposal [Wilshire et al., 1994], highlighting the importance of understanding particle movement rates on these surfaces [Miller, 1997].
Figure 1. Field sites (stars) located in the Mojave Desert, southern California. East Range Road and Goldstone are located at Ft. Irwin (FI). Inset maps with shading show the location of San Bernardino County in California as well as in the United States. IM, Iron Mountain; CM, Chemehuevi Mountains.

[4] Pebble tracing, which follows the history of individual grains over time, has been used primarily to study sediment movement in fluvial systems, specifically the confined channels of flowing or ephemeral rivers [Hassan et al., 1984, 1999; Hassan and Church, 1992; Hassan et al., 1991; Ferguson and Wathen, 1998; Hassan, 1990, 1993; Ergenzinger and Custer, 1983; Slattery et al., 1995; Laronne and Carson, 1976; Schick and Leckach, 1995; Aberahams et al., 1984]. Only one study has tracked pebbles and clasts down desert hillslopes [Aberahams et al., 1984]. Never has sediment been tracked across the unconfined drainage network of a sandy, unconsolidated desert piedmont, despite the ubiquity of this landform in arid regions.

[5] This study analyzes the movement of a total of 1600 (400 per site) painted and numbered pebbles over 24 months (from May 2000 to May 2002) on 4 piedmonts in the Mojave Desert, California (Figure 1). Two sites were revisited in January, 2005. Our measurements include over 10,000 data points to overcome the problem of noise and to ensure that the individual grains are representative of the larger population of which they are part [Hassan and Church, 1992].

2. Study Areas

[6] All four study sites are located in the Mojave Desert (Figure 1). Average annual precipitation in the Mojave can be as low as ~3 cm or as high as ~24 cm (1961–1990, National Weather Service Needles, California, station normal = 12 cm) occurring as gentle winter rains and heavy summer downpours. The vegetation is predominantly creosote bush (Larrea tridentata) and desert sage (Salvia dorrii). Field sites are located on coarse sand and fine gravel surfaces [Nichols and Bierman, 2001]. Source lithologies are dominantly granitic or coarse crystalline, metamorphic rocks.

[7] We designed our research to measure how sediment movement rates vary on desert surfaces. All of the study areas are on low angle (~3°) slopes consisting of unconsolidated sediment. At two of the sites, Chemehuevi and Iron Mountain, the surfaces are drained by shallow (5–15 cm) ephemeral channel networks with unconsolidated banks (Figure 2). The other two sites, East Range Road and Goldstone, have no distinguishable channels. The interfluves between channels dominate the landscape (Table 1).

[8] Two sites have been or are being disturbed by human action (Figure 2). The Iron Mountain piedmont was heavily impacted as an army training facility during World War II. This site was compacted by vehicular and foot traffic from 1942 to 1944 [Prose, 1985] but is now fenced preventing vehicle entrance. There is some foot traffic as tourists occasionally visit the site. The Iron Mountain piedmont has sparse vegetation, 14% vegetation cover, a field site slope of 1.9°, is 3 km from the range front, and is dissected by numerous ephemeral channels (Table 1 and Figure 2). In contrast, the East Range Road piedmont is an active Army training range, which is heavily and continually impacted by off-road vehicle use including tanks. The site has sparse vegetation, 12% vegetation cover, a field site slope of 2.7°, is 3 km from the range front, and has no channels (Table 1 and Figures 2 and 3).

[9] The other two sites are undisturbed. The Goldstone piedmont is located within the Goldstone Deep Space Communications Complex, operated by the National Aeronautics and Space Administration. There is no disturbance on this site because vehicle use is prohibited and the public is restricted from entering. The Goldstone piedmont has 39% vegetation cover, a field site slope of 2.3°, and is only 0.14 km from the range front (Table 1). There are no channels at this field site (Figure 2 and 4). The Chemehuevi Mountain piedmont is remote and receives infrequent vehicular traffic. There are a few World War II vintage tank tracks several kilometers up the piedmont from the pebble lines. Vegetation covers 25% of the surface at the site, the site slope is 1.0°, and the site is 12 km from the range front, the furthest of all four sites (Table 1 and Figures 2, 3, and 4).

3. Methods

[10] In order to quantify how sediment moves on short time and spatial scales, we placed 400 painted and individually numbered pebbles of 1 cm sized crushed angular granite on each of the four field sites. At each site, the pebbles were laid out in 2 orthogonal, 20 m long lines (Figure 2). One line was oriented down gradient, the other line was oriented parallel to contour. The pebble lines crossed several channels and interfluves at the Chemehuevi and Iron Mountain sites with bank heights of 5–20 cm (Figure 4). At Goldstone, pebble lines went over 10 cm high sediment mounds near large creosote bushes. At East Range...
Road, surface microtopography was dominated by tank tracks.

[11] We used these clasts to track sediment movement because they were large enough to see and similar in size and shape to pebbles naturally occurring on all four study sites [Nichols and Bierman, 2001]. Sediment movement rates can be influenced by particle size [Abrahams et al., 1984; Ferguson and Wathen, 1998]; however, in ephemeral arid region streams, particle size and distance traveled are often unrelated [Hassan and Church, 1992; Hassan et al., 1991; Laronne and Reid, 1993] because flows do not last long enough to sort the sediment and transport grains selectively. Thus our data for centimeter-sized clasts are probably also representative of other grain sizes.

[12] To determine the amount and direction of movement of these 1600 pebbles over time, we repeatedly resurveyed each pebble using a Pentax 2cs electronic total station, which provided centimeter-scale accuracy. Repeated surveys of 4 rebar control pins at each site, pounded 1 m into the desert surface, suggest average long-term survey uncertainty (2σ) of 0.042 m when data from all sites at all measurement times (n = 96) are considered [Persico, 2002].

[13] Background topography, >500 points in a 40 by 40 m area surrounding the pebble lines, was surveyed at each site using a Trimble 4400 real time kinematic differential GPS at centimeter resolution. These data were supplemented with soil density measurements and descriptions, vegetation identification and enumeration, and channel

Figure 2. Topographic site maps for pebble cross locations. Gray circles represent vegetation, dark polygons are channels, light polygons are walk ways, and black crosses are pebble lines. There are no distinguishable channels at East Range Road and Goldstone. Coordinates are in GPS datum (NAD 27), meters. Arrow is down-gradient direction. Elevation is in meters. CI, contour interval.
measurements to characterize further the surfaces on which
the pebbles are located (Table 1).

To calculate pebble movement and resolve such
movement into down-gradient and cross-gradient com-
ponents, a best fit planar equation in the form,
\[ Z(x, y) = ax + by + c, \]
was used to describe the piedmont surface. The coefficients
\( a, b, \) and \( c \) were calculated using SURFER\textsuperscript{1} and
the centimeter-resolution background topography for each plot.

The down-gradient (DG) movement of each pebble, that is, the movement perpendicular to the strike line passing
through each pebble’s initial position, was calculated using
\[
DG = \frac{a(1 + a^2 + b^2)(E_n - E_0) + b(1 + a^2 + b^2)(N_n - N_0) + c(a^2 + b^2)}{\sqrt{a^2 + b^2 + (a^2 + b^2)^2}},
\]
where \( a, b, \) and \( c \) are coefficients of the planar surface
equation and where \( E_0 = \) original easting, \( E_n = \) new easting,
\( N_0 = \) original northing, and \( N_n = \) new northing. Negative
movements indicate pebbles moving uphill.

Each pebble’s cross-gradient (CG) movement, that is, the movement parallel to the strike line, was calculated using
\[
CG = \frac{-b(E_n - E_0) + a(N_n - N_0)}{\sqrt{a^2 + b^2}}.
\]

The Pythagorean theorem was used to calculate the absolute value of the total movement of each pebble
\[
TO = \sqrt{(E_n - E_0)^2 + (N_n - N_0)^2}.
\]
Such a calculation indicates gross, scalar, movement. Down
or upgradient movement was assigned based on the sign of
the DG movement.

Mean and median movements and speeds were
calculated for down-gradient movement, cross-gradient
movement, and total movement for all pebbles by separat-
ing pebbles on the line parallel to contour (LPC) from the
line oriented down gradient (LDG) for each of the four sites.

Each calculation consisted of 200 pebbles and every pebble

\begin{table}[h]
\centering
\caption{Characteristics of the Four Mojave Desert Field Sites}
\begin{tabular}{|l|c|c|c|c|}
\hline
Site Characteristics & East Range Road & Iron Mountain & Chemehuevi Mountains & Goldstone \\
\hline
Total number of plants/bushes/cactia\textsuperscript{a} & 153 & 138 & 226 & 340 \\
Number of sage plants\textsuperscript{a} & 99 & 101 & 158 & 269 \\
Number of creosote bushes\textsuperscript{a} & 47 & 30 & 58 & 63 \\
Average individual vegetation area,\textsuperscript{a, b} m\textsuperscript{2} & 1.31 & 1.72 & 1.79 & 1.85 \\
Median individual vegetation area,\textsuperscript{a, b} m\textsuperscript{2} & 1.1 & 1.3 & 1.3 & 1.4 \\
Maximum individual vegetation area,\textsuperscript{a, b} m\textsuperscript{2} & 3.6 & 5.2 & 12.6 & 7.1 \\
Total vegetation area,\textsuperscript{a} m\textsuperscript{2} & 191 & 226 & 392 & 617 \\
Soil density, \( \text{g cm}^{-3} \) & 1.43 & 1.55 & 1.44 & 1.46 \\
Distance to range front, km & 3 & 3 & 12 & 0.14 \\
Percent of surface covered by channels & no channels & 11 & 15 & 2.0 \\
Average channel width, cm & no channels & 117 & 106 & 90 \\
Field site slope, deg & 2.7 & 1.9 & 1 & 2.3 \\
Piedmont slope, deg & 5.2 & 0.2 & 0.3 & 4.6 \\
Rainfall in 2001, cm & 10.4 & 9.4 & 9.6 & 14.3 \\
Highest intensity 1 hour storm,\textsuperscript{a} cm hr\textsuperscript{-1} & no data & 1.4 (1.4) & 0.7 (2.4) & 0.9 \\
Highest intensity 15 min storm,\textsuperscript{a} cm hr\textsuperscript{-1} & no data & 3.9 (3.9) & 1.3 (4.0) & 1.5 \\
Highest intensity 10 min storm,\textsuperscript{a} cm hr\textsuperscript{-1} & no data & 4.9 (4.9) & 1.4 (4.4) & 1.8 \\
Highest intensity 5 min storm,\textsuperscript{a} cm hr\textsuperscript{-1} & no data & 7.3 (7.3) & 1.4 (4.6) & 2.4 \\
Highest intensity 2 min storm,\textsuperscript{a} cm hr\textsuperscript{-1} & no data & 7.6 (7.6) & 1.4 (5.3) & 3.1 \\
\hline
\end{tabular}
\end{table}

\textsuperscript{a}A 1600 m\textsuperscript{2} area encompassing pebble cross.
\textsuperscript{b}Vegetation area was determined by tape measure, measuring the largest diameter of each bush.
\textsuperscript{c}First value indicates time period November 2000 to May 2002. Value in parentheses indicates time period November 2000 to January 2005.

Figure 3. Schematic cross section of piedmont showing the pebble cross locations in relation to the range front. ER, East Range Road; IM, Iron Mountain; CM, Chemehuevi Mountain; GS, Goldstone.
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was incorporated into the mean and median calculation regardless of distance moved. Separate means and medians were also calculated for pebbles in channels versus pebbles on interfluves. For statistical testing, the data were natural log transformed to better approximate a normal distribution.

Pebbles that move great distances and then disappear greatly affect mean movement rates because most pebbles move only centimeters. For this reason, when a pebble was lost, the last known position of the pebble was used from then on to determine travel distance for the calculation of movement rates. By recording the last known location of each pebble, we calculate minimum pebble mean and median movements. It is unlikely that lost pebbles are either buried or transported further down gradient. Although some pebbles move centimeters up slope due to animal activity, it is unlikely that lost pebbles moved up slope any significant distance by natural means. In fact, there were survey periods when we did not find a pebble but located it during the following survey. Each time such pebbles were relocated, they were found further down gradient than the previous observation.

Precipitation amounts and intensities were measured using tipping bucket rain gauges (0.25 mm precision) and digital rainfall loggers to record the quantity, duration, and time of rainfall at each of the field locations except East Range Road. In the Chemehuevi Mountains, we installed two rain gauges, one at the pebble cross, 12 km down the piedmont, and the other, 4 km from the range front. The rain gauges at Goldstone, Chemehuevi upper, Chemehuevi lower, and Iron Mountain measured rainfall totals during 2001 of 14.3 cm, 10.7 cm, 9.6 cm, and 9.4 cm [Persico, 2002], similar to the amount measured at the permanent gauge at Fort Irwin, the location of the East

4. Site Characteristics

Infiltration rates differ between sites (Table 2) although soil densities are similar (Table 1). The highest infiltration rate was measured at Goldstone (>23.8 cm h⁻¹) where runoff could not be produced. The lowest infiltration rate was measured at Chemehuevi (4.7 cm h⁻¹). The two infiltration tests at East Range Road gave very different results. Both tests incorporated parts of a tank track in order to represent the larger piedmont surface. The first test produced no run off due to a collapsed animal burrow, which captured the runoff that started to form. The second test, made less than 5 meters away, indicated a much lower rate of infiltration, 6.7 cm h⁻¹. The infiltration rate at the Iron Mountain site was similar to second test at East Range Road, 6.5 cm h⁻¹ (Table 2).

The rain gauges at Goldstone, Chemehuevi upper, Chemehuevi lower, and Iron Mountain measured rainfall totals during 2001 of 14.3 cm, 10.7 cm, 9.6 cm, and 9.4 cm [Persico, 2002], similar to the amount measured at the permanent gauge at Fort Irwin, the location of the East

Table 2. Infiltration Rates of the Four Mojave Desert Field Sites

<table>
<thead>
<tr>
<th>Site</th>
<th>Sprinkling Intensity, cm hr⁻¹</th>
<th>Plot Size, m²</th>
<th>Duration, min</th>
<th>Final Rate, cm hr⁻¹</th>
<th>First Runoff, min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron Mountain</td>
<td>7.0</td>
<td>0.624</td>
<td>180</td>
<td>6.5</td>
<td>33</td>
</tr>
<tr>
<td>Chemehuevi Mountains</td>
<td>7.9</td>
<td>0.662</td>
<td>150</td>
<td>4.7</td>
<td>16</td>
</tr>
<tr>
<td>Goldstone</td>
<td>8.2/23.8*</td>
<td>0.637</td>
<td>130</td>
<td>&gt;23.8</td>
<td>NA*</td>
</tr>
<tr>
<td>East Range Road A²</td>
<td>10.3</td>
<td>0.617</td>
<td>60</td>
<td>&gt;10.3</td>
<td>NA*</td>
</tr>
<tr>
<td>East Range Road B⁴</td>
<td>10.9</td>
<td>0.635</td>
<td>66</td>
<td>6.7</td>
<td>2</td>
</tr>
</tbody>
</table>

*Sprinkling rate increased after 60 min without runoff.
1NA: no run off.
²Collapse of burrow under plot ended test.
⁴Plot area not recorded; average of other plot areas used.
Range Road site, 10.4 cm. Our Goldstone gauge measured 2.2 cm more precipitation in 2001 than the permanent gauge installed 5 km away. The 3 maximum 1 day precipitation events occurred at Goldstone (1.80 cm, 6 March 2001; 1.68 cm, 11 January 2001; and 1.45 cm, 26 February 2001). The 2 highest 1 hour intensities occurred at Iron Mountain (1.35 and 0.94 cm h⁻¹ occurring on 6 July 2001 and 9 March 2001, respectively); the third highest intensity was Goldstone (0.85 cm h⁻¹, 24 November 2001). The highest 15, 10, and 5 min intensities were all recorded during one storm (6 July 2001) at Iron Mountain, 3.9, 4.9, and 7.3 cm h⁻¹, respectively. Precipitation data collected between March

**Figure 5.** Number of pebbles moving more than 0.042 m (long-term 2σ measurement uncertainty). (a) Down-gradient pebble movement, both lines, each site. (b) Total pebble movement, both lines, each site. DG, down-gradient movement; TO, total movement.

Range Road site, 10.4 cm. Our Goldstone gauge measured 2.2 cm more precipitation in 2001 than the permanent gauge installed 5 km away. The 3 maximum 1 day precipitation events occurred at Goldstone (1.80 cm, 6 March 2001; 1.68 cm, 11 January 2001; and 1.45 cm, 26 February 2001). The 2 highest 1 hour intensities occurred at Iron Mountain (1.35 and 0.94 cm h⁻¹ occurring on 6 July 2001 and 9 March 2001, respectively); the third highest intensity was Goldstone (0.85 cm h⁻¹, 24 November 2001). The highest 15, 10, and 5 min intensities were all recorded during one storm (6 July 2001) at Iron Mountain, 3.9, 4.9, and 7.3 cm h⁻¹, respectively. Precipitation data collected between March

**Figure 6.** Three distinct types of pebble movement were observed. (a) Bioturbation, which is characterized by small movements in any direction. Arrows point to pebbles highlighted with white circles. Each pebble is approximately 1-cm in diameter. The line is not straight, and a pebble is missing, indicating animal activity. (b) Channel movement, which is characterized by pebbles moving down-gradient great distances. Arrow shows pebble moved down channel. (c) Human disturbance, which is characterized by large or small movements in any direction. Photograph of the pebble line is parallel to contour at East Range Road. The tank track was not present when the pebble line was set out. Arrow shows one of many pebbles moved by tanks.
2002 and January 2005 show higher peak precipitation intensities. The highest 1 hour and 15, 10, 5, and 2 min intensities were all exceeded at Chemehuivi during a rain event on 13 August 2004 (maximum intensity of 5.3 cm h\(^{-1}\) during the 2 min interval).

The vegetation at the unimpacted sites, Chemehuevi and Goldstone, was larger and more closely spaced than at the two impacted sites (Table 1). Goldstone had twice as much vegetation as East Range Road and the average individual vegetation area was 29% greater. The percent vegetation cover at both Iron Mountain and East Range Road was less than 15%. Chemehuevi and Goldstone had 25% or more vegetation cover.

5. Results

Both field observations and survey data demonstrate that piedmont pebbles move and that such movement can be traced over time (Figure 5). In 24 months, 78% of our 1600 pebbles moved further than our 1σ measurement uncertainty and 53% moved more than 2σ. In 55 months, 85% of the 800 pebbles at Chemehuivi and Iron Mountain moved further than 1σ measurement uncertainty and 63% moved further than 2σ measurement uncertainty. Walking pebble lines during each field visit, we observed that many pebbles had not moved and others had moved small amounts in different directions (Figure 6a). Pebbles located on interfluves generally moved small amounts. A greater percentage of pebbles in channels than pebbles on interfluves moved beyond the 2σ measurement uncertainty. Indeed, a few pebbles in channels had been swept long distances (meters to tens of meters) down gradient, presumably by flowing water (Figure 6b). We also noted evidence suggesting that pebbles were bioturbated. Pebbles were buried by animals burrowing and moved small distances up, down, or parallel to contour. Animal burrowing was most intense at the Goldstone site, which had the most vegetation (Table 1). Many large animal burrows were located in creosote bush mounds; no burrows were observed in channels.

Pebbles were moved varying distances by vehicles at East Range Road. Some pebbles were scattered great distances by tanks. Others were disturbed as vehicles passed over the pebble line, mounding sediment into berms (Figure 6c). In contrast to bioturbation, during which an animal disturbs only a few pebbles, vehicles push many pebbles (up to 20 at the same time) creating berms and mounds in which pebbles are buried or on which pebbles are perched.

Probability density functions (PDFs) of pebble movement for each line at each site have different patterns reflecting different movement processes (Figure 7). At East Range Road, where pebbles are scattered primarily by off-road vehicles, pebble movement amounts are broadly distributed (Figure 7a and 8) because off-road vehicles scatter pebbles over a wide range of distances in random directions.
At other sites, such as Goldstone, pebbles have moved several centimeters up and down gradient, a dichotomous pattern we suspect is the result of bioturbation (Figure 7b). At Chemehuevi, pebbles on the line parallel to contour appear to have advected several centimeters down gradient and dispersed (Figure 7c), although such an apparent peak shift could result from a combination of systematic measurement errors. PDFs for cross-gradient movement reveal few pebbles moving more than the 2σ survey uncertainty, indicating that most pebbles, except those in channels, do not move significantly cross gradient (Figure 7d).

5.1. Pebble Recovery

Pebble recovery rates on our piedmont sites were much higher than in comparable studies of fluvial systems [Hassan and Church, 1992; Laronne and Carson, 1976; Ferguson and Wathen, 1998], varied between sites, and declined over time (Figure 9). Pebble recovery rates on surfaces not affected by off-road vehicles were high; after two years, we found 98% of the pebbles at Chemehuevi and 93% at Goldstone. In areas previously or currently impacted by off-road vehicles, recovery rates were lower, 87% at Iron Mountain and 75% at East Range Road. After an extremely large storm in December, 2004 pebble recovery dropped at the two sites we revisited, Chemehuevi (93%) and Iron Mountain (44%).

Some pebbles, lost when water flowed through channels, reappeared in subsequent surveys potentially biasing the interpretation of why and when pebbles moved. For example, at the Iron Mountain site, mean pebble movement on both lines increased between October 2001 and April 2002 even though there was very little rain during this period [Persico, 2002]. All of the large movements in April were pebbles that were lost or buried in a channel.

Figure 8. Bar and whisker plots of down-gradient, cross-gradient, and total pebble movement. The whiskers represent the 10th and 90th percentiles; the boxes are formed by the 25th and 75th percentiles, and the line is the median, 50th percentile, movement. Human-impacted sites (East Range Road (ER) and Iron Mountain (IM)) have greater pebble movement than the other two sites, demonstrating the ability of channels and off-road vehicles to transport pebbles significant distances. Numbers in parentheses on CG IM LPC are 75th and 90th percentiles. CM, Chemehuevi Mountains; GS, Goldstone; LDG, line oriented down gradient; LPC, line oriented parallel to contour. Number in parentheses on CG IM LDG is 90th percentile.
during the October survey (they were most likely buried in the high-intensity storm on 6 July 2002) and then resurfaced before the April survey. This is an example of survivorship bias influencing movement calculations. This bias, described by Hassan and Church [1992], reflects movement rates of found particles when in fact, lost particles exhibit a different behavior. Our very high recovery rates over the first two years (Figure 9) suggest such bias does not greatly affect our data for this time period; however, recovery rates dropped sufficiently so that by 2004 the meaning of the pebble location data is less certain and now represents only a lower limit for pebble movements. Thus we base most of our conclusions and all of our statistical tests on the first 2 years of data.

5.2. Influence of Channels and Interfluves on Pebble Movement

Pebble movement rates separated by piedmont landform position (channel versus interfluve) show pebbles in channels moved greater distances down gradient than pebbles on interfluves at the two sites where such data are available (IM, n = 400, p < 0.001; CM, n = 400, p < 0.001). However, median movement of channel pebbles remains less than 2 measurement uncertainty at both sites suggesting that most pebbles, even those in channels, did not move significantly during our 2 year study.

Figure 9. Pebble recovery rate. Pristine sites (Goldstone and Chemehuevi) have the highest pebble recovery rates. East Range Road has lower recovery rates because tanks scattered pebbles great distances. Drop in pebble recovery at Iron Mountain between months 12 and 15 and again at month 55 reflects flow in ephemeral channels. ER, East Range Road; IM, Iron Mountain; CM, Chemehuevi Mountain; GS, Goldstone.

Figure 10. Mean pebble movement increases over time. Diagrams show total, down-gradient, and cross-gradient pebble movement; dotted lines indicate storms with largest 1-hour intensities at each site. (a) Movement at Chemehuevi (CM). Movement after month 10 reflects channelized flow moving a few pebbles great distances. (b) Movement at East Range Road (ER). Down-gradient pebble movement after month 10 is caused by tank traffic or surface flow. (c) Small amount of mean pebble movement at Goldstone (GS). (d) Movement at Iron Mountain (IM). The large jump after month 12 is caused by channelized flow. Total movement (circles) is not visible where it is overlain by DG squares.
The data clearly show that pebbles located in ephemeral channels have the potential to move great distances down gradient during rainstorms when flow is concentrated in channels. At Chemehuevi, one channel pebble moved >25 m in two or more events over 12 months. At Iron Mountain, five pebbles moved down gradient ≥5 m and 17 pebbles moved ≥5 m cross gradient between May and October 2001. Most likely, all movement occurred during the large storm on 6 July 2001. One pebble moved an exceptional 18 m down gradient and 42 m cross gradient,

![Figure 11](image1.png)

**Figure 11.** Lognormal cumulative frequency plots, which show right-skewed distribution (caused by fluvial pebble transport) for all sites except Goldstone, where surface flow did not occur during our experiment. Cumulative frequency plots include all pebble measurements, regardless of distance moved.

![Figure 12](image2.png)

**Figure 12.** Mean pebble movement, May 2000 to April 2002 (cross gradient, down gradient, and total), at the four field sites. (a) Line oriented down gradient (LDG). (b) Line oriented parallel to contour (LPC). Bars represent 1σ standard error of the mean. ER, East Range Road; IM, Iron Mountain; CM, Chemehuevi Mountain; GS, Goldstone; TO, total movement; DG, down-gradient movement; CG, cross-gradient movement.
highlighting the importance of channels in long-distance pebble transport.

[33] At the 3 sites where pebbles could confidently be assigned to interfluves, the average pebble displacement down gradient on the interfluves was indistinguishable from our survey uncertainty and did not differ between sites. Over two years, less than half the interfluve pebbles (35% at CM, 45% at IM, and 50% at GS) moved beyond the 2σ uncertainty of our survey measurements. Some moved uphill, others down, but the small net average down-gradient movement (within our 2σ measurement uncertainty) likely reflects the influence of gravity and the tendency of disturbed pebbles to move down even the gentle piedmont slopes. In the absence of flowing water, these pebbles were likely moved biologically, turbated by the action of animals which inhabit the piedmont such as desert tortoises, jackrabbits, and lizards. In extreme events, such as December 2004, we observed that a single pebble, caught in channel-margin flow, had moved several meters on an interfluve.

[34] A spatially weighted average pebble movement rate can be calculated from pebble movement data (grouped by channel versus interfluve) and the percent channel cover of the surface determined by walking 1 km transects counting channels and quantifying their width (Table 1). For the Iron Mountain and Chemehuevi sites, such weighted averages rates are 0.066 and 0.126 m yr⁻¹, respectively. These rates are similar to those calculated directly from the pebble line data without weighting (0.093 and 0.089 m yr⁻¹) suggesting that our plots have a density of channels similar to the two piedmonts as a whole.

5.3. Statistical Analysis of Pebble Movement

[35] Mean down-gradient, cross-gradient, and total pebble movement increased over time at all sites (Figure 10). At all sites except Goldstone, where there are no channels, pebbles move in a step progression characterized by long periods of rest and short periods of rapid movement. The distinct jumps in average pebble movement reflect sediment transport events, predominantly runoff in channels at Iron Mountain and Chemehuevi and tank disturbance in possible combination with fluvial transport at East Range Road. Because constant traffic at East Range road destroys any channels that might form, we cannot separate these two mechanisms, both of which move pebbles.

[36] At each site, mean pebble movement was always greater than median pebble movement because a few pebbles moved great distances in channels, right skewing the distributions (Figures 8, 11, and 12). Median values of both down and cross-gradient movement remain low and similar through time, in most cases less than survey uncertainty indicating that most pebbles moved only small amounts during the two year survey period (Figure 11 and Table 3). The processes moving pebbles affect the mean and median movement values for each line at each site. Just a few far-moving channel pebbles inflate mean values but make little difference to medians; thus median values better reflect the most common movement distance (Figure 8). Means greatly exceeding medians predominate on lines oriented parallel to contour because such lines cross channels more frequently than lines oriented down gradient. Goldstone does not display this disparity because no channels cross pebble lines there (Table 3).

[37] Mean pebble movements varied between sites and between lines (Table 3). At each site, during every survey interval, the mean down-gradient, cross-gradient, and total pebble movements were higher on lines oriented parallel to contour than on lines oriented down gradient (Table 3). On 2 of 4 pebble lines oriented down gradient, mean down-gradient movement, 0.021, and 0.022 m, was similar to our 1σ measurement uncertainty. At East Range Road and Iron Mountain, the sites most disturbed by vehicles, mean pebble movement on the down-gradient line (0.080 m and 0.104 m) exceeded measurement uncertainty (0.042 m, 2σ). Pooling data from all sites, we find the conclusion that pebbles on lines oriented parallel to contour move faster than pebbles on lines oriented down gradient is statistically robust (p < .001, n = 1600).

[38] Human impact appears to increase pebble movement rates. Mean down-gradient movement of pebbles on lines parallel to contour over 24 months from May 2000 to April 2002 was greatest at the human-impacted sites, East Range Road and Iron Mountain, 0.68 and 0.35 m, respectively and less at the unimpacted Goldstone and Chemehuevi sites, 0.04 m and 0.34 m, respectively. Pooling data and comparing impacted versus non impacted sites suggests that pebbles at impacted sites indeed moved more quickly down gradient (p < 0.001, n = 1600). Down-gradient pebble movement at the currently active training site, East Range Road, is greater than at the site that was disturbed > 50 years ago, Iron Mountain (p = 0.001, n = 800).

[39] We compared mean total pebble movement speeds at channelized sites (Iron Mountain and Chemehuevi) and unchannelized sites (East Range Road and Goldstone), but found no significant difference (p = 0.2, n = 1600). We attribute this finding to the effect of tanks at East Range Road, both their influence on movement rates and their destruction of channels that otherwise might change the characterization of this site. If we do not include East Range Road in the analysis, then total pebble movement speeds are far greater at Iron Mountain and Chemehuevi, the two channelized sites than at Goldstone, the one unchannelized site (p = 0.019, n = 1200).

[40] Pebble movements were calculated for the Chemehuevi and Iron Mountain sites in January 2005, 55 months after the initial placement of the pebble lines and after the large storms of fall and winter 2004. Mean down-gradient pebble movements on the line parallel to contour were 0.99 m at Iron Mountain and 0.37 m at Chemehuevi, an increase of more than 200% at Iron Mountain, but only 10% at Chemehuevi. These data represent minimum movements because many pebbles were lost (Figure 9) and movements were calculated from the last known pebble positions.

6. Discussion

[41] Three distinct processes move pebbles across piedmonts: bioturbation, flow in ephemeral channels, and human activity (Figure 6). Bioturbation, which includes animal burrowing and surface disturbance, moves many pebbles centimeters to decimeters predominantly on interfluves. Bioturbated pebbles move up, down, or across the low-gradient slopes and are easily found unless they are buried by burrowing such as we observed at Goldstone (Figure 6). Pebbles in channels can move meters to tens of meters during flow events. Many pebbles moving in chan-
Pebble Speeds and Movement at the Mojave Desert Field Sites (May 2000 to April 2002)

Table 3.

<table>
<thead>
<tr>
<th>East Range Road</th>
<th>Iron Mountain</th>
<th>Goldstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site</td>
<td>LPC</td>
<td>LDG</td>
</tr>
<tr>
<td></td>
<td>Channel, n=159</td>
<td>Channel, n=158</td>
</tr>
<tr>
<td></td>
<td>Interfluve, n=41</td>
<td>Interfluve, n=42</td>
</tr>
<tr>
<td></td>
<td>Channel, n=200</td>
<td>Channel, n=200</td>
</tr>
<tr>
<td></td>
<td>Interfluve, n=200</td>
<td>Interfluve, n=200</td>
</tr>
<tr>
<td></td>
<td>LPC, n=0</td>
<td>LDG, n=0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total mean movement, m</th>
<th>0.737</th>
<th>0.684</th>
<th>0.238</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total median movement, m</td>
<td>0.000</td>
<td>0.080</td>
<td>0.022</td>
</tr>
<tr>
<td>DG mean movement, m</td>
<td>0.690</td>
<td>0.000</td>
<td>0.222</td>
</tr>
<tr>
<td>CC mean movement, m</td>
<td>0.254</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Total mean speed, m/yr</td>
<td>0.368</td>
<td>0.119</td>
<td>0.044</td>
</tr>
<tr>
<td>DG mean speed, m/yr</td>
<td>0.342</td>
<td>0.040</td>
<td>0.004</td>
</tr>
</tbody>
</table>

Percent DG pebble movements past 1 year: 45, 63, 80, 62, 79, 62, 60, 49, 56, 40, 71

Percent DG pebble movements past 2 years: 30, 44, 42, 34, 76, 30, 33, 27, 34, 21, 43

6.1. Pebble Recovery

[42] The number of pebbles recovered over time is influenced by land use. Sites impacted by human activity have lower pebble recovery rates than the pristine sites (Figure 9). The temporal patterns of pebble loss are similar at the two human-disturbed sites, but the process by which pebbles are lost differs. At Iron Mountain, pebbles are lost due to flow in channels. At East Range Road, pebbles are lost by the direct action of tanks, which move and bury many pebbles. Iron Mountain, the site recovering from Army impacts half a century ago, has wider channels than the other three sites (Table 1) suggesting that more pebbles will move when channels are activated by rainstorms. In contrast, at the unimpacted Goldstone site, which has very few channels, pebble loss is due entirely to animal burrowing. Pebble loss at Goldstone is gradual in comparison to the sharp drops in pebble recovery observed following rainstorms or off-road vehicular events at Iron Mountain and East Range Road, respectively (Figure 9).

6.2. Relation of Pebble Movement to Pebble Location on the Piedmont: Channel Versus Interfluve

[43] At two of the field sites, Iron Mountain and Chemehuevi, pebbles can be separated into two classes, pebbles located in channels and pebbles located between channels on interfluves. Field observations suggest that most flow was confined to channels during our study. Immediately after the December 2004 storm, fresh cutbanks and the filling of established channels by sediment, demonstrate the importance of lateral migration in reworking interfluve sediment. Similarly, cosmogenic nuclide data [Nichols et al., 2002] suggest that the interfluves are reworked on submillenial timescales probably by lateral channel migration that erodes the unconsolidated banks (such as we observed) or perhaps by piedmont-covering sheet flow [McGee, 1897] as demonstrated by the movement of a single interfluve pebble as well as fresh splay deposits caused by the winter 2004 storm. Our data clearly show that most pebble transport during our study period occurred in channels and the interfluves were stable geomorphic surfaces over the 4 year observation period. At Chemehuevi and Iron Mountain, only 34 and 53% of channel pebbles moved past our 2σ measurement uncertainty (Table 3), respectively, suggesting that flows of depth sufficient to dislodge pebbles did not fill entire channel widths.

6.3. Relation of Pebble Movement to Rainfall and Infiltration

[44] Pebble movements can be correlated to rainfall occurrence and intensity. For example, the largest mean pebble movement at the Iron Mountain site occurred between May 2001 and October 2001, during which time the largest and most intense rainstorm (6 July 2001) occurred
During this interval, it is probable that a rainfall event produced flows in two channels that moved 18 pebbles more than 5 m from their previous positions. Even larger storms occurred later in November and December 2004. Field observations once again suggest that such large, but rare events are responsible for most pebble movements in channels. In contrast, at all of the sites, only small movements were recorded between October 2001 and April 2002. This period of stability correlates with a paucity of rain. Importantly, even during the largest recorded events most pebbles located on interfluves are not moved unless by bank collapse.

During the intensive 2 year monitoring period, Iron Mountain had rainfall intensity sufficient to exceed our measured infiltration rate (Table 1). The highest 5 min rainfall intensity at Iron Mountain was 7.3 cm h\(^{-1}\), exceeding the measured infiltration rate (6.5 cm h\(^{-1}\)). During the infiltration test, 33 min of irrigation were required to initiate runoff. Although the 15 min (3.9 cm h\(^{-1}\) ) intensity of this storm was significantly lower than the infiltration rate (6.5 cm h\(^{-1}\) ), significant wetting of the soil probably occurred before the short cloudburst decreasing the amount of time needed to generate surface runoff. Furthermore, the infiltration rates that we measured represent upper limits because of lateral drainage from our small plots during the test [Limerinos, 1973].

Field observations (fresh bed forms and pebbles swept down stream) also suggest at least two periods of channelized runoff occurred at the Chemehuevi and Iron Mountain sites. Runoff events at Iron Mountains and Chemehuevi occurred sometime before the installation of rain gauges in November 2000 and again during the fall 2004 storms. Because only pebbles in channels moved great distances at our sites and because only the largest storms produced even minimal flow-induced features on the interfluves, we infer that most flow of sufficient depth and velocity to move 1 cm clasts was restricted to channels.

Mojave Desert summer monsoons are known for high rainfall intensity reaching 14.6 cm h\(^{-1}\) during the largest thunderstorms [Osborn and Renard, 1969, 1970]. On the basis of our measured infiltration rates, intensities of such magnitude would create runoff at Chemehuevi, East Range Road, and Iron Mountain. The largest 10 year storms still do not produce enough water to create runoff at Goldstone, suggesting that the surface at Goldstone rarely generates overland flow, an inference supported by the lack of channels on this surface. Thus very rare but high-intensity summer rains as well as longer duration, low-intensity winter storms must play a important role in pebble movement over long timescales, filling channels, eroding their weakly cohesive banks, and thus eventually moving pebbles on interfluves.

Pebble locations that are significantly down gradient from the range front, such as the site at Chemehuevi must have multiple runoff generation sources. It is unlikely that runoff moving pebbles in channels at the Chemehuevi site originates in mountains because they are 12 km away and a major road traverses the piedmont between the mountains and the pebble lines. Thus areas just upgradient of the pebble site, such as the extensive midpiedmont desert pavements must play an important role in creating runoff. These pavements and their extensive, low-permeability Av soil horizons likely function as local runoff sources during high-intensity rainfall events.

6.4. Relation of Pebble Movement to Piedmont Morphology

Pebble movement is correlated to different piedmont characteristics (Table 4). Specifically, pebble movement and the number and size of vegetation at each site are well and negatively correlated. Total mean movement and down-gradient mean movement of pebbles on the line parallel to contour have a strong negative correlation with the amount of vegetation found at each site, \( r^2 = 0.96 \) (\( p = 0.04 \)) and \( r^2 = 0.82 \) (\( p = 0.18 \)), respectively. The values of mean individual vegetation area, median individual vegetation area, and total vegetation area all display a high negative correlation with pebble movement because the Goldstone and Chemehuevi sites, where pebbles moved slowly, have larger and more abundant vegetation than the other sites (Table 1). Down-gradient movement on the line oriented parallel to contour has the greatest number of significant correlations; 8 out of 17 factors have \( r^2 \) values \( \geq 0.7 \) (\( p \leq 0.3 \)) including total number of plants/bushes/cacti, average individual vegetation area, median individual vegetation area, percent of surface covered by vegetation, average channel width and infiltration rate. There is also a positive correlation, \( r^2 = 0.68 \) (\( p \leq 0.32 \)), between down-gradient mean movement on the line oriented down gradient and the field site slope which could be attributed to increased movement of pebbles by gravity when pebbles are bioturbated.

The correlation between pebble movement rates and vegetation size and abundance suggests that vegetation changes piedmont micro morphology and thus pebble behavior. Vegetation, by means of living and dead roots, increases infiltration rates, thus decreasing the amount of surface flow [Dunne, 1980]. Vegetation acts as roughness elements, slowing down and dispersing surface runoff, perhaps inhibiting channel initiation. Increased surface microtopography, caused by vegetation mounds, traps wind-blow sand. The hummocky surface, created by vegetation mounds, forces pebbles to move up and down while in transport, thereby decreasing the overall down-gradient movement of pebbles.

6.5. Relation of Pebble Movement to Human Impact

The pebble data are consistent with human impact increasing pebble movement speeds. The most disturbed site, the off-road vehicle training complex at East Range Road, has the highest mean down-gradient speed of the four sites. Plausible physical explanations for the increased pebble speeds we observed include movement of pebbles in tank treads, compaction-reduced infiltration rates and increased surface runoff [Iverson, 1980] as well as disturbance of the cryptogamic crust which stabilizes the soil surface [Johansen, 1993]. Iron Mountain, the site disturbed more than half a century ago by Army training has lower mean down-gradient pebble speeds than East Range Road, speeds which are less than an undisturbed site of similar morphology (Chemehuevi); thus, although our data do not definitively show that past activities at Iron Mountain still affect pebble movement speeds, human impacts most certainly affect soil compaction and infiltration [Prose, 1985].
piedmont morphology and the pattern of sediment transport [Nichols and Bierman, 2001].

6.6. Comparison to Other Estimates of Desert Surface Sediment Transport Rates

[53] There are few other data sets with which to compare our findings. Stones traced on desert hillslopes [Abrahams et al., 1984] moved far slower than the piedmont stones we traced. Hillslope stone movements ranged from 1 to 100 cm over 16 years, averaging 10 cm. The hillslopes were steeper (7°–23°) than our field sites (<1°–5°) and the size of the particles used on hillslopes was mostly larger (8 to 70 mm). Abrahams et al. [1984] conclude that creep is the dominant process moving pebbles down slope, whereas we conclude that far-moving pebbles on piedmonts are transported primarily in channels where flow is concentrated. The difference in average movement speeds between slopes and piedmonts appears to reflect the importance of channelized flow on the latter landform.

[53] Recently, in situ produced cosmogenic nuclides have been used, in conjunction with interpretive models, to estimate rates of sediment movement across desert piedmonts integrated over millennia [Nichols et al., 2002, 2005]. At the Iron Mountain site, pebble speeds measured by tracing in this study are slower than those measured by Nichols et al. [2002] using in situ produced 10Be and 26Al. Cosmogenic data suggest pebbles move on average 0.65 to 1.22 m yr⁻¹ at Iron Mountain, whereas average down-gradient pebble speed determined by two years of pebble tracing at Iron Mountain is 0.18 m yr⁻¹, over four years pebble speed was greater, >0.22 m yr⁻¹. At the Chemehuevi Mountains, cosmogenic nuclide data suggest millennial-scale sediment movement of ~0.2 m yr⁻¹ [Nichols et al., 2005], similar to the 0.17 m yr⁻¹ measured in this study. Cosmogenic nuclide data from the East Range Road site suggest long-term sediment movement of 0.08 to 0.28 m yr⁻¹ [Nichols, 2002], slower than the two year average based on pebble tracing (0.34 m yr⁻¹).

[54] The two years during which we intensively monitored these piedmonts, did not include any exceptional storms. Thus our short-term estimates for pebble movement, for all but the highly disturbed East Range Road piedmont, likely underestimate long-term geologic transport rates, which reflect rare, decadal to centennial, rainfall and transport events [cf. Kirchner et al., 2001]. Indeed, after a very large storm in Fall 2004 we revisited two of the sites and documented significant channel reworking and large amounts of sediment transport. Many channel pebbles were lost, buried in situ or transported by stream flow. The loss of so many pebbles effectively ended the experiment but conclusively demonstrated the importance of rare, large magnitude events.

7. Conclusions

[55] Using 1600 painted pebbles, we measured short-term particle movement rates across 4 low-gradient desert piedmonts. Higher down-gradient mean pebble speeds were measured on human-impacted surfaces (East Range Road 0.34 m yr⁻¹) and sites previously impacted by off-road vehicles (Iron Mountain 0.18 m yr⁻¹) than on pristine sites, Goldstone and Chemehuevi, 0.02 m yr⁻¹ and 0.17 m yr⁻¹, respectively. Impacted sites also have lower pebble recovery rates after 2 years than pristine sites. During our study, significant down-gradient pebble transport occurred only in channels. On the interfluves, pebbles moved mostly small amounts, most likely the result of bioturbation. Although interfluves are the dominant piedmont morphology, shallow ephemeral channels, because they have the potential to move pebbles many meters in one event, control pebble movement rates. There is strong correlation between down-gradient pebble movement and piedmont micro morphology. Vegetation increases piedmont roughness decreasing down-gradient pebble movement speeds. Perhaps the loss of vegetation at human-impacted sites leads to higher
pebble movement speeds by eliminating vegetation-mound microtopography.

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