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12. T. M. Scott in "The Plio-Pleistocene stratigraphy and paleontology of southern Florida," T. M. Scott and W. D. Allmon, Eds. (Spec. Publ. 36, Florida Geological Survey, 1992), pp. 21–25. The terms Pinecrest Beds, Caloosahatchee Formation, Bermont Formation, and Fort Thompson Formation were never formally proposed as lithostratigraphic units but are, in actuality, simply faunizones. In anticipation of a formal biozonational scheme for southern Florida, I have adopted a transitional nomenclature, referring to the previous "formations" as "faunas" within Scott's proposed "Okeechobee Formation" and within a redefined Tamiami Formation. With this scheme, the Sarasota Unit, Buckingham "Formation," the Ochopee "Member," and the Pinecrest Beds are included within the Tamiami Formation, and the Caloosahatchee "Formation," Griffin Pit Unit, Holey Land Unit, Bermont "Formation," and Fort Thompson "Formation" are included in the new Okeechobee Formation.
13. Although Allmon *et al.* (*8*) included the Pinecrest Beds as a single faunal unit, chronologically equivalent to the Caloosahatchee and Bermont Formations, recent geochronological data [D. S. Jones *et al.*, *J. Geol.* **99**, 637 (1991)] and faunal analyses (*10*) have shown that the Pinecrest Beds contain three separate sequential faunas and that the total unit is chronologically three times as large as either the Caloosahatchee, Bermont, or Fort Thompson faunizones. As shown in (*10*), Pinecrest Beds unit 10 (and the thinner units 8 and 9) contains a base set of species (essentially the same fauna as contained in the "*Ecphora* zone" of the Jackson Bluff Formation of northwestern Florida), whereas Pinecrest Beds unit 7 (and the thinner units 5 and 6) contains a separate suite of species descended from the unit 10 fauna, and Pinecrest Beds unit 3 (and also units 4 and 2) (this fauna has also been collected in the Mule Pen quarry in Naples, Collier County, Florida) contains yet another separate suite descended from the unit 7 fauna. The highly endemic Kissimmee River valley fauna is here included with the stratigraphically equivalent Pinecrest Beds.
14. On the basis of (*10*, *13*), Pinecrest Beds unit 10 is now dated at 3.5 Ma, Pinecrest Beds unit 7 at 3 Ma, Pinecrest Beds unit 3 at 2.5 Ma, the Caloosahatchee and Griffin Pit faunas at 1.5 to 2 Ma, the Bermont fauna at 1 Ma, and the Fort Thompson Fauna at 150,000 years before present.
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Geomorphically Driven Late Cenozoic Rock Uplift in the Sierra Nevada, California

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Geologists have long accepted that the Sierra Nevada, California, experienced significant late Cenozoic tectonically induced uplift. A flexural-isostatic model presented here shows, however, that a large fraction of the primary evidence for uplift could be generated by the lithospheric response to coupled erosion of the Sierra Nevada and deposition in the adjacent Central Valley and therefore requires less tectonic forcing than previously believed. The sum of range-wide erosion and the resultant isostatic rock uplift would have lowered Sierra mean elevation by 200 to 1000 meters since 10 million years ago and could also have increased summit elevations during the current period of relief production.

For a century, geologists have thought that the Sierra Nevada (Sierra) crest (Fig. 1) has been uplifted about 2000 m by tectonic forces in the late Cenozoic (*1*–*3*). This uplift event is enigmatic because it occurred 100 million years after arc-related crustal thickening in the Sierra (*4*). England and Molnar (*5*) proposed that much evidence used to infer mountain uplift, similar to that reported for the Sierra, may actually reflect either exhumation or isostatically driven rock uplift rather than tectonically driven surface uplift. In addition, they hypothesized (*6*) that much of the data interpreted as evidence for late Cenozoic uplift events could instead have been generated by global cooling, thereby challenging proposals that the reputed late Cenozoic uplift had caused global cooling (*7*).

Surface uplift is the change in mean elevation with respect to the geoid averaged over $>10^3$ km^2, rock uplift is displacement of individual points (rocks) with respect to the geoid, and exhumation is displacement of points with respect to the surface (*5*). These terms are related: surface uplift equals rock uplift minus exhumation. Rock uplift can be driven by tectonic forcing or by the isostatic response to exhumation. Before using any geologic data to constrain the amount of surface uplift attributable to tectonic forcing, one must first assess how much of this geologic signal was generated by exhumation and the resultant isostatically driven rock uplift. Here, we quantify what fraction of the evidence for late Cenozoic Sierra uplift was produced by these latter processes.

The primary evidence previously used to calculate the magnitude and timing of Sierra uplift was the westward tilt of markers (Fig. 2) (*1*–*3*), including stratigraphic horizons in the eastern Great Valley sedimentary sequence and abandoned fluvial channels filled with dated volcanic flows and alluvium along the western Sierra margin. Most studies, as well as our own, have focused on uplift north of 36.5°N because tilted markers do not exist farther south (Fig. 1). In previous studies, crestal uplift was calculated by simple linear projection of tilted markers to the crest (Fig. 2). Four assumptions were made in these studies: (i) the Sierran block rotated rigidly, (ii) there was a constant hinge line position, (iii) all tilt exceeding modern stream gradients indicates deformation, and (iv) there was no erosion (*2*, *3*). The last assumption was not explicitly stated. The tilt rate deduced from stratigraphic markers more than doubles 3 to 4 million years ago (Ma); this observation lead researchers to argue for accelerated uplift toward the present (*2*). Huber (*2*) calculated about 2000 m of crestal uplift since 10 Ma, with 1000 m of this uplift occurring since 3 Ma. This crestal uplift corresponds to a 1000-m increase in mean elevation (surface uplift) since 10 Ma if all four of these assumptions are valid. Secondary evidence used to argue for late Cenozoic uplift comes from studies of paleobotany (*8*), sediment provenance (*9*), and the depletion of deuterium in Great Basin ground water (*10*).

The tilt of western Sierra geologic markers unambiguously records differential rock uplift, with greater rock uplift occurring within the Sierra than in the adjacent Central Valley. Rock uplift could have been driven by tectonic forcing or by the isostatic response to geomorphic forcing, or both. Tilt observed at the western Sierra margin can be used to quantify tectonically driven surface uplift of the range only in the absence of exhumation (*5*), that is, when surface uplift equals rock uplift. Previous researchers have implicitly assumed that tilt indicates differential surface uplift and, therefore, that it is both tectonic in origin and has increased Sierra mean elevation. Several time-dependent tectonic mechanisms have been proposed to explain the accelerating increase in mean elevation

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since 10 Ma (*11*). Debate about these mechanisms continues (*12, 13*). We hypothesize that a large fraction of the westward tilt of markers, and therefore of the differential rock uplift this tilt represents, is instead the product of upward forcing from erosion to the east and downward forcing from deposition to the west of these markers. This erosion and deposition (geomorphic forcing), and the resultant flexural-isostatic response, would certainly have lowered the mean elevation and would possibly have increased the maximum elevation of the range.

The same rock uplift that tilted markers could also have increased summit elevations. The elevation at any point will increase if erosion is slower than rock uplift, regardless of whether rock uplift is driven by erosion or tectonics. Lithospheric rigidity distributes the response to loading over a horizontal distance of 10 to 100 km; therefore, summit elevations will increase if upward lithospheric deflection from regional erosion (unloading) exceeds lowering of peaks by local erosion.

Many Sierra peaks appear to be eroding more slowly than the surrounding landscape. If true, then peak elevations could be increasing as a result of regional erosional unloading. The Sierra crest is dotted with summit flats (Fig. 1) that display slopes <10° and show no evidence of erosion by the fluvial or glacial processes that have been active in the surrounding landscape. Instead, periglacial creep is the dominant geomorphic process (*14*). The erosion of flats appears to be limited by the slow rate (*15*) at which bedrock weathering produces material transportable by this creep. Erosionally driven rock uplift only increases peak elevations during intervals of relief production, that is, when summits erode more slowly than valleys. Although it appears that Sierran relief is currently increasing because summits are capped by slowly eroding flats, no evidence suggests that flats and associated relief production have existed since 10 Ma. Because the history of relief production is unknown, we modeled the rate at which peak elevations are currently increasing as a result of erosional unloading.

We explored what fraction of the measured tilt of 10-million-year-old geologic markers could be due to the lithospheric response to geomorphic forcing. Any remaining tilt requires tectonic forcing. In our calculations, we used a one-dimensional flexural-isostatic model similar to that used in many recent studies (*16*), with loading constrained by measured Central Valley deposition and less well known magnitudes and patterns of Sierra erosion. Because the magnitude and timing of tilt is similar along the axis of the Sierra north of 36.5°N (*3*), we compared our calculated tilt to the measured tilt of a 10-million-year-old lava-filled San Joaquin River paleochannel (*2*) (Fig. 1). We also tracked changes in mean and maximum elevation along a model swath, $<z>(x)$ and $z_{max}(x)$, and changes in mean elevation over the entire model swath, $<z>_{SN}$ (*17*). Because only changes in elevation were modeled, our results are independent of both present and past topography.

The geomorphic forcing in our model has four components, of which we varied the latter three (Fig. 3): (i) Central Valley deposition, (ii) mean erosion rate, $<\varepsilon>_{SN}$, within our model swath, (iii) pattern of mean erosion rates along the swath, $<\varepsilon>(x)$, and (iv) summit flat erosion rate ε_s. Central Valley well data were used to determine sediment thickness above an 8-million-year-old marker horizon (Fig. 3A) (*18*). We then converted this sediment thickness to a 10-million-year depositional load by assuming no deposition between 8 and 10 Ma (yielding a minimum estimate of loading during this period and, hence, a minimum estimate of related tilt), and by converting sediment thickness to rock mass using porosity-depth relations (Fig. 3B) (*19*). Apatite fission track studies indicate that $<\varepsilon>_{SN}$ over the past 15 to 30 million years has been 0.07 to 0.20 mm year^{-1} (*20*). Estimates of erosion rates from sediment mass balance and geobarometry studies in the Sierra, and from a global denudation-relief relation, support this range of values over time scales from 100 to 100 million years (*21*). We varied $<\varepsilon>_{SN}$ beyond the range suggested by these studies to illustrate fully the relation between tilt and erosional unloading. The crossing of modern and paleochannels indicates minor mean erosion at the western Sierra margin. Because no other constraints on the range-normal pattern of mean erosion rates exist, a boxcar erosional load that tapers to zero at the western range margin was used (Fig. 3B). We examined the sensitivity of our results

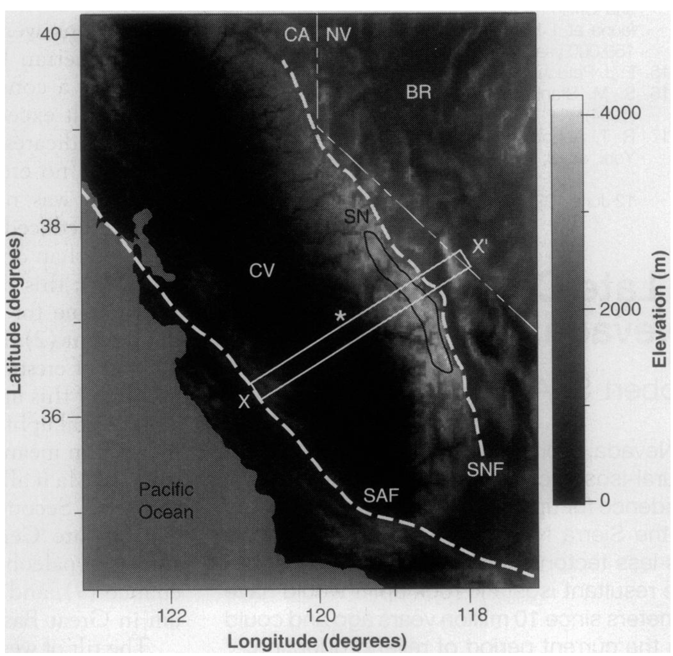

Fig. 1. Sierra Nevada topography from 30″ digital elevation model (DEM) data. The Sierra Nevada (SN) is separated from the Basin and Range (BR) province on the east by the Sierra Nevada fault system (SNF). The Central Valley (CV) bounds the Sierra on the west. Central Valley deposition does not constrain Sierra erosion because the valley has not been a closed basin continuously since 10 Ma (*31*) and has received sediment from both the Sierra and the Coast Ranges to the west. Mean and maximum elevations along a 20-km-wide range-normal swath (X-X′), from the San Andreas fault (SAF) into the Basin and Range, are shown in Fig. 3A. Tilted stratigraphic horizons and abandoned fluvial channels are common along the western Sierra margin north of 36.5°. The asterisk (*) denotes the 10-Ma San Joaquin River paleochannel. Summit flats are common at the Sierra crest (outlined area).

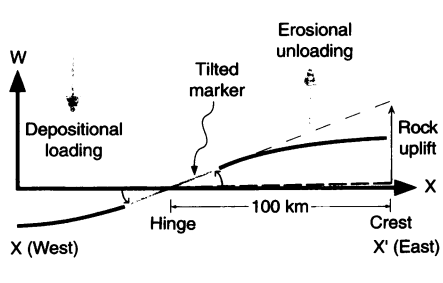

Fig. 2. Schematic of both our hypothesis for the origin of tilt of Sierra geologic markers and the method used by previous researchers to calculate uplift of the Sierra crest, after (*2*). The 10-Ma San Joaquin River paleochannel (gray line labeled "Tilted marker") is tilted 25 m/km, whereas the present stream gradient is 1 m/km through this area (thick dashed line) (*2*). Previous researchers linearly projected markers to the crest of the range to calculate uplift (thin dashed line), assuming rotation of a nearly horizontal line (thick dashed line). Upward forcing from erosion to the east and downward forcing from deposition to the west (large arrows) of markers located at the hinge line could produce the observed tilt. The resulting deformation pattern, *w*(*x*), is shown (solid line) for a case with reas onable flexural rigidity.

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to three other mean erosion rate patterns (Fig. 3B). Sierra summit flats and ridgetops across the range are not datums that constrain either the magnitude or pattern of mean erosion since 10 Ma because their age and erosional history are unknown. The 10-Ma elevations at current summit flat and ridgetop locations could have been above or below the general paleotopography at that time, depending both on the pattern and magnitude of mean erosion, and on the total erosion from present summit flat and ridgetop locations since 10 Ma. As the erosion of summit flats appears to be weathering-limited (*14*), we assumed that ε_s is 0.01 mm year^{-1}, the bare granite weathering rate measured with cosmogenic radionuclides 10 km east of the Sierra crest (*15*).

We modeled the lithospheric response to this geomorphic forcing as that of a thin, uniformly rigid elastic plate overlying a viscous substrate (*22*). The effective elastic thickness, T_e, and the lateral boundary conditions control the lithospheric response to distributed loads. Flexural subsidence modeling indicates that T_e in the southern Central Valley has been about 20 km over the past 10 million years (*18*, *23*). We examined the sensitivity of our results to a range of T_e's bracketing this value and also performed all model runs with the lithosphere both broken and continuous across the Sierra Nevada fault (SNF), representing end-member calculations for how vertical shear and fiber stresses are transmitted across this edge of the Basin and Range province (*24*).

The tilt and elevation changes were calculated by summing erosion and lithospheric deflection, w, at every position along the model swath, x (Fig. 3). Tilted markers exist only where there has been no erosion since the marker was emplaced. Because markers are not eroded, changes in their elevation are due solely to the total local deflection since they were emplaced 10 Ma. It follows that the tilt of a marker is equal to the local gradient in deflection, dw/dx. Markers at the western Sierra margin are tilted up to the east because the deflection gradient is positive in that direction (Fig. 3C). The change in mean elevation at any section along our swath is the sum of the total mean erosion [the product of $\langle\varepsilon\rangle(x)$ with an elapsed time, t, of 10 million years] and the total deflection since 10 Ma at that x position [$\Delta\langle z\rangle(x) = \langle\varepsilon\rangle(x)t + w(x)$] (Fig. 3D). Because eroded crust is less dense than the underlying mantle asthenosphere, the combined effects of mean erosion and deflection lower the mean elevation of the entire swath, $\langle z\rangle_{SN}$. Along the Sierra crest where slowly eroding summit flats exist, the rate of change of maximum elevations is the sum of the local erosion rate, ε_s, and the deflection rate [total deflection divided by the elapsed time (10 million years)] at the crest [$dz_{max}(\text{crest})/dt = \varepsilon_s + w(\text{crest})/t$] (Fig. 3D). Upward deflection from regional unloading is greater than the lowering of summit flats by local erosion, resulting in increases in maximum elevation (Fig. 3D).

Our results show that a large percentage of the observed tilt of 10-Ma geologic markers can be generated solely by geomorphic forcing and the resulting lithospheric response (Fig. 4A). For the expected range of $\langle\varepsilon\rangle_{SN}$ and T_e (gray boxes in Fig. 4), the amount of tilt produced by geomorphic forcing varies from 40 to 140% of that observed. This result suggests that tectonic forcing produced <60%, and perhaps none, of the differential rock uplift recorded by tilted markers. Previous estimates of the amount of tectonic rock uplift therefore

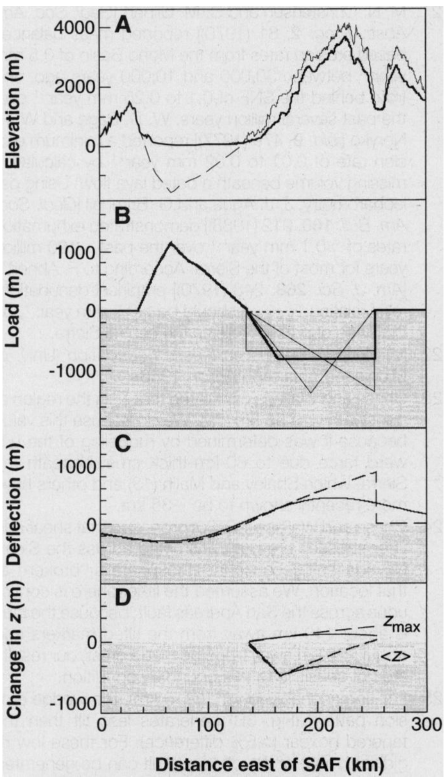

Fig. 3. (**A**) Mean (thick line) and maximum elevation (thin line) along swath X-X′ (in Fig. 1) from 3″ DEM data. The dashed line is the depth of an 8-million-year-old marker horizon in the Central Valley (*18*). (**B**) Thickness of positive depositional load in the Central Valley and of the tapered boxcar erosional load in the Sierra, with density ρ_c = 2700 kg/m^3 (thick line) (*32*). All three other erosion patterns examined (thin lines) and the tapered boxcar have equal mean erosion rates, $\langle\varepsilon\rangle_{SN}$ = 0.07 mm year^{-1} for 10 million years. Where summit flats exist along the swath, local erosion lowers peaks by 0.01 mm year^{-1}, or a total of 30 m if flats have persisted since 3 Ma (dashed line). (**C**) Deflection from tapered boxcar and Central Valley loading in (B) for a continuous (solid line) and broken lithosphere (dashed line) of T_e = 30 km. The density contrast between crust and mantle is −500 kg/m^3 (we assume a mantle density ρ_m of 3200 kg/m^3). The discontinuity is the break at the Sierra Nevada fault. (**D**) Changes in mean elevation ($\langle z\rangle$) for continuous (solid) and broken (dashed) lithosphere as a result of the sum of tapered boxcar erosion in (B) and the lithospheric response to this loading in (C). The sharp trough in mean elevation change (at 160 km) is caused by the corner in the tapered boxcar erosion pattern. Changes in maximum elevation (z_{max}) are due to the sum of summit flat erosion in (B) and deflection from the boxcar load in (C), for summit flats that have persisted since 3 Ma.

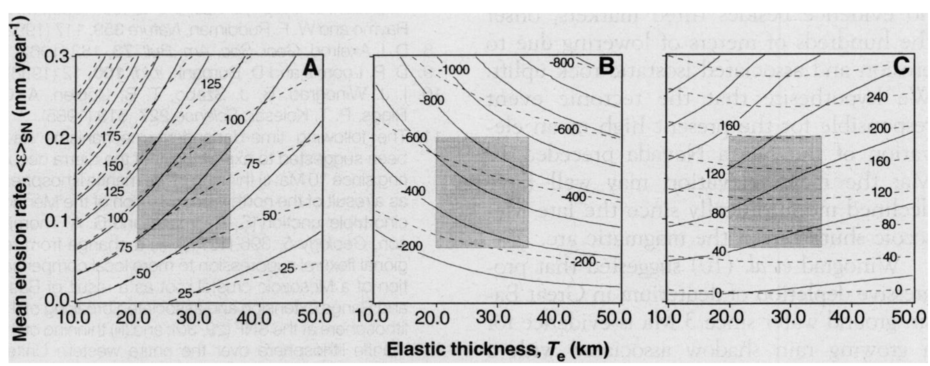

Fig. 4. (**A**) Lines of equal calculated tilt at the western Sierra margin, shown as a percent of observed tilt (*2*), due to geomorphic forcing (tapered boxcar) and lithospheric response over 10 million years, as a function of $\langle\varepsilon\rangle_{SN}$ and T_e. Continuous lithosphere calculations are shown with solid lines, broken lithosphere with dashed lines [same in (B) and (C)]. A value of 100% indicates that the calculated tilt equals the observed tilt of the 10-Ma San Joaquin River channel. Values less than 100% indicate that the calculated tilt is less than the observed tilt. The shaded rectangle represents the most likely values of $\langle\varepsilon\rangle_{SN}$ and T_e for the Sierra since 10 Ma [same in (B) and (C)] (*18*, *20*, *21*). When $\langle\varepsilon\rangle_{SN}$ = 0.0, tilt is driven solely by Central Valley deposition. (**B**) Lines of equal calculated mean elevation change (in meters), $\langle z\rangle_{SN}$, from the sum of modeled erosion and associated rock uplift over 10 million years, as a function of $\langle\varepsilon\rangle_{SN}$ and T_e. Note that all values are negative, indicating that geomorphic forcing would lower the mean elevation since 10 Ma. (**C**) Lines of equal rate of change of maximum elevation (meters per million years) for peaks with slowly eroding summit flats (for $\langle\varepsilon\rangle_s$ = 0.01 mm year^{-1}). All values are positive. For every increase of 0.01 mm year^{-1} in $\langle\varepsilon\rangle_s$, the rate of peak elevation change decreases by 10 m per million years for any combination of $\langle\varepsilon\rangle_{SN}$ and T_e.

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appear to be too high (*1–3*). Even in the extreme minimum case of no Sierra erosion since 10 Ma ($<\varepsilon>_{SN}$ = 0.0 mm year^{-1}), the well-documented Central Valley deposition alone would still have generated about 25% of observed tilt (Fig. 4A). Modeled tilt at the western Sierra margin is similar for both continuous and broken lithosphere cases because markers recording tilt are far enough away from the SNF that the boundary condition applied there does not alter the local deflection pattern (Fig. 3C). Poor constraints on the mean erosion pattern do not detract from our conclusions because modeled tilt is insensitive to the details of this pattern, especially when $T_e \geq 25$ km. Results in Fig. 4 were generated with the tapered boxcar pattern (Fig. 3B), which either produces a minimum estimate of tilt or is within 5% of the minimum, from among the four erosion rate patterns examined for all reasonable $<\varepsilon>_{SN}$ and T_e (*25*).

Concomitant with tilting generated by geomorphic forcing is a 200- to 1000-m decrease in mean elevation of the entire model swath, $<z>_{SN}$, depending on $<\varepsilon>_{SN}$, T_e, and the lateral lithospheric boundary conditions (Fig. 4B). The modeled mean elevation decrease is less for a broken lithosphere because this boundary condition promotes a more local, rather than regional, isostatic response to erosion near the SNF and, hence, results in more rock uplift within the range. The total change in Sierra mean elevation since 10 Ma is the sum of elevation changes from geomorphic and tectonic processes. Therefore, Sierran mean elevation should have decreased over the past 10 million years unless tectonic forcing, for which there is no evidence besides tilted markers, offset the hundreds of meters of lowering due to erosion and associated isostatic rock uplift. We hypothesize that the tectonic event responsible for the present high mean elevation of the Sierra Nevada preceded 10 Ma; the mean elevation may well have declined monotonically since the late Mesozoic shutdown of the magmatic arc.

Winograd *et al.* (*10*) suggested that progressive depletion of deuterium in Great Basin ground water since 3 Ma is evidence for a growing rain shadow associated with a several hundred meter rise in the Sierra crest. Our modeling suggests that the elevations of Sierra peaks capped by slowly eroding flats are currently increasing by 30 to 200 m per million years because of geomorphic forcing and associated isostatic flexure (Fig. 4C). Unlike our tilt calculations, the modeled rate of peak elevation increase is less well constrained because it is sensitive to all input variables, in particular the lithospheric boundary condition at the SNF (*26*). For the continuous lithosphere case, which provides a minimum estimate of peak elevation increase, summit elevations would still have risen 100 to 500 m since 3 Ma (*27*) if the current rate of relief production persisted throughout this interval. It therefore seems plausible that geomorphically driven uplift of the Sierra crest could have produced the intensified orographic effect inferred from Great Basin ground water studies (*10*).

If geomorphic forcing is responsible for a large fraction of the observed tilt since 10 Ma, then accelerated tilt recorded by markers could be due to increased erosion rates rather than intensified tectonic forcing (*2*). The increase in Sierra tilt rate about 3 Ma is roughly coeval with the global cooling event responsible for Northern Hemisphere continental ice sheet growth (*28*). It seems likely that the onset of Sierra alpine glaciation also occurred about 3 Ma. This onset would have enhanced the rates of erosional unloading of the range and associated depositional loading of the Central Valley, producing the accelerated tilt rates recorded by markers. If this scenario is correct, then our results support Molnar and England's (*6*) notion that evidence being used to infer tectonic uplift may instead be an effect of, and hence evidence for, global cooling.

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24. Chase and Wallace (*29, 30*) proposed that shear and fiber stresses are not transmitted across the Sierra Nevada fault because the lithosphere is "broken" at that location. We assumed the lithosphere is continuous across the San Andreas fault; because the fault is about 140 km away from the tilted markers and about 220 km away from the Sierra crest, our results are not sensitive to this boundary condition.
25. For unreasonably low T_e (≤15 km), the wedge erosion pattern (Fig. 3B) generates less tilt than the tapered boxcar (>5% difference). For these low rigidities, most of the observed tilt can be generated by any of the erosion patterns examined (Fig. 4A).
26. Because the Sierra crest is within 10 to 20 km of the SNF, the amount of rock uplift at the crest, and therefore the rate of summit elevation increase, due to erosional unloading for the broken lithosphere case is nearly two times that of the continuous lithosphere case (Fig. 4C).
27. D. R. Montgomery [*J. Geophys. Res.* **99**, 13913 (1994)] calculated that Sierra peak elevations would rise a maximum of 200 m since 10 Ma as a result of erosional unloading. This calculation was not a true maximum for two reasons: (i) his assumed 10-Ma paleotopography was not an envelope at the elevation of the highest peaks, and therefore did not maximize erosional unloading with respect to the highest peaks; and (ii) his use of local isostatic compensation did not allow for the possibility that rapid erosion within the range could have driven elevation increases at the crest.
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