Pace of landscape evolution in the Sierra Nevada, California, revealed by cosmogenic dating of cave sediments

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ABSTRACT

We report $^{26}Al/^{10}Be$ based ages of Sierra Nevada caves that constrain detailed late Pliocene and Quaternary river incision histories for five river canyons. Rapid incision of ~0.2 mm/yr from 2.7 to ca. 1.5 Ma slowed markedly to ~0.03 mm/yr thereafter, likely reflecting the combined effects of a transient erosional response to Pliocene rock uplift and periodic mantling of riverbeds with glacially derived sediment in the late Quaternary. While ~400 m of incision has occurred in the past 2.7 m.y., outpacing interfluve erosion and thereby increasing the local relief, canyons as deep as 1.6 km existed prior to that time. These new erosion rates strengthen the case for tectonically driven late Cenozoic uplift.

Keywords: caves, cosmogenic dating, bedrock incision, landscape evolution, Sierra Nevada.

INTRODUCTION

Recent geologic data have polarized the debate about whether the Sierra Nevada underwent late Cenozoic (ca. 10 Ma to the present) uplift. This debate has suffered from a lack of landscape erosion rates, particularly from the rugged southern Sierra Nevada. We report new erosion rates that link many of the previous data sets and inspire new conceptual models of the late Cenozoic topographic evolution of the range.

The present Sierra Nevada is a west-tilted block with a relatively uniform western slope and a steep normal-faulted escarpment east of the crest (Fig. 1). Study of ancient river channels, volcanic flows, and tilted Central Valley strata suggests ~1.5–2.5 km of rock uplift at the crest over the past 10 m.y., most of the uplift occurring in the past 3–5 m.y. (Huber, 1981; Unruh, 1991; Wakabayashi and Sawyer, 2001). Renewed river incision in the range and accelerated sedimentation in the adjacent Central Valley around this time support these conclusions (Wakabayashi and Sawyer, 2001).

Two mechanisms have been suggested to explain this uplift. The first calls upon the flexural isostatic response to accelerated erosion impelled by late Cenozoic climate change. Modeling of the erosional unloading of the range and simultaneous sediment deposition in the Central Valley suggests that roughly half to all of the observed tilt could be explained by a climatic mechanism (Small and Anderson, 1995). Several lines of evidence have since emerged that support a tectonic mechanism. The southern Sierra Nevada lacks a deep crustal root, implying that the modern topography must instead be compensated primarily by density variations in the mantle (Wernicke et al., 1996). Changes in xenolith composition (Ducea and Saleeby, 1998) and magma chemistry (Manley et al., 2000; Farmer et al., 2002) indicate delamination of an eclogite root from beneath the eastern Sierra Nevada between 3 and 10 Ma. Loss of a 10–40-km-thick root and its replacement with asthenosphere could drive the proposed 1–2 km of crestal uplift (Ducea and Saleeby, 1996).

Low-temperature geochronology studies suggest that the southern Sierra Nevada had high elevations and relief as early as the Late Cretaceous, when the range was an active volcanic arc (House et al., 1998, 2001). The $\delta^{18}O$ in authigenic minerals east of the Sierra Nevada crest suggests a persistent rain shadow throughout the Miocene (Poage and Chamberlain, 2002), indicating that elevations were high then as well. These data have been used to argue for a monotonic decline in mean elevation and local relief through the Cenozoic, implying no recent uplift.

We note that these data are not necessarily at odds. Tectonically driven rock uplift, such as that incited by delamination, would rejuvenate incision in pre-existing canyons, resulting in further flexural isostatic uplift. The late Cenozoic depth history of Sierra Nevada river canyons can therefore help to clarify these models of Cenozoic topographic evolution.

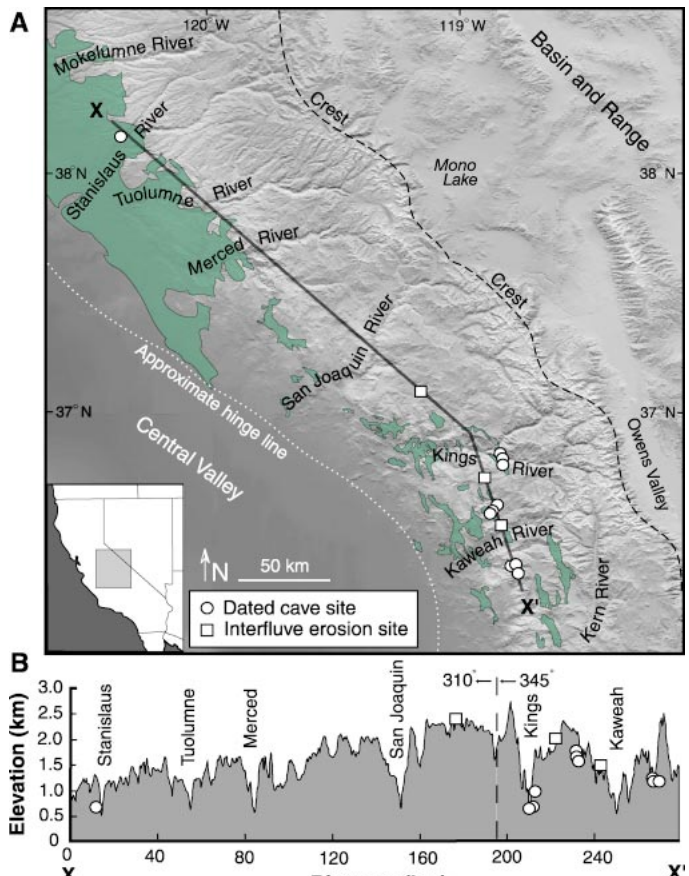

Figure 1. A: Geologic and topographic setting of Sierra Nevada. Highly fragmented Paleozoic and Mesozoic metamorphic belt containing cave-bearing marble (green) bounds predominantly Cretaceous granitic rocks of Sierra Nevada Batholith. Line X–X′ delineates study transect. Lack of marble and suitable caves between Tuolumne and San Joaquin Rivers limits incision estimates in this region. B: Topographic profile along X–X′. Mean elevation and local relief increase systematically south of Stanislaus River, reaching maximum in vicinity of Kings River.

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DETERMINING RATES OF RIVER INCISION

Fluvial terraces are scarce in Sierra Nevada canyons, so previous estimates of river incision have been deduced from remnants of late Cenozoic volcanic flows emplaced in ancient river canyons that now stand high as meandering tablelands. In the San Joaquin River canyon, such flows yield maximum incision rates of 0.09 mm/yr for the period 10–3.5 Ma, and 0.13 mm/ yr for the period 3.5 Ma to the present (Huber, 1981; Wakabayashi and Sawyer, 2001). In northern canyons, ca. 5 Ma andesitic flows of the uppermost Mehrten Formation provide incision rates averaging ~0.15 mm/yr (Wakabayashi and Sawyer, 2001). The lack of widespread volcanic deposits in the southern Sierra Nevada has prohibited estimates of late Cenozoic incision rates in this region.

There are numerous caves in canyons cut in marble bedrock within a belt of metamorphic rocks flanking the western edge of the batholith. These caves delineate a northwest-trending study transect across the central and southern Sierra Nevada, through the middle reaches of the major river canyons (Fig. 1). Caves can record river incision because many are former river levels etched into bedrock. As the elevation of the most deeply incised river defines the local water table, sinking streams flowing through fractured carbonate rock dissolve caves that are graded to river level (Palmer, 1991). Alternatively, a portion of the river is sometimes diverted into the canyon wall, forming cave passages parallel to the river. Bedload sediment is often deposited in either type of passage. Subsequent incision of the river through bedrock lowers the river relative to the caves, leaving sediment-laden passages perched high in canyon walls. A vertical sequence of cave passages is therefore analogous to a flight of strath terraces. Sediments shielded within bedrock hillslopes can be much longer lived than such terraces; cave sediments millions of years old are often exquisitely preserved.

BURIAL DATING OF CAVE SEDIMENTS

We dated caves using the ratio of cosmogenic ^{26}Al and ^{10}Be concentrations in buried sediments (Lal, 1991; Granger et al., 1997, 2001; Granger and Muzikar, 2001). Sediment accumulates ^{26}Al and ^{10}Be during exhumation from hillslopes and transport through river systems. While the nuclide production rates vary in space and time, ^{26}Al is always produced ~6 times faster than ^{10}Be, setting the inherited $^{26}Al/^{10}Be$ ratio in sediments to ~6. Burial of sediment >20 m in caves prevents further nuclide production, and the $^{26}Al/^{10}Be$ ratio declines as the ^{26}Al ($\tau_{26} = 1.02 \pm 0.04$ m.y. [Norris et al., 1983]) decays about twice as fast as the ^{10}Be ($\tau_{10} = 2.18 \pm 0.09$ m.y. [Hofmann et al., 1987]). The $^{26}Al/^{10}Be$ ratios may be used to determine sediment burial ages over 0.1–5 m.y. (Granger and Muzikar, 2001).

We collected 15 granitic bedload sediment samples from 10 caves in 5 river canyons (Fig. 1). We isolated ^{26}Al and ^{10}Be using the techniques of Granger et al. (2001) (Appendix 1[1]) and measured them by accelerator mass spectrometry at Lawrence Livermore National Laboratory.

RESULTS

Cave sediment burial ages extend back 2.7 m.y. and, as expected, increase with elevation above modern rivers (Fig. 2; Table DR1 [see footnote 1]). Long-term average incision rates deduced from the oldest caves (~0.12 mm/yr) are similar to those reported from northern and central Sierra Nevada rivers (Wakabayashi and Sawyer, 2001). Furthermore, an incision rate of 0.15 mm/yr averaged over 2.7 m.y. from the South Fork Kings canyon closely matches a 5 m.y. average rate of 0.13 mm/yr from an equivalent upstream position in the San Joaquin canyon.

[1]GSA Data Repository item 2004032, Table DR1, Table DR2, and Appendix 1, methods, is available online at www.geosociety.org/pubs/ft2004.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, Colorado, 80301-9140, USA.

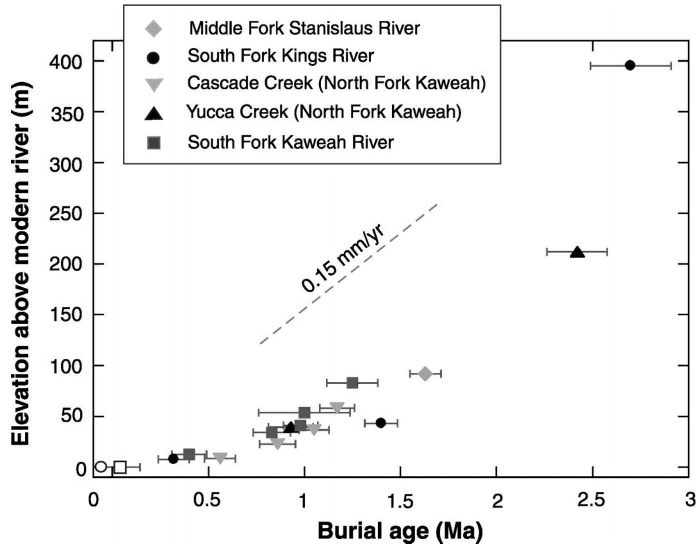

Figure 2. River incision history from Sierra Nevada caves. Modern river sediment, shown by open symbols, yield burial ages indistinguishable from zero, so there appears to be no inherited burial signal in cave sediments. Change in incision rate ca. 1.5 Ma is evident across study transect. Dashed line denotes 5 Ma average rangewide incision rate (Wakabayashi and Sawyer, 2001). Errors are 1σ analytical uncertainty.

In the South Fork Kings (Fig. 3) and Yucca Creek canyons, tiered caves in the canyon walls reveal that high incision rates of ~0.2 mm/yr from 2.7 to 1.5 Ma markedly declined to ~0.03 mm/yr thereafter (Fig. 2). In all other canyons, caves younger than 1.5 Ma also reveal low incision rates of 0.02–0.05 mm/yr, considerably lower than the range-wide long-term rate (Wakabayashi and Sawyer, 2001).

PACE OF LANDSCAPE EVOLUTION

The caves provide snapshots of the landscape as it evolved toward its present form. For example, the depth of the South Fork Kings canyon prior to 2.7 Ma was at least 1600 m, the distance from the highest dated cave to the adjacent north rim of the canyon (Fig. 3A). Caves in other drainages also show that substantial (400–1100 m) local relief was present when the caves formed, in accord with work reporting high relief in the southern Sierra Nevada prior to the late Pliocene (Huber, 1981; Wakabayashi and Sawyer, 2001; House et al., 1998, 2001). We do not know when rapid incision began at the cave sites, only that it had started by 2.7 Ma. If rapid incision, driven by rock uplift, began at 3.5 Ma (Manley et al., 2000) or 5 Ma (Unruh, 1991; Wakabayashi and Sawyer, 2001), then only a small fraction of the present relief was produced in response to late Cenozoic uplift. Considering reported low Eocene to Miocene sedimentation rates (Wakabayashi and Sawyer, 2001), much of the present relief may be relict from the Late Cretaceous.

Some researchers have posited that high relief produced in the Late Cretaceous declined monotonically during the Cenozoic (House et al., 1998, 2001), implying that interfluve erosion always outpaces river incision. A late Cenozoic pulse of river incision, however, could lead to an increase of relief. In order to discriminate between these scenarios, we measured interfluve erosion rates using concentrations of ^{26}Al and ^{10}Be (Lal, 1991) in granitic rocks exposed along the study transect (Fig. 1). On average, these interfluves are eroding at 0.012 mm/yr averaged over ~75 k.y. (Table DR2; see footnote 1). These rates are comparable to rates measured on the Sierra Nevada crest and in other alpine environments over equivalent time scales (Small et al., 1997), and are more than an order of magnitude lower than late Pliocene to early Quaternary incision rates. They remain a factor of two

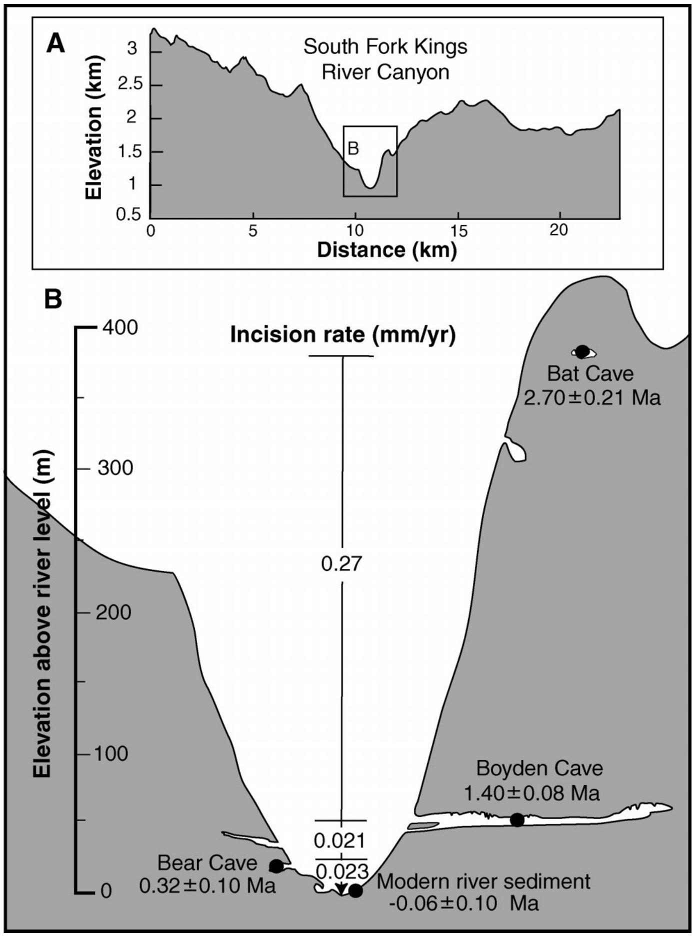

Figure 3. Cave-derived river incision rates in South Fork Kings River canyon. A: Topographic profile across South Fork Kings River canyon in vicinity of Boyden Cave. Note ~2 km local relief. B: Inner gorge of South Fork Kings River canyon, containing suite of dated caves preserved by exceptionally steep canyon walls. These caves reveal order of magnitude decline in incision rate toward present. While oldest cave demonstrates 400 m of canyon cutting in past 2.7 m.y., larger context shown in A shows that this represents only ~20% of present local relief.

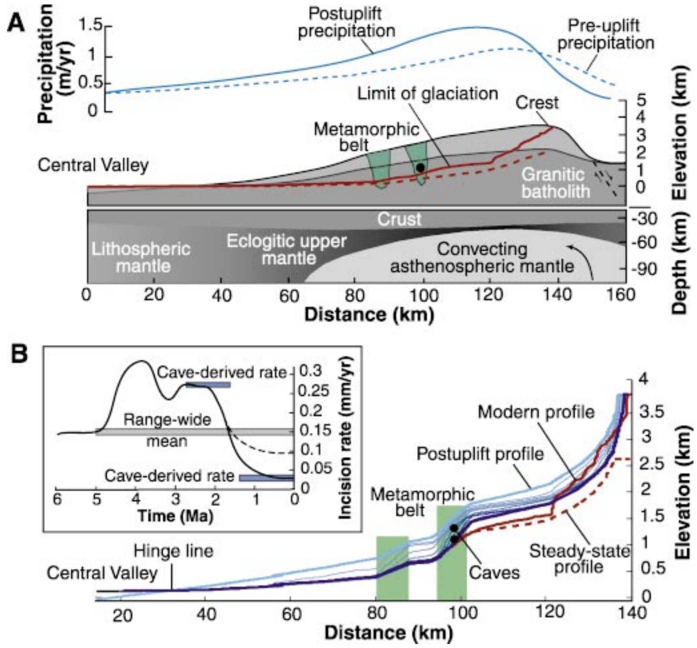

Figure 4. Response of South Fork Kings River to late Cenozoic tectonic and climatic events. A: Conceptual model of late Cenozoic uplift. Westward tilting steepens pre-uplift surface (dark gray) and river profile (dashed red); surface uplift increases orographic precipitation on western slope of range and enhances rain shadow to east. Thin crust beneath range crest (Wernicke et al., 1996) likely reflects delamination of batholithic root (Ducea and Saleeby, 1998). B: Example of stream power-based numerical simulation. Steady river profile (dashed red) with steps corresponding to quartzite in two metamorphic belts is subjected to ~1.5 km of crestal uplift. 1 m.y. profiles (blue) show that over next 9 m.y., wave of rapid incision begins at hinge line and propagates up profile. Inset shows 6 m.y. incision history at cave site; wave of rapid incision passes between ca. 5 and 2 Ma, followed by return to low pre-uplift rates (dashed curve after 2 Ma). Further reduction in late Quaternary rates (solid curve after 2 Ma) reflects sediment mantling of bed associated with large glaciers in headwaters. Final modeled river profile (purple) fits modern profile (red) to just upstream of cave site, above which glacial erosion, not represented in our river incision rule, has dominated past few million years.

to three less than late Quaternary incision rates. As our erosion rate measurements are averaged over glacial-interglacial transitions, they are likely representative of Quaternary rates. Furthermore, climatic effects on granitic weathering rates in the Sierra Nevada appear to be negligible (Riebe et al., 2001). If correct, then local relief along the study transect, already substantial in the middle Pliocene, was enhanced by rapid river incision in the late Pliocene and early Quaternary; the inner gorges that characterize many southern Sierra Nevada canyons (e.g., see Fig. 3) probably formed during this time.

Our findings of considerable pre-Quaternary relief and low interfluve erosion rates place new limits on the amount of flexural isostatic rock uplift impelled by late Cenozoic erosion. Our erosion rates are less than those used in flexural isostatic models (Small and Anderson, 1995), suggesting that late Cenozoic erosion alone is insufficient to drive all of the rock uplift inferred from tilted markers. This diminishes the climatic effect on uplift, strengthening the case for tectonically driven uplift.

TEMPORAL PATTERN OF RIVER INCISION

River incision rate changes at a point can reflect any combination of the temporal rock uplift pattern, a transient erosional response to rock uplift, and/or climatically driven changes in river discharge and sediment supply. Only in the absence of these events do incision rates scale linearly with rock uplift rates. In order to illuminate the complex response of rivers to tectonic and climatic perturbations, we constructed stream power-based numerical models of river profile evolution (Appendix 1; see footnote 1). Bedrock incision is commonly taken to be proportional to stream power, the product of river slope and river discharge (e.g., Whipple and Tucker, 1999). Therefore, both tectonic uplift and climate change can cause changes in river incision rates. The two mechanisms are linked through a set of positive feedbacks. For example, surface uplift of the Sierra Nevada crest would increase orographic precipitation (Roe et al., 2002), river discharge, and bedrock incision on the western slope, which in turn would drive further flexural isostatic uplift (Fig. 4A).

Numerical models incorporating these feedbacks indicate that tilting necessary to drive 1–2 km of crestal uplift should initiate a wave of erosion that begins at the mountain front and propagates upriver (Fig. 4B). Discrete points along the profile, such as those marked by caves, should undergo rapid incision as the knick zone sweeps by, followed by a return to slower rates. We find that the temporal pattern of incision as recorded by the caves is well modeled as a transient erosional response to late Cenozoic rock uplift (Fig. 4B). However, the modeled late Quaternary incision rates are higher than those we document from the caves, suggesting that an additional mechanism has acted to inhibit incision.

One possible mechanism may involve the initiation of major global glaciation ca. 2.5 Ma. Study of the Kings River alluvial fan indicates that rapid aggradation occurred in response to higher sediment supply during glaciations (Weissmann et al., 2002). Significant aggradation would armor riverbeds against bedrock incision (e.g., Sklar and Dietrich, 2001), and incision could not resume until the sediment was excavated during interglacials (Hancock and Anderson, 2002). The onset of Pleistocene glaciation might therefore be expected to reduce long-term bedrock incision rates. Furthermore, the transition from 41 k.y. glacial cycles to 100 k.y. cycles ca. 1 Ma (Clark et al., 1999) was associated with an increase in the magnitude of glaciations, presumably increasing aggradation. Incorporating in the model a progressive increase in bed armoring during the Quaternary produces the low incision rates shown by the caves (Fig. 4B inset). Our preliminary model results therefore suggest that the profile evolution recorded by the caves reflects both a transient erosional response to late Cenozoic uplift and sediment armoring of the bed associated with Quaternary glaciations.

SUMMARY

The detailed 2.7 m.y. incision history revealed by the caves, along with the measured interfluve erosion rates, suggests the following history of Cenozoic topographic evolution. The Sierra Nevada grew during arc volcanism in the Cretaceous. As volcanism waned in the Late Cretaceous, erosion reigned, leading to rapid sedimentation in the Central Valley (Wakabayashi and Sawyer, 2001). During this time the southern Sierra Nevada likely displayed substantial (>1.5 km) local relief (House et al., 1998, 2001); remnant topography persisted in this region well into the Miocene (Poage and Chamberlain, 2002).

Following a long period of topographic decay through the mid-Cenozoic, the eclogitic root beneath the crest delaminated from 3 to 10 Ma (Ducea and Saleeby, 1998; Manley et al., 2000). This incited rock uplift (Huber, 1981; Unruh, 1991; Wakabayashi and Sawyer, 2001) in a pattern that steepened the gradients of westward-flowing rivers. These rivers responded in a wave of incision that propagated upriver from the edge of the Central Valley, deepening preexisting canyons. Incision in the marble belt reached its maximum rate as the wave of rapid incision passed from 5 to 2 Ma. In the southern Sierra Nevada, local relief increased as river incision outpaced interfluve erosion. Following passage of the knick zone, incision rates slowed considerably. As major late Quaternary glaciers etched the high Sierra Nevada, the sediment they produced mantled the riverbeds, further reducing incision rates. We conclude that the Sierra Nevada is currently in the midst of a transient geomorphic response to recent renewed uplift.

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