

Ancient hillslope deposits: Missing links in the study of climate controls on sedimentation

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ABSTRACT

Rare outcrops of Miocene-Pliocene buried hillslopes and colluvium present in proximal basin-fill exposures in the arid southwestern United States, in settings free of tectonic influences, reveal hillslope-sediment production and delivery to piedmonts that vary as a function of climate change. A petrologic weathering index for sand, clay-mineral data, and stratigraphic relations indicates that episodes of greater production and delivery of colluvium from hillslopes coincide with more intense chemical weathering and thus greater effective moisture. Strata recording limited colluviation, less intense weathering, and piedmonts dominated by eolian processes very likely correspond to drier conditions. The mode of climate-driven hillslope and piedmont landscape responses evident in these older stratigraphic records corroborates the conceptual model developed by Quaternary researchers for arid environments—even though climate change was operating at higher amplitudes and different frequencies in the Quaternary. This evidence of long-term continuity in the mode of landscape response to climate change provides a new level of support for using the geologic record to understand the effects of future climate change.

Keywords: hillslopes, sediment yield, climate, basins, colluvium.

INTRODUCTION

Hillslope processes must be understood before clastic sedimentary records can be interpreted in terms of tectonic, climatic, or human controls. In particular, the poorly understood influence of climate change on sediment yield and sedimentary stratigraphy cannot be addressed without considering the primary variability of sediment and water transport off hillslopes. Buried hillslopes and their related sediment have not been recognized in pre-Quaternary stratigraphic records before, and although seemingly crucial for studies of the older geologic record, research on hillslopes and their response to climate has been left to Quaternary scientists. Yet, given the relatively high amplitude and high-frequency variability of Quaternary climate, it is unclear whether this research is actually applicable to the ancient record. Partly because of the missing connections between hillslopes and depositional basins, the use of Quaternary models of hillslope dynamics to help interpret older stratigraphic records has been overlooked. Likewise, our ability to look to the geologic record to predict the effect of future climate change on the physical landscape has been limited.

There is a significant body of geomorphic research on the influence of climate change on hillslope weathering, soils, and piedmont landforms (e.g., Kirkby, 1976; Bull and Schick, 1979; Gerson, 1982; Wells et al., 1987). Our understanding of these processes is largely based upon studies of the latest glacial to interglacial climate

transition, and much of this work has concentrated on arid settings, resulting in a conceptual model of climate-driven hillslope and piedmont dynamics (Bull, 1991; Harvey and Wells, 1994). Increased weathering of bedrock during cold and/or wet episodes results in development of hillslope colluvial mantles and transport of sediment to basins by fluvial systems. This colluvial mantle is stripped during the wet to dry transition, and a strong pulse of hillslope sediment is delivered to the piedmont because of the loss of binding hillslope vegetation and possible increased intensity or seasonality of precipitation events. Dry periods coincide with reduced production of hillslope detritus and more active eolian processes. This general model is applicable only to arid regions, and different or differently timed responses are evident in other climates (e.g., Bull, 1991; Reneau and Dietrich, 1991; Kirkby and Cox, 1995; Ritter et al., 1995; Mason and Knox, 1997).

We report results of stratigraphic, sedimentologic, and petrologic study of previously unrecognized late Miocene and Pliocene buried hillslopes and colluvium in super-proximal basin exposures in southeastern Nevada. The meaning of the term “colluvium” varies in the literature. It is used here in a broad sense to mean detritus, transported by various processes, that is still adjacent to or on its source hillslope. Stratigraphic records of hillslopes have the potential to inform us not only about climate controls on sedimentation, but also about the resilience and utility of existing Quaternary models of landscape response to climate change.

SETTING

Neogene colluvium and buried hillslopes are found in the Pliocene Panaca Formation and upper

Miocene and Pliocene Muddy Creek Formation in the Panaca and Table Mesa basins, respectively (Fig. 1). Approximate age controls for the strata are provided by tephrostratigraphic (Pederson, 1999) and paleontologic and magnetostratigraphic data (Mou, 1998). These formations are dominated by fluvial and eolian sand and mud, fossil-spring travertine, pond, and saline lake deposits (Bohannon, 1984; Kowallis and Everett, 1986; Schmidt, 1994; Pederson, 1999), and were deposited as late-stage basin fill in internally drained basins after the main early to middle Miocene episode of Basin and Range extension (Anderson, 1971; Bohannon, 1984; Bartley et al., 1988). This timing and the absence of range-front faults at the study localities allow us to attribute stratigraphic variability in these deposits solely to climatic, rather than tectonic, driving forces.

A thick Paleozoic succession of mostly carbonate rocks and Cenozoic intermediate to felsic volcanic rocks compose the bedrock in the region. Three key exposures of ancient colluvium in this study are partly distinguished by their associated bedrock types: the Owl Gulch locality adjacent to carbonate bedrock and the volcanic locality abutting Oligocene latite tuff, both at 1500 m elevation in the semiarid Panaca basin, and the southern locality adjacent to Mississippian carbonate bedrock at 730 m in the arid Table Mesa basin (Fig. 1).

Field observations indicate large-scale changes in the delivery of colluvium from hillslopes in the Neogene, Quaternary, and modern records of the

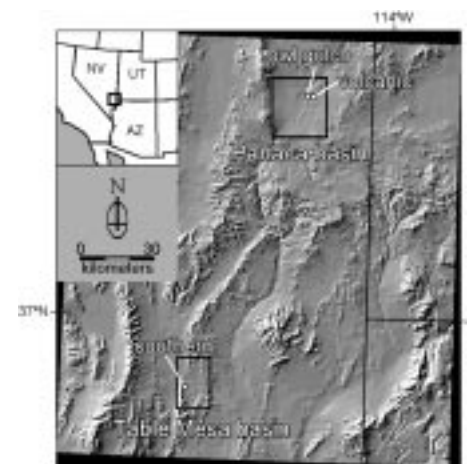


Figure 1. Location of study basins in southwestern United States and three key sites discussed in text.

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study area. Coarse colluvium in upper Miocene and Pliocene basin fill, although variable, typically extends only a few meters from basin-bounding bedrock slopes. In contrast, during the late Pliocene and Quaternary the same hillslopes produced and delivered gravel that episodically prograded several kilometers basinward. Modern hillslopes of carbonate bedrock are weathering limited and stripped of colluvium, but volcanic slopes are transport limited and typically mantled with <0.5 m of stable regolith and colluvium (Pederson, 1999). The lack of coarse facies development in the Neogene record, its contrast with that of the late Pliocene and Quaternary, and its similarity to the modern record are commonly observed in the region.

METHODS

A detailed stratigraphic section was measured through 10–50 m of interfingering Neogene colluvium and finer grained basin fill at each of the super-proximal localities. Samples were systematically taken from both colluvial wedges and interfingering sandy or silty basin fill to resolve petrologic distinctions between these distinct facies. Studies of the clay mineralogy and sand petrology of these samples, as well as of unweathered bedrock (or its insoluble residue), were undertaken to identify signals of past weathering. The generally arid environment of the study area, the lack of deep or long burial, and the absence of significant diagenesis indicate that primary petrologic features have probably been retained in the sedimentary record.

Traditional methods of displaying and interpreting the compositional maturity of sand samples through ternary plots (e.g., Blatt, 1967; Suttner et al., 1981; Johnsson and Meade, 1990) were not useful because the subtle chemical weathering in this arid environment has been masked by overwhelming signals of volcanic versus Paleozoic carbonate provenance. Instead, a sand-weathering index recording the alteration of relatively labile volcanic lithic grains was utilized. During point counting of fine-sand fractions (400 counts per sample), volcanic grains weathered to the point of having well-formed rims or mineral alteration distributed across the entire grain were recorded as weathered lithic fragments (L_W) rather than volcanic lithic fragments (L_V). The ratio $L_W/(L_W + L_V)$ provides the weathering index.

X-ray diffraction analysis of oriented, glycolated, Mg-saturated, clay-fraction mounts (Moore and Reynolds, 1997) was used to assess variability in illite, smectite, and kaolinite clay-mineral content, and grains from select samples were analyzed by scanning electron microscope. Quantitative estimates of the relative percentages of these clay-mineral classes were obtained by application of NEWMOD software (Reynolds and Reynolds, 1995) with an accuracy of $\pm 3\%$ – 5% (Moore and Reynolds, 1997). The reader is re-

ferred to Pederson (1999) for additional information on the results and implications of clay-mineral analyses.

RESULTS AND INTERPRETATIONS

The Owl Gulch section, presented here as an example, was measured through onlapping Pliocene basin fill and interfingering colluvium extending from a bedrock slope of Cambrian limestone (Fig. 2A). Pebbly hillslope detritus is typically restricted to within 15 m of the buried bedrock hillside, yet cyclicity is evident in the production and delivery of detritus, colluvial wedges extending as much as 100 m from the hillslope (Fig. 2B). The distinctive undulatory bedded, lower meter of gravel above the bedrock is a buried colluvial mantle, indicating that when this now-stripped bedrock hillside was onlapped and buried in the Pliocene, it was covered by its own detritus. Colluvial wedges interfinger with basin fill, and sedimentary structures and grain-size data indicate that eolian processes played a large role in recycling and depositing this finer grained sediment (Pederson, 1999).

Neogene colluvial progradation and retrogradation cycles are defined at two or more scales; those illustrated in Figure 2B are larger in scale than the basic interfingering couplets of facies evident in outcrop (Fig. 2A). The compound stratigraphic nature of each colluvial wedge indicates that the basic units are not the products of single events. Given the gross limitations of the magnetostratigraphy data (Mou, 1999), the colluvial cycles evident at the Owl Gulch and volcanic localities have a poorly constrained periodicity of between 15 and 77 k.y. (Pederson, 1999). Colluvial cycles in the Panaca basin stratigraphy may possibly record climate forcing at 23 or 41 k.y. orbital frequencies, consistent with marine isotopic evidence that Pliocene climate was dominated by precession and, especially, obliquity cyclicity (Raymo et al., 1989; Clemens and Tiedemann, 1997).

Colluvial wedges in the Pliocene Panaca Formation have a reddened, clay-rich matrix, and, in places, reddened zones associated with pedogenic horizonation extend basinward from the hillslope (Fig. 2A). In contrast to Quaternary aridisols that formed in the basin (Rowley and Shroba, 1991), these paleosols are dominated by rubified argillic horizons, and they lack calcic horizons. Deposition of soil carbonate may have been impeded by relatively high effective moisture, relatively thick vegetation, or calcium-poor dust input to the soils. The paleosol weathering profiles are commonly developed in the finer grained basin-fill facies and, in almost all cases, are stratigraphically below prograding colluvial wedges. When traced to the hillslope, the weathering profiles merge with the matrix of the colluvium.

The petrographic weathering index of colluvial wedges differs from that of interfingering fill at the three localities (Fig. 3A), the sand fraction of colluvial pulses being more deeply weathered.

Of all samples analyzed, $46.8\% \pm 12.3\%$ of the volcanic-lithic fragments in colluvial wedges are weathered, whereas $32.0\% \pm 11.6\%$ of volcanic-lithic fragments in the sandy fill are weathered. The means of these two populations are significantly different at the 98% confidence interval, and the difference between colluvial and basin-fill samples from just the Owl Gulch locality is significant at the 99% confidence interval. Samples from the volcanic locality are similarly distinct, although the difference is not as statistically significant (80% confidence interval), possibly because of the lower number of samples. Results from the more arid southern locality, although showing the same pattern, have high standard errors and are not significantly different, at least in part because of the low total percentage of volcanic-lithic fragments.

Latite bedrock at the volcanic locality contains phenocrysts of plagioclase, biotite, hornblende, and quartz in a silica and K-feldspar groundmass. Clay-mineral analysis of weathered Pliocene regolith (buried and recently reexposed) from this source rock indicates significant poorly structured smectite and, notably, authigenic kaolinite (Pederson, 1999) (bottom of Fig. 3B). Insoluble residue of Paleozoic carbonate bedrock is rich in illite with small amounts of smectite, but the matrix of upper Miocene colluvium derived from carbonate bedrock near the southern locality is dominated by smectite (top of Fig. 3B), much of which may be from eolian input. These background data indicate that clay minerals, potentially formed through weathering of volcanic bedrock in the Neogene, are typified by smectite, as expected in arid environments (Birkeland, 1984; Weaver, 1989; Johnsson et al., 1993). However, effective moisture in the Pliocene was great enough at times to possibly weather potassium-rich volcanic material to kaolinite, a process that typically occurs in temperate to tropical environments (Birkeland, 1984; Weaver, 1989).

There is more kaolinite in Panaca basin colluvium and less in interbedded fill in nearly all cases (Fig. 3B). Considering the laboratory and analytical error of the quantitative estimates, some neighboring samples may not be significantly different, but the consistency of the pattern produces a robust signal. The strong correlation between increased kaolinite and increased illite in samples from the volcanic and Owl Gulch localities is interpreted as a signal of both greater volumes of volcanic source material and more intense weathering of that material during colluvial progradation. Clay percentages from the southern locality have no systematic pattern, a testament to the minor degree of chemical weathering in the carbonate-bedrock-dominated, more arid setting of Table Mesa basin in the late Miocene.

CONCLUSIONS

Although complex interactions between vegetation, soils, runoff, temperature, and precipita-

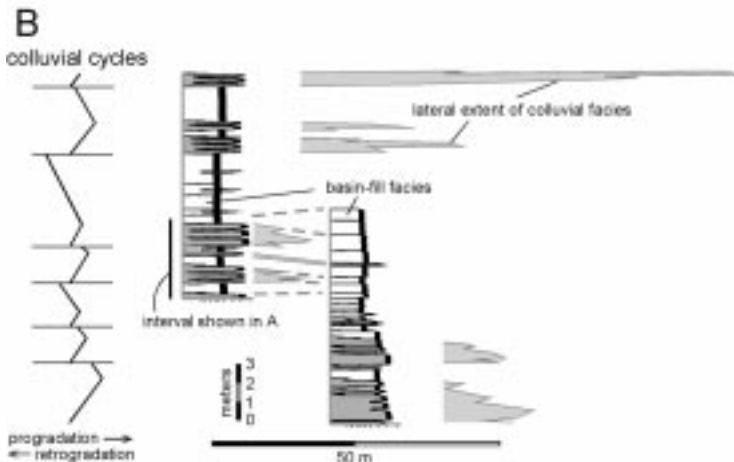


Figure 2. A: Part of Owl Gulch locality with interfingering pebbly colluvium and silty basin fill (contact follows black dashed lines) onlapping hill-slope of Cambrian limestone. Sample numbers in white boxes are for colluvium; black boxes are basin-fill samples. Petrologic data that include these units are presented in Figure 3. Recessive horizon at top of unit p-135 and overlain by prograding p-136 colluvium is interpreted as part of paleosol. Stadia rod is 2 m tall. B: Correlated proximal stratigraphic sections at Owl Gulch with colluvial wedges shown extending basinward. Interpreted cycles of colluvial progradation and retrogradation are at left.

tion regime must have affected the study hillslopes, our results suggest a general correlation between increased sediment production and greater effective moisture. Analytical results indicate that episodically more intense physical and chemical weathering in the Neogene, very likely at times of greater effective moisture, produced the hillslope detritus composing colluvial wedges in the stratigraphic record. These colluvial bodies are, in part, correlative to paleosol weathering profiles in adjacent piedmont deposits, which may indicate that hillslopes were being stripped of detritus with a sediment pulse delivered basinward during wet to dry climate transitions. Intervening layers marked by eolian deposition, very

little colluviation, and relatively unweathered sediment very likely represent drier periods. Although this pattern has been evident in research from arid Quaternary settings it has not previously been demonstrated through study of an older stratigraphic record.

A three-part conceptual model of hillslope and piedmont responses to climate with wet, wet to dry transition, and dry components best explains the Neogene record in the study area (Fig. 4). It also exactly describes the model that Quaternary researchers have developed for the last glacial to interglacial transition in arid landscapes. This similarity has dual implications: first, this pre-Quaternary stratigraphic record corroborates the

Quaternary conceptual model, and second, Quaternary records, with their relatively high amplitude climate changes, apparently are valid as an interpretive tool extending back into the Miocene. With careful consideration of local paleoclimate, it seems that it may be appropriate to interpret climate controls on sedimentary basin stratigraphic sequences in Quaternary terms because the modes of change have been the same through time, although the magnitude has clearly varied. This evidence of temporal continuity in hillslope and piedmont responses to climate change lends confidence to use of the geologic record as a reference when predicting landscape responses to future climate change.

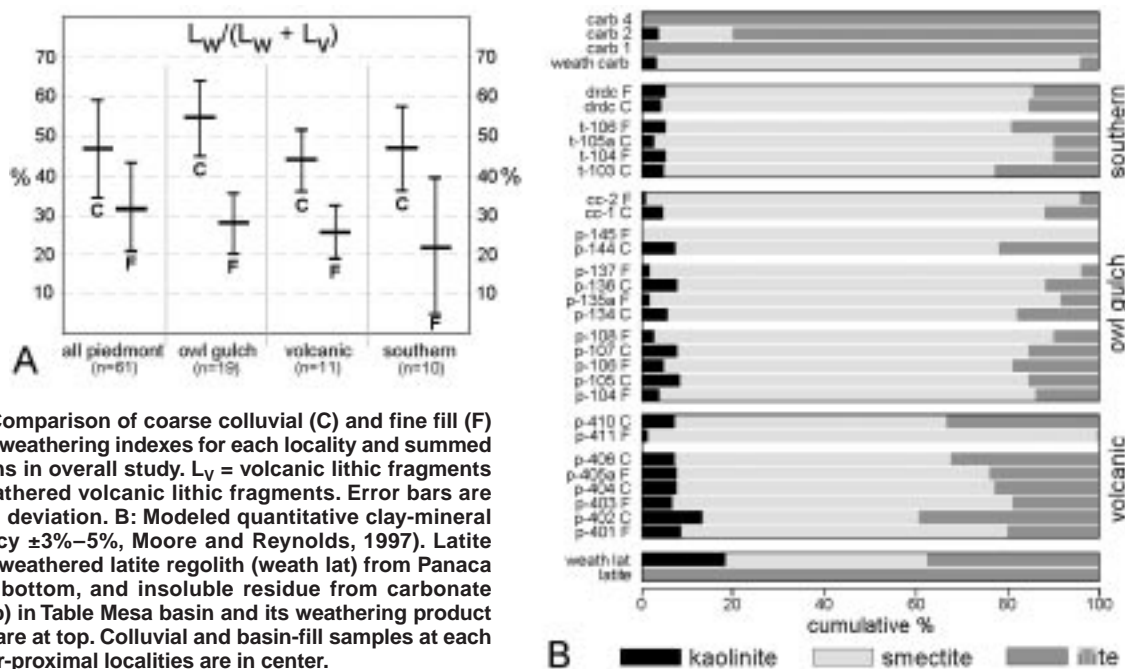


Figure 3. A: Comparison of coarse colluvial (C) and fine fill (F) petrographic weathering indexes for each locality and summed for all sections in overall study. L_v = volcanic lithic fragments and L_w = weathered volcanic lithic fragments. Error bars are one standard deviation. B: Modeled quantitative clay-mineral data (accuracy $\pm 3\%$ – 5% , Moore and Reynolds, 1997). Latite bedrock and weathered latite regolith (weath lat) from Panaca basin are at bottom, and insoluble residue from carbonate bedrock (carb) in Table Mesa basin and its weathering product (weath carb) are at top. Colluvial and basin-fill samples at each of three super-proximal localities are in center.

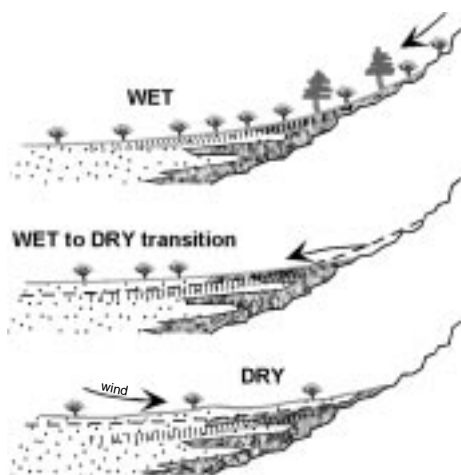


Figure 4. Three-part conceptual model of hillslope and piedmont response to climate change from this research, which is consistent with model of Quaternary researchers in arid and semiarid environments. Wetter conditions result in increased physical and chemical weathering of bedrock, producing colluvium that mantles hillslopes and progrades onto piedmont. Transition from wetter to dryer climate may be marked by vegetation loss, stripping of colluvial mantles, and detrital pulse to piedmont. Drier conditions are marked by low bedrock-weathering rates, more active eolian processes, and stable hillslopes.

Although rare, pre-Quaternary buried hillslopes and their deposits exist in the stratigraphic record. Identification and future study of ancient colluvium should clarify the relation between hillslopes and depositional basins, increasing our understanding of climate controls on sedimentation and landscape change.

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