Influence of soil development on the geomorphic evolution of landscapes: An example from the Transverse Ranges of California

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ABSTRACT

Soil development can significantly influence the topographic evolution of a tectonically deforming mountain piedmont. Faults and folds associated with the North Frontal thrust system deform piedmont sediments of variable compositions along the north flank of the San Bernardino Mountains. The topographic expressions of folds with similar structural characteristics diverge appreciably, primarily as a function of differences in sediment composition and associated soil development. Soils with petrocalcic horizons in limestone-rich deposits are resistant to erosion, and anticlinal folds form prominent ridges. Folds forming in granite-derived deposits with argillic soil horizons are eroded and/or buried and are therefore topographically less pronounced. We propose that these landform contrasts can be explained by differences in soil-controlled hydrologic and erosion characteristics of deposits without calling upon changes in tectonic style along the mountain front.

Keywords: soil, landscape evolution, tectonics, folds, erosion, San Bernardino Mountains.

INTRODUCTION

Understanding the relationships between climate, tectonics, and surficial processes is critical for an accurate interpretation of the geologic record. Numerous links and feedbacks between climate, tectonics, and surficial processes as they relate to long-term landscape evolution have been established (Beaumont et al., 1992; Brozovic et al., 1997; Small and Anderson, 1998; Brandon et al., 1998); however, the relative importance of climate versus tectonics to surficial processes continues to be debated (e.g., Ritter et al., 1995; Riebe et al., 2001). A primary means of assessing interactions between tectonics and climate and surficial processes is the interpretation of the geomorphic characteristics of alluvial piedmonts of both active and inactive mountain fronts (Bull and McFadden, 1977; Bull, 1991). Although geomorphologic studies of alluvial piedmonts almost always include soils as stratigraphic markers or indicators of surface age, the extent to which soil-forming processes might affect landscape evolution is not fully appreciated.

Soil development can drastically alter the physical properties of unconsolidated deposits (see Birkeland, 1999). These properties can strongly influence hydrologic and erosion processes (Dunne, 1978; Wells et al., 1987; McAuliffe, 1994). On the basis of more than two decades of research and data collection from numerous soil-landscape studies in arid-semiarid landscapes (e.g., Gile et al., 1981; Wells et al., 1987; Harden et al., 1991; Reheis et al., 1992; McDonald, 1994; McFadden et al., 1998; Eppes et al., 1999), we hypothesize that progressive soil development exerts an increasingly significant control on surficial processes that may either enhance or mask the influence of tectonic deformation on the morphology of a landscape. In this paper we present an example of the type of landscape and landforms for which this hypothesis may be reasonably applied.

The north- and south-dipping thrust faults that bound the Transverse Ranges of southern California are commonly blind and associated with folds in Neogene sediments. Most of these blind thrust structures that have been studied (e.g., the Wheeler Ridge anticline; Bullard and Lettis, 1993; Keller et al., 1998, 2000) are the result of such high uplift rates that associated geomorphic surfaces are never sufficiently stable to enable more than weak soil development. The north flank of the San Bernardino Mountains (Fig. 1), however, has been moderately active since the early Pleistocene ($<$1mm/yr, Meisling and Weldon, 1989), but sufficiently stable to allow significant soil development in Quaternary deposits. In addition, soils vary significantly across the piedmont of the north flank as a function of sediment composition of alluvial fans (Eppes et al., 1998). There is significant lateral variability in the topographic expression of landforms associated with similar reverse-fault–related structures along the north flank. Here we present data that suggest that these landform contrasts can be accounted for by differences in the soils of deposits that are being deformed without calling upon significant differences in rates or styles of deformation of structures.

GEOLOGIC SETTING

The convergent tectonic activity that produced the present relief and topography along

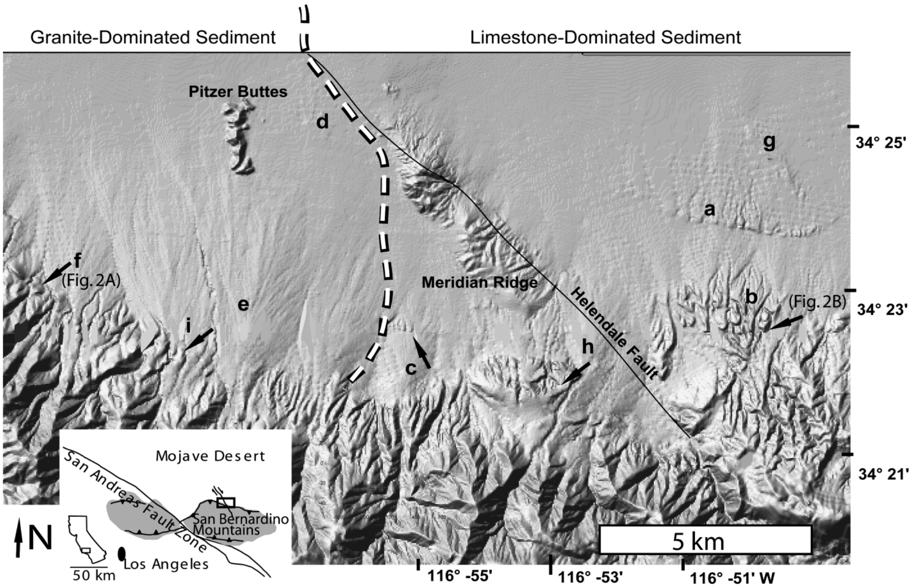

Figure 1. Shaded-relief image of 30 m spaced digital elevation model (DEM) from north flank of San Bernardino Mountains, modified in areas to reduce DEM data error effects. Dashed line represents relatively sharp transition in alluvial fan composition from limestone-dominated to granite-dominated sediments. See text for explanation of lettered areas.

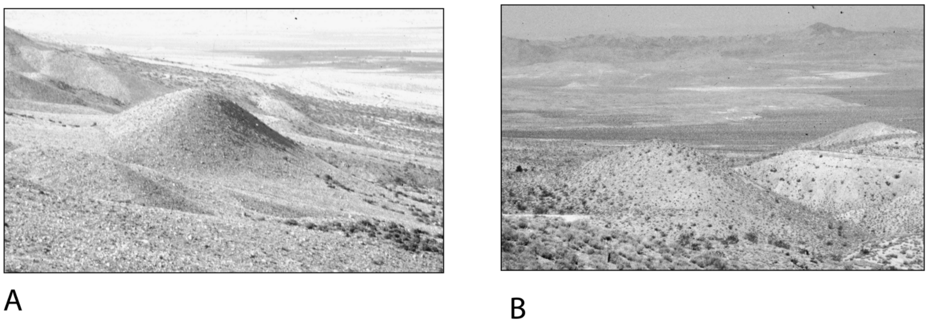

Figure 2. Similar granite-cored folds in (A) granite and (B) limestone terranes. North is to right in both photographs. See Figure 1 for locations.

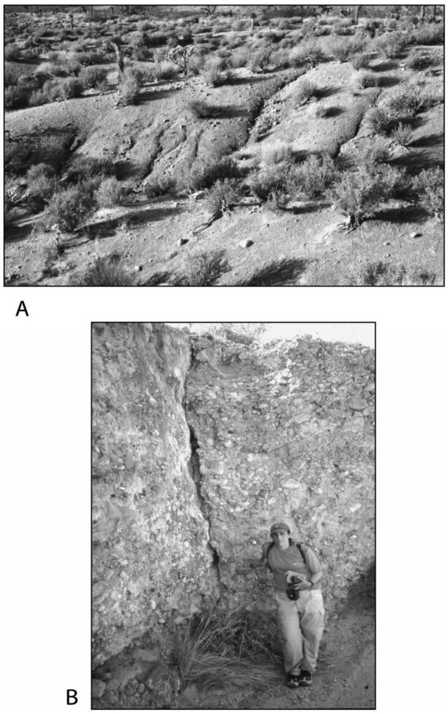

Figure 3. A: Rills developing in argillic soil exposed on side slope of typical channel in granite terrane. B: Stage IV petrocalcic horizon incised by drainage on limestone-derived fan. Fracture shown is typical of these soils and is lined with calcium carbonate.

the northern flank of the San Bernardino Mountains began in the late Pliocene–early Pleistocene (Meisling and Weldon, 1989; Spotila et al., 1998).

The north flank piedmont constitutes the rim of a closed desert basin. Piedmont stratigraphy consists of weathered granite bedrock overlain by 100–500 m of Miocene and Pliocene basin and distal piedmont sediments that grade upward into poorly sorted gravel to boulder alluvial-fan units of Quaternary age (Miller et al., 1998; Powell et al., 2000; Spotila and Sieh, 2000). The drainage basin area does not vary by more than an order of magnitude in the basins that contribute to alluvial fans in the piedmont; however, rock types exposed in these drainage basins range from primarily Mesozoic batholithic granites in the western half of the field area to primarily Precambrian to Paleozoic metasedimentary roof pendants, particularly metalimestones, in the eastern half of the study area. Consequently, alluvial-fan deposit composition varies from more than 95% granite rocks in the west to more than 95% carbonate rocks in the east (Fig. 1). The presence of similar vegetation communities at similar elevations suggests that climate does not vary significantly along the piedmont within the study area.

PIEDMONT STRUCTURES AND THEIR MORPHOLOGY

The North Frontal thrust system of the San Bernardino Mountains consists of a complicated series of overlapping, east-striking reverse faults and fault-cored folds. These structures incorporate basement and the entire Neogene stratigraphic section of the piedmont (Miller et al., 1998; Powell et al., 2000; Newland, 2001). Geomorphic indicators (e.g., degree of dissection) provide evidence that folds adjacent to the mountain front are older than those in the medial and distal piedmont (Powell et al., 2000). The north flank piedmont is cut by the Helendale fault and other northwest-striking high-angle faults that exhibit both strike-slip and reverse-slip motion (Fig. 1). The relationship between these faults and the North Frontal thrust system is ambiguous. Structures with this northwest trend (g in Fig. 1) are prominent east of the Helendale fault and less evident to the west (Spotila and Anderson, 2000). Fault-related folds with similar structures and thrust faults with similar geometries, however, are present to both the east and west of the Helendale fault (e.g., a and c in Fig. 1, Fig. 2; Miller et al., 1998; Powell et al., 2000; Newland, 2001).

The topographic expressions of fold structures vary as a function of sediment type and soil characteristics[1]. Folds in the granite-derived piedmont are often buried on their back limbs, and/or eroded on their forelimbs, resulting in an overall ridge and/or scarp morphology (e and i in Fig. 1). Detailed geologic and geomorphic mapping in the granite piedmont revealed the existence of previously unrecognized folds not associated with surface fault rupture (Newland, 2001; d and e in Fig. 1). These structures have low relief and lie along the strike of folds to the east (a and c in Fig. 1) that are developing in limestone-derived deposits. Folds in limestone-derived deposits are armored by petrocalcic horizons and therefore form prominent anticlinal ridges. Petrocalcic horizons on these folded landforms are associated with deformed primary stratigraphy, indicating that they did not form in situ. When less resistant basin deposits are exposed at the core of these anticlines, the core erodes and the flanks of the fold assume an amphitheater (h in Fig. 1) or a ridge (a and b in Fig. 1) morphology. The degree of dissection of these fold features, combined with the fact that they are east of the maximum relief of the mountain front escarpment (~1060 m of relief at 116°53′W vs. ~770 m at 116°51′W), suggests that their topographic prominence is not related to higher slip rates or youth. When bedrock is exposed at the core of limestone folds, the landforms more closely resemble those found in the granite piedmont (Fig. 2).

SOILS AND SURFICIAL PROCESSES

Two separate limestone and granite soil chronosequences were developed on alluvial fan surfaces along the north flank. Three pits were examined on most surfaces. Soil and deposit ages were estimated by comparison of soil and geomorphic properties with other well-dated chronosequences in southern California (e.g., Reheis et al., 1992; McDonald, 1994). Field morphologic data (Soil Survey Staff, 1975) for ~40 soils indicate that soil development and weathering characteristics of granite- and limestone-derived deposits diverge with time in three geomorphically important ways: (1) soil profile horizons, (2) weathering of individual clasts, and (3) surface characteristics.

Early and middle Pleistocene granite deposits exhibit 0.5–5-m-thick argillic horizons (Fig. 3), granite clasts commonly weathered into grus, and minimal carbonate accumulating only at great depths (>4 m). Younger alluvial fan sediments often bury these soils (Eppes et al., 1998). The upper 10–20 cm of granite deposits, regardless of age, are characterized by unconsolidated grus-rich sand with minimal soil and stone pavement development.

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[1] GSA Data Repository item 2002017, Additional photographs and descriptions of examples of fault and fold structures in the San Bernardino Mountain piedmont, California, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA, editing@geosociety.org, or at www.geosociety.org/pubs/ft2002.htm.

In contrast, limestone-derived early and middle Pleistocene deposits exhibit 2–5-m-thick, rock-like petrocalcic (K) horizons with stage IV–stage V calcic horizon development that grade into groundwater-cemented calcrete at depth (Fig. 3). Limestone clasts weather primarily by dissolution of calcium carbonate that is then locally reprecipitated (Treadwell-Steitz and McFadden, 2000). Both early and middle Pleistocene deposits are typically capped by 20–30 cm of alluvium that exhibits Av and Bwk horizons and moderately to well-developed desert pavements. These surface soils do not appear to be genetically related to underlying petrocalcic horizons, and are likely developing in younger, reworked alluvium.

Abundant grus and clay-rich argillic horizons facilitate fluvial and diffusional erosion of granite fan surfaces, while rock-like petrocalcic soils inhibit erosion of limestone fan surfaces. Conversion of granite clasts to grus produces an abundant moderately sorted, pebbly sand grus sediment source; accordingly, granite alluvial fan surfaces and channels are transport-limited environments that are much more susceptible to diffusional processes such as creep, bioturbation, and raindrop splatter than equivalent limestone environments. Abundant active and inactive-backfilled small drainages developing on argillic horizons (Fig. 3) provide evidence that these horizons produce significant runoff when exposed, favoring drainage migration over fan surfaces.

In contrast, the antiquity and abundance of petrocalcic horizons in the limestone piedmont attest to their overall stability in the landscape, despite major glacial-interglacial climate changes and active tectonics. Indurated stage III K horizons can form in limestone-dominated alluvium in as little as 50–100 k.y. (e.g., Gile et al., 1981; Reheis et al., 1992; McDonald, 1994). Channels in the limestone piedmont have only a thin veneer of sediment and are typically deeply incised into petrocalcic horizons (Fig. 3). The lack of backfilled and abandoned channels indicates that these channels do not migrate laterally once incised. Laminar carbonate precipitating along channel walls via abundant fractures in K horizons suggests that fracture flow may contribute to channel discharges. The presence of cemented animal burrows in the top 50 cm of petrocalcic horizons indicates minimal surface erosion of limestone alluvial fans since their initial development.

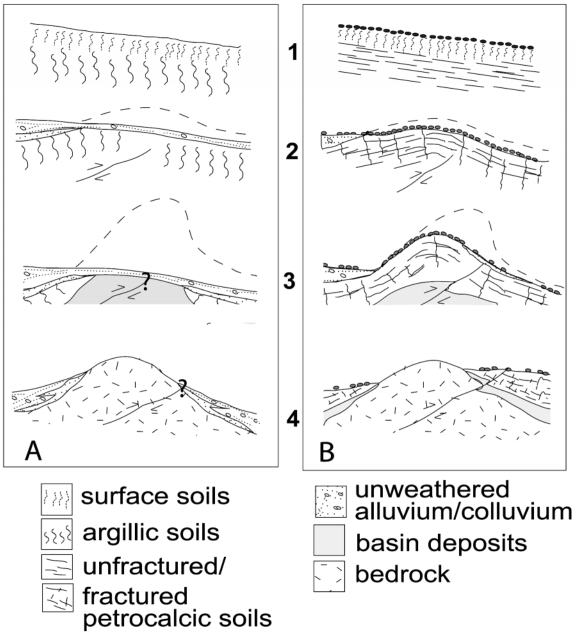

Figure 4. Model of topographic evolution of folds in (A) granite and (B) limestone parent materials. (1) Landscape stability allows for development of mature soils in both settings. (2) Incipient folding results in removal of surface soil horizons in both settings; however, underlying argillic horizons in granite-derived alluvium easily erode, whereas petrocalcic horizons fracture but do not erode significantly. (3) As folding continues, incised streams in limestone setting bypass growing structures, whereas anastamosing channels on granite fans laterally erode and exhume underlying basin deposits. (4) When granite bedrock is exhumed in either setting, fault-cored folds begin to assume similar morphologies.

DISCUSSION

To elucidate potential interactions between geologic, geomorphic, and soil-forming processes, we have constructed two simple conceptual models for the development of landforms produced by folding of granite and limestone alluvial fans (Fig. 4). We offer these models as an example of how our general soil-landscape hypothesis could account for the topographic variability of one type of mesoscale structure, not as a definitive answer to overall landscape evolution of the San Bernardino Mountain piedmont. A few basic assumptions characterize these models. First, although these models roughly assume fault-propagation–style folding as described by Suppe (1983) and others for fold-and-thrust belts in southern California, the models focus primarily on geomorphic and pedogenic processes, not a specific fault or fold mechanism. However, based on the highly fractured characteristic of petrocalcic horizons as well as bedrock at the core of folds, we assume that macroscopic folding of these strata at the surface is likely accomplished by brittle cataclasis. If a fault ruptures the surface in either model, fault-propagation–type folding would stop, and a fault scarp would develop. In addition, we assume that the initial hydrologic and rheologic properties of limestone and granitic alluvial sediments are essentially the same, so that until soils develop, they would both erode and deform similarly in response to faulting. Clearly, rates and timing of tectonic deformation will play a role in the efficacy of the hypothesized processes. If deformation rates are too fast for sufficient soils to develop, then the model is inappropriate: therefore, a key assumption is that a sufficiently long initial period of landscape stability has passed, relative to the rate of deformation, to enable at least moderately developed argillic and petrocalcic horizons.

Surface soil horizons (~0–30 cm) on both granite- and limestone-derived alluvial fans are eroded in response to initial folding. Exposure of an underlying argillic horizon of a granite-derived deposit favors beveling and burial of the growing fold by both fluvial and diffusion processes. Growing folds in granite-derived deposits will thus maintain a subdued convex morphology (d in Fig. 1) until folding rates exceed erosion rates. In contrast, rapid fracture-dominated through flow and the great resistance of the petrocalcic horizon to mechanical and chemical weathering favor only very low surface erosion rates when petrocalcic horizons are exposed at the surface. Erosion is primarily restricted to large channels that can incise through increasingly larger folds and that transport sediment through the anticlinal landforms. Consequently, as deformation continues, the limestone-derived alluvial fan surface is abandoned and preserved as an elevated, undulating surface with high relief (a and b in Fig. 1). When granite bedrock is exhumed in either setting, surface processes become similar, and fault-cored folds begin to assume similar morphologies (Fig. 2; see b and f in Fig. 1).

Variability in soil characteristics is sufficient to account for a significant portion of the topographic variability of mesoscale structures along the San Bernardino mountain front. Variable soils and soil-controlled landscape-modifying processes, however, could also influence other processes such as fault-scarp denudation and alluvial fan aggradation. In addition, because soil development changes the rheologic characteristics of sediments, their response to both fold and fault deformation will differ. Additional data will be required to determine to what degree landscape variability across the piedmont of the San Bernardino Mountains can be attributed to soil and surficial processes rather than to changes in tectonic rates or style. This study suggests, however, that variability of Quaternary landforms across the north flank as well as other tectonically active piedmonts should not be employed as definitive evidence for changes in the character of their associated tectonic structures.

CONCLUSIONS

In the piedmont of the north flank of the San Bernardino Mountains, soils dictate the types of surficial processes that modify the local landscape. Soil variability associated with deposit age and rock type modulates surface erodibility, the development and characteristics of ephemeral channels, and ultimately patterns of erosion and deposition on the piedmont. Soil-geomorphic processes are a viable explanation for much of the observed topographic variability of landforms associated with tectonic deformation of alluvial fans in the piedmont. The results of this study provide a clear example of the significant role that soils can play, in this case largely independent of climate change, in influencing the long-term evolution of mountain piedmonts as well as other landscapes. A complete understanding of the past and current behavior of landscapes as they relate to tectonics and climate change is not possible until that role is clearly characterized.

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