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Numerical modeling of the Cenozoic geomorphic evolution of the southern Sierra Nevada, California

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Abstract

Recent geomorphic studies suggest that significant (~1.5 km) late Cenozoic surface uplift occurred in the southern Sierra Nevada, a conclusion that is difficult to reconcile with recent stable-isotopic paleoaltimetry studies. Numerical modeling can play an important role in resolving this dispute. In this paper I use two models of bedrock channel erosion, the stream-power model and a sediment-flux-driven model, to test hypotheses for the fluvial Cenozoic geomorphic evolution and surface uplift history of the southern Sierra Nevada. Cosmogenic data for upland erosion and river incision rates allow each model parameter to be uniquely constrained. Numerical experiments using the sediment-flux-driven model suggest that the modern southern Sierra Nevada was constructed from a 1.0-km pulse of range-wide surface uplift in the latest Cretaceous (~60 Ma) and a 0.5-km pulse in the late Miocene (~10 Ma). The persistent geomorphic response to latest Cretaceous uplift in this model is the result of limited "cutting tools" supplied from the upland low-relief Boreal Plateau. This uplift history correctly predicts the modern topography of the range, including the approximate elevations and extents of the Chagoopa and Boreal Plateaux and their associated river knickpoints. Numerical experiments using the stream-power model are most consistent with a 1-km pulse of uplift in the late Eocene (~30 Ma) and a 0.5-km pulse in the late Miocene (~7 Ma). Both models suggest that the remaining rock uplift required to produce the 4-km peak elevations of the modern southern Sierra Nevada was produced by flexural-isostatic uplift in response to river incision. The balance of evidence, including the dominance of sediment-flux-driven erosion in granitic rocks, previous paleoaltimetry studies, and the timing of sediment accumulation in the Great Valley, support the conclusions of the sediment-flux-driven model, i.e. that the Sierra Nevada experienced range-wide surface uplift events in the latest Cretaceous and late Miocene. More broadly, these results indicate that nonequilibrium landscapes can persist for long periods of geologic time, and hence low-relief upland landscapes do not necessarily indicate late Cenozoic surface uplift.

Keywords: Sierra Nevada; paleoaltimetry; bedrock channel erosion; numerical modeling

1. Introduction

In the past few years, stable-isotopic and geomorphic approaches have been used to infer the Cenozoic surface uplift history of the Sierra Nevada of California (e.g. Poage and Chamberlain, 2002; Clark et al., 2005b; Mulch et al., 2006), the Himalaya and southern Tibet (e.g. Clark et al., 2005a, 2006; Currie et al., 2005; Grujic et al., 2006), and the central Andes (e.g. Ghosh et al., 2006; Barke and Lamb, 2006). In some cases, strong arguments exist both for and against late Cenozoic surface uplift for a particular region. In the Sierra

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Nevada, for example, the presence of a slowly eroding plateau perched 1.5 km above narrow river canyons suggests late Cenozoic surface uplift of ~1.5 km in the southern part of that range (Clark et al., 2005b). Stable-isotope paleoaltimetry of Eocene gravels (Mulch et al., 2006), however, imply that the northern Sierra Nevada achieved an elevation of at least 2.2 km by Eocene time. These results are not necessarily contradictory since they represent different parts of the range, but they require distinctly different Cenozoic surface uplift histories in the northern and southern Sierra Nevada in order to be reconciled.

Three additional lines of geomorphic evidence suggest that significant late Cenozoic rock uplift occurred throughout the Sierra Nevada, bolstering the claim for widespread late Cenozoic surface uplift. Unruh (1991) documented 1.4° of post-late-Miocene westward tilting of the northern Sierra Nevada based on the stratigraphy of the Great Valley. Huber (1981, 1990) documented approximately 700 m of stream incision/rock uplift along the mainstem San Joaquin and Tuolumne drainages (southern and central Sierra Nevada) since 10 Ma. Wakabayashi and Sawyer (2001) extended Huber's work to drainages in the northern Sierra Nevada, documenting as much as 1 km of late Cenozoic (<10 Ma) incision but limited Eocene–Miocene incision in drainage headwaters. These authors argued that stream incision and surface uplift are equivalent near the crest of the range because of the low cosmogenic erosion rates measured there (i.e. ~0.01 mm/yr). Stock et al. (2004, 2005) dated cave sediments cosmogenically to document a pulse of relatively high channel incision rates (~0.3 mm/yr) between 1.5 and 3 Ma in the South Fork Kings River and nearby drainages of the southern Sierra Nevada. The broad geographic range of these studies clearly indicates that significant late Cenozoic rock uplift occurred throughout the range. Similarity in the large-scale topographic form of the northern and southern Sierra Nevada (i.e. both have asymmetric profiles with steep eastern escarpments and gently dipping western slopes), as well as similar Cenozoic exhumation rates (Cecil et al., 2006), suggest that the northern and southern Sierra Nevada may have undergone similar surface uplift histories. Nevertheless, the northern and southern parts of the range have significant structural differences: the northern Sierra Nevada is a west-dipping tilt block, while deformation within the southern Sierra Nevada is accommodated on a series of normal faults (Clark et al., 2005b).

Despite extensive research, the relationship between rock uplift and surface uplift in the Sierra Nevada remains uncertain for two reasons. First, surface uplift triggers knickpoint retreat along mainsteam rivers, but the time lag between incision at the range front and incision tens of kilometers upstream is not well constrained. Thermochronologic data have been collected from many sites (e.g. House et al., 1997, 1998, 2001; Clark et al., 2005b; Cecil et al., 2006), but the westernmost samples are located approximately 30 km from the range front. In the southern part of the range, these data provide a 32 Ma maximum age for the onset of stream incision at sample localities. Range-wide surface uplift could have occurred significantly earlier than 32 Ma, however, given the time that may have been required for knickpoints initiated at the range front to propagate 30 km or more upstream. Knickpoint retreat rates of 1 m/kyr, for example, would result in a 30 Myr time lag between range-wide surface uplift and knickpoint passage at westernmost sample localities. Second, rock uplift, stream-incision, and local surface uplift can all occur in the absence of range-wide surface uplift. As stream incision removes topographic loads from the crust, for example, isostatic rebound raises slowly eroding upland plateau remnants to elevations much higher than the original, regionally extensive surface. As such, no simple relationship exists between the timing of local surface uplift and range-wide surface uplift.

The goal of this paper is to evaluate hypotheses for range-wide surface uplift of the southern Sierra Nevada and to refine our understanding of the spatial and temporal distribution of uplift and erosion using numerical landscape evolution modeling. This paper focuses on the southern Sierra Nevada because of the limited impact of Plio-Quaternary glaciation in valleys of this part of the range (Clark et al., 2005b). Cosmogenic erosion rate studies provide key constraints on numerical model parameters, enabling the relationship between specific uplift histories and the topographic evolution of the range to be uniquely determined, including the effects of transient knickpoint migration and flexural-isostatic response to erosion. In the next section I review key aspects of the geomorphology and geochronology of the southern Sierra Nevada that provide calibration or validation data for the numerical model.

2. Geomorphology and rates of landscape evolution in the Sierra Nevada

Two distinct topographic surfaces have long been recognized in the southern Sierra Nevada (Webb, 1946) (Fig. 1). The Boreal Plateau is a high-elevation, low-relief surface that dips to the west at 1° (Fig. 1B). The Chagoopa Plateau is an intermediate "bench" surface,