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Cenozoic migration of topography in the North American Cordillera

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ABSTRACT

Continental topography is the result of complex interactions among mantle convection, continental dynamics, and climatic and erosional processes. Therefore, topographic evolution of mountain belts and continental interiors reflects directly upon the coupling between mantle and surface processes. It has recently been proposed that the modern topography of western North America is partly controlled by the removal of the subducting Farallon plate and replacement of lithospheric mantle by hot asthenosphere, creating surface uplift of the Colorado Plateau, the southwestern United States, and northern Mexico, while concomitant subsidence characterizes the central United States. How the topography of the Cenozoic North American Cordillera evolved in the past is largely unknown, yet currently debated tectonic models each have a predictable topographic response. Here we examine Cenozoic surface uplift patterns of western North America based on a record of ~3000 stable isotope proxy data. This data set is consistent with Eocene north to south surface uplift in the Cordillera, culminating in the assembly of an Eocene–Oligocene highland 3–4 km in elevation. The diachronous record of surface uplift and associated magmatism further supports tectonic models calling for the convective removal of mantle lithosphere or removal of the Farallon slab by buckling along an east-west axis. The Eocene–Oligocene development of rainout patterns similar to present-day patterns along the flanks of the Cordilleran orogen is therefore unlikely to be the result of late Mesozoic crustal thickening and associated development of an Andean-style Altiplano.

INTRODUCTION

It is widely accepted that the North American Cordillera underwent late Mesozoic and Cenozoic subduction, contraction, and subsequent extension (DeCelles, 2004). However, despite a wealth of studies, significant disagreement remains surrounding the tectonic mechanisms for the topographic evolution of the Cenozoic North American Cordillera. Two end members summarize such models: (1) gravitational collapse of a Late Cretaceous to early Paleogene low-relief, high-elevation (~3–4 km) plateau, the "Nevadaplano" (analogous to the Andean Altiplano) to a mountainous region of lower mean elevation (DeCelles, 2004; Jones et al., 1996; Sonder et al., 1987), and (2) the rise of topography in the early Cenozoic as hot asthenosphere replaced mantle lithosphere due to lithospheric removal or changes in Farallon slab geometry and subduction dynamics (Humphreys, 1995; Moucha et al., 2008; Liu et al., 2010). While there have been numerous studies on the paleoelevation of the North American Cordillera, all of these studies lack the combined spatial and temporal coverage to fully evaluate which, if any, of the proposed tectonic and/or surface evolution models are viable. The most thorough spatial coverage to date comes from paleoelevation studies using fossil flora. These studies suggest the existence of Eocene–Miocene highlands that extended from southern British Columbia through the Rocky Mountains and central Great Basin (Forest et al., 1995; Wolfe et al., 1997, 1998; Chase et al., 1998). While highly informative because of their combined paleoclimatic and paleotopographic information, these paleofloral studies lack the temporal coverage to determine how these highlands developed.

Here we examine the impact of surface uplift of the North American Cordillera on hydrogen and oxygen isotopes in precipitation using ~3000 stable isotopic analyses of different terrestrial paleoclimate proxies, from published and new data collected in this study. The spatial and temporal patterns of $\delta^{18}O$ of precipitation ($\delta^{18}O_p$) show that surface uplift occurred as a topographic wave that swept southward, appearing first in southern British Columbia ca. 50 Ma and reaching central Nevada ca. 40 Ma. The data presented here confirm earlier stable isotopic studies in central Nevada that suggested that surface uplift was diachronous in the North American Cordillera (Horton et al., 2004).

CALCULATION OF PALEOPRECIPITATION AND PALEOELEVATION

We examined the Cenozoic surface uplift history using stable isotope paleoclimate proxies. We take advantage of abundant authigenic and secondary mineral proxies in well-dated stratigraphic sections within the Cenozoic North American geologic record to determine past stable isotopic compositions of surface waters. Stable isotope paleoaltimetry relies on the systematic depletion of ^{18}O and D in precipitation as an air mass rises over an orographic barrier, creating an altitude effect of hydrogen and oxygen isotopes in precipitation. This altitude effect can be reconstructed from hydrous authigenic minerals that record the isotopic fingerprint of the meteoric water cycle (Mulch et al., 2004). Because the isotopic composition of precipitation, in part, directly scales with elevation, it is possible to reconstruct first-order topographic histories of mountain belts.

We present a series of maps (Figs. 1A–1C) showing $\delta^{18}O_p$ calculated from $\delta^{18}O$ and δD measured in a wide range of mineral proxies. To calculate the $\delta^{18}O_p$ from mineral proxies, we used equilibrium fractionation equations with isotope exchange temperatures based on nearby paleofloral assemblages (Chase et al., 1998; Wolfe et al., 1997) (see the GSA Data Repository[1]). We created $\delta^{18}O_p$ maps for time bins to highlight the major isotopic shifts observed within individual basins along the Cordillera (Horton et al., 2004; Kent-Corson et al., 2006). Based on these spatially extensive maps of paleoprecipitation, we calculated paleoelevations for the time interval when the western North American Cordillera was most likely at its peak height. Using the model of Rowley et al. (2001), we purposefully did this only for samples for which there were nearby estimates of paleoelevation from leaf physiognomic studies for comparison and in locations that currently receive the bulk of their precipitation from Pacific-sourced air masses. These samples belong to (1) the Elko Basin in northeast Nevada (36–28 Ma), (2) the Copper Basin in northeast Nevada (ca. 37 Ma), (3) the Sage Creek Basin in southwestern Montana (38.8–32.0 Ma), and (4) the Princeton Basin in southern British Columbia (ca. 49 Ma).

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[1]GSA Data Repository item 2011040, discussion of isotopic effects, extended methods, supplemental references, and Table DR1 (isotopic values used in the compilation), is available online at www.geosociety.org/pubs/ft2011.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

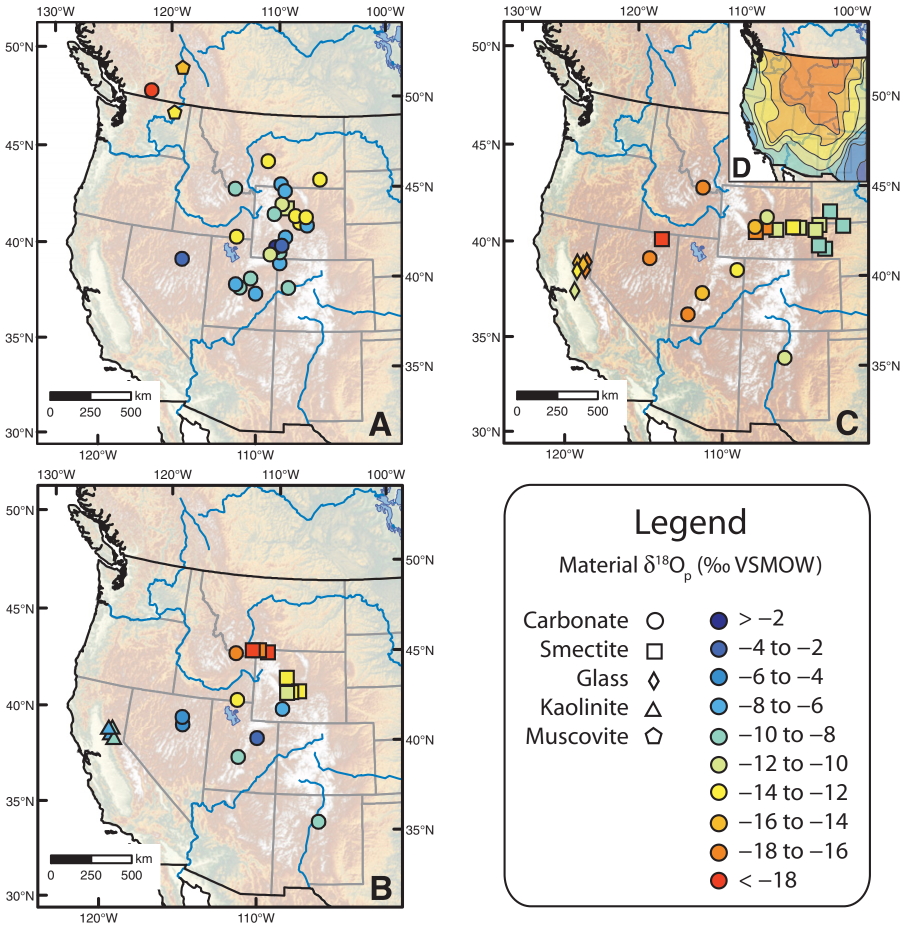

Figure 1. Isotopic compositions of paleoprecipitation ($\delta^{18}O_p$). A: $\delta^{18}O_p$ pre–49 Ma, number of samples in each bin, n = 2098. B: $\delta^{18}O_p$ from 49 to 39 Ma, n = 398. C: $\delta^{18}O_p$ from 39 to 28 Ma, n = 264. D: Modern $\delta^{18}O_p$ (after Kendall and Coplen, 2001). VSMOW—Vienna standard mean ocean water.

RESULTS AND INTERPRETATION

We make four first-order observations from our data set. First, prior to the Middle Eocene (ca. 49 Ma), the North American Cordillera south of Montana and Idaho was marked by high $\delta^{18}O_p$ values, with most $\delta^{18}O_p$ estimates >–12‰. In contrast, basins from northern Montana, Washington, and Canada display lower $\delta^{18}O_p$ values, with nearly all $\delta^{18}O_p$ estimates being −14‰ or less (Fig. 1A). Second, by the Middle to Late Eocene, $\delta^{18}O_p$ values decreased in southwestern Montana from −10‰ or greater to −16‰, while areas to the south remained unchanged (Fig. 1B). Third, by the Late Eocene to Oligocene, ^{18}O-depleted precipitation began to dominate the western United States, with $\delta^{18}O_p$ of −14‰ or less across Nevada, Utah, Idaho, and western Wyoming, similar to the $\delta^{18}O_p$ patterns observed today (Figs. 1C and 1D). Fourth, this broad region characterized by low $\delta^{18}O_p$ values was bordered by steep isotopic gradients on the western flanks of the Sierra Nevada and on the eastern flanks of the Rocky Mountains.

One of the most striking features shown by our paleoprecipitation data set is the progressive development of a precipitation regime matching the modern by the Late Eocene to Early Oligocene. The Eocene–Oligocene $\delta^{18}O_p$ gradients on the western flank of the Sierra Nevada and eastern flank of the Front Range are a prominent feature observed in modern western North America (Kendall and Coplen, 2001) (Fig. 1D). The modern gradient bounding the western margin of North America reflects the distillation of air masses originating from the Pacific by the orographic barriers of the Sierra Nevada and Cascades. The gradients to the east and south of the modern Cordillera reflect distillation of monsoonal precipitation originating from the Gulf of Mexico and Gulf of California, and their interaction with the Rocky Mountain front. Therefore, we interpret the first appearance of such opposite $\delta^{18}O_p$ gradients in the geologic record to reflect development of highlands in the continental interior with steep flanks on either side of the orogen.

Our results suggest that these Eocene–Oligocene highlands developed as a topographic wave that swept southward through time. High-standing areas originated in the Canadian Cordillera in the Middle Eocene and developed into broad highlands across a large portion of western North America by the Late Eocene–Oligocene. The diachronous isotopic shifts that result from this southward sweep of topography are currently recorded in two intermontane basins within the Cordilleran hinterland. At 49–47 Ma, a negative $\delta^{18}O$ shift of ~−6‰ occurred in the Sage Creek Basin of Montana (Kent-Corson et al., 2006), and ca. 40 Ma a $\delta^{18}O$ shift of similar magnitude occurred in the Elko Basin in northeastern Nevada (Horton et al., 2004). These rapid changes to lower $\delta^{18}O$ values are also observed within intraforeland Laramide basins east of the Cordilleran hinterland. In the Green River Basin, $\delta^{18}O$ values decrease by 6‰ at 49 Ma (Carroll et al., 2008), in the Uinta Basin (Utah) by 6‰ ca. 43 Ma, and farther south in Lake Claron (Utah) by 5‰–8‰ ca. 35 Ma (Davis et al., 2009). These north-to-south shifts to lower $\delta^{18}O_p$ values in the foreland lake basins have been interpreted to be the result of drainage reorganization that occurred within the headwaters of the rising Cordilleran hinterland (Davis et al., 2009).

The results presented here shed some light on a major geologic conundrum: Abundant geologic (DeCelles, 2004), tectonic (Coney and Harms, 1984), geophysical, and volcanologic evidence (Best et al., 2009) points to thickening of the western North American crust through protracted Mesozoic to earliest Cenozoic crustal shortening. Isostatic compensation behind the Sierran arc makes it likely that such crust supported regionally extensive high surface elevations that, by analogy with modern orogenic plateaus, may have been characterized by relatively smooth relief. Our stable isotopic data, however, show strong evidence that a major episode of surface uplift in the Great Basin occurred much later during the Eocene. This does not deny the existence of a late Mesozoic Nevadaplano highland, but documents that the combined effects of Eocene changes in subduction dynamics and geometry, flow of partially molten middle crust, magmatism, and core complex formation had considerable effects on the elevation and relief structure of western North America, and that the Great Basin reached its highest elevations during Eocene and Oligocene time.

How high was this Eocene–Oligocene highland? It is notoriously difficult to quantify past elevations in continental interiors because precipitation patterns generally reflect contributions from multiple air masses and highly dynamic atmospheric flow patterns (Galewsky, 2009). In contrast, simplified stable isotope paleoaltimetry models require a single moisture

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source (Rowley et al., 2001), and further work will integrate coupled isotope-tracking atmospheric moisture and climate models (Ehlers and Poulsen, 2009). Trying to be appropriately cautious when interpreting the stable isotope data (see the Data Repository), we acknowledge that our interpretation does not take into account some potential atmospheric or climate-related impacts on isotopes in precipitation, e.g., temporal changes in strength and position of the jet stream or the development of Arctic sea ice (Poulsen et al., 2007). However, to alleviate some of the complexities of reconstructing paleoelevation in continental interiors associated with complex atmospheric flow patterns, we conservatively selected four sites for paleoaltimetry that today receive the bulk of their precipitation from the Pacific and are not affected by the North American monsoon (NAM). Our calculated paleoelevations of these Eocene–Oligocene highlands range from 3.4 to 4.2 km (Fig. 2). These elevations are somewhat higher than those determined from nearby paleofloral assemblages (Table 1). The lower elevations based on leaf physiognomy as compared to stable isotope paleoaltimetry, however, reflect the fact that fossil flora record the local climate and elevation of the basin in which they are growing, whereas stable isotopes in precipitation reflect the hypsometric mean of the surrounding mountain ranges that drain into these basins.

The Sage Creek (Montana) and Elko (Nevada) basins exhibit relatively large (–6‰; see the Data Repository) and rapid (Carroll et al., 2008) negative shifts in $\delta^{18}O_p$ that support our argument that the Sevier hinterland was at lower elevations prior to the development of a continental plateau. Taken at face value, a change of –6‰ in surface waters would imply ~2.5 km of surface uplift in <2 m.y., assuming an Eocene isotopic lapse rate (Mulch et al., 2006). Given the common complications of stable isotope paleoaltimetry (Molnar, 2010), we are not overly confident that these estimates of surface uplift are robust because $\delta^{18}O_p$ values, in part, directly reflect upon the changing roles of multiple air masses and interaction of atmospheric flow patterns with growing mountain ranges (Galewsky, 2009). The isotope effect of multiple air masses is evident in the 49–39 Ma time bin for which basins in Nevada and Utah have higher $\delta^{18}O_p$ values than the Sierra Nevada upstream, an effect that is unlikely during progressive rainout of Pacific-derived moisture (Fig. 1B). This result requires the influence of relatively high $\delta^{18}O$ summer precipitation originating from the Gulf of Mexico and/or Mississippi Embayment in addition to storms originating in the Pacific. Moreover, high-resolution regional circulation models of early Paleogene western North America show that a strong east to west monsoon originating in the Mississippi Embayment brought summer precipitation to the Rocky Mountain front. These summer storms penetrated farther to the northwest as temperatures warmed during the summer months (Sewall and Sloan, 2006).

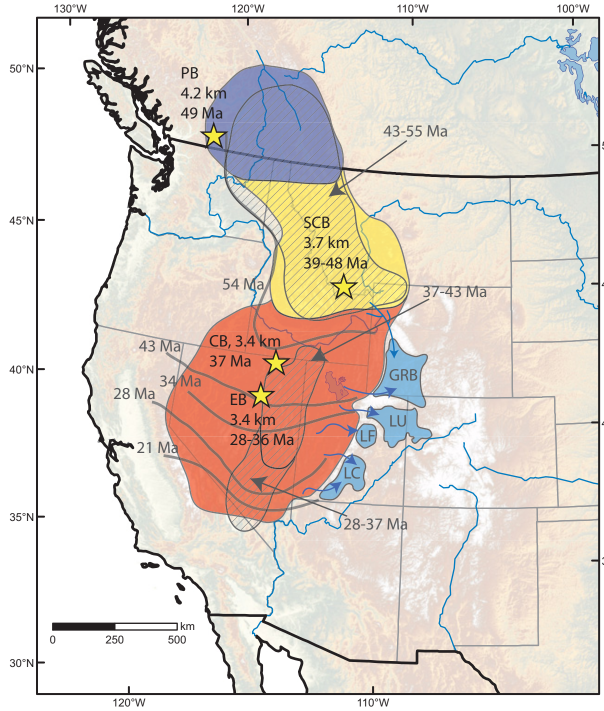

Figure 2. Correlation between magmatism, extension, and uplift. Regions of low $\delta^{18}O_p$ (isotopic composition of paleoprecipitation) interpreted as elevations >3 km are shaded purple (by 49 Ma), yellow (by 39 Ma), and red (by 28 Ma). Yellow stars show calculated paleoelevations from this study (Table 1). Gray lines show location of magmatic fronts at age noted beside them. Areas striped with diagonal lines show regions of extension with ages corresponding to core complex formation. Lakes in Laramide foreland show capture of waters from highlands. Abbreviations: PB—Princeton Basin; SCB—Sage Creek Basin; CB—Copper Basin; EB—Elko Basin; GRB—Green River Basin; LU—Lake Uinta; LF—Lake Flagstaff; LC—Lake Claron.

TABLE 1. PALEOELEVATION ESTIMATES FROM STABLE ISOTOPES AND PALEOFLORAL ASSEMBLAGES FROM AREAS THAT RECEIVE THE DOMINANT PRECIPITATION FROM THE PACIFIC OCEAN

Site	Time interval (Ma)	Elevation—isotopes (km)	Error (m) (1σ)	Elevation—paleofloral (km)
Princeton Basin (BC)	ca. 49	4.2	758, –487	2.9
Sage Creek (MT, ID)	48–39	3.7	477, –375	2
Copper Basin (NV)	ca. 37	3.4	516, –363	2
Elko Basin (NV)	36–28	3.4	530, –367	2
Northern Sierra Nevada (CA) (Mulch et al., 2006)	52–49	2.2		
Northern Sierra Nevada (CA) (Cassel et al., 2009)	31–28	3.2		
Columbia River Detachment (BC, WA) (Mulch et al., 2004)	50–48	3.5–4.5		2.9

Note: BC—British Columbia (Canada); MT, ID, NV, CA, WA—Montana, Idaho, Nevada, California, Washington (United States). Paleofloral elevation data after Wolfe et al. (1998).

We interpret the north-to-south pattern of low $\delta^{18}O_p$ values to reflect the combined effects of surface uplift, adapted moisture transport, and a decreasing influence of the NAM, an interpretation that is consistent with current regional circulation model results. In the case of the modern NAM, summer warming of the Cordillera and Colorado Plateau causes a zone of low pressure that draws in moisture from the Gulf of Mexico and Gulf of California. The data presented here suggest that the NAM penetrated much farther north in the Eocene than today. This observation agrees with previous studies showing increasing monsoonal intensity during warmer times in the past (Fricke et al., 2010). We tentatively argue that the north-to-south topographic wave produced orographic barriers and a corresponding southward migration of the NAM front.

Because of the coupling among precipitation patterns and developing topography (Ehlers and Poulsen, 2009; Galewsky, 2009), the distribution of moisture in the atmosphere (and hence isotope patterns in precipitation) may not uniquely reflect changes in relief and surface elevation. Despite these complications, however, we are confident that our results document the first-order topographic characteristics of Eocene–Oligocene highlands in the North American Cordillera.

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CONCLUSIONS

Our results place several constraints on competing tectonic models for the Cenozoic evolution of the North American Cordillera. Surface uplift was most likely diachronous, occurring ca. 49 Ma in southern Montana and British Columbia and ca. 40 Ma in central Nevada. This topographic development coincided with north-to-south migration of magmatism and metamorphic core complex formation (Fig. 2). The intimate relationship between surface uplift, magmatism, and mid-crustal extension supports models calling for the removal of cold, lower mantle lithosphere and the subsequent replacement by hot asthenosphere. This may occur as the downward drip of a lithospheric blob (e.g., Houseman et al., 1981), by the thermal erosion of the lithosphere by hot upwelling asthenosphere (e.g., Saltus and Thompson, 1995), or by removal of the subducting Farallon slab (Humphreys, 1995; Sigloch et al., 2008). Based on coupled surface uplift, magmatism, and extension, it is clear that this occurred in a migrating pattern, beginning in the southern Canadian Cordillera in the Early Eocene followed by Late Eocene–Oligocene surface uplift in the central Great Basin.

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