ABSTRACT. We used the cosmogenic nuclides, $^{10}$Be and $^{26}$Al, as cosmic-ray dosimeters to track sediment movement across the incised Chemehuevi Mountain piedmont surface. The piedmont extends 12 km from highland source basins to an ephemeral wash at the toe of the piedmont. Nuclide activity in sediment from steep source basins and from the bedrock pediment allows us to estimate rates of sediment generation and thus the rate at which sediment is supplied to the piedmont from weathering rock. Analysis of amalgamated sediment samples, collected along 4-km-long transects spaced at 1 km intervals from the mountain front provide context for understanding nuclide activity in sediment samples collected from two soil pits and demonstrate that sediment steadily moves down the channel network. Samples from the two soil pits allow for estimates of sediment deposition rates and thus further illuminate piedmont history.

Model results suggest that the Chemehuevi Mountains are eroding about 40 mm ky$^{-1}$ whereas the mountain-proximal bedrock pediment and the interpiedmont Sawtooth Range are eroding more slowly, 10 to 21 mm ky$^{-1}$ and 9.5 mm ky$^{-1}$, respectively. Cosmogenic nuclide profiles in two soil pits suggest a complex history of deposition (at rates between 19 to 39 mm ky$^{-1}$) and stability over the past 60 ky. A change in process from sediment deposition to sediment transport occurred distally on the piedmont approximately 8 ky ago, while the mid-piedmont piedmont surface has been stable since the mid-Holocene.

The incised Chemehuevi Mountain piedmont is changing at rates similar to planar and uniformly active piedmonts such as those adjacent to the Iron and Granite Mountains. All three piedmonts have average sediment grain velocities of decimeters per year, long-term source basin erosion rates between 35 to 40 mm ky, depositional hiatuses around the Pleistocene-Holocene climatic transition from moister to drier conditions, and Pleistocene deposition rates of 18 to 39 mm ky. Such similarity in piedmont behavior, despite clear differences in morphology and appearance, might suggest large scale geologic and climatic controls on the generation, transport and deposition of sediment in the Mojave Desert.

INTRODUCTION

Desert piedmonts, the broad, low-gradient surfaces that extend from mountain fronts, are ubiquitous in arid regions. Such landforms have been the focus of study and debate for over a century as researchers have tried to develop widely applicable
unifying theories of piedmont formation (McGee, 1897; Paige, 1912; Bull, 1964; Mabbutt, 1966; Denny, 1967; Hooke, 1968; Oberlander, 1974). However, complex interactions between tectonic activity, climate, lithology, and source basin characteristics call into question the utility of such wide-ranging theories (Cooke and Warren, 1973; Oberlander, 1974; Lecce, 1990; Bull, 1991).

Some workers suggest that desert piedmonts developed under climatic conditions different from today; therefore, the processes currently modifying piedmonts are not those that formed them (Oberlander, 1974; Dohrenwend, 1987; Quade, 2001). Others have tried to deduce the mechanisms of piedmont formation using contemporary piedmont morphometries (Schumm, 1962; Mammelickx, 1964). Since piedmonts are long-lived landforms and the processes that modify piedmonts operate slowly and irregularly, one cannot with certainty, use morphometric analysis or short-term process rates to represent the longer-term behavior (Abrahams and others, 1984; Edinger-Marshall and Lund, 1999; Kirchner and others, 2001).

In order to understand better the processes that shape and modify desert piedmonts, one needs to quantify long-term processes of the piedmont system from sediment source to sink. Such process models include the style and rate of sediment production in source areas such as the bedrock uplands, erosional pediments, and reworked alluvium. Sediment is then transported, in small increments over long time-scales, to sinks through ephemeral channel networks (Bull, 1997) or down piedmonts during sheet flood events (McGee, 1897; Rahn, 1967). The ephemeral channel sediment can either be transported to external drainages, terminate in ephemeral lakes, or be deposited and incrementally buried on piedmonts. By quantifying process rates and dating when these processes were active, we can refine models of how desert piedmonts respond to climatic and tectonic change.

In this paper, we chose the incised Chemehuevi Mountain piedmont in order to determine the sediment dynamics of a multi-surfaced piedmont. We use cosmogenic $^{10}$Be and $^{26}$Al activities to quantify the long-term surface history and the process rates active on the incised piedmont (12-km-long by 4 km-wide; fig. 1) and compare this history and behavior with that of planar piedmonts studied previously (Nichols and others, 2002). By using $^{10}$Be and $^{26}$Al in a geomorphic framework we can trace sediment from the source basins, through the ephemeral channel network, to deposition on the piedmont surface. Although this study focuses on soil-pit depth profiles, for context we also consider sediment generation in bedrock source basins and the mountain-proximal piedmont, as well as the distribution of nuclide activity down piedmont in amalgamated surface samples (Nichols and others, 2005). Together, these data allow us to quantify piedmont erosion, deposition, and transport over tens of thousands of years and in combination with previously published data (Nichols and others, 2002) allow us to begin speculating about Mojave Desert piedmont behavior in general.

AMERICAN SOUTHWEST PIEDMONT

Desert piedmonts of the American southwest are well represented in the geomorphological literature (Bull, 1963; Denny, 1967; Hooke, 1967; Oberlander, 1974; Parsons and Abrahams, 1984; McFadden and others, 1989; Edinger-Marshall and Lund, 1999; Nichols and others, 2002). Piedmont is a general term that does not suggest a specific process. Piedmonts, as a class of landforms, include erosional pediments as well as depositional alluvial fans, plains, or slopes. Pediments are low-gradient, erosional surfaces beveled across bedrock or alluvium (for example, McGee, 1897; Hadley, 1967; Whitaker, 1979); in contrast, alluvial fans are low gradient depositional surfaces. In some locations, pediments abut the mountains while alluvial fans are down gradient from pediments. Some piedmonts have a zone of transport, intermediate between the pediment and the alluvial ‘fans’, where neither net erosion nor net deposition occurs.
Only a few papers discuss piedmonts in their entirety and describe both the erosional and depositional processes acting on the same piedmont (Denny, 1967; Cooke and Mason, 1973).

Several hypotheses have been advanced to describe the formation of pediment surfaces, including lateral migration of channels to form the “smooth” floor (Gilbert, 1877; Paige, 1912; Johnson, 1932; Howard, 1942), parallel retreat of mountain fronts by slope processes (Lawson, 1915; Rich, 1935), denudation of mountain masses (Parsons and Abrahams, 1984), and weathering under a sediment mantle (Mabbutt, 1966). Similar attention has been paid to depositional alluvial fans or plains (Denny, 1967; Bull, 1977; Harvey, 1997). Alluvial fan research addresses fan morphometry (Bull, 1964, Rachocki, 1981), the processes that segment or incise alluvial fans (Denny, 1967; Bull, 1991), and the long-term behavior of alluvial fans (Hooke, 1967, 1968; McFadden and others, 1989).

Desert piedmonts have been studied using a variety of approaches: observation (Gilbert, 1877; McGee, 1897), soil development and chronosequences (McFadden and others, 1989; Eppes and others, 2002), mapping (Wells and others, 1987; House, 1999; Harvey and Wells, 2003; McDonald and others, 2003), and morphometric analysis (Mammerickx, 1964; Cooke, 1970; Cooke and Reeves, 1972; Abrahams and others, 1984). Each of these methods provides information over different temporal and spatial

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**Fig. 1.** Shaded relief map of the Chemehuevi Mountain piedmont. Black lines represent 4 km long transects spaced at 1 km intervals from the Chemehuevi Mountains. Black dots represent locations of source basin samples for both the Chemehuevi Mountains (CMV) and the Sawtooth Range (SRV). Black squares represent location of the soil pits (CP). The Sawtooth Range is located at CMT-4. Small black box in inset map shows the location of the Chemehuevi Mountain piedmont in the eastern Mojave Desert.
scales. For example, measurements of bedload or surface clast movement on desert surfaces over a few years can quantify short-term, small-scale processes of clast transport (Laronne and Reid, 1993; Edinger-Marshall and Lund, 1999; Persico and others, 2005); soil development can provide a relative longer-term history of deposition and erosion (McFadden and others, 1989; McAuliffe and McDonald, 1995; Eppes and others, 2002).

Over the past 20 years, sediment transport on piedmonts and in arid basins has received ample attention. Some studies characterize sediment movement after successive flood events (Schick and others, 1987; Laronne and Reid, 1993; Reid and Laronne, 1995) or over years of hillslope processes (Abrahams and others, 1984). Other studies use rainfall simulators to produce runoff and characterize the resulting sediment transport on desert piedmonts (Abrahams and others, 1988; Luk and others, 1993). Although physical sediment transport processes are well understood, the lack of long-term data precludes quantification of transport rates over long time scales.

Recent advances in the measurement of in-situ-produced cosmogenic nuclides now allow estimates of long-term sediment transport and deposition rates and patterns on desert piedmonts. The first attempt to use cosmogenic nuclides as sediment tracers provided only limiting sediment transport rates on the Ajo Mountain piedmont in Arizona (Pohl, 1995). A later study, at the Iron and Granite Mountains in California, used cosmogenic nuclides as tracers of piedmont sediment from the source basins to more than 5 km down the piedmont (Nichols and others, 2002). Surfaces of the planar piedmonts that they studied were uniformly active, well-mixed, and lacked stable or deeply incised segments. The long-term ($10^4$ years) average sediment velocities on the planar/active Iron and Granite Mountain piedmonts were decimeters per year (Nichols and others, 2002) and soil pits showed a change in piedmont behavior from an environment of slow sediment deposition to one of sediment transport at the Pleistocene-Holocene transition. Recent work (Nichols and others, 2005) has shown that cosmogenic nuclides can be used to construct sediment budgets for desert piedmonts.

**GEOLOGIC SETTING**

The Chemehuevi Mountains, which are a source of piedmont sediment and directly abut the piedmont, are located in the area of maximum crustal extension in the center of the 50 to 100 km-wide Colorado River extensional corridor (Howard and John, 1987). Extension occurred most rapidly between 19 and 15 Ma (John and Foster, 1993). After cessation of movement on the low angle ($\approx 15^\circ$) normal faults, erosion of the hanging wall rocks caused the granite, gneiss, metasedimentary rocks of the footwall to dome and create the Chemehuevi Mountains (John and Foster, 1993). A sequence of Tertiary volcanic rocks, the 1 km wide Sawtooth Range (John, 1987), crops out parallel to contour four kilometers from the mountain front (fig. 2).

The source basins that supply sediment to the Chemehuevi Mountain piedmont are small and narrow. Maximum relief is only 150 m; total basin area is 1.5 km$^2$ along the 4 km study area, 32 times less area that the 48 km$^2$ piedmont. The piedmont has three sections (fig. 3), typical of many in southwestern North America (Bull, 1991). The area between the Chemehuevi Mountains and the Sawtooth Range, a pediment, is a low relief (< 15 m) bedrock surface with patches of thin (< 2 m), well-varnished, pavemented alluvium capping rocks in some places (fig. 3A). Down gradient of the Sawtooth Range, bedrock is absent and the broad alluvial surfaces are capped by varnished pavements suggesting at least several thousand years of surface stability. The broad surfaces are incised up to 2 m by active ephemeral channels (fig. 3B). Approximately 10 km from the Chemehuevi Mountain front, the incised surface and the active ephemeral channels begin to merge into a wash surface (fig. 3C) similar to those that dominate the Granite and Iron Mountain piedmonts (Nichols and others, 2002). On
the wash surface, channels are less than 0.5 m deep and the varnished pavements are absent (fig. 3D).

Maximum clast sizes on the piedmont range from > 30 cm near the mountain front to only a few centimeters at the distal end of the piedmont (12 km away from the range front). Down gradient of the Sawtooth Range, surface clasts are rarely greater than 10 cm. The Chemehuevi Mountain piedmont merges with the Turtle Mountain piedmont at Chemehuevi Wash (> 13 km from the mountain front) and eventually drains to the Colorado River. The piedmont slopes 3.5° degrees at the mountain front and 0.7°, 12 km away.
The Chemehuevi Mountain piedmont is hot and dry. The city of Needles, California, located 55 km north of the Chemehuevi Mountain piedmont, has average temperatures of 11°C in January and 35°C in July and receives an average of 11.9 cm of rain annually (EarthInfo, 2001). Most of the precipitation comes either in short duration, intense summer cyclonic events or in long duration, less intense winter frontal storms.

**METHODS**

**Sediment Collection for $^{10}$Be and $^{26}$Al Analysis**

*Source sediment samples.*—We use $^{10}$Be activities measured in sediment exiting source basins to estimate sediment generation rates. Cosmogenic $^{10}$Be production decreases exponentially at depth (fig. 4). Thus, the rate that the surface is eroded is inversely proportional to the amount of $^{10}$Be in the produced sediment (Brown and others, 1995; Granger and others, 1996; Bierman and Steig, 1996).

Sediment is sourced from the Chemehuevi Mountains, the Sawtooth Range, and the mountain-proximal bedrock pediment between the two ranges (fig. 3). We determined long-term basin erosion and sediment generation rates of the Chemehuevi Mountains and the Sawtooth Range by analyzing sediment samples collected from...
streams exiting small, steep source basins. The Chemehuevi Mountain front is lithologically heterogeneous. We sampled sediment exiting three adjacent basins where porphyritic monzogranite, gneiss, and migmatite crop out (CMV-123) and three other adjacent basins where porphyritic biotite granodiorite and monzogranite crop out (CMV-456) (fig. 1). We combined the sediment from basins dominated by similar lithologies into one sample. We also mixed sediment exiting three small basins from the volcanic rock of the Sawtooth Range (SRV-123) to estimate its sediment yield. In order to estimate the sediment flux from the bedrock pediment, we collected several bedrock and colluvium samples from transects located at 1 and 3 km from the rangefront. Each transect was represented by both an amalgamated bedrock sample and an amalgamated colluvium sample (table 1).

Soil pit samples.—Soil-pit profiles of $^{10}$Be and $^{26}$Al allow us to quantify piedmont process rates (Lal and Arnold, 1985; Phillips and others, 1998; Clapp and others, 2001; Nichols and others, 2002). Although interpreting nuclide profiles is an inverse problem and the data can be modeled by using several different combinations of surficial processes and rates, generally, nuclide profiles in which activity increases at depth represent depositionsal surfaces while nuclide profiles in which activity decreases at depth represent stable or slowly eroding surfaces (fig. 4). Uniform nuclide activity profiles with depth represent either well-mixed soil profiles or very rapid deposition.

We used a backhoe to open 2 soil pits (2.34 m and 2.20 m deep) on the Chemehuevi Mountain piedmont (fig. 1). We noted soil horizonation, color, texture, structure, and carbonate percentage (table 1). The depth intervals of our soil samples were based on changes in soil stratigraphy and soil horizonation. Using these soil observations to define our sampling intervals, we sampled the entire pit wall.

Transect samples.—We laid out twelve transects spaced at 1-km intervals away from the Chemehuevi Mountain front (fig. 1). Along each transect we collected an equal volume of surface sediment (0 to 10 cm deep) from up to 21 sampling stations, spaced
at ~200 m intervals (fig. 1). We characterized each sampling station according to its geomorphic unit: ephemeral channel, abandoned terrace, colluvium, or exposed bedrock knobs. For each transect we combined sediment from like geomorphic units, resulting in multiple samples for each transect (table 2). The predetermined sampling stations were located in the field using a hand-held Garmin 12 Global Positioning System (GPS). A horizontal GPS uncertainty of several meters randomized the sampling locations.

**Laboratory Methods**

Samples were prepared for nuclide analysis at the University of Vermont. All samples were sieved and weighed. Grain size ranged from several centimeters to <125 μm. We analyzed the 500 to 850 μm size fraction to reduce the possibility of analyzing sediment transported by wind. We did not analyze different grain sizes because previous measurements of $^{10}$Be and $^{26}$Al in arid region alluvium determined that all grain sizes have statistically similar nuclide activities (Granger and others, 1996; Clapp and others, 2000, 2001, 2002). We assume that the 500 to 850 μm size-fraction represents all fluvially transported material.

All samples were ultrasonically etched with 6 N HCl and up to four 1 percent HF and 1 percent HNO$_3$ baths in order to remove any atmospheric $^{10}$Be and to isolate 30

### Table 1

**Soil pit descriptions for Chemehuevi Mountain piedmont**

<table>
<thead>
<tr>
<th>Pit</th>
<th>Horizon$^1$</th>
<th>Depth (cm)</th>
<th>Color$^2$</th>
<th>Texture$^3$</th>
<th>Structure$^4$</th>
<th>Carbonate$^5$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP1</td>
<td>1Av</td>
<td>0-8</td>
<td>7.5YR 4/4</td>
<td>10YR 6/4</td>
<td>SL</td>
<td>3 f/m pl</td>
</tr>
<tr>
<td></td>
<td>1Bw</td>
<td>8-20</td>
<td>7.5YR 5/4</td>
<td>10YR 6/3</td>
<td>LS</td>
<td>2 m/c sbk</td>
</tr>
<tr>
<td></td>
<td>1Ck</td>
<td>20-39</td>
<td>10YR 5/4</td>
<td>10YR 6/4</td>
<td>LS</td>
<td>2 f sbk</td>
</tr>
<tr>
<td></td>
<td>2Btkb</td>
<td>39-75</td>
<td>10YR 5/4</td>
<td>10YR 6/4</td>
<td>SL</td>
<td>2 c sbk</td>
</tr>
<tr>
<td></td>
<td>2Btkb2</td>
<td>75-96</td>
<td>7.5YR 5/4</td>
<td>10YR 6/3</td>
<td>SL</td>
<td>2 f sbk</td>
</tr>
<tr>
<td></td>
<td>2kB</td>
<td>96-130</td>
<td>10YR 6/3</td>
<td>10YR 7/2</td>
<td>L</td>
<td>m</td>
</tr>
<tr>
<td></td>
<td>3Ckox</td>
<td>130-189</td>
<td>10YR 5/3</td>
<td>10YR 6/3</td>
<td>SL</td>
<td>sg/st/m sbk</td>
</tr>
<tr>
<td></td>
<td>3Kb2</td>
<td>189-234</td>
<td>10YR 6/4</td>
<td>10YR 7/3</td>
<td>SL</td>
<td>m</td>
</tr>
<tr>
<td>CP2</td>
<td>1Av</td>
<td>0-5</td>
<td>10YR 5/3</td>
<td>10YR 6/4</td>
<td>SL</td>
<td>2 m pl</td>
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<td></td>
<td>1Ck2</td>
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<td>10YR 5/3</td>
<td>10YR 6/4</td>
<td>SL</td>
<td>sg</td>
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<tr>
<td></td>
<td>2Bwb</td>
<td>12-32</td>
<td>10YR 5/3</td>
<td>10YR 6/4</td>
<td>SL</td>
<td>2 m/c sbk</td>
</tr>
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<td>32-52</td>
<td>7.5YR 5/4</td>
<td>10YR 6/4</td>
<td>L</td>
<td>1 f sbk</td>
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<td></td>
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<td>SL</td>
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<tr>
<td></td>
<td>2Bwbk</td>
<td>68-89</td>
<td>7.5YR 5/4</td>
<td>7.5YR 7/3</td>
<td>L</td>
<td>2 m/c sbk</td>
</tr>
<tr>
<td></td>
<td>3Btkb</td>
<td>89-110</td>
<td>7.5YR 5/4</td>
<td>7.5YR 6/4</td>
<td>SL</td>
<td>2 f/m abk</td>
</tr>
<tr>
<td></td>
<td>3Btkb2</td>
<td>110-151</td>
<td>7.5YR 5/4</td>
<td>7.5YR 6/4</td>
<td>SL</td>
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<tr>
<td></td>
<td>3Kb2</td>
<td>151-188</td>
<td>7.5YR 6/4</td>
<td>7.5YR 7/3</td>
<td>SL</td>
<td>2 f/m abk</td>
</tr>
<tr>
<td></td>
<td>3Kb3</td>
<td>188-220</td>
<td>7.5YR 5/4</td>
<td>7.5YR 6/4</td>
<td>SL</td>
<td>1/2 f sbk</td>
</tr>
</tbody>
</table>

$^1$Numbers preceding the horizon designation represent the following, for CP1 1 = interbedded gravelly sand and sandy gravel, 2 = coarse poorly sorted angular gravelly sand, 3 = moderately sorted sandy gravel with coarse and fine lenses, for CP2 1 = Av with gravel 0–2 cm, silty sand 2–5 cm, 2 = interfingering lenses of sandy pebbles (Bwb2), and pebbly sands (Bwb), 3 = poorly sorted pebbly sand; $^2$Color determined using Munsel color charts; $^3$Textures are defined as SL = sandy loam, LS = loamy sand, L = loam; $^4$Structure defined as f = fine, m = medium, pl = platy, c = coarse, sbk = sub-angular blocky, sg = sand and gravel, f = fine, abk = angular blocky; $^5$Carbonate development defined as ef = effervesces with dilute HCl, m ef = mildly effervesces, ef v = effervesces violently.
to 40 g of pure quartz (Kohl and Nishiizumi, 1992). Samples underwent HF digestion with the addition of 250 μm of Be carrier followed by cation exchange to separate Be and Al (Bierman and Caffee, 2001). We used accelerator mass spectrometry (AMS) at Lawrence Livermore National Laboratory to determine $^{10}$Be/$^{9}$Be and $^{26}$Al/$^{27}$Al ratios. Samples ratios were normalized to standards prepared by Nishiizumi. All measurements were corrected using similar-sized procedural blanks. Blanks were prepared with each batch of seven samples and analyzed at the same time as other samples in the batch using AMS. We calculated $^{10}$Be and $^{26}$Al activities from $^{9}$Be (added as carrier) and native $^{27}$Al measured in duplicate aliquots, removed from HF solutions, by Inductively Coupled Argon Plasma Spectrometry – Optical Emission.

### Data Interpretation Methods

For data reduction, we used the nominal production rates (sea level and $> 60^\circ$ latitude) of 5.2 $^{10}$Be atoms g$^{-1}$ and 30.4 $^{26}$Al atoms g$^{-1}$ (Clark and others, 1996; Bierman and others, 1996; Stone, 2000; Gosse and Phillips, 2001). We scaled the nominal production rates to the Chemehuevi altitude and latitude (Lal, 1991), using only neutrons.

In order to translate measured nuclide activities into process rates and piedmont histories, we use several mathematical models. Sediment generation rate models are based on the nuclide activity of sediment exiting the source basins (Brown and others, 1995; Bierman and Steig, 1996; Granger and others, 1996). Rates of sediment deposition on the piedmont are based on soil pit data and the models developed in Lal and Arnold (1985), Phillips and others (1998), Clapp and others (2001), and Nichols and others (2002). Estimates of the stability (or age) of alluvial surfaces are calculated using the approach of Anderson and others (1996), and checked with soil development indices for similar soils in the Mojave Desert and southern Great Basin (Harden and others, 1991a, 1991b; McDonald, 1994; McFadden and McAuliffe, 1997). We used these models and nuclide data from piedmont transects to develop a mass and nuclide budget for the Chemehuevi Mountain piedmont (Nichols and others, 2005). The nuclide budget constrains the long-term average sediment speeds down the piedmont.

We make several simplifying assumptions in order to use these models. We assume that the processes active on the surface operate on a time scale much shorter than the nuclide half-lives. Therefore, the rate and distribution of surface processes, not radioactive decay, control nuclide activities. We assume that there is no preferential dissolution of the other minerals and thus, no quartz enrichment in the arid environment of the Chemehuevi Mountains (Small and others, 1999; Riebe and others, 2001a).

### Results

All 39 samples from the Chemehuevi Mountains and the adjoining piedmont have been well dosed by cosmic radiation allowing us to make relatively precise measurements of both nuclides. Measurement precision averaged 3 percent for $^{10}$Be and 5 percent for $^{26}$Al. Because $^{10}$Be and $^{26}$Al data are well correlated and consistent (fig. 5), we base most of our interpretations on $^{10}$Be, the more precisely measured nuclide. The $^{26}$Al to $^{10}$Be ratios for 32 of the 39 samples are within 1σ of 6.0, the nominal ratio at production (Nishiizumi and others, 1989); at 2σ, the ratios for all but 1 sample are indistinguishable from 6.0 (fig. 5; table 2). The ratio data indicate that the sediment we sampled has not been buried after or during exposure below the depth of significant nuclide production ($>1$ or $2$ m) for more that $10^5$ ky (Nishiizumi and others, 1991; Bierman and others, 1999).

#### Sediment Source Samples

The Chemehuevi Mountain source basin samples (CMV-123 and CMV-456) have nuclide activities that overlap at 1σ (table 2) indicating similar cosmic-ray dosing.
Table 2
Cosmogenic nuclide data for Chemehuevi Mountain piedmont

<table>
<thead>
<tr>
<th>Sample</th>
<th>Elevation (m)</th>
<th>Northing (UTM)</th>
<th>Easting (UTM)</th>
<th>$^{10}$Be activity (10$^6$ atoms g$^{-1}$)</th>
<th>$^{26}$Al activity (10$^6$ atoms g$^{-1}$)</th>
<th>$^{26}$Al/$^{10}$Be</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMV-123</td>
<td>790</td>
<td>3832763</td>
<td>718571</td>
<td>0.132 ± 0.004</td>
<td>0.82 ± 0.054</td>
<td>6.22 ± 0.46</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3832571</td>
<td>718796</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3832263</td>
<td>718885</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>CMV-456</td>
<td>790</td>
<td>3831700</td>
<td>719904</td>
<td>0.128 ± 0.004</td>
<td>0.82 ± 0.051</td>
<td>6.40 ± 0.45</td>
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<tr>
<td></td>
<td></td>
<td>3831491</td>
<td>719954</td>
<td></td>
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<td></td>
<td>3831059</td>
<td>720463</td>
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<tr>
<td>CMT-1B</td>
<td>670</td>
<td>3829529</td>
<td>720542</td>
<td>0.216 ± 0.007</td>
<td>1.25 ± 0.061</td>
<td>5.78 ± 0.34</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3832482</td>
<td>717860</td>
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</tr>
<tr>
<td>CMT-1C</td>
<td>600</td>
<td>3828156</td>
<td>719046</td>
<td>0.195 ± 0.005</td>
<td>1.16 ± 0.072</td>
<td>5.92 ± 0.41</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3831125</td>
<td>716328</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>CMT-3C</td>
<td></td>
<td>3826824</td>
<td>717558</td>
<td>0.217 ± 0.006</td>
<td>1.30 ± 0.067</td>
<td>6.03 ± 0.36</td>
</tr>
<tr>
<td>CMT-3F</td>
<td></td>
<td>3829774</td>
<td>714858</td>
<td>0.275 ± 0.008</td>
<td>1.83 ± 0.123</td>
<td>6.66 ± 0.49</td>
</tr>
<tr>
<td>CMT-3H</td>
<td></td>
<td>3832471</td>
<td>716069</td>
<td>0.455 ± 0.011</td>
<td>2.58 ± 0.121</td>
<td>5.67 ± 0.30</td>
</tr>
<tr>
<td>CMT-5F</td>
<td></td>
<td>3823471</td>
<td>713399</td>
<td>0.381 ± 0.011</td>
<td>2.38 ± 0.114</td>
<td>6.25 ± 0.35</td>
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<tr>
<td>CMT-7C</td>
<td>500</td>
<td>3824108</td>
<td>714583</td>
<td>0.434 ± 0.012</td>
<td>2.65 ± 0.127</td>
<td>6.09 ± 0.34</td>
</tr>
<tr>
<td>CMT-9C</td>
<td>470</td>
<td>3827076</td>
<td>711926</td>
<td>0.435 ± 0.010</td>
<td>2.43 ± 0.124</td>
<td>6.13 ± 0.35</td>
</tr>
<tr>
<td>CMT-9F</td>
<td></td>
<td>3822684</td>
<td>712374</td>
<td>0.420 ± 0.011</td>
<td>2.47 ± 0.116</td>
<td>5.75 ± 0.31</td>
</tr>
<tr>
<td>CMT-12C</td>
<td>430</td>
<td>3825029</td>
<td>705667</td>
<td>0.471 ± 0.015</td>
<td>2.74 ± 0.130</td>
<td>5.81 ± 0.33</td>
</tr>
<tr>
<td>CMT-12F</td>
<td>430</td>
<td>3822820</td>
<td>716955</td>
<td>0.497 ± 0.013</td>
<td>2.97 ± 0.162</td>
<td>5.99 ± 0.36</td>
</tr>
<tr>
<td>SRV-123</td>
<td>590</td>
<td>3830310</td>
<td>716253</td>
<td>0.462 ± 0.018</td>
<td>2.71 ± 0.16</td>
<td>5.87 ± 0.42</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3830057</td>
<td>716353</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>CP1 0-8</td>
<td>520</td>
<td>3826877</td>
<td>715949</td>
<td>0.392 ± 0.014</td>
<td>2.48 ± 0.146</td>
<td>6.32 ± 0.44</td>
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<tr>
<td>CP1 8-20</td>
<td></td>
<td>3832676</td>
<td>715949</td>
<td>0.376 ± 0.011</td>
<td>2.35 ± 0.112</td>
<td>6.27 ± 0.35</td>
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<tr>
<td>CP1 20-39</td>
<td></td>
<td>3832775</td>
<td>715949</td>
<td>0.353 ± 0.011</td>
<td>2.27 ± 0.108</td>
<td>6.42 ± 0.37</td>
</tr>
<tr>
<td>CP1 39-75</td>
<td></td>
<td>3832876</td>
<td>715949</td>
<td>0.433 ± 0.013</td>
<td>2.72 ± 0.138</td>
<td>6.28 ± 0.37</td>
</tr>
<tr>
<td>CP1 75-96</td>
<td></td>
<td>3832977</td>
<td>715949</td>
<td>0.484 ± 0.014</td>
<td>2.98 ± 0.141</td>
<td>6.16 ± 0.34</td>
</tr>
<tr>
<td>CP1 96-115</td>
<td></td>
<td>3833078</td>
<td>715949</td>
<td>0.474 ± 0.016</td>
<td>2.89 ± 0.154</td>
<td>6.08 ± 0.38</td>
</tr>
<tr>
<td>CP1 115-130</td>
<td></td>
<td>3833179</td>
<td>715949</td>
<td>0.371 ± 0.011</td>
<td>2.42 ± 0.118</td>
<td>6.53 ± 0.38</td>
</tr>
<tr>
<td>CP1 130-150</td>
<td></td>
<td>3833280</td>
<td>715949</td>
<td>0.364 ± 0.016</td>
<td>2.08 ± 0.106</td>
<td>5.72 ± 0.38</td>
</tr>
<tr>
<td>CP1 150-170</td>
<td></td>
<td>3833381</td>
<td>715949</td>
<td>0.282 ± 0.009</td>
<td>1.94 ± 0.095</td>
<td>6.87 ± 0.41</td>
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<tr>
<td>CP1 170-190</td>
<td></td>
<td>3833482</td>
<td>715949</td>
<td>0.305 ± 0.010</td>
<td>1.83 ± 0.105</td>
<td>6.02 ± 0.40</td>
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<tr>
<td>CP1 190-234</td>
<td></td>
<td>3833583</td>
<td>715949</td>
<td>0.557 ± 0.016</td>
<td>3.19 ± 0.161</td>
<td>5.72 ± 0.33</td>
</tr>
<tr>
<td>CP2 0-12</td>
<td>420</td>
<td>3822105</td>
<td>712484</td>
<td>0.430 ± 0.014</td>
<td>2.72 ± 0.125</td>
<td>6.34 ± 0.35</td>
</tr>
<tr>
<td>CP2 12-32</td>
<td></td>
<td>3832206</td>
<td>712484</td>
<td>0.428 ± 0.012</td>
<td>2.60 ± 0.123</td>
<td>6.06 ± 0.33</td>
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<tr>
<td>CP2 32-52</td>
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<td>3832307</td>
<td>712484</td>
<td>0.427 ± 0.012</td>
<td>2.42 ± 0.128</td>
<td>5.68 ± 0.34</td>
</tr>
</tbody>
</table>
histories and thus source-basin erosion rates (table 2). The average nuclide activity of the sediment delivered from basins in the Sawtooth Range is more than three times higher than the nuclide activity in sediment from Chemehuevi Mountain source basins (table 2). The $^{10}$Be activity of the bedrock and colluvium from the mountain-proximal piedmont has nuclide activities intermediate between those of the Chemehuevi Mountain and Sawtooth Range source basins (table 2).

Soil Pit Samples

The two soil pits on the Chemehuevi Mountain piedmont have different nuclide activity trends as a function of depth indicating that the mid-piedmont, ~6 km from

Table 2 (continued)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Elevation (m)</th>
<th>Northing (UTM)</th>
<th>Easting (UTM)</th>
<th>$^{10}$Be activity ($10^5$ atoms g$^{-1}$)</th>
<th>$^{26}$Al activity ($10^5$ atoms g$^{-1}$)</th>
<th>$^{26}$Al/$^{10}$Be</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP2 52-68</td>
<td>0.489 ± 0.014</td>
<td>2.74 ± 0.130</td>
<td>5.62 ± 0.31</td>
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<tr>
<td>CP2 68-89</td>
<td>0.521 ± 0.015</td>
<td>3.39 ± 0.162</td>
<td>6.50 ± 0.36</td>
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<td></td>
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</tr>
<tr>
<td>CP2 89-110</td>
<td>0.542 ± 0.015</td>
<td>3.21 ± 0.154</td>
<td>5.93 ± 0.33</td>
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</tr>
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<td>CP2 110-130</td>
<td>0.546 ± 0.016</td>
<td>3.17 ± 0.149</td>
<td>5.80 ± 0.32</td>
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<tr>
<td>CP2 130-151</td>
<td>0.560 ± 0.016</td>
<td>3.39 ± 0.158</td>
<td>6.06 ± 0.33</td>
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</tr>
<tr>
<td>CP2 151-170</td>
<td>0.472 ± 0.013</td>
<td>2.91 ± 0.148</td>
<td>6.16 ± 0.35</td>
<td></td>
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</tr>
<tr>
<td>CP2 170-188</td>
<td>0.498 ± 0.014</td>
<td>3.00 ± 0.152</td>
<td>6.02 ± 0.35</td>
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<tr>
<td>CP2 188-220</td>
<td>0.537 ± 0.015</td>
<td>3.33 ± 0.150</td>
<td>6.20 ± 0.33</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1Sample notation: CM = Chemehuevi Mountain, V = source basin sample, triple numbers after valley samples represent amalgamation of three valley samples, T = transect sample, B = amalgamated bedrock, C = channel sediment, S and H = amalgamated colluvium, F = terrace sediment, single number after transect sample represents the distance from the mountain front, SR = Sawtooth Range, CP1 represents soil pit located ~6 km from the Chemehuevi Mountain front, CP2 represents soil pit located ~12 km from the Chemehuevi Mountain front, numbers located after CP% represent depth intervals in centimeters. All elevations are average mountain valley elevation, based on basin hypsometry, and average elevation of the 4 km-long transects. Northing and Easting values are NAD 27 zone 11S UTM datum. Coordinates are listed for all averaged valley samples. Endpoint coordinates are listed for transect samples. Error is counting statistics from AMS with 2% uncertainty for stable Be and 4% uncertainty for stable Al, combined quadratically.

Fig. 5. Comparison of $^{10}$Be data and $^{26}$Al data. Regression line suggests a $^{26}$Al/$^{10}$Be ratio of 5.9 for entire data set, suggesting no long-term ($10^5$ yr) burial after or during exposure of sediment samples.
the mountain front, and distal piedmont, ~12 km from the mountain front, have different depositional and erosional histories. The soil pit located 6 km from the mountain front (CP1) has $^{10}$Be activities that both decrease and increase as a function of depth. A discontinuity in nuclide activity is associated with a buried soil at 39 cm (fig. 6). The highest nuclide activity is in the sample from the bottom of the pit.

The soil pit 12 km from the mountain front (CP2) has nuclide activities that mostly increase as a function of depth (fig. 7). The top-most 52 cm of sediment is well mixed and there is no variation in the $^{10}$Be activity (fig. 7A). At 52 cm, there is a discontinuity with higher $^{10}$Be activities below. From 52 cm to 220 cm, the $^{10}$Be activities increase systematically as a function of depth with the exception of a second discontinuity at 151 cm.

**Transect Samples**

We collected separate samples for each geomorphic unit along 12 transects spaced at 1-km intervals from the Chemehuevi Mountains. We analyzed samples from transects 1, 3, 5, 7, 9, and 12 (fig. 8). Nuclide activities in ephemeral channel sediment...
increase in a nearly linear fashion down piedmont (fig. 8). Nuclide activities of amalgamated sediment from the incised alluvial surface (5 to 9 km; E) do not increase systematically down piedmont and are higher than the activities of ephemeral channel sediment suggesting a longer exposure history (fig. 8). At distances greater than 10 km from the mountain front, the incised alluvial surface merges with a wash surface that lacks a varnished pavement (fig. 3B). The average nuclide activity of sediment collected from the interflues within the wash surface 12 km from the rangefront is inseparable from the ephemeral channel sediment nuclide activity at 1σ (fig. 8). Amalgamated colluvium and bedrock samples (LETED), collected 1 km and 3 km from the mountain front, have significantly higher nuclide activities than samples from the ephemeral channels (fig. 8) indicating longer exposure histories.

**Discussion**

Nuclide data allow unique insights into piedmont behavior and history. The results from the incised, multi-surfaced Chemehuevi Mountain piedmont, when considered along with previous results from the active and planar Iron and Granite Mountain piedmonts that do not exhibit varnished pavement surfaces (Nichols and...
allow us to generalize and constrain piedmont process rates that have, until recently, not been quantified. Such results allow us to address long-standing questions about the distribution of surficial processes and the Late Pleistocene histories of piedmonts that have distinct differences in morphology.

**Sediment Generation**

The average surface lowering rates of the bedrock sediment sources are 41 mm ky$^{-1}$ for the Chemehuevi Mountain drainage basins, 21 and 10 mm ky$^{-1}$ at 1 and 3 km on the mountain-proximal piedmont, respectively, and 9.5 mm ky$^{-1}$ in the Sawtooth...
Range drainage basins (table 3). Estimated rates of basin-wide lowering for the Chemehuevi source basins are similar to the long-term basin-wide lowering rates measured using cosmogenic nuclides in several other arid to semi-arid drainage basins while lowering rates in the Sawtooth Range are a factor of 2 to 6 slower.

Adjusting for previously accepted nuclide production rates used in previous studies, the Chemehuevi Mountains are lowering at rates similar to the granitic Iron and Granite Mountains in the Mojave Desert (33 and 31 mm ky\(^{-1}\); Nichols and others, 2002), the granite, gneiss, and schist in the Nahal Yael basin, Israel (28 ± 5 mm ky\(^{-1}\); Clapp and others, 2000), and a gneissic basin in Yuma Wash, Arizona (26 mm ky\(^{-1}\); Clapp and others, 2002). The basin-wide lowering rates at the Chemehuevi Mountains are also similar to basin-wide lowering rates of the granitic Fort Sage Mountains (30 to 60 mm ky\(^{-1}\); Granger and others, 1996) and to several tectonically quiescent basins in the Sierra Nevada (range from 24 to 61 mm ky\(^{-1}\) for six different basins; Riebe and others, 2001a, 2001b). Similarities in the erosion rates of quartz-rich crystalline rocks across different climatic settings suggest that factors, such as lithology and slope, play significant roles in controlling sediment generation rates.

**Piedmont Sediment**

Nuclide activities in ephemeral channel sediment increase steadily down piedmont. The activity of ephemeral channel sediment is the cumulative result of both cosmic-ray dosing of sediment in the channel and the addition of differentially-dosed sediment from four distinct sources, the Chemehuevi Mountains (10%), the bedrock piedmont (39%), the Sawtooth Range (3%), and the incised alluvial surface (48%).
The nuclide activity of sediment released from the incised alluvial surface, from 5 to 9 km down piedmont, is higher than the activity of the ephemeral channel sediment suggesting that the incised surface has been stable for an extended period of time, consistent with observations of a varnished surface pavement (fig. 8). At 12 km from the rangefront, the nuclide activities of channel sediment (CMT 12C = $4.71 \pm 0.15 \times 10^5$ $^{10Be}$ atoms g$^{-1}$) and the adjacent interfluve sediment (CMT 12F = $4.97 \pm 0.13 \times 10^5$ $^{10Be}$ atoms g$^{-1}$) are similar suggesting that sediment is temporarily stored in interfluves, and is repeatedly reworked, on timescales less than the few millennia required to generate measurably different nuclide activities.

The current pattern of increasing nuclide activity down ephemeral channels has not always been characteristic of the Chemehuevi Mountain piedmont. The incised alluvial surface, from 5 to 9 km, has uniform nuclide activities today (fig. 8). Such activities suggest that a pulse, or several pulses, of sediment could have covered that entire area in a relatively short period, probably less than a few thousand years. Following the incision of that alluvial surface, the current trend of increasing nuclide activities down the ephemeral channel network resulted from cosmic ray bombardment during sediment transport and the addition of more highly dosed sediment from outcrops up-piedmont. By calculating the mass flux of sediment and the resulting nuclide flux down the ephemeral channels, we determined the nuclide activity resulting from cosmic ray bombardment of sediment while in the channels and thus the time that channel sediment was exposed during transport down piedmont (Nichols and others, 2005). For the Chemehuevi Mountain piedmont average sediment speeds are 10s of meters per year in the confined bedrock channels, meters per year in the confined incised alluvium, and only decimeters per year in the unconfined and highly permeable active alluvial surface (Nichols and others, 2005).

Soil Pit Interpretive Models

Cosmogenic nuclide analysis of soil profiles provides insight into the past rates and distribution of processes that have operated on the Chemehuevi Mountain piedmont. Specifically, interpretive models of the nuclide activity in the 2-m deep soil profiles that we sampled and analyzed allow for quantification of the rates at which sediment, or more specifically bedload, is deposited on the piedmont, the timing and duration of depositional hiatuses (Lal and Arnold, 1985; Nichols and others, 2002), and the duration of surface stability (Anderson and others, 1996). Qualitatively, intervals of slow aggradation are defined by increasing nuclide activity with depth; stable paleosurfaces are identified by decreasing nuclide activity with depth and depositional hiatuses are identified by nuclide activity discontinuities with depth (fig. 4). Below we interpret nuclide data and field observations from the two soil pits in the context of soil morphologic and stratigraphic observations. Each soil pit history model represents what we consider to be the most parsimonious scenario of erosion and deposition based on the nuclide data and the soils observations. To determine the precision of each soil pit model, we used Monte Carlo simulation. We generated normally distributed values for the activity of each sample from each soil pit profile considering each sample’s analytical uncertainty. Based on the 20 model runs where different activities for each sample were used, we determined the mean and standard deviation of each parameter in the soil pit results (hiatus and deposition duration as well as aggradation rate).

Soil pit in active surface 12 km from mountain front (CP2).—The distal portion of the Chemehuevi Mountain piedmont is characterized by an active surface that exhibits neither varnish nor pavement; ephemeral channels are < 30 cm deep (fig. 3D). The soil pit excavated on this portion of the piedmont (CP2) has an uppermost interval where nuclide activities were uniform, two lower intervals where nuclide activities increased with depth, and two discontinuities where nuclide activity changed abruptly
Using the model of Nichols and others (2002) to interpret the nuclide data, we describe a plausible piedmont history in the vicinity of the pit over approximately the past 68 ky.

Nuclide data indicate that the lower piedmont is an area of sediment transport and deposition. The upper 52 cm is well-mixed (fig. 7) and thus probably represents material actively in transport. We make this assertion based not only on field evidence but also on the similarity between the nuclide activity in this topmost sample and the average nuclide activity of ephemeral channel sediment in the amalgamated transect closest to the soil pit (CMT 12). An abrupt increase in nuclide activity below 52 cm could reflect a depositional hiatus lasting for about the last $8 \pm 2$ kys, the time required to create the nuclide discontinuity under 52 cm of reworked sediment. The pattern of nuclide activity in samples collected between 52 cm and 151 cm suggests sediment was deposited at $39 \pm 4$ mm ky$^{-1}$ for 25 ky. Below 151 cm, there is a distinct step to lower $^{10}$Be activities perhaps reflecting a change in sediment source at that time, about 33 ky ago. From 151 cm to the bottom of the pit at 220 cm, sediment was deposited at $20 \pm 1$ mm ky$^{-1}$ for 35 ky. The total time represented in pit CP2 is $\sim 68$ ky (fig. 7).

The rates and style of the deposition suggested by nuclide-based model agree well with observations of soil development. The soil pit excavated into this portion of the piedmont has soil stratigraphic relationships that are consistent with cumulic soil profile development. Cumulic soil profiles are formed under conditions of episodic deposition, in this case bedload deposition, leading to a slowly rising land surface with soil development between the depositional episodes. The result of cumulic soil development is a relatively under-developed soil profile, over thickened where the soil associated with any one depositional hiatus is “welded” to the bottom of the soil associated with the overlying depositional unit, making individual buried soils difficult to identify. Such cumulic soil development is consistent with the nuclide model of a slowly aggrading surface.

Soil pit in mid-piedmont incised alluvial surface (CP1).—The middle section of the Chemehuevi Mountain piedmont has extensive varnished and pavemented alluvial surfaces that have been incised by active ephemeral streams (fig. 3B). The presence of the pavement, an Av-horizon, and the development of a weak B-horizon suggest that the surface has been stable for thousands but not tens of thousands of years (McFadden and others, 1989). The field observations of stability are supported by transect data which show that the nuclide activity of incised piedmont sediment is significantly higher than the nuclide activity of the ephemeral channel sediment (fig. 8). Below the stable surface, increasing and decreasing trends of nuclide activity with depth suggest a complex history of deposition, stability, and erosion at the location of the mid-piedmont soil pit CP1 (fig. 6). Here, we present a plausible, although non-unique, surface history considering both nuclide and soils data together.

Taken at face value, the smooth decrease of nuclide activity with depth between the surface and the first buried soil suggests that the top 39 cm has been stable for about 26 ky (model of Anderson and others, 1996) exceeding by several fold the age unambiguously suggested by the lack of soil development. Since there is substantial agreement in the soil geomorphology community that a 26-ky-old soil should exhibit soil development that is more advanced than the observed Av-Bw-Ck horizonation at CP1 (Harden and others, 1991a, 1991b; McDonald, 1994; McFadden and McAuliffe, 1997), we conclude that the cosmogenic data and model do not accurately represent the surface age.

A jump to higher nuclide activity occurs abruptly at the buried soil horizon (39 cm; fig. 6). The presence of this Bt-horizon (table 1) suggests little deposition and minimal sediment erosion. Therefore, assuming the discontinuity in nuclide activities represents either a period of sediment transport or a period of surface stability, the
duration of the depositional hiatus is ~26 ± 3 ky (Anderson and others, 1996; Nichols and others, 2002). Increasing nuclide activities with depth, from 39 cm to 96 cm, suggest deposition rates of 19 ± 1 mm ky⁻¹ for 30 ky (fig. 6). Below 96 cm, nuclide activities decrease with depth, similar to the top 39 cm, suggesting sediment from 190 cm to 96 cm was deposited rapidly. The decrease in deposition rate at 96 cm happened quickly. The 96 cm boundary is in the middle of the Btkb2 soil horizon thus, the nuclide activities in samples above and below 96 cm are consistent with a decrease in deposition rate, rather than surface stability. The total time represented in the soil pit to a depth of 190 cm is ~61 ky.

The bottom of the soil pit, from 190 cm to 234 cm represents a second buried soil horizon (table 1). At 190 cm, the soil changes from a Ck horizon above to a K horizon below. Such a pattern is consistent with stripping of soil that was previously above the K horizon followed by deposition and formation of the current soil. Using a model that assumes surface production of nuclides in the sediment below 190 cm, the depositional hiatus lasted at least 36 ky. This is a minimum duration, because sample CP1 190-234 was buried under an unknown amount of now-eroded sediment mandating a lower effective production rate and thus, a longer depositional hiatus.

Sediment pit comparison.—The model ages and process rates at CP1 (the mid-piedmont site) and CP2 (the distal site) are geomorphically and temporally consistent. Deposition rates at CP1 from ~61 to 30 ky were 19 ± 1 mm ky⁻¹ (fig. 6). Deposition rates at CP2 from ~68 to 33 ky were 20 ± 1 mm ky⁻¹ (fig. 7). The similarity in both the timing and rate of deposition at these widely separated sites suggests that the piedmont as a whole was aggrading during the last interstade. At 33 ky, the deposition rate at the distal CP2 site increased to 39 ± 4 mm ky⁻¹ coincident with an increase in nuclide activity of the incoming sediment (fig. 7). This change in deposition rate and in the nuclide activity of the sediment arriving at the distal CP2 site is both coincident and consistent with the changes occurring up piedmont at site CP1. At CP1, we infer a change from deposition to erosion at ~30 ky (fig. 6). Incision of the mid-piedmont alluvial surface (CP1) would both contribute more highly-dosed sediment to the down-piedmont sediment flux and increase the volume of sediment moving down piedmont.

Changes in climate can have significant impact on sediment generation and transport regimes in arid regions (Bull, 1991). At the Chemehuevi Mountains, cosmogenic data suggest that piedmont processes changed both in the mid-Holocene and approximately 30 to 33 ky ago. There is ample research demonstrating that the Mojave Desert had a wetter climate during the mid-Holocene than present (Spaulding, 1991; Anderson and Wells, 2003; Lancaster and Tchakerian, 2003), having storms of both greater magnitude and runoff power (Harvey and Wells, 2003). Such increased storm magnitude and runoff power would have catalyzed incision of unconsolidated alluvial surfaces (Bull, 1991; Harvey and Wells, 2003) and is thus consistent with mid-Holocene incision of the alluvial surface at CP1. It appears that the transition from interstadial to early glacial times (approximately 30 to 33 ky ago) resulted in erosion mid-piedmont, 6 km from the rangefront, and deposition distally, 12 km from the rangefront. The increase in distal deposition rates roughly coincides with a wet period at approximately 30 ky ago as demonstrated by alluvial fan activity (Harvey and Wells, 2003) and the existence of several perennial lakes in the Mojave Desert (Li and others, 1996; Lowenstein, 2002; Anderson and Wells, 2003). Such increased moisture effectiveness could cause runoff great enough to shift the locus of deposition down piedmont.

INSIGHTS INTO MOJAVE DESERT PIEDMONT BEHAVIOR

Piedmonts are a common, in many ways dominant landform in the Mojave Desert. Although piedmont morphology varies from active-planar to incised surfaces, all piedmonts serve as surfaces of transport across which sediment generated in mountainous highlands moves toward playas and ephemeral washes. The field and cosmogenic
data in this and previous studies (Nichols and others, 2002, 2005) provide a new and quantitative means by which to understand the history, rate, and distribution of surface processes active on these landscape-dominating landforms.

The Chemehuevi Mountain piedmont is an incised, multi-age, multi-level surface similar to many other Mojave Desert piedmonts. It stands in stark contrast to the planar and uniformly active piedmont surfaces first studied using cosmogenic nuclides (Nichols and others, 2002). Although active-planar surfaces and incised surfaces certainly differ in appearance, data and model results from the incised Chemehuevi Mountain piedmont and the active-planar Iron and Granite Mountain piedmonts suggest that both types have similar histories and modification rates over the late Pleistocene and Holocene.

The Chemehuevi Mountain piedmont differs morphologically in many other ways from the Iron and Granite Mountain piedmonts (Nichols and others, 2002). The large Chemehuevi Mountain piedmont (12 km long) is fed sediment by drainage basins in which multiple lithologies crop out. The Chemehuevi Mountain piedmont contains multiple geomorphic surfaces that include active ephemeral channels, incised bedrock, incised varnished and pavemented alluvium, and an unvarnished and unpavemented active surface that is frequently reworked by migrating channels. The Chemehuevi Mountain piedmont also includes a small, inter-piedmont mountain range (the Sawtooth Range) that contributes some additional sediment (~3%; Nichols and others, 2005) to the transport system. In contrast, the Granite and Iron Mountain piedmonts are short (6 km) and fed by granitic basins. These two piedmonts are dominated by unvarnished and unpavemented active surfaces that are reworked by ephemeral channels; there are no additional sediment sources on the Iron and Granite Mountain piedmonts.

Despite significant morphological differences, cosmogenic nuclide analyses and modeling suggest that the three piedmonts have strikingly similar process rates and similar histories over the past several tens of thousands of years. For example, measured deposition rates on the Iron Mountain piedmont were 17 mm ky$^{-1}$ from 49 ky ago until the Pleistocene-Holocene transition (2.2 km from the rangefront) and 37.5 mm ky$^{-1}$ from 29 ky ago until the Pleistocene-Holocene transition (4.7 km from the rangefront) (Nichols and others, 2002). Deposition rates at CP2, the distal portion of the Chemehuevi Mountain piedmont, were in the same range, 20 ± 1 mm ky$^{-1}$ until about from 68 to 33 ky, and then increased to 39 ± 4 mm ky$^{-1}$ until the Pleistocene-Holocene transition. At the Pleistocene-Holocene transition, active surfaces on both piedmonts changed from a depositional to a transportational (or erosional) regime. Such similar process rates and behavior, measured and inferred on piedmonts having such disparate morphologies, suggests a climatic control on piedmont behavior.

The active surfaces on the Chemehuevi, Iron, and Granite Mountain piedmonts appear similar and indeed, cosmogenic nuclide analysis and modeling suggests that they behave similarly (fig. 9). On the active surfaces of all three piedmonts, channels have migrated across the wash-surface and slowly transported sediment for several millennia (Nichols and others, 2002, 2005). Incorporation and transportation of interfluve sediment occurs when low and unconsolidated channel banks are easily eroded during flood events. The localized erosion of channel banks creates high sediment loads and thus localized deposition. Such repeated erosion and deposition causes a slow but steady march of sediment down the piedmont over long time-scales. Shifting the locus of deposition over long-time scales results in widespread deposition over the piedmont (Hooke, 1967). Cosmogenic nuclide data now demonstrate that such piedmont resurfacing has occurred at both the Iron Mountain (Nichols and others, 2002) and the Chemehuevi Mountain piedmonts (this paper). Conversely, during periods of low sediment yield and high stream power, channels can either
incise or migrate across the piedmont and bevel the surface. Truncated soils at both the active-planar Iron Mountain piedmont and the incised Chemehuevi Mountain piedmont, suggest that channels on both have beveled and slowly eroded the underlying alluvial substrate.

**CONCLUSIONS**

Cosmogenic nuclide analysis demonstrates that Mojave Desert piedmonts are organized and dynamic systems when studied at spatial scales of km$^2$ and time-scales of $10^3$ to $10^4$ y. Analysis of cosmogenic nuclides has begun to constrain the rates and dates of long-term piedmont processes that have, for so long, gone unquantified. Using cosmogenic nuclides, one can quantify sediment generation rates and trace the resulting sediment down the channel network to calculate long-term average downslope sediment transport speeds that range from decimeters per year on unconfined wash surfaces, where runoff infiltrates the alluvium, to tens of meters per year in confined bedrock channels where runoff accumulates and is channelized (Nichols and others, 2005). By measuring cosmogenic nuclides in soil and sediment depth profiles, and by using nuclide activity models in concert with soil profile development data, one can quantify rates of deposition, ages of surface stability, and identify changes in up-gradient sediment supply.

Although, measurement of nuclide activities in this study quantifies piedmont modification rates of the Holocene and later Pleistocene, such measurements do not address the debate regarding mechanisms of piedmont genesis, specifically pediment formation (for example, Rich, 1935; Schumm, 1962; Mabbutt, 1966; Moss, 1977). Since piedmont processes are so slow and episodic, it is difficult and probably non-representative to extrapolate process rates and changes in these landforms from
data collected on human-time scales (Persico and others, 2005). Even the many millennia of history integrated by cosmogenic nuclide analyses are insufficient to address fundamental issues in piedmont genesis. Further complicating analysis of these landforms is the belief, by some, that piedmonts are remnants from previous climatic conditions (Oberlander, 1974); thus, contemporary processes and process rates are not germane to understanding landform development. Such slow processes and old landforms will need be approached using new tools and new techniques that can provide insight into past geomorphic processes and the sequence of events leading to the formation of piedmonts that dominate many desert landscapes.

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Chemehuevi Mountain Piedmont, Mojave Desert, deciphered using $^{10}$Be and $^{26}$Al