[American Journal of Science, Vol. 312, February, 2012, P. 81–89, DOI 10.2475/02.2012.01]

American Journal of Science

FEBRUARY 2012

PALEOTOPOGRAPHY IN THE WESTERN U.S. CORDILLERA

PETER W. REINERS
AMERICAN JOURNAL OF SCIENCE ASSOCIATE EDITOR
Geosciences, University of Arizona, Tucson, Arizona 85721;
reiners@email.arizona.edu

INTRODUCTION

Issue #2 of Volume 312 of the *American Journal of Science* brings together several new papers bearing on the history of orogenesis, paleotopography, and paleoclimate in a region whose geologic record has been more important to the modern development of ideas about these processes than any other in the world: the American Cordillera of the western U.S. Here, a conspiracy of lithospheric and atmospheric processes have created complex topography with geologic significance (for example, Clark, 2007) as the primary manifestation of fundamental forces and phenomena that we would like to know much more about.

In the contiguous western United States, numerous mountain ranges stand about one to three kilometers above their surrounding landscapes over horizontal distances only about ten times larger than their height. They compose a vast region of rugged topography that, combined with aridity, is arguably the defining characteristic of the region. This scale of topographic relief is so common that many individual ranges like those towering over the deserts of Nevada are simultaneously awe-inspiring and unremarkable. The region is also home to large continuous areas with average elevations between 2 to 3 km above sea level. This is low compared with the Tibetan plateau, whose average elevation over an area the size of the western U.S. is higher than the highest peak in the western U.S. But most geologists recognize that many of the ranges and still impressive regions of high elevation in the western U.S. are just remnants of a much broader region that has since been chopped up and dropped down by late Cenozoic extension.

Our understanding of paleotopography in the western U.S. is not great. It turns out that even the ~1 to 3 km of relief characteristic of so much of the region today is a challenge to resolve in the past using any of the clever and carefully calibrated proxies available to paleoaltimetrists. This is reflected in the vigorous debates on the paleotopography of mountain ranges and plateaux the world over. As well-studied as the ones in the western U.S. are, their topographic evolution remains controversial. That such a fundamental feature as elevation of the land surface, so easy to precisely measure in real time, and with such important geodynamic implications, should be so difficult to retrodict, is a little embarrassing. But progress is being made as paleotopographic proxies are developed and refined and their numerous qualifications and dependencies are constrained. Indeed, the challenge and reward of paleotopographic study is that it doesn't lend itself well to routine application of shopworn approaches. Translating isotopic compositions of dirt, shapes of leaves, size-distributions of paleobubbles in lava, or cooling ages of minerals, to name just a few, to inferred elevations with uncertainties that are sufficiently small to be geologically useful requires both careful consideration of potential complications and some audacity, which keeps it interesting.

THE SIERRA NEVADA

Few, if any, mountain ranges have engendered more paleotopographic debate than California's Sierra Nevada (for an excellent review and analysis on this topic see Jones and others, 2004). Perspectives on the topographic history of the Sierra Nevada have tended towards bimodality. Either its height and modern topographic expression are old, as in late Cretaceous or so, or young, as in as late as Pliocene. The Sierra Nevadan youngers trace their intellectual ancestry at least as far back as articles in this journal by LeConte (1880, 1886), who observed and wrote eloquently on the auriferous gravels of the ancient river systems on the west side of the northern part of the range. These paleofluival deposits, described earlier by J. D. Whitney (1865, 1879), were, of course, at least informally well known to the burgeoning local economic geology community by 1849. Interestingly, very similar auriferous deposits of about the same age in southeastern Oregon also record westward drainage of the Idaho batholith, the erstwhile northern extension of the Sierra Nevada prior to Miocene extension (Stearns, 1954; Taubeneck, 1955; Allen, 1991; Cisneros, 1999; Trafton, 1999; Reiners and others, 2005). In any case, LeConte (1886) and many later studies (Lindgren, 1911; Hudson, 1955; Christensen, 1966; Huber, 1981, 1990; Unruh, 1991; Wakabayashi and Sawyer, 2001) interpreted relatively recent incision and tilting in the Sierran auriferous gravels and their channels as evidence for Late Cenozoic uplift of the Sierran crest, to the tune of about 1.5 to 2.5 km.

If there was a general consensus that the modern height of the Sierra Nevada was mostly late Cenozoic, it was disrupted by a groundbreaking study by House and others (1998), in one of the first applications of apatite (U-Th)/He thermochronology, a technique that constrains the timing of rock exhumation through ~1 to 2 km depths. House and others observed cooling age variations along strike of the range that they interpreted as requiring topographic relief of ~2 to 3 km across the major western canyons of the west side as early as ~60 to 80 Ma. Combined with other lines of evidence this pointed to a late Cretaceous–early Paleogene Sierra that was likely at least as high, maybe much higher, than today's. This was supported by another but different type of analysis of the same data, which suggested that the relief across the major canyons of the western Sierra today is about two times smaller than it was at 60 to 80 Ma (Braun and others, 2002).

Several studies examining stable isotope compositions of paleoprecipitation also provided support for an old high Sierra Nevada. Poage and Chamberlain (2002) showed that authigenic clays east of the range were severely depleted in ^{18}O at least as far back as mid-Miocene, reflecting the massive rain shadow cast by the range at that time. Working in the range itself but mostly on the other side, Mulch and others (2006) and Cassell and others (2009) showed that H isotopes in authigenic minerals in LeConte's paleofluvial deposits required Eo-Oligocene elevations and topographic gradients essentially the same as today's. These results were also consistent with similar reconstructions using organic biomarkers (Hren and others, 2010). Complications of paleoclimatic effects on isotopic lapse rates notwithstanding (see for example, Molnar, 2010), both thermochronologic and paleoclimatic proxies seem to point to the same story of a high Sierra Nevada as early as early Cenozoic or late Cretaceous.

Nevertheless, several compelling lines of evidence point to young rock and/or surface uplift of the Sierra Nevada. These include hypsometric evidence for episodes of late Cenozoic incision over large parts of the range (Clark and others, 2005), cosmogenic nuclide evidence for a pulse of rapid river incision between ~2 to 3 Ma (Stock and others, 2004), and the long-recognized tilting of sedimentary units on the west flank (Huber, 1981, 1990; Unruh, 1991; Wakabayashi and Sawyer, 2001).

Playing into the evidence for a young Sierra Nevada, seismic data show that the range lacks the buoyant lithospheric root one might expect to find beneath a long-lived, high mountain range. Instead felsic crust beneath at least the southern Sierra appears to disappear at the surprisingly shallow depth of ~35 km, where it transitions abruptly to what looks seismically like hot mantle asthenosphere (Wernicke and others, 1996). This leads to the reasonable interpretations that a) the range's current height is dynamically supported by upwelling asthenosphere, and b) at least part of the range must have somehow lost a deep crustal root. Ironically though, absence of the root is typically taken to mean that it must have been dense and convectively unstable relative to the underlying mantle, rather than buoyant. This makes sense for the expected composition of subarc lithosphere at the pressures of interest (Ducea and Saleeby, 1996; Ducea, 2001), so the expectation of a buoyant, lower crustal, sub-arc root may have been a red herring in the first place. In any case, strong support for Neogene loss of a dense root comes from changes in compositions and depths of xenoliths brought to the surface in and around the southern Sierrra in the late Miocene (Ducea and Saleeby, 1996). Manley and others (2000) also suggested that changes in flux and composition of mantle-derived magmatism at 3 to 4 Ma reflect loss of a juicy lithospheric root about this time.

Convective loss of lithosphere may produce surface elevation changes through isostatic adjustments, but in detail predicting the amount and even direction of surface elevation change from convective instabilities is not straightfoward (see for example, Elkins-Tanton, 2007). West of the southern Sierra, seismic data appear to reveal a disturbed Moho consistent with the picture of a dense blob that may be dripping or delaminating down to wherever it is that convectively destabilized lithosphere goes (Zandt and others, 2004). In this region, the surface appears to be subsiding (Saleeby and Foster, 2004). It is possible that upwelling asthenosphere to the east of this blob is causing uplift of the high Sierra. This could explain GPS and InSAR observations of modern vertical upward motion rates of 1 to 2 mm/yr for the Sierra Nevada (Hammond and others, 2011). This breakneck speed relative to adjacent regions can't have been going on for more than a couple million years at the most or the Sierra would be much taller than it is today.

The upshot of all this is that good evidence supports the Sierra Nevadan paleotopographic stories of both the older and younger camps. Thermochronologic and paleoclimatic evidence tend to favor the older camp, whereas a variety of geologic evidence and the convective instability paradigm supports the younger camp. The good news is that the Sierra Nevada has proven a useful testing ground for developing new methods and integrating diverse data sets to bear on a fascinating problem; the bad news is that it's not been clear what will resolve it. Contributing new data and potentially key insights to the debate here in the same journal that LeConte used to kick things off in 1880 are two new studies by McPhillips and Brandon and Cassel and others.

McPhillips and Brandon

McPhillips and Brandon present a new analysis of low-temperature cooling ages from the apatite (U-Th)/He system over a large area in the southern Sierra that may move the older and younger camps closer. The authors develop a model to explain the modern distribution of observed apatite (U-Th)/He cooling ages throughout the region, accounting for cooling of rocks as they are exhumed by erosion and deformed by differential uplift in the shallow crust. They contend that the modern age distribution requires large-scale westward tilting of the southern part of the range, tilting the "isochrones" or contours of constant cooling age across the landscape [also known as "chrontours" (Armstrong, 1966), or "thermochrons" (Harper, 1967)]. In the end their model requires ~3 degrees of tilting, ~2 km of surface uplift near the crest, and an increase in topographic relief in the southern Sierra of about a factor of two, sometime between 30 and 10 Ma. This 30 to 10 Ma window is a little older than might be preferred by the convective instablizers, but in other ways it is more consistent with geomorphic arguments for late uplift (Clark and others, 2005; Pelletier, 2007). Notably, McPhillips and Brandon argue that the range was almost certainly quite high in the Cretaceous, long before the 30 to 10 Ma uplift event, so it must have lost considerable relief sometime between the late Cretaceous and the 30 to 10 Ma event. But intriguingly, their analysis does not find evidence for the large magnitude late Cretaceous paleotopography of the long-wavelength canyons inferred by House and others (1998, 2001) and Braun (2002).

Cassell and Others

Taking a very different approach, Cassell and others address the question of the Eocene paleotopography of part of the Sierra Nevada to the north, using provenance of detrital zircon grains in the famous paleofluvial deposits studied by LeConte in the 19th century. A similar approach was also taken by Cecil and others (2010), who showed that although external sources to the east of the range could not be ruled out, U/Pb crystallization and (U-Th)/He cooling ages of the detrital zircons could be explained by entirely local Sierran sources with steep axial drainages, suggesting relief similar to today's. Cassel and others' result also support the conclusion of a relatively high-relief western Sierra dominated by local sources, but they also document increasing proportions from external sources in younger, late Eocene–early Oligocene, deposits. These probably came from more distal volcanic sources to the east, supporting the long-held view that the pre-Basin-and-Range Sierra Nevada was the western margin of a much larger orogenic plateau termed the Nevadaplano (Wolfe and others, 1997; House and others, 2001; DeCelles, 2004).

THE LARAMIDE

Almost everywhere in the Sierra Nevada, the vast majority of low-temperature apatite and zircon cooling ages are ~50 to 80 Ma (for example, Dumitru and others, 1990; House and others, 1997, 1998, 2001; Cecil and others, 2006, 2010; Ali and others, 2009; Maheo and others, 2009). To first order this means that erosion has been extremely slow (~0.02-0.06 mm/yr) since this time. Just as important though is the upper bound on these ages, which means that prior to ~80 Ma, cooling, and presumably erosional exhumation, was relatively fast. This abrupt change coincides with the end of rapid magmatic emplacement in the arc (for example, Ducea and others, 2001), as well as a fundamental shift in the style of deformation in the retroarc foreland. Between about 80 and 50 Ma, much of the retro-arc shortening in the U.S. Cordillera was accomplished on thrusts that penetrated the crystalline basement of the continent and manifested itself in relatively high-angle and mixed vergence systems that broke up the foreland. This style, region, and rough timing of deformation, confusingly conflated into the single term Laramide, leaves a broad thermochronologic and sedimentologic record, but nowhere are its results as topographically conspicuous today as in Wyoming, and to a lesser degree parts of Colorado and Montana.

Some aspects of Laramide deformation are well understood (Dickinson and Snyder, 1978; Dickinson and others, 1988; Steidtmann and Middleton, 1991; Erslev, 1993) but there is surprisingly little consensus about several aspects of it, including the relative timing of deformation and exhumation, both among and also within individual ranges. Previous estimates come mostly from sedimentary records in basins between ranges and some thermochronology from the ranges themselves (see summary in Peyton and others). Both of these are of course doubly indirect proxies of deformation and paleotopography (deposition and cooling imperfectly record erosion, which imperfectly records surface uplift) but until we can do a better job with more direct paleoaltimetric methods, in many cases these are the techniques we have to work with.

Peyton and Others

Peyton and others attempt to clarify the timing and rates of erosional exhumation in four ranges in Wyoming using apatite (U-Th)/He thermochronology. Previous results from Wyoming Laramide ranges using this technique yielded somewhat surprising results that point to opportunities for better understanding of these structures, the systematics of the technique, or both (Reiners and Farley, 2001; Beland, ms, 2002; Crowley and others, 2002). Peyton and others find similar results in their study. As expected, their thermochronologic ages generally decrease with increasing paleodepth in the Precambrian basement in these ranges, but in many cases they also show complications that are difficult to explain with simple models, possibly due in part to prolonged histories of the rocks at relatively shallow crustal depths. Nonetheless, the results point to several intriguing methodologic and geologic conclusions, one of which is that at least in one case, exhumation appears to have occurred significantly later in the west (the Beartooths) than in the east (the Bighorns). Evidence for relatively young Beartooth exhumation is also supported by sedimentary and other thermochronologic evidence (DeCelles and others, 1991; Omar and others, 1991). Peyton and others also find evidence for stacked slivers of basement between multiple thrust faults at depth in drill cores, similar to the intriguing results of Beland (ms, 2002).

THE BIG PICTURE

The last of these four papers takes a more direct approach to reconstructing paleoaltimetry than the thermochronologic or paleogeographic approaches of the other three. Since Dansgaard (1964) made clear the potential of systematic relationships between the modern O- and H-isotopic composition of modern precipitation and modern altitude, a great deal of work has focused on using proxies for paleoisotopic compositions of paleoprecipitation to constrain paleoaltitude. Authigenic minerals or phases that absorb water at or very near the land surface provide this proxy. To the extents that these minerals remain faithful over the years and that we can establish a reference relationship for the elevation-isotopic composition relationship for the time of interest, we can therefore retrodict the elevation at which an authigenic mineral formed. A good deal of pioneering and modern work on this approach has been published in *American Journal of Science,* including seminal regional studies (Fricke and Wing, 2004; Horton and others, 2004; Graham and others, 2005; Saylor and others, 2009; Quade and others, 2011), and critical work examining the rules of the game (Poage and Chamberlain, 2001; Blizniuk and Stern, 2005; Lechler and Niemi, 2012).

Chamberlain and Others

Chamberlain and others take an ambitious approach to reconstructing surface water isotopic compositions from multiple proxies over most of the western U.S. Cordillera from the late Cretaceous to the present. They recognize that isotopic compositions of surface waters (and the minerals that form in equilibrium with them) are not functions of elevation alone but are also influenced by global climate (for example, potential temperature at a given latitude at a given time) and complexities of local topography and atmospheric moisture trajectories and recycling. But they contend that the effects of global climate shifts on isotope-elevation relationships are small compared with the magnitude of elevation changes they infer, and that by examining isotopic changes at large length scales they minimize complicating local effects. The authors also complement their analysis with temperature proxies from paleobotanical records. The result is a synoptic picture of both paleotopographic and paleoclimatic evolution of the western US over the last ~80 Myr. The authors suggest that their data and complementary geologic observations require that at the dawn of the Cenzoic, an already moderately high proto-Nevadaplano was flanked on the west by a high Sierra Nevada and on the east by a broken foreland basin of Laramide uplifts. Between about 55 to 40 Ma this region was jacked up significantly higher, but in a transgressive wave from north to south. The rate of this surface uplift was fast, perhaps >1 km/Myr, and probably requires an explanation involving sublithospheric processes. Alas, this Eocene surface uplift was also the beginning of the end, as it was accompanied by widespread extension and the collapse that followed. By the Miocene the center of the Nevadaplano had collapsed, leaving only the flanks—the Sierra and the high Rockies as peripheral remnants.

A SINGLE ELEPHANT?

These four new studies continue the venerable conversation about paletopography of the western U.S. Cordillera that has been well represented in this journal from at least 1880. They also point to intriguing, if imperfect, connections with one another, and with previous work, suggesting they may be feeling out different parts of the same elephant. Chamberlain and others' analysis leads them to interpret the highest elevations for the Cordilleran interior and its western flank—the Sierra Nevada—during the Eocene, not earlier, when most of the shortening in the Cordillera and nearly all of the magmatism in the Sierra Nevada happened. Besides underscoring the perils of inferring simple relationships between horizontal tectonics (or voluminous magmatism) and surface elevation, this points to a potentially important role for sublithospheric processes on rock and surface uplift, both in general and in this specific case.

Moving to observations from the west flank of the Sierra Nevada, Eocene uplift of the Cordilleran interior may play into Cassel and others' observations of a shift from entirely local Sierran sources in the early Eocene to increased contributions from more distal easterly, interior, sources by the late Eocene. It is possible this provenance shift reflects uplift of the interior of the Cordilleran interior as much as, or instead of, eastward migration of Sierran drainage divides.

Relating McPhillips and Brandon's inferred uplift of the Sierra between 30 and 10 Ma to the larger elephant is less straightforward. Although some geomorphic studies also suggest Sierran uplift in this window (Clark and others, 2005; Pelletier, 2007), this is too young for the Eocene event affecting the Cordilleran interior, and too old for the Pliocene event favored by the Sierran youngers. But it seems reasonable that the western flank of the Cordillera may have experienced its own uplift event about this time, possibly associated with extensional collapse of the Cordilleran interior to the east, especially if it also involved westward tilting away from the extended interior. A later, potentially Pliocene, event could have also contributed elevation gain but might not yet have left much of an erosional/cooling record beyond some channel incision.

Finally, Peyton and others' observations that exhumation in the Beartooths probably started much later (~58 Ma) than in the Bighorns isn't consistent with simple expectations of eastward propagation of deformation in a retroarc thrust belt. While one could invoke *ad hoc* out-of-sequence thrusting to explain this, it could also be related to the nearby Eocene uplift of the Cordilleran interior. This would be expected to have a much stronger influence on exhumation, and possibly late deformation, in the Beartooths than in the Bighorns, which may be too far out on the eastern flank to participate in Eocene uplift.

Regardless of whether we can accurately make the bigger-picture connections between these studies yet, not to mention between the many other studies of western U.S. Cordillera paleotopography, these four papers represent important regional and methodological steps in defining the various parts of the beast that we will eventually come to see as the Cenozoic topographic history of western North America and its geodynamic significance.

ACKNOWLEDGMENT

I appreciate helpful discussions with George Zandt and many others who have imparted just enough knowledge on these issues to be dangerous, hopefully.

References

Ali, G. A. H., Reiners, P. W., and Ducea, M. N., 2009, Unroofing history of Alabama and Poverty Hills basement blocks, Owens Valley, California, from apatite (U-Th)/He thermochronology: International Geology Review, v. 51, n. 9–11, p. 1034–1050, http://dx.doi.org/10.1080/00206810902965270

Allen, J. E., 1991, The case of the inverted auriferous paleotorrent—exotic quartzite gravels on Wallowa Mountain peaks: Oregon Geology, v. 53, n. 5, p. 104–107.

Armstrong, R. L., 1966, K/Ar dating of plutonic and volcanic rocks in orogenic belts, *in* Schaeffer, O. A., and Zähringer, J., editors, Potassium Argon Dating: Heidelberg, Springer-Verlag, p. 117–131.

Beland, P. E., ms, 2002, Apatite fission track and (uranium-thorium)/helium thermochronology and vitrinite reflectance of the Casper Arch, Maverick Springs Dome, and the Wind River Basin: Implications for late Cenozoic deformation and cooling in the Wyoming foreland: Laramie, Wyoming, University of Wyoming, MS Thesis, p. 97.

Blisniuk, P. M., and Stern, L. A., 2005, Stable isotope paleoaltimetry: A critical review: American Journal of Science, v. 305, n. 10, p. 1033–1074, http://dx.doi.org/10.2475/ajs.305.10.1033

Braun, J., 2002a, Quantifying the effect of recent relief changes on age-elevation relationships: Earth and Planetary Science Letters, v. 200, n. 3–4, p. 331–343, http://dx.doi.org/10.1016/S0012-821X(02)00638-6

Cassel, E. J., Graham, S. A., and Chamberlain, C. P., 2009b, Cenozoic tectonic and topographic evolution of the northern Sierra Nevada, California, through stable isotope paleoaltimetry in volcanic glass: Geology, v. 37, n. 6, p. 547–550, http://dx.doi.org/10.1130/G25572A.1

Cecil, M. R., Ducea, M. N., Reiners, P. W., and Chase, C. G., 2006, Cenozoic exhumation of the northern Sierra Nevada, California, from (U-Th)/He thermochronology: Geological Society of America Bulletin, v. 118, n. 11–12, p. 1481–1488, http://dx.doi.org/10.1130/B25876.1

Cecil, M. R., Ducea, M. N., Reiners, P., Gehrels, G., Mulch, A., Allen, C., and Campbell, I., 2010, Provenance of Eocene river sediments from the central northern Sierra Nevada and implications for paleotopography: Tectonics, v. 29, n. TC6010, http://dx.doi.org/10.1029/2010TC002717

Christensen, M. N., 1966, Late Cenozoic crustal movements in the Sierra Nevada of California: Geological Society of America Bulletin, v. 77, n. 2, p. 163–182, http://dx.doi.org/10.1130/0016-7606(1966)77[163:LCCMIT]2.0.CO;2

Cisneros, G., 1999, Reconstruction of a Late Cretaceous–Paleocene river system—Geometry of an Early Tertiary nonconformity in the Elkhorn Mountains, northeastern Oregon, *in* Mendelson, C. V., and Mankiewicz, C., compilers, 12th Keck Research Symposium in Geology, Proceedings: Northfield, Minnesota, Fairway Foods, p. 291–294.

Clark, M. K., Maheo, G., Saleeby, J., and Farley, K. A., 2005. The non-equilibrium landscape of the southern Sierra Nevada, California: GSA Today, v. 15, n. 9, p. 4–10, http://dx.doi.org/10.1130/1052-5173(2005)015[4:TNLOTS]2.0.CO;2

Clark, M. L., 2007, The significance of paleotopography: Reviews in Mineralogy and Geochemistry, v. 66, n. 1, p. 1–21, http://dx.doi.org/10.2138/rmg.2007.66.1

Crowley, P. D., Reiners, P. W., Reuter, J. M., and Kaye, G. D., 2002, Laramide exhumation of the Bighorn Mountains, Wyoming: An apatite (U-Th)/He thermochronology study: Geology, v. 30, n. 1, p. 27–30, http://dx.doi.org/10.1130/0091-7613(2002)030⟨0027:LEOTBM⟩2.0.CO;2

Dansgaard, W., 1964, Stable isotopes in precipitation: Tellus, v. 16, n. 4, p. 436–468, http://dx.doi.org/10.1111/j.2153-3490.1964.tb00181.x

DeCelles, P. G., 2004, Late Jurassic to Eocene evolution of the Cordilleran thrust belt and foreland basin system, Western U.S.A.: American Journal of Science, v. 304, n. 2, p. 105–168, http://dx.doi.org/10.2475/ajs.304.2.105

DeCelles, P. G., Gray, M. B., Ridgway, K. D., Cole, R. B., Srivastava, P., Pequera, N., and Pivnik, D. A., 1991b, Kinematic history of a foreland uplift from Paleocene synorogenic conglomerate, Beartooth Range, Wyoming and Montana: Geological Society of America Bulletin, v. 103, n. 11, p. 1458–1475, http://dx.doi.org/10.1130/0016-7606(1991)103⟨1458:KHOAFU⟩2.3.CO;2

Dickinson, W. R., and Snyder, W. S., 1978, Plate tectonics of the Laramide Orogeny, *in* Matthews, V., editor, Laramide folding associated with basement block faulting in the western United States: Geological Society of America Memoir 151, p. 355–366.

Dickinson, W. R., Klute, M. A., Hayes, M. J., Janecke, S. U., Lundin, E. R., McKittrick, M. A., and Olivares, M. D., 1988, Paleogeographic and paleotectonic setting of Laramide sedimentary basins in the central Rocky Mountain region: Geological Society of America Bulletin, v. 100, p. 1023–1039, http://dx.doi.org/10.1130/0016-7606(1988)100⟨1023:PAPSOL⟩2.3.CO;2

Ducea, M. N., 2001, The California Arc: Thick granitic batholiths, eclogitic residues, lithospheric-scale thrusting, and magmatic flare-ups: GSA Today, v. 11, p. 4–10, http://dx.doi.org/10.1130/1052-5173(2001)011⟨0004:TCATGB⟩2.0.CO;2

Ducea, M. N., and Saleeby, J. B., 1996, Buoyancy sources for a large, unrooted mountain range, the Sierra Nevada, California: Evidence from xenolith thermobarometry: Journal of Geophysical Research, v. 101, n. B4, p. 8229–8244, http://dx.doi.org/10.1029/95JB03452

Dumitru, T. A., 1990, Subnormal Cenozoic geothermal gradients in the extinct Sierra Nevada magmatic arc: Consequences of Laramide and post-Laramide shallow-angle subduction: Journal of Geophysical Research, v. 95, n. B4, p. 4925–4941, http://dx.doi.org/10.1029/JB095iB04p04925

Elkins-Tanton, L. T., 2007, Continental magmatism, volatile recycling, and a heterogeneous mantle caused by lithospheric gravitational instabilities: Journal of Geophysical Research, v. 112, B03405, http://dx.doi.org/10.1029/2005JB004072

Erslev, E. A., 1993, Thrusts, back-thrusts and detachment of Laramide foreland arches, *in* Schmidt, C. J., Chase, R. B., and Erslev, E. A., editors, Laramide basement deformation in the Rocky Mountain foreland of the western United States: Geological Society of America Special Paper 280, p. 339–358.

Fricke, H. C., and Wing, S. L., 2004, Oxygen isotope paleobotanical estimates of temperature and δ^{18}O-latitude gradients over North America during the early Eocene: American Journal of Science, v. 304, n. 7, p. 612–635, http://dx.doi.org/10.2475/ajs.304.7.612

Graham, S. A., Chamberlain, C. P., Yue, Y., Ritts, B. D., Hanson, A. D., Horton, T. W., Waldbauer, J. R., Poage, M. A., and Feng, X., 2005, Stable isotope records of Cenozoic climate and topography, Tibetan plateau and Tarim basin: American Journal of Science, v. 305, n. 2, p. 101–118, http://dx.doi.org/10.2475/ajs.305.2.101

Hammond, W. C., Blewitt, G., Li, Z., Kreemer, C., and Plag, H.-P., 2011, EarthScope Plate Boundary Observatory Reveals Uplift of the Sierra Nevada: Austin, Texas, EarthScope National Meeting, May 17–20, 2011, Abstract and presentation available at: http://www.earthscope.org/meetings/national_meeting_11; last accessed 24 March 2012.

Harper, C. T., 1967, On the interpretation of potassium-argon ages from Precambrian shields and Phanerozoic orogens: Earth and Planetary Science Letters, v. 3, p. 128–132, http://dx.doi.org/10.1016/0012-821X(67)90023-4

Horton, T. W., Sjostrom, D. J., Abruzzese, M. J., Poage, M. A., Waldbauer, J. R., Hren, M., Wooden, J., and Chamberlain, C. P., 2004, Spatial and temporal variation of Cenozoic surface elevation in the Great Basin and Sierra Nevada: American Journal of Science, v. 304, n. 10, p. 862–888, http://dx.doi.org/10.2475/ajs.304.10.862

House, M. A., Wernicke, B. P., and Farley, K. A., 1998, Dating topography of the Sierra Nevada, California, using apatite (U-Th)/He ages: Nature, v. 396, p. 66–69, http://dx.doi.org/10.1038/23926

——— 2001, Paleo-geomorphology of the Sierra Nevada, California, from (U-Th)/He ages in apatite: American Journal of Science, v. 301, n. 2, p. 77–102, http://dx.doi.org/10.2475/ajs.301.2.77

House, M. A., Wernicke, B. P., Farley, K. A., and Dumitru, T. A., 1997, Cenozoic thermal evolution of the central Sierra Nevada, California, from (U-Th)/He thermochronometry: Earth and Planetary Science Letters, v. 151, n. 3–4, p. 167–179, http://dx.doi.org/10.1016/S0012-821X(97)81846-8

Hren, M. T., Pagani, M., Erwin, D. M., and Brandon, M., 2010, Biomarker reconstruction of the early Eocene paleotopography and paleoclimate of the northern Sierra Nevada: Geology, v. 38, n. 1, p. 7–10, http://dx.doi.org/10.1130/G30215.1

Huber, N. K., 1981, Amount and timing of late Cenozoic uplift and tilt of the central Sierra Nevada, California—Evidence from the upper San Joaquin river basin: U.S. Geological Survey Professional Paper, v. 1197, 28 p.

——— 1990, The late Cenozoic evolution of the Tuolumne River, central Sierra Nevada, California: Geological Society of America Bulletin, v. 102, n. 1, p. 102–115, http://dx.doi.org/10.1130/0016-7606(1990)102⟨0102:TLCEOT⟩2.3.CO;2

Hudson, F. S., 1955, Measurement of the deformation of the Sierra Nevada, California, since middle Eocene: Geological Society of America Bulletin, v. 66, n. 7, p. 835–869, http://dx.doi.org/10.1130/0016-7606(1955)66[835:MOTDOT]2.0.CO;2

Jones, C. H., Farmer, G. L., and Unruh, J., 2004, Tectonics of Pliocene removal of lithosphere of the Sierra Nevada, California: Geological Society of America Bulletin, v. 116, n. 11–12, 1408–1422, http://dx.doi.org/10.1130/B25397.1

Lechler, A. R., and Niemi, N. A., 2011, Controls on the Spatial Variability of Modern Meteoric δ^{18}O: Empirical Constraints from the Western U.S. and East Asia and Implications for Stable Isotope Studies: American Journal of Science, v. 311, n. 8, p. 664–700, http://dx.doi.org/10.2475/08.2011.02

LeConte, J., 1880, The old river beds of California: American Journal of Science, Third Series, v. 19, p. 176–190.

——— 1886, A post-Tertiary elevation of the Sierra Nevada shown by the river beds: American Journal of Science, Third Series, v. 32, 167–181.

Lindgren, W., 1911, The Tertiary gravels of the Sierra Nevada of California: U.S. Geological Survey Professional Paper 73, 226 p.

Mahéo, G., Saleeby, J., Saleeby, Z., and Farley, K. A., 2009, Tectonic control on southern Sierra Nevada topography, California: Tectonics, v. 28, n. 6. TC6006, http://dx.doi.org/10.1029/2008TC002340

Manley, C. R., Glazner, A. F., and Farmer, G. L., 2000, Timing of volcanism in the Sierra Nevada of California: Evidence for Pliocene delamination of the batholithic root?: Geology, v. 28, n. 9, p. 811–814, http://dx.doi.org/10.1130/0091-7613(2000)28⟨811:TOVITS⟩2.0.CO;2

Molnar, P., 2010, Deuterium and oxygen isotopes, paleoelevations of the Sierra Nevada, and Cenozoic climate: Geological Society of America Bulletin, v. 122, n. 7–8, p. 1106–1115, http://dx.doi.org/10.1130/B30001.1

Mulch, A., Graham, S. A., and Chamberlain, C. P., 2006, Hydrogen isotopes in Eocene river gravels and paleoelevation of the Sierra Nevada: Science, v. 313, n. 5783, p. 87–89, http://dx.doi.org/10.1126/science.1125986

Omar, G. I., Lutz, T. M., and Giegengack, R., 1994, Apatite fission-track evidence for Laramide and post-Laramide uplift and anomalous thermal regime at the Beartooth overthrust, Montana-Wyoming: Geological Society of America Bulletin, v. 106, n. 1, p. 74–85, http://dx.doi.org/10.1130/0016-7606(1994)106⟨0074:AFTEFL⟩2.3.CO;2

Pelletier, J., 2007, Numerical modeling of the Cenozoic geomorphic evolution of the southern Sierra Nevada, California: Earth and Planetary Science Letters, v. 259, n. 1–2, p. 85–96, http://dx.doi.org/10.1016/j.epsl.2007.04.030

Poage, M. A., and Chamberlain, C. P., 2001, Empirical Relationships Between Elevation and the Stable Isotope Composition of Precipitation and Surface Waters: Considerations for Studies of Paleoelevation Change: American Journal of Science, v. 301, n. 1, p. 1–15, http://dx.doi.org/10.2475/ajs.301.1.1

——— 2002, Stable isotopic evidence for a pre-middle Miocene rainshadow in the western Basin and Range: implications for the paleotopography uplift of the Sierra Nevada: Tectonics, v. 21, n. 1034, p. 1–10, http://dx.doi.org/10.1029/2001TC001303

Quade, J., Breecker, D. O., Daëron, M., and Eiler, J., 2011, The paleoaltimetry of Tibet: An isotopic perspective: American Journal of Science, v. 311, n. 2, p. 77–115, http://dx.doi.org/10.2475/02.2011.01

Reiners, P. W., and Farley, K. A., 2001, Influence of crystal size on apatite (U-Th)/He thermochronology: an example from the Bighorn Mountains, Wyoming: Earth and Planetary Science Letters, v. 188, n. 3–4, p. 413–420, http://dx.doi.org/10.1016/S0012-821X(01)00341-7

Reiners, P. W., Campbell, I. H., Nicolescu, S., Allen, C. M., Hourigan, J. K., Garver, J. I., Mattinson, J. M., and Cowan, D. S., 2005, (U-Th)/(He-Pb) double dating of detrital zircons: American Journal of Science, v. 305, n. 4, p. 259–311, http://dx.doi.org/10.2475/ajs.305.4.259

Saleeby, J., and Foster, Z., 2004, Topographic response to mantle lithosphere removal in the southern Sierra Nevada region, California: Geology, v. 32, n. 3, p. 245–248; http://dx.doi.org/10.1130/G19958.1

Saylor, J. E., Quade, J., Dettman, D. L., DeCelles, P. G., Kapp, P. A., and Ding, L., 2009, The late Miocene through present paleoelevation history of southwestern Tibet: American Journal of Science, v. 309, n. 1, p. 1–42, http://dx.doi.org/10.2475/01.2009.01

Stearns, H. T., 1954, Evidence of a missing Lower Paleozoic (?) Formation in the Hells Canyon area, Idaho-Oregon: Geological Society of America Bulletin, v. 65, n. 9, p. 939–940, http://dx.doi.org/10.1130/0016-7606(1954)65[939:EOAMLP]2.0.CO;2

Steidtmann, J. R., and Middleton, L. T., 1991, Fault chronology and uplift history of the southern Wind River Range, Wyoming: Implications for Laramide and post-Laramide deformation in the Rocky Mountain foreland: Geological Society of America Bulletin, v. 103, n. 4, p. 472–485, http://dx.doi.org/10.1130/0016-7606(1991)103⟨0472:FCAUHO⟩2.3.CO;2

Stock, G. M., Anderson, R. S., and Finkel, R. C., 2004, Pace of landscape evolution in the Sierra Nevada, California, revealed by cosmogenic dating of cave sediments: Geology, v. 32, n. 3, p. 193–196, http://dx.doi.org/10.1130/G20197.1

Taubeneck, W. H., 1955, Age of the Bald Mountain batholith, northeastern Oregon: Northwest Science, v. 29, p. 93–96.

Trafton, K. S., 1999, Paleogeographic implications of Late Cretaceous–Early Tertiary quartzite-bearing fluvial sediments, Elkhorn Mountains, Northeast Oregon, *in* Mendelson, C. V., and Mankiewicz, C., compilers, 12th Keck Research Symposium in Geology, Proceedings: Northfield, Minnesota, Fairway Foods, p. 287–290.

Unruh, J. R., 1991, The uplift of the Sierra Nevada and implications for late Cenozoic epeirogeny in the western Cordillera: Geological Society of America Bulletin, v. 103, n. 11, p. 1395–1404, http://dx.doi.org/10.1130/0016-7606(1991)103⟨1395:TUOTSN⟩2.3.CO;2

Wakabayashi, J., and Sawyer, T. L., 2001, Stream incision, tectonics, uplift and evolution of topography of the Sierra Nevada, California: The Journal of Geology, v. 109, n. 5, p. 539–562, http://dx.doi.org/10.1086/321962

Wernicke, B., Clayton, R., Ducea, M., Jones, C. H., Park, S., Ruppert, S., Saleeby, J., Snow, J. K., Squires, L., Fliedner, M., Jiracek, G., Keller, R., Klemperer, S., Luetgert, J., Malin, P., Miller, K., Mooney, W., Oliver, H., and Phinney, R., 1996, Origin of high mountains in the continents: The southern Sierra Nevada: Science, v. 271, n. 5246, p. 190–193, http://dx.doi.org/10.1126/science.271.5246.190

Whitney, J. D., 1865, Geological Survey of California: Geology, v. 1: Sherman and Company, Philadelphia, p. 498.

——— 1879, The auriferous gravels of the Sierra Nevada: Memoirs of the Museum of Comparative Zoology at Harvard College, v. 6, p. 569.

Wolfe, J. A., Schorn, H. E., Forest, C. E., and Molnar, P., 1997, Paleobotanical evidence for high altitudes in Nevada during the Miocene: Science, v. 276, n. 5319, p. 1672–1675, http://dx.doi.org/10.1126/science.276.5319.1672

Zandt, G., Gilbert, H., Owens, T. J., Ducea, M., Saleeby, J., and Jones, C. H., 2004, Active foundering of a continental arc root beneath the southern Sierra Nevada in California: Nature, v. 431, p. 41–46, http://dx.doi.org/10.1038/nature02847