

## Uplift of the Sierra Nevada, California

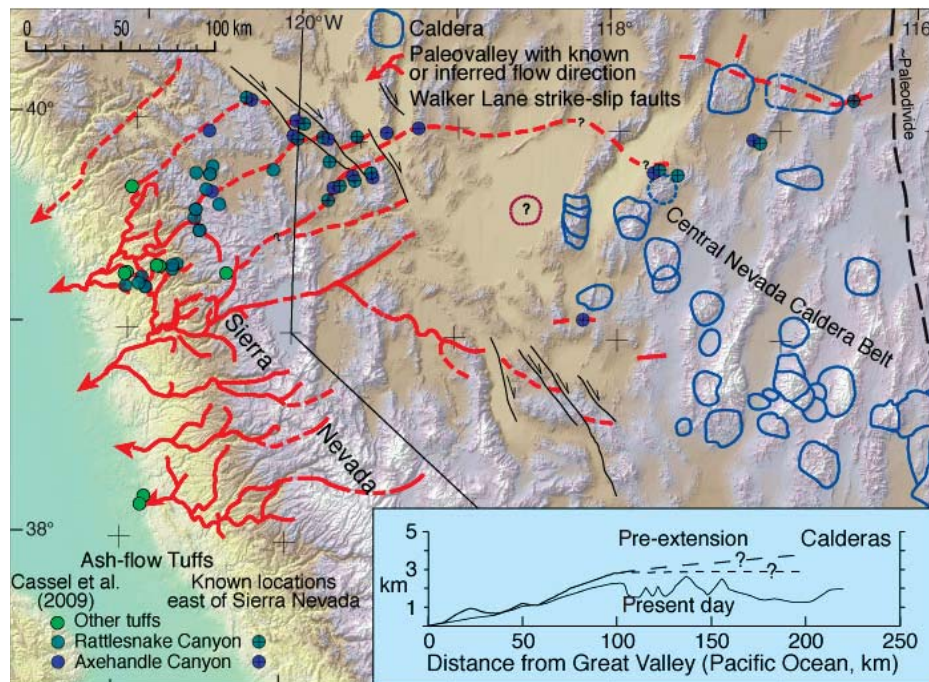
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Topography is a first-order indicator of geology, from features as local and simple as resistant strata making ledges, to as regional and complex as how continental-scale mountain ranges are supported by thick crust. Understanding the character and evolution of topography is fundamental to understanding a region's tectonic evolution. Variations in topography through time have profound implications for processes as obvious as erosion and sedimentation and as diverse as global climate and the formation of mineral deposits.

The interplay between topography and tectonics is exemplified by the evolution of topography of the Sierra Nevada and Great Basin (United States), and by geologists' interpretation of that evolution. The formation of the Sierra Nevada and its relationship to the adjacent Great Basin have been major geologic questions since the 1800's (LeConte, 1886). From the study of Eocene gold-bearing paleoriver deposits in the Sierra Nevada, Lindgren (1911) concluded that the Eocene mountain range had similar relief but was slightly lower than the modern range. He also inferred a drainage divide roughly coincident with the modern divide, but many geologists subsequently recognized that the paleorivers drained from at least as far east as the Basin and Range of western Nevada (e.g., Yeend, 1974). We now recognize that an extensive paleoriver system drained much of what is now the western Great Basin into the Pacific Ocean by the Eocene (Fig. 1; Faulds et al., 2005; Garside et al., 2005; Henry, 2008). Oligocene ash-flow tuffs erupted from calderas in central Nevada flowed westward down these drainages (Deino, 1985; Faulds et al., 2005). What is now the Great Basin probably was a high plateau formed during Mesozoic contraction and crustal thickening (Dilek and Moores, 1999; DeCelles, 2004). DeCelles (2004) named this plateau the Nevadaplano, by analogy to the Altiplano of the Andes Mountains. Continuity of paleodrainages from central Nevada across the Sierra Nevada to the Pacific Ocean demonstrates that the Sierra Nevada was the flank of the Nevadaplano, but does not resolve the absolute elevation of either.

Following Lindgren (1911), consensus until recently was that Sierran uplift occurred in the last 10 Ma, predominantly by westward block tilting of the entire range (e.g., Unruh, 1991; Wakabayashi and Sawyer, 2001). Conversely, many recent studies argue that the



**Figure 1.** Cassel et al. (2009) determined  $\delta D$  of hydration water in volcanic glass from 31–28 Ma old ash-flow tuffs in the Sierra Nevada and westernmost Basin and Range. Their data indicate that the Sierra Nevada near Lake Tahoe was ~2800 m high at the time, consistent with early (Late Cretaceous–early Cenozoic) uplift. The tuffs erupted from calderas in central Nevada and flowed down an extensive paleoriver system that drained to the Pacific Ocean, which was in the Great Valley at the time (Faulds et al., 2005; Garside et al., 2005). The Sierra Nevada was the western flank of a high plateau, the Nevadaplano of DeCelles (2004), in what is now the Great Basin. Cassel et al.'s data also suggest topography flattened abruptly across what is now the Sierra Nevada–Basin and Range boundary (short dashed line in topographic profile), which suggests much of the plateau was at a similar, 2800 m, elevation. If elevation rose even gently eastward (long dashed line), the plateau could have been significantly higher.

Sierra Nevada was uplifted in the late Mesozoic, and remained high or even subsided in the late Cenozoic (Small and Anderson, 1995; Wernicke et al., 1996). In this case, late Miocene faulting on its eastern flank represents subsidence of the Basin and Range, rather than uplift of the Sierra Nevada.

Analysis of stable isotopes in material that incorporated ancient meteoric water is an important tool for determining paleoelevation. In the western United States, the underlying premise is that precipitation depletes  $^{18}O$  and D from air moving eastward off the Pacific Ocean and rising over the Sierra Nevada. Depletion causes moisture in the air and precipitation to become progressively isotopically lighter eastward. Authigenic minerals can record the isotopic signature of ancient rainfall and thus

preserve the signature of this elevation-induced Sierra Nevada isotopic rain shadow.

Mulch et al. (2006) analyzed  $\delta D$  of kaolinite resulting from Eocene weathering in the paleovalleys of the northern Sierra Nevada and concluded that the mountain range near Lake Tahoe was  $\geq 2200$  m high in the Eocene, similar to what it is today. Mulch et al. limited their sampling to only part of the western slope of the Sierra Nevada, but Cassel et al. (2009, p. 547 in this issue of *Geology*) extended this approach by analyzing  $\delta D$  of hydration waters of volcanic glass in Oligocene ash-flow tuffs that occupy the paleovalleys. They were able to sample from the former Pacific shoreline at the western edge of the Sierra Nevada eastward into the western Basin and Range (Fig. 1). In addition to sampling a much longer transect that

crosses a major tectonic boundary, they sampled zero-elevation deposits that provide a baseline for comparison with higher-elevation data. Cassel et al. concluded that the modern crest of the Sierra Nevada near Lake Tahoe was ~2800 m high in the Oligocene, even greater than it is today. They also concluded that the region up to 50 km to the east, in the modern Basin and Range, was at about the same elevation; i.e., rivers were steep across the Sierra Nevada but flattened eastward across the Great Basin toward their headwaters. Their data thus support uplift of the Sierra Nevada in the Late Cretaceous or early Cenozoic, and allow but do not require post-Oligocene uplift.

Several studies using stable isotopes concluded that a rain shadow existed east of the Sierra Nevada since at least the middle Miocene (Poage and Chamberlain, 2002). However, a rain shadow should have formed as soon as the Sierra Nevada became a topographic high, so analysis of the older (pre-middle Miocene) isotopic record in the Great Basin is worthwhile. For example, a study of ~40 Ma old mineral deposits in northeastern Nevada (Hofstra et al., 1999) indicates  $\delta D$  of meteoric water at that time overlapped with that found by Cassel et al. (2009) in western Nevada, potentially suggesting a similar high elevation. The mineral deposits formed close to the paleodivide inferred for the Nevadaplano at that time (Henry, 2008), thus presumably at its highest elevations.

The evolution of topography says a lot about the mechanisms that generated the topography. The data of Mulch et al. (2006) and Cassel et al. (2009) support interpretations based on other data that uplift of the area now occupied by the Sierra Nevada occurred in the Late Cretaceous or early Cenozoic, probably as a result of crustal thickening related to contraction and voluminous batholithic magmatism. Thermochronology in the same region investigated by Cassel et al. indicates rapid exhumation between 90 and 60 Ma ago, and is consistent with Late Cretaceous or early Cenozoic uplift (Cecil et al., 2006). In contrast, westward tilt of sedimentary deposits along the western edge of the Sierra Nevada and analysis of gradients in the Eocene rivers support late Cenozoic uplift (Wakabayashi and Sawyer, 2001; Jones et al., 2004). In one proposed mechanism, Ducea and Saleeby (1996) and Jones et al. (2004) attribute ~1 km of late Cenozoic uplift to removal of a dense, eclogitic root to the Sierra Nevada batholith. Studies of xenoliths in late Cenozoic igneous rocks support removal of the eclogitic root (Farmer et al., 2002), and coeval, rapid increase in river incision support uplift at that time (Stock et al., 2004).

Many questions remain about uplift of the Sierra Nevada and Great Basin. To what extent did the topography of these regions develop and evolve together or separately? As pointed

out by Jones et al. (2004), uplift of the Sierra Nevada has consequences for adjacent regions, so events in the adjacent regions ought to reflect this uplift. Ash-flow tuffs like those investigated by Cassel et al. are found across the Great Basin, so similar paleoaltimetry could be done across possibly the entire Great Basin. What do the character of Eocene sedimentary deposits in paleovalleys indicate about river gradients, and what do the gradients say about regional topography? Are there other possible mechanisms to drive late Cenozoic uplift? Could uplift in part be relative to a subsiding Basin and Range?

Cassel et al. (2009) provide powerful new evidence for an early, high Sierra Nevada and western Great Basin, but their data will certainly not be the final word in the debate about Sierran uplift. Whatever conclusions are drawn about uplift, the recent revolution of thinking is a grand illustration of how consensus views change through time and with new and different research methods.

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