A Miocene to Pleistocene climate and elevation record of the Sierra Nevada (California)

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Orographic precipitation of Pacific-sourced moisture creates a rain shadow across the central part of the Sierra Nevada (California) that contrasts with the southern part of the range, where seasonal monsoonal precipitation sourced to the south obscures this rain shadow effect. Orographic rainout systematically lowers the hydrogen isotope composition of precipitation (δD_{ppt}) and therefore δD_{ppt} reflects a measure of the magnitude of the rain shadow. Hydrogen isotope compositions of volcanic glass (δD_{glass}) hydrated at the earth's surface provide a unique opportunity to track the elevation and precipitation history of the Sierra Nevada and adjacent Basin and Range Province. Analysis of 67 well dated volcanic glass samples from widespread volcanic ash-fall deposits located from the Pacific coast to the Basin and Range Province demonstrates that between 0.6 and 12.1 Ma the hydrogen isotope compositions of meteoric water displayed a large (>40%) decrease from the windward to the leeward side of the central Sierra Nevada, consistent with the existence of a rain shadow of modern magnitude over that time. Evidence for a Miocene-to-recent rain shadow of constant magnitude and systematic changes in the longitudinal climate and precipitation patterns strongly suggest that the modern first-order topographic elements of the Sierra Nevada characterized the landscape over at least the last 12 million years.

climate | hydrogen | paleoaltimetry | stable isotopes | volcanic glass

Most of our knowledge of climate evolution is based on isotopic and paleontological data from the oceans. By contrast, terrestrial climate records are still sparse despite their paramount importance for our understanding of land-ocean climate connections and the impact of mountain ranges on late Cenozoic atmospheric circulation patterns. Here, we present the results of a hydrogen isotope study of hydrated volcanic glass that reconstructs the elevation and precipitation patterns of the Sierra Nevada (California) and Basin and Range Province (Nevada) over the last 12.1 Ma. Tephra erupted from the Snake River–Yellowstone hot spot sources, the Cascade Range, and volcanic sources east of the central and southern Sierra Nevada, as well as from other sources in the western United States, are a ubiquitous component of Miocene-to-recent sedimentary successions in the western United States and serve as important stratigraphic and time markers in the terrestrial geologic record (1–6). Explosive eruptions of tephra eject ash particles into the upper troposphere where winds distribute them rapidly over large areas. These ashes, almost instantaneously deposited at the earth's surface, are virtual time horizons, and the tephra layers therefore provide unique time-equivalent markers across almost the entire Cenozoic landscape of the western United States. Freshly erupted glass is nearly anhydrous (7), but within only thousands of years after deposition, rhyolitic volcanic glass deposited at the earth's surface incorporates large amounts of meteoric water (3–5 wt %) into the glass structure (8–10). This near-surface hydration process parallels a change in the hydrogen isotope composition of the rhyolitic glass (δD_{glass}), and the hydrogen isotope composition of the hydration water (δD_{water})

can be calculated by using empirically calibrated glass–water fractionation factors (8). The δD_{glass} values, therefore, represent a unique fingerprint of the hydrogen isotope composition of meteoric water present during hydration that ultimately allows the reconstruction of the isotopic composition of precipitation ($\delta D_{precipitation}$). The latter is one of the most important indicators of long-term terrestrial changes in precipitation patterns and continental moisture transport.

Numerous studies over the past decade indicate that certain authigenic and biogenic minerals provide reliable and useful terrestrial climate records. However, the general utility of these isotopic proxies is limited by either general availability (relative scarcity in the geologic record) or difficulties in determining a relatively precise age of formation. Over a decade ago, Friedman and others (9) proposed that hydrated volcanic glasses might provide a useful proxy for past climate. However, since then, the utility of hydrated volcanic glass as a paleoclimate and paleoprecipitation proxy has remained largely unexploited. This is particularly astonishing because hydrated glasses can provide a precisely dated hydrogen isotope record that can be directly linked to paleoclimatic and precipitation regimes within and adjacent to mountain ranges.

One important criterion for isotopic climate proxies is that the investigated material preserves its original isotopic composition over geologic time. By comparison with modern water compositions over large latitudinal (and climate) gradients, Friedman and others (8, 9) demonstrated that once the glass is completely hydrated, hydration water does not undergo significant further isotopic exchange with its environment. This result is corroborated in this study by (i) the preservation of modern δD –elevation relationships in Pleistocene samples (see below) and (ii) comparison of Miocene δD_{glass} values with modern water compositions [supporting information (SI) Table S1]. In areas that are located at various distances from the modern (and ancient) rain shadow of the Sierra Nevada, we find large deviations from glass–water hydrogen isotope equilibrium when compared with modern near-surface groundwaters for samples where the δD_{water} has changed over time. This disequilibrium is best explained by initial (rapid) hydration of volcanic glass and (once fully hydrated) sluggish hydrogen isotope exchange reactions at surface temperatures.

Once identified and correctly correlated, widely distributed ashes may, therefore, serve as excellent paleoclimate and pa-

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Fig. 1. Orographic rainout and associated change in the hydrogen isotope composition of modern precipitation across the Sierra Nevada. (A) Smoothed topographic profile across the central Sierra Nevada and northern Basin and Range province along 39°N latitude based on 1-km-resolution SRTM30 data. The solid black line indicates mean elevation with 2σ uncertainty shown in gray. The dashed lines indicate maximum and minimum elevation. (B) Hydrogen isotope composition of precipitation ($\delta D_{\text{precipitation}}$) and volcanic glass in equilibrium with precipitation-derived meteoric water (δD_{glass}), as well as precipitation rates for the modern central Sierra Nevada. The rain shadow produced by orographic rainout on the windward side of the range results in a decrease in $\delta D_{\text{precipitation}}$ by $\sim 50\%$. The hydrogen isotope composition of precipitation (δD_{ppt}) is from ref. 12. δD_{glass} values for glass in equilibrium with modern meteoric water were calculated by using the hydrogen glass–water fractionation factor from ref. 8.

leaoaltimetry proxies because (i) deposition and hydration are rapid on geologic timescales and can be dated with high temporal resolution, (ii) the chemical composition of the proxy material is constant over large areas (100–100,000 km²) (3, 7), and (iii) interpretation of spatial variations in the hydrogen isotope composition of time-equivalent proxy materials of identical composition only requires knowledge of relative changes in δD_{glass} , thus reducing additional sources of uncertainty compared with studies that need to account for absolute changes in the isotopic composition of the proxy material. Herein, we build on empirical studies (8, 11) that show that the hydrogen isotope record in hydrated volcanic glass can be used in paleoclimatology and paleoaltimetry studies. Specifically, we use the hydrogen isotope composition of volcanic glasses in ashes distributed over extensive regions of the western United States to evaluate the timing of surface uplift of the Sierra Nevada.

The Sierra Nevada of California and the adjacent Basin and Range Province to the east represent an ideal target area for studying the impact of high topography on paleoclimate and paleoprecipitation patterns for two reasons: the remarkably strong modern rain shadow with highly asymmetric rain fall on the windward and leeward side of the mountains (Fig. 1), and the relatively simple atmospheric circulation patterns with moisture

sourced in the Pacific ocean and zonal atmospheric flow patterns (12, 13). Yet, despite numerous lines of research, the elevation history of the Sierra Nevada is still highly debated, mainly because methods to directly determine paleoaltimetry have only been developed and successfully applied within the last decade (14–16). On one side, geomorphic studies of tilted strata and associated river incision patterns suggest significant (≥ 1.5 km) late Cenozoic (3–5 Ma) surface uplift in the southern and central Sierra Nevada (17–22). Evidence for these conclusions came from tilted Tertiary sedimentary units on the western flanks of the Sierra Nevada and the development of angular unconformities that suggest post-5-Ma range-wide tilting of a rigid Sierra block resulting in up to 2 km of surface uplift of the Sierra Nevada crest (19). A major phase of Pliocene (≈ 3 –5 Ma) surface uplift contrasts results of stable isotope (15, 16), thermochronological (23–25), cosmogenic nuclide (26), and numerical modeling studies (27) that conclude that the modern orographic barrier of the Sierra Nevada has been a long standing topographic feature of the landscape in the western United States. In summary, these studies conclude that crustal thinning during Basin and Range extension could be held responsible for even an elevation loss since the late Miocene (28) and suggest that a Sierra Nevada rain shadow has been in place since that time (15). Results of (U-Th)/He thermochronology support such a view, and House *et al.* (23, 24) reconciled differential cooling and exhumation patterns in the southern Sierra Nevada by a model of Early Paleogene (65–50 Ma) river incision and attributed a much older age to canyon incision (and inferred range uplift) than previously thought. Recent surface process modeling approaches (27) of bedrock channel erosion, river stream power, and sediment flux support such a view by identifying two major pulses of surface uplift that took place in the latest Cretaceous (≈ 70 –65 Ma) and the late Miocene (≈ 10 –15 Ma).

These apparently strongly different interpretations of landscape evolution are not necessarily contradictory because they reflect observations made in different parts of the mountain range that may have had different geomorphic and tectonic histories. To be reconciled, however, they necessitate distinctly different late Cenozoic surface elevation histories in different parts of the Sierra Nevada.

We present new hydrogen isotope data from 67 well dated and compositionally well correlated volcanic glasses from both the windward and leeward sides of the Sierra Nevada to reconstruct the impact of the Sierra Nevada orographic barrier on the late Cenozoic precipitation pattern of the western United States. As the isotopic composition of precipitation systematically scales with elevation of the orographic barrier, this approach further aims at elucidating the paleoaltimetric history of the Sierra Nevada by systematic comparison of well dated proxies in the sedimentary record from either side of the mountain range, thus drastically reducing uncertainties associated with formation conditions of the analyzed proxy materials. Glasses from individual non-peralkaline tephra layers found from the Central Valley of California across the Basin and Range cover an age range of 575 ka to 12.07 Ma (Table S2). These data allow us to test the hypothesis that surface uplift of the Sierra Nevada occurred during the Early Pliocene, an event that should be reflected in variable intensity of the rain shadow on the leeward side of the range. We conclude that our hydrogen isotope data of the volcanic and sedimentary record show a pronounced ($>40\%$) decrease in δD_{glass} from the windward (western) to the leeward (eastern) side of the Sierra Nevada for the entire time interval studied, consistent with the existence of a rain shadow of similar magnitude such as exists today, since at least 12.1 Ma.

Results

The modern Sierra Nevada orographic barrier effectively blocks a large fraction of Pacific-sourced moisture, creating a strong

Fig. 2. Shaded relief map of topography in the western United States and hydrogen isotope compositions of volcanic glass samples from individual tephra layers grouped by age. Combined δD_{glass} data (Table S2) are from the following tuffs and ash beds: (A) Rockland (0.575 Ma), Lava Creek B (0.639 Ma), and Bishop (0.774 Ma); (B) Huckleberry Ridge (2.09 Ma); (C) Upper Horse Hill (3.10 Ma), Nomlaki (3.34 Ma), and Putah (3.4 Ma); (D) Kilgore (4.45 Ma) and Lawlor (4.83 Ma); (E) Pinole (5.2–5.4 Ma), Wolverine Creek (5.59 Ma), Silver Peak Range (6.1 Ma), Roblar (6.26 Ma), Blacktail Creek (6.70 Ma), Zammoroni Quarry (7.26 Ma), Faust (7.49), Roblar (9.36 Ma), Hazen (9.81 Ma), CPT XV (10.5 Ma), Ibex Hollow (11.93 Ma), and CPT V (12.07 Ma) (4–6, 30–32). The gray line indicates the location of topographic swath profile at $\approx 39^\circ\text{N}$ latitude referred to in Fig. 1. #, samples from ref. 9.

asymmetry across the mountain range with precipitation rates of $>1,500$ mm/a on the windward and <500 mm/a on the leeward side (Fig. 1). By condensation processes within the ascending cloud systems, rainout preferentially removes the heavy isotope, deuterium, from the water vapor. This isotope effect scales with elevation, and the rate of change of the hydrogen isotope composition of precipitation with elevation measured along mountain river profiles attains $15\text{--}25\text{‰}/\text{km}$ in mid-latitude, moderate-elevation mountain belts (29, 30). Thus, the rain shadow effect induced by the 2,000- to 2,500-m-high northern and central Sierra Nevada should create a change in δD_{glass} [further referred to as $\Delta(\delta D_{\text{glass}})$] on the order of $\sim 50\text{‰}$; a value that agrees well with modern water measurements (Fig. 1B).

We have grouped the hydrogen isotope data within five different time slices that cover critical intervals in the history of the Sierra Nevada (Fig. 2). We want to emphasize that the stratigraphic, geochronological, and compositional characterization of these ashes has been elaborated to a much higher level of detail than depicted in Fig. 2, and details about the chronostratigraphy of these ashes can be found in refs. 1–6 and 31–34, and in Table S2.

The Pleistocene dataset (0.575–0.774 Ma; Fig. 2A) displays the three main characteristics of the modern precipitation

pattern in the western United States. First, there is a strong decrease in δD_{glass} values across the central and northern Sierra Nevada. From the Central Valley across the Sierra Nevada, $\Delta(\delta D_{\text{glass}})$ attains values of -45‰ to -50‰ . The Nevada sampling sites immediately east of the range crest receive most of their precipitation during the winter when strong westerly jet streams force moist air from the Pacific over the peaks of the range (35). Further inland, toward Utah, δD_{glass} values continuously decrease to values as low as $\delta D_{\text{glass}} = -178\text{‰}$ (Fig. 2), most likely reflecting the combined effects of orographic rainout forced by the elevation of the Sierra Nevada (“orographic effect”) and progressive rain-out during subsequent continental moisture transport (“continentality effect”) (36).

Second, despite the much higher relief and mean elevations (locally exceeding 4,000 m) (20), the southern termination of the Sierra Nevada does not show a very distinct separation between δD_{glass} values on the windward and leeward sides of the mountain range (Fig. 2A). In the modern precipitation record (35), similarly elevated $\delta D_{\text{precipitation}}$ values (that should directly correlate with δD_{glass}) occur in regions of California and Nevada where a significant fraction of the annual precipitation is sourced in the tropical Pacific, in the Gulf of California, and during the summer in the Gulf of Mexico (35). Thus, these values charac-

Fig. 3. Elevation profile for Rockland Ash (0.575 Ma) and Bishop Tuff (0.774 Ma) glass samples. Orographic rainout along the western (windward) flank of the northern Sierra Nevada and associated decrease in δD of hydration water with elevation is reflected in the δD_{glass} data. Dashed lines indicate expected change in δD_{glass} with elevation using empirical hydrogen isotope lapse rates of the Sierra Nevada: (1), Ingraham and Taylor (12); (2), Poage and Chamberlain (29).

terize the impact of a component of meridional moisture transport during the summer monsoon in the western United States. Third, even though based on a limited amount of data, we observe a $\Delta(\delta D_{\text{glass}}) = -10\text{‰}$ to -20‰ from sampling sites at the Pacific coast to sites within the Central Valley, consistent with a deuterium-depletion in cloud vapor due to rain-out across the Coast Mountains.

When interpreting the stable isotope compositions of waters that have already passed an orographic barrier and leave their isotopic fingerprint in proxy material on the lee-side of the mountain range, one frequently encountered problem in stable isotope paleoaltimetry is poor control on the isotopic composition of the water before it passed the orographic barrier. During orographic ascent, rain-out, and runoff, the isotopic compositions of these waters may be variably affected by processes such as evaporation and changing storm and precipitation patterns, thus collecting water from different (and largely unknown) sources (37). Some of these uncertainties can be circumvented when analyzing isotopic proxy materials on the windward side of the mountain range. Following the approach presented in ref. 16, we directly tested whether isochronous volcanic glass sampled at different elevations on the windward side of the mountain range tracks changes in $\delta D_{\text{precipitation}}$. For this purpose, we have chosen the 0.575-Ma Rockland Ash and 0.774-Ma Bishop Tuff, because it is very unlikely that significant changes in the absolute elevation of the sampling sites occurred since deposition of the air-fall ashes. The Rockland tephra was erupted from a source in the southern Cascade Range of northeastern California, near the present location of Lassen Peak. Elevation of the ash near the eruptive source is $\approx 1,100$ – $1,200$ m. Tephra from this source was transported by winds primarily toward the east and west, with smaller components toward the southeast and north. Tephra from this eruption has been found in northern Utah, in sediment cores from the eastern Pacific Ocean, and east of the central Sierra Nevada in California. As is the case for all explosive eruptions, ash particles, consisting primarily of pumice and volcanic glass shards together with smaller amounts of mineral grains and lithic fragments, decreased systematically in grain size with distance from the source area.

The Bishop Tuff was erupted from the Long Valley caldera just east of the central Sierra Nevada, in east-central California. Deposits of this tephra range in elevation from $\approx 2,000$ – $2,200$ m

Fig. 4. Hydrogen isotope compositions of volcanic glass samples (δD_{glass}) on the windward and leeward sides of the northern and central Sierra Nevada. The large (-45‰ to -53‰) difference in hydrogen isotope compositions of volcanic glass [$\Delta(\delta D_{\text{glass}})$] mimics the modern precipitation patterns across the Sierra Nevada. $\Delta(\delta D_{\text{glass}})$ is due to orographic rain-out on the windward side of the range, for the entire time interval studied (0.575–12.07 Ma). $\Delta(\delta D_{\text{glass}})$ values are slightly lower than for modern precipitation allowing for a small (<500 m) amount of Pliocene-to-Pleistocene surface uplift in the central and northern Sierra Nevada. The black dashed line indicates calculated δD_{glass} values for glass in equilibrium with modern meteoric water using the hydrogen glass–water fractionation factor from ref. 8.

at or near the present caldera floor to $\approx 1,400$ m in the vicinity of Bishop, south of the Caldera. Tephra from this eruption was carried primarily toward the east and south, with smaller components toward the southwest (3). This tephra has been identified as far east as Nebraska, $\approx 1,800$ km from the source area, and in sediment cores obtained from near Guadalupe Island, in the Pacific Ocean, $\approx 1,200$ km south of the source. Ashes were sampled over $\approx 2,000$ m of elevation difference from the base of the Central Valley to locations near the peak of Mt. Lassen (California). When plotted against elevation, the combined data for Rockland Ash and Bishop Tuff follow the empirically calibrated isotopic lapse rates for the Sierra Nevada (12, 29), thus confirming the reliability of the hydrogen isotope record in hydrated volcanic glass (Fig. 3).

The patterns of δD_{glass} values for older time intervals (2.09, 3.10–3.40, 4.45–4.83, and 5.59–12.07 Ma; Fig. 2 B–E) mimic the Pleistocene δD_{glass} record (Fig. 2A). During the entire time interval between 0.575 and 12.1 Ma, the hydrogen isotope compositions of meteoric water display a large ($>40\text{‰}$) decrease from the windward to the leeward side of the central Sierra Nevada, and absolute δD_{glass} values remain fairly constant on either side of the mountain range (Fig. 4).

Discussion

Numerous characteristics render hydrated volcanic glass a potentially important paleoclimate proxy, but only few studies (8, 11) have systematically investigated the reliability of this approach. By comparison with modern waters, Friedman and others (8) showed that at or near the earth's surface, volcanic glass shards in tephra layers reliably retain their δD_{glass} values over geologic time scales. This conclusion is supported by the results of this study where we observe large differences between calculated and measured hydrogen isotope compositions of ambient meteoric waters at various sampling sites for the oldest of the investigated samples (Table S1). If continuous hydrogen isotope exchange had occurred, the volcanic glass samples should have δD_{glass} values in equilibrium with modern surface waters. Thus, re-equilibration of the hydrogen isotope composition with ambient meteoric water likely did not occur, further suggesting that for temperatures at or near the earth's surface

($\leq 30^\circ\text{C}$), the volcanic glass reliably retains the δD_{glass} values over geologic time.

Besides orographic rain-out, the relative roles of precipitation and evapotranspiration during atmospheric water vapor transport control the depletion of the heavy isotope (^{18}O or D) of large-scale near-surface hydrologic systems ("continentality effect") (36). Documented decreases in δD_{ppt} with increasing distance from the coast range from $<0.1\text{‰}/100\text{ km}$ in tropical rainforest (38) and $>3\text{‰}/100\text{ km}$ over continental Central Europe (39, 40) to values as high as $60\text{‰}/100\text{ km}$ at the Pacific coast of California (12, 41).

The modern Great Basin (Nevada) is characterized by a vast area of internal drainage and very small decreases in δD_{ppt} with distance from the Pacific coast (12) (Fig. 1) attesting to a (nearly) closed system behavior of precipitation and evapotranspiration in this area. In contrast, for all time intervals investigated in sufficient detail in this study (Fig. 2 *A*, *D*, and *E*), we observe a decrease in δD_{glass} of $\approx 20\text{‰}$ across the northern Great Basin, corresponding to a change in δD_{ppt} of $\approx 5\text{‰}/100\text{ km}$ and higher when taking into account the effects of Basin and Range extension. This discrepancy between modern precipitation patterns and those recorded by even our youngest dataset (575–770 ka) could be due to either a rearrangement of Basin and Range topography or modified circulation patterns that at current permit atmospheric moisture to penetrate deeper into the continental interior. From tectonic and isostatic considerations it appears unlikely that major readjustments in relief and mean surface elevation occurred in the northern Great Basin over the last several hundred thousand years. However, it is possible that a more northerly located (and weaker) jet stream may have brought more moisture-saturated air into the area and that the low δD_{glass} values in the continental interior represent a conspiracy of different climate and different elevation patterns. At this point, we can only speculate that a combination of developing topography and climate-controlled atmospheric circulation patterns may have overstepped some critical threshold value that at current results in a lower winter-to-summer precipitation ratio. Our current results lack the temporal resolution to clearly validate and identify the causes of such a process but demonstrate that long-term reconstructions of precipitation patterns in the northern Great Basin will greatly enhance our understanding of coupled topographic and climatic changes across the western United States.

The observation that δD_{glass} –elevation profiles of late Pleistocene samples (Rockland Ash and Bishop Tuff; Fig. 3) reliably record changes in $\delta D_{\text{precipitation}}$ due to rainout at higher elevations has consequences for interpretations of δD_{glass} (or other authigenic or pedogenic stable isotope proxy) values on the leeward, rain shadow side of the mountain range. Measurements of the difference in hydrogen isotope composition of proxy materials of identical composition and age on both sides of a mountain range reduces uncertainties compared with studies where low-elevation starting compositions of meteoric waters are largely unknown (15, 42–45) and permits quantification of the mean elevation of the orographic barrier. Values for $\Delta(\delta D_{\text{glass}})$ across the Sierra Nevada do not change significantly over the time interval studied here. For the central part of the Sierra Nevada (38–40°N latitude) $\Delta(\delta D_{\text{glass}})$, values are -45‰ (0.575–0.77 Ma), -53‰ (3.10–3.40 Ma), -54‰ (4.45–4.83 Ma), and -52‰ (5.6–12.1 Ma) (Fig. 4) over a distance of $\approx 200\text{ km}$ across the entire range. When compared with the effects of continentality [with $\Delta(\delta D_{\text{ppt}})$ values below $5\text{‰}/100\text{ km}$], the differences in δD_{glass} on the windward and leeward side of the Sierra Nevada document that a very large fraction of the $\Delta(\delta D_{\text{glass}})$ is due to the effects of topography rather than continentality. We would like to reiterate that the approach presented here, tracking the development of a rain shadow over geologic time, reliably records first-order topographic changes in developing mountain ranges but fails to address the detailed surface uplift

history of parts of a mountain range, where a dominant fraction of the annual precipitation does not cross the orographic barrier (as, e.g., shown for the southern termination of the Sierra Nevada; Fig. 2). Therefore, we cannot rule out that some component of differential uplift of the southern (high elevation) part of the Sierra Nevada occurred during the late Neogene.

The isotopic data presented here, however, support a hypothesis that the Sierra Nevada has existed as a major topographic feature since at least the Late Miocene with mean elevations comparable with the modern, a conclusion in good agreement with stable isotope paleoaltimetry data from weathering products on the leeward side of the mountain range (15), low-temperature thermochronology of deeply incised ancestral rivers in the southern Sierra Nevada (23, 24), and numerical modeling approaches of the geomorphic evolution of drainages and river profiles of the Sierra Nevada (27). Our data, however, are not consistent with several other studies calling for large-magnitude surface uplift in the last 3–4 Ma as a result of delamination and removal of a dense continental lithospheric root beneath the Sierra Nevada (46–49). We do not dismiss the excellent geologic and geophysical evidence for delamination of dense lithospheric material below the Sierra Nevada, but our data indicate that the surface response (surface uplift) to such a process has been much smaller ($<1\text{ km}$) over large areas of the Sierra Nevada than previously estimated. Alternatively, the crustal structure in the northern and central Sierra Nevada may have been fundamentally different from its southern counterpart during most of the Cenozoic. It is possible that a thick and dense crustal root under the northern Sierra Nevada may have never existed or that mantle delamination in the north occurred much earlier (pre-45 Ma) in the history of the Sierra Nevada. Understanding the combined geophysical and surface elevation data will thus have fundamental implications for future geodynamic numerical and geophysical models that aim at incorporating surface and lithospheric processes but also for our understanding of mantle contributions to modern elevation of continental plateaus such as Tibet or the Altiplano-Puna.

Methods

Volcanic glass shards used in this study were obtained from the U.S. Geological Survey and University of Utah tephrochronology reference collections. Glass fractions of $>99.5\%$ purity were prepared by crushing each sample in a mortar and sieving through brass sieves. The 60–120 mesh fraction was treated in 10% HCl for 15–20 min and washed thoroughly in distilled water to remove any carbonate minerals. Samples were treated with 5% HF in an ultrasonic cleaner to remove clay alteration, washed repeatedly in distilled water, and dried at 80°C . Repeated passes through a Frantz Isodynamic Separator removed magnetic and nonmagnetic minerals from the glass. The purity of each sample was checked with a petrographic microscope. Hydrogen isotope ratios were measured in the Biogeochemistry Laboratory at Stanford University by high-temperature thermal combustion and continuous-flow gas mass spectrometry using a Thermo Electron TC-EA coupled to a Thermo Electron delta+ XL mass spectrometer. Approximately 0.8–1.5 mg of pure glass shards were enclosed in silver foil, dried under vacuum, and then immediately flushed with dry He gas within a zero-blank auto sampler. Five internationally referenced standard materials and in-house working standards were run with the samples, random samples were duplicated and tested for consistency, and the raw isotope data were corrected for mass bias, daily drift of the thermal combustion reactor, and offset from the certified reference values. After correction, NBS30 (biotite), PEF1 (polyethylene foil), and NBS22 (oil) reference materials yielded $\delta D = -65\text{‰}$, -101‰ , and -120‰ , respectively. Repeated measurements of various standards and unknowns yielded precision of $\pm 2.0\text{‰}$ for δD . All isotopic ratios are reported relative to SMOW.

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