

# Cenozoic tectonic and topographic evolution of the northern Sierra Nevada, California, through stable isotope paleoaltimetry in volcanic glass

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## ABSTRACT

We determine the paleoelevation of the northern Sierra Nevada (California) in the Oligocene based on hydrogen stable isotope compositions of meteoric water preserved within volcanic glass from ignimbrites sampled across the range. A 48‰ decrease in the isotopic composition of hydrated glass from ignimbrites located near paleo-sea level to ignimbrites 100 km to the east reflects the effect of ancient high topography on precipitation. These data show that 31–28 Ma ago, the northern Sierra Nevada had a steep western gradient and elevations similar to the present. This study, placed in the context of other paleoaltimetry studies, suggests that the range was a high topographic feature throughout the Cenozoic and that the majority of uplift occurred in the Late Cretaceous to early Cenozoic, much earlier than some studies have proposed.

## INTRODUCTION

The striking topography of the Sierra Nevada of California has motivated scientific inquiry for the past century, yet the evolution of the range since the Cretaceous and the timing and drivers for uplift remain controversial. Along the western slopes of the northern Sierra Nevada, and across the range crest into Nevada, a sequence of Oligocene ignimbrites preserves isotopic compositions of meteoric waters incorporated soon after emplacement, reflecting the influence of ancient topography on precipitation (Fig. 1). This study uses the hydrogen isotope composition ( $\delta D$ ) of hydrated volcanic glass to determine the Oligocene elevation gradient of the range. This study presents a complete transect across the northern Sierra Nevada in a time period for which we have no isotope paleoaltimetry data (50–18 Ma ago), providing a critical link between isotopic studies from Miocene to Holocene (cf. Crowley et al., 2008; Mulch et al., 2008) and the isotopic study of weathered Eocene fluvial deposits in the Sierra Nevada foothills (Mulch et al., 2006).

The northern Sierra Nevada is an ideal setting for a stable isotope paleoaltimetry study because of a dominant wind direction (west to east); proximity to the ancient ocean, marked by Eocene Ione Formation deposits preserved along the eastern edge of the Great Valley (Dickinson et al., 1979); and extensive exposure of ignimbrites containing unaltered glass, allowing for measurements of  $\delta D$  upgradient (Fig. 1). We present a hydrogen isotopic composition profile of the Sierra Nevada and a determination for paleoelevation 31–28 Ma ago, based on 150  $\delta D$  values from hydrated volcanic glass sampled at 30 locations along two northeast-southwest transects and two locations at approximate paleo-sea level (Fig. 1; GSA Data Repository Table DR1<sup>1</sup>). This study uses recent advances in measurement of hydrogen isotopes of volcanic glasses to determine the past topographic and climatic history, as applied by Mulch et al. (2008) to Miocene–Holocene glasses from ashes deposited across the western U.S. Cordillera. Our

<sup>1</sup>GSA Data Repository item 2009126, stable isotope analyses methods and Table DR1, is available online at [www.geosociety.org/pubs/ft2009.htm](http://www.geosociety.org/pubs/ft2009.htm), or on request from [editing@geosociety.org](mailto:editing@geosociety.org) or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

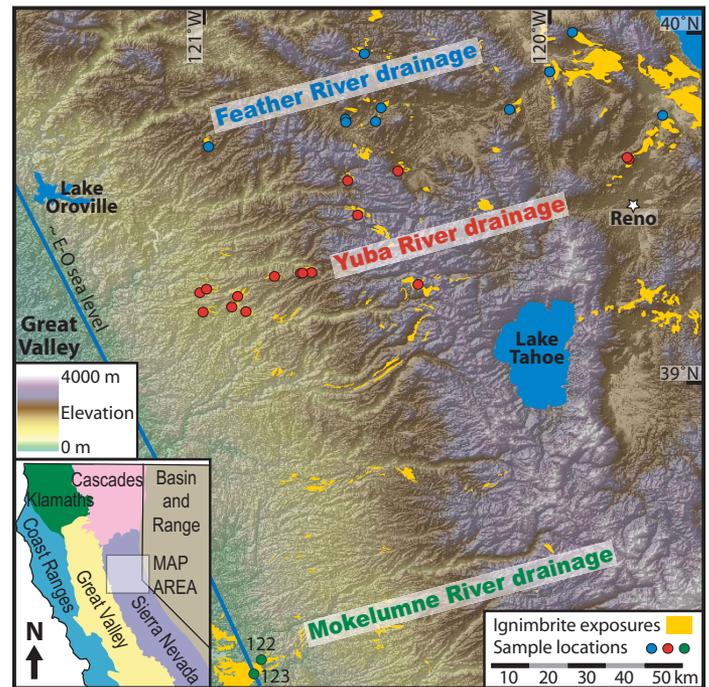


Figure 1. Map of study area in northern Sierra Nevada. Sample locations (circles): red—Yuba River drainage; blue—Feather River drainage; green—Mokelumne River drainage. Paleo-sea level based on Ione Formation coastal deposits. Digital elevation model from the U.S. Geological Survey National Map (<http://nationalmap.gov/index.html>).

data provide the basis for estimates of total Oligocene topographic relief and the timing of uplift, and improve our understanding of the topographic evolution of the range.

## GEOLOGIC FRAMEWORK

An amalgam of Paleozoic–Mesozoic continental margin, accretionary prism, and arc plutonic rocks form the basement of the western slope of the northern Sierra Nevada (Chen and Moore, 1982; Girty et al., 1996; Ducea, 2001). The northern range has lower mean and peak elevations than the south; the deepest batholithic rocks are exposed in the south (Ague and Brimhall, 1988), whereas Cenozoic cover strata well preserved in the north are not generally present in the south. These differences likely reflect contrasting Cenozoic tectonic and geomorphic histories (Clark et al., 2005).

Overlying the basement in the northern Sierra Nevada, the fluvial “auriferous gravel” or “prevolcanic gravel” was exposed by hydraulic gold mining from 1853 C.E. to 1882 C.E., and is composed of Eocene–Oligocene gravel, sand, and minor clay (Lindgren, 1911; Bateman and Wahrhaftig, 1966). These strata are overlain by Oligocene rhyolitic

ignimbrites, tuffaceous paleosol horizons, and volcanoclastic fluvial sand (Valley Springs or Delleker Formations; Wagner et al., 2000). Two geochemically distinct, unwelded ignimbrites in the northern Sierra Nevada correlate with units identified and isotopically dated in western Nevada: the tuffs of Rattlesnake Canyon and Campbell Creek (Henry et al., 2004; Cassel and Graham, 2008). These ignimbrites were sourced from calderas in central Nevada and have  $^{40}\text{Ar}/^{39}\text{Ar}$  ages of  $31.0 \pm 0.1$  and  $28.8 \pm 0.1$  Ma old, respectively (Faulds et al., 2005). The lithology, exposure, and preservation of Oligocene ignimbrites allow for excellent sample density, age control, and geographic coverage.

## PREVIOUS RESEARCH

Previous northern Sierra Nevada studies have used Cenozoic and older units to interpret uplift in three ways: (1) comparisons of modern topographic gradients and projections of tilted strata (Lindgren, 1911; Hudson, 1960; Huber, 1981, 1990; Unruh, 1991; Wakabayashi and Sawyer, 2001; Jones et al., 2004); (2) Eocene and Miocene paleobotanical and stable isotopic proxies for paleoelevation (Axelrod, 1957; Wolfe et al., 1997, 1998; Chamberlain and Poage, 2000; Poage and Chamberlain, 2002; Horton et al., 2004; Mulch et al., 2006, 2008; Crowley et al., 2008); and (3) estimates of long-term exhumation rates through (U-Th)/He thermochronology of bedrock (Cecil et al., 2006). These three types of studies have yielded diverse and sometimes conflicting results.

Stratal studies have used the modern position and dip of Cenozoic units to estimate the timing of surface uplift, assuming that the Sierra Nevada was a low-elevation landscape after Late Cretaceous–early Cenozoic denudation of the volcanic arc, and was then tilted to the southwest as a rigid block 8.4–3.4 Ma ago, causing uplift at the range crest (Lindgren, 1911; Hudson, 1960; Christensen, 1966; Huber, 1981, 1990; Unruh, 1991; Wakabayashi and Sawyer, 2001; Jones et al., 2004). Estimates of late Cenozoic surface uplift are commonly between 1500 and 2500 m, and Jones et al. (2004) suggested the removal of dense lithosphere as a driver (Ducea and Saleeby [1996, 1998], Zandt et al. [2004], and Boyd et al. [2004] proposed this mechanism for the southern Sierra Nevada). This method of estimating topographic change, however, often relies on uncertain correlation of units with geographically limited exposures, such as the prevolcanic gravel. Some studies have mistaken rock uplift for surface uplift by projecting gradients and tilted units directly up to the modern crest position to estimate changes in elevation (cf. England and Molnar, 1990), and assumed no erosion of the range, ignoring significant and localized Eocene–Oligocene fluvial deposition and the tilt produced due to erosional loading (Small and Anderson, 1995).

Paleoaltimetry studies based on isotopic or botanical proxies (cf. Wolfe et al., 1998; Mulch et al., 2006, 2008), however, indicate a relatively high Sierra Nevada in the Eocene and middle Miocene with little to no late Cenozoic surface uplift. Mulch et al. (2006) used the  $\delta\text{D}$  of kaolinite in Eocene prevolcanic gravel in the northern Sierra Nevada foothills to estimate paleoelevation and proposed significant pre-Eocene surface uplift, followed by lesser amounts of late Cenozoic uplift. Studies of authigenic minerals in strata east of the Sierra Nevada (Chamberlain and Poage, 2000; Poage and Chamberlain, 2002; Horton et al., 2004), and of mammalian tooth enamel (Crowley et al., 2008) and volcanic glasses (Mulch et al., 2008) from both sides of the current range crest, indicate the presence of a rainshadow effect produced by high topography since the middle Miocene (12–18 Ma ago).

Crustal structure modeling and thermochronology from the southern Sierra Nevada also support Cenozoic high topography (Wernicke et al., 1996; House et al., 1998, 2001), but studies have focused almost exclusively on the southern range. Based on xenolith, seismic, and crustal strain data, Wernicke et al. (1996) found that southern Sierra Nevada crust is similar in thickness to the highly extended Basin and Range, and suggested that the range maintained or lost elevation in the Cenozoic. Using

(U-Th)/He ages, House et al. (1997, 1998, 2001) concluded that ancient fluvial relief and mean elevation in the southern Sierra Nevada have either not changed or gradually lowered in the Cenozoic. Clark et al. (2005) confirmed this pattern of cooling ages, but noted the lack of temporal constraints on elevation changes between 32 and 3.5 Ma ago. Thermochronology along the Yuba River in the northern Sierra Nevada (Cecil et al., 2006) showed that total exhumation in the past 60 Ma was  $<3$  km, with faster exhumation rates in the Cretaceous, but these data do not provide the resolution necessary to deduce smaller elevation changes within the Cenozoic (see Farley, 2002). Furthermore, surface uplift cannot be uniquely inferred from thermochronologic methods alone (Small and Anderson, 1995).

## STABLE ISOTOPE PALEOALTIMETRY

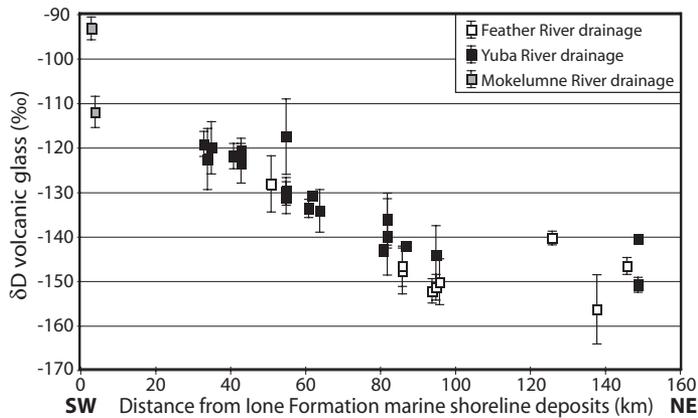
Stable isotope paleoaltimetry is based on the observation that the isotopic composition of precipitation changes with altitude due to Rayleigh distillation, resulting in precipitation that is progressively depleted in  $^{18}\text{O}$  and D at higher elevations (Dansgaard, 1964; Chamberlain and Poage, 2000; Rowley et al., 2001). The  $\delta\text{D}$  of precipitation scales at a predictable rate with elevation (Poage and Chamberlain, 2001), which acts as the dominant control on  $\delta\text{D}$ ; thus the change in elevation along a transect can be estimated based on the change in  $\delta\text{D}$  of hydration water in volcanic glass. Meteoric water enters erupted glass through early low-temperature hydration and  $\text{H}^+$  exchange for  $\text{Na}^+$  and  $\text{K}^+$  ions (Cerling et al., 1985). Friedman et al. (1993) showed that hydration water preserves the  $\delta\text{D}$  of ancient meteoric waters, and does not exchange further once the glass is saturated, which occurs within 5 ka of deposition. Sample values, however, cannot be interpreted as a direct measure of  $\delta\text{D}$  of precipitation, but reflect changes in meteoric water composition upgradient. Some higher elevation precipitation is incorporated into meteoric waters downstream through groundwater and surface transport, so the glass records the  $\delta\text{D}$  of the hypsometric mean of the elevation of the drainage basin above that sample location (cf. Rowley et al., 2001; Rowley, 2007), resulting in dilution of less-enriched waters lower in the basin and an overall minimum estimate of topographic gradient. This minimum estimate is nonetheless useful for discerning between tectonic models.

Ignimbrites were sampled at exposures north of  $38^\circ\text{N}$ , and the  $\delta\text{D}$  of ancient hydration water in matrix glass separates was determined at each location (Fig. 1). Glass fractions of 99% purity were prepared through size, magnetic, and gravity separations, and checked for purity and alteration with a petrographic microscope. Samples with any clay alteration or visible birefringence were not analyzed (see the Methods description in the Data Repository).

## RESULTS AND DISCUSSION

The  $\delta\text{D}$  of the volcanic glass samples decreases at a steady rate from  $-95\text{‰} \pm 3\text{‰}$  and  $-115\text{‰} \pm 4\text{‰}$  at the most western locations, to values ranging from  $-149\text{‰} \pm 7\text{‰}$  to  $-156\text{‰} \pm 3\text{‰}$  at the locations  $\sim 100$  km east of the Ione marine deposits (Fig. 2; Table DR1). This  $\sim 48\text{‰}$  decrease in  $\delta\text{D}$  of meteoric water is similar to the isotopic gradient of precipitation over the range today (Ingraham and Taylor, 1991), and reflects an increase in mean elevation from west to east 31–28 Ma ago. Values from samples taken in western Nevada are between  $-145\text{‰}$  to  $-160\text{‰}$   $\delta\text{D}$ , indicating no significant increase in Oligocene elevation farther east (Methods; see the Data Repository). These results show that, contrary to many previous studies, the northern Sierra Nevada was an area of high topography in the Oligocene, comparable to the modern range. This study is consistent with stable isotope paleoaltimetry studies from the Eocene (Mulch et al., 2006) and Miocene (e.g., Chamberlain and Poage, 2000; Crowley et al., 2008; Mulch et al., 2008), suggesting that the range was a significant topographic feature throughout the Cenozoic.

The isotopic lapse rate (the average change in  $\delta\text{D}$  with elevation) is based on the distribution of condensation and is controlled by



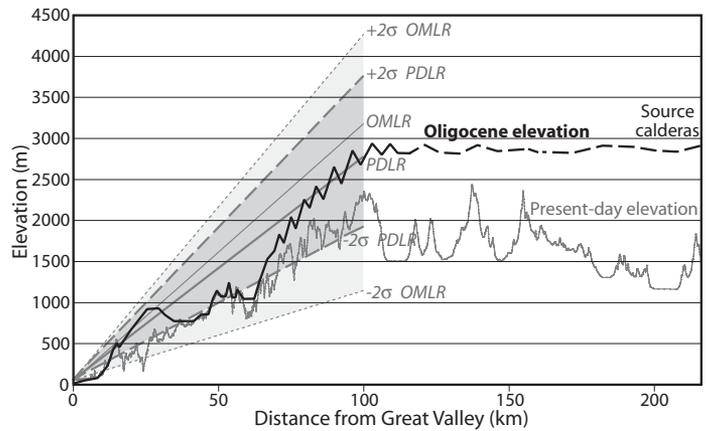
**Figure 2.** Hydrogen isotopic composition of hydration water from volcanic glass ( $\delta D\text{‰}$ ) versus distance of sample from lone Formation coastal deposits (measured as minimum distance from approximate paleo-sea level; Fig. 1). Glass sampled from ignimbrites at modern elevations of 205–1924 m. Black—Yuba River drainage samples; white—Feather River drainage samples; gray—Mokelumne River drainage samples. Values represent averages of multiple analyses of each sample,  $\pm 2\sigma$  error bars (Table DR1; see footnote 1).

low-elevation temperature and relative humidity (Rowley et al., 2001). The modern northern Sierra Nevada lapse rate, an empirical linear calibration of surface and shallow groundwater data from a transect across a similar latitude to this study, is  $-1.74\text{‰}/100\text{ m}$  (Ingraham and Taylor, 1991). This estimate applied to our data indicates an overall change in elevation across the Oligocene transect of  $2800\text{ m} \pm 900\text{ m}$  ( $2\sigma$  error; Fig. 3). An Oligocene lapse rate and elevation estimate were calculated using the model of Rowley et al. (2001) and Rowley (2007), combined with climate estimates based on paleobotanical data and an Oligocene general circulation model (Wolfe et al., 1998; Lunt et al., 2007). The elevation change estimated by the model is  $3200\text{ m} +1100/-2000\text{ m}$  ( $2\sigma$  error; see Rowley et al., 2001; Fig. 3). These results indicate that the western side of the Oligocene Sierra Nevada had a steep gradient, similar to the present range.

Little to no surface movement from the Oligocene to the present, as indicated by our results, implies that uplift of the Sierra Nevada occurred in the Late Cretaceous to early Cenozoic, likely driven by geodynamic processes related to Mesozoic subduction along the Pacific margin, and coinciding with relatively faster exhumation rates (Cecil et al., 2006). Maximum late Cenozoic uplift in the northern Sierra Nevada, such as that proposed by Jones et al. (2004), is 700 m (present-day lapse rate) or 1400 m (Oligocene modeled lapse rate) (Fig. 3), although it is likely that mean surface elevations of the western flank of the range were not greatly affected by late Cenozoic tectonics (cf. Small and Anderson, 1995; Wernicke et al., 1996; Cecil et al., 2006). The Oligocene Sierra Nevada isotopic profile shows a significant increase in mean elevation along the transect, and ignimbrites are preserved on both sides of the modern crest of the range, so the source calderas were likely located in a region of similarly high topography to the east of the modern range (Wolfe et al., 1997; Faulds et al., 2005; Cassel and Graham, 2008).

## CONCLUSIONS

To gain a better understanding of the Cenozoic tectonic evolution of the northern Sierra Nevada, Oligocene ignimbrites were the focus of a detailed stable isotope paleoaltimetry study. Hydrated glass was used as a proxy for  $\delta D$  of Oligocene meteoric water, which decreases steadily from west to east by  $48\text{‰}$  (Fig. 2), reflecting an increase in mean elevation along the transect across the ancestral range. Based on these data, the northern Sierra Nevada was an area of high topography in the early Oligo-



**Figure 3.** Topographic profile comparison of present-day and Oligocene elevations along Yuba River drainage in northern Sierra Nevada based on stable isotope paleoaltimetry results (solid thick line: present-day lapse rate [PDLR]; thin line: Oligocene modeled [OMLR]; dashed lines:  $\pm 2\sigma$  error bars). Location of ignimbrite source calderas noted (assuming 20% extension within western Nevada, 100% in central Nevada).

cene, similar to the modern range. Ignimbrites traveled from their source calderas in central Nevada across what is now the crest of the range, indicating that the Oligocene drainage divide must have been much farther east than it is today (Fig. 3).

This study provides paleoelevation data for a critical time period (31–28 Ma ago) and, placed in the context of other recent studies (e.g., Wolfe et al., 1997; Mulch et al., 2006, 2008), shows that the range was likely a long-standing topographic feature throughout the Cenozoic, with a persistent steep western gradient and a region of high topography to the east of the range where Oligocene source calderas were located (Fig. 3). Our conclusions are also consistent with thermochronologic and crustal structure studies throughout the Sierra Nevada (Wernicke et al., 1996; House et al., 1998, 2001; Cecil et al., 2006). Thus, the high surface elevations present today cannot all be attributed to late Cenozoic tectonics; major surface uplift in the northern Sierra Nevada occurred in the Late Cretaceous–early Cenozoic, likely driven by geodynamic processes related to Mesozoic subduction.

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