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LATE CENOZOIC UPLIFT OF THE SIERRA NEVADA, CALIFORNIA? A CRITICAL ANALYSIS OF THE GEOMORPHIC EVIDENCE

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ABSTRACT. From the earliest days of California geology, the ramp-like profile of the northern half of the Sierra Nevada mountains and putative signs of recent incision have been interpreted as evidence that the range was formed by the tilting of a rigid block in the late Cenozoic. Over the years, various geomorphic analyses have been used to quantify the magnitude of uplift and to establish its timing, such as analyzing the gradients of ancient channels, examining the tilt of sedimentary beds, and reconstructing the incisional history of rivers. Most studies that have used these methods have supported substantial (>500 m) recent uplift of the Sierra. In contrast, investigations based on other sources of paleotopographic information, such as isotope records, thermochronology, and detrital zircon geochronology, have found that the Sierra have been at high elevations for much of the Cenozoic. This set of contradictory results motivates a re-examination of the geomorphic evidence for late Cenozoic uplift. A critical assessment of these geomorphic studies, based on new topographic analyses and field investigations, reveals that their conclusions are not well supported. For example, several studies based their results on reconstructions of ancient channels that would have flowed up and over bedrock ridges as high as 190 m, a physical impossibility. Other weaknesses include unjustified assumptions regarding the original tilt of fluvial deposits, misinterpretations of stratigraphic relationships, and inadequate recognition of the effect of lithology on channel profiles. The studies supporting recent tilting in the *northern* Sierra Nevada are inconclusive and rely on observations not unique to tectonic forcing. Indeed, much of the evidence based on the paleogradients of the Tertiary channels is consistent with an early trellis drainage network formed across alternating bands of resistant and weak lithologies. In addition, analyses are presented to demonstrate that deep northern Sierran canyons thought to have been recently incised were, instead, cut as early as the Eocene-Oligocene. Two geomorphic studies from the *southern* Sierra are consistent with late Cenozoic tilting and uplift although ongoing tectonic activity may be insignificant. Finally, I present a conceptual model of the evolution of the Sierran landscape, applicable primarily to the northern half of the range, illustrating the development of three different drainage networks since the late Jurassic.

Key words: Landscape evolution, western Cordillera, tilt markers, tectonic geomorphology

INTRODUCTION

The Sierra Nevada range forms the topographic spine of California, extending ~650 km along the eastern half of the state. The southern part of the range is dominated by batholithic rocks emplaced by continental arc magmatism during subduction in the Mesozoic (for example, Ducea, 2001) (fig. 1). As the range extends northward, belts of Paleozoic and Mesozoic metamorphic suites flank the western margin of the batholith and grow wider until, eventually, the batholithic rocks become limited to isolated plutons (Bateman and Wahrhaftig, 1966). In the late Cretaceous, the Sierra Nevada was already at high elevations (Bateman and Wahrhaftig, 1966; DeGraaff-Surpless and others, 2002) and, during the Eocene and Oligocene, braided gravel-bedded rivers flowed down the western slope of the range, depositing sediment that filled valleys and eventually spilled out over upland surfaces (Lindgren, 1911; Cassel and Graham, 2011). These deposits, often referred to as "auriferous" gravels

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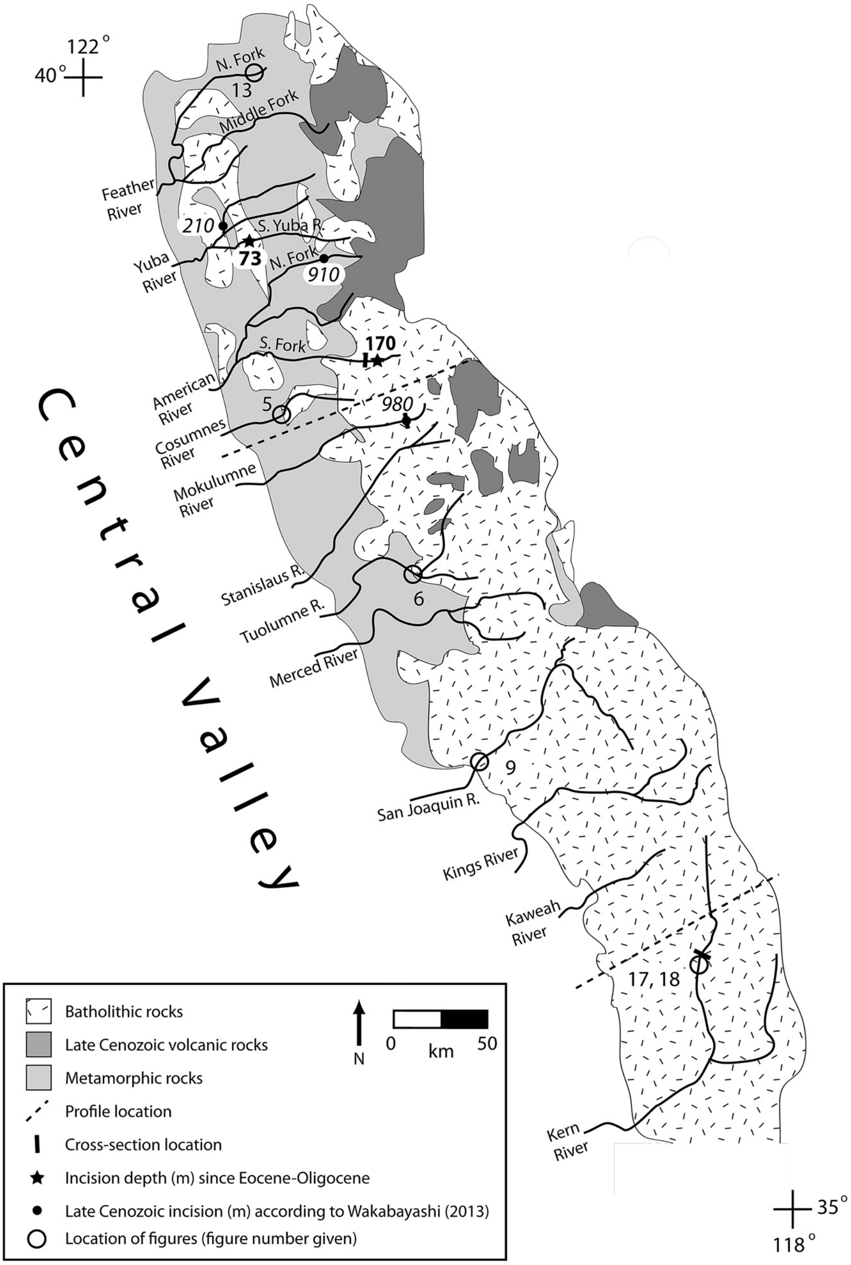
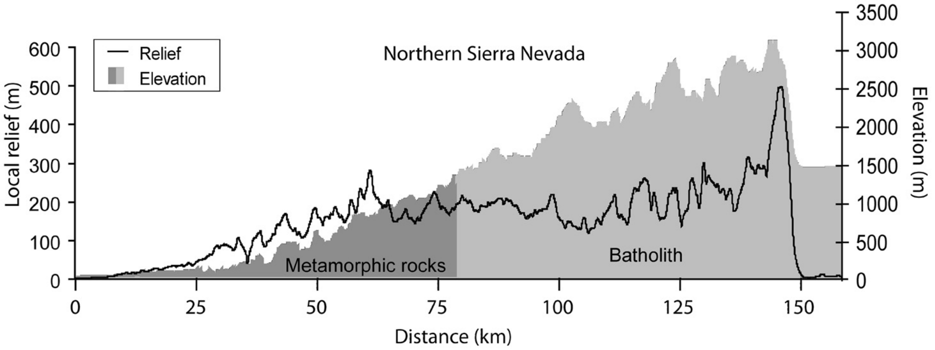


Fig. 1. Simplified general lithological map of the Sierra Nevada geomorphic province (Hinds, 1952). Only bedrock is shown. The Frontal Fault system forms the eastern margin of the range (Wakabayashi and Sawyer, 2000). For clarity, only branches of rivers discussed in this paper are labeled. Adapted from Parrish (2006) and Wakabayashi (2013).

although this term is also applied to younger alluvium, are mainly restricted to the northern part of the range. In the Oligocene–early Miocene (30-22 Ma) rhyolitic tuffs, ash flows, and volcaniclastic debris covered the northern Sierra to depths of ~250 m,



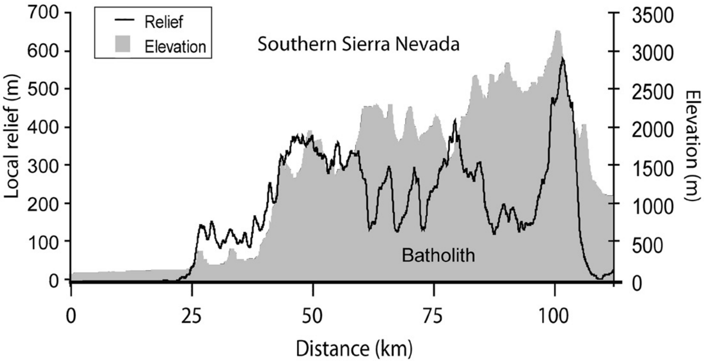


Fig. 2. Elevation and relief profiles across the northern (upper) and southern Sierra Nevada (lower) from 30-m DEM (digital elevation model). Local relief calculated along elevation profile as the difference between the maximum and minimum elevations in a 5-km radius search window. Both plots have identical vertical and horizontal scales. Lithological labels only apply to surface exposure of rock in the mountainous areas; valley fill is at both ends of the profiles. Locations of transects shown in figure 1.

filling in small valleys (Slemmons, 1966; Busby and others, 2008; Busby and Putirka, 2009). This period of volcanism was followed by several pulses of andesitic eruptions in the Miocene, 16 to 6 Ma, which left behind a thicker sequence of deposits that buried the northern section of the range to depths of ~1000 m and forced a re-organization of the drainage network (Slemmons, 1966; Busby and Putirka, 2009). Both volcanic packages cover broad swaths of terrain in the north and become progressively less extensive southward. Smaller eruptive episodes continued into the Quaternary throughout the range (Bateman and Wahrhaftig, 1966).

Just as the northern and southern halves of the range differ lithologically with respect to basement rocks and Cenozoic cover, they are also topographically distinct. In the south, the Sierra, with a width of ~75 km, rises abruptly from the Central Valley and rises to average maximum elevations of ~3500 m (fig. 2). The northern section, in contrast, is wider (~125 km) and rises gradually from the Central Valley to reach maximum elevations averaging ~3000 m. Indeed, the ramp-like appearance of the northern Sierra, which has a gentle western slope and a steep eastern boundary (fig. 2), and the dissection of its low-relief surfaces by deep canyons in the heart of the range have compelled geologists from the beginning of Sierran research to assume that this landscape was rejuvenated through westward tilting of the Sierran block in the late Cenozoic (Lindgren, 1911). The interpretation of the Sierra as a recently tilted block was influenced by the listing slabs of the Basin and Range immediately to the east (Hudson, 1955) and has been a dominant paradigm in California geology for over a century. Initial attempts to estimate the timing and magnitude of uplift relied on stratigraphic and geomorphic evidence and concluded that tilting raised the Sierran crest by substantial amounts (>500 m) over the past 5 to 10 my (for example, Huber, 1981; Unruh, 1991). Since then, other approaches have been used to reconstruct the history of the range with oftentimes contradictory or ambiguous results. For example, low-temperature thermochronology supports recent uplift in the southern Sierra (Maheo and others, 2009; McPhillips and Brandon, 2010; Chapman and others, 2012) but suggests tectonic quiescence in the central and northern parts of the range (House and others, 1998; Cecil and others, 2010). Similarly, paleobotanical studies have been used to argue for (Axelrod, 1997) and against (Wolfe and others, 1998; Hren and others, 2010) late Cenozoic tilting of the range. Isotopic analyses of ancient rainwater have suggested that the Sierra Nevada was as high throughout much of the Cenozoic as it is today (Poage and Chamberlain, 2002; Mulch and others, 2006; Crowley and others, 2008; Mulch and others, 2008; Cassel and others, 2009; Hren and others, 2010); however, these studies have been criticized for relying on coarse paleotopographic reconstructions (Lechler and Galewsky, 2012).

The current debate over the Cenozoic history of the Sierra Nevada and its outcome affects not only our understanding of regional tectonic processes (for example, Jones and others, 2004; Chamberlain and others, 2012; Gilbert and others, 2012) but also the reconstruction of the geologic history of the entire western U.S. Cordillera (DeCelles, 2004; Henry and others, 2012). Furthermore, our inability to conclusively determine whether a major mountain range has recently been tilted skyward presents a critical challenge to the field. In this paper, previous geomorphic techniques used to infer the paleotopography of the range are assessed and the results of new analyses are presented. Although numerical models based on geomorphological principles have been used to address the question of recent uplift (for example, Small and Anderson, 1995; Stock and others, 2004; Pelletier, 2007), the focus is on empirical studies. The general approach taken in this review is to examine the assumptions used to interpret the geomorphic data and evaluate whether they are strongly supported. The analyses are grouped according to the following categories: differential tilts of bedrock paleoreaches, the tilts of ancient fluvial deposits, the tilts of cave deposits, and fluvial incision.

TECHNIQUES FOR INFERRING UPLIFT

Differential Tilt Of Lindgren's Tertiary Rivers

In 1911, a detailed report on the Eocene-Oligocene auriferous gravels in the Sierra Nevada presented reconstructions of the presumed ancestral courses of large "Tertiary rivers" draining the northern half of the range, from the Yuba south to the Tuolumne (Lindgren, 1911). The ancient channels were reconstructed by linking together isolated fluvial deposits often separated by many kilometers. The report noted that the range-normal reaches of the channel remnants were steeper than their range-parallel counterparts. With the assumptions that the gravels had been deposited by single bedrock rivers that were continuous in time and space and that these channels had once had smooth profiles with only gradual changes in slope, the higher gradients of the range-normal reaches were attributed to post-depositional tilting of the Sierran block. The difference in slopes between both sets of reaches was used to estimate 0.7° of westward tilt or ~1300 m of uplift at the Sierran crest (Lindgren, 1911).

Following the observation that the slopes of the paleoreaches vary according to their orientation, several studies have also based uplift estimates on Lindgren's (1911)

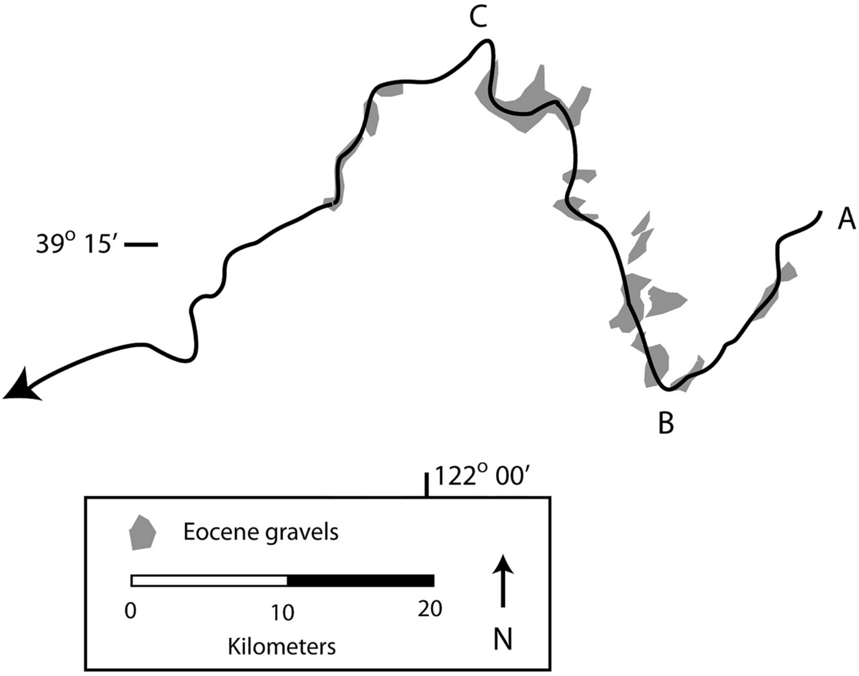


Fig. 3. Section of Lindgren's (1911) reconstructed South Yuba River superimposed on a modern lithological map (Saucedo and Wagner, 1992). The location of this site is near the "73" at the top of figure 1.

reconstructions of the ancient rivers. Hudson (1955) quantified the amount of post-Eocene tilt by solving systems of equations derived to restore the original gradients of reaches of Lindgren's Tertiary Yuba River (fig. 3). As with Lindgren (1911), Hudson's approach was founded on the assumption that adjacent reaches of the ancient river had originally had similar gradients. With this technique, it was estimated that the Sierran crest had been uplifted ~600 m. Hudson (1955, p. 850), however, noted that that this approach often yielded unrealistic values and that only data from reaches that provided "proper solutions" were presented. Because of its lack of scientific rigor, Christensen (1966) dismissed Hudson's work a decade later. Lindgren's ancestral Yuba River was also investigated in Yeend (1974) which, based on a comparison of the gradients of range-parallel and range-normal paleoreaches, concluded that there had been 0.8° of late Cenozoic tilt. Following a different approach, Jones and others (2004) analyzed the gradients of the Yuba's paleoreaches according to their azimuth. This technique was used to gauge the effects of subtracting various amounts of tilt to restore the reaches' presumed original slopes. From this analysis, it was estimated that the Sierran block had been tilted 0.7 to 1.0° in a generally southwest direction.

A fundamental requirement underpins the use of paleoreaches with different orientations to estimate tilt: the profile of the original channel was relatively smooth so that contiguous reaches would have had similar gradients. Because this condition is impossible to validate, it has been replaced by a more practical assumption: the paleoreaches were all once part of a river that was in topographic steady-state (Cassel and Graham, 2011). By presuming that the gradients of adjoining reaches throughout a river at steady-state are similar, the fundamental condition is satisfied, albeit indirectly. If, however, the paleoreaches are not the remnants of a contemporaneous or spatially continuous steady-state river, the assumption that they once had similar gradients is not supported. As noted by Lindgren (1911, p. 140), his reconstructions were not universally accepted. The reconstruction of the Tertiary Jura River was discredited in Durrell (1966), and Yeend (1974), after an analysis of the auriferous gravels that included numerous paleocurrent observations, modified the original course of Lindgren's Yuba River. Moreover, Cassel and Graham (2011) and Cassel and others (2012) concluded that incision and aggradation were occurring at different times throughout the region and that the assumption that the gravels and their paleovalleys represent a contemporaneous river system is invalid.

Lindgren's (1911) reconstructed channels can be directly tested by plotting their longitudinal profiles. The patches of Eocene-Oligocene gravel linked together to form the ancestral rivers on Lindgren's map were identified on modern geological maps, and the elevations of the contacts between the sediments and the bedrock were used to create profiles of the channels. Two reaches defined by the gravels are found to be physically impossible: the Tertiary South Yuba River would have flowed uphill over a 150-m bedrock ridge (figs. 3 and 4A), and the Tertiary North Yuba River would have flowed up a 190-m bedrock ridge (fig. 4B). In each case, the ridge is perpendicular to the channel axis, is laterally continuous, and forms a drainage divide; moreover, there is no evidence that the ridges are the result of post-depositional faulting. Perhaps due to the absence of detailed topographic maps in 1911, these errors were not recognized by Lindgren and paleoflow indicators were apparently not used to test the reconstructions. Although Hudson (1955) used paleocurrent indicators at one site for the South Yuba and Yeend (1974) nearly 20, the number of indicators were not sufficient to detect the defects in these reconstructions. Indeed, Hudson's (1955, p. 850) admission that his mathematical approach "often produce[d] absurd results" is compelling evidence that the reconstruction of the ancient Yuba River is faulty. Nevertheless, the strong relationship between paleoreach orientation and gradient (Jones and others, 2004) merits an explanation.

The detailed descriptions of the ancient channels provided by Lindgren (1911, p. 34-37, 45, 124) demonstrate that the longitudinal reaches ran through long, broad depressions that followed along the escarpments of ridges formed by resistant rock, whereas the transverse reaches flowed down deep, narrow canyons that cut across the ridges. In addition, Lindgren wrote that the Tertiary Calaveras River "possessed in striking degree the alternating longitudinal and transverse stretches characteristic of the Sierran Tertiary rivers (p. 198)." These observations describe a trellis drainage network, a pattern that arises as a river system develops across alternating bands of weak and resistant lithologies (for example, in the Appalachian Mountains): long range-parallel reaches flow over the soft rock while short transverse reaches cut across the hard rock (Knighton, 1998, p. 10). This pattern can be detected in the remnants of the Tertiary channels; for example, a long section of Lindgren's ancestral Yuba River flowed in a range-parallel direction across relatively erodible argillite and then turned westward to cut a transverse reach through granitic and greenstone bedrock (Lindgren, 1911). Indeed, the overall structural grain of the northern Sierra favored longitudinal channels, leading early gold miners to conclude that "the auriferous gravels were deposited by a series of north-trending streams" (Bateman and Wahrhaftig, 1966, p. 134). Because rivers flowing over resistant rock will have higher gradients than those flowing over weak rock (Hancock and others, 1999), the transverse reaches of the Tertiary channels would have been steeper than the longitudinal reaches, even under steady-state conditions (Yeend, 1974). Although the modern river system that flows directly down the Sierran ramp has superseded the original trellis

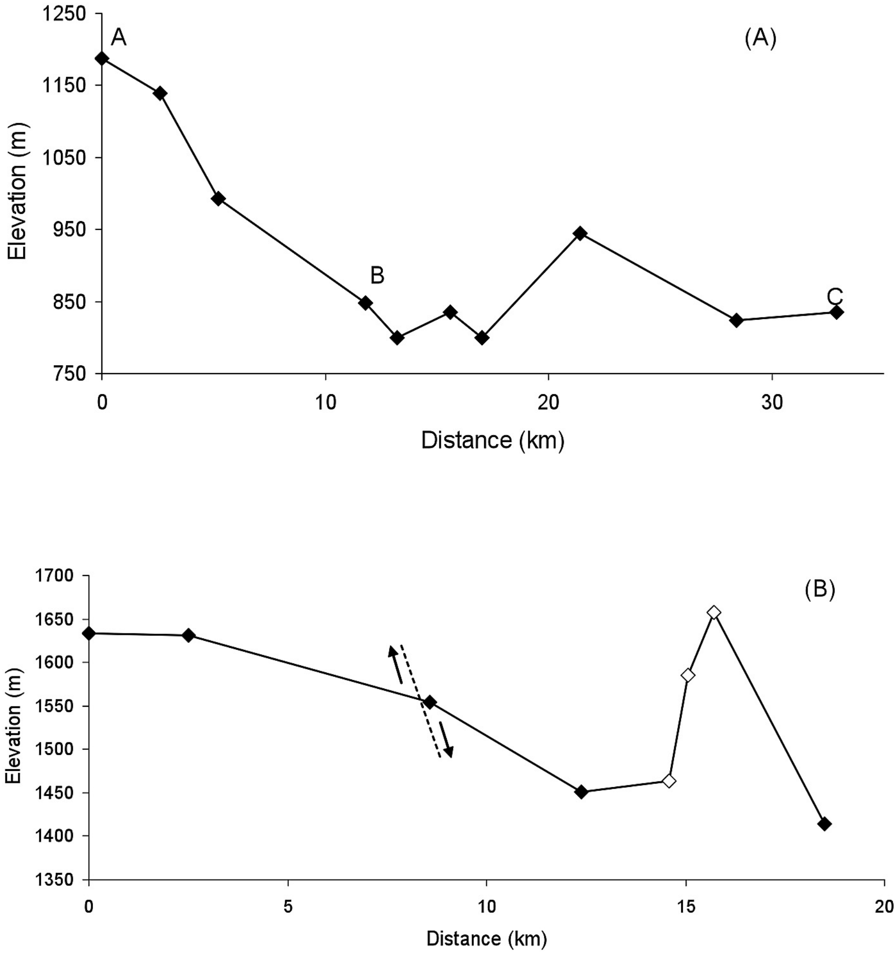


Fig. 4. Longitudinal profiles of Lindgren's (1911) reconstructed channels. Profiles are based on the lowest-elevation gravel-bedrock contact of each major gravel deposit. Both profiles imply that the rivers flowed up high ridges, invalidating the reconstructions. (A) Lindgren's ancestral South Yuba River (fig. 3) based on Yeend's (1974) 1:62,500 map. (B) Lindgren's ancestral North Yuba River (Gibsonville branch) based on Hietanen's (1981) 1:48,000 map. Filled diamonds represent the channel profile. Empty diamonds are elevations of a 5-km-long bedrock ridge (39.629692°, −120.979100) interrupting Lindgren's channel.

network, the lithological control on channel orientation and gradient is still apparent in certain locations (fig. 5).

Finally, Lindgren's (1911) reconstructed South Yuba River includes three adjacent north-northeast-trending reaches that were identified as having uphill gradients ranging from 0.0027 to 0.008. These reverse gradients have been presented as strong evidence for recent tilting of the Sierran block (Lindgren, 1911; Jones and others, 2004; Wakabayashi, 2013) and the flow direction of one of the reaches has been confirmed with paleocurrent indicators (Yeend, 1974). This argument rests on the assumption that the original disposition of these paleoreaches has not been upset by local faulting. These three reaches, however, are in the Melones Fault Zone, a region riven by multiple faults (Hudson, 1955; Jennings and Saucedo, 1999). Hudson (1955) reported the vertical displacement of a patch of auriferous gravel along one of the

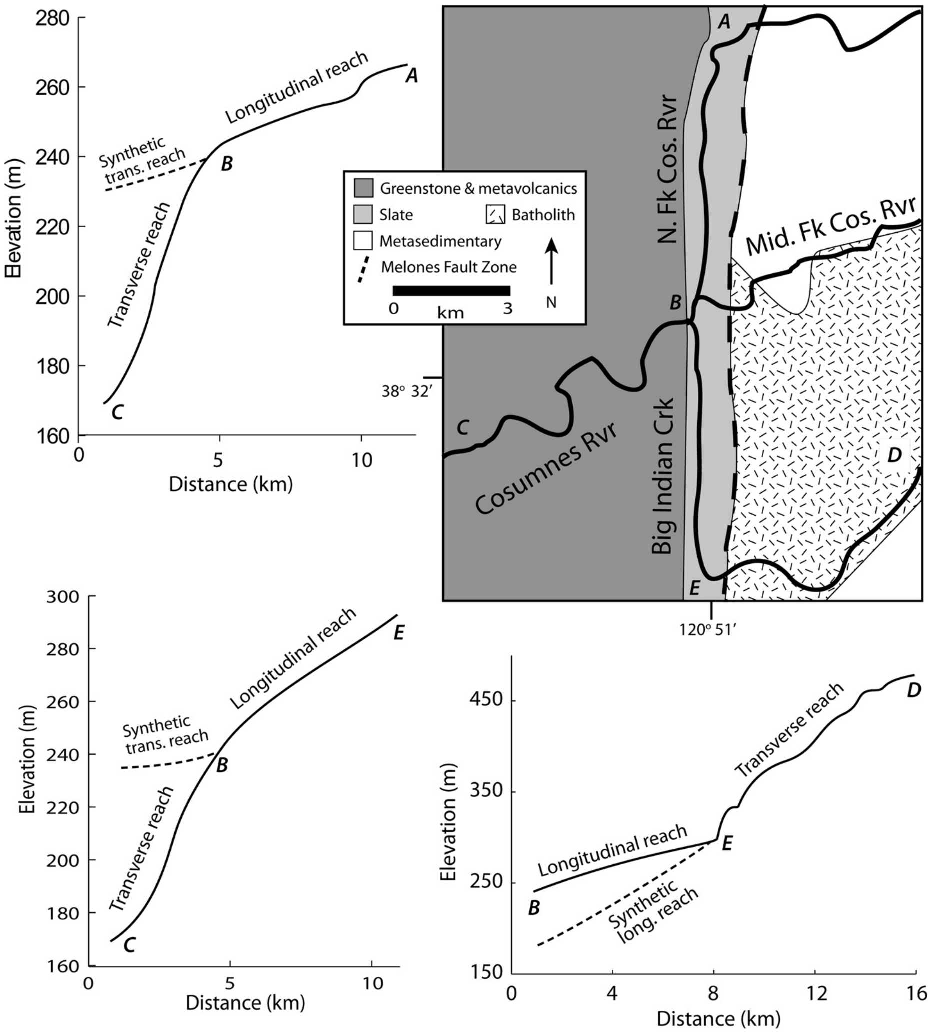


Fig. 5. Trellis drainage network on the Cosumnes River. Letters on longitudinal profiles refer to positions on map. The longitudinal reaches flowing through relatively soft bedrock (slate), which may have been additionally weakened by faulting, are gentler than the transverse reaches cutting through the resistant lithologies. Synthetic reaches were calculated according to Royden and Perron (2013) to illustrate what the gradient would be if the lithology were uniform throughout each profile; this method accounts for changes in drainage area, an important consideration given that the Middle Fork of the Cosumnes River enters at the break-in-slope of two of the profiles.

faults in this zone, and at least two of the faults have exhibited dip-slip motion as recently as the late Cenozoic (Schwartz and others, 1996; Wakabayashi and Sawyer, 2000). Local faulting, therefore, has changed the original disposition of these paleoreaches and little is known of the full history of this region's fault activity since the Eocene-Oligocene. Considering that these north-northeast-flowing reaches ran approximately parallel to the range and, thus, likely had low original slopes (Lindgren, 1911), and considering that the present uphill gradients of their deposits are also low, minor amounts (that is, tens of meters per km) of local tilting since the Eocene-Oligocene would have been sufficient to flip the polarity of their slopes. Therefore, although the

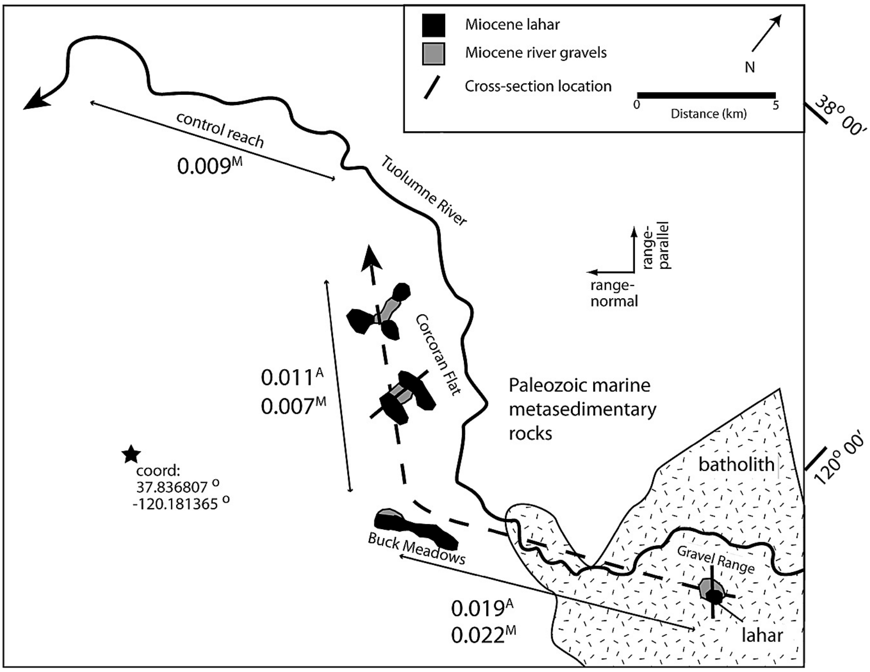
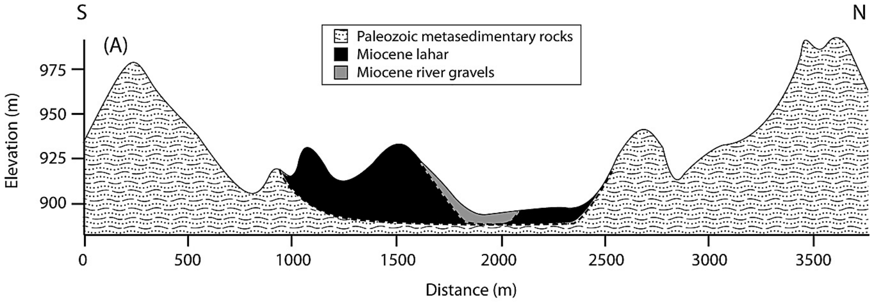


Fig. 6. Map of Tuolumne River sites (Strand, 1967) for gradient calculations (M = modern, A = ancestral). See figure 1 for location. Dashed line is reconstructed route of the ancient channel from Huber (1990). To conform to Huber's method, the gradients are calculated over linear distances (that is, not river distances). Dotted lines indicate cross-section locations for figure 6. Gradients calculated from 1:24,000 topographic maps. Note that the 1991 1:250,00 map of this area (Wagner and others, 1991) mistakenly does not show the gravels at this site (C. Merguerian, personal communication).

reversed gradients of these reaches is suggestive of large-scale tilting of the Sierran block, their presence within an intensely faulted region dilutes their potential significance.

Tilted paleochannel remnants were also used in Huber (1990) to estimate the timing and magnitude of late Cenozoic Sierran uplift. Volcanic deposits in contact with gravels of the Tertiary Tuolumne River (Lindgren, 1911), which are presently 550 m above the modern channel, were interpreted as the remains of a lahar that had flowed down the ancient channel bed and buried its coarse sediment (fig. 6). Based on the elevation of the gravel-lahar contact, the gradient of a range-normal reach of the paleochannel (0.021 or 1.2°) was found to be steeper than the gradient of an adjacent range-parallel reach (0.0095 or 0.5°) (Huber, 1990). With the assumption that the ancient Tuolumne River's gradient was uniform over the 20-km section, Huber determined that tilting of the Sierran block had steepened the range-normal reach by ~0.7°, resulting in 1100 m of uplift at the Sierran crest. In addition, it was assumed that the ancient Tuolumne River had originally been at the same elevation as the modern Tuolumne River, and an additional 381 m of uplift was added for a total of 1481 m of rise at the Sierran crest. In this study, the timing of presumed uplift, bracketed between 9.5 to 23 Ma, could not be well-constrained, and an age of 10 Ma was chosen, albeit without substantial justification. With this approach, Huber estimated ~1500 m of uplift since 10 Ma for the southern Sierran crest.

Huber's (1990) conclusion that the lahar capped the fluvial sediment appears contradicted by the stratigraphic evidence. At two of the sites examined in Huber



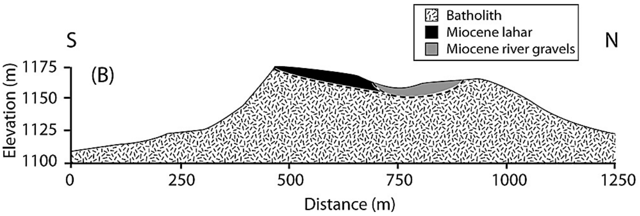


Fig. 7. Topographic and lithological profiles of lahar and fluvial deposits of ancient Tuolumne River derived from 1:250,000 geological map (Strand, 1967) draped over 30-m DEM. Locations shown in figure 6. Contacts below the surface (dashed lines) are inferred from adjacent topography. (A) Profile at Corcoran Flat (coord: 37.847443°, −120.145245) demonstrates that the river incised into the lahar. The modern Tuolumne River canyon is to the right of this figure. (B) Profile at Gravel Range (37.862149, −119.997805°) indicates that the lahar is resting on the bedrock and not capping the gravels.

(1990), the gravels are inset within the lahar (Corcoran Flat; figs. 6 and 7A). For another (Gravel Range; fig. 6), Huber presented a map (his fig. 4) showing a patch of lahar completely surrounded by gravel, reflecting the interpretation that the lahar had flowed over the gravel. I recently visited this site (37.861164°, −119.998627) and found that, in fact, the lahar directly overlies basement rocks without any intervening fluvial deposits (fig. 7B). The parsimonious interpretation of this stratigraphic sequence is that the lahar advanced down a bedrock valley and was subsequently incised by the river. Because the lahar is not inset within a broader fluvial sedimentary unit, Lindgren's paleochannel may have been a short-lived diversion of the Tuolumne River onto a nearby upland until it regained its former course (fig. 8).

Even if Huber's (1990) stratigraphic interpretations were correct, the role of lithology in fluvial erosion must be considered. Using the gravel-bedrock contact for calculating slopes and following Huber's approach of assuming linear paleoreaches, the gradient of the range-parallel reach (Buck Meadows to Corcoran Flat) is 0.011 and the gradient of the range-normal reach (Gravel Range to Buck Meadows) is 0.019 (fig. 6). This revised analysis might appear to support the conclusion of post-depositional tilting (Huber, 1990), except that the steeper reach is primarily on batholithic rocks whereas the gentler reach is on Paleozoic metasedimentary rocks (Wagner and others, 1991). Because resistance to fluvial incision can vary by orders of magnitude depending on rock type (Sklar and Dietrich, 2001), the difference in gradients between the reaches may be due to lithology (for example, Hancock and others, 1999). Two reaches of the present-day Tuolumne River that run alongside the two aforementioned reaches of the ancient Tuolumne River have a similar difference in gradients: the

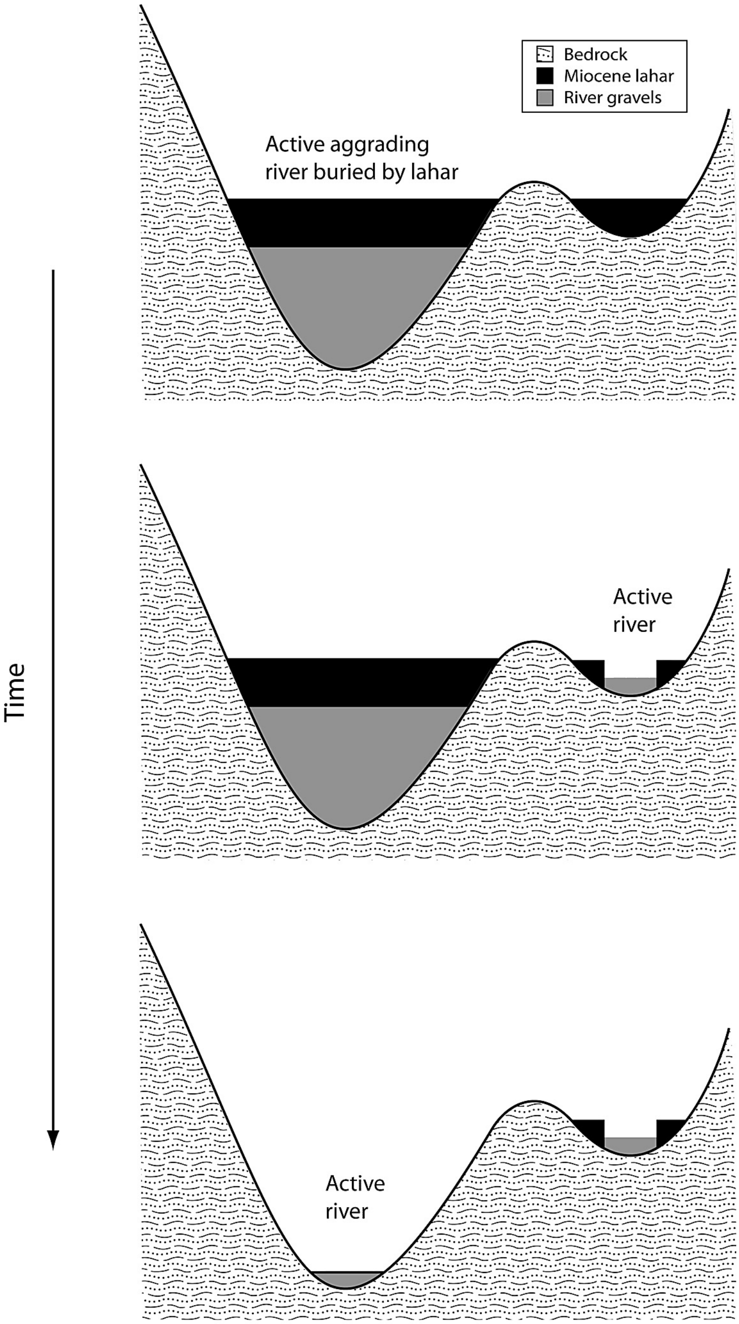


Fig. 8. Possible response of the ancient Tuolumne River after burial by lahar. (Top) The Tuolumne River was originally in a canyon, perhaps filled with sediment. The lahar buried the canyon and an adjacent valley. (Middle) The river was diverted by the lahar into the valley and incised through the volcanic deposits. (Bottom) Later, the river avulsed back into the original canyon, perhaps as a knickpoint migrated upstream through the easily erodible gravels. This sequence would explain how gravels were inset in the lahar within a bedrock valley (fig. 7A).

modern range-normal reach in batholithic rock has a slope of 0.022 while the modern range-parallel reach in the metamorphic rock has a slope of 0.007 (fig. 6). Furthermore, the slope of a range-normal reach through the metamorphic rock (the "control reach" on fig. 6) is 0.009, similar to that of the range-parallel reach through the same bedrock, thus demonstrating that lithology is likely the dominant control on channel steepness at this site. Finally, Huber's (1990) estimate of an additional 381 m of uplift based on the assumption that the ancient Tuolumne River would have been at the same elevation as the present Tuolumne River is not supported by any evidence.

Tilt Of Fluvial Deposits

Instead of comparing one set of paleoreaches against another, some studies have compared the slopes of paleoreaches with modern analogs to extract an uplift history. Christensen (1966) compared the slope of Lindgren's (1911) Tertiary channels to a compilation of modern channel gradients and, finding that the former were steeper than the latter, concluded that the ancient rivers had been titled. Although Wakabayashi and Sawyer (2000) claimed that Christensen's data were collected from rivers from a variety of climates and regions throughout the world, this is not the case. Christensen (1966) lists two sources for its data on modern rivers. The first is a compilation of river flows throughout the United States (USGS, 1960); for the comparison, 15 rivers from California were selected, 13 of which are from semi-arid central and southern California. The second source, Leopold and Miller (1956), is a study of sand-bedded ephemeral streams in arid New Mexico. Christensen's data set, therefore, is limited to rivers, some sand-bedded, from two small regions in the United States, both dry. Because the modern rivers used in this comparison are poor analogs for the Eocene gravel-bedded rivers that flowed down the Sierra during a wet subtropical climate, the conclusion that the range was tilted after the deposition of the gravels is not supported. Moreover, the slope estimate for the Tertiary channels reported in Christensen (1966), 0.017, is within the range of modern gravel-bedded rivers (Mueller and others, 2005) and, thus, supports tectonic quiescence since the Eocene-Oligocene.

Widely cited in later works, Huber (1981) presented an uplift estimate that was also based on an examination of ancient fluvial deposits. Along the lower reach of the San Joaquin River (fig. 1), there is a series of flat-topped "table" mountains composed of the remnants of a 10 Ma trachyandesite flow. Since the table mountains are aligned with the present course of the San Joaquin and some (but not all) of the flow remnants cap alluvial deposits, the lava was presumed to have flowed down the valley of the ancestral river. Further, based on the presence of columnar joints within the flow, it was assumed that the flow had ponded and, thus, cooled with a relatively horizontal upper surface (Huber, 1981). Because the surface of the flow now has a slope of 0.024 (1.4°) down towards the west, it was concluded that tilting of the Sierran block since 10 Ma had changed the original disposition of the deposits. In addition, the contact between the lower surface of the flow and the ancient alluvial deposits was found to define a plane with a slope of 0.022 (1.3°) (Huber, 1981).

To calculate the total amount of tilt at the Sierran crest, Huber (1981) made a critical assumption: the reach of the ancestral San Joaquin River preserved underneath the trachyandesite had had an original low slope of 0.001, the gradient of the modern San Joaquin River in its lower reaches. Huber supported this assumption by proposing that the large-amplitude meanders of the modern bedrock San Joaquin River were formed when the river was a low-gradient channel flowing over alluvium. According to this hypothesis, similar to the one proposed to explain the sinuous course of bedrock channels on the Colorado Plateau (Schumm, 1963), the meandering pattern became fixed when uplift caused incision of the ancestral river down through its alluvium and into bedrock. The presence of silt and gravel in the alluvial deposits underlying some

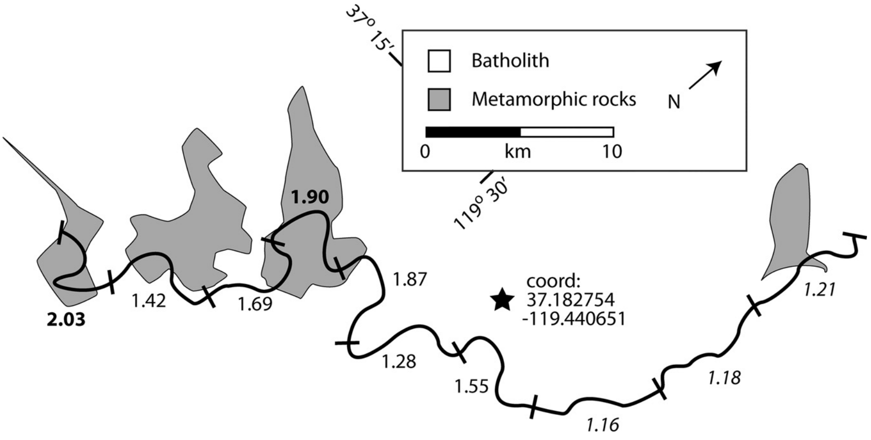


Fig. 9. Lower bedrock reach of the San Joaquin River; flow direction is to the left (see fig. 1 for location). Bedrock is batholithic rock except for the gray patches, which are metamorphic rocks (Strand, 1967). The average sinuosity of the reaches through the metamorphic rocks (bold numbers) is significantly higher than through the granitic rocks, indicating that the river's planform is not a relic feature. Although the italicized values are also for batholithic bedrock, they are substantially lower than the other set and were not included in the comparison to avoid biasing the results. Sinuosity was calculated along 8 km reaches, a length based on the width of the metamorphic bedrock patches; analysis reaches are delineated by perpendicular lines. The most sinuous reaches of the Kings River to the south also flow through metamorphic rocks (36.866612°, −119.291629).

of the table mountains was also noted and the fine-grained material was considered diagnostic of a low gradient channel (Huber, 1981). Therefore, tilting increased the slope of the alluvial deposits underneath the table mountains from 0.001 to 0.022 (an increase of 1.2°) and extrapolation of this increase in gradient along the width of the range yielded 2150 m of uplift at the Sierran crest over the past 10 Ma (Huber, 1981).

Some of the observations presented in Huber (1981) are not unique to very low gradients (that is, 0.001 or 0.06°). For example, the presence of columnar joints is not diagnostic of ponded lava flows (Hetenyi and others, 2012), and shield volcanoes have slopes of 1 to 5° (Tarbuck and Lutgens, 2008), demonstrating that even low viscosity lavas can cool at slopes of several degrees. In addition, although it was once thought that meanders in bedrock channels were fixed and inherited features (Schumm, 1963), it is now understood that bedrock rivers in mountainous terrain can migrate laterally to form sinuous and dynamic planforms (Stark and others, 2010; Finnegan and Dietrich, 2011). Indeed, the varying sinuosity (that is, river length/valley length) of the modern San Joaquin River indicates that the channel's planform evolved as it cut down through the bedrock: the river is significantly more sinuous through metamorphic rock than batholith (t-test; $\alpha = 0.05$) (fig. 9). If the planform were a relic from a pre-incision past (Huber, 1981), the sinuosity would be independent of lithology.

Finally, only qualitative observations were used to justify assigning the modern river's gradient to its 10 Ma bed (Huber, 1981). To evaluate whether 0.001 was a reasonable estimate for the ancestral channel's original gradient, I analyzed a patch of coarse gravel under the trachyandesite flow at Table Mountain (37.010617°, −119.610102°). A pebble count (n=100) at the site revealed a median particle diameter (D_{50}) of 0.08 m such that a paleoslope (S) can be estimated with

$$S = \frac{0.094 D_{50}}{h} \tag{1}$$

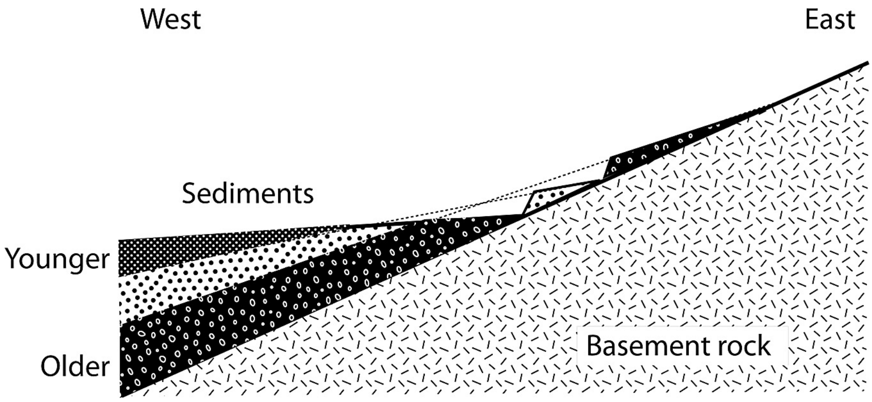


Fig. 10. General representation of sedimentary beds along the eastern margin of the Central Valley (Unruh, 1991); dotted lines connect the terrace surfaces to the basin deposits. The dip of the beds steepen downsection and the older beds have been dissected, forming terraces and cuestas further upslope. These features are typical of a decrease in sediment supply following a cessation of uplift (Miall, 1996).

where *h* is flow depth (m) (Paola and Mohrig, 1996). The gravel outcrops were not sufficiently exposed to estimate the flow depth from stratigraphic clues, however, a range of reasonable depths can be used to calculate a range of possible paleoslopes. For large braided rivers, bankfull flow depths vary from 3 to 5 m (Mueller and others, 2005); applying these values and accounting for the factor-of-2 uncertainty in the technique (Paola and Mohrig, 1996) yields paleoslopes of 0.005 to 0.0008, which bracket Huber's estimate of 0.001 for the ancestral San Joaquin (given the uncertainty in flow depths, accounting for the difference between river slope and valley slope is unnecessary). The critical assumptions underlying this calculation are that (1) the ancient San Joaquin river was a braided channel, (2) the outcrop analyzed was representative of its bed sediment, (3) the depth estimates are approximately correct, and (4) the channel's banks were noncohesive (Paola and Mohrig, 1996). If these conditions are met, the paleoslope estimate from Huber (1981) and, by extension its tilt calculation, is supported by this analysis. However, the calculated uplift at the range's crest is based on the unlikely assumption of a rigid Sierran block; bending of the block would reduce the tilt from the Sierra's western edge to its eastern escarpment (Martel and others, 2014). Therefore, although the tilt estimate appears to be supported by this analysis, the uplift estimate from Huber (1981) is likely too high.

In another analysis of fluvial deposits to infer an uplift history, Unruh (1991) examined the dip of sedimentary beds primarily composed of alluvium that was transported down the western slope of the Sierra Nevada and accumulated along the eastern margin of the Central Valley (that is, the western edge of the Sierran block). Two observations motivated this study. First, the oldest beds on the northern valley margin have been dissected by erosion and it was hypothesized that they had been tilted up and exposed to channel incision (fig. 10). Second, the oldest beds are also the most steeply dipping and, as the beds become younger, their dip becomes more shallow; the increase in dip with age suggested the beds were being tilted as uplift raised the Sierran crest (Unruh, 1991). Dip data was compiled from a range of sources and, with the assumption that the Sierran block is structurally rigid, it was concluded that the Sierra had been tilted twice, once in the mid-Cenozoic and again ~5 Ma. The latter event was determined to have tilted the Sierran block westward 1.4° (Unruh, 1991).

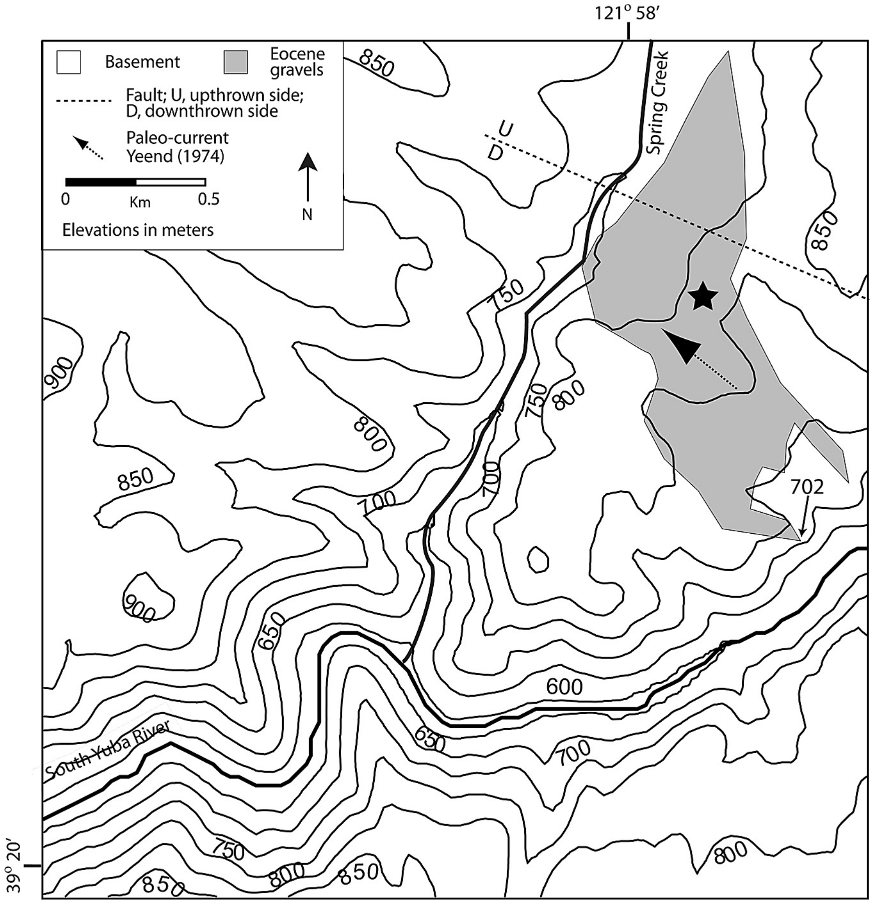


Fig. 11. Map of Spring Creek and Eocene-Oligocene gravels (Yeend, 1974). A field visit confirmed the position of the gravels along Spring Creek. Vertical displacement along the fault is ~22 m. Coordinates at the star: 39.351423, −120.977461. Location of this site designated with a star near "73" on the upper portion of figure 1.

The plausibility of this tilt estimate for the late Cenozoic uplift can be tested. As noted in Schaffer (1997), Yeend (1974) mapped a patch of Eocene-Oligocene gravel along Spring Creek, a tributary to the South Yuba River (Yeend, 1974; Saucedo and Wagner, 1992) (fig. 11). The minimum elevation of the deposit is 702 m and it is 50 km from the presumed tilt axis (Unruh, 1991), which is at an elevation of approximately 30 m; the gravels, therefore, are resting on an assumed plane that is projected to form a 0.8° angle from horizontal (fig. 12). Subtracting Unruh's (1991) tilt estimate (1.4°) from this value implies that the gravels would have been at an angle of 0.6° below horizontal prior to 5 Ma (Schaffer, 1997). Because sea level varied by no more than ~50 m from the Eocene to the Pleistocene (Van Sickel and others, 2004), the gravels would have been ~500 m beneath the ocean's surface according to the results presented in Unruh (1991). Marine sediments have not been found in association with the gravels (Saucedo and Wagner, 1992), indicating that the estimate of late Cenozoic uplift in Unruh (1991) is not supported by field evidence in the northern Sierras. Note that, although the Spring Creek gravel patch rests on the headwall of a down-dropped graben (Yeend, 1974), the ~22 m of vertical displacement since deposition is insignifi-

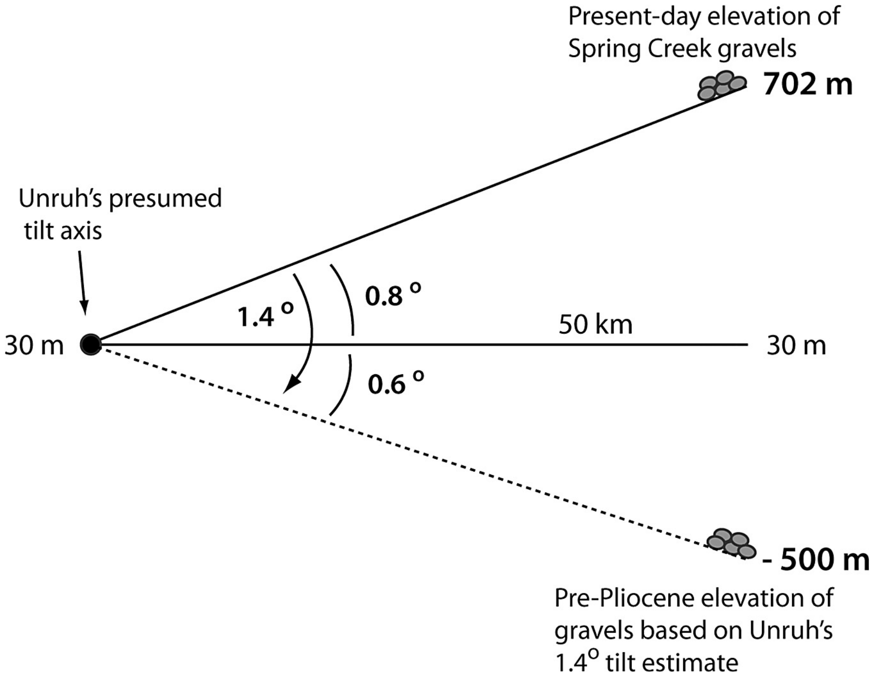


Fig. 12. Geometric analysis challenging Unruh's (1991) tilt estimate. All elevations relative to sea level. Based on the position of Unruh's presumed tilt axis (elev. 30 m) at the eastern margin of the Central Valley, the Eocene-Oligocene Spring Creek gravels (elev. 702 m) presently rest on a plane that forms a 0.8° angle from horizontal. Subtracting the 1.4° degrees of post-Miocene uplift estimated in Unruh (1991) implies that the gravels would have been 500 m below sea level before 5 Ma.

cant relative to the total amount of uplift inferred for this location on the basis of Unruh's tilt estimate (~1200 m).

As noted in Unruh (1991), non-tectonic processes can explain the two main observations that motivated the study; specifically, a long-term decrease in sediment supply from the Sierra could have led to the dissection of the older beds and a decline in the slope of the younger beds. Alluvial channels steepen in response to increases in sediment supply and, conversely, become gentler when sediment supply diminishes; concomitantly, the region along a river's profile that divides its erosional zone from its depositional zone shifts downstream when the supply decreases (Schumm, 1963). Addressing the geomorphic response to tilting, Miall (1996) states:

> Between periods of tectonic rejuvenation the rate of source-area erosion may exceed the rate of isostatic rebound. Progressive downcutting results in channel incision, leaving earlier fan segments as terraces and depositing a new cone of sediment as an offlapping wedge, with a gentler depositional slope, at the distal end of the fan.

Examples of tectonically quiescent ranges with eroded, older beds with steep slopes and younger beds with shallower slopes (fig. 10) have been documented by Bull (1964) and Miall (1978). Moreover, Miall (1978) concluded that uplift would lead to progressively *steeper* beds upsection. The dissection of the older beds along the margins of the Central Valley is, therefore, likely not a response to recent tilt and uplift, but the opposite: it is diagnostic of a tectonically inactive mountain range with a dwindling sediment supply.

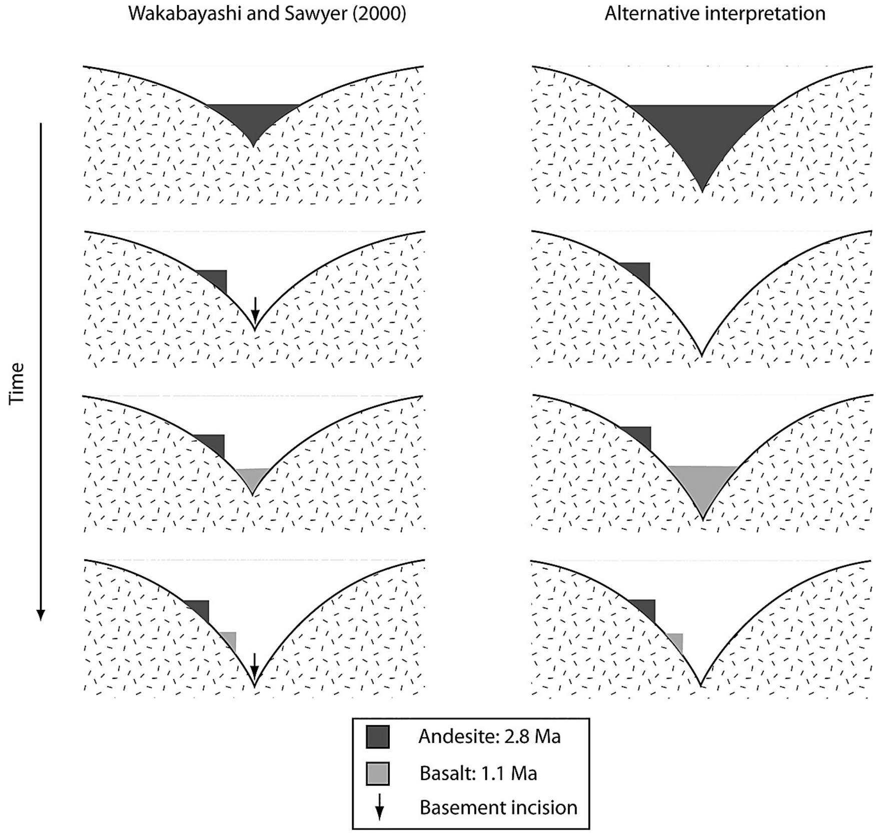


Fig. 13. (Left column) Wakabayashi and Sawyer's (2000) technique for estimating incision rates on the North Fork Feather River assumes that the bases of the volcanic units represent the bedrock bed of the channel when the lava flowed down the canyon. (Right column) Alternative interpretation of the sequence of volcanic rocks. The valley was already deep before being partially filled by the 2.8 Ma andesite flow and a smaller basalt flow 1.1 Ma. Over time, the volcanic rocks have been mostly eroded away but there has been no basement incision. Field evidence cannot distinguish between these 2 scenarios.

The results from Unruh (1991), as well as from other studies (for example, Christensen, 1966; Huber, 1981; Huber, 1990), were synthesized in Wakabayashi and Sawyer (2001), which also presented a new estimate of late Cenozoic Sierran uplift and timing based on the presumed tilt of fluvial deposits capped by volcanic rocks. In this 2001 paper, two lava flows were examined, the 9-Ma Table Mountain Latite near the Stanislaus River and the 16-Ma Lovejoy Basalt near the Feather River (fig. 1). The slope of the contact between the flows and the underlying sediment was measured, and by assuming an original gradient for the lava-sediment contacts, a tilt estimate was calculated as the difference between the ancient and modern channel slopes. To constrain the original slope of the base of the lava flow, Wakabayashi and Sawyer (2000) adopted Huber's (1981) estimate of 0.001 for the ancestral San Joaquin River as a minimum paleogradient for both of the sites and the slope of the modern rivers as a maximum. The timing of uplift was estimated with a 2-step process. First, the elevation difference between the remnants of 1.1 and 2.8 Ma volcanic rocks along the sides of the North Fork Feather River canyon was computed (fig. 13). With the assumption that the base of the volcanic units represented the bedrock surface of the paleo-Feather River at different points in time, an incision rate was estimated. The presumed incision rate was then used to calculate the time that the river would have needed to incise from the canyon rim down to the oldest volcanic rocks (Wakabayashi and Sawyer, 2001). On the basis of this calculation and the assumption that incision of the canyon would have been driven by tilting, it was determined that uplift had begun 5 Ma. From this analysis, Wakabayashi and Sawyer (2001) estimated that there had been 1710 to 1930 m of uplift of the Sierran crest (~1° of tilt) over the past 5 my.

The results from Wakabayashi and Sawyer (2001) rest on several assumptions that merit examination. For example, quantitative evidence was not presented to support the premise that these sites would have had the same original slope as the ancestral San Joaquin River, which is 140 km to the south of the Stanislaus River and 320 km to the south of the Feather River. In addition, using the modern river gradients to constrain the maximum paleogradients excludes the possibility that the Sierra were already high in the Miocene and have eroded since; in other words, the finding for recent uplift is preordained by the presumption of low paleogradients. An uplift estimate based on the paleogradient of a feature is so dependent on its presumed initial disposition, there is the risk that the conclusion becomes, essentially, a restatement of the assumption. In fact, the present slopes of these Miocene volcanics are typical for lava flows: the depositional angle of the western portions of the Lovejoy Basalt (Saucedo and Wagner, 1992), ~1.7°, and the Table Mountain Latite (Rogers, 1966), ~1.3°, are similar to the slopes of shield volcanoes (Tarbuck and Lutgens, 2008). The lava flows, therefore, could be used to argue against significant tilting. Second, with respect to the calculated bedrock incision rates, there is no evidence that the bases of the volcanic rocks along the North Fork Feather River represent the elevation of the channel's bedrock surface at the time of the eruptions. For instance, the remnants of the volcanic rocks could be on terraces that were at some undeterminable height above the channel bed (fig. 14). As an endmember counter-example, the valley could have been excavated to its present depth prior to 5 Ma and then partially filled by 2 flows, the second smaller than the first (fig. 13). The tilt estimates in Wakabayashi and Sawyer (2001) likely only represent upper bounds, with tilting of zero degrees being consistent with the field evidence and representing a lower bounds. Moreover, on the basis of the estimated incision rates along the North Fork Feather River, Wakabayashi (2013) calculated a knickpoint migration rate along this river and found it to be comparable to rates estimated in the Waipaoa River basin in New Zealand (Crosby and Whipple, 2006). Given that the North Fork Feather River runs through highly resistant metamorphic and granitic rocks (Sklar and Dietrich, 2001) (fig. 1) while the Waipaoa River flows through weak siltstone and mudstone (Crosby and Whipple, 2006), it is unlikely that knickpoints could travel up both drainages at similar rates, even after accounting for differences in climate. Their calculation of this unusually fast knickpoint migration rate presents a further challenge to the methodology used in Wakabayashi and Sawyer (2001).

Finally, Cassel and Graham (2011) examined, in detail, outcrops of auriferous gravels in the northern Sierra to reconstruct the topographic and geomorphic conditions of the region during their deposition in the Eocene and Oligocene. In contrast to Lindgren's (1911) conclusion that the gravels traced the course of a few contemporaneous meandering channels, it was determined that the deposits had been created by different braided rivers during different periods of time as sediment backfilled eastward behind a ridge of resistant metamorphic bedrock. Paleo-slopes in the range of 0.004 to 0.055 were estimated on the basis of particle size analyses and were found to match the gradients of modern braided rivers compiled by Whiting and others (1999). Because the estimated paleoslopes of the ancient rivers are similar to the gradients of the treads of adjacent exposed paleoterraces (0.020-0.063), it was concluded that the northern Sierra had not been significantly tilted since Eocene-

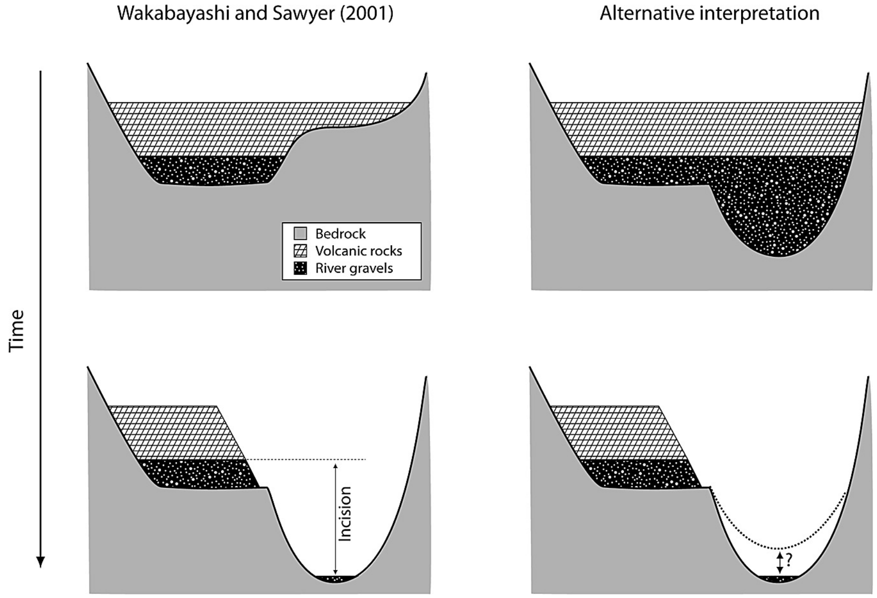


Fig. 14. (Left column) Wakabayashi and Sawyer's (2001) interpretation of stratigraphy and topography for their calculations of incision depths (adapted from their fig. 4). (Right column) Alternative interpretation in which gravels are perched on an ancient strath terrace and the river has cut back down through its own sediment and re-occupied its original valley. Without knowing the original elevation of the valley bottom, an incision depth cannot be estimated.

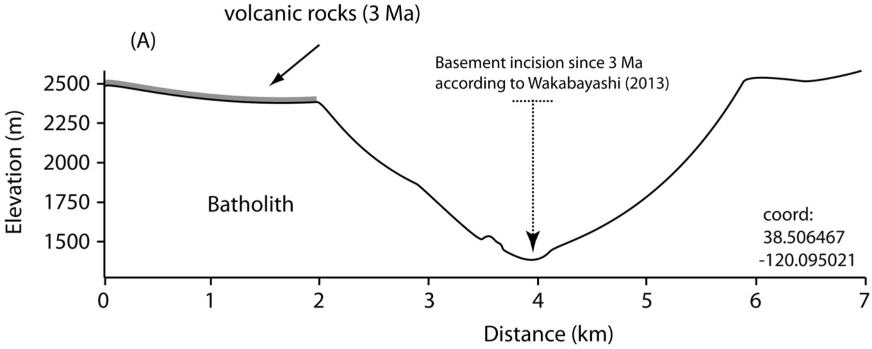
Oligocene times (Cassel and Graham, 2011). Moreover, the presence of long-traveled cobbles and boulders were presented as evidence that the ancient rivers had been steep and energetic.

Cassel and Graham (2011) demonstrated that the gravels could yield quantitative paleotopographic information through careful examination but the range of calculated paleoslopes varies by an order of magnitude, a limitation of the technique (Paola and Mohrig, 1996) and the uncertainties in estimating channel depths. However, as reported in Cassel and Graham (2011), the estimated gradients are slightly lower than the terrace slopes; this observation may support their results: the slope of a terrace should be slightly steeper than the river that created it because the gradient of a terrace is measured along the line of steepest descent whereas the channel follows a sinuous path.

Tilt Of Cave Deposits

The preceding sections have demonstrated that determination of an original slope is the critical challenge in using deposits to estimate tilting and uplift. Granger and Stock (2004) solved this problem by measuring the tilt of calcite shelfstone deposits found in caves in the southern Sierra. Precipitated on the surface of ponded water, these deposits had an original slope of zero. Granger and Stock found that shelfstones formed during glacial periods were no longer horizontal and attributed the tilt to post-glacial rebound. However, a 116,300 year-old shelfstone was level, presumably because it had formed during an inter-glacial period (Granger and Stock, 2004).

The absence of tilt of this deposit is evidence against significant tilt of the southern Sierra since ~100 ka, even within measurement error. Granger and Stock reported a measurement precision of 0.5 mm over a distance of 4500 mm, or 0.006°. Given the age



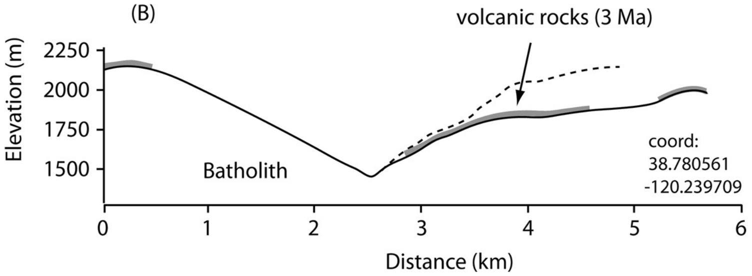


Fig. 15. (A) Profile across upper reach of Mokulumne River (Wagner and others, 1981). Based on the elevation difference between the Pliocene volcanic rocks and the bottom of the canyon, Wakabayashi (2013) concluded that there had been 980 m of recent incision. (B) Profile across upper reach of the South Fork of the American River, ~30 km north of the Mokulumne River reach shown above (Loomis, 1964). The Pliocene volcanic rocks in the canyon, ~200 m above the valley floor, demonstrate that incision predates the volcanism. The right canyon wall where the volcanic rocks are preserved is low and shallow relative to the rest of the valley; the dashed line is a representative profile of this side of the canyon, ~2.5 km upstream of the full profile. Cross-section locations shown on figure 1. Thickness of volcanic deposits exaggerated for illustrative purposes; actual elevations represented by black line.

of the horizontal shelfstone, the maximum undetectable tilt rate, to the east or the west, would be 0.006° over the past 116,300 yr. Therefore, these deposits constrain any potential westward tilting of the southern Sierra to rates between 0 and 5×10^{-5} °/ky. For comparison, Huber's (1981) results imply a rate of 1.2×10^{-4} °/ky averaged over the past 10 My.

Fluvial Incision

Wakabayashi and Sawyer (2001) and, more recently, Wakabayashi (2013) estimated the amount of late Cenozoic deepening of valleys throughout the Sierra as a means of inferring tectonic activity. Their technique consisted of measuring the elevation difference between the base of dated volcanic rocks on the sides of canyons and the elevation of the bottom of the canyons (fig. 15A). With this method, it was concluded that there had been up to ~1000 m of incision over the past 3 to 20 my and that it had been caused by significant amounts of uplift.

As demonstrated earlier, the use of marker horizons to estimate incision rates depends critically on the ability to pinpoint the original elevation of the river. Wakabayashi (2013) and Wakabayashi and Sawyer (2001) assumed that the remnants of the volcanic rocks were faithful recorders of the elevation of the ancient bedrock channels. The Spring Creek gravel patch offers an opportunity to test this methodol-

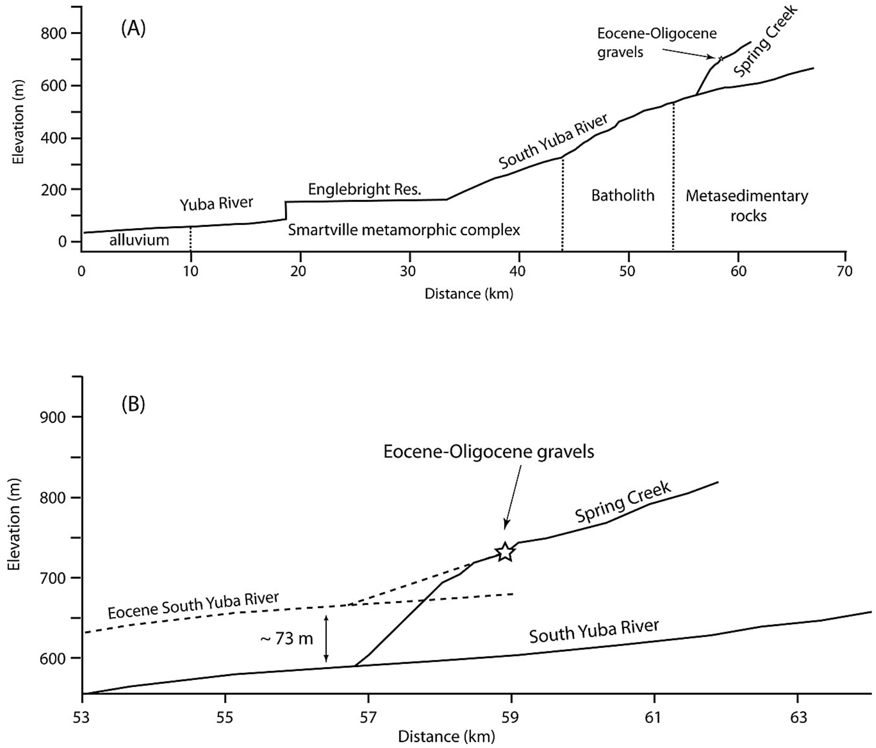


Fig. 16. Profiles of Yuba River and Spring Creek from 1:24,000 U.S.G.S. topographic quads. Lithology from Saucedo and Wagner (1992). (A) Profile begins in the Central Valley. Lithological labels depict only material exposed at surface. Note the changes in gradient associated with changes in bedrock. Bedrock profile underneath Englebright Reservoir is unknown. (B) Spring Creek–South Fork Yuba River junction. Extending the reach of Spring Creek containing the gravels out to the junction suggests ~73 m of incision on the South Yuba River since the Eocene-Oligocene.

ogy (Schaffer, 1997). Extending Spring Creek smoothly from where it cuts into the auriferous gravels out to where it would have met the ancestral South Yuba River yields ~73 m of bedrock incision since the Eocene-Oligocene (fig. 16). Taking the end-member case in which Spring Creek had a gradient of zero between the gravels and its junction with the South Yuba Rivers provides an absolute upper bound of 134 m of incision for this 250-m deep canyon since the deposition of the gravels. Alternatively, the Eocene-Oligocene profile of Spring Creek could have been steep and irregular, particularly since it crosses a lithological transition (Yeend, 1974; Schaffer, 1997); in this case, the amount of incision would have been less than 73 m. Despite these uncertainties, the Spring Creek gravel patch indicates that the South Yuba River was already in its present canyon in the Eocene-Oligocene, and the estimated 73 m of incision since then contrasts with the value of 210 m of incision estimated since 3 Ma on a nearby reach of the Yuba River (Wakabayashi, 2013) (fig. 1). Because the South Yuba grades smoothly into the trunk stream (fig. 16A), there is no indication that the main channel has been incised 3 times deeper than its tributary.

At another site, Wakabayashi (2013) estimated that, since 3 Ma, there had been 910 m of incision on the North Fork of the American River and 980 m on the Mokulumne (fig. 1); between these two rivers lies the canyon of the South Fork of the American River. In the upper reach of the South Fork, at approximately the same topographic position as Wakabayashi's site on the N. Fork, Lindgren (1911, p. 185) noted that the channel had incised only ~170 m since the Eocene. Lindgren's observation is supported by Pliocene-age pyroclastic debris deep within the canyon of the South Fork (fig. 15B). These volcanic rocks are *in situ* and were not transported downslope by a deep-seated landslide (Spittler and Wagner, 1998); indeed, they escaped erosion because they were deposited on a relatively gently-sloped surface in an otherwise steep-walled canyon. Lindgren's report and the position of the Pliocene volcanic rocks demonstrate that the canyon of South Fork of the American River has been deep throughout much of the Cenozoic (Schaffer, 1997) whereas Wakabayashi (2013) proposed that the canyons of the N. Fork of the American and the Mokulumne were cut in the past 3 Ma. Therefore, for Wakabayashi's interpretation to be correct, the S. Fork of the American would have to have been incised before the andesitic eruptions, ~20 Ma, while its northern branch and the nearby Mokulumne River (~30 km to the south of the S. Fork) would have been spared. Then, 3 Ma, the N. Fork of the American and the Mokulumne River would have carved canyons nearly a kilometer-deep but, this time, the S. Fork of the American would have been spared. The conclusion that the canyons of the Mokulumne and the N. Fork of the American were incised since 3 Ma requires that two branches of the same river (the American), as well as two rivers within ~30 km of each other, had contradictory responses to the same regional events. A simpler explanation is that all the canyons were cut before the period of volcanism and then blanketed by volcanic rocks that, over time, were mostly eroded away. If deepening of these canyons had been driven by recent uplift (Wakabayashi, 2013), the S. Fork of the American should have suffered similar amounts of incision as its immediate neighbors. The assumption that volcanic rocks on canyon rims define the channel bed elevation at the time they were deposited is therefore falsified by the presence of volcanic rocks in the S. Fork of the American River canyon, the observations in Lindgren (1911), and the location of the Spring Creek gravels. As a result, the approach used in Wakabayashi (2013) and Wakabayashi and Sawyer (2001) yields only maximum possible depths of recent incision and the true values appear to be considerably less (see also Saleeby and others, 2013).

Another approach to understanding the incisional history of rivers is through the use of cosmogenic isotopes, which can provide a relatively high temporal resolution. By analyzing the $^{26}Al/^{10}Be$ ratios measured in gravels trapped in caves along canyon walls, Stock and others (2004, 2005) calculated rates of bedrock channel incision across a transect spanning several large river systems of the southern Sierra Nevada, from the South Fork of the Kaweah River up to the Stanislaus (fig. 1). The cave sediment revealed that there had been 400 m of downcutting on the S. Fork of the Kings and 200 m on Yucca Creek since ~2.5 Ma but that there had also been significant relief prior to that time (see also Wakabayashi and Sawyer, 2001). In addition, Stock and others found that incision rates were higher during the late Pliocene and early Pleistocene and have declined since. Remarkably, all the studied rivers converged to the same narrow range of incision rates (0.015-0.043 mm/y). Stock and others (2004) proposed that the decline in rates marked the trailing end of an incision wave that had swept through the watersheds after a late Cenozoic pulse of uplift. Interpreting a precise tectonic history from records of incision, however, remains a challenge.

For a given rock type, the factors controlling bedrock channel incision rates are thought to include changes in the topographic boundary conditions, discharge, and the supply of sediment (for example, Hancock and others, 1998; Sklar and Dietrich, 1998; Sklar and Dietrich, 2001). Of these three factors, the sediment supply may be the most difficult to constrain in reconstructing a landscape's geological history yet it may be the most important. For example, in Dearborn Creek (Montana), Foley (1980a, 1980b) found that bedrock incision rates were over 10-times higher during glacial

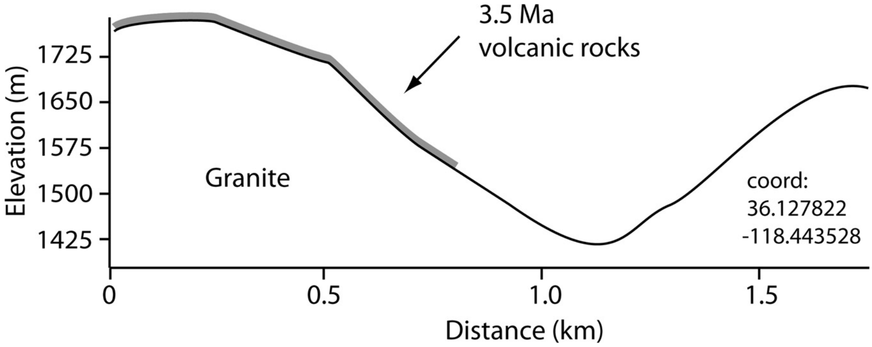


Fig. 17. Cross-section across Kern River canyon (see fig. 1 for location). Pliocene volcanic rocks descend to an elevation of 1544 m and the canyon bottom is at 1419 m, constraining the maximum possible amount of incision since 3.5 Ma to 125 m. Another example can be seen at 36.123141°, −118.454522. Profile created by draping l:250,000 lithological map (Matthews and Burnett, 1965) over 30-m DEM. Thickness of volcanic deposits exaggerated for illustrative purposes; actual elevations represented by black line.

periods than the present and attributed the increase to the presence of bed-material supplied by glaciers. Because batholithic rock and some Sierran metamorphic rocks are among the most resistant to abrasion (Sklar and Dietrich, 2001), the need for sediment in the incision of channels composed of these lithologies should be particularly acute. Moreover, while abrasion mill experiments suggest that changes in sediment concentration can vary erosion rates 10-fold, increases in sediment size may boost the erosion rate 1000-fold (Sklar and Dietrich, 2001). Thus, whereas the amount of sediment delivered to channels is important in fluvial incision, the caliber of the sediment can have an even greater impact. Given these various factors, a particular incision history could be due to different time-varying combinations of uplift rate, discharge, sediment supply, and sediment size. Although the relatively rapid rates of downcutting documented by Stock and others (2004) in the southern range, as well as inner gorges in the canyons of the San Joaquin and Kings rivers, are consistent with late Cenozoic tectonic activity in the southern Sierra, the mechanics of bedrock incision are not sufficiently understood to attribute them to a particular magnitude and timing of uplift.

In addition to incision rates, knickpoints in modern channels of the southern Sierra have also been used to extract uplift information. Clark and others (2005) examined profiles in the Kern and King river drainages to reconstruct an uplift and incision history for the southern Sierra Nevada. Knickpoints were identified on tributaries to these two rivers and, with the assumption that they were a result of tectonic activity, they were used to re-create the channels' smooth "pre-uplift" profiles. From this analysis, Clark and others concluded that there had been ~350 to 400 m of uplift-driven incision along the Kern and King rivers since 3.5 Ma and that, since 32 Ma, the Sierran crest had risen ~2500 m. Similarly, Figueroa and Knott (2010) attributed knickpoints in the profiles of southern Sierran rivers to recent uplift-driven incision.

The presence of 3.5 Ma (Dalrymple, 1963) basalt flows deep within Kern canyon and only 125 m above the Kern River constrains the maximum amount of recent incision and challenges Clark and others' conclusions (fig. 17). The contrast in incision depths determined by field evidence, ≤125 m, and those estimated in Clark and others (2005), 350 to 400 m, exposes the problem of analyzing knickpoints in granitic terrain to infer an uplift history. Convexities in river profiles were first used to reconstruct the history of Yosemite Valley (Matthes, 1930) but this work was criticized by others who refuted the assumption that channels in granitic bedrock have smooth steady-state profiles (Wahrhaftig, 1965; Christensen, 1966). When covered by soil and exposed to moisture, granite is weakened by chemical weathering and decomposes to sand-sized gruss, which is easily eroded by physical processes; when bare, however, chemical weathering processes are relatively ineffective and the rock is resistant to erosion (Twidale and Vidal Romani, 2005; Gabet and others, 2006). This differential erosion in granite creates a peculiar stepped landscape characterized by flat surfaces bordered by cliffs and canyons, as well as irregular stream profiles with autogenic knickpoints (Wahrhaftig, 1965). For example, Wahrhaftig (1965, p. 1186) demonstrated that knickpoints in the San Joaquin River basin were not caused by downcutting events and concluded that "a bench, summit flat, or nickpoint can develop in granitic terrain at any altitude at any time."

Given the weathering and erosional behavior of granitic landscapes, their bedrock stream profiles are unreliable for inferring uplift and incision histories (Wahrhaftig, 1965; Bateman and Wahrhaftig, 1966). For example, Clark and others (2005) determined that a large knickpoint on Durrwood Creek, a tributary to the Kern River, was the result of ~1000 m of uplift-driven incision. If this interpretation is correct, nearby tributaries should all record the same tectonic signal. Instead, the longitudinal profiles of the 4 nearest streams are all different from Durrwood Creek and are also different from each other (fig. 18) (see Webb, 1946 for profiles of all the Kern's tributaries). Depending on which stream was chosen, 200 m of incision (Freeman Creek) or 400 m (Needlerock Creek) might be estimated from one pulse of uplift, 1000 m of incision from 4 pulses of uplift (Peppermint Creek), or none at all (Rattlesnake Creek); similar examples can be found in the Kings River drainage. As noted in Wahrhaftig (1965, p. 1175), knickpoints found in granitic Sierran streams cannot "be projected to any common base-level." These profiles therefore falsify the assumption that knickpoints in these rivers are related to uplift-driven incision.

Analysis Summary

All but one of the studies concluding that there has been recent tilting and uplift in the *northern* Sierra are based on observations consistent with explanations unrelated to uplift or are founded on unsupported assumptions (table 1). The reverse gradients of three Eocene-Oligocene paleoreaches are suggestive of post-depositional uplift; however, because these reaches are within an active fault zone, they do not provide conclusive evidence for tilting of the Sierran block. Furthermore, tectonic quiescence is suggested by a paleohydraulical analysis of the Tertiary auriferous gravels (Cassel and Graham, 2011). Finally, the location of the Spring Creek gravel patch and Lindgren's observation on the S. Fork of the American River demonstrate that, by the Eocene-Oligocene, deep canyons had already been cut into the northern Sierra and that there has been relatively little bedrock incision since.

Some of the studies presenting direct evidence for significant late Cenozoic uplift of the *southern* Sierra are also compromised by unsupported assumptions (table 1). Nevertheless, this hypothesis is supported by Stock and others' (2004) study showing 200 to 400 m of incision since ~2.5 Ma and Huber's (1981) estimate of 1.2° of tilting at the western margin of the range since 10 Ma. However, horizontal shelfstone deposits in southern Sierran caves indicate that there has been little to no tilting since at least ~116 ka (Granger and Stock, 2004). Although modern vertical uplift rates of 1 to 2 mm/y have been attributed to tectonic activity (Hammond and others, 2012), crustal flexure from groundwater depletion in the Central Valley (Amos and others, 2014) may be primarily responsible. There is little geomorphic evidence, therefore, for active tectonic uplift in the southern half of the range.

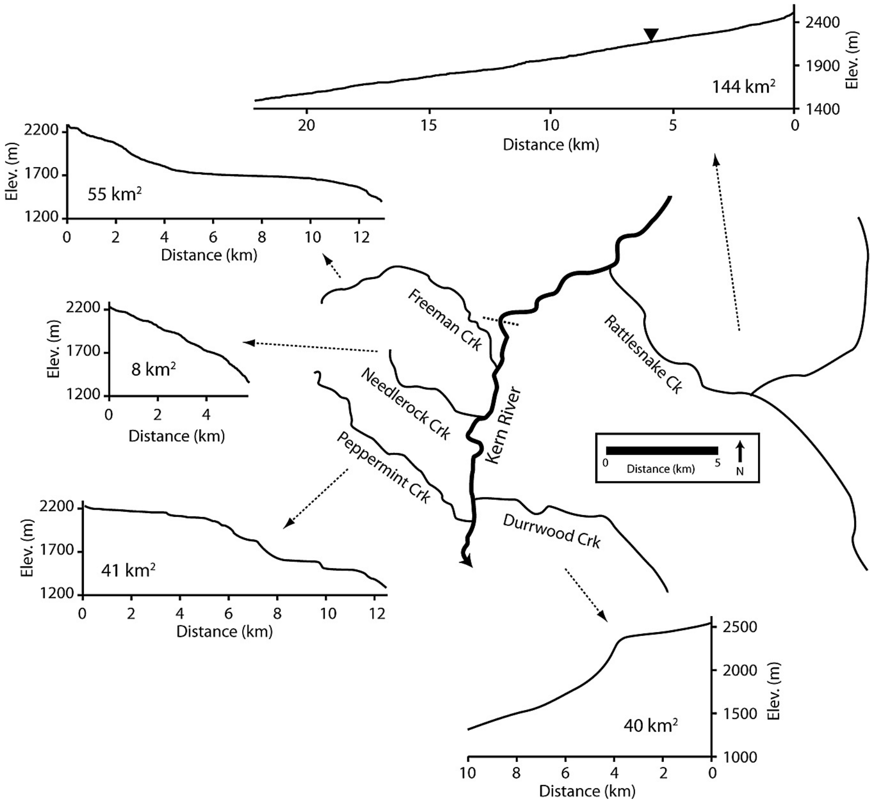


Fig. 18. Longitudinal profiles of tributaries to the Kern River (see fig. 1 for location). Each profile is plotted with the same vertical and horizontal scales. Although Clark and others (2005) attributed Durrwood Creek's ~1000-m knickpoint to a recent episode of uplift and incision, the profiles of nearby streams challenge this interpretation. Drainage areas given in plots; for Rattlesnake Creek, triangle marks location where the drainage area is the same as Durrwood Creek's. There is no correlation between knickpoint location and drainage area. There are no knickpoints on the Kern through this reach. Dashed line upstream of Freeman Creek is the location for the cross-section in figure 17. Coordinates for Durrwood Creek–Kern River junction: 36.061158, −118.466219. Profiles extracted from 30-m DEM.

A COMPLICATED GEOMORPHIC HISTORY OF THE SIERRA NEVADA

Attempts to infer the timing and magnitude of Sierran uplift have been confounded by lithological contrasts, multiple reconfigurations of drainage networks, and climatic changes. Differences in lithology between the northern and southern Sierra, divided approximately by the Merced River, suggest that it may be more appropriate to treat each half as a separate range that has evolved along its own trajectory (Wahrhaftig, 1965; Christensen, 1966). The southern half, composed primarily of batholithic rock, rises steeply from the Central Valley, a characteristic typical of granitic inselbergs (Twidale and Vidal Romani, 2005) (fig. 2). In the northern half, in contrast, the granitic core is buttressed along its western edge by a belt of resistant metamorphic rocks (Lindgren, 1911; Sklar and Dietrich, 2001; Cassel and Graham, 2011) that have served as a base-level to the granitic watersheds upstream and have given this part of the range its distinctive ramp-like profile (fig. 2). As a consequence of these lithological contrasts, the relief in the southern Sierra increases quickly from the Central Valley into the mountains whereas, in the north, the increase in relief is gradual (fig. 2). The differences in bedrock thus confound attempts to use basic geomorphic indices to

Table 1

Summary of techniques reviewed. Techniques used to support late Cenozoic uplift

Evidence used to support Late Cenozoic uplift	Analysis and Re-Assessment of the Evidence	Supports late Cenozoic uplift?
Northern Sierra Nevada		
Range-normal Eocene-Oligocene paleochannels presently tilted 0.7° more than range-parallel paleochannels (Lindgren, 1911).	Two of the reconstructed channels run uphill over >100m ridges, a physical impossibility. The paleoreaches were not part of single channels continuous in time and space.	No
Lindgren's (1911) ancestral South Yuba has three NNE-trending paleo-reaches tilted upstream.	These reaches are in a fault zone; post-depositional tectonic deformation could have produced the reversed gradients	?
Tertiary channel remnants are steeper than modern channels (Christensen, 1966)	Christensen's (1966) data set for modern rivers are primarily from small, semi-arid channels and is not applicable to the subtropical rivers of the Eocene Sierra. The gradients of the Tertiary remnants overlap with those of modern gravel-bedded rivers and, thus, argue against tilt. Paleoslope calculations based on grain size analysis of the ancient gravels also argue against tilt (Cassel and Graham, 2011).	No
Huber (1990) determined that a range-normal reach of the ancient Tuolumne River is steeper than a range-parallel reach and estimated 0.7° of tilt	Huber (1990) did not account for differences in lithology between the two reaches.	No
Older alluvial beds along western margin of the Sierra steeper than younger beds. Unruh (1991) used the difference in gradients to calculate 1.4° of tilt since 5 Ma. This tilt would explain the observation that the older alluvial beds are more dissected than the younger beds.	Extending 1.4° of tilt 50 km eastward to a patch of Eocene gravels at an elevation of 672 m implies that the deposit would have been ~500 m below sea level 5 Ma; there are no marine sediments associated with the gravels. A temporal decrease in sediment supply explains both the decrease in slope of the younger alluvial beds and the increased incision of the older beds.	No
Upper surface of fluvial sediments from ancestral Stanislaus and Feather Rivers steeper than the ancestral San Joaquin River (Wakabayashi and Sawyer, 2001)	There is no evidence that these paleorivers would have had the same paleoslope as the ancestral San Joaquin River	No
Paleoelevations of N. Fk. Feather River, inferred from 2.8 and 1.1 Ma volcanic deposits, used to calculate incision rates and knickpoint migration rates (Wakabayashi and Sawyer, 2001; Wakabayashi, 2013)	The volcanic deposits may not represent the paleochannel thalwegs at 2.8 and 1.1 Ma; other incision histories are possible. Calculated knickpoint migration rates are unusually fast given the lithology and, thus, cast doubt on the approach.	No
Paleoslopes of Eocene-Oligocene channel calculated from sediment size (Cassel and Graham, 2011)	Estimated paleoslopes similar to contemporaneous strath terraces and modern braided rivers.	No
Basal contacts of volcanic deposits used to infer 210 m of incision in the Yuba River since 3 Ma (Wakabayashi, 2013).	No evidence that volcanic rocks were deposited on bed of active channel. Eocene gravels along South Yuba River tributary suggests ~73 m of incision since Eocene- Oligocene.	No
Basal contacts of volcanic deposits used to infer > 900 m of incision in the N. Fk. American River and Mokulumne River since 3 Ma (Wakabayashi, 2013)	No evidence that volcanic rocks were deposited on bed of active channel. The S. Fk. American River lies between these two rivers and only incised 170 m since Eocene- Oligocene. Pliocene volcanic rocks mapped 200 m above valley floor of S. Fk. American River.	No

Table 1

(continued)

Evidence used to support Late Cenozoic uplift	Analysis and Re-Assessment of the Evidence	Supports late Cenozoic uplift?
Southern Sierra Nevada		
Tilted (1.4°) 10-Ma trachyandesite flow along San Joaquin River assumed to have cooled with horizontal surface because of columnar joints (Huber, 1981).	Lava can freeze with a sloping surface (for example, shield volcanoes). Lava does not need to be ponded to form columnar joints (Hetenyi and others, 2012).	No
The modern bedrock San Joaquin River inherited its meandering pattern from when it flowed over a gently-sloped alluvial plain (Huber, 1981).	Meanders can form in bedrock channels (Stark and others, 2010; Finnegan and Dietrich, 2011). Sinuousity along the modern San Joaquin River is dependent on lithology and, thus, its meanders are not inherited.	No
Fluvial deposits from the ancient San Joaquin River indicative of a channel with a slope of 0.001 (Huber, 1981).	Paleoslope calculation based on a pebble count at one site yields a range of gradients from 0.005 to 0.0008, consistent with Huber's (1981) assumed low original slope for the ancient San Joaquin River.	Yes
116 Ka calcite deposits in cave retain original horizontal surface (Granger and Stock, 2004).	Consistent with no significant tilting since 116 Ka.	Not since 116 Ka
Burial ages of cave deposits imply faster river incision in early Pliestocene than today (Stock and others, 2004).	Consistent with the waning effects of a period of uplift	Yes
Knickpoints in channel profiles interpreted as imprint of tectonic pulse (Clark and others, 2005; Figueroa and Knott, 2010).	Knickpoints in granitic rock commonly form independently of tectonic processes (Wahrhaftig, 1965; Christensen, 1966).	No
Extrapolation of tributary profiles downstream of knickpoints used to infer 350-400 m of uplift-driven incision on the Kern River since 3.5 Ma.	3.5 Ma basalt flows mapped 125 m above the Kern River.	No

infer spatial patterns in uplift rates, especially considering the anomalous weathering behavior of granitic rocks (Wahrhaftig, 1965). For example, the north-south decrease in mountain front sinuosity that has been used to argue for greater tectonic activity in the southern Sierra (Figueroa and Knott, 2010) coincides with the transition from metamorphic rocks to batholithic along the base of the range.

Furthermore, multiple generations of drainage networks have evolved over this lithological template. Although the dearth of Cenozoic deposits in the southern Sierra complicates efforts to reconstruct its geomorphic evolution, there is evidence for three different river systems in the northern Sierra. The first, in the late Jurassic-early Cretaceous (DeGraaff-Surpless and others, 2002), was a trellis network with gentle longitudinal reaches flowing northward in broad valleys cut through weak rocks; the longitudinal reaches were joined by steep transverse reaches cut through resistant rock, similar to the modern-day Appalachians (Matthes, 1930) (fig. 19A). This network was bounded to the west by a resistant ridge of greenstone that formed a drainage divide. In the late Cretaceous, this divide was breached by the headward advance of rivers on the western slope of the ridge (fig. 19B) (DeGraaff-Surpless and others, 2002). The elevations of these new rivers were lower than those of the trellis network, leading to stream piracy and drainage capture (Matthes, 1930; Matthes, 1960). As the

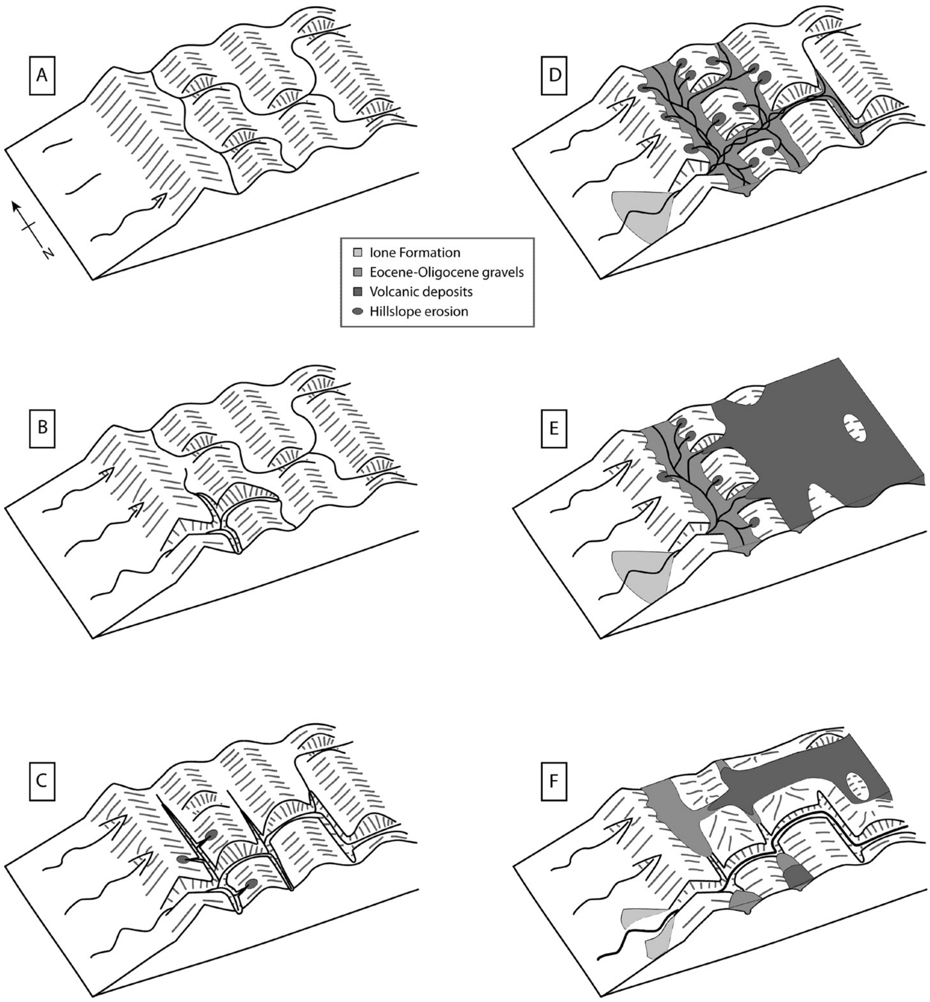


Fig. 19. Geomorphic evolution of the northern Sierra Nevada. (A) By the late Jurassic–early Cretaceous, a trellis network had developed, with a greenstone ridge forming a western drainage divide. (B) In the late Cretaceous, headward erosion of rivers across the greenstone ridge begins to capture channels from the trellis network. (C) Knickpoints moving up tributaries cut trenches through the longitudinal valleys. Hillslopes begin to shed their deep mantle of weathered regolith. (D) By the Eocene-Oligocene, a transverse river system has developed. High sediment supply and a low transport capacity through the greenstone ridge leads to widespread aggradation and braided rivers; fine-grained material deposited west of the ridge creates the Ione Formation (Cassel and Graham, 2011). (E) Oligocene-Miocene volcanic eruptions bury much of the range. (F) Rivers incise back down through the volcanic and fluvial sediment, eventually reoccupying the transverse network. Figures A–C modified from DeGraaff-Surpless and others (2002).

heads of the new rivers cut eastward, they likely exploited and deeply incised some of the transverse reaches of the original trellis network to create the second major drainage system, one that ran primarily down the Sierran ramp (fig. 19C). During this period, the deep canyons of the Sierra Nevada, like that of the South Fork of the American River (Lindgren, 1911) and the South Yuba River, were cut to nearly their present elevations. Similarly, apatite (U-Th)/He ages suggest that deep canyons had also been incised in the southern Sierra by this time (House and others, 1998). With the deepening of the trunk streams, knickpoints moved up into the original longitudinal valleys, carving deep trenches [Lindgren (1911) referred to these as "gutters"] and destabilizing the hillslopes. This era of landscape rejuvenation is well documented by relatively rapid erosion rates of nearly 1 mm/y (Cecil and others, 2010). As the wave of incision continued its sweep eastward and up tributaries, thick regolith was stripped from the landscape and delivered to the fluvial system. By Eocene-Oligocene times, the sediment supply from local erosion as well as from the vast amounts of material delivered from further upstream overwhelmed the transport capacity of the rivers and the valleys began to aggrade (fig. 19D) (Cassel and Graham, 2011). Cassel and Graham (2011) concluded that sediment ponded behind a greenstone ridge in the Sierran foothills and, over time, the locus of deposition moved eastward up the range. Referring to the ancestral Yuba, Lindgren (1911, p. 34) similarly observed that its gravels were "held back as if by a dam by the narrow canyon of the lower, transverse river course." As the valleys aggraded, the bedrock channels were buried by braided rivers, the third fluvial network. These two generations of river systems can be seen in Spring Creek (fig. 11): the presence of auriferous gravels along the modern stream demonstrates that Spring Creek's valley already existed by the Eocene-Oligocene and was oriented southwards into a deep South Yuba River canyon (Yeend, 1974; Schaffer, 1997). Paleo-current indicators in the gravel deposits, however, attest to a later river flowing to the northwest (Yeend, 1974).

With the removal of weathered regolith from the hillslopes, the sediment supply would have waned while peak discharges increased, leading to incision into the fluvial deposits [an example of Schumm's (1993) complex response]. In some instances, the channels reached the original bedrock surface (for example, Lindgren, 1911, Plate XXV). However, volcanic eruptions from the mid-Oligocene to the late Miocene again buried the valleys (fig. 19E) (Slemmons, 1966; Busby and others, 2008; Busby and Putirka, 2009). Since then, the rivers have cut back down through the accumulations of volcanic and fluvial sediment. Rivers such as the South Yuba and the South Fork of the American (Lindgren, 1911) have slipped back into their original canyons to reoccupy the transverse drainage network (fig. 19F). The intermittent access that these flows have had to basement rock throughout the Cenozoic explains the relatively minor amounts of net incision on these two rivers since Eocene-Oligocene times. Presently, with the bottoms of the major canyons now clear of the auriferous gravels and volcanic material, the rivers have a renewed opportunity to attack their bedrock beds. Indeed, Hurst and others (2012) have documented an incision wave traveling up hillslopes along the Middle Fork Feather River, and strath terraces several meters above the active channel can be seen along this channel and the South Yuba.

Finally, the significant changes in climate over the course of the Sierra's Cenozoic history also complicate efforts to reconstruct its geomorphic evolution. Since the Early Eocene Climatic Optimum, global temperatures have been in general decline, with a steep plunge in the Miocene (Zachos and others, 2001). The Sierra Nevada, therefore, has evolved under a range of conditions, from subtropical to glacial (Chamberlain and others, 2012), and climatic influences must be filtered out before geomorphic evidence can be used to infer tectonic events (Molnar and England, 1990). The role of climate may be especially important in the evolution of granitic landscapes. As noted earlier, the incision rate of a channel may be strongly controlled by the size of its sediment (Sklar and Dietrich, 2001). Under warm and wet conditions, granitic rocks weather quickly to gruss, relatively fine material inefficient at eroding bedrock beds (Wahrhaftig, 1965). During the canyon-cutting period in the Sierra, tributaries supplied with only gruss may not have been able to keep pace with their rapidly incising trunk streams. As a result, the low relief highlands became somewhat geomorphologically decoupled from the deep canyons to produce a landscape often interpreted as an old eroded surface that has been recently uplifted and incised (for example, Lindgren, 1911; Wakabayashi, 2013).

CONCLUSION STATEMENT

The review of the techniques in these papers suggests three potentially fruitful avenues of geomorphic research for understanding the Cenozoic history of the Sierra Nevada. First, extending the record of channel incision through time and space with careful studies (for example, Stock and others, 2004; Ward and others, 2005; Fuller and others, 2009) would help disentangle the roles of climate, sediment supply, and uplift in the evolution of the Sierran landscape. In the north, Spring Creek could be a particularly favorable field site for this type of investigation because its upper reach has not changed since Eocene-Oligocene times; in essence, the 2-km stretch between the gravels and the junction with the South Yuba River is a bridge between the present and the Sierra's deep past. Paired strath terraces along the San Joaquin and Kings rivers in the southern Sierra also present opportunities for investigating the timing of channel incision in the range. Second, the discovery of tilt-markers whose original positions can be determined with certainty would be helpful in reconstructing the range's tectonic history. Granger and Stock (2004) were able to use shelfstone calcite deposits to precisely measure Sierran post-glacial rebound because the concretions had formed on a level water surface; there may be similar unrecognized opportunities to measure tilt over longer time-scales, such as paleoshorelines. Finally, as demonstrated by Cassel and Graham (2011), detailed examinations of the sediments that once covered the Sierra can provide paleotopographic information and this approach could be applied throughout the region. Reconstructing in 3 dimensions the original extent of the auriferous gravels and the volcanic deposits would be invaluable in deciphering the geomorphic history of the range.

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