Cosmogenically enabled sediment budgeting

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ABSTRACT

We used ^{10}Be and ^{26}Al to constrain the millennial-scale sediment and nuclide budget for a common, long-studied, but poorly understood landform in arid regions, the desert piedmont. We sampled the Chemehuevi Mountain piedmont, a complex multisurfaced landform in the Mojave Desert, western United States. The nuclide data indicate that sediment is produced more rapidly (1.1×10^{5} kg·yr^{-1}·km^{-2}) in steep mountain source basins than on the low-gradient pediment (4.0×10^{4} kg·yr^{-1}·km^{-2}) or the intrapiedmont mountain range (2.5×10^{4} kg·yr^{-1}·km^{-2}). However, the bulk of the sediment in transport is derived from erosion of the large abandoned alluvial surface (3.9×10^{4} kg·yr^{-1}·km^{-2}). The combination of mass and nuclide budgeting suggests that sediment transport speeds decrease downslope from tens of meters per year in confined channels on the proximal pediment to decimeters per year in unconfined distributaries on distal wash surfaces. The sediment and nuclide budgeting approach we use is particularly valuable in arid regions where geomorphically significant events are infrequent and dating control is poor, thus confounding traditional sediment-budgeting techniques.

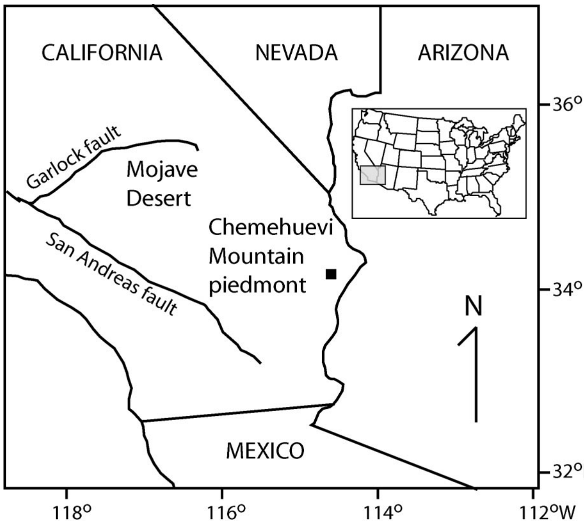

Figure 1. Location map. Black box represents location of Chemehuevi Mountain piedmont, eastern Mojave Desert.

Keywords: sediment yield, piedmont, erosion, sediment transport, Mojave Desert, ^{10}Be.

INTRODUCTION

Sediment budgets quantify the generation, storage, and movement of sediment over landscapes and are prerequisite to understanding the behavior of Earth's surface as a system (Dietrich and Dunne, 1978). Field mapping, dating of sedimentary sequences, and contemporary sediment flux estimates are commonly used to constrain sediment budgets over different time frames (Dietrich and Dunne, 1978; Kelsey et al., 1987). In arid regions, where sediment movement is slow and sporadic, contemporary sediment budgets can be created only by using multidecadal campaigns of field measurements (Schick and Lekach, 1993; Yair and Kossovsky, 2002); yet, because sediment-transport events are so infrequent, the accuracy of such budgets over longer time frames remains uncertain.

In arid regions where datable materials are often absent, reliable millennial-scale sediment budgeting requires a better approach. Cosmogenic nuclides appear well suited to this task. Nuclide measurements have been used to estimate basin-scale rates of sediment generation (Brown et al., 1995; Granger et al., 1996; Matmon et al., 2003; Schaller et al., 2001), date periods of sediment storage within basins (Anderson et al., 1996), identify sources of sediment (Clapp et al., 2002), determine rates of sediment production (Heimsath et al., 1997), and estimate rates of sediment transport (Nichols et al., 2002). We combine these approaches to generate a quantitative Holocene sediment and nuclide budget for a desert piedmont.

Desert piedmonts connect mountainous highlands to lowland basins (Bull, 1991). Understanding how piedmonts function requires quantifying rates of sediment input and export over millennia. In spite of more than a century of research (e.g., Gilbert, 1877; McGee, 1897), sediment fluxes moving down a desert piedmont have never been quantified. The paucity and spottiness of desert precipitation make it difficult to predict and characterize piedmont behavior and suggest slow integrated rates of change, yet massive amounts of sediment can move rapidly in single flood events (Laronne and Reid, 1993; Schick, 1995).

Desert piedmonts are not all the same. Piedmonts may be primarily depositional (fans or bajadas) or they may be erosional (pediments). Sediment on simple piedmonts is supplied by the backing highlands and is transported in shallow ephemeral channels that rework the entire piedmont surface on millennial or submillennial time scales (Nichols et al., 2002). Most piedmonts are complex, displaying multiple geomorphic surfaces (and sediment sources) of differing age and elevation; thus, most through-going sediment transport currently occurs on only part of the piedmont, the incised, interconnected ephemeral-channel network (Bull, 1991, 1997).

STUDY AREA

The Chemehuevi Mountain piedmont (Fig. 1) has three distinct geomorphic surfaces: a proximal, channelized bedrock pediment, a central incised alluvial reach, and a distal wash surface (Fig. 2). From the mountain front to the intrapiedmont Sawtooth Range, 4 km away, ephemeral channels incise the bedrock pediment and its patchy alluvial cover (Fig. 3A). Although perpendicular to the steepest piedmont gradient, the highly dissected Sawtooth Range does not inhibit the flux of sediment down piedmont (Fig. 3B). Down gradient of the Sawtooth Range, channels incise an alluvial pavement surface, the clasts on which are varnished (Fig. 3C). The alluvial pavement surface merges with the ephemeral channels ~10 km down gradient. Beyond 10 km from the mountains is the wash surface where channel banks average less than a few decimeters high and are easily eroded (Fig. 3D).

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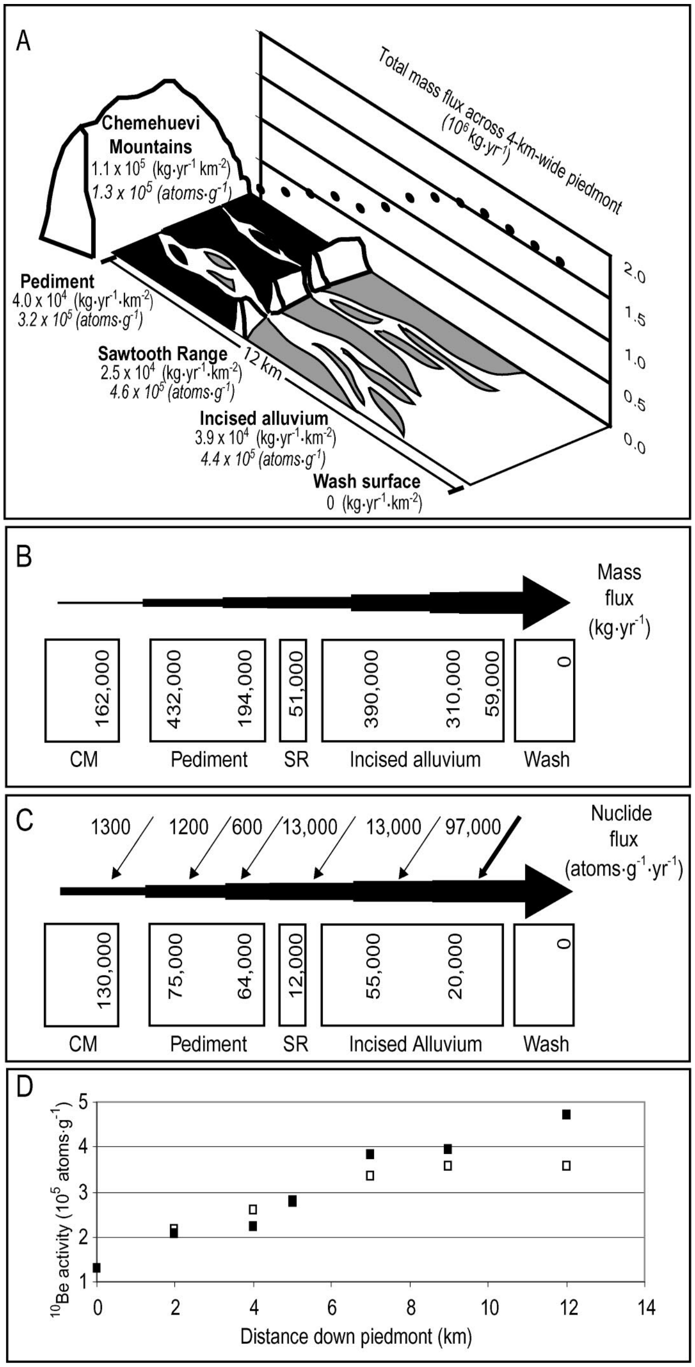

Figure 2. Sediment and nuclide budget for Chemehuevi Mountain piedmont. A: Schematic diagram of Chemehuevi Mountain piedmont from source basins to last transect 12 km southwest of mountain front. On piedmont, black represents bedrock surface, gray represents alluvial surface, and white represents ephemeral channels. Top numbers under geomorphic unit labels represent average addition of mass (kg·yr^{-1}·km^{-2}) from that unit; italicized numbers represent nuclide activity (atoms·g^{-1}). Total mass flux increases down piedmont as shown by graph adjacent to piedmont. B: Mass flux of sediment moving down Chemehuevi Mountain piedmont. Arrow thickness represents cumulative flux of sediment. Numbers represent mass fluxes of sediment from transect locations, on geomorphic units, to ephemeral channels. CM—Chemehuevi Mountains; SR—Sawtooth Range. C: Cumulative flux of nuclides moving down Chemehuevi Mountain piedmont represented by horizontal arrow thickness. Addition of nuclides from geomorphic surfaces is represented by vertical numbers. Small diagonal arrows and associated numbers represent additional nuclide activity from dosing as sediment moves down piedmont. D: Nuclide activity of ephemeral-channel sediment (solid squares) and nuclide-balance model (open squares) without dosing during transport. Nuclide-balance model closely predicts channel measurements in pediment region where sediment speeds are fast. Nuclide-balance model and channel data diverge on distal piedmont where sediment speeds are slower. Difference is due to dosing by cosmogenic radiation during transport (represented by diagonal arrows in 2C).

METHODS

We collected 17 amalgamated samples to characterize nuclide activities on the Chemehuevi Mountain piedmont (Data Repository Table DR1[1]). We collected source-basin samples from the Chemehuevi Mountains (two samples) and the Sawtooth Range (one sample), each consisting of ephemeral-channel sediment from three valleys with similar lithologies. We collected 12 sets of transect samples spaced at 1 km intervals away from the Chemehuevi Mountain front. Each transect sample contains up to 21 equally spaced (200 m apart) surface-sediment samples, located by using global positioning system, of only one distinct geomorphic unit (ephemeral channels, surface sediment from the incised alluvium, bedrock, or colluvium). We analyzed six transect samples of amalgamated ephemeral-channel sediment (1, 3, 5, 7, 9, and 12 km), four samples of incised alluvial-fan sediment (5, 7, 9, and 12 km), two samples of amalgamated pediment bedrock (1 and 3 km), and two samples of amalgamated colluvium (1 and 3 km).

We used measured ^{10}Be and ^{26}Al in quartz to calculate rates of bedrock erosion and sediment generation from pediment bedrock and locally derived colluvium (thus, no nuclide inheritance correction; Lal, 1991). From source-basin alluvial sediment, we calculated basin-wide sediment-generation rates (Bierman and Steig, 1996; Brown et al., 1995; Granger et al., 1996). Samples were prepared at the University of Vermont by using standard techniques (Bierman and Caffee, 2001) and measured at Lawrence Livermore National Laboratory. We estimated an integrated sediment-generation rate for the incised alluvium by considering the surface age and the volume of sediment eroded by the incised ephemeral channels between 5 and 10 km from the mountain front.

SEDIMENT AND NUCLIDE BUDGET

Sediment Sources

Sediment is generated by bedrock weathering in the Chemehuevi Mountains, on the pediment that extends 4 km from the Chemehuevi Mountains, and in the Sawtooth Range. Additional sediment is reworked from older alluvium between 5 and 10 km from the range front. The nuclide activities we measured suggest that the sediment-generation rates we report are integrated over tens of thousands of years.

Chemehuevi Mountains. Nuclide activity indicates that basin-wide average sediment-generation rates in the granitic and metamorphic parts of the Chemehuevi Mountains basins are the same, 1.1 × 10^5 kg·yr^{-1}·km^{-2}, the equivalent of bedrock erosion at ~40 mm·k.y.$^{-1}$. Because the Chemehuevi Mountain basin area is small (1.5 km^2 along 4 km of mountain front), the overall sediment-generation rate in the mountains abutting the piedmont is only 1.6 × 10^5 kg·yr^{-1} (Fig. 2).

Pediment. Small bedrock knobs, covered in part by a thin layer of colluvium, characterize the pediment between the Chemehuevi Mountains and the Sawtooth Range. Nuclide-based sediment-generation rates (and bedrock-lowering rates) range from 2.3 × 10^4 kg·yr^{-1}·km^{-2} (8 mm·k.y.$^{-1}$) for colluvium (3 km from the mountain

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[1] GSA Data Repository item 2005016, Appendix DR1, surface-age estimate, Table DR1, nuclide data, Table DR2, incised channel volumes, and Table DR3, nuclide-balance parameters, is available online at www.geosociety.org/pubs/ft2005.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

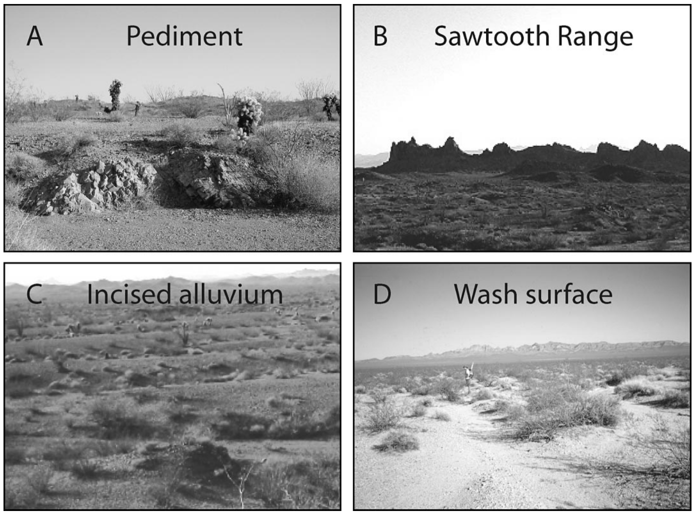

Figure 3. Chemehuevi Mountain piedmont geomorphic units. A: Pediment surface; incised bedrock face is ~0.5 m high. B: Sawtooth Range on horizon; total relief of range in view is ~100 m. C: Incised alluvium down gradient of Sawtooth Range; channels are incised ~2 m. D: Wash surface from 10 to 12 km down piedmont; channel banks are <30 cm high.

front) to 5.9 × 10^4 kg·yr^{-1}·km^{-2} (22 mm·k.y.$^{-1}$) for the flat bedrock surface (1 km from the mountain front). The spatially weighted average sediment-generation rate of the pediment is 4.0 × 10^4 kg·yr^{-1}·km^{-2} (~15 mm·k.y.$^{-1}$). Because the pediment covers 16 km^2, the sediment contribution is 6.3 × 10^5 kg·yr^{-1}, almost four times the mass of sediment contributed by the much smaller mountain source basins. Thus, the pediment is the dominant supplier of sediment to the uppermost 4 km of the piedmont.

Sawtooth Range. The Sawtooth Range, composed of Tertiary volcanic rocks, is heavily varnished, implying low rates of erosion. Nuclide measurements indicate that the Sawtooth Range generates sediment at 2.5 × 10^4 kg·yr^{-1}·km^{-2}, equivalent to a basin-wide average lowering rate of 9.5 mm·k.y.$^{-1}$. The slow erosion and small basin area (~2 km^2) of the Sawtooth Range contribute only 5.1 × 10^4 kg·yr^{-1} of sediment to the piedmont, about three times less mass than contributed by the Chemehuevi Mountains.

Reworked Alluvium. Down gradient of the Sawtooth Range, the ephemeral channels are incised into an alluvial pavement surface with varnished clasts. The incised surface has similar surface nuclide activities from 5 to 9 km along each transect, suggesting a common exposure history (age) for the entire surface. The surface age can be estimated both by modeling depth-profile nuclide data (Table DR1; see footnote 1; Anderson et al., 1996) and by using soil development (Birkeland, 1999); however, the ages are in conflict. We choose to use the field evidence rather than the nuclide data because homogeneously weak soil development was exposed across the entire 10-m-long soil trench we opened. Thus, we estimate that the surface age is ca. 5 ka, probably only accurate to several tens of percent (Appendix DR1 [see footnote 1] describes the nuclide-based surface-age estimate). The total volume of sediment evacuated from the channels decreases from 7.5 × 10^5 m^3 (6 km from the range front) to 1.8 × 10^5 m^3 (9 km from the range front; Table DR2 [see footnote 1]). Assuming the surface age is 5 ka, the sediment flux ranges from 5.8 × 10^4 kg·yr^{-1}·km^{-2}, 6 km down piedmont, to 1.5 × 10^4 kg·yr^{-1}·km^{-2}, 9 km down piedmont, where the incised alluvial surface merges with the distal wash surface. The average sediment flux is 3.9 × 10^4 kg·yr^{-1}·km^{-2} for the entire alluvial surface, for a sediment contribution of 7.6 × 10^5 kg·yr^{-1} (Fig. 2). The total amount of sediment issuing from the incised alluvial surface exceeds the sediment generated by pediment erosion because the abandoned alluvial surface is 4 km^2 larger than the pediment. However, if the nuclide- rather than soil-based age is correct, the sediment flux would decrease by a factor of 5, and the bedrock pediment would contribute most sediment to the ephemeral channels.

Mass Flux

The mass flux of sediment moving down piedmont depends on the spatial extent of the sediment sources and their sediment-generation rates. The Chemehuevi Mountain piedmont sediment budget indicates that highland basins generate sediment more rapidly than other landscape elements but only account for 10% of the total sediment flux because they are so small (Fig. 2). The slowly eroding Sawtooth Range provides only ~3% of the total sediment flux. Sediment-generation rates from the bedrock pediment and from the incised alluvial surface are similar (4.0 and 3.9 × 10^4 kg·yr^{-1}·km^{-2}, respectively) and are slower than the sediment-generation rates in the Chemehuevi Mountain basins. Because they cover large areas, however, the bedrock pediment (16 km^2) and incised alluvium (20 km^2) are the greatest contributors of sediment (39% and 48%, respectively) to the down-piedmont sediment flux.

The distal part (10–12 km down piedmont) of the Chemehuevi Mountain piedmont is geomorphically distinct, having only shallow channels (<25 cm), unconsolidated channel banks, and little relief. At 12 km from the mountain front, samples of amalgamated channel and bar sediment have similar nuclide activities (Table DR2; see footnote 1); because any additional irradiation of bar sediment is too small to be detected, ephemeral channels must migrate across the surface rapidly. Thus, the entire distal surface is active on the millennial time scale, and no additional sediment is added here to the flux moving down piedmont.

Nuclide Flux and Sediment-Transport Speed

The nuclide budget for the Chemehuevi piedmont considers both the measured ^{10}Be activity of sediment and the mass of sediment, derived in most cases from the measured ^{10}Be activity by using interpretive models, added from each source. Weighting the mass flux of sediment from each different geomorphic unit by its ^{10}Be activity, we calculate the nuclide flux at each kilometer down piedmont and find that the calculated ^{10}Be activity is usually less than the measured activity (Fig. 2D). We interpret this difference as representing the production of ^{10}Be during sediment transport down the channel network. Having measured, in the field, the depth to which channel sediment is well stirred, we modeled different sediment-transport speeds, using equation 1, until the difference between observed and modeled ^{10}Be activity was minimized (Table DR3; see footnote 1).

$$N_x = N_{x-1} + \left(\frac{X}{S}P_d \cdot 1 - \frac{N_G}{\Sigma N}\right) + N_G\left(\frac{M_X}{\Sigma M}\right), \qquad (1)$$

where N_x is the nuclide activity (atoms g^{-1}) of ephemeral channel sediment at distance x from the mountain front, N_{x-1} is the nuclide activity (atoms g^{-1}) of ephemeral channel sediment at previous transect at distance x from the mountain front, X = distance between N_x and N_{x-1} (m), S is the sediment transport speed (m·yr^{-1}), P_d is the average nuclide production rate in the actively moving sediment (atoms·g^{-1}·yr^{-1}), N_G is the nuclide activity of sediment added from the geomorphic unit at distance x from the mountain front (atoms·g^{-1}), ΣN is the sum of nuclides contributed by all up-gradient geomorphic units (atoms·g^{-1}), M_X is the mass of sediment added from sediment source at distance x from the mountain front (kg·yr^{-1}), and ΣM is the mass sum of all up-gradient sediment sources (kg·yr^{-1}).

The best-fit nuclide-flux model requires sediment speeds that decrease from tens of meters per year in the bedrock-confined channels of the pediment and the dissected Sawtooth Range, to ~1 m·yr^{-1}

through the incised alluvium where channels are wider and more numerous, to 0.2 m·yr^{-1} in the distal active wash part of the piedmont where channels migrate across the surface. Such decreasing speeds are consistent with sediment moving through increasingly larger channel areas down piedmont as well as loss down piedmont of sediment-transporting floodwaters by infiltration.

DISCUSSION

Cosmogenic nuclide and field measurements together allow calculation of a quantitative, millennial-scale sediment budget for the complex Mojave Desert piedmont at Chemehuevi. The sediment budget illuminates the distribution and relative importance of sediment sources, suggesting that reworked alluvium is a major source of sediment moving down the piedmont and that lesser contributions are derived from the highlands and proximal pediment. Identifying reworked alluvium as a major sediment source is important for understanding piedmont response to disturbance, both natural and human-induced. Because so much sediment comes from unconsolidated alluvial surfaces, hydrologic changes affecting such reaches, including climate change and development, are likely to rapidly trigger a systematic response down piedmont. Incision will result if sediment supply is reduced; aggradation will occur if sediment supply is increased.

By considering both the mass and nuclide activity of sediment derived from various sources, as well as the down-piedmont increase in sediment nuclide activity, piedmont sediment-transport speeds can be calculated. Such speeds vary from meters per year near the range front, where ephemeral streams are confined to bedrock channels, to decimeters per year in washes on the lower piedmont. Sediment speeds on simpler wash piedmonts in the Mojave, calculated on the basis of a very different analytical approach (Nichols et al., 2002), were slower than speeds calculated herein for the upper channelized part of the Chemehuevi piedmont (meters per year), yet they were similar to the lowest wash sections of the Chemehuevi piedmont (decimeters per year).

The model we created, as well as most others employed for analysis of cosmogenic data, presumes steady state. However, the Holocene age of the middle piedmont surface is at face value inconsistent with steady behavior and implies at least resurfacing of this surface <10 k.y. ago if not deposition of decimeters of material. However, if the sediment-transport speeds we calculate are correct, then sediment takes only centuries to move from the highlands across the pediment to the alluvial reach; transit through the alluvial section takes at most a few millennia. Thus, sediment reaching the distal wash surface today has moved through the piedmont channels since incision of the alluvial surface, implying that the steady-state assumption is reasonable over the Holocene time frame we consider with this sediment budget.

The application of cosmogenic nuclides at Chemehuevi differs from that employed previously and offers a blueprint for using isotopes such as ^{10}Be to quantify the rate and distribution of terrestrial sediment movement on a millennial time scale. Earlier arid region research used outcrop (Nishiizumi et al., 1986) and fluvial samples (Granger et al., 1996) to model the erosion rate of points on the landscape and drainage basins, respectively. We followed a similar approach but then used the model results to create a combined sediment and nuclide budget considering both the mass and nuclide activity of sediment shed from each landscape element (cf. Clapp et al., 2001; Perg et al., 2003). By using amalgamated samples that were collected progressively down piedmont (cf. Nichols et al., 2002), we used the nuclide budget in concert with field data (channel width and active-layer depth) to back out sediment-transport speeds. Thus, by considering the landscape as a whole, by balancing a combined nuclide and mass budget, and by using the power of amalgamation, one can draw broad conclusions about the rate and distribution of sediment-transport processes through the use of relatively few samples.

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