QUANTIFYING DESERT SURFACE PROCESSES USING ^{10}Be AND ^{26}Al

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ABSTRACT

Cosmogenic nuclide analyses of amalgamated surface, soil pit, and source basin sediment samples collected from the Chemehuevi and East Range Road piedmonts, Mojave Desert, provide a four-dimensional (time as the fourth dimension) view into piedmont behavior. Quantifying long-term piedmont process rates of the undisturbed, complex Chemehuevi Mountain and the disturbed, complex East Range Road piedmonts, provide baseline data to understand better long-term piedmont processes and histories. Since development is rapidly changing piedmont sediment dynamics, one can compare baseline data to contemporary measurements in order to determine better the effect of human disturbance on piedmont processes.

Sediment supplied to the Chemehuevi Mountain piedmont is mainly from the source basins (4.0×10^4 kg km^{-2} y^{-1}) and the proximal bedrock pediment (3.3×10^4 kg km^{-2} y^{-1}), while little sediment is added from erosion of incised alluvium and the channel bed (0.2×10^4 kg km^{-2} y^{-1} and 0.1 to 0.3×10^4 kg km^{-2} y^{-1}, respectively). Based on the sediment budget and the down piedmont increase in nuclide activity, I used mixing models to estimate average sediment velocities of 8 to 39 cm y^{-1}. Cosmogenic nuclide analysis of soil pit sediment from the distal piedmont suggests sediment deposition (17 to 37 mm ky^{-1}) until ~8,000 years ago when deposition was replaced by sediment transport in an ~25 cm think layer of sediment. The proximal piedmont soil pit suggests deposition until 34 ky ago, an 8 ky depositional hiatus, a pulse of deposition at 26 ky ago, and surface stability to the present.

The highly disturbed East Range Road piedmont receives 3.6×10^4 kg y^{-1} km^{-2} of sediment from the upland basins and 1.3×10^4 kg y^{-1} km^{-2} of sediment from the eroding proximal surface. The sediment is transported down piedmont at rates of 8 to 23 cm y^{-1}. Cosmogenic nuclide analysis of soil pit sediment suggests that the proximal surface is at least 76 ky old, and the distal piedmont has several periods of deposition followed by stability.

The long-term rates at which sediment is transported down the multi-surface Chemehuevi Mountain and East Range Road piedmonts are similar to previously measured transport rates on the single surface Iron and Granite Mountain piedmonts (decimeters per year). Such results suggest that the complexity of piedmont morphology does not influence long-term piedmont transport rates. Since the rates are similar for the undisturbed Chemehuevi Mountain piedmont and for the highly disturbed East Range Road piedmont, human disturbance does not appear to affect the use of cosmogenic nuclides to measure long-term sediment transport rates down the East Range Road piedmont. Contemporary sediment movement on the East Range Road piedmont however, is up to an order of magnitude greater than the nuclide-based rates. The comparison demonstrates that Army training has accelerated the movement of sediment down the piedmont.

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Chapter 1: Introduction

This dissertation revisits a classic landform that has been intensively studied for over a hundred years, the *desert piedmont*. ‘Piedmont’ is a general term that signifies the low-gradient surfaces that abut mountainous areas. Inclusive in the term piedmont, are sub-terminologies that imply specific geomorphic processes such as: alluvial fan (conical shaped depositional surface; Bull 1977; Hooke 1967; Wells and Harvey 1987), alluvial plain or bajada (planar depositional surfaces), and pediment (erosional surface cut into bedrock or older alluvium; Cooke and Reeves 1972; Dohrenwend et al. 1987; Hadley 1967; Howard 1942; Rahn 1967). Because surface expressions of piedmonts are difficult to classify, the literature is riddled with ambiguous landform classifications and misunderstood terminologies. To avoid the implied processes associated with alluvial fans, alluvial plains, bajadas, and pediments, I use the general term *piedmont* and, in this dissertation, describe, model, and quantify processes active at the surface of these landforms.

Piedmonts have been studied using a number of different approaches. Early piedmont literature was descriptive and dominated by theoretical models (Blackwelder 1931; Johnson 1932; McGee 1897; Paige 1912; Rich 1935). As the science of geomorphology evolved, the type and style of research procedures expanded. Some quantified short-term and small-scale piedmont processes using monitoring, morphometric analysis, and simulation models (Abrahams, Parsons, and Luk 1988; Cooke and Reeves 1972; Mammerickx 1964; Schick, Lekach, and Hassan 1987). Others tried to understand the relative long-term and large-scale history of piedmonts relying on geologic relationships and soil development (Eppes et al. 2002; McAuliffe and McDonald 1995; McFadden, Ritter, and Wells 1989; Wells, McFadden, and Dohrenwend 1987).

A significant number of papers do not discuss entire piedmonts systems; rather they only discuss one portion or aspect of a piedmont (Cooke and Mason 1973). In this dissertation, I use cosmogenic nuclides to expand the typical quantification of piedmont processes from small to large spatial scales and from short time-scales (years), typical of most process studies, to millennia. My research quantifies the average long-term history of sediment moving across, being deposited on, and eroding from the entire piedmont/drainage basin system.

Field Area

I have two field sites, Chemehuevi Mountain piedmont and the East Range Road piedmont, located in the Mojave Desert, California (Figure 1). The Mojave Desert extends from the San Andreas Fault in the south, to the Garlock Fault in the north. The eastern edge of the Mojave Desert is not well defined but some researchers use the Colorado River. Others, who delineate desert boundaries using vegetation assemblages, suggest that the Mojave Desert boundary is less clearly defined and have excluded the Chemehuevi Mountains from the Mojave Desert (Spaulding and Graumlich 1986; Spaulding, Leopold, and Devender 1983). To be consistent with the geological literature, I include the Chemehuevi Mountains as part of the Mojave Desert.

The Chemehuevi Mountain piedmont is low angle (3.5 to 0.7 degrees) and extends > 12 km from the Chemehuevi Mountains to Chemehuevi Wash, which empties into the Colorado River. The Chemehuevi Mountains are made of granite, gneiss, and metasedimentary rocks (John 1987).   The piedmont has several distinctive surfaces. Adjacent to the mountain front is a 4 km zone of incised bedrock and patchy capping alluvium. At 4 km, an interpiedmont mountain range, the Sawtooth Range parallels contour. Down gradient from the Sawtooth Range is an abandoned alluvial surface (incised by ephemeral channels) that has a moderately well formed pavement in which stones are covered by rock varnish, indicating at least several thousand years of stability. Farthest from the mountain front is a low relief (< 0.5 m) zone without pavement and varnish. Ephemeral channels rework this entire distal piedmont surface; thus, it is termed a wash surface.

I chose to study the Chemehuevi Mountain piedmont because it is complex. It is long (12 km), has multiple geomorphic surfaces, and is relatively undisturbed. Previous work suggests long-term process rates are quantifiable on 6-km-long single surface piedmonts where ephemeral channels migrate across the surface rapidly (Nichols et al. 2002). The Chemehuevi Mountain piedmont allows me to investigate the long-term processes of a complex piedmont and compare them to the processes active on simple piedmonts.

The East Range Road piedmont in Fort Irwin, a U.S. Army training facility, is similar in its complexity to the Chemehuevi Mountain piedmont. The East Range Road piedmont has an incised (up to 3 m) alluvial surface adjacent to the uplands, and a low-relief wash surface furthest from the uplands. The East Range Road uplands however, are composed of old Tertiary alluvial fan deposits and not crystalline bedrock (Sobieraj 1994).

East Range Road is an area of frequent, large-scale Army training and war simulation. Each month, for the past two decades, thousands of wheeled and tracked vehicles traversed the surface. From more than two years of observations, the vehicle disturbance is significant enough to obliterate the shallow and weak banked ephemeral channels and thus, destroy any signs of a piedmont drainage network.

I chose the East Range Road piedmont because it is long (6 km), complex, and because it is highly disturbed by Army training. I investigated two similarly long and complex piedmonts in order to determine whether their behavior is similar or different. By studying an undisturbed piedmont (Chemehuevi) and a highly disturbed piedmont (East Range Road) I can determine whether disturbance interferes with our ability to detect average, long-term rates of piedmont change using ^{10}Be and ^{26}Al.

Significance of my research

This dissertation adds significantly to desert science in several ways. My research, although geologically based, is of interest to several different groups including: geomorphologists, desert ecologists, land-managers and engineers, and geologists interested in the utility of cosmogenic nuclides. I am the first to quantify average long-term rates of change on complex desert piedmonts and to determine a sediment budget for desert piedmonts. This research is the first to gain a quantitative understanding of the anthropogenic influence on long-term piedmont process rates, and is one of only a few to quantify average processes rates over a landscape-scale rather than over small-scales.

The sediment amalgamation technique that I employ will be useful to quantify slow rates of change on other landforms, such as sediment movement down soil-mantled hillslopes.

Outline

Four papers prepared for publication comprise the body of this dissertation. The second chapter serves as a literature review and provides the context for Chapters 3 through 5. Chapter 2 is a review paper that synthesizes the current state of the desert piedmont literature. This chapter is important because it has been 35 years since the last review paper on piedmonts was published (Denny 1967). Chapter 3 is a paper for submission to *Nature*. This paper quantifies, for the first time, an average long-term sediment budget for a desert piedmont. The results of this chapter have important implications for land-managers and engineers. Chapter 4 is a paper for submission to *The American Journal of Science.* This paper quantifies the long-term process rates, such as sediment velocities, sediment deposition, the duration of depositional hiatuses, and the duration of surface stability, of a complex piedmont (Chemehuevi) and compares the results to simple, single surface piedmonts in the Mojave Desert (Nichols et al. 2002). Chapter 5 is a paper for submission to *Quaternary Research.* This paper quantifies long-term piedmont process rates of the highly disturbed East Range Road piedmont. This paper has important implications for our ability to characterize, and place in perspective, the anthropogenic influence on piedmont processes. Chapter 6 is a synthesis of papers in this dissertation and a short discussion on where desert piedmont research is headed. Following Chapter 6 is a comprehensive bibliography.

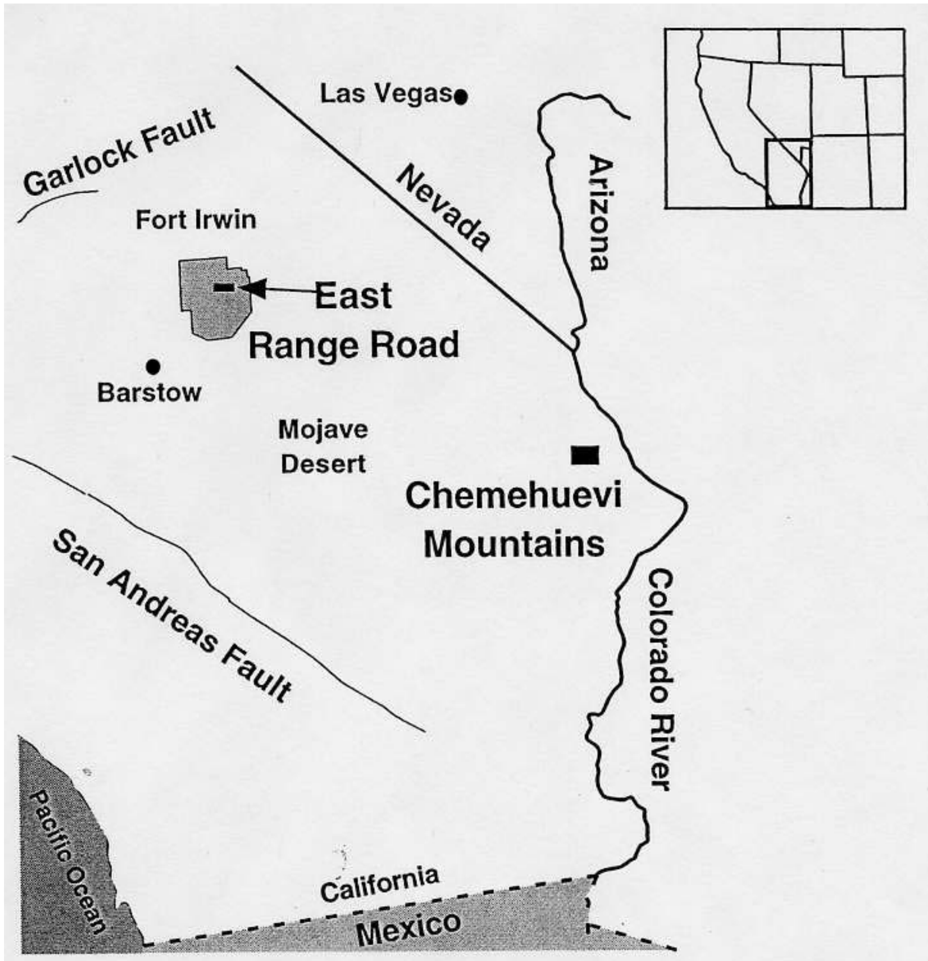

FIGURE 1. Location map of the East Range Road and Chemehuevi Mountain piedmonts in the Mojave Desert, California. Inset map show location of the Mojave Desert in the southwestern United States.

CHAPTER 2: Paper submitted to Quaternary Science Reviews

For submission to *Quaternary Science Reviews*

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AFTER A HUNDRED YEARS OF STUDY: PIEDMONTS, FANS, AND PEDIMENTS IN AMERICAN SOUTHWEST

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Abstract

Desert piedmonts, low gradient surfaces extending from mountainous uplands, are ubiquitous in the American southwest and have been studied for over a century. Piedmont histories, and the rate and distribution of processes that form and modify piedmonts, are poorly known because dating of piedmonts and their sediments is difficult. Relative piedmont histories are determined from soil development and geologic relationships. Short-term monitoring and precipitation simulations, on small piedmont areas, quantify piedmont process rates over short time-scales. A variety of qualitative models relate piedmont histories and processes to longer-term changes in climate and tectonic activity.

Recent technological advances allow the investigation of piedmonts using new approaches. Luminescence dating, cosmogenic nuclide techniques, and spectral analysis of piedmont surfaces are valuable tools for dating piedmonts. In addition, cosmogenic nuclides, measured in desert piedmont sediment, allow for the determination of long-term piedmont histories and process rates that were previously unknown. Geophysical data can provide a better understanding of the deep structure of piedmonts. By utilizing these techniques, investigators are beginning to address questions that gone unanswered for over 100 years.

1. Introduction

Deserts have captured the attention of American geomorphologists for over a century (Gilbert, 1877; McGee, 1897). One landform that has been, and continues to be, a focus of study is the *desert piedmont.* Over the last century, thousands papers have been published on one or more aspects of desert piedmonts (Nilsen and Moore, 1984; Whitaker, 1973). The goal of this paper to present and provide a focused discussion of the most germane concepts and findings that explain the history and processes active on desert piedmonts in southwestern North America. The geographic scope is limited to this region because the most significant body of the piedmont research was conducted in the American Southwest (Thomas, 1997).

2. Terminology

A major obstacle to understanding and synthesizing desert piedmont research is the misuse of piedmont terminology (Whitaker, 1979). In this paper, we define *piedmont* as a 'planar' surface that includes all low-gradient geomorphic features abutting mountainous uplands. Piedmonts can be landforms of erosion, deposition, or they can act as surfaces of transport (Fig. 1). All three functions may occur at one time on a single piedmont. Piedmont surfaces may be stable, exhibiting well-defined stone pavements with heavily varnished clasts (Fig. 2A) or may be reworked surfaces (Fig. 2B). Such an inclusive definition of piedmonts includes several other related terms that traditionally implied formation processes; such terms include but are not limited to: *pediment*, *low angle bedrock slope*, *alluvial fan*, *alluvial plain*, *alluvial slope*, *alluvial apron,* and *bajada*.

Pediments are low angle erosional surfaces cut into bedrock (Whitaker, 1979) or alluvium (Hadley, 1967; Mackin, 1970) which abut high angle mountain masses. The term pediment first appeared with a geological meaning in McGee's (1897) seminal paper on sheetflood erosion. McGee used the term because the bedrock slope was reminiscent of the pediment in Greek architecture. Several other terms are synonymous with pediment for example, *low angle bedrock slope* (Thomas, 1997)*, rock fans* (Rich, 1935), *rock-cut surfaces* (Paige, 1912), *rock floors* (Davis, 1930), *sub-alluvial bench* (Lawson, 1915), and *rockplains* (Johnson, 1932). Most pediment literature considers arid regions of North America and Australia (Cooke, 1970; Denny, 1967; Mabbutt, 1966; Tuan, 1959). There are however, papers that describe pediments in other climate zones and on other continents (e.g., Davis, 1930; Frye and Smith, 1942).

Fans are primarily depositional landforms. Fan processes were first studied almost a century and a half ago (Haast, 1864). Early fan research was conducted in New Zealand (Haast, 1864; Thompson, 1873), the Indus Basin (Drew, 1873), England (Miller, 1883), and the United States (Davis, 1905; Dutton, 1880; Gilbert, 1877; McGee, 1897). Many fans have morphologies that extend radially from a mountain source basin. Similar to alluvial fans are *alluvial slopes* and *alluvial plains*. Instead of having a radial fan shape they are planar. *Bajadas* form when fans coalesce.

A low gradient bedrock surface covered by a thin layer of alluvium might be classified as a pediment by one researcher, an alluvial plain by another, and a bajada by third. Classification of such landforms is difficult because these specific terms require knowledge of geomorphic process, and the third dimension, both of which are difficult to assess in sparsely populated arid regions. Thus, we focus on research that addresses desert piedmont formation and modification processes.

3. Formation hypotheses

The piedmont literature is filled with qualitative, often speculative models of landscape genesis. Many of the models attempt to explain the formation of pediments by erosion (Gilbert, 1877; Johnson, 1932; Lawson, 1915; McGee, 1897). Other models address the formation of fans by deposition (Bull, 1964; Denny, 1967; Hooke, 1967). Little attention has been paid to understanding complex desert piedmonts as a system that includes both erosional and depositional regimes.

Pediments. Process models of pediment formation fall into three main categories: hydrologic, slope retreat, and exhumation. Many early pediment formation models championed hydrologic processes as the maker of pediments (Gilbert, 1877; Johnson, 1932; Lawson, 1915; McGee, 1897; Paige, 1912). One hydrologically driven process, termed lateral plantation, suggests that ephemeral streams migrate across bare bedrock or shallowly covered bedrock in order to plane the rock below (Johnson, 1932). Such streams could also flow parallel to the mountain front, erode the toe of the mountains, and cause the slopes to retreat while maintaining the steep mountain and low pediment slopes (Gilbert, 1877; Howard, 1942; Johnson, 1932). The lateral plantation model has been used to explain a variety of landforms including the Henry Mountains (Gilbert, 1877), the Sacaton Mountains (Howard, 1942), and according to Johnson (1932), the Sierrita Mountains, although this initial interpretation of the Sierrita Mountain pediment was debated (Tuan, 1959).

Alternatively, some suggest that sheetfloods may produce pediments by erosion (Lawson, 1915; McGee, 1897; Rahn, 1967; Rich, 1935). It appears that evidence for the erosive power of sheetfloods stems from the direct observation and vivid description of such a flood by McGee (1897). According to the hypothesis, sheetfloods and rill action cause hillslope weathering and remove detritus thus, sheetfloods are a dominant pedimentation processes. There is a problem with the sheetflood hypothesis. In order to attain a sheetflood, the topography over which water flows already must be nearly planar. Therefore, it appears that sheetfloods are a result of low relief plains not a cause of them. It is most likely that sheetfloods are a piedmont-modifying process rather than piedmont-forming processes.

Gilbert (1877) proposed parallel slope retreat as a pediment forming process. The original hypothesis suggested that migrating streams undercut mountain fronts causing slope failure, parallel retreat of the mountain front, and pedimentation (Gilbert, 1877; Howard, 1942). Alternatively, removal of embayment divides may account for a faster mountain retreat rates compared to parallel slope retreat rates (Parsons and Abrahams, 1984).

Pediments may result from exhumation. Observations of residual patches of saprolite resting on bedrock pediments suggest exhumation (Lawson, 1915; Paige, 1912; Twidale, 1967). Exhumation may be catalyzed by uplift from faulting and removal of sediment by lateral plantation (Paige, 1912). Lawson (1915) supports exhumation as a pediment formation mechanism but concludes that sheetfloods might be the better detritus removal mechanism. Other exhumation-related pediment formation models include mantled controlled plantation (Mabbutt, 1966; Moss, 1977; Twidale, 1967). Mantle controlled plantation hypothesis suggests that a sediment or saprolite mantle holds water longer than exposed bedrock. Thus, bedrock under the sediment mantle weathers faster than the exposed rock (Mabbutt, 1977; Moss, 1977). Erosion of the sediment mantle either by sheetfloods or by stream meandering uncovers the bedrock surface.

Papers discussing processes of fan formation are also generously represented in the literature (Nilsen and Moore, 1984). Many large fans form in tectonically active areas (Bull, 1977; Denny, 1967; Dohrenwend, 1987) such as the basin and range (Hooke, 1967; Hooke, 1972). Here, mountains are uplifted and source basin streams respond by incising into the mountains as they adjust to lowering baselevels. The change in slope from steeper mountains to the lower gradient basin floor starts sediment deposition (Bull, 1977). Deposition is not always due to a change in slope. The gradients of many fan surfaces are similar to the gradients of the source stream within the mountain range (Bull, 1964; Dohrenwend, 1987; Hooke, 1967). Deposition therefore, may be a result of a hydrologic change from a confined channel in the mountains, where flow is deep and rapid, to shallow unconfined flow on the fan. Shallowing of water depth reduces stream competency for sediment transport and results in sediment deposition.

Some fans are in fact, not alluvial at all; they are debris flow fans. Although debris fans can have similar morphologies and slopes as alluvial fans, debris fan material is made up of poorly sorted sediments up to boulder size (Whipple and Dunne, 1992). Surface topography of debris fans can be hummocky or smooth depending on the surfical smoothing (erosion) processes and the grain size of sediment making up the fan. Debris fans are common in weak lithologies of steep basins (Harvey, 1984).

4. Piedmont history

Deciphering piedmont histories is prerequisite to understanding desert piedmont behavior. Piedmont histories have been explained using a variety of tools and approaches. Some determine long-term piedmont histories over geologic time scales (McFadden et al., 1989; Wells et al., 1987), while others determine short-term piedmont histories involving human impact (Prose, 1985; Nichols and Bierman, 2001; Iverson, 1980; Iverson et al., 1981). Recently, some have begun to quantify piedmont histories using cosmogenic nuclides (Nichols et al., 2002; Phillips et al., 1998; Pohl, 1995; Zehfuss et al., 2001)

Paramount to understanding piedmont histories is age control over a variety of time scales. Some dating is difficult to do in desert regions. For example, radiocarbon analysis, a technique commonly employed to date Late Pleistocene and Holocene age material, is difficult to apply on piedmonts because carbon is rapidly destroyed by oxidation in arid climates (Pohl, 1995). Pack rat middens, with carbon preserved by amberrat (fossil rat urine), are readily datable to the 10^4 year time-scale but their age is not necessarily germane to the surface on which they are found. However, midden data allow for reconstructing paleovegetation and thus reconstructing past climates (Spaulding and Graumlich, 1986; Spaulding et al., 1983).

Rock varnish was used to date directly surface clasts. The first attempt, cation-ratio dating, seemed promising in the 1980s (Dorn, 1983). However, problems of laboratory reproducibility (Bierman et al., 1991; Reneau and Raymond, 1991), and the lack of understanding of the varnish systematics (Bierman and Gillespie, 1994) ended the use of this method leaving the meaning of dates unclear. A second attempt used radiocarbon to date rock varnish on surface clasts (Dorn et al., 1986). This technique required that the top 90% of only micrometers thick varnish be scraped off. Then in the bottom 10%, one could extract small amounts of carbon for Accelerator Mass Spectrometric dating (Dorn et al., 1986). This technique was also abandoned when samples reanalyzed by others revealed that the dated carbon was comprised of two distinct populations of different ages (Beck et al., 1998).

Piedmont histories have been investigated using soil development and geologic relationships (Denny, 1967; Dohrenwend, 1987; McFadden et al., 1989; Oberlander, 1974; Wells et al., 1987). Soil development depends on a variety of factors including climate and microclimates, length surface stability, local sources and fluxes of carbonate and dust (Gile et al., 1966). Relative piedmont histories, in part based on soil data, are common in the American southwest (Eppes et al., 2002; Harrison et al., 1992; McFadden et al., 1989; Wells et al., 1987). Although it is difficult to quantify these variables over time, soil development is a powerful technique for constraining long-term piedmont histories (McFadden et al., 1989; Wells et al., 1987).

Geologic relationships constrain incision and deposition histories on piedmonts. For example, stratigraphic relationships of fan surfaces can constrain incision histories of fans (Bull, 1991; Denny, 1967). Stratigraphic relationships can also reveal important information about piedmont ages. For example, Oberlander (1974) found a pediment that was capped by a basaltic flow. The age of the basalt is Tertiary thus; the pediment is at least Tertiary in age. This stratigraphic sequence led Oberlander (1974) to conclude that pediments could be inherited forms and the process active today do not necessarily represent the processes that formed them. Although some stratigraphic relationships can constrain piedmont histories, such relations can be difficult to find and interpret in the field.

Recently developed techniques useful for determining piedmont histories include cosmogenic nuclides and thermoluminescence dating (Anderson et al., 1996; Bierman et al., 1995; Clarke, 1994; Nichols et al., 2002; Phillips et al., 1998; Pohl, 1995; Porat et al., 1997; Siame et al., 1997; Zehfuss et al., 2001). Cosmogenic nuclides can date stable depositional piedmont surfaces by measuring the build of nuclides in the substrate over time (Anderson et al., 1996) or nuclides can constrain surface piedmont ages and thus the timing of faulting (Bierman et al., 1995; Siame et al., 1997; Zehfuss et al., 2001). Thermoluminescence dating of buried sediments allows for estimates of when sediment was last at the surface (Clarke, 1994; Porat et al., 1997) thus, allowing constraint on surface ages and potentially stirring processes (Heimsath et al., 2002). These techniques, when put in a context of soil development, can quantify the depositional history of the piedmont (Nichols et al., 2002; Phillips et al., 1998).

The history of human impact on desert piedmonts has received considerable attention. Investigating human impact is done by measuring piedmonts that are currently being disturbed (Iverson, 1980; Iverson et al., 1981; Persico et al., 2001) or by measuring the recovery of desert surfaces after the disturbance has ceased (Nichols and Bierman, 2001; Prose, 1985; Webb et al., 1986; Wilshire and Webb, 1980).

Off-road vehicle use is common on desert piedmonts and is the most widespread human impact outside of development. Studies of contemporary processes conclude that ORVs accelerate soil erosion by an order of magnitude, compact soils by several fold, and lower infiltration capacities by up to an order of magnitude (Iverson, 1980). Other studies measure the persisting effects of well-documented World War II army training and the abandonment of towns on the desert surface (Nichols and Bierman, 2001; Prose, 1985; Webb et al., 1986; Wilshire and Webb, 1980). Such studies conclude that many decades to a few centuries are required for the soil bulk density to return to nominal values (Prose, 1985; Webb et al., 1986; Wilshire and Webb, 1980). Similar time-scales are required for piedmont drainage networks to return to pre-disturbance conditions (Nichols and Bierman, 2001).

5. Quantifying desert piedmont processes

Several studies have attempted to quantify different aspects of desert piedmonts. The earliest studies attempted to quantify piedmont morphometery, focused on morphometric analysis of fans and pediments. Several studies quantified alluvial fan characteristics and related them to the character of source basins (Bull, 1963; Hooke, 1967). These studies concluded that although it is possible to develop empirical relationships for fans, the scaling parameters depend on drainage basin characteristics (such as lithology), climate, and the tectonic setting (Bull, 1991; Denny, 1967). The attempts at defining similar relationships between pediment slopes, pediment length, drainage basin size, and the pediment lithology proved inconclusive (Mammerickx, 1964) suggesting that pediments are less closely tied to their drainage basins than fans.

Grain size has commonly been measured on desert pediments (Abrahams et al., 1988; Cooke and Reeves, 1972; Vincent, 1995; Vincent and Sadah, 1995). The goal of these studies was to deduce pediment formation mechanisms by finding systematic changes in grain size as a function of distance from the mountain front (Cooke and Reeves, 1972; Vincent, 1995; Vincent and Sadah, 1995). However, such studies found either an inverse correlation of grain size with distance from the mountains or no correlation at all. Inverse correlations are consistent with grain size decreases down pediment, suggesting a transportation regime such as sheetfloods or lateral plantation. No correlation between grain size and distance down pediment is consistent with exhumation processes.

Other quantitative studies monitored the dispersion and movement rate of grains across piedmont surfaces (Abrahams et al., 1988; Edinger-Marshall and Lund, 1999; Hooke, 1967; Persico et al., 2001). Monitoring studies rarely track grain movement longer than a few years. However, even short-term studies suggest that microtopography and land disturbance are both important controls on grain movement (Edinger-Marshall and Lund, 1999; Persico et al., 2001). Simulations of precipitation regimes suggest that movement of sediment grains is strongly dependent on rainfall and overland flow (Abrahams et al., 1988).

Recently, use of cosmogenic nuclides has quantified piedmont process rates that modify entire piedmonts (Bierman and Caffee, 2001; Bierman et al., in press; Nichols et al., 2002). These studies quantify a variety of piedmont process rates such as time to fully rework wash surfaces by channel meandering (1000 to 2000 years), long-term sediment velocities (decimeters per year), sediment deposition rates (decimeters per thousand years), and durations of surface stability (Bierman and Caffee, 2001; Nichols et al., in review-a and b; Nichols et al., 2002; Nishiizumi et al., 1998) Although these studies quantify the rates of piedmont modification processes, they do not address mechanisms of piedmont formation.

6. Process response models

Two major influences on piedmont formation and process rates appear to be climate and tectonic setting. Many studies focus on the Pleistocene-Holocene climate transition (Bull, 1991; Bull and Schick, 1979; Mayer and Bull, 1981; McFadden et al., 1989; Wells et al., 1987) because the effects are still visible and can be easily characterized in the field. One model suggests that during the more moist Pleistocene, sediment and water were retained on hillslopes by vegetation (Bull and Schick, 1979), lowering stream power on piedmonts and thus, promoting deposition. The Holocene brought a change to warmer, drier, and less moisture-effective conditions. Vegetation became sparser on hillslopes allowing for more runoff and increased stream power, which produced higher sediment yield. Higher stream power stripped the slopes of sediment and incised (segmented) many piedmonts (Bull, 1991). A modification of the Bull and Schick (1979) model suggests increased deposition distally on piedmonts, the result of incision up gradient (Reheis et al., 1996). Such deposition was caused by increased sediment load which outpaced the transport capacity low on piedmonts.

Piedmonts respond to tectonic activity. Tectonic activity causes the relative lowering of baselevel (Bull, 1991) which increases the gradient of mountain streams and increases their erosive ability. The upgradient stream reaches can strip hillslopes of sediment and transport it to lower gradient reaches down stream of the fault (Bull and Schick, 1979; Reheis et al., 1996). Analysis of cosmogenic nuclides in fan and boulder deposits has proven to be useful to constrain tectonic histories of fan surfaces (Bierman et al., 1995; Siame et al., 1997; Zehfuss et al., 2001).

7. Outstanding questions

After a century of desert piedmont research, there are still outstanding questions waiting to be addressed. The two most prominent are: 1.) How can one understand better piedmont formation processes? 2.) How, and at what tempo, are piedmonts changing? The formation question may never be answered satisfactorily. Some piedmonts may be fossil landscapes and it will be difficult to determine how these piedmonts formed (Oberlander, 1972; Oberlander, 1974). Ironically, the erosion that forms piedmont surfaces removes the most valuable evidence one could use to determine piedmont histories.

After 100 years, the germane processes and rates of piedmont modification are still understood poorly in part, because of slow rates of change; yet, progress is being made. Numerous studies quantify the rate of change on piedmonts. Most likely, the human time-scale is too short to understand fully the behavior of such long-lasting landforms. However, there are other methods that allow us to look back in time and gain insight into piedmont histories and the processes that modify these landforms.

Technology is changing rapidly. Today geologists have new technologies and methods at their disposal. We can use these technologies to test hypotheses of piedmont formation and to understand the rates of change on existing piedmont surfaces. For example, we can use deeply penetrating geoseismic technology to determine the geometry and structure of sediment and rock underlying piedmonts. Such information allows for the reconstruction paleolandforms and provides insight to the past morphology of piedmonts. Perhaps geophysics could test Lawson's (1915) exhumation hypothesis. In addition, advances in remote sensing (Fisher et al., 1993; Gillespie et al., 1994) and thermoluminescence dating (Clarke, 1994; Porat et al., 1997) constrain surface ages, paramount to understanding the tempo of surface change.

Cosmogenic nuclides have already provided insight into piedmont history (Bierman et al., 1995; Siame et al., 1997; Zehfuss et al., 2001) and rates of piedmont processes (Nichols et al., in review-a and b; Nichols et al., 2002). One could use cosmogenic nuclide on piedmonts that have a sediment mantle (Moss, 1977) to determine the erosional history of the piedmont. Measuring nuclide activities along a depth profile (in saprolite or alluvium) constrains the erosion and/or deposition history of the piedmont (Nichols et al., 2002). Such testing might provide insight into the exhumation of pediments. One could measure cosmogenic nuclides in a long core from a depositional piedmont to obtain age control and constrain process rates (c.f. Granger et al., 1997).

There are still enough questions left unanswered to make desert piedmonts a focus of study for the next 100 years. Each decade provides new technologies to study desert piedmonts using different approaches to acquire new and interesting data. Although understanding the timing and mechanisms of piedmont formation remains a challenge, it is increasingly possible to understand better piedmont histories and processes.

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Figure captions

Figure 1. Schematic diagrams of piedmont morphologies. A. Piedmonts can be mostly erosional and have a thin capping alluvial layer. B. Tectonically active piedmonts can form deep basins that are filled with sediment to form depositional piedmonts. C. Complex piedmonts can have erosion on the proximal piedmont, transportation on the mid-piedmont, and deposition on the distal piedmont. All three processes can be active at any one time.

Figure 2. Common piedmont surfaces. A. Photograph of a varnished, pavemented, and stable surface of the Chemehuevi Mountain piedmont, Mojave Desert, California. These surfaces are commonly incised. B. Photograph of the reworked Iron Mountain, California, piedmont surface exhibiting recent sediment mixing.

FIGURE 1

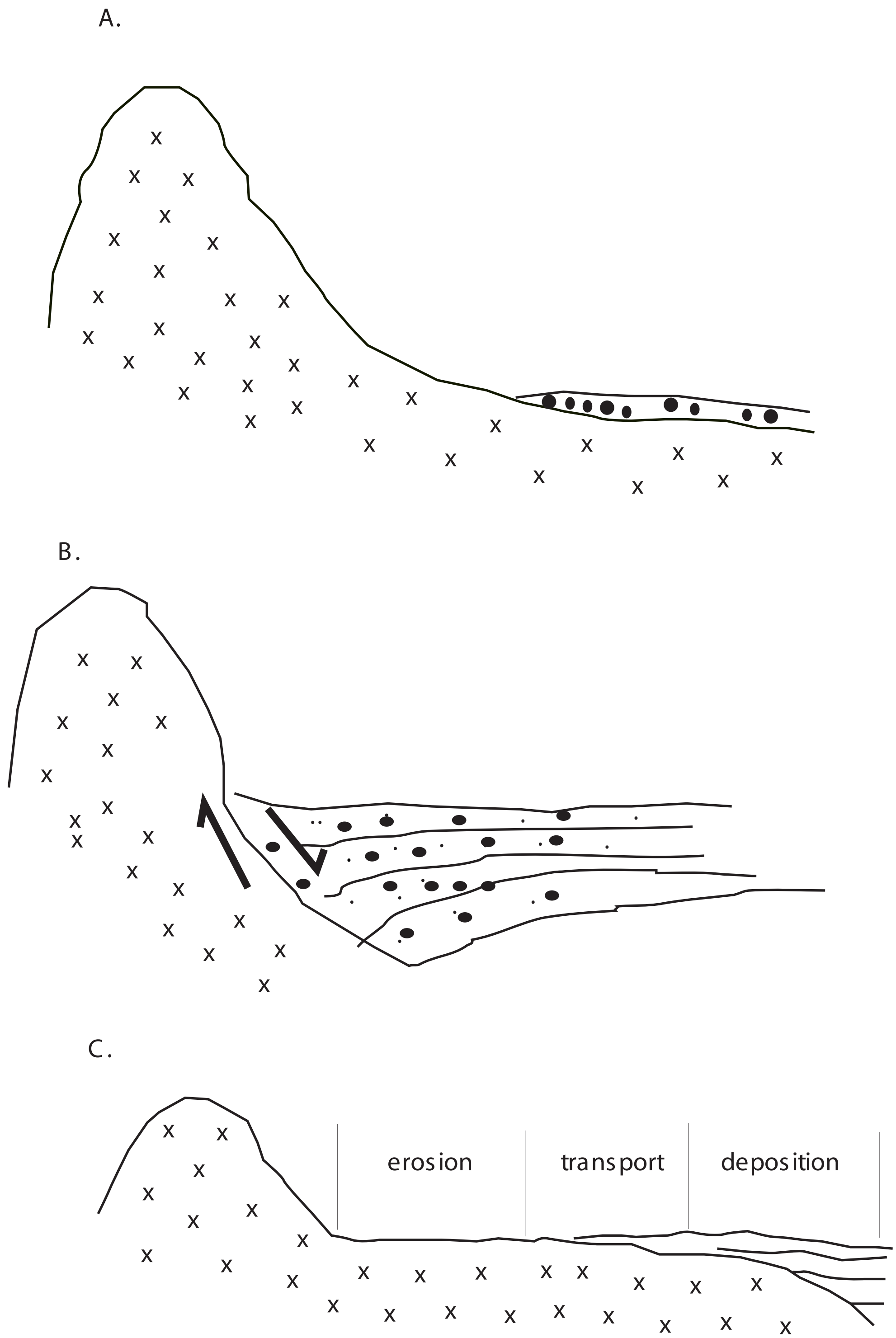
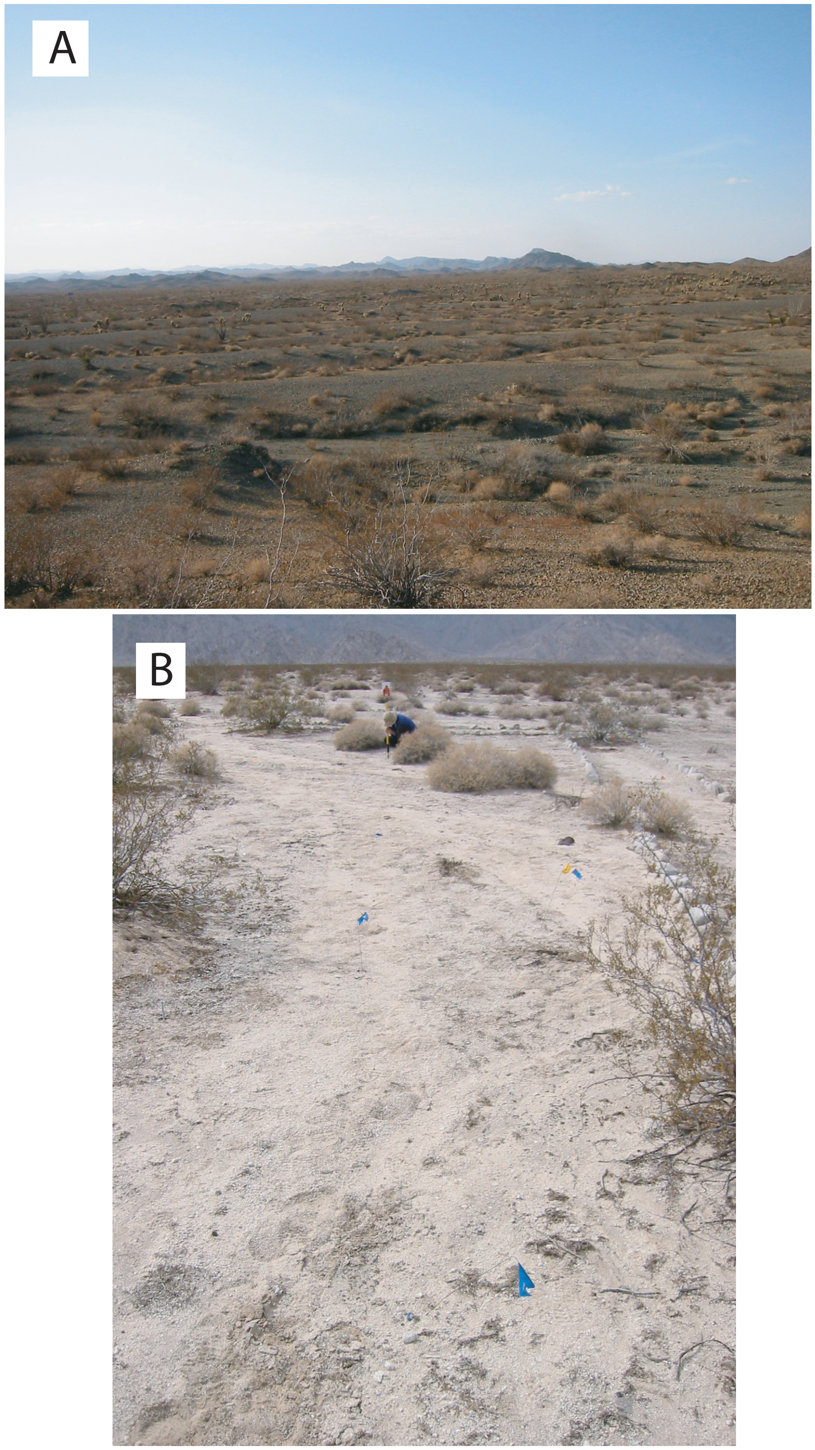


FIGURE 2



CHAPTER 3: Paper submitted to Nature

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Sediment budgeting for desert piedmonts

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Deserts cover more than 30% of the continents[1]. Ubiquitous and dominant in these arid regions are long, featureless, low-gradient slopes, generally termed piedmonts, which connect mountainous highlands to basins occupied by ephemeral lakes or rivers. As human populations increase, piedmonts are a favored site for development because they are gently sloping and readily accessible[2]. In spite of more than a century of research[3,4], little is known about the transport speed or mass flux of sediment down desert piedmonts. The paucity and spottiness of desert precipitation suggest slow integrated rates of change; yet, massive amounts of sediment can move rapidly in single flood events[5,6]. Here, we use in situ-produced

^{10}Be and ^{26}Al, measured in piedmont sediment, to construct a sediment budget and quantify the average speed at which sediment moves down desert piedmonts over millennial time-scales. The results suggest that most sediment is derived from the mountain source basins and the adjacent bedrock pediment, that sediment grains move on average decimeters per year down piedmont, and that sediment movement is systematic and predictable for many kilometers away from mountain fronts.

Over the last century, understanding how desert piedmonts, some of the most common and aerially extensive desert landforms, change through time has remained a challenge because change occurs rarely and episodically[7]. Infrequent and non-uniform desert rainfall and the uncertain response of desert landforms to climate change, make it difficult to predict and characterize piedmont behavior[4,7-10]. In order to understand the behavior of desert piedmonts and to evaluate the hazards presented to increasing human settlement on them[11], one needs a better understanding of the rates and processes that modify these ubiquitous landforms over both the short (annual) and the long (millennial) scales[12].

A full understanding of desert piedmonts requires quantifying rates of sediment input and export, as well as understanding the speed at which sediment moves, over millennia. For example, the Environmental Protection Agency and the Nuclear Regulatory Commission demand that the nuclear repository at Yucca Mountain, Nevada (ringed by desert piedmonts) hold high-level radioactive waste safely, on site, for 10,000 years[13]. Such, regulations highlight the importance of understanding the rates and distribution of both erosion and sediment transport processes active on Earth’s changing surface[14]. However, quantifying sediment transport in desert regions is difficult, time consuming, labor intensive, and uncertain. Contemporary process studies last only years to decades, usually missing rare but significant geomorphic events that likely cause the majority of geomorphic change[5,6]. Long-term climate change makes short-term extrapolation of data sets to the 10,000-year time scale a risky and unreliable endeavor[15].

Not all desert piedmonts are similar. A few are *simple*, with shallow ephemeral channels reworking the entire piedmont surface on millennial or submillenial time scales[16]. Most piedmonts are *complex*, displaying multiple geomorphic surfaces of differing age and elevation indicating that active sediment transport occurs on only part of the piedmont[17]. Piedmonts may be primarily depositional, in which case they are referred to as *fans* or *bajadas*, or they may be erosional in which case they are termed *pediments*. Here, we report new data from the complex, multi-surface Chemehuevi Mountain piedmont, a landform similar to many others in the Mojave, and other deserts[17], in that it has both fan and pediment-like sections.

In order to quantify sediment movement down the Chemehuevi Mountain piedmont, we analyzed *in situ*-produced cosmogenic ^{10}Be and ^{26}Al in quartz-bearing drainage basin and piedmont sediment, constructed a sediment budget, and used interpretive models[16,18,19] that conserve both mass and nuclide activity. Cosmogenic nuclides are produced within the upper few meters of Earth's surface[20]. As sediment is transported from the mountain basins across the piedmont, nuclide activity increases due to cosmic-ray bombardment. Since the rate at which the ^{10}Be and ^{26}Al are produced at and near Earth's surface has been estimated[21-23], one can use piedmont sediment as a cosmic-ray dosimeter in order to determine how rapidly sediment moves down desert surfaces[16].

To characterize the average ^{10}Be and ^{26}Al activity of sediment as a function of distance down the Chemehuevi Mountain piedmont (Fig. 1), we used an amalgamation technique[16]. We collected and then combined separate aliquots, along 4-km-long transects, from up to 21 ephemeral channels and from the incised surfaces through which the channels flow. Transects were spaced at 1 km intervals away from the mountain front (Fig. 1). Thus, as a group, the samples reflect the average dosing of ephemeral channel sediment as it is transported down the piedmont from the mountains to the valley-bottom ephemeral wash. Samples from incised surfaces allow us to model nuclide and mass inputs to the channels.

The Chemehuevi Mountain piedmont has three distinct and different geomorphic surfaces: a proximal, channalized bedrock pediment, a central incised alluvial reach, and a distal wash surface (Fig. 2). From the mountain front to the Sawtooth Range, 4 km away, ephemeral channels incise the bedrock pediment and its patchy alluvial cover (Fig.1). The dissected Sawtooth Range, composed of Tertiary volcanic rocks[24], is perpendicular to the steepest piedmont gradient but does not inhibit the flux of sediment down piedmont. Down gradient of the Sawtooth Range, channels incise a pavemented alluvial surface, the clasts on which are varnished. At 10 km down gradient, the pavemented surface merges with the ephemeral channels and the surface becomes uniformly active, a wash surface similar to those on piedmonts having a simple morphology.

Sediment is generated from erosion of the Chemehuevi Mountain source basins, erosion of incised pediment bedrock and patchy alluvial cover (from the mountain front to 4 km down piedmont), erosion of the Sawtooth Range, and erosion of weak banks of incised alluvium (from 5 to 10 km down piedmont). Using measured nuclide activity (see methods), we find that the flux of sediment from the small but mountainous source basins (4.0×10^4 kg y^{-1}) is similar to the flux from bedrock and colluvial incision occurring over the proximal 4 km of piedmont (3.3×10^4 kg y^{-1})[25-27]. The piedmont-crossing, ephemeral channels do not meander extensively; thus, sediment input from the weak alluvial banks is minimal (0.2×10^4 kg y^{-1}; Fig. 2). These results suggest that the majority of the sediment transported down piedmont is generated in the source basins and from the erosion of the incised bedrock pediment surface (Fig. 2).

Nuclide activity of ephemeral channel sediment increases steadily down piedmont (Fig. 3; Supplementary Table 1) indicating that cosmic ray dosing during transport must be regular and systematic. Sediment issuing from the mountain basins (average ^{10}Be activity is 130,000 atoms g^{-1}) has a steadily increasing nuclide activity (20,000 atoms km^{-1}) for the next 12 km down piedmont. The regular increase in nuclide activity down the 12-km-long Chemehuevi piedmont is striking considering the different geomorphic units through which the channels cut. The rate at which nuclide activity increases in ephemeral channel sediment is constant through incised bedrock, incised alluvium, and the wash surface (Fig. 3). Such a trend is consistent with most sediment moving slowly and steadily down the channels in numerous episodic transport events. Using a mixing model that conserves both nuclide activity and mass[16], we estimate that the average grain velocity down the Chemehuevi Mountain piedmont ranges from 8 cm y^{-1} at the mountain front to 39 cm y^{-1} on the wash surface, 12 km down gradient. Such grain speeds suggest that the average transit time for a grain moving down the 12 km long Chemehuevi Mountain piedmont is ~54,000 years.

Results from the complex, multi-surface Chemehuevi Piedmont are strikingly similar to those from the simple, wash-dominated Iron and Granite Mountain piedmonts[16] indicating that the modern-day complexity of piedmont surfaces has little influence on the patterns and rates of long-term sediment transport. On all three piedmonts, nuclide activity on active transport surfaces increases down gradient at 20,000 to 30,000 atoms km^{-1} (Fig. 3). All three mountain ranges supply similarly dosed sediment to their respective piedmonts implying similar rates of sediment generation (5.6 to 6.6 x 10^4 kg km^{-2} y^{-1}) and thus basin-scale erosion (35 to 41 mm ky^{-1})[16]. Sediment is transported in an active layer[16] only a few tens of centimeters deep at all three piedmonts (Supplementary Fig.1)[16]. Average grain speeds down the Iron, Granite, and Chemehuevi Mountain piedmonts are all decimeters per year[16].

The regular increase in sediment nuclide activity down the Chemehuevi, Iron, and Granite Mountain piedmonts mandates that sediment is regularly and systematically transported down the surface of these landforms over tens of thousands of years. Such long-term systematic transport is remarkable in light of the well-documented changes in desert climate through the Pleistocene and at the Holocene transition[17]. The similarity of nuclide data from an incised, multi-surface piedmont (Chemehuevi Mountain) and from simple planar wash surfaces (Iron and Granite Mountains) suggests that ephemeral channels on these three Mojave Desert piedmonts systematically transport sediment at similar speeds regardless of surface complexity.

The Chemehuevi Mountain piedmont sediment budget indicates that little material is currently provided by ephemeral channel incision of widespread, mid-piedmont alluvium. Most sediment in transport originates either in the mountainous drainage basins or from erosion of the mountain-proximal, bedrock pediment. However, when piedmonts are settled by humans and covered over by impervious surfaces, such as roads and roofs, the frequency, volume, and peak discharge of storm flows increase[11,28].

Such increased discharges cannot be accommodated by the present ephemeral channel geometry; mid-piedmont channels will readjust by eroding their weak alluvial banks, shifting laterally, and endangering property by undercutting[29]. Such responses will increase sediment flux, generating inundation and sedimentation hazards down piedmont. Cosmogenic nuclide data allow the construction of long-term sediment budgets for ubiquitous desert landforms thus, providing baseline data necessary to validate and inform new regulatory approaches to hazard mitigation[11].

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Figure Captions:

Fig. 1. Aerial photograph mosaic shows the Chemehuevi Mountains and the adjacent piedmont. White dashed lines represent 4-km long transects spaced at 1-km intervals from the Chemehuevi Mountains. Topography based on the Snaggletooth, Calif., and the Chemehuevi Peak, Calif., U.S.G.S. 7.5' minute quadrangles. Contour interval 30 m. The "850" marks location of highest peak in source basins. Arial photographs are NAPP 6797-74 to 77, NAPP 6798-200 to 203, and NAPP 6799-9 to 12. Inset map shows location of the Chemehuevi Mountain piedmont in the Mojave Desert, California.

Fig. 2. Generalized sediment budget of the Chemehuevi Mountain piedmont from the source basins to the last transect 12 km from mountain front. Black represents bedrock surface, gray represents alluvial surface, and white represents ephemeral channels. Bold numbers represent addition of mass, italicized numbers represent nuclide activity. Total mass flux down piedmont (10^4 kg y^{-1} km^{-2}) is shown adjacent to piedmont.

Fig. 3. ^{10}Be data from the Chemehuevi, Granite, and Iron Mountain piedmonts normalized to high latitude and sea level using Lal (1991) considering only neutrons. Data show similar slopes of nuclide activity with distance down piedmont. 1.) Closed squares (■) represent Chemehuevi Mountain data, this paper. 2.) Open squares (□) represent Granite Mountain data[16]. 3.) Open circles (O) represent Iron Mountain data[16]. IM = Iron Mountains, GM = Granite Mountains, WS = migrating channels on wash surface, CM = Chemehuevi Mountains, P = pediment, SR = Sawtooth Range, and IA = channels incised into varnished alluvium. Samples plotting at negative distance from mountain front are drainage basin samples.

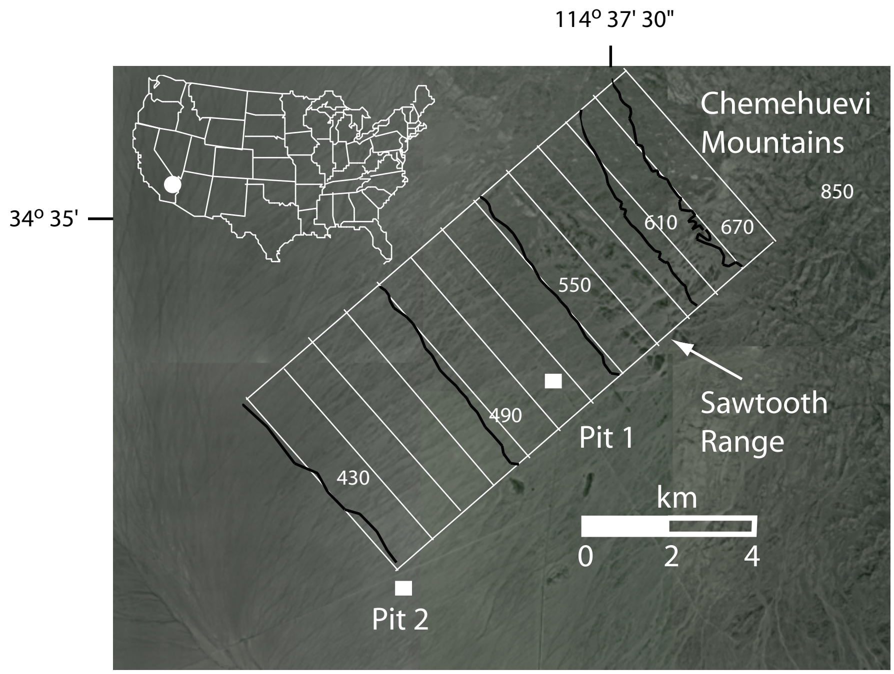
Methods

We collected amalgamated samples to characterize nuclide activities of sediment on the Chemehuevi Mountain piedmont. We collected two amalgamated source basin samples, each consisting of ephemeral stream sediment from three valleys that have similar lithologies[24]. We collected 12 sets of transect samples spaced at 1-km intervals away from the Chemehuevi Mountain front. Each transect sample is an amalgamation of up to 21 equal volume surface sediment samples (0 to 10 cm deep) spaced at ~200 m intervals along each transect. Each sample contains sediment from only one distinct geomorphic unit: ephemeral channels, surface sediment from the incised alluvium, or amalgamated bedrock. Predetermined sampling stations were located in the field using a hand-held Garmin 12 Global Positioning System (GPS).

To translate the nuclide data into sediment generation rates and sediment velocities we use the nominal production rates (sea level and > 60° latitude) of 5.2 ^{10}Be atoms g^{-1} and 30.4 ^{26}Al atoms g^{-1} [22,23,26] scaled to the Chemehuevi altitude and latitude using no muons[30]. Estimates of sediment generation are based on accepted models[25-27]. To estimate sediment speed down piedmont, we use a mixing model that conserves mass and nuclide activity[16]. The model considers measured parameters (the rate of nuclide activity increase down piedmont and the decrease in thickness of actively moving sediment down piedmont), calculated parameters (sediment flux from the mountains, the upper bedrock piedmont, and from erosion of the stable alluvial surface), and parameters taken from the literature (nuclide production rates). The model addresses erosion of substrate, deposition of sediment from the channels, and the changing thickness of sediment in transport down piedmont[16].

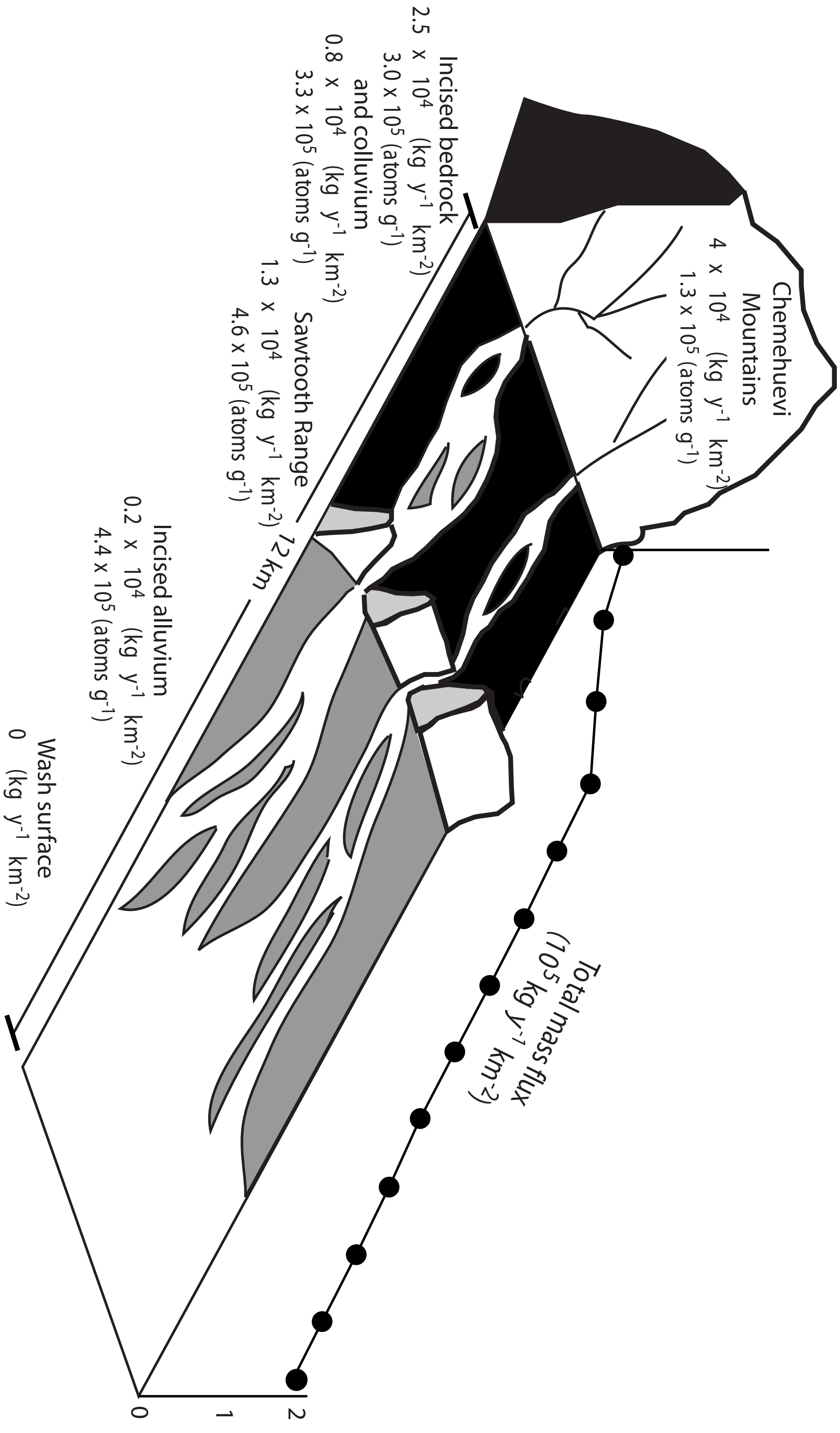
We make several simplifying assumptions in order to use these models. We assume that the processes active on the surface operate on a time scale much shorter than the nuclide half-lives. Therefore, the rate and distribution of surface processes, not radioactive decay, control nuclide activities. We assume that there is no preferential dissolution of the other minerals and thus, no quartz enrichment in the arid environment of the Chemehuevi Mountains[18].

FIGURE 1



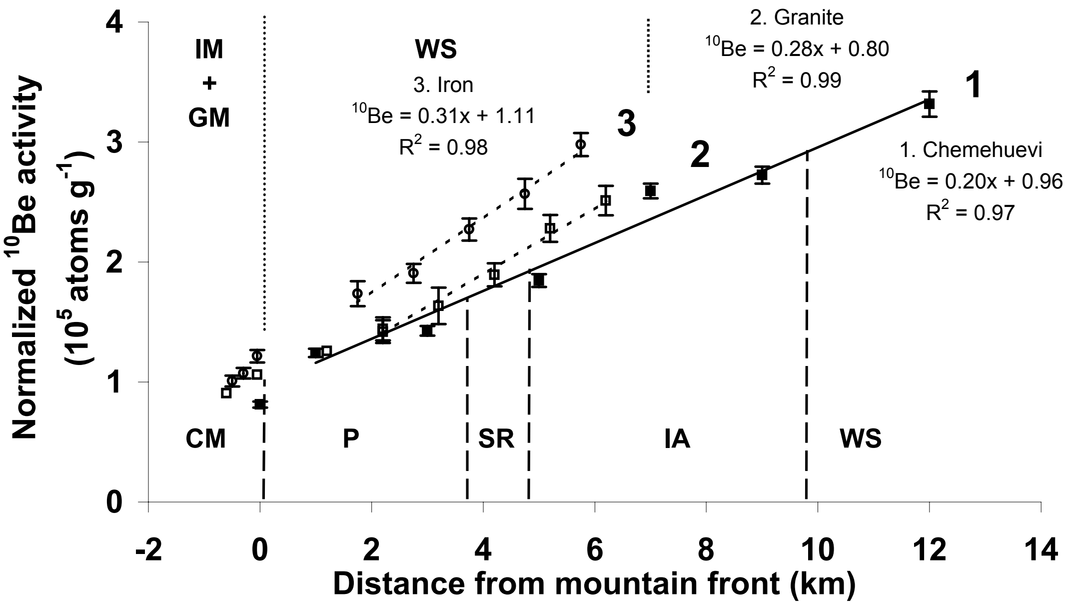
Nichols and others. Fig. 1

FIGURE 2



Chemehuevi Mountains
4 x 10^4 (kg y^-1 km^-2)
1.3 x 10^5 (atoms g^-1)
Incised bedrock
2.5 x 10^4 (kg y^-1 km^-2)
3.0 x 10^5 (atoms g^-1)
and colluvium
0.8 x 10^4 (kg y^-1 km^-2)
3.3 x 10^5 (atoms g^-1)
Sawtooth Range
1.3 x 10^4 (kg y^-1 km^-2)
4.6 x 10^5 (atoms g^-1)
12 km
Incised alluvium
0.2 x 10^4 (kg y^-1 km^-2)
4.4 x 10^5 (atoms g^-1)
Wash surface
0 (kg y^-1 km^-2)
Total mass flux
(10^5 kg y^-1 km^-2)
0
1
2

FIGURE 3



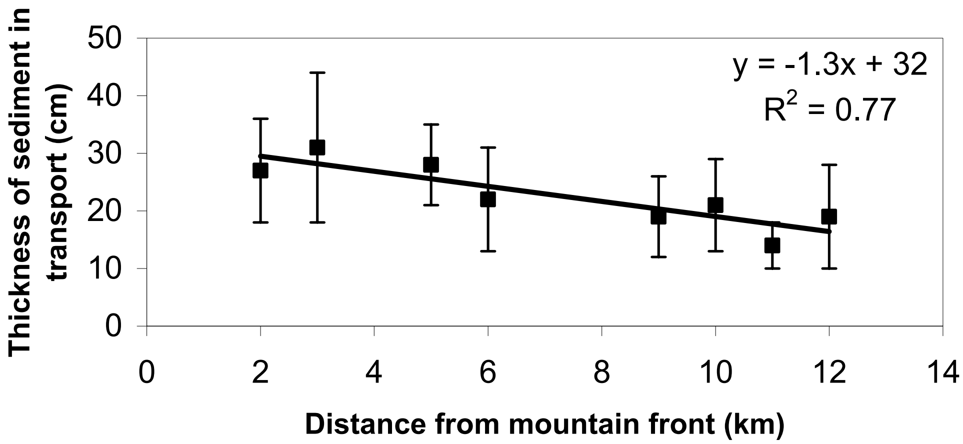
Nichols et al. Fig. 3

Supplementary Table 1. Measurements of cosmogenic nuclide activities, Chemehuevi Mountain piedmont

Sample	Elevation (m)	Northing (m)	Easting (m)	^{10}Be (10^6 atoms g^{-1})	^{26}Al (10^6 atoms g^{-1})	^{26}Al:^{10}Be
CMV-123	790	3832763	718571	0.132 ± 0.004	0.82 ± 0.054	6.22 ± 0.46
		3832571	718796			
		3832263	718885			
CMV-456	790	3831700	719904	0.128 ± 0.004	0.82 ± 0.051	6.40 ± 0.45
		3831491	719954			
		3831059	720463			
CMT-1B	670	3829529	720542	0.216 ± 0.007	1.25 ± 0.061	5.78 ± 0.34
		3832482	717860			
CMT-1C				0.195 ± 0.005	1.16 ± 0.072	5.92 ± .41
CMT-1S				0.287 ± 0.034	1.32 ± 0.074	4.60 ± 0.61
CMT-3B	600	3828156	719046	0.381 ± 0.011	2.16 ± 0.134	5.67 ± 0.39
		3821125	716328			
CMT-3C				0.217 ± 0.006	1.30 ± 0.067	6.03 ± 0.36
CMT-3F				0.333 ± 0.010	1.88 ± 0.102	5.65 ± 0.35
CMT-3H				0.546 ± 0.017	3.21 ± 0.154	5.88 ± 0.34
CMT-5C	550	3826824	717558	0.275 ± 0.008	1.83 ± 0.123	6.66 ± .049
		3829774	714858			

CMT-5F				0.455 ± 0.011	2.58 ± 0.121	5.67 ± 0.30
CMT-7C	500	3825471	716069	0.381 ± 0.011	2.38 ± 0.114	6.25 ± 0.35
		3828427	713399			
CMT-7F				0.434 ± 0.012	2.65 ± 0.127	6.09 ± 0.34
CMT-9C	470	3824108	714583	0.395 ± 0.010	2.43 ± 0.124	6.13 ± 0.35
		3827076	711926			
CMT-9F				0.430 ± 0.011	2.47 ± 0.116	5.75 ± 0.31
CMT-12C	430	3822084	712374	0.471 ± 0.015	2.74 ± 0.130	5.81 ± 0.33
		3825029	709667			
CMT-12F	430	3822084	712374	0.497 ± 0.013	2.97 ± 0.162	5.99 ± 0.36
		3825029	709667			
CP1 39-75	520	3826877	715949	0.433 ± 0.013	2.72 ± 0.138	6.28 ± 0.37
CP2 52-68	420	3822105	712484	0.489 ± 0.014	2.74 ± 0.130	5.62 ± 0.31
SRV-123	590	3828280	716955	0.462 ± 0.018	2.71 ± 0.16	5.87 ± 0.42
		3830310	716253			
		3830057	716353			

Sample notation: CM = Chemehuevi Mountain, V = valley sample, triple numbers after V indicate amalgamation of three valley samples, T = transect sample, single number after T indicates distance from the mountain front, B = bedrock, C = channel sediment, S and H = colluvium, F = terrace sediment, CP = soil pit, SR = Sawtooth Range. Numbers after CP1 and CP2 are the depth interval, that the sediment was collected from in the soil pit. All elevations are average elevations for mountain valleys, based on basin hypsometry, and for transects. Northing and Easting values are NAD 27 zone 11S UTM datum. Coordinates are listed for all valley samples. Endpoint coordinates are listed for transect samples. ^{10}Be and ^{26}Al error is counting statistics from AMS with 2% uncertainty for stable Be and 4% uncertainty for stable Al, combined quadratically.



Nichols et al., Supplementary Fig. 1. Active transport layer thickness in ephemeral channels down piedmont. Each data point represents average depth to the B-horizon of 9 shallow soil pits dug along a transect. Error bars represent 1 standard deviation. Black line represents linear model of the decrease in ATL thickness down piedmont.

CHAPTER 4: Paper submitted to The American Journal of Science

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DECIPHERING THE LATE PLEISTOCENE AND HOLOCENE HISTORY OF THE COMPLEX CHEMEHUEVI MOUNTAIN PIEDMONT USING ^{10}Be AND ^{26}Al

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ABSTRACT. **We use the cosmogenic nuclides ^{10}Be and ^{26}Al as cosmic ray dosimeters to track sediment across the complex Chemehuevi Mountain piedmont surface 12 km from source basins to the toe of the piedmont. Sediment from steep source basins constrains basin-wide erosion and thus sediment generation rates. Amalgamated sediment samples, collected along 4 km long transects spaced at 1 km intervals from the mountain front, indicate the exposure history of sediment as it is transported down the piedmont. Sediment samples from two soil pits allow for estimates of deposition rates and piedmont history.**

Model results suggest that the Chemehuevi Mountains are eroding at 41 mm ky^{-1}. Steadily increasing, down-piedmont nuclide activities suggest that sediment is systematically dosed during transport at average sediment grain velocities from 9 to 38 cm y^{-1}. Cosmogenic nuclide profiles in both soil pits suggest a similarly complex history of deposition at 18 to 37 mm ky^{-1}. A change in process from sediment deposition to sediment transport occurred distally on the piedmont ~8,000 years ago, while the proximal piedmont surface has been stable for the past 25,000 years.

The complex Chemehuevi Mountain piedmont is changing at rates similar to those that are modifying the much simpler, uniformly active Iron and Granite Mountain piedmonts. All three piedmonts have average sediment velocities of decimeters per year, long-term source basin erosion rates of 34 to 41 mm ky, depositional hiatuses around the Pleistocene/Holocene climatic transition from moister to drier conditions, and Pleistocene deposition rates of 18 to 37 mm ky. These similarities suggest that the rates of piedmont process are independent of piedmont morphology.

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 (Bull, 1964; Denny, 1967; Hooke, 1968; Mabbutt, 1966; McGee, 1897; Oberlander, 1974; Paige, 1912). However, the complex interactions between tectonic activity, climate, lithology, and source basin characteristics have diminished the utility of such wide-ranging theories (Bull, 1991; Cooke and Warren, 1973; Lecce, 1990; Oberlander, 1974). Some suggest that desert piedmonts developed under climatic conditions different from today; therefore, the processes currently modifying piedmonts are not those that formed them (Dohrenwend, 1987; Oberlander, 1974). Others have tried to deduce the mechanisms of piedmont formation using contemporary piedmont morphometries (Mammerickx, 1964; Schumm, 1962). 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).

Desert piedmonts of the American southwest are well represented in the geomorphological literature (Bull, 1963; Denny, 1967; Edinger-Marshall and Lund, 1999; Hooke, 1967; McFadden, Ritter, and Wells, 1989; Nichols and others, 2002; Oberlander, 1974; Parsons and Abrahams, 1984). However, many of the contributions discuss piedmont end members: *erosional pediments* or *depositional alluvial fans or plains*. Pediments are low gradient erosional surfaces cut into bedrock (for example (McGee, 1897; Whitaker, 1979) or, as some have suggested, cut into older alluvium (Hadley, 1967). Alluvial fans are low gradient surfaces where deposition dominates. On many piedmonts, pediments abut the mountains and depositional alluvial plains occur down gradient. Some piedmonts have a zone of transport, intermediate between the pediment and the alluvial plain, where neither net erosion nor net deposition occurs (Cooke and Mason, 1973; Moss, 1977). Only a few papers discuss piedmonts in their entirety and describe both the erosional and depositional processes acting on the same piedmont (Cooke and Mason, 1973; Denny, 1967).

Several hypotheses have been advanced to describe the formation of pediment surfaces, including lateral migration of channels to form the "smooth" bedrock floor (Gilbert, 1877; Howard, 1942; Johnson, 1932; Paige, 1912), 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; Twidale, 1967). Similar attention has been paid to depositional alluvial fans or plains (Bull, 1977; Denny, 1967; Harvey, 1997). Alluvial fan research addresses fan morphometery (Bull, 1964; Rachocki, 1981; Wells and Harvey, 1987), the processes that segment or incise alluvial fans (Bull, 1991; Denny, 1967; Ritter, 1972), and the long-term behavior of alluvial fans (Hooke, 1967; Hooke, 1968; McFadden, Ritter, and Wells; 1989).

Desert piedmonts have been studied using a variety of approaches: observation (Gilbert, 1877; McGee, 1897), soil development (Eppes and others, 2002; McFadden, Ritter, and Wells, 1989), mapping (House, 1999; Wells and Harvey, 1987), and morphometric analysis (Abrahams and others, 1984; Cooke, 1970; Cooke and Reeves, 1972; Mammerickx, 1964). Each of these methods provides information over different temporal and spatial 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 (Edinger-Marshall and Lund, 1999; Laronne and Reid, 1993; Persico, Nichols, and Bierman, 2001); soil development can provide a relative longer-term history of deposition and erosion (Eppes and others, 2002; McAuliffe and McDonald, 1995; McFadden, Ritter, and Wells, 1989).

Over the past 20 years, sediment transport on piedmonts and in arid basins has received considerable attention. Some studies characterize sediment movement after successive flood events (Laronne and Reid, 1993; Reid and Laronne, 1995; Schick, Lekach, and Hassan, 1987) 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, Parsons, and Luk, 1988; Luk, Abrahams, and Parsons, 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 rates and patterns on desert piedmonts. The first attempt to use cosmogenic nuclides as tracers provided only limiting rates for sediment transport 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 the more than 5 km down the piedmont (Nichols and others, 2002). The surface of the simple piedmonts that they studied is uniformly active, well mixed, and lacks stable or deeply incised segments. The long-term (10^4 years) average sediment velocities at the simple Iron and Granite Mountain piedmonts were estimated at decimeters per year (Nichols and others, 2002).

In this paper, we use cosmogenic ^{10}Be and ^{26}Al activities to trace sediment from the source basins, through the proximal bedrock pediment, into a section of varnished and pavemented surfaces incised by ephemeral channels (alluvial fan), and finally through the uniformly active wash surface or alluvial plain (fig. 1). Using cosmogenic nuclides we determine long-term piedmont behavior and quantify piedmont process rates.

GEOLOGIC SETTING

Broad complex alluvial piedmonts are common in the Mojave Desert. We chose a 4-km-wide and 12-km-long section of the Chemehuevi Mountain piedmont to quantify long-term rates of sediment generation, movement, and deposition (fig. 1). The Chemehuevi Mountains, which are the 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 (~15°) normal faults, the hanging wall rocks eroded and doming of the granite, gneiss, metasedimentary rocks of the footwall created the Chemehuevi Mountains (John and Foster, 1993). Thus, the piedmont we studied must be Miocene age or younger.

The Chemehuevi Mountain front roughly follows the Chemehuevi-Sacramento detachment fault (fig. 2). The domed Chemehuevi Mountains are mapped as the foot wall, while most of the rocks between the mountain front and the Sawtooth Range are mapped as the hanging wall (John, 1987). Chemehuevi Mountain source basins that feed the 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. Surface clasts on the piedmont range in size from less than a centimeter up to > 30 cm near the mountain front. Down gradient of the Sawtooth Range, surface clasts are rarely greater than 10 cm. The 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 has three sections, 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). At four kilometers from the mountain front, the narrow Sawtooth Range (< 1 km wide), a sequence of Tertiary volcanic rocks (John, 1987), parallels contour. Down gradient of the Sawtooth Range are broad surfaces 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).

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 (http://www.wrcc.dri.edu/htmlfiles/ca/ca.avg.html). The Needles area receives an average of 11.9 cm of rain annually (http://www.wrcc.dri.edu/cgi-bin/cliNORMtM.pl?caneed). 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

Valley Samples. We determined long-term basin erosion and sediment generation rates of the Chemehuevi Mountains 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. 2). We amalgamated sediment from basins dominated by similar lithologies.

Transect Samples. We collected twelve transect samples spaced at 1-km intervals away from the Chemehuevi Mountain front. Each transect sample integrated an equal volume of surface sediment (0 to 10 cm deep) collected from up to 21 sampling stations, spaced at ~200 m intervals, along each 4-km transect (fig. 1). Along each transect, we separately amalgamated sediment samples from ephemeral channels that incised alluvium, from the abandoned varnished surface, and from colluvium exposed on low bedrock knobs where these cropped out. Predetermined sampling stations were located in the field using a hand-held Garmin 12 Global Positioning System (GPS). A horizontal GPS uncertainty of ± 20 m randomized the sampling locations.

Soil Pit samples. Soil-pit profiles allow us to estimate the depth to which sediment is currently well-mixed and allow us to quantify past piedmont process rates (Clapp and others, 2001; Lal and Arnold, 1985; Nichols and others, 2002; Phillips and others, 1998). 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, soil color, texture, structure, and carbonate percentage (table 1). On the basis of soil stratigraphy and soil horizonation, we divided each pit into continuous depth intervals so that we sampled sediment from the entire pit wall.

We dug shallow soil pits (n = 90) in channels along the transects spaced at 1 km intervals down the Chemehuevi Mountain piedmont to determine the depth of the layer of sediment that is in active transport. We assume that the soil above the B-horizon is in active transport down the piedmont and the B-horizon a represents stable substrate over which sediment transport occurs (Lekach and others, 1998; Nichols and others, 2002).

Laboratory methods.

Samples were prepared for nuclide analysis at the University of Vermont. All samples were sieved (>2000μm, 2000 to 850 μm, 850 to 500 μm, < 500 μm) and weighed. 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 (Clapp, Bierman, and Caffee, 2002; Clapp and others, 2001; Clapp and others, 2000; Granger, Kirchner, and Finkel, 1996). 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% HF and 1% HNO_3 baths in order to remove any atmospheric ^{10}Be and to isolate 30 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. 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° latitude) of 5.2 ^{10}Be atoms g^{-1} and 30.4 ^{26}Al atoms g^{-1} (Bierman and others, 1996; Clark, Bierman, and Larsen, 1995; Gosse and Phillips, 2001; Stone, 2000). We scaled the nominal production rates to the Chemehuevi altitude and latitude using no muons (Lal, 1991).

In order to translate the nuclide activities into quantifiable process rates and piedmont histories, we use several mathematical models. Sediment generation rates of the source basins are modeled using the approach of Brown and others (1995), Bierman and Steig (1996), and Granger, Kirchner, and Finkel (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, Repka, and Dick (1996). Sediment transport models are based on mass and nuclide flux (McKean and others, 1993; Monaghan and others, 1992; Nichols and others, 2002; Small, Anderson, and Hancock, 1999). Each of these models that we use to quantify piedmont process rates and histories are described in detail in Nichols and others (2002).

We must 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 (Riebe and others, 2001a; Small, Anderson, and Hancock, 1999).

RESULTS

All 41 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% for ^{10}Be and 5% for ^{26}Al. Because ^{10}Be and ^{26}Al data are well correlated and consistent (fig. 4), 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 41 samples are within 1σ of 6.0, the nominal ratio at production (Nishiizumi and others, 1989); at 2σ, the ratio for all but 2 samples are indistinguishable from 6.0 (fig. 4; table 2). The ratio data indicate that the sediment we sampled has not been buried below the depth of significant nuclide production (>1 or 2 m) for more that 10^5 ky (Bierman and others, 1999; Nishiizumi and others, 1991).

Source basin samples. The Chemehuevi Mountain source basin samples (CMV-123 and CMV-456) have similar nuclide activities that overlap a 1σ (table 2) indicating similar cosmic-ray dosing histories and thus source-basin erosion rates. The average ^{10}Be activity of the source basins is $1.30 \pm 0.04 \times 10^5$ atoms g^{-1} and the average ^{26}Al activity is $8.20 \pm 0.53 \times 10^5$ atoms g^{-1} (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 ($4.62 \pm 0.18 \times 10^5$ ^{10}Be atoms g^{-1} and $2.71 \pm 0.16 \times 10^6$ ^{26}Al atoms g^{-1}; table 2).

Soil pit samples. The two soil pits on the Chemehuevi Mountain piedmont (~6 km and ~12 km from the mountain front) have different nuclide activity trends as a function of depth indicating that the proximal and distal piedmont have different histories. The soil pit located 6 km from the mountain front (CP1) has ^{10}Be nuclide 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. 5). The highest nuclide activity is in the sample from the bottom of the pit.

The soil pit at 12 km from the mountain front (CP2) has nuclide activities that mostly increase as a function of depth (fig. 6). The top most 52 cm of sediment is well mixed and there is no variation in the ^{10}Be activity (fig. 6A). 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.

The depth to the B-horizon, measured in 90 shallow soil pits, allows us to estimate the depth and volume of sediment that is in active transport down the piedmont. Assuming that the top of the B-horizon represents stable soil for at least a few thousand years, the sediment in transit above the B-horizon comprises the *active transport layer* (ATL; Lekach and others, 1998; Nichols and others, 2002). The depth to the B-horizon decreases down piedmont at a rate of 1.3 cm per kilometer (fig. 7). The frequency of channels across the 4 km long transects increases from 43 channels at 5 km from the rangefront to 308 channels at 12 km. The average channel width decreases from > 7 m at 5 km from the rangefront to an average of ~ 2 m between 9 km to 12 km (table 3).

Transect samples. We collected independent samples for each of the geomorphic units present along 12 transects spaced at 1-km intervals from the Chemehuevi Mountains. We analyzed 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) do not increase systematically down piedmont and are higher than the ephemeral channel activities suggesting a longer exposure history (fig. 8; O). At distances greater than 10 km from the mountain front, the incised alluvial surface merges with a wash surface that lacks varnish and pavement (fig. 3B). The average nuclide activity of sediment collected from the interfluves within the wash surface 12 km from the rangefront is inseparable from the ephemeral channel sediment nuclide activity at 1σ (fig. 8) indicating that channels rework the surface rapidly. Amalgamated colluvium and bedrock samples (□), 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 complex, multi-surfaced Chemehuevi Mountain piedmont, when taken in concert with previous results from the simpler, wash-dominated Iron and Granite Mountain piedmonts (Nichols and others, 2002), 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 surfical processes and the Late Pleistocene histories of piedmonts that have distinct differences in morphology.

Source basin sediment generation.

The average basin-wide lowering rate of the Chemehuevi Mountains is ~41 mm ky^{-1}, equivalent to a sediment flux per meter of mountain front of 0.026 m^3 y^{-1} exiting the 1.5 km^2 source basins. 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. Taking into account different 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}, respectively; 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 the gneissic basin in Yuma Wash, Arizona (26 mm ky^{-1}; Clapp, Bierman, and Caffee, 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, Kirchner, and Finkel, 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, b).

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 2-m deep profiles allow for quantification of the rates at which sediment is deposited onto the piedmont, the timing and duration of depositional hiatuses (Lal and Arnold, 1985; Nichols and others, 2002), and the duration of surface stability (Anderson, Repka, and Dick, 1996). Qualitatively, each process can be defined by the nuclide activity trends with depth (fig. 9). Below we interpret two soil pits, one located more proximal to the range front (CP1) and the other located more distally (CP2).

Soil pit in distal wash surface (CP2). The distal portion of the Chemehuevi Mountain piedmont is characterized by a wash surface that does not exhibit varnish or pavement; ephemeral channels are < 30 cm deep (fig. 3D). The soil pit excavated on this portion of the piedmont (CP2) has an interval where nuclide activities are uniform, two intervals where nuclide activities increase with depth, and two discontinuities where nuclide activity changes abruptly (fig. 6). 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 the past ~70 ky.

Nuclide data indicate that the lower piedmont is an area of sediment transport and deposition. The upper 52 cm is well mixed and thus probably represents material actively in transport. An abrupt increase in nuclide activity at 52 cm could reflect a depositional hiatus lasting for about the last 8 kys. The pattern of nuclide activity in samples collected between 52 cm and 151 cm suggests sediment was deposited at 37 mm ky^{-1} for 26 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 34 ky ago. From 151 cm to the bottom of the pit at 220 cm, sediment was deposited at 20 mm ky^{-1} for 35 ky. The total time represented in CP2 is ~70 ky (fig. 6).

Soil pit in proximal 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 B-horizon suggest that the surface has been stable for at least thousands of years (McFadden, Ritter, and Wells, 1989). Below the stable surface, increasing and decreasing trends of nuclide activity with depth suggest a complex history of deposition, stability, and erosion at soil pit CP1 (fig. 5).

The smooth decrease of nuclide activity with depth between the surface and 36 cm suggests that the alluvium into which the pit was dug has been stable for about 26 ky (model of Anderson, Repka, and Dick, 1996) exceeding by several fold the age suggested by soil development. A jump to higher nuclide activity occurs abruptly at a buried soil horizon (39 cm; fig. 5). The presence of this Bt-horizon (table 1) suggests little deposition and minimal sediment erosion. Therefore, assuming the discontinuity in nuclide activities represents either sediment transport or a stable period, the duration of the depositional hiatus is ~13 ky (Anderson, Repka, and Dick, 1996; Nichols and others, 2002). Increasing nuclide activities with depth, from 39 cm to 96 cm, suggest deposition at 18 mm ky^{-1} for 32 ky (fig. 5). 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. Soil development does not indicate a surface of stability at 96 cm. Similarly, there is not a nuclide discontinuity between the sample above 96 cm and the sample below 96 cm. Therefore, the soil development and the nuclide data are consistent with a decrease in deposition rate, not stability. The total time represented in the soil pit to 190 cm is ~70 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 erosion 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 proximal site) and CP2 (the distal site) are geomorphically and temporally consistent. Deposition rates at CP1 from ~70 to 38 ky were 18 mm ky^{-1} (fig. 5). Deposition rates at CP2 from ~70 to 34 ky were 20 mm ky^{-1} (fig. 6). 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 34 ky, the deposition rate at the distal CP2 site increased to 37 mm ky^{-1} coincident with an increase in nuclide activity of the incoming sediment (fig. 6). This change in deposition rate and in nuclide activity of the sediment arriving at the 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 38 ky (fig. 5). Incision of the proximal 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. It appears that the transition from interstadial to early glacial times resulted in erosion up piedmont and deposition distally.

Incised alluvial surface

The Chemehuevi piedmont has an older alluvial surface that is inactive and isolated from current sediment transport processes. The incised alluvial surface, found between 5 and 10 km distal from the mountain front, has nuclide activities that do not change down piedmont, suggesting similar exposure histories (fig. 8). Simply interpreted, the higher alluvial surface was deposited quickly and has a uniform age. The simultaneous deposition of the higher alluvial surface is different than the slow steady march of sediment down the piedmont of today. The cosmogenic data from soil pit CP1, dug into this surface, suggest that the alluvial surface was deposited rapidly ~26 ky.

Sediment mixing model.

The transect nuclide data allow us to construct a sediment budget for the present-day Chemehuevi Mountain piedmont. In order to quantify the change in sediment flux down piedmont, we developed a sediment mixing model that tracks mass and nuclide contributions from various piedmont elements including source basins, bedrock, and colluvial outcrops on the proximal piedmont, input from the Sawtooth Range, and bank erosion in the incised middle piedmont (fig. 10; table 4). To streamline the sediment budget, we report the average values for each geomorphic surface (fig. 10).

The source basins contribute the most sediment (4×10^4 kg y^{-1} km^{-2}; fig. 10). The bedrock pediment between the mountain front and the Sawtooth Range is adding an average of 2.5×10^4 kg y^{-1} km^{-2} to the down piedmont sediment flux. Colluvium derived from the bedrock pediment supplies 0.8×10^4 kg y^{-1} km^{-2}. Little sediment is contributed from the small patches of alluvium on the piedmont from the mountain front to the Sawtooth Range because the ephemeral channels that incise the surface show little signs of meandering. The Sawtooth Range has a high nuclide activity that suggests low basin-wide erosion rates; it contributes 1.3×10^4 kg y^{-1} km^{-2} of sediment.

Sediment added from the incised alluvial surfaces (5 to 10 km) to the ephemeral channels is minimal. The ephemeral channels incised into the varnished and pavemented alluvial surface do not show evidence of extensive meandering or bank erosion. By summing the bank exposures along each channel (table 3) and by assuming incision of 3 m of alluvium in 25,000 years, an average of 0.2×10^4 kg^{-1} y^{-1} km^{-2} is added to the sediment flux from the incised alluvial reach.

The distal Chemehuevi piedmont is a wash surface. Sediment in the wash surface is reworked on ≤ 2000 y time-scale (exposure time required for the low terrace sample,CMT-12F, and the channel sediment, CMT-12C, to not overlap at 1σ based the altitude and latitude of the Chemehuevi Mountains). The wash surface is neither aggrading, based on the nuclide discontinuity at 52 cm, nor degrading significantly based on the presence of the Bw horizon. Rather, the channels move sediment and deposit it for ≤ 2000 years, and then entrain and transport the sediment again; thus, there is no net sediment contribution to the sediment flux from the wash surface.

Sediment velocity

To quantify the sediment velocity down the Chemehuevi Mountain piedmont we employ the mass and nuclide balance model of Nichols and others (2002). The model uses a variety of parameters that are directly measured (ATL thickness and nuclide activity), calculated (sediment flux from source basins and the piedmont), and taken from the literature (nuclide production rates, neutron attenuation lengths). Even though we understand contemporary measurements of the piedmont well, we do not know how well they reflect past values under different climatic regimes.

The nuclide and mass balance model, in conjunction with the sediment budget outlined above, represents our best understanding of sediment dynamics on the Chemehuevi piedmont because it considers sediment in transit, incorporation of sediment from the piedmont, and deposition of sediment from the ATL. The model represents the portion of the piedmont that is actively in transport (ephemeral channels and the wash surface). Furthermore, we can incorporate changes in the ATL thickness, deposition rate, and the nuclide activity of the eroded sediment down the piedmont. Using the parameters we measured at the Chemehuevi Mountain piedmont, the nuclide and mass balance model fits the data well (fig. 11). For this model, we used the production rates of Bierman and others (1996), the nuclide based estimates of sediment flux from the source basins, the piedmont sediment budget, the soil pit-based estimates of nuclide activity in the top of the underlying B-horizon, the accepted neutron attenuation factor (165 g cm^{-2}), and the measured change in ATL thickness down piedmont.

The model results allow for quantification of piedmont process rates that would otherwise be difficult to quantify. It suggests that present-rates of substrate erosion range from 5 mm ky^{-1} near the mountain front to 10 mm ky^{-1}, 12 km down piedmont. The average grain speed down the Chemehuevi Mountain piedmont increases from 8 cm y^{-1} from the mountain front to 39 cm y^{-1} at the last transect, 12 km down gradient. The total transit time for sediment from the source basins to the last transect is ~54,000 years.

INSIGHTS INTO GENERALIZED MOJAVE DESERT PIEDMONT BEHAVIOR

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

The Chemehuevi Mountain piedmont differs morphologically from the Iron and Granite Mountain piedmonts (Nichols and others, 2002) in several ways. The large and planar Chemehuevi Mountain piedmont (12 km) is fed by multiple lithologies. The piedmont is part of an open system; sediment can be transported into the Colorado River. The Chemehuevi Mountain piedmont has multiple surfaces that include active ephemeral channels, incised bedrock, incised varnished and pavemented alluvium, and an unvarnished and unpavemented wash surface that is frequently reworked by migrating channels. The Chemehuevi Mountain piedmont includes a small, interpiedmont mountain range (the Sawtooth Range) that adds additional sediment to the piedmont.

In contrast, the shorter (6 km) Iron and Granite Mountain piedmonts are fed by homogenous granitic rocks and are part of a closed system where sediment is deposited before or at Danby Lake playa, ~12 km from the mountain fronts (Nichols and others, 2002). The Iron and Granite Mountain piedmonts are dominated in their entirety by unvarnished and unpavemented wash surfaces that are reworked by ephemeral channels

(Nichols and Bierman, 2001); there are no additional sediment sources on the Iron and Granite Mountain piedmonts. Despite these differences, cosmogenic nuclide analyses and modeling suggest that the three piedmonts have similar process rates and histories over the past several tens of thousands of years.

Nuclide activities increase in a systematic fashion down all three piedmonts (29,000, 36,000, and 32,000 ^{10}Be atoms km^{-1}, respectively). The source basins for all piedmonts have similar long-term erosion rates (Chemehuevi = 41 mm ky^{-1}, Iron = 33 mm ky^{-1-}, Granite = 34 mm ky^{-1}). Soil pits on both the Chemehuevi and Iron Mountain piedmonts suggest a hiatus in deposition and change in process from deposition to transport at approximately the Pleistocene/Holocene climatic transition. The Iron and Chemehuevi Mountain piedmonts have long-term deposition rates that range between 17 and 37 mm ky^{-1}. All three piedmonts have average sediment speeds of decimeters per year (Nichols and others, 2002).

SUMMARY

Mojave Desert piedmonts are organized and dynamic systems when studied at large spatial (km^2) and long time-scales (10^3 to 10^4 y). Analysis of cosmogenic nuclides has opened a window into the long-term piedmont processes that have for so long gone unquantified. Although such nuclides quantify piedmont modification rates and not piedmont genesis, we demonstrate that contemporary process rates are similar regardless of piedmont surface morphology. Even though Mojave Desert piedmonts may have formed by any number of processes, our results suggest that the rate and distribution of surface processes during the Pleistocene and Holocene are controlled by “recent” factors, most importantly climate.

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FIGURE CAPTIONS

Fig. 1 Aerial photograph mosaic shows Chemehuevi Mountains and adjacent piedmont. Sub-parallel ephemeral channels that drain the study section of the piedmont and sub-parallel contour lines indicate little convergence or divergence of sediment down piedmont. The white dashed lines represent 4 km long transects spaced at 1 km intervals from the Chemehuevi Mountains. Topography based on the Snaggletooth, Calif. and the Chemehuevi Peak, Calif., U.S.G.S. 7.5' minute quadrangles. Contour interval 60 m. The "850" marks location of highest peak in source basins. Arial photographs are NAPP 6797-74 to 77, NAPP 6798-200 to 203, and NAPP 6799-9 to 12. Inset map shows location of the Chemehuevi Mountain piedmont in the Mojave Desert, California.

Fig. 2. Generalized bedrock map of the Chemehuevi source basins and adjacent piedmont to the Sawtooth Range. Xgn = gneiss and migmatite, granite amphibolite facies, orthogneiss. Yg = porphyritic monzogranite. Kpg = Cretaceous porphyritic biotite granodiorite and monzogranite. Tv = Tertiary mafic, intermediate and silicic volcanic flows that compose the Sawtooth Range. Qa/Qta = Incised alluvium and ephemeral channels. Channel widths are too small to accurately display on map. Gray portions represent unit Xgn of the hanging wall. Black lines are 4 km long and represent transect locations. The Chemehuevi-Sacramento detachment fault is within 1.5 km of the mountain front. Barbs are on the hanging wall. Map based on U.S.G.S. open-file report 87-666 (John, 1987).

Fig. 3 Schematic diagram showing geomorphic units on the Chemehuevi Mountain piedmont. Low bedrock knobs of the pediment (black) are dominant from the mountain front to the Sawtooth Range. Varnished and pavemented incised alluvium (gray) is present from the mountain front to ~10 km but dominates from 5 – 10 km. Wash surface (white) dominates from 10 to 12 km. A. Incised bedrock and alluvium from mountain front to 4 km. B. Incised alluvial surface 6 km from the mountain front. C. Incised varnished and pavemented alluvial surface merging with the wash surface 10 km from the mountain front. D. Wash surface 11 km from the mountain front. Channel banks are weak and are < 50 cm high. Interfluves lack varnish and pavement.

Fig. 4. Graph 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 burial of sediment samples.

Fig. 5. Nuclide data for CP1 (^{10}Be data (A) and ^{26}Al data (B)). Data points represent mid-point of depth interval. Black lines show model fit. Dashed lines represent buried soil horizons. A. Modeled surface age. B. Modeled duration of depositional hiatus. C. Duration of deposition at 20 mm ky^{-1}. D. Rapidly deposited sediment at ~70 ky ago. E. Total time represented in the soil pit. Error bars represent 1σ analytical uncertainty.

Fig. 6. Nuclide data for CP2 (^{10}Be data (A) and ^{26}Al data (B)). Data points represent mid-point of depth interval. Black lines show model fit. Dashed lines represent buried

soil horizons. The top 52 cm are well mixed. A. Duration of depositional hiatus. B. and C. Duration of deposition of 37 mm ky^{-1} and 20 mm ky^{-1}, respectively.

Fig. 7. Active transport layer thickness down piedmont. Each data point represents average depth to the B-horizon of 9 shallow soil pits dug along a transect. Error bars represent 1 standard deviation. Black line represents linear model of the decrease in ATL thickness down piedmont.

Fig. 8. Source basin and transect nuclide data for the Chemehuevi Mountain piedmont (^{10}Be data (A) and ^{26}Al data (B)). The ephemeral channel sediment represented by black diamonds (♦), higher alluvial sediment is represented by open circles (O), Sawtooth Range is represented by filled square (■), the hillslope colluvium is represented by open triangles (Δ), and the amalgamated bedrock samples are represented by open squares (□). The black line represents a linear model fit to the ephemeral channel data. Error bars represent 1σ analytical uncertainty.

Fig. 9. Generalized graph showing nuclide activity trends in sediment using typical Chemehuevi Mountain piedmont parameters. A. Nuclide activities that decrease at depth represent stable surface. B. Nuclide activities that are uniform at depth represent well-mixed or recently deposited sediment. C. Nuclide activities that increase at depth represent deposition.

Fig. 10. Generalized sediment budget of the Chemehuevi Mountain piedmont from the source basins to the last transect 12 km from mountain front. Black represents bedrock surface, gray represents alluvial surface, and white represents ephemeral channels. Bold numbers represent addition of mass; italicized numbers represent nuclide activity. Total mass flux down piedmont (10^4 kg y^{-1} km^{-2}) is shown adjacent to piedmont.

Fig. 11. Best fit of nuclide mixing model to the ^{10}Be data. Black line represents model; triangles represent ^{10}Be data. 1σ analytical error bars are smaller than the symbols. RMS error of the model is 24,000 atoms.

Table 1

Soil pit descriptions for Chemehuevi Mountain piedmont

Pit	Horizon[1]	Depth (cm)	Color[2] Moist	Dry	Texture[3]	Structure[4]	Carbonate[5] (%)
CP1	1Av	0-8	7.5YR 4/4	10YR 6/4	SL	3 f/m pl	ef
	1Bw	8-20	7.5YR 5/4	10YR 6/3	LS	2 m/c sbk	ef
	1Ck	20-39	10YR 5/4	10YR 6/4	LS	2 f sbk	m ef
	2Btkb	39-75	10YR 5/4	10YR 6/4	SL	2 c sbk	ef v
	2Btkb2	75-96	7.5YR 5/4	10YR 6/3	SL	2 f sbk	ef v
	2Kb	96-130	10YR 6/3	10YR 7/2	L	m	ef v, stage III
	3Ckox	130-189	10YR 5/3	10YR 6/3	SL	sg/sf/m sbk	m ef
	3Kb2	189-234	10YR 6/4	10YR 7/3	SL	m	ef v, stage III
CP2	1Av	0-5	10YR 5/3	10YR 6/4	SL	2 m pl	
	1Ck2	5-12	10YR 5/3	10YR 6/4	SL	sg	
	2Bwb	12-32	10YR 5/3	10YR 6/4	SL	2 m/c sbk	
	2Bwb2	32-52	7.5YR 5/4	10YR 6/4	L	1 f sbk	
	2Bwb3	52-68	7.5YR 5/4	10YR 6/4	SL	2 m/c sbk	
	2Bwbk	68-89	7.5YR 5/4	7.5YR 7/3	L	2 m/c sbk	stage I
	3Btbk	89-110	7.5YR 5/4	7.5YR 6/4	SL	2 f/m abk	stage II+
	3Btbk2	110-151	7.5YR 5/4	7.5YR 6/4	SL	3 m abk	
	3Bkb	151-188	7.5YR 6/4	7.5YR 7/3	SL	2 f/m abk	stage II+
	3Bkb3	188-220	7.5YR 5/4	7.5YR 6/4	SL	1/2 f sbk	

[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.

Table 2

Cosmogenic nuclide data for Chemehuevi Mountain piedmont

Sample[1]	Elevation[2] (m)	Northing[3] (UTM)	Easting[3] (UTM)	^{10}Be activity[4] (atoms g^{-1})	^{26}Al activity[4] (atoms g^{-1})	^{26}Al/^{10}Be
CMV-123	790	3832763	718571	0.132 ± 0.004	0.82 ± 0.054	6.22 ± 0.46
		3832571	718796			
		3832263	718885			
CMV-456	790	3831700	719904	0.128 ± 0.004	0.82 ± 0.051	6.40 ± 0.45
		3831491	719954			
		3831059	720463			
CMT-1B	670	3829529	720542	0.216 ± 0.007	1.25 ± 0.061	5.78 ± 0.34
		3832482	717860			
CMT-1C				0.195 ± 0.005	1.16 ± 0.072	5.92 ± 0.41
CMT-1S				0.287 ± 0.034	1.32 ± 0.074	4.60 ± 0.61
CMT-3B	600	3828156	719046	0.381 ± 0.011	2.16 ± 0.134	5.67 ± 0.39
		3821125	716328			
CMT-3C				0.217 ± 0.006	1.30 ± 0.067	6.03 ± 0.36
CMT-3F				0.333 ± 0.010	1.88 ± 0.102	5.65 ± 0.35
CMT-3H				0.546 ± 0.017	3.21 ± 0.154	5.88 ± 0.34
CMT-5C	550	3826824	717558	0.275 ± 0.008	1.83 ± 0.123	6.66 ± 0.49
		3829774	714858			
CMT-5F				0.455 ± 0.011	2.58 ± 0.121	5.67 ± 0.30
CMT-7C	500	3825471	716069	0.381 ± 0.011	2.38 ± 0.114	6.25 ± 0.35
		3828427	713399			
CMT-7F				0.434 ± 0.012	2.65 ± 0.127	6.09 ± 0.34
CMT-9C	470	3824108	714583	0.395 ± 0.010	2.43 ± 0.124	6.13 ± 0.35
		3827076	711926			
CMT-9F				0.430 ± 0.011	2.47 ± 0.116	5.75 ± 0.31
CMT-12C	430	3822084	712374	0.471 ± 0.015	2.74 ± 0.130	5.81 ± 0.33
		3825029	709667			
CMT-12F	430	3822084	712374	0.497 ± 0.013	2.97 ± 0.162	5.99 ± 0.36
		3825029	709667			
SRV-123	590	3828280	716955	0.462 ± 0.018	2.71 ± 0.16	5.87 ± 0.42
		3830310	716253			
		3830057	716353			
CP1 0-8	520	3826877	715949	0.392 ± 0.014	2.48 ± 0.146	6.32 ± 0.44
CP1 8-20				0.376 ± 0.011	2.35 ± 0.112	6.27 ± 0.35
CP1 20-39				0.353 ± 0.011	2.27 ± 0.108	6.42 ± 0.37
CP1 39-75				0.433 ± 0.013	2.72 ± 0.138	6.28 ± 0.37
CP1 75-96				0.484 ± 0.014	2.98 ± 0.141	6.16 ± 0.34
CP1 96-115				0.474 ± 0.016	2.89 ± 0.154	6.08 ± 0.38

CP1 115-130				0.371 ± 0.011	2.42 ± 0.118	6.53 ± 0.38
CP1 130-150				0.364 ± 0.016	2.08 ± 0.106	5.72 ± 0.38
CP1 150-170				0.282 ± 0.009	1.94 ± 0.095	6.87 ± 0.41
CP1 170-190				0.305 ± 0.010	1.83 ± 0.105	6.02 ± 0.40
CP1 190-234				0.557 ± 0.016	3.19 ± 0.161	5.72 ± 0.33
CP2 0-12	420	3822105	712484	0.430 ± 0.014	2.72 ± 0.125	6.34 ± 0.35
CP2 12-32				0.428 ± 0.012	2.60 ± 0.123	6.06 ± 0.33
CP2 32-52				0.427 ± 0.012	2.42 ± 0.128	5.68 ± 0.34
CP2 52-68				0.489 ± 0.014	2.74 ± 0.130	5.62 ± 0.31
CP2 68-89				0.521 ± 0.015	3.39 ± 0.162	6.50 ± 0.36
CP2 89-110				0.542 ± 0.015	3.21 ± 0.154	5.93 ± 0.33
CP2 110-130				0.546 ± 0.016	3.17 ± 0.149	5.80 ± 0.32
CP2 130-151				0.560 ± 0.016	3.39 ± 0.158	6.06 ± 0.33
CP2 151-170				0.472 ± 0.013	2.91 ± 0.148	6.16 ± 0.35
CP2 170-188				0.498 ± 0.014	3.00 ± 0.152	6.02 ± 0.35
CP2 188-220				0.537 ± 0.015	3.33 ± 0.150	6.20 ± 0.33

[1]Sample 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. [2]All elevations are average mountain valley elevation, based on basin hypsometry, and average elevation of the 4 km-long transects. [3]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. [4]Error is counting statistics from AMS with 2% uncertainty for stable Be and 4% uncertainty for stable Al, combined quadratically.

Table 3

Channel characteristics from 5 to 12 km on the Chemehuevi Mountain piedmont

Transect	Number[1]	Total width[2] (m)
5	43	302
6	89	520
7	N.D.	N.D.
8	N.D.	N.D.
9	229	458
10	263	526
11	284	568
12	308	616

[1]Total number of channels not originating on incised alluvial surface; [2]Transects 5 and 6 are measured channel widths, transects 9 through 12 are estimated channel widths of 2 meters. N.D. = no data.

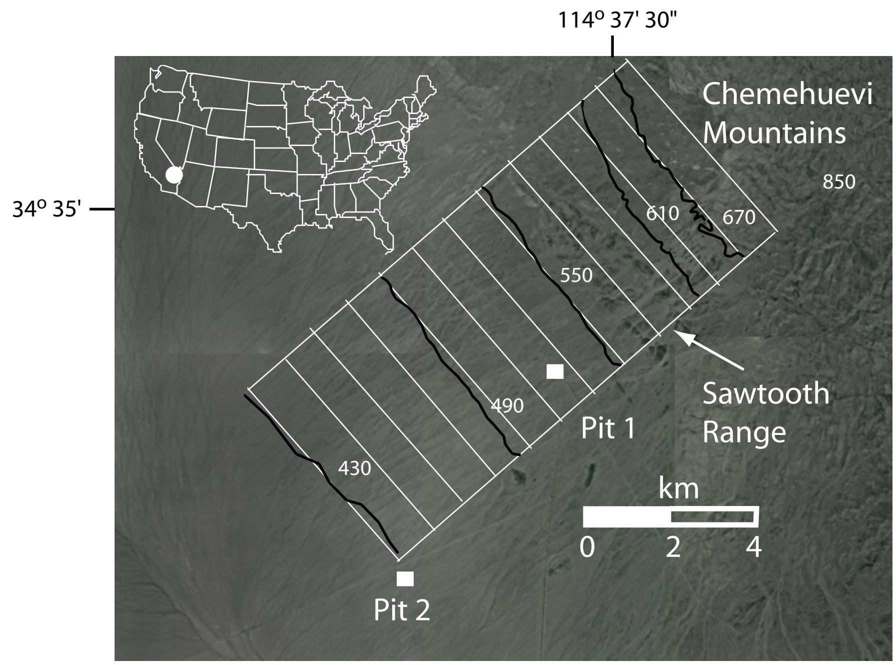
Table 4

Sediment generation rates for the Chemehuevi Mountain piedmont

Location	Sample[1]	Production rate[2] (atoms g^{-1})		Lowering rate (mm ky^{-1})		Mixing[3] (percentage)	Sediment yield[4] (m^3 y^{-1})	
		^{10}Be	^{26}Al	^{10}Be	^{26}Al		^{10}Be	^{26}Al
Chemehuevi Source basins[5]	CMV-123	8.47	49.6	39	37	26	26	24
Chemehuevi Source basins[6]	CMV-456	8.69	51.1	41	38	74	77	71
Source basin total							103	95
Bedrock at 1 km[7]	CMT-1B	7.90	46.5	22	22	75	111	111
Colluvium at 1 km[8]	CMT-1S	7.90	46.5	17	21	25	29	37
Bedrock at 3 km[9]	CMT-3B	7.72	45.9	12	12	12.5	10	10
Colluvium at 3 km[10]	CMT-3H	7.72	45.9	8.4	8.2	25	14	14
Sawtooth Range[11]	SRV-123	7.45	43.8	9.5	9.4	100	32	32
5 km[12]	N.A.	N.A.	N.A.	12	N.A.	100	1.4	N.A.
6 km	N.A.	N.A.	N.A.	12	N.A.	100	2.8	N.A.
7 km	N.A.	N.A.	N.A.	12	N.A.	100	4.2	N.A.
8 km	N.A.	N.A.	N.A.	12	N.A.	100	5.4	N.A.
9 km	N.A.	N.A.	N.A.	12	N.A.	100	7.3	N.A.
10 km[13]	N.A.	N.A.	N.A.	12	N.A.	100	0	N.A.
11 km	N.A.	N.A.	N.A.	12	N.A.	100	0	N.A.
12 km	N.A.	N.A.	N.A.	12	N.A.	100	0	N.A.

N.A. = not available; [1]Name of sample used to determine sediment generation rates; [2]Production rates of Bierman and others, (1996) scaled using Lal (1991) no muons; [3]Represents percentage of total sediment added at respective distances from the mountain front; [4]Sediment generation is based on either nuclide data or on estimated erosion of channel banks; [5]Quartz poor source basins that are 26% of total source area; [6]Quartz rich source basins that are 74% of total source area (John, 1987). Basin-wide lowering rates are similar for both lithological classification, therefore no correction based on quartz percentage is necessary; [7]Amalgamated bedrock collected 1 km from mountain front covers 75% of surface; [8]Amalgamated colluvium collected 1 km from mountain front covers 25% of surface; [9]Amalgamated bedrock collected 3 km from mountain front covers 50% of surface; [10]Amalgamated colluvium collected 3 km from mountain front covers 25% of surface; [11]Additional sediment generated from Sawtooth Range ~4 km from Chemehuevi mountain front; [12]Sediment generation from 5 to 9 km is based 3 m of channel bank erosion and incision over 26 ky, not on nuclide based sediment generation rates; [13]From 10 to 12 km from the Chemehuevi Mountain front the channels migrate across the surface and do not incorporate new or stable sediment except by erosion of the substrate which is minimal in volume.

FIGURE 1



Nichols and others. Fig. 1

FIGURE 2

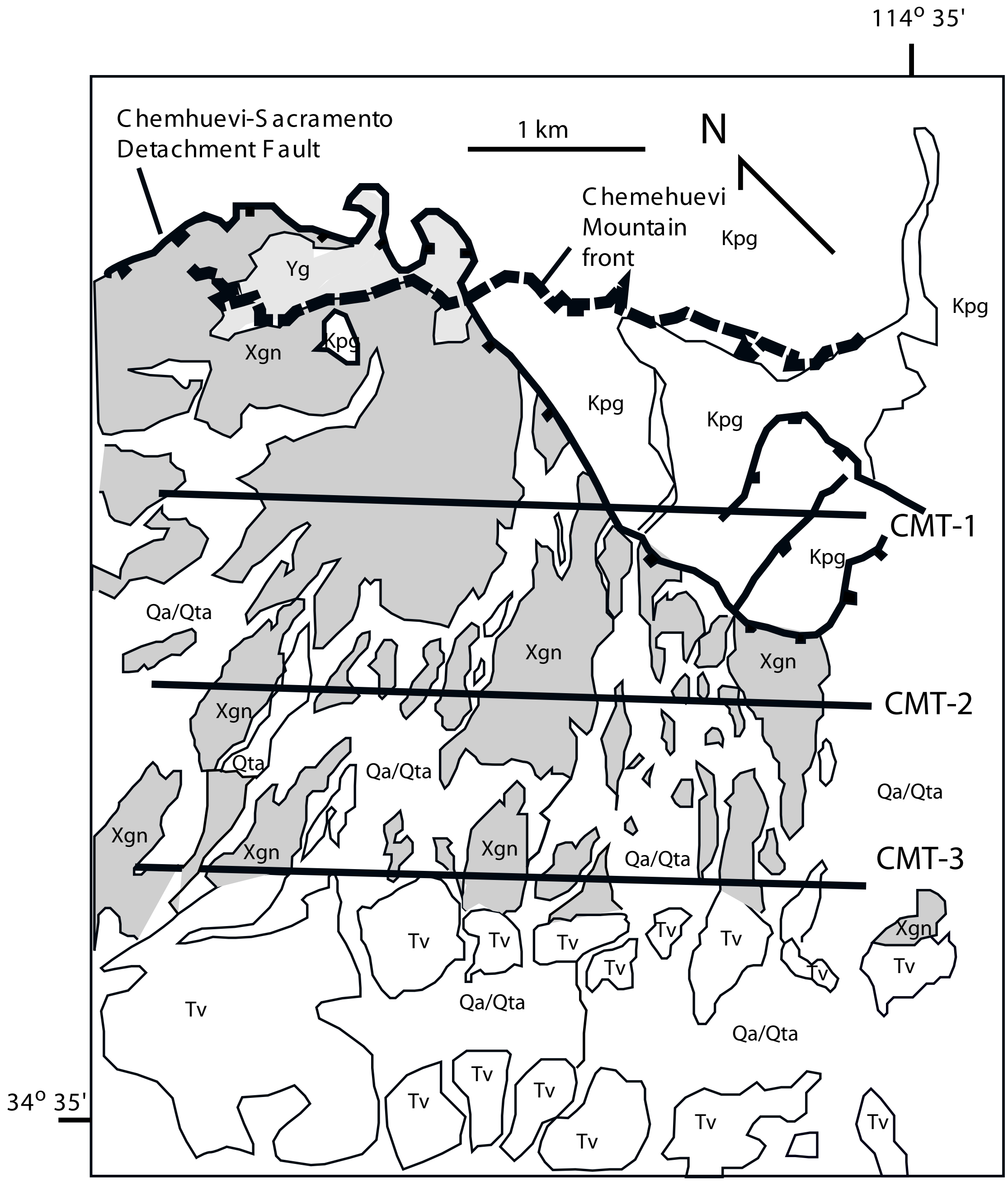

114° 35'
Chemhuevi-Sacramento Detachment Fault
1 km
N
Chemehuevi Mountain front
Kpg
Yg
Xgn
Qa/Qta
Qta
Tv
CMT-1
CMT-2
CMT-3
34° 35'

FIGURE 3

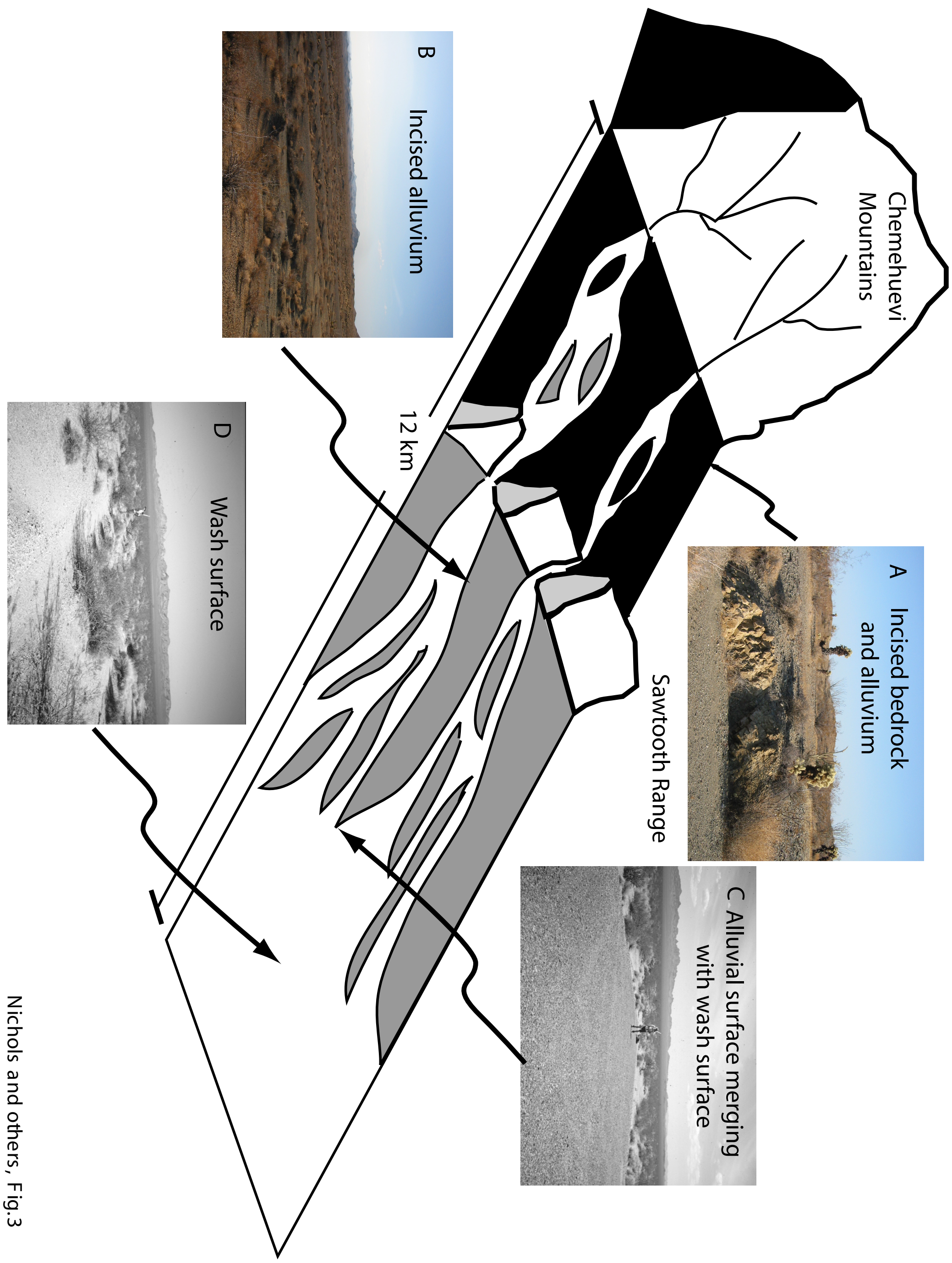
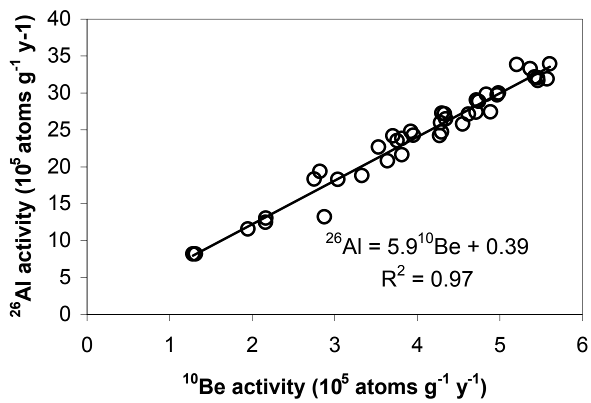
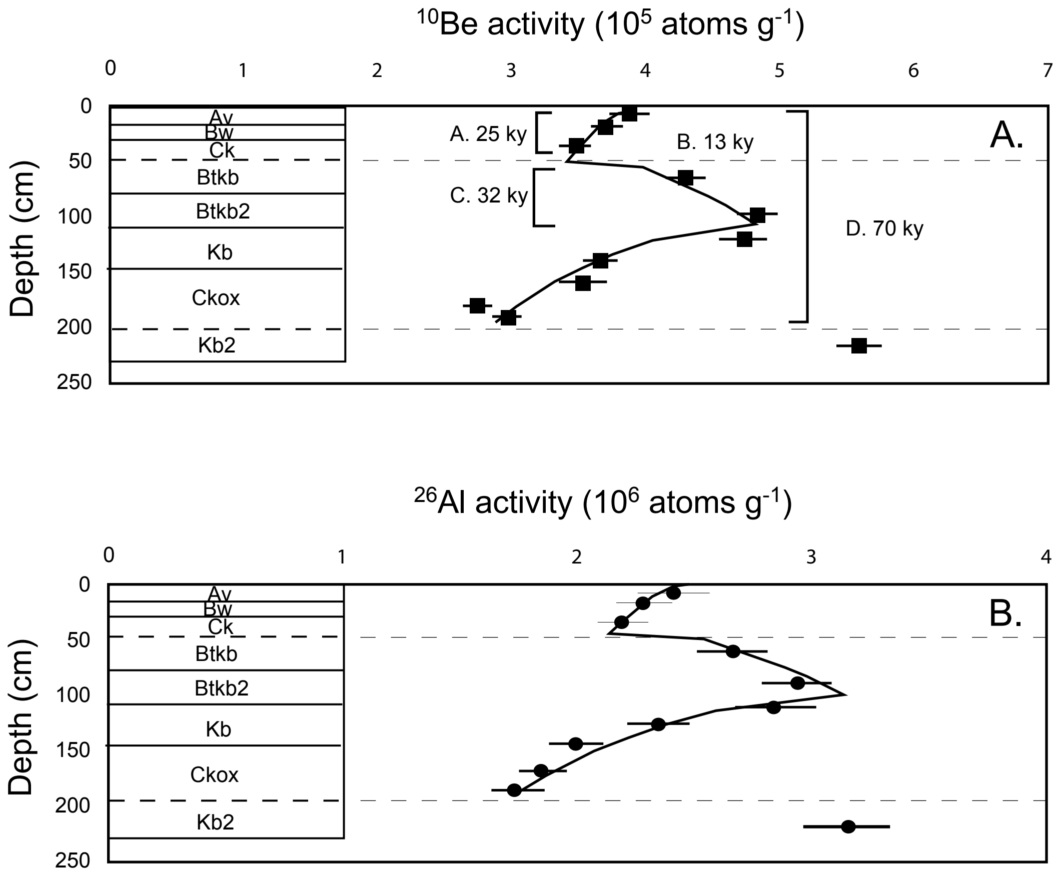

Chemehuevi
Mountains
B Incised alluvium
12 km
D Wash surface
A Incised bedrock
and alluvium
Sawtooth Range
C Alluvial surface merging
with wash surface
Nichols and others, Fig.3

FIGURE 4



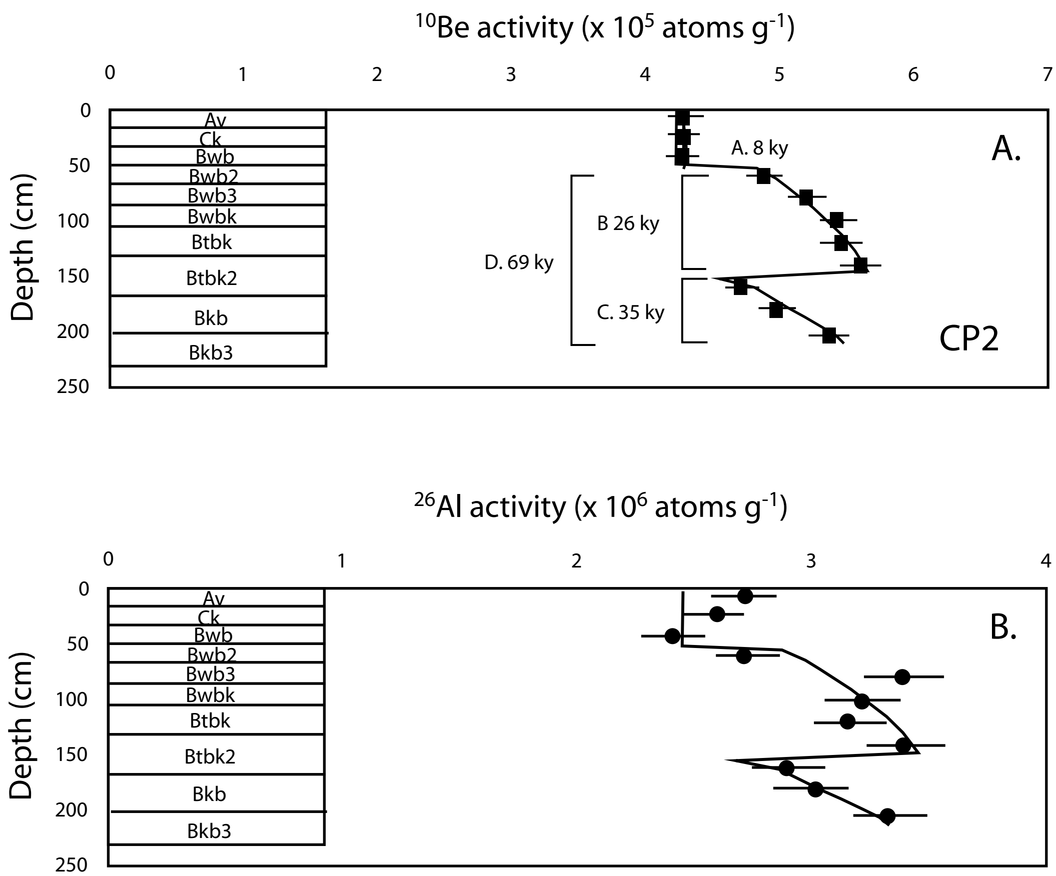
Nichols and others, Fig. 4

FIGURE 5



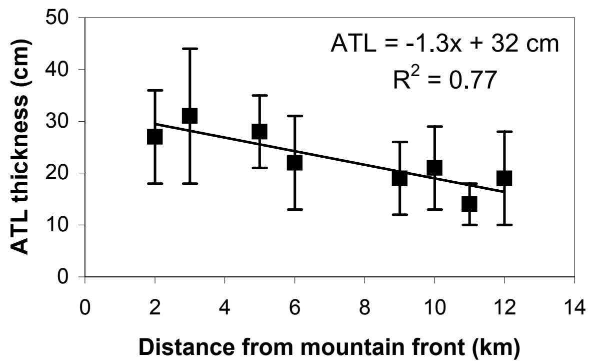
Nichols and others, Fig. 5

FIGURE 6



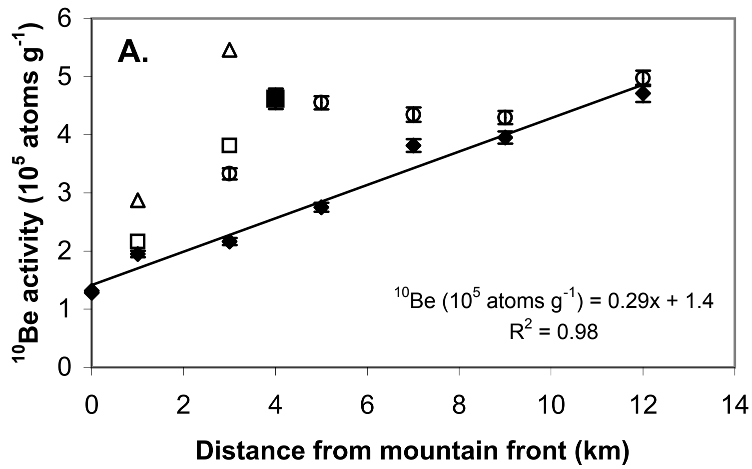
Nichols and others, Fig. 6

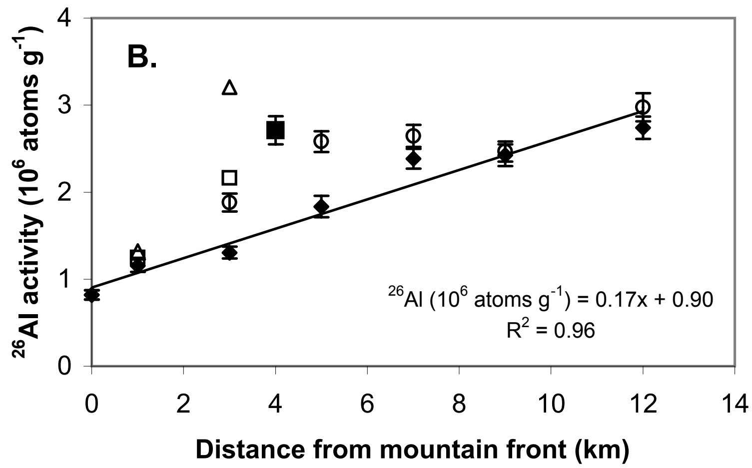
FIGURE 7



Nichols and others, Fig. 7

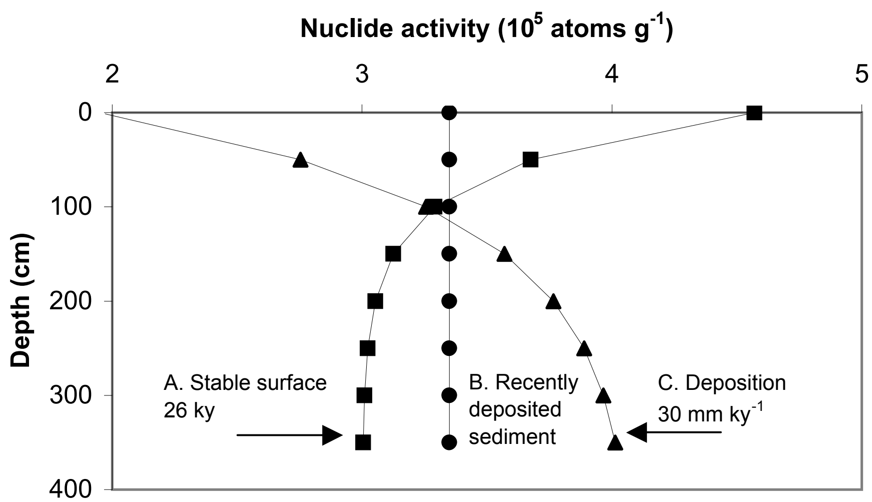
FIGURE 8





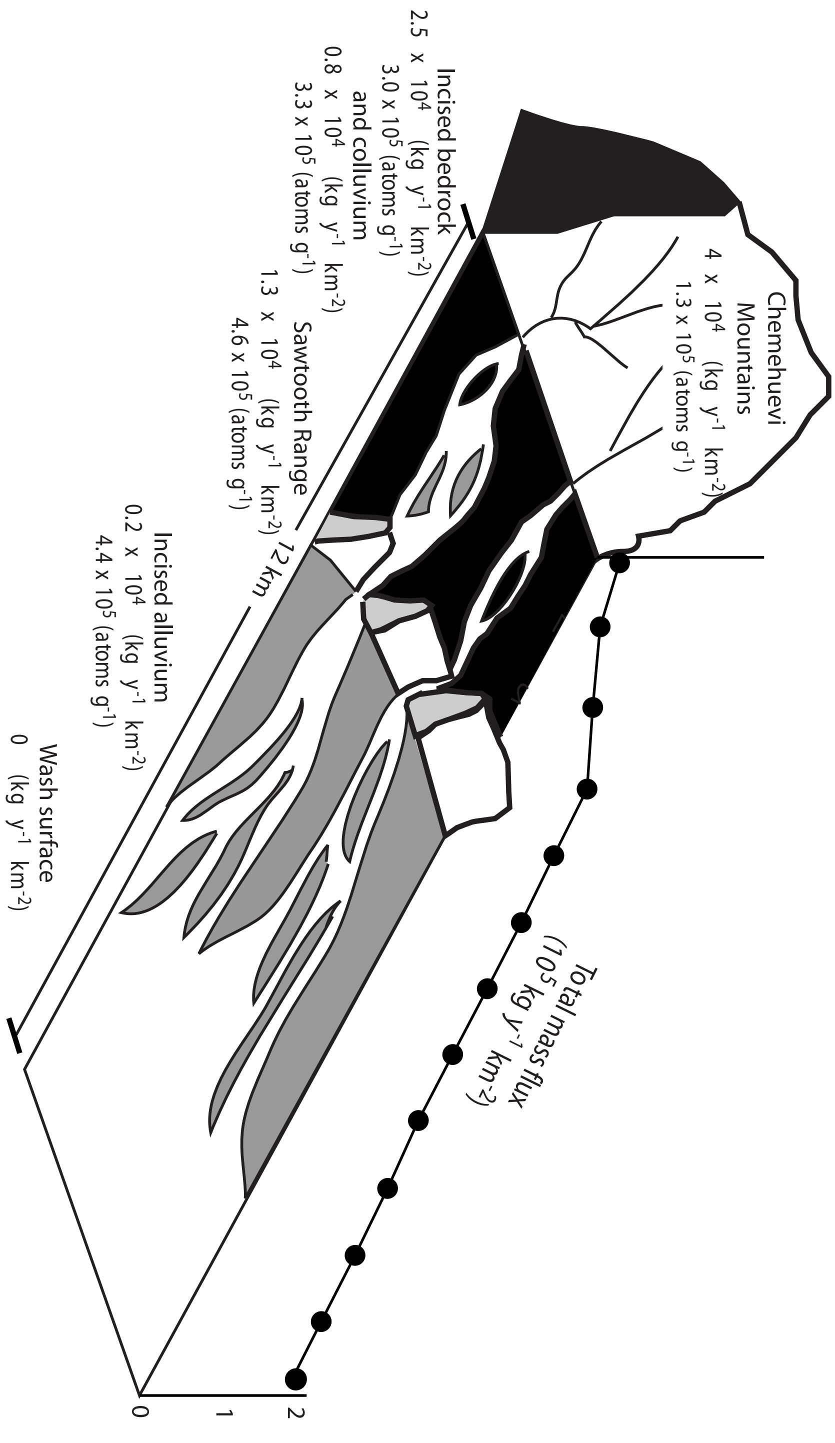
Nichols and others, Fig. 8

FIGURE 9



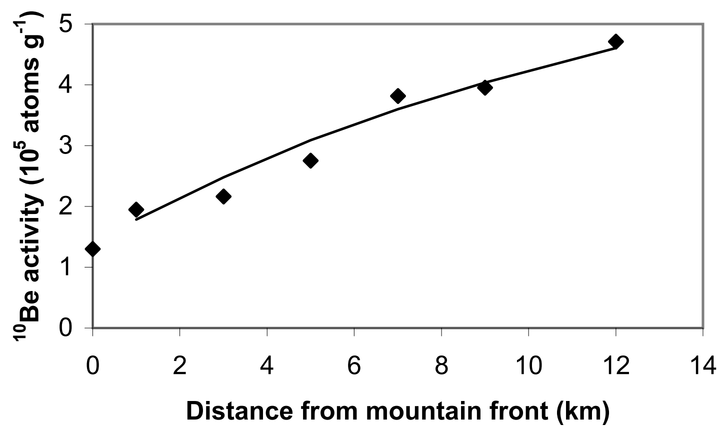
Nichols and others, Fig. 9

FIGURE 10



Nichols and others, Fig. 10

FIGURE 11



Nichols and others, Fig. 11

CHAPTER 5: Paper submitted to Quaternary Research

For submission to *Quaternary Research*

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QUANTIFYING EROSION AND DEPOSITION PROCESSES ON A COMPLEX, DISTURBED DESERT PIEDMONT, FT. IRWIN, CALIFORNIA

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ABSTRACT

We measured ^{10}Be and ^{26}Al in 29 samples of piedmont sediment to estimate histories and process rates on the complex and heavily disturbed East Range Road piedmont, in the Mojave Desert. The upland basin erosion rates are low, 13 ± 3 mm kyr^{-1}. Thus, upland basins supply comparatively little sediment to the piedmont. A large volume of sediment, which is now eroding, was deposited proximal to the uplands ~ 76,000 yrs ago. Deposition histories of the distal piedmont suggest three stable periods over the last 70,000 yrs. Long-term average sediment velocities range from 8 cm y^{-1} to 23 cm yr^{-1} from the uplands to 6 km down piedmont.

Sediment velocities down the Army disturbed East Range Road piedmont are similar to sediment velocities down three other undisturbed piedmonts in the Mojave Desert. Such similarity suggests that neither piedmont morphology nor human disturbance affect the average, long-term rates of piedmont sediment transport. The approach we have taken provides baseline data with which to compare to contemporary sediment transport rates in order to understand better the degree to which human impact affects desert piedmonts.

INTRODUCTION

Long, low gradient surfaces (termed *piedmonts*) that extend away from desert mountains or uplands are common in the Mojave Desert and elsewhere (Thomas, 1997). Piedmonts, because they have a low-gradient and are accessible, are rapidly being developed to accommodate increasing population (O'Hara, 1997). Human impact, mostly off-road vehicular disturbance, has been quantified over small areas and short time-scales (Iverson, 1980; Iverson *et al*., 1981; Nichols and Bierman, 2001; Persico *et al*., 2001; Prose, 1985). However, the impact of human activities on large-scale piedmont process is relatively unknown. The true impact of human disturbance on piedmonts cannot be understood without quantifying the baseline, long-term process rates that modify piedmont surfaces.

Piedmont morphology allows one to define qualitatively the dominant processes modifying the surface. *Simple* planar piedmonts may experience sheetfloods (McGee, 1897; Nichols *et al*., in review; Rahn, 1967; Schumm, 1962); some have uniformly active surfaces where all exposed sediment is transported down piedmont (Nichols *et al*., 2002). Alternatively, simple piedmonts may have shallow ephemeral channels that migrate laterally over the entire piedmont surface on sub-millennial time-scales (Nichols *et al*., 2002). *Complex* piedmonts have sediment that is transported in discrete ephemeral channels over only a small percentage of the surface area (Bull, 1991; Denny, 1967). Complex piedmonts have multiple surfaces of varying ages, and may have sediment erosion, deposition, and transport active at any one time in different places.

Most understanding of desert piedmont process rates comes either from direct measurement or modeling (Abrahams *et al*., 1988; Abrahams *et al*., 1991; Cooke, 1970; Cooke and Mason, 1973; Cooke and Reeves, 1972; Edinger-Marshall and Lund, 1999; Parsons and Abrahams, 1984; Rahn, 1967). Direct measurement of piedmont processes provides data for only a few years or decades (Laronne and Reid, 1993; Reid and Laronne, 1995; Schick *et al*., 1987). Such short-term data may not capture the geomorphically significant events that control long-term average process rates (Kirchner *et al*., 2001; Trimble, 1977). Measured rates are only representative for the time period over which the data were collected thus; extrapolation to longer-terms is not reliable (Kirchner *et al*., 2001). Alternatively, controlled models of simulated rainfall on desert piedmonts or in flumes (Abrahams *et al*., 1988; Luk *et al*., 1993) can replicate changing climatic regimes. However, simulation models only quantify process rates for small, uniform areas (m^2). Scaling experimental results to an entire piedmont is difficult.

Long-term rates of piedmont processes are difficult to quantify because sediment transport, deposition, and erosion processes are affected by changing climates and piedmont morphologies (Baker and Twidale, 1991; Bull, 1991). Understanding soil development is a powerful for investigating the long-term behavior of piedmonts because it depends on climate and time (Birkeland, 1984; McFadden *et al*., 1989; Wells *et al*., 1987). However, since soil development also depends on several difficult-to-measure regional variables, including carbonate influx and microclimate (Birkeland, 1984), soil data mostly provide relative piedmont histories.

Recently, application of cosmogenic nuclides and mathematical models, set in a context using soil development, has extended our knowledge of piedmont behavior by quantifying long-term process rates that modify both simple and complex piedmonts (Nichols *et al*., in review; Nichols *et al*., 2002; Phillips *et al*., 1998; Pohl, 1995). Such studies demonstrate that the rate of piedmont processes, including average downslope sediment velocities (decimeters per year), sediment deposition rates (mm ky^{-1}), and the timing of depositional hiatuses (process transition), are similar regardless of the complexity of piedmont surfaces (Nichols *et al*., in review).

We chose to investigate a multi-surface, disturbance-impacted piedmont in the Mojave Desert, at the Ft. Irwin army facility (Fig. 1). Measuring cosmogenic nuclides in samples collected over this wide (3 km) and long (6 km) piedmont allows us to quantify baseline piedmont processes over long time and large spatial-scales. Our data provide the context in which to understand the affects of human disturbance on piedmont process rates.

GEOLOGIC SETTING

Fort Irwin (> 2,400 km^2) contains numerous desert piedmonts. We chose the *East Range Road* piedmont because it is backed by quartz-rich uplands and because it is wide and long (Fig. 1). Like most of the northern Mojave Desert, Fort Irwin has experienced extensive tectonic activity throughout the late Cenozoic (Sobieraj, 1994).

The uplands that supply sediment to the East Range Road piedmont consist of poorly indurated Tertiary alluvial fan deposits (mostly derived from granitic parent material) and have a maximum relief of ~ 300 m. The upland sediments conformably overlie a thick sequence (165 m) of lacustrine deposits, suggesting filling of a playa basin (Sobieraj, 1994). The lacustrine deposits are 11.65 my old (^{40}Ar-^{39}Ar date from Sandine crystals from an interbedded crystal-rich tuff) thus, providing a limiting age for overlying fan deposits and the East Range Road piedmont (Sobieraj, 1994).

The East Range Road piedmont has two main surfaces. From the uplands, extending ~1.5 km down piedmont, there is a higher surface (incised < 4 m by ephemeral channels) which exhibits weak deserts pavements, with some varnished clasts (Fig. 2A). The presence of clasts of soil carbonate at the surface suggests that the upper piedmont is eroding. At ~1.5 km from the mountain front, the incised surface and the ephemeral channels merge to form a broad active surface (Fig. 2B). The surface lacks large clasts and it appears that all sediment was recently in transport. Most military activity happens on the low surface. The average slope from the uplands to 6 km away is 1.9°. The piedmont drains to ephemeral Red Lake playa (~ 20 km away).

The East Range Road piedmont has been used periodically as an U.S. Army training range since 1940. In 1981, Ft. Irwin became a permanent training facility and the East Range Road piedmont has experienced significant disturbance since then. Each month, wheeled and tracked vehicles (tanks) traverse the surface during training exercises destroying the shallow channels that drain the piedmont and most of the vegetation (Fig. 2B). Therefore, each runoff event establishes new ephemeral channels that are soon destroyed by the next round of training exercises.

The East Range Road piedmont is warm and dry. At Barstow, California, ~60 km south of the East Range Road piedmont, average maximum temperature ranges from 15.4°C in December to 39°C in July and an average of 10.3 cm of rain falls annually (http://www.wrcc.dri.edu/cgi-bin/cliNORMtM.pl?cabars). Most of the precipitation comes either in short-duration intense summer cyclonic events or in long-duration, less intense frontal storms.

METHODS

East Range Road piedmont sediment is supplied by several narrow basins which cut into the upland Tertiary fan deposits (Fig. 1). In order to obtain the baseline nuclide activity of sediment exiting the uplands, we amalgamated sediment from three ephemeral channels that drain the upland source basins (Fig. 1). Such nuclide activities allow us to determine source basin sediment generation rates (Bierman and Steig, 1996; Brown *et al*., 1995; Granger *et al*., 1996).

The piedmont surface that abuts the uplands is incised (< 4 m) by active ephemeral channels both connected to the drainages from the uplands and originating on the incised surface. These locally sourced channels erode and supply sediment to the through-going channels sourced in the uplands. In order to determine both the mass and cosmogenic nuclide contribution of the incised surface, we amalgamated sediment from three channels that originate on and drain only the incised surface.

The sediment supplied to the piedmont is a mixture of sediment derived from the uplands (ERV-UB; Fig. 3) and sediment derived from erosion of the incised alluvial surface (ERV-P; Fig. 3). We collected a sediment sample at the distal end of the incised surface from the channels that originate in the uplands but also are fed by smaller channels arising on the incised surface. Since upland and incised surface sediments have different nuclide activities, we develop a simple mixing model to determine the percentages of sediment entering the piedmont from each source.

We amalgamated sediment along 3 km long transects spaced 1 km intervals down the East Range Road piedmont to reflect the long-term average exposure of sediment that is transported down the wash surface (ERT-2 to ERT-6). Each transect sub-sample consisted of an equal volume of sediment mixed from 21 sampling locations spaced at 150 m intervals (piedmont transects). The piedmont transect samples are representative of the nuclide activity down the uniformly active lower piedmont surface.

We used a backhoe to open 2 pits (2.0 m and 1.4 m deep) on the East Range Road piedmont (Fig. 1). One pit was located on the incised surface close to the uplands (1.5 km); the other was located on the uniformly active surface near the middle of the piedmont (4 km from the uplands). We noted soil color, stratigraphy, grain size, texture, consistence, and soil horizonation (Table 1). On the basis of soil stratigraphy and soil horizonation, we divided each pit into depth intervals to sample for cosmogenic nuclide analysis. Each interval was continuous, so that the entire soil column exposed in each pit was analyzed.

Due to numerous unexploded ordinance on the East Range Road piedmont, we did not dig additional shallow soil pits to understand better the thickness of sediment that is in active transport termed the *active transport layer (ATL)*. Such thicknesses are usually determined from the depth to the B horizon (Lekach *et al*., 1998; Nichols *et al*., 2002). In the few soil pits that we dug at East Range Road piedmont, the depth to the B-horizon is a few decimeters. We assume that the thickness of the ATL on the East Range Road piedmont is not significantly different than the thickness of the ATL on several other Mojave Desert piedmonts, a few decimeters (Nichols *et al*., in review; Nichols *et al*., 2002).

Samples were processed using accepted methods (Bierman and Caffee, 2001; Kohl and Nishiizumi, 1992). We analyzed quartz in the 500 to 850 μm size fraction to minimize the possibility of analyzing aeolian sediment. We did not analyze different grain sizes because previous grain size analyses demonstrate that all sediment grain sizes in arid regions have statistically similar nuclide activities (Clapp *et al*., 2002; Clapp *et al*., 2001; Clapp *et al*., 2000; Granger *et al*., 1996). Therefore, we assume that the 500 to 850 μm size-fraction represents all fluvially transported material. Accelerator mass spectrometry (AMS) analysis, at Lawrence Livermore National Laboratory, determined the $^{10}Be/^{9}Be$ and $^{26}Al/^{27}Al$ ratios. All measurements were blank corrected. In order to model the East Range Road data we use nominal production rates (sea level and > 60° latitude) of 5.2 ^{10}Be atoms g^{-1} and 30.4 ^{26}Al atoms g^{-1} (Bierman *et al*., 1996; Gosse and Phillips, 2001; Stone, 2000). We scaled the nominal production rates to the East Range Road altitude and latitude using no muons (Lal, 1991).

In order to quantify piedmont histories and processes, we use mathematical models to translate the nuclide activities into ages and rates. East Range Road piedmont surface processes rates operate on time scales much shorter than the nuclide half-lives (^{10}Be = 1.5 myr, ^{26}Al = 0.7 myr) therefore, surface processes control the nuclide activities, not radioactive decay. Since the uplands are dominantly quartz-rich Tertiary fan deposits, we assume no quartz enrichment through preferential dissolution of other minerals at East Range Road (Small *et al*., 1999).

We use previously published models of nuclide activity in sediment to estimate long-term basin erosion and sediment generation rates (Brown *et al*., 1995; Clapp *et al*., 2002; Clapp *et al*., 2000; Granger *et al*., 1996), to determine the near surface history of the piedmont, to quantify surface stability (Anderson *et al*., 1996), to quantify deposition rates (Lal and Arnold, 1985; Nichols *et al*., 2002; Phillips *et al*., 1998), and to determine the duration of depositional hiatuses (either erosion or surface of transport; Nichols *et al*., 2002). Sediment transport models use a mass and nuclide balance approach to translate the piedmont nuclide activities into long-term average sediment transport velocities (Nichols *et al*., 2002).

RESULTS

Regression of the ^{26}Al and ^{10}Be data indicate a ratio of 6.03 suggesting that the sediment samples have simple exposure histories (Fig. 4; Nishiizumi *et al*., 1989). The parent materials of the upland basin sediment are Tertiary alluvial fan deposits, suggesting possible complex exposure histories. However, the best-fit ^{26}Al/^{10}Be ratio (6.03) suggests that the sediments do not carry significant nuclide inheritance from the Tertiary sediments and that the sediment has not been buried under significant cover ($\geq$ 1 m) long enough ($\geq 10^5$ yrs) for the decay of ^{26}Al to deviate from the nominal ratio. Measurement precision averages 3% for ^{10}Be and 5% for ^{26}Al, therefore we base our models on ^{10}Be data because they are the more precisely measured.

Sediment sources for the East Range Road piedmont are the upland basins and the eroding proximal piedmont. The upper basin samples have the lowest average nuclide activity of all samples ($4.59 \pm 0.15 \times 10^5$ ^{10}Be atoms g^{-1}; Fig. 5), suggesting the shortest surface exposure history. The basins that drain only the incised alluvial surface (the eroding section of the piedmont) have higher average nuclide activities than the upland basins ($6.30 \pm 0.17 \times 10^5$ ^{10}Be atoms g^{-1}; Fig. 5), suggesting longer exposure histories than the upland sediment. The amalgamated sample that consists of mixed upland basin sediment and incised alluvial surface sediment has an intermediate nuclide activity (5.02 $\pm$ 0.14 x 10^5 ^{10}Be atoms g^{-1}; ERV-LB in Fig. 5), consistent with the mixing of higher dosed sediment from the proximal piedmont and the lower dosed sediment from the upland basins.

Nuclide depth profiles for the two soil pits on the East Range Road piedmont have distinctively different shapes. EP1 has nuclide activities that generally decrease with depth (Fig. 6). EP2 has nuclide activities that neither increase nor decrease at depth (Fig. 7). The top-most three samples of EP1, which is closer to the uplands and up gradient of EP2, have higher nuclide activities than the all samples from EP2.

The nuclide activities for the piedmont transects increase in a nearly linear fashion from 0.77×10^6 atoms g^{-1} at ERT-2 to 1.02×10^6 atoms g^{-1} at ERT-6 (Fig. 5). These nuclide activities suggest that the source of transect sediment is a mixture of upland basin sediment (0.46×10^6 atoms g^{-1}) and proximal piedmont sediment (0.85 to 0.96×10^6 atoms g^{-1}). The steady increase in nuclide activities down the piedmont suggest regular dosing of sediment in transport.

DISCUSSION

Nuclide data allow for long-term insight into the East Range Road piedmont behavior. Mathematical models translate nuclide activities into sediment generation rates, sediment velocities, sediment deposition rates, and the age of the incised alluvial surface. By understanding the style, distribution, and rates of processes active on the East Range Road piedmont, we can better place contemporary human impact in the context of baseline piedmont behavior.

Sediment generation rates of upland basins and the eroding piedmont.

Sediment is generated from the uplands and from the eroding proximal piedmont. Using the sediment generation models, the average basin-wide lowering rate (average of ^{10}Be and ^{26}Al data) is 13 ± 3 mm ky^{-1} equivalent to a sediment flux from the upland basins to the piedmont of 3.62 x 10^4 kg y^{-1} km^{-2}. These rates are low compared to other basin-wide erosion rates in arid regions. The Iron and Granite Mountains in the southern Mojave Desert are lowering at 31 to 33 mm ky^{-1} (Nichols *et al*., 2002). The Chemehuevi Mountains in the eastern Mojave Desert are lowering at 41 mm ky^{-1} (Nichols *et al*., in review; Nichols *et al*., 2002). The granitic Fort Sage Mountains are lowering at 30 to 60 mm ky^{-1} (Granger *et al*., 1996). Perhaps the low basin-scale erosion rates (and the low basin sediment yields to the East Range Road piedmont) may be, in part, due to the greater infiltration capacity, and thus low runoff yield, of Tertiary alluvial fan deposits compared to crystalline bedrock.

The eroding proximal piedmont supplies additional sediment to the distal piedmont surface. Assuming a weighted average mixing model, the uplands supply 75%

of sediment to the distal piedmont and the more highly-dosed, incised proximal piedmont supplies 25% of the sediment (Fig. 3). The proximal piedmont supplies an additional 1.31×10^4 kg y^{-1} km^{-2} to the down piedmont sediment flux.

Soil pit interpretive models

Incised alluvial surface pit (EP1). The nuclide activity in the soil pit located on the proximal incised alluvial surface (EP1) decreases as a function of depth, suggesting rapid deposition followed by stability. Averaging the ^{10}Be and ^{26}Al data, we calculate that the upper surface is at least 76,000 years old (Fig. 6; Anderson *et al*., 1996). This is a minimum limiting age because soil carbonate, exposed on the incised surface suggests erosion. The calculated nuclide inheritance of the sediment exposed in EP1 at the time of deposition is 4.5×10^5 atoms g^{-1}, which is similar to the nuclide activity of sediment currently issuing from the upland basins ($4.6 \pm 0.1 \times 10^5$ atoms g^{-1}). Such similarity in nuclide activity suggests that source basin erosion rates have been constant over at least the past 76,000 years. The ≥ 76,000 yr age of the eroding piedmont is reasonable considering the soil development in the pit and the K-horizon (stage III) at the bottom of the pit (Birkeland, 1984).

Wash surface pit (EP2). Three distinct buried soil horizons in EP2 (43 cm, 84 cm, and 118 cm) represent times of surface stability on the distal piedmont; however, nuclide activities neither increase nor decrease with depth in this pit as would be expected if there were extended periods of stability and soil formation (Fig. 7). The simplest interpretation of the nuclide data suggests recent and rapid deposition of all of the sediment to a depth of 118 cm. However, a stage III K-horizon at the bottom of the soil pit, and the intensity of soil development throughout the pit argue against recent, rapid deposition.

There are depositional scenarios consistent with both the soil and nuclide data. Such scenarios require that the nuclide activities of the deposited sediment change over time. We constrain inherited nuclide activities within limits set by upland basin sediment ($4.6 \pm 0.15 \times 10^5$ atoms g^{-1}).

Using the mathematical model of Nichols *et al*. (2002), we quantify deposition rates and durations of stability at pit EP1. The period of stability for each buried soil is modeled between 7,000 and 10,000 years at 118 cm, 15,000 to 25,000 at 84 cm, and 20,000 years at 43 cm (Fig. 7). Deposition rates range from 40 to 150 mm ky^{-1} between 118 and 84 cm, 80 to 100 mm ky^{-1} between 84 to 43 cm, and 250 mm ky^{-1} from 43 cm to the surface. The total time represented by these scenarios is between 57,000 to 75,000 years. Such soil pit ages are sufficient to develop the observed soils (Fig. 7).

The top 43 cm of EP1 can also be interpreted as young soil (< 2,000 years). The average nuclide activity of the top most 43 cm ($8.46 \pm 0.25 \times 10^5$ atoms g^{-1}; Fig. 7) is similar to the average nuclide activity of sediment in transport down the piedmont (8.33×10^5 atoms g^{-1}; Fig. 5) at the location (4 km) of the soil pit. Since nuclide activities of sediment in transport and of sediment at the soil pit are similar, and soil development is weak, the top 43 cm of sediment is consistent with sediment in active transport down the piedmont on the a time-scale of < 2000 years.

Comparison of EP1 and EP2 and regional climate. The two soil pits are consistent with similar piedmont histories. More than 76,000 years ago, a large volume of sediment was delivered to the entire piedmont. Such sediment deposition is consistent with a more moisture effective climate and pluvial lake level rises in and near Death Valley 80,000 yr ago (Reheis *et al*., 1996). Subsequently, a change to a drier climate reduced vegetation and increased stream power, which eroded the source basins and the higher-dosed proximal piedmont sediment and deposited it on the distal piedmont. Lake Manley in Death Valley had another highstand ~30,000 yr. ago (Lowenstein *et al*., 1994) which is consistent with deposition on the distal piedmont (EP2; 84 cm to 43 cm) at that time.

Sediment transport velocities. We quantify the sediment velocity down the East Range Road piedmont using a mass and nuclide balance model (Nichols *et al*., 2002). Using the parameters we measured at the East Range Road piedmont, the nuclide and mass balance model fits the data well (Fig. 8). The model suggests that present-rates of substrate erosion range from 1 mm ky^{-1} near the mountain front to 5 mm ky^{-1}, 6 km down piedmont. The average grain speed down the Chemehuevi Mountain piedmont increases from 8 cm y^{-1} from the mountain front to 23 cm y^{-1} at the last transect, 6 km down gradient. The total transit time for sediment across the East Range Road piedmont is ~48,000 years.

EAST RANGE ROAD PIEDMONT AND OTHER MOJAVE DESERT PIEDMONTS

The East Range Road piedmont has process rates and histories similar to several other Mojave Desert piedmonts (Nichols *et al*., in review; Nichols *et al*., 2002). Sediment transport velocities down the complex East Range Road piedmont, the complex

Chemehuevi Mountain piedmont, and the simple Iron and Granite Mountain piedmonts all average decimeters per year (Nichols *et al*., in review; Nichols *et al*., 2002). Similar sediment velocities suggest that average long-term sediment transport does not depend on piedmont morphology.

Piedmont depositional histories however, correlate poorly (Fig. 9). Such lack of correlation could be due to differing source basin sensitivity to climate change. Where uplands erode more quickly (Iron and Chemehuevi Mountains; Nichols *et al*., in review; Nichols *et al*., 2002), sediment supply is large enough to allow uniform deposition on distal piedmonts until the Pleistocene-Holocene climate change (~ 10 kyr ago), when there is a change in process to sediment transport. Where uplands erode slowly (East Range Road uplands) sediment supply is small enough that deposition is not uniform and piedmont-wide (Fig. 9). Such depositional gaps create stable surfaces and allow soil development (EP2).

On complex piedmonts, Chemehuevi Mountain piedmont and East Range Road piedmont, proximal surfaces do not have similar morphologies, ages, or periods of erosion (Fig. 9). Such differences in proximal piedmont process could be due to sediment flux from the uplands (climate perturbations) not supplying enough sediment to resurface the proximal piedmont. Alternatively, the channels incised into the proximal piedmont surface could be too deep to allow surface deposition.

ANTHROPOGENIC INFLUENCE ON LONG-TERM PIEDMONT PROCESSES

The cosmogenic nuclide technique that we employed suggests similar long-term average sediment velocities down the highly disturbed East Range Road piedmont, the undisturbed Chemehuevi Mountain piedmont (Nichols *et al*., in review), and the Iron and Granite Mountain piedmonts which were disturbed for only a short time during World War II (Nichols and Bierman, 2001; Nichols *et al*., 2002). These results suggest that measurements of long-term piedmont process rates are robust in spite of different land use and disturbance histories. Therefore, one can measure contemporary sediment velocities on disturbed piedmonts and compare them to baseline rates to understand the magnitude of disturbance.

At the East Range Road piedmont, the Army has disturbed the surface for over six decades. Short-term sediment movement rates, as determined from monitoring 400 surface pebbles over 23 months, average 80 cm y^{-1} (Persico, 2002). During this 2 yr study precipitation gauges surrounding the East Range Road piedmont did not record significant rainfall volumes or intensities. Increased overland flow would have created more runoff and larger discharges increasing the average sediment movement rate. For comparison, long-term sediment movement rates estimated using cosmogenic nuclides, at the East Range Road piedmont are 8 to 23 cm y^{-1}. Only by measuring both contemporary and baseline rates of sediment movement, can we estimate that extensive Army disturbance has increased average sediment movement rates four to ten fold. Extensive disturbance by wheeled and tracked vehicles has significantly altered the sediment movement rates on the East Range Road piedmont.

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FIGURE CAPTIONS

Figure 1. Aerial photograph of the East Range Road piedmont. The upland/piedmont border is represented by dashed line. The upland basin sample (ERV-UB) is an amalgamation of sediment collected from the locations of the three black dots. Black lines spaced at 1 km intervals represented transect locations (3 km long; ERT designation). Black boxes represent soil pit locations (EP1 and EP2). The eroding proximal piedmont sample (ERV-P) is an amalgamation of sediment collected from channels draining only incised alluvial surface (white dots). The sediment sample that contains sediment sourced from both the source basins and the eroding piedmont (ERV-LB) is dots represented by the gray dots. White lines on piedmonts are roads used by tanks and wheeled vehicles.

Figure 2. Photographs of the East Range Road surface. A. Backhoe is on incised proximal piedmont surface. Foreground of photograph shows active channel. B. Photograph of wash surface on the East Range Road piedmont. The numerous tank tracks have destroyed the piedmont drainage network.

Figure 3. Sediment budget for East Range Road piedmont. Uplands (ERV-UB) supply 75 % of sediment to distal piedmont while the eroding piedmont (ERV-P) supplies 25 %. Percentages calculated to form a weighted nuclide activity of the mixed sediment entering the distal piedmont (EV-LB).

Figure 4. Regression of the ^{10}Be and the ^{26}Al data. The regression trendline of entire data set has a slope similar to the nominal production ^{10}Be/^{26}Al ratio of 6.0 indicating no significant burial or nuclide inheritance from Tertiary source basin rocks.

Figure 5. Graph of nuclide activity down the piedmont for ^{10}Be data (A) and ^{26}Al data (B). Black squares represent transect data. Open square represents amalgamated sample characterizing incised alluvial surface sediment and ephemeral channel sediment (ERT-1). Open circle represents upland sediment datum (ERV-UB). Gray circle represents eroding piedmont datum (ERV-P). Black circle represents sediment mixture of ephemeral channel sediment and sediment eroded from piedmont (ERV-LB).

Figure 6. ^{10}Be data (A) and ^{26}Al data (B) for EP1. Data points represent mid-point of depth interval. Error bars represent 1σ analytical uncertainty. Black lines show model fit of 76,000 yrs. of surface stability.

Figure 7. ^{10}Be data (A) and ^{26}Al data (B) for EP2. Nuclide data do not have an increasing or a decreasing trend with depth. Data points represent mid-point of depth interval. Black lines show model fit. Dashed lines represent buried soil horizons. Error bars represent 1σ analytical uncertainty.

Figure 8. Best fit of nuclide mixing model to the ^{10}Be data. Black line represents the model; the squares represent the ^{10}Be data. 1σ analytical error bars are smaller than the symbols. RMS error of the model is 38,000 atoms.

Figure 9. Depositional histories for proximal (P) and distal (D) soil pits on Iron Mountain (IM), Chemehuevi Mountain (CM), and East Range Road (ER) piedmonts. IM has simple surface morphology. CM and ERR have complex surface morphologies.

TABLE 1

Soil Pit Descriptions for the East Range Road Piedmont

Pit	Horizon[a]	Depth (cm)	Color[b] Moist	Dry	Texture[c]	Structure[d]	Carbonate[e] (%)
EP1	Av	0-6	10YR 4/4	10YR 6/3	L	3 c pl	
	Bw	6-16	7.5YR 4/4	10YR 5/4	L	f/m sbk	ef
	Bt	16-44	7.5YR 4/6	7.5YR 5/4	SL	2 m/c sbk	
	Btk	44-59	7.5YR 5/6	7.5YR 5/4	L	2 f/m sbk	stage II
	Btk2	59-77	7.5YR 4/4	7.5YR 5/4	SL	1 f sbk	stage I
	1Ck	77-100	7.5YR 4/4	10YR 6/4	LS	0.5 vf sbk	
	2Ck/K	100-210					
	Ck2		10YR 4/4	10YR 6/3	LS	sg	
	K		10YR 5/4	10YR 7/3	LS	m	stage III
EP2	A	0-5	10YR 4/3	10YR 6/4	LS	sg	
	Av	5-11	10YR 4/3	10YR 6/4	LS	2 m sbk	
	Bw	11-29	10YR 4/4	10YR 6/3	LS	2 m/c sbk	
	Ck	29-43	10YR 4/4	10YR 6/4	LS	1 f sbk	
	2Bkmb	43-60	7.5YR 5/4	10YR 6/5	LS	2 vf sbk	
	2Ck	60-84	10YR 5/4	10YR 6/5	LS	1 f sbk	
	Btbk	84-106	10YR 5/4	10YR 6/5	LS	2 m sbk	
	3Ck	106-118	10YR 5/4	10YR 6/4	LS	1 vf sbk	
	K	118-140	10YR 5/4	10YR 7/3	LS	m	stage III

[a]Numbers preceding the horizon designation represent the following, for CP1 1= gravelly sand, 2 = sandy gravel, for EP2 overall coarsening down sequence from 1 to 3; [b]Color determined using Munsel color charts; [c]Textures are defined as L = loam, SL = sandy loam, and LS = loamy sand; [d]Structure defined as c = coarse, pl = platy, f = fine, m = medium, sbk = sub-angular blocky, vf = very fine, sg = sand and gravel; [e]Carbonate development defined as ef = effervesces with dilute HCl.

TABLE 2

Cosmogenic Nuclide Data for East Range Road Piedmont

Sample[1]	Elevation[2] (m)	Northing[3] (UTM)	Easting[3] (UTM)	^{10}Be activity[4] (10^6 atoms g^{-1})	^{26}Al activity[4] (10^6 atoms g^{-1})	^{26}Al/^{10}Be
ERV-UB	990	3918672	548155	0.459 ± 0.015	2.62 ± 0.146	5.78 ± 0.37
	1000	3918524	549577			
	930	3917713	550513			
ERV-LB	900	3917584	548022	0.502 ± 0.015	2.88 ± 0.136	5.73 ± 0.32
	840	3916421	549596			
	830	3916107	550302			
ERV-P	860	3916800	548269	0.630 ± 0.017	3.69 ± 0.172	5.86 ± 0.31
	830	3916069	549922			
	860	3916746	550367			
ERT-1	870	3917000	547800	0.587 ± 0.016	3.34 ± 0.155	5.68 ± 0.31
		3916750	550800			
ERT-2	810	3616000	547650	0.771 ± 0.021	3.93 ± 0.186	5.10 ± 0.28
		3915750	550650			
ERT-3	760	3915000	547500	0.802 ± 0.021	4.38 ± 0.204	5.47 ± 0.29
		3914750	550500			
ERT-4	720	3914000	547350	0.864 ± 0.028	4.78 ± 0.229	5.53 ± 0. 32
		3913750	550350			
ERT-5	695	3913000	547200	0.899 ± 0.024	4.95 ± 0.241	5.50 ± 0.30
		9312750	550200			
ERT-6	680	3912200	547050	1.018 ± 0.035	5.78 ± 0.269	5.68 ± 0.33
		3911950	550050			
EP1 0-6	840	3916585	548869	0.850 ± 0.026	5.54 ± 0.289	6.51 ± 0.39
EP1 6-16				0.959 ± 0.028	5.49 ± 0.256	5.73 ± 0.31
EP1 16-30				0.877 ± 0.025	5.08 ± 0.256	5.79 ± 0.34
EP1 30-44				0.833 ± 0.022	4.69 ± 0.227	5.64 ± 0.31
EP1 44-59				0.773 ± 0.023	4.66 ± 0.217	6.03 ± 0.33
EP1 59-77				0.790 ± 0.023	5.08 ± 0.272	6.44 ± 0.39
EP1 77-90				0.719 ± 0.027	4.14 ± 0.202	5.75 ± 0.36
EP1 90-100				0.707 ± 0.018	4.07 ± 0.185	5.75 ± 0.30
EP1 100-125				0.726 ± 0.019	4.18 ± 0.190	5.76 ± 0.30
EP1 152-150				0.562 ± 0.016	3.49 ± 0.172	6.21 ± 0.35
EP1 150-175				0.566 ± 0.016	2.07 ± 0.102	3.65 ± 0.21
EP1 175-200				0.555 ± 0.016	3.25 ± 0.152	5.86 ± 0.32
EP2 0-11	755	3914895	549055	0.847 ± 0.023	5.00 ± 0.288	5.91 ± 0.38
EP2 11-29				0.856 ± 0.026	5.17 ± 0.248	6.03 ± 0.34
EP2 29-43				0.837 ± 0.023	5.18 ± 0.291	6.19 ± 0.39
EP2 43-60				0.835 ± 0.027	4.63 ± 0.219	5.55 ± 0.32
EP2 60-84				0.808 ± 0.022	4.19 ± 0.189	5.18 ± 0.28

EP2 84-95	0.808 ± 0.0 21	4.26 ± 0.204	5.27 ± 0.29
EP2 95-106	0.836 ± 0.023	4.88 ± 0.233	5.84 ± 0.32
EP2 106-118	0.762 ± 0.021	4.12 ± 0.194	5.40 ± 0.30
EP2 118-140	0.815 ± 0.023	4.43 ± 0.234	5.44 ± 0.33

[1]Sample notation: ER = East Range Road, V = source basin sample, UB = upland basin, LB = mixture of upland sediment and eroding sediment, P = eroding piedmont sediment, UB, LB, and P each are an amalgamation of three samples, T = transect sample, EP1 represents proximal soil pit to the uplands, EP2 represents distal soil pit located ~4 km from uplands, numbers located after EP# represent depth intervals in centimeters. [2]All elevations are average upland valley elevation, based on basin hypsometry, and average elevation of the 3 km-long transects. [3]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. [4]Error is counting statistics from AMS with 2% uncertainty for stable Be and 4% uncertainty for stable Al, combined quadratically.

FIGURE 1

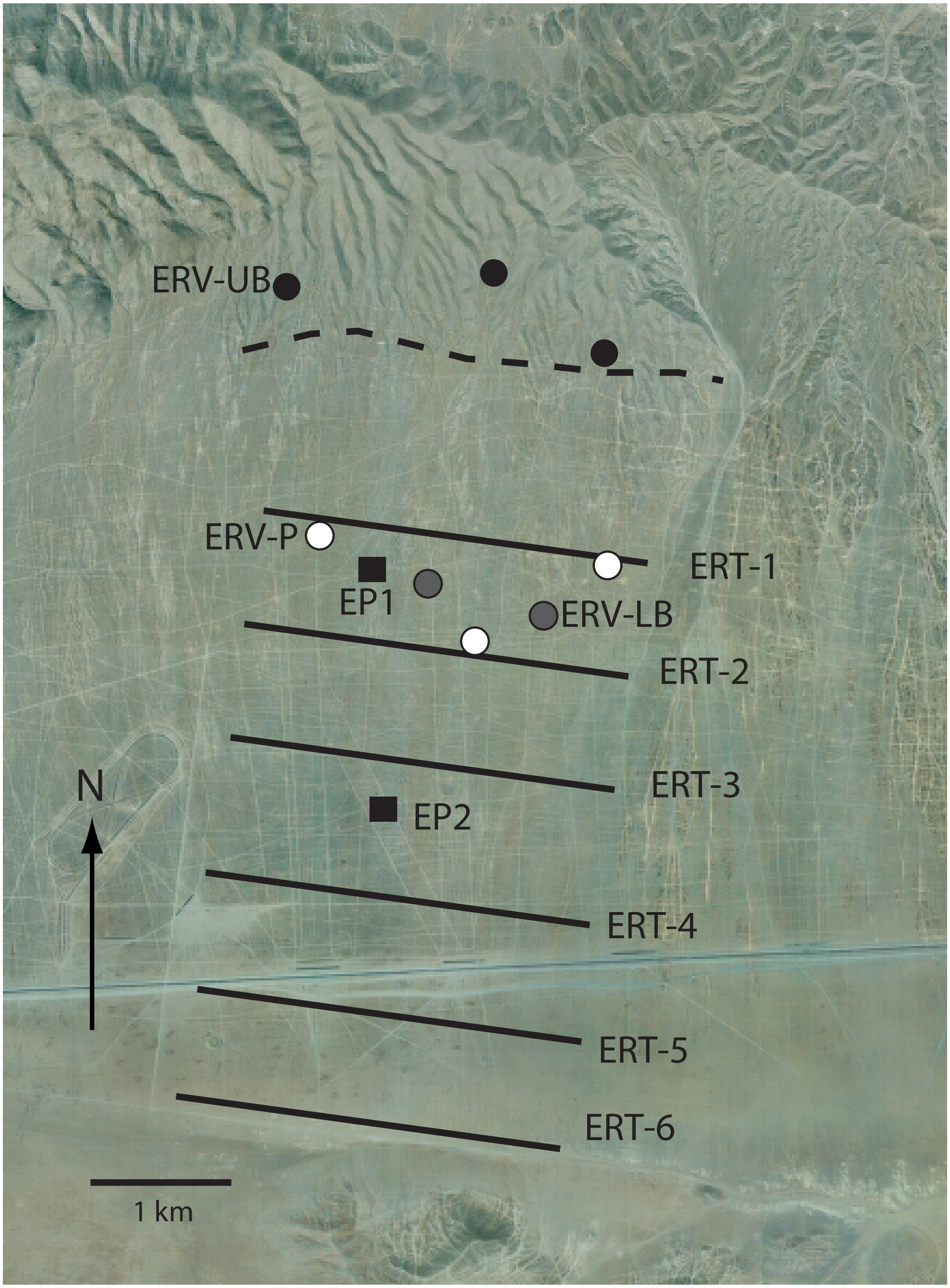


FIGURE 2

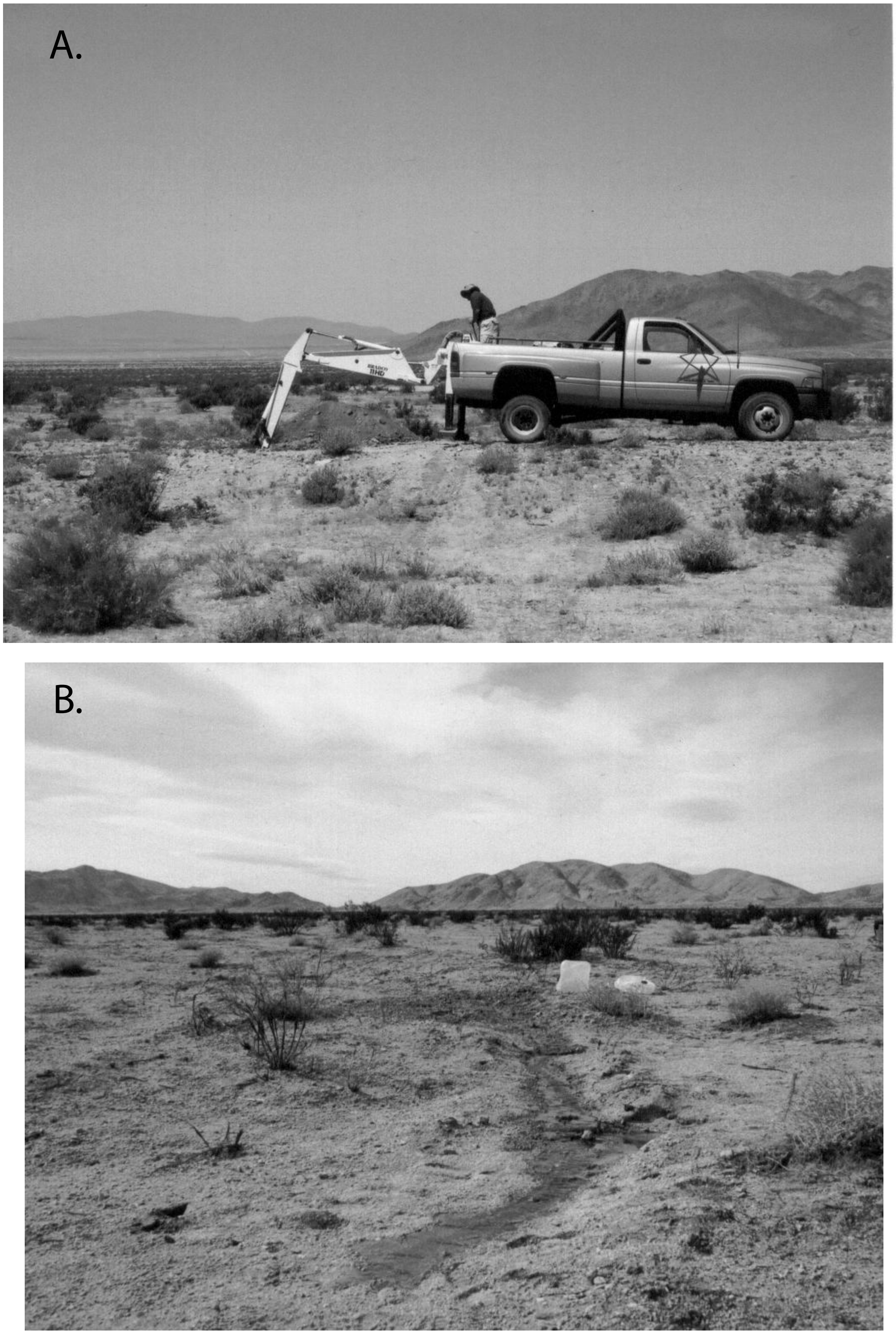
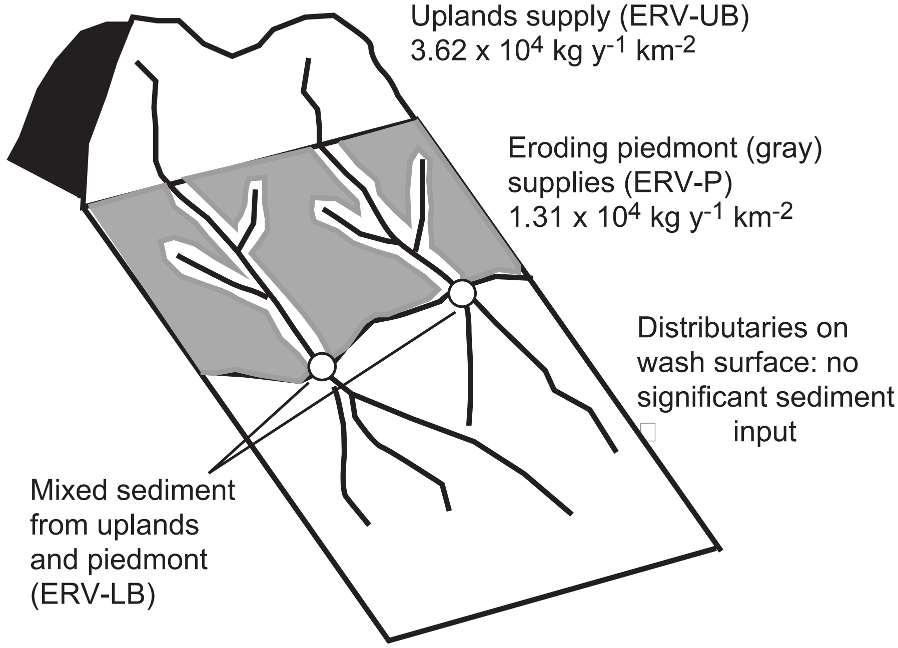
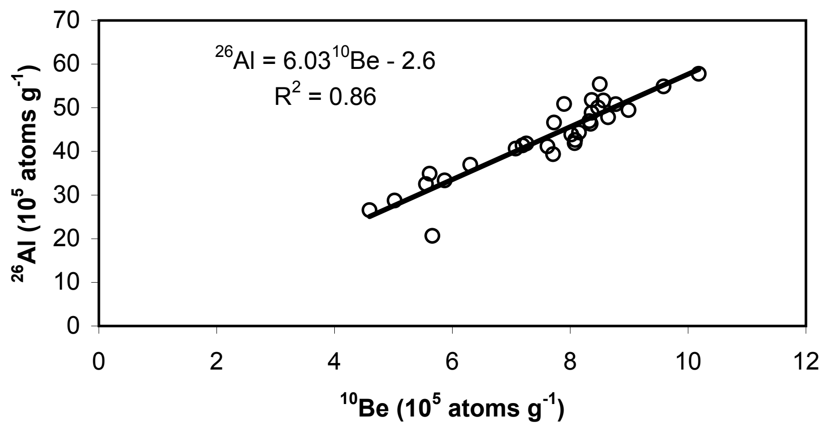


FIGURE 3



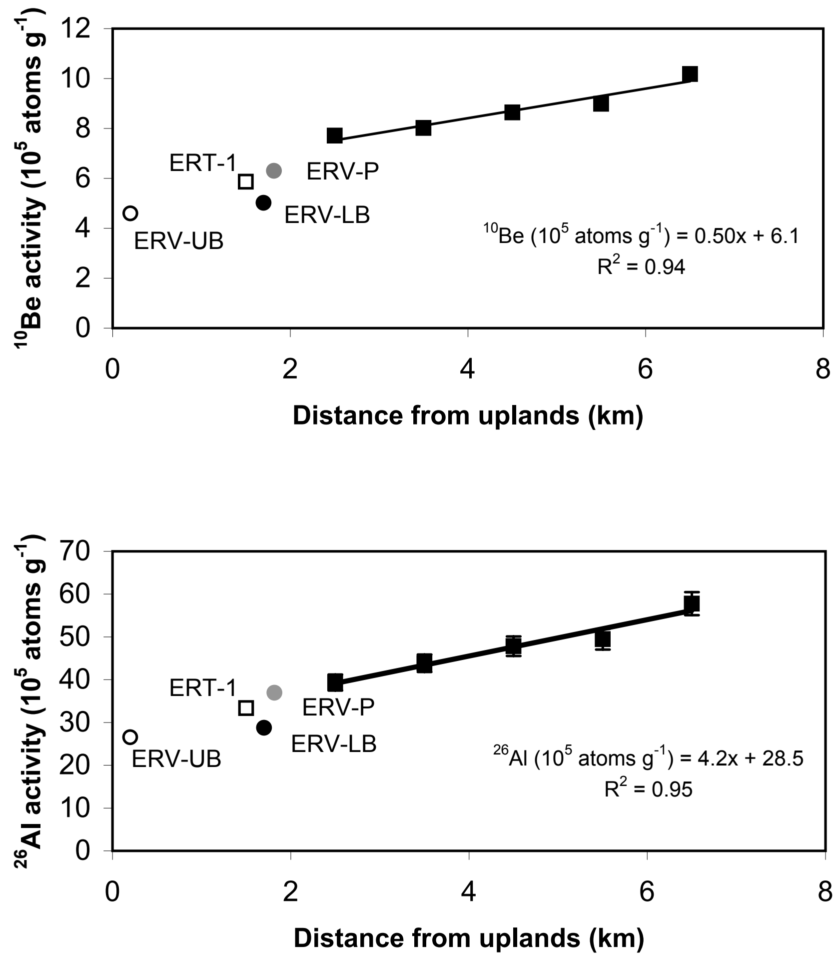
Uplands supply (ERV-UB)
3.62 x 10^4 kg y^-1 km^-2
Eroding piedmont (gray)
supplies (ERV-P)
1.31 x 10^4 kg y^-1 km^-2
Distributaries on
wash surface: no
significant sediment
input
Mixed sediment
from uplands
and piedmont
(ERV-LB)

FIGURE 4



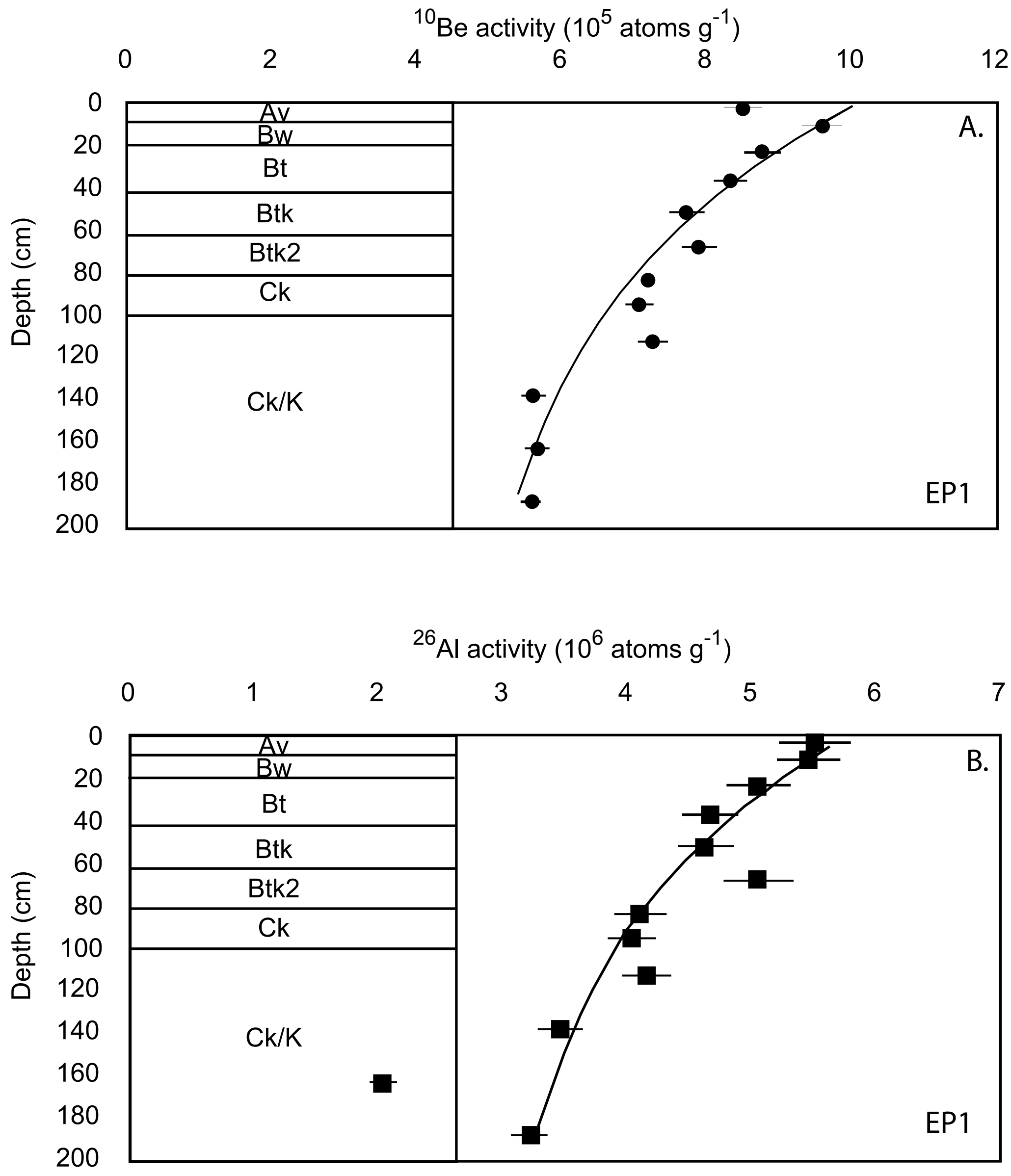
Nichols et al. Fig. 4

FIGURE 5



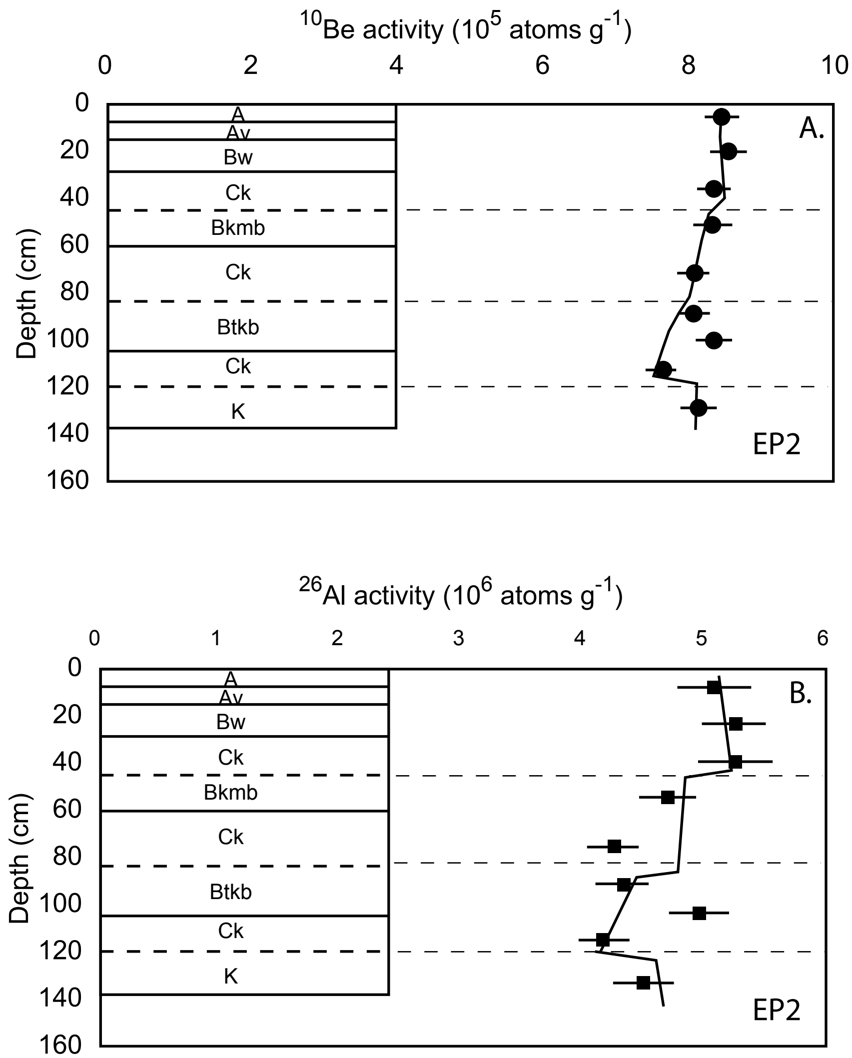
Nichols et al. Fig 5

FIGURE 6



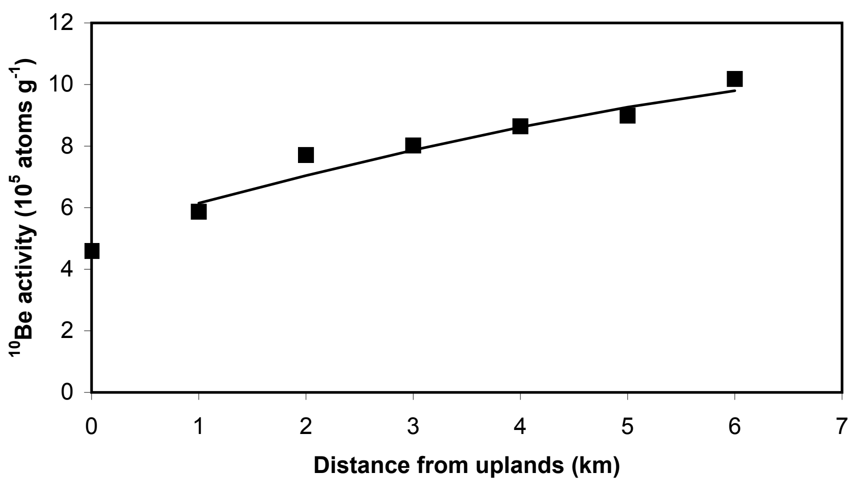
10Be activity (10^5 atoms g^-1)
0 2 4 6 8 10 12
Depth (cm)
0 20 40 60 80 100 120 140 160 180 200
Av
Bw
Bt
Btk
Btk2
Ck
Ck/K
A.
EP1
26Al activity (10^6 atoms g^-1)
0 1 2 3 4 5 6 7
Depth (cm)
0 20 40 60 80 100 120 140 160 180 200
Av
Bw
Bt
Btk
Btk2
Ck
Ck/K
B.
EP1

FIGURE 7



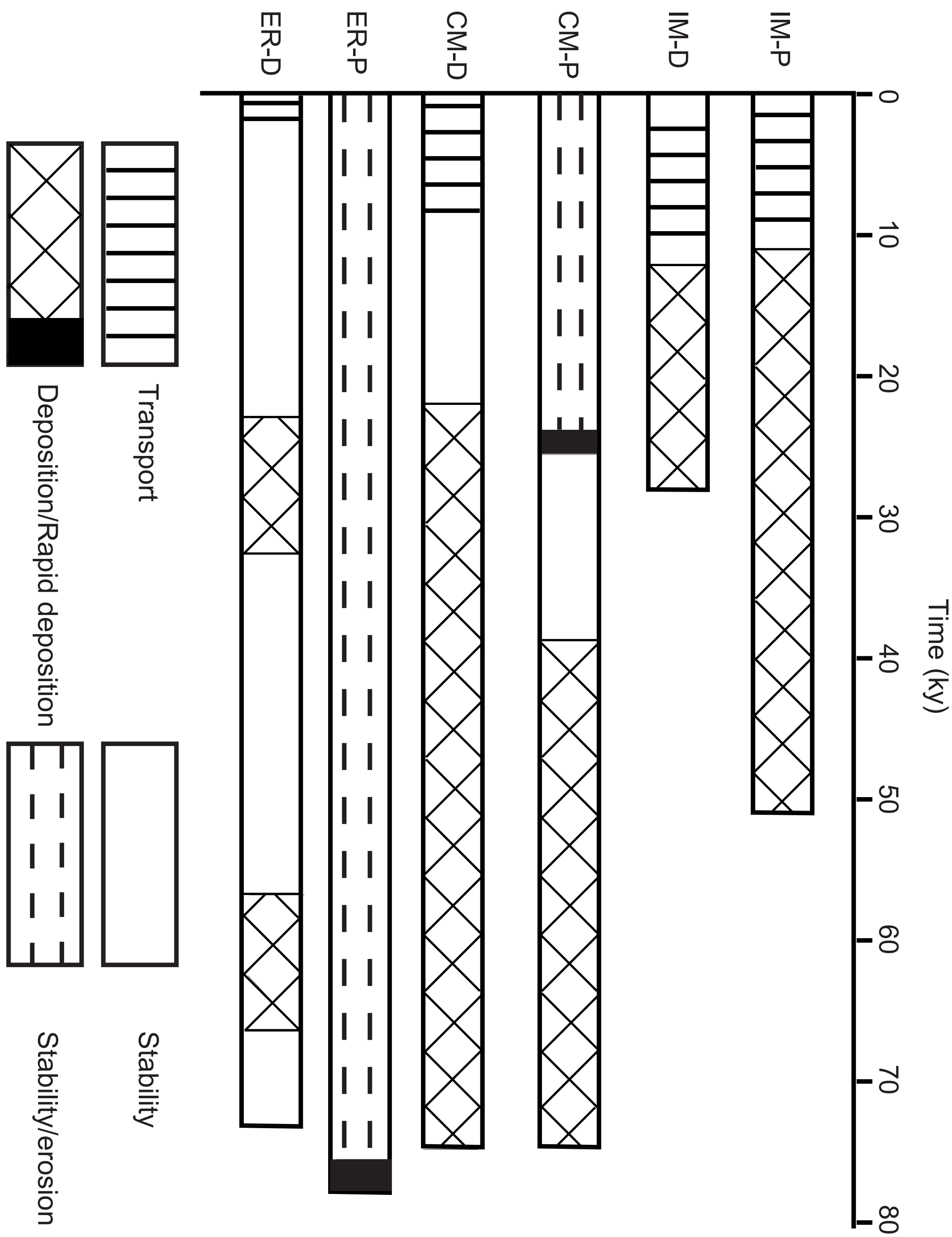
^{10}Be activity (10^5 atoms g^{-1})
0
2
4
6
8
10
Depth (cm)
0
20
40
60
80
100
120
140
160
A
Av
Bw
Ck
Bkmb
Ck
Btkb
Ck
K
A.
EP2
^{26}Al activity (10^6 atoms g^{-1})
0
1
2
3
4
5
6
Depth (cm)
0
20
40
60
80
100
120
140
160
A
Av
Bw
Ck
Bkmb
Ck
Btkb
Ck
K
B.
EP2

FIGURE 8



Nichols et al. Fig. 8

FIGURE 9


IM-P
IM-D
CM-P
CM-D
ER-P
ER-D
Time (ky)
0
10
20
30
40
50
60
70
80
Transport
Deposition/Rapid deposition
Stability
Stability/erosion

CHAPTER 6: Summary

There is an expansive body of research that investigates desert piedmonts. However, due to the paucity of good data, much of the early research is descriptive and addresses theoretical models (Gilbert 1877; McGee 1897; Paige 1912; Rich 1935). Later research focused on quantitative small-scale simulation models and monitoring. For example, Abrahams and colleagues use a small portion of a desert piedmont in Arizona and flume studies to simulate rainfall and measure the ensuing sediment transport (Abrahams, Parsons, and Luk 1988; Abrahams, Parsons, and Luk 1991; Luk, Abrahams, and Parsons 1993). Schumm (1962) monitored a small pediment in Badlands National Monument of South Dakota to understand the processes active on larger pediments. However, it is difficult to extrapolate such small-scale studies to larger-scales because the scaling relationships are unknown.

Other research has discussed large-scale piedmont histories. Much of this large-scale piedmont history literature uses soil development or geologic relationships to understand piedmont histories (Dohrenwend et al. 1987; Eppes et al. 2002; McFadden, Ritter, and Wells 1989; Oberlander 1974; Wells, McFadden, and Dohrenwend 1987). Although such large-scale piedmont studies provide a fundamental understanding of piedmont geography and history, historical studies tell less about piedmont process rates.

By using cosmogenic nuclides, I provide important data that quantifies piedmont processes and histories. My research quantifies piedmont process rates over long time and large spatial-scales and provides baseline data to compare to the short-term process rates. My research also quantifies time scales of surface stability, depositional hiatuses, and rates of sediment deposition and transport. Such insight into long-term piedmont behavior is difficult to gain using more traditional methods.

By studying two geomorphically complex piedmonts (Chemehuevi Mountain and East Range Road), I compared the rates of processes that modify common landforms found in deserts around the world over the long-term. By comparing the rates that modify an undisturbed piedmont (Chemehuevi) and a human disturbed piedmont (East Range Road), I deduce the anthropogenic effect on average long-term process rates. Both of these results provide a major step forward in understanding baseline rates of piedmont change.

Never has a sediment budget been established for a desert piedmont. By using long-term average sediment generation rates, based on cosmogenic nuclides, I detail the sources and amount of sediment that is transported down the Chemehuevi Mountain piedmont. My results suggest that most sediment is derived from the source basins. Where piedmonts have a proximal bedrock pediment, a significant amount of additional sediment is added to the down-piedmont flux. Incised alluvium supplies little additional sediment if the channels do not migrate and erode the banks. Model results suggest that minimal sediment is added from channel erosion of the substrate.

The sediment amalgamation technique I developed and used to measure average nuclide activities across 3 to 4 km long transects works on complex piedmonts as well as simple wash surfaces. The average sediment velocities calculated for both the Chemehuevi Mountain piedmont and the East Range Road piedmont are similar, and similar to previously modeled sediment velocities on the Iron and Granite Mountain piedmonts (decimeters per year; Nichols et al. 2002). Such uniform transport rates suggest that average long-term sediment velocities are largely independent of the piedmont geomorphology.

I demonstrate that cosmogenic nuclides have great potential to quantify complex piedmont histories of deposition and stability. Interpretations based on cosmogenic nuclides alone however, may lead to erroneous results. I find that data interpretation should be set in context using observation of surface morphology and soil development. Two soil pits on the Chemehuevi Mountain and East Range Road piedmonts suggest geomorphically consistent piedmont histories of sediment deposition, erosion/stability, and transport. The Chemehuevi Mountain piedmont has deposition rates that are similar to those on the Iron Mountain piedmont (Nichols et al. 2002).

Quantifying human impacts on desert piedmonts is difficult. Short-term measurement of process rates on disturbed piedmonts integrates both long-term average rates and short-term rates. Measurement of the long-term average rates provide baseline data on piedmont behavior. The short-term piedmont process rates are affected by human disturbance (Iverson 1980; Nichols et al. 2002; Prose 1985) or by significant geomorphic events (Baker and Twidale 1991). By measuring both the average long- and short-term rates, on can understand better the affect of human disturbance or significant geomorphic events on piedmonts (Nichols 2000).

For example, the East Range Road piedmont has experienced more than two decades of intensive Army training. The average long-term sediment velocities of the East Range Road piedmont are similar to the long-term velocities of the undisturbed

Chemehuevi Mountain piedmont. Such results suggest that extensive human disturbance does not affect the measurement of long-term process rates. By measuring short-term sediment movement on East Range Road (Persico, Nichols, and Bierman 2001), one can see that sediment movement over two years (without significant precipitation events) is five fold faster than the long-term average. Such results imply accelerated erosion of the piedmont due to the passage of wheeled and tracked vehicle and the likelihood of increased sediment deposition down gradient.

As the above examples illustrate, it is now possible to quantify average long-term piedmont process rates using the techniques I developed in this dissertation. Such rates are paramount to understand the baseline behavior of this ubiquitous desert landform. Furthermore, in order to understand the affect of human disturbance on piedmont change, one must understand the average long-term behavior of desert piedmonts.

Future direction of research

Although piedmonts have been investigated for over a century, the ability to estimate the average long-term process rates is in its infancy. In order to determine if the piedmont process rates measured in this dissertation can be generalized to similar climates and tectonic settings, there needs to be further testing of complex desert piedmonts. To understand piedmonts that have different climatic and tectonic settings, the technique used in Chapters 4 and 5 could be implemented on piedmonts outside of the Mojave Desert.

The use of cosmogenic isotopes in soil pits, set in context with soil development, has promise to be a powerful tool to understanding past rates of piedmont behavior

(Nichols et al. 2002; Phillips et al. 1998). The estimates of deposition rates coupled with surface age, in the four soil pits in this dissertation, shed light on the effects of climatic change on deposition and sediment yield to piedmonts. However, two soil pits on a surface provide only a small-scale insight to broad piedmonts. Greater spatial coverage of piedmont surfaces is needed to characterize entire piedmont surfaces. Currently, the significant number of samples needed to characterize a soil pit and the high cost of sample analysis limits the number of soil pit samples that can be collected on any individual surface.

This dissertation, although it provides an important step to understanding a large portion of Earth's surface, only addresses piedmont modification processes. In order to understand piedmont formation, one needs to investigate the third dimension (depth). The best way to proceed is to use geophysical data to characterize the thickness of alluvium and the depth to bedrock. Once the thickness of alluvial cover is determined one could core and analyze isotopically the piedmont deposits to estimate limiting ages and potentially investigate piedmont processes and rates that extend back millions of years. Additionally, the use of cosmogenic nuclides in pediment mantles could estimate the rate at which these proximal sections of desert piedmonts are presently being exhumed.

Finally, measuring long-term process rates has implications for desert land management. Since cosmogenic nuclides can provide estimates of long-term process rates quickly (analysis time of a year or less), land managers and engineers could use the amalgamation technique to understand the baseline process rates prior to development.

By acquiring such baseline data and monitoring the change in piedmont processes due to human disturbance, one can determine better the human impact on the desert environment.

The possibilities of using cosmogenic nuclides to address century-old questions about desert piedmonts are copious. I have only begun to address piedmont behavior by quantifying sediment transport rates, sediment deposition rates, the duration of surface stability, and sediment budgets for desert piedmonts. Further interest in piedmont research will provide a larger and broader insight into the behavior and formation of desert piedmonts.

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