Downloaded from geology.gsapubs.org on May 1, 2012

Geology

Sedimentologic and isotopic constraints on the Paleogene paleogeography and paleotopography of the southern Sierra Nevada, California

Alex R. Lechler and Nathan A. Niemi

Geology 2011;39;379-382
doi: 10.1130/G31535.1

Email alerting services	click www.gsapubs.org/cgi/alerts to receive free e-mail alerts when new articles cite this article
Subscribe	click www.gsapubs.org/subscriptions/ to subscribe to Geology
Permission request	click http://www.geosociety.org/pubs/copyrt.htm#gsa to contact GSA

Copyright not claimed on content prepared wholly by U.S. government employees within scope of their employment. Individual scientists are hereby granted permission, without fees or further requests to GSA, to use a single figure, a single table, and/or a brief paragraph of text in subsequent works and to make unlimited copies of items in GSA's journals for noncommercial use in classrooms to further education and science. This file may not be posted to any Web site, but authors may post the abstracts only of their articles on their own or their organization's Web site providing the posting includes a reference to the article's full citation. GSA provides this and other forums for the presentation of diverse opinions and positions by scientists worldwide, regardless of their race, citizenship, gender, religion, or political viewpoint. Opinions presented in this publication do not reflect official positions of the Society.

Notes

© 2011 Geological Society of America

THE
GEOLOGICAL
SOCIETY
OF AMERICA

Sedimentologic and isotopic constraints on the Paleogene paleogeography and paleotopography of the southern Sierra Nevada, California

Alex R. Lechler and Nathan A. Niemi
Department of Geological Sciences, University of Michigan, Ann Arbor, Michigan 48109, USA

ABSTRACT

Detrital zircon U-Pb provenance and stable isotopic studies of three Paleogene southern Sierra Nevada (California) basins place new constraints on the paleoelevation history of the region. Age spectra from the Paleocene Witnet Formation within the southernmost Sierra Nevada link these sediments to source terranes that were at or near sea level in the early Cenozoic, while age spectra from the Paleocene Goler Formation, east of the Sierra Nevada, demonstrate isolation of southern Sierra Nevada basins from the continental interior and tapping of Jurassic and Triassic arc flank sources during the Paleocene. West of the Sierra Nevada, strata of the Eocene Tejon Formation are dominated by Cretaceous zircons sourced from the Sierran batholith. Goler Formation carbonate $\delta^{18}O$ suggests Paleocene paleoelevations of 1–2 km for the central and southern Sierra Nevada. Taken together, these data indicate a Paleogene southern Sierra Nevada with modest elevations, locally dissected to sea level by rift basins formed by Late Cretaceous lithospheric collapse. These results place new limits on the amount of regional middle to late Cenozoic elevation gain that may have resulted from the loss of dense, mantle lithosphere from below the central and southern Sierra Nevada, and point to possible north-south variations in the topographic evolution of the Sierra Nevada.

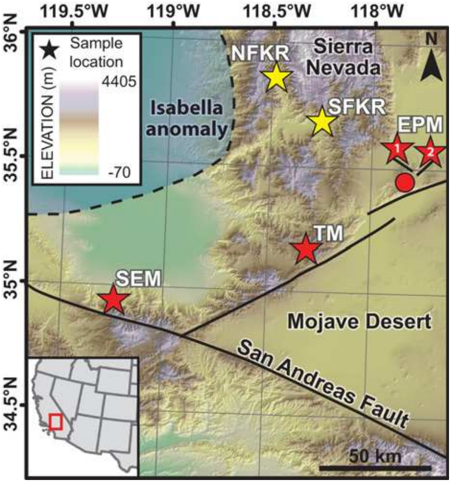

Figure 1. Color digital elevation model (DEM) with sandstone (red stars), modern sand (yellow stars), and micrite (red circle) sample locations (see the Data Repository [see footnote 1]). Goler Formation samples are marked by numbered stars. Blue swath shows approximate position of Isabella anomaly imaged at ~150 km depth (Zandt et al., 2004). Inset map of southwest United States shows approximate DEM extent. NFKR—North Fork Kern River, SFKR—South Fork Kern River, EPM—El Paso Mountains, TM—Tehachapi Mountains, SEM—San Emigdio Mountains.

INTRODUCTION

The topographic evolution of the Sierra Nevada (California) is a key constraint on tectonic and geodynamic models of the southwest United States; however, various elevation histories have been proposed. At one end of the spectrum, geomorphic evidence has been used to argue for a low elevation (<1 km) northern (north of the San Joaquin River) and moderate elevation (2–2.5 km) central Sierra Nevada (Mount Whitney region) throughout much of the Cenozoic, with modern elevations achieved by 1.5–2 km of Late Miocene–early Pliocene uplift (Unruh, 1991; Wakabayashi and Sawyer, 2001). At the other end, low-temperature thermochronologic data have been interpreted as requiring a high-standing (~4.5 km) central Sierra since the Late Cretaceous (House et al., 1998), while in the northern Sierra, stable isotope and molecular proxies suggest Eocene range elevations comparable to the modern (2–2.5 km; Mulch et al., 2006; Hren et al., 2010). A multistage evolution for the central Sierra Nevada, based on thermochronometric and geomorphic evidence, has also been proposed in which early Cenozoic surfaces (~1.5 km) underwent >2 km of uplift between 32.5 and 3.5 Ma, raising the central Sierra to its modern (~4 km) elevations (Clark et al., 2005).

The contrasting elevation histories for the central and northern Sierra Nevada may in part be the result of along-strike variations (e.g., Busby and Putirka, 2009). Validation of this idea is limited, however, due to a lack of robust paleoelevation constraints for the Sierra Nevada south of Mount Whitney. This region has undergone a unique tectonic evolution, including early Cenozoic lithospheric collapse (e.g., Saleeby et al., 2007) and late Cenozoic loss of a dense lithospheric root (the seismically imaged Isabella anomaly), (e.g., Zandt et al., 2004; Fig. 1). Recent thermochronologic and structural data suggest that the southern Sierra Nevada experienced a multistage uplift history consistent with the Clark et al. (2005) model for the central Sierra (Maheo et al., 2009), but the magnitude and timing of regional uplift is poorly constrained. We present new detrital zircon U-Pb dates and $\delta^{18}O$ data from southern Sierra Nevada Paleogene basins (Fig. 1) to provide constraints on early Cenozoic regional paleogeography and paleotopography.

EARLY CENOZOIC BASINS

The Sierra Nevada magmatic arc formed in response to Mesozoic subduction along the western margin of North America (Evernden and Kistler, 1970). A shift to low-angle subduction during the latest Cretaceous–early Paleogene led to widespread oblique extension throughout much of the arc and arc flank that resulted in a sequence of local rift basins that preserve early Cenozoic sediments in the southern Sierra Nevada region (Wood and Saleeby, 1997). East of the Sierra Nevada, these sediments are represented by the Paleocene Goler Formation, a 4-km-thick, fossil-bearing, continental clastic sequence best exposed in the El Paso Mountains (Fig. 1). The Early Paleocene lower Goler Formation (members 1–3; Cox, 1982) is interpreted as a sequence of alluvial fan conglomerates and sandstones derived primarily from local Triassic plutonic rocks (Cox, 1982). Middle Paleocene upper Goler Formation (members 4a–4d) fluvial sandstones and conglomerates contain a diverse clast assemblage of plutonic, volcanic, and siliciclastic cobbles indicative of a more distal source (Cox, 1982). Marine mollusks in member 4d, along with ray teeth, turtle, and crocodilian fossils in members 3, 4a, and 4b, require the Goler basin to have been alternately inundated by or adjacent to the paleo–Pacific Ocean during the Paleocene (e.g., Lofgren et al., 2008).

Within the southernmost Sierra Nevada, the Witnet Formation comprises the oldest preserved Cenozoic sediments (Fig. 1). This sequence of plutonic-cobble and volcanic-cobble conglomerates and sandstones (Buwalda, 1954) is lithologically indistinguishable from the lower Goler Formation (members 1 and 2). This similarity

---

Geology, April 2011; v. 39; no. 4; p. 379–382; doi: 10.1130/G31535.1; 3 figures; Data Repository item 2011122.

has led to speculation that the two units are correlative (Cox, 1982). However, poor age control on the Witnet Formation, with estimates spanning from latest Cretaceous (Wood and Saleeby, 1997) to Oligocene (Buwalda, 1954), preclude a definitive correlation.

West of the southern Sierra Nevada, the oldest Cenozoic sediments preserved are the Middle Eocene Tejon Formation, which was deposited in a shallow-marine basin directly on top of crystalline basement rocks now exposed in the San Emigdio Mountains (Fig. 1). Like the Witnet and Goler Formations, the siliciclastic Tejon Formation contains abundant plutonic and volcanic detritus. Sandstone petrology suggests that Tejon sediments were derived from sources in the southern Sierra Nevada, northern Mojave Desert, and basement rocks of the San Emigdio and Tehachapi Mountains (Critelli and Nilsen, 2000).

DETRITAL ZIRCON U-PB AND CARBONATE $\delta^{18}O$ DATA

Six medium- to coarse-grained, arkosic to lithic sand and sandstone samples from the southern Sierra Nevada region (Fig. 1) were analyzed at the University of Arizona LaserChron Center (see the GSA Data Repository[1]). In total, 578 analyses satisfied concordance and reproducibility requirements (Data Repository) and were incorporated into age-probability plots for each basin (Fig. 2A).

In order to constrain the amount of Sierran detritus deposited in early Cenozoic basins, U-Pb age spectra were compiled from two modern river sand samples collected from the Kern River, which drains the southern Sierra Nevada batholith (Fig. 1). Both North (NFKR) and South (SFKR) Fork samples are dominated by mid-Cretaceous and Late Jurassic zircons with subordinate Middle Jurassic age peaks. A minor Early Jurassic age peak is also evident in the SFKR sample (Fig. 2A).

Two sandstone samples were collected from the fluvial portion of the Goler Formation (EPM-1 from member 4d, EPM-2 from member 4b; Fig. DR1 in the Data Repository). Both Goler samples are dominated by Middle and Late Jurassic ages, with a minor peak of Late Triassic–Early Jurassic ages (Fig. 2A). A shift to younger ages is observed in the upper Goler sample (EPM-1), which also contains a well-defined peak of mid-Cretaceous zircons not observed in EPM-2.

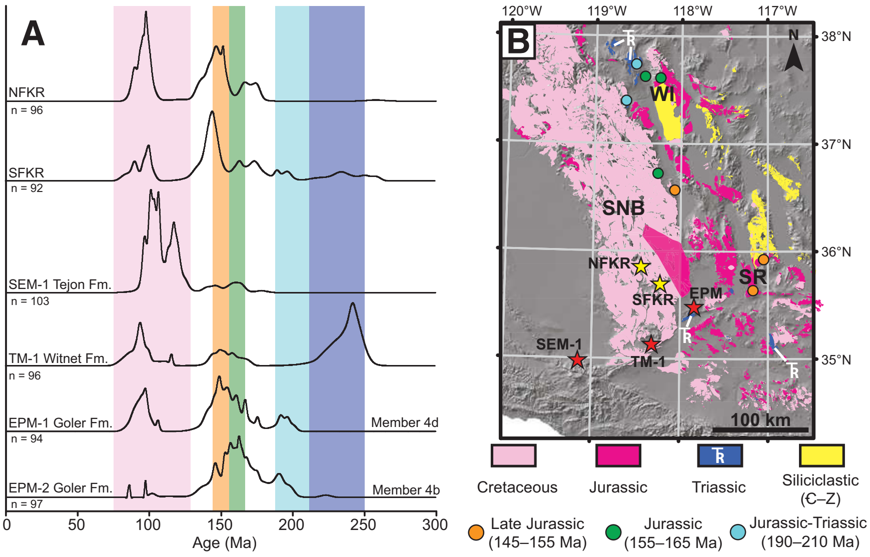

Figure 2. A: 0–300 Ma detrital zircon U-Pb age-probability plots (see the Data Repository [see footnote 1]). Colored swaths highlight diagnostic age populations. B: Digital elevation model (DEM) of Sierra Nevada region with modern distribution of igneous and siliciclastic rocks, color-coded by age (compiled from various sources; see the Data Repository). Location of diagnostic ages denoted by colored dots with same color code as A. Stars mark sample locations. WI—White-Inyo Mountains; SR—Slate Range; SNB—Sierra Nevada batholith; NFKR—North Fork Kern River, SFKR—South Fork Kern River, EPM—El Paso Mountains.

Age spectra from the Witnet (TM-1) and Tejon (SEM-1) Formations are distinct from those of the upper Goler Formation. Witnet sediments are dominated by mid-Cretaceous and Early Triassic zircons, while mid-Cretaceous zircons are the only significant population in the Tejon sample (Fig. 2A).

All samples display a paucity of pre-Mesozoic zircons (Fig. DR2). Proterozoic and Paleozoic ages compose ~9% of the Goler samples, and are even rarer in the Witnet (4%) and Tejon (2%) samples.

Lacustrine micrite sampled from Goler Formation member 4a (Cox, 1982) provides isotopic ($\delta^{18}O$) constraints on Goler basin waters. The micrite has an average $\delta^{18}O$ (Peedee belemnite) value of –12.3‰ (see the Data Repository). The $\delta^{18}O$ of the water in which the micrite precipitated was calculated (O'Neil et al., 1969) using a regional Eocene sea-level temperature range of 20–25 °C (Yapp, 2008; Hren et al., 2010). Corresponding $\delta^{18}O_{SMOW}$ (SMOW—standard mean ocean water) values of –10.1‰ to –11.2‰ are presumed to represent Goler basin waters at the time of micrite deposition.

SEDIMENTARY PROVENANCE

We identify prospective source regions for each Paleogene basin using the modern distribution of igneous and siliciclastic rocks in the Sierra Nevada region (Fig. 2B). This approach is limited by the assumption that modern distributions are representative of early Cenozoic exposures, but the uniqueness of detrital age spectra (Fig. 2A) and the systematic age distribution of igneous rocks in this region (Fig. 2B) permit this approach.

The Sierran batholith is discounted as a major source for Goler sediments based on the dominance of Middle to Late Jurassic zircon U-Pb ages over Cretaceous ages and the presence of a mixed plutonic and volcanic clast assemblage in the upper Goler Formation, an interpretation consistent with the observation that Sierran detritus is a minor component of El Paso basin sediments prior to 8 Ma (Loomis and Burbank, 1988). Middle and Late Jurassic plutonic and volcanic rocks are currently exposed east of the Sierra Nevada (Fig. 2B) in the White-Inyo Mountains (Dunne et al., 1998) and the Slate Range (Dunne and Walker, 2004). The Slate Range has been proposed as a source region for the upper Goler Formation, based on west-directed paleocurrent indicators and clast lithologies (Cox, 1982). Our data do not preclude the Slate Range as a sedimentary source for the upper Goler Formation, but observed 190–210 Ma and 155–165 Ma zircon age populations have no known source in the Slate Range. The 190–210 Ma zircon population is perhaps most diagnostic, as igneous rocks of this age are scarce in the Sierra Nevada region. The most viable source for 190–210 Ma zircons, as well as 155–165 Ma and Proterozoic populations, is west of the northern White Mountains (Fig. 2B; Fig. DR2).

Witnet Formation U-Pb ages require a sedimentary source distinct from that of the upper

---

[1]GSA Data Repository item 2011122, detailed sample locations and descriptions (Table DR1, Fig. DR1), all zircon U-Pb (Table DR2, Fig. DR2) and $\delta^{18}O$ (Table DR3) data and procedures, and Figure 2B map sources (Fig. DR3), 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.

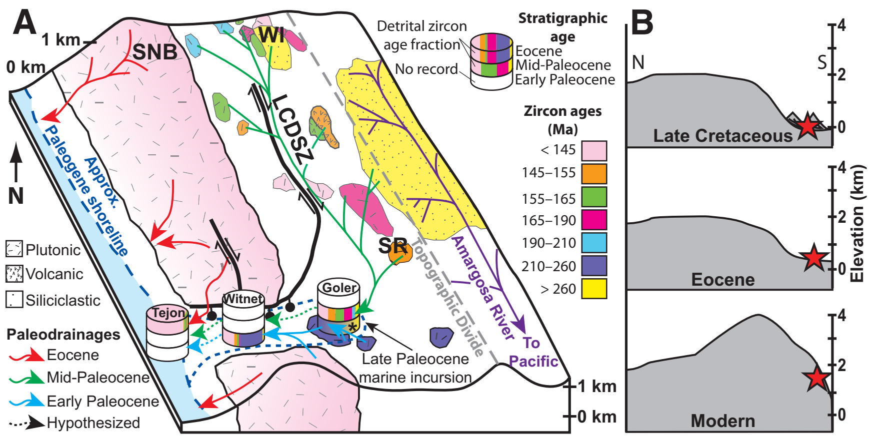

Figure 3. A: Diagram of early Paleogene southern Sierra Nevada regional paleotopography and paleogeography constrained by detrital zircon U-Pb age spectra and correspondence with plutonic, volcanic, and siliciclastic source terranes (see Fig. 2B). Late Cretaceous dextral shear zones (LCDSZ) and rift basins provided fluvial pathways and depocenters for Paleogene sediment transport and deposition. Amargosa River paleogeography is from Howard (1996) and Wernicke (2011). Asterisk indicates lower Goler Formation detrital composition constrained by clast and sandstone point counts (Cox, 1982), not through detrital zircon U-Pb dating. SR—Slate Range; SNB—Sierra Nevada batholith; WI—White-Inyo Mountains. B: Schematic north-south cross sections showing Late Cretaceous to modern mean elevation distributions of Sierra Nevada. Red star marks position of Witnet basin through time.

Goler Formation (Fig. 2A). Mid-Cretaceous zircons in the Witnet Formation are likely derived from local Sierran basement sources (Fig. DR1). The prominent peak of Early Triassic ages, however, must be derived from a more distal source. The most likely sources are Triassic plutons in the basement of the El Paso Mountains and northern Mojave Desert (Fig. 2B; Cox, 1982). These plutons were also the primary source for locally derived sediments in the lower Goler Formation (Cox, 1982), which supports proposed correlations of the lower Goler and Witnet Formations, and suggests that both were part of the same sedimentary system, with proximal Goler alluvial fans supplying sediment to the Witnet basin via a west-flowing, trans-Sierran river. This interpretation places new bounds on the age and paleoelevation of the Witnet Formation, constraining deposition to Early Paleocene time, at elevations at or below those of the near-sea-level Goler basin.

The dominance of mid-Cretaceous zircons in the Tejon Formation indicates that the Tejon basin was fed by a fluvial system with headwaters in the Sierran batholith, and was isolated from the arc flank regions sourcing the Goler and Witnet Formations. Thus, the Paleocene rivers transecting the southernmost Sierra Nevada appear to have been cut off or redirected during the Eocene.

The small proportion of pre-Mesozoic zircons in all detrital samples (≤9%) places additional constraints on sedimentary provenance. Paleoproterozoic and Mesoproterozoic zircon ages dominate Neoproterozoic and Paleozoic quartzite-rich strata in the Great Basin (e.g., Gehrels et al., 1995). As a result, Proterozoic zircons and associated quartzite clasts would have been abundant in continental interior–sourced Paleogene fluvial systems, as observed in Amargosa paleoriver deposits (Fig. 3A; Howard, 1996; Wernicke, 2011). Quartzite is subordinate to igneous clasts throughout the upper Goler Formation (Cox, 1982). This, along with the relative lack of pre-Mesozoic zircons in the Goler, Witnet, and Tejon Formations, suggests that southern Sierra Nevada fluvial systems were isolated from the continental interior during the early Paleogene (Fig. 3A), a result consistent with observed endemism of Goler fossil species (Lofgren et al., 2008).

EARLY CENOZOIC PALEOTOPOGRAPHY AND PALEOGEOGRAPHY OF THE SOUTHERN SIERRA NEVADA

Our provenance work on southern Sierra Nevada Paleogene basins places important constraints on the early Cenozoic paleoelevation history of the region. Paleontologic evidence puts the Goler basin at or near sea level during deposition (Lofgren et al., 2008). As Witnet sediments appear to be coeval with, deposited downstream from, and share a common source with the lower Goler Formation, the Witnet Formation must have also been deposited at or near sea level, ~1500 m lower than modern exposure elevations.

Water $\delta^{18}O_{SMOW}$ values of –10.1‰ to –11.2‰ derived from Goler Formation lacustrine micrites are significantly depleted relative to Eocene sea-level $\delta^{18}O_{SMOW}$ estimates of –6.7‰ to –8.9‰ (Yapp, 2008; Hren et al., 2010). Goler Formation paleosol carbonate nodules from the same stratigraphic interval as the micrite (member 4a) exhibit $\delta^{18}O_{SMOW}$ values (–10.5 to –11.6‰; calculated from Torres, 2010) remarkably similar to those of the micrite. Paleosol carbonate $\delta^{18}O$ reflects local precipitation falling directly into the basin, whereas lacustrine carbonates integrate the isotopic signal from throughout the contributing catchment. The observed isotopic depletion in each proxy system suggests that all waters falling (precipitation) and transported (fluvial) into the Goler basin were subject to orographic rainout over a topographic barrier on the windward side of the Goler basin and White-Inyo Mountains source region, likely in the Paleocene central and southern Sierra Nevada. With early Cenozoic $\delta^{18}O$-elevation gradients of ~–2‰/km (Mulch et al., 2006; Hren et al., 2010), a $\delta^{18}O$ depletion of –1.2‰ to –4.5‰ for Goler waters relative to Eocene sea level indicates that the Paleocene central and southern Sierra Nevada had paleoelevations of 1–2 km.

In combination, the provenance and isotopic data suggest that the Paleocene southern Sierra Nevada had modest elevations, in agreement with estimates derived for the Paleocene–Eocene central Sierra Nevada (~1.5 km; Clark et al., 2005); however, on a local scale, near-sea-level basins transected the range. These basins likely developed in response to Late Cretaceous orogenic collapse of the southernmost Sierra Nevada (Saleeby et al., 2007). Localization of the source terranes for Goler sediments adjacent to the position of Late Cretaceous dextral shear zones associated with Sierran orogenic collapse further underscores the apparent tectonic control on the paleogeographic evolution of the early Cenozoic southern Sierra (Fig. 3A; Bartley et al., 2007). During the Eocene, the west-directed fluvial systems feeding the Goler and Witnet basins appear to have been cut off or redirected. This truncation may record a phase of regional Eocene uplift (e.g., Goodman and Malin, 1992); however, based on similarities between the net post-Paleocene uplift of the Witnet Formation (~1500 m), and the proposed post-Eocene uplift of the central and southern Sierra Nevada (~2000 m; Clark et al., 2005), the amount of Early Eocene uplift was presumably minor.

The results presented here provide a coherent Cenozoic uplift history for the central and southern Sierra Nevada, consistent with previous models (Clark et al., 2005; Maheo et al., 2009). The applicability of this history to the entire orogen, however, depends on whether the northern Sierra Nevada is a long-lived (e.g., Mulch et al., 2006) or young (e.g., Wakabayashi and Sawyer, 2001) topographic feature. In addition, the work presented here, along with existing paleontologic (Lofgren et al., 2008) and sedimentologic (Cecil et al., 2011) evidence, suggests that Sierra

Nevada coastal basins were isolated from continental interior drainages in Paleocene–Eocene time (Fig. 3A). This contrasts with Oligocene reconstructions in which fluvial systems rising in the Great Basin traversed the Sierra Nevada (north of 38°N), connecting the high-standing continental interior to the coast (e.g. Henry and Faulds, 2010), and calls into question models in which a high-standing orogenic plateau over present-day Nevada extended as far south as the latitude (~36°N) of the southern Sierra (e.g., Ernst, 2010).

CONCLUSIONS

Combined zircon U-Pb provenance and $\delta^{18}O$ data constrain the Paleocene paleoelevation of the southern Sierra Nevada to be modest (1–2 km), with local dissection by low-elevation basins and fluvial systems tapping the eastern arc flank region. Near-sea-level deposition of the Witnet Formation requires ~1500 m of absolute uplift of the southern Sierra Nevada since the Paleocene. Most of this uplift is likely post-Eocene, given similarities to published uplift estimates of the central and southern Sierra Nevada based on geomorphic criteria (Clark et al., 2005), and may be the result of the loss of a dense lithospheric root. These results contrast with models of a topographically stable northern Sierra Nevada (e.g., Mulch et al., 2006), thus underscoring the possibility of spatial variability in Cenozoic Sierra Nevada paleogeography, and highlighting the roles that local tectonic events have played in controlling the topographic and geodynamic evolution of the Cordilleran margin.

ACKNOWLEDGMENTS

We thank G. Gehrels and A. Pullen at the University of Arizona LaserChron Center for assistance with U-Pb analyses, and K. Lohmann and L. Wingate at the University of Michigan Stable Isotope Lab for collaboration on isotopic analyses. We also thank C. Henry, E. Nadin, and K. Putirka for thoughtful reviews. U-Pb analysis was supported by National Science Foundation grant EAR-0607458 to M.K. Clark and a University of Michigan Turner Award to Lechler.

REFERENCES CITED

Bartley, J.M., Glazner, A.F., Coleman, D.S., Kylander-Clark, A., Mapes, R., and Friedrich, A.M., 2007, Large Laramide dextral offset across Owens Valley, California, and its possible relation to tectonic unroofing of the southern Sierra Nevada, *in* Till, A.B., et al., eds., Exhumation associated with continental strike-slip fault systems: Geological Society of America Special Paper 434, p. 129–148.

Busby, C.J., and Putirka, K., 2009, Miocene evolution of the western edge of the Nevadaplano in the central and northern Sierra Nevada: Palaeocanyons, magmatism, and structure: International Geology Review, v. 51, p. 670–701, doi: 10.1080/00206810902978265.

Buwalda, J.P., 1954, Geology of the Tehachapi Mountains, California, *in* Jahns, R.H., ed., Geology of southern California: California Division of Mines and Geology Bulletin 170, p. 131–142.

Cecil, M.R., Ducea, M., Mulch, A., Allen, C., and Campbell, I., 2011, Provenance of Eocene river sediments from the central-northern Sierra Nevada and implications for paleotopography: Tectonics, v. 30 (in press), doi: 10.1029/2010TC002717.

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, p. 4–10, doi: 10.1130/1052-5173(2005)015[4:TNLOTS]2.0.CO;2.

Cox, B.F., 1982, Stratigraphy, sedimentology, and structure of the Goler Formation (Paleocene), El Paso Mountains, California: Implications for Paleogene tectonism on the Garlock Fault Zone [Ph.D. thesis]: Riverside, University of California, 248 p.

Critelli, S., and Nilsen, T.H., 2000, Provenance and stratigraphy of the Eocene Tejon Formation, Western Tehachapi Mountains, San Emigdio Mountains, and Southern San Joaquin Basin, California: Sedimentary Geology, v. 136, p. 7–27, doi: 10.1016/S0037-0738(00)00080-4.

Dunne, G.C., and Walker, J.D., 2004, Structure and evolution of the East Sierran thrust system, east-central California: Tectonics, v. 23, TC4012, doi: 10.1029/2002TC001478.

Dunne, G.C., Garvey, T.P., Oborne, M., Schneidereit, D., Fritsche, A.E., and Walker, J.D., 1998, Geology of the Inyo Mountains Volcanic Complex: Implications for Jurassic paleogeography of the Sierran magmatic arc in eastern California: Geological Society of America Bulletin, v. 110, p. 1376–1397, doi: 10.1130/0016-7606(1998)110<1376:GOTIMV>2.3.CO;2.

Ernst, W.G., 2010, Young convergent margins, climate, and crustal thickness—A Late Cretaceous–Paleogene Nevadaplano in the American Southwest?: Lithosphere, v. 2, p. 67–75, doi: 10.1130/L84.1.

Evernden, J.F., and Kistler, R.W., 1970, Chronology of emplacement of Mesozoic batholithic complexes in California and western Nevada: U.S. Geological Survey Professional Paper 623, 42 p.

Gehrels, G.E., Dickinson, W.R., Ross, G.M., Stewart, J.H., and Howell, D.G., 1995, Detrital zircon reference for Cambrian to Triassic miogeoclinal strata of western North America: Geology, v. 23, p. 831–834, doi: 10.1130/0091-7613(1995)023<0831:DZRFCT>2.3.CO;2.

Goodman, E.D., and Malin, P.E., 1992, Evolution of the southern San Joaquin basin and mid-Tertiary transitional tectonics, central California: Tectonics, v. 11, p. 478–498, doi: 10.1029/91TC02871.

Henry, C.D., and Faulds, J.E., 2010, Ash-flow tuffs in the Nine Hill, Nevada, paleovalley and implications for tectonism and volcanism of the western Great Basin, USA: Geosphere, v. 6, p. 339–369, doi: 10.1130/GES00548.1.

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, doi: 10.1038/23926.

Howard, J.L., 1996, Paleocene to Holocene paleodeltas of ancestral Colorado River offset by the San Andreas fault system, southern California: Geology, v. 24, p. 783–786, doi: 10.1130/0091-7613(1996)024<0783:PTHPOA>2.3.CO;2.

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, p. 7–10, doi: 10.1130/G30215.1.

Lofgren, D.L., Honey, J.G., McKenna, M.C., Zondervan, R.L., and Smith, E.E., 2008, Paleocene primates from the Goler Formation of the Mojave Desert in California, *in* Wang, X., and Barnes, L.G., eds., Geology and vertebrate paleontology of western and southern North America, Contributions in Honor of David P. Whistler: National History Museum of Los Angeles County Science Series Volume 41, p. 11–28.

Loomis, D.P., and Burbank, D.W., 1988, The stratigraphic evolution of the El Paso basin, southern California: Implications for the Miocene development of the Garlock fault and uplift of the Sierra Nevada: Geological Society of America Bulletin, v. 100, p. 12–28, doi: 10.1130/0016-7606(1988)100<0012:TSEOTE>2.3.CO;2.

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

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, p. 87–89, doi: 10.1126/science.1125986.

O'Neil, J.R., Clayton, R.N., and Mayeda, T.K., 1969, Oxygen isotope fractionation in divalent metal carbonates: Journal of Chemical Physics, v. 51, p. 5547–5558, doi: 10.1063/1.1671982.

Saleeby, J., Farley, K.A., Kistler, R.W., and Fleck, R.J., 2007, Thermal evolution and exhumation of deep-level batholithic exposures, southernmost Sierra Nevada, California, *in* Cloos, M., et al., eds., Convergent margin terranes and associated regions: A tribute to W.G. Ernst: Geological Society of America Special Paper 419, p. 39–66, doi: 10.1130/2007.2419(02).

Torres, M., 2010, Paleoclimatic and paleoenvironmental interpretations of the Paleocene Goler Formation of southern California [B.S. thesis]: Claremont, California, Pitzer College, 77 p.

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, p. 1395–1404, doi: 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: Journal of Geology, v. 109, p. 539–562, doi: 10.1086/321962.

Wernicke, B., 2011, The California River and its role in carving the Grand Canyon: Geological Society of America Bulletin, v. 123, doi: 10.1130/B30274.1.

Wood, D., and Saleeby, J., 1997, Late Cretaceous–Paleocene extensional collapse and disaggregation of the southernmost Sierra Nevada batholith: International Geology Review, v. 39, p. 973–1009, doi: 10.1080/00206819709465314.

Yapp, C.J., 2008, $^{18}O/^{16}O$ and D/H in goethite from a North American Oxisol of the Early Eocene climatic optimum: Geochimica et Cosmochimica Acta, v. 72, p. 5838–5851, doi: 10.1016/j.gca.2008.09.002.

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, doi: 10.1038/nature02847.

Manuscript received 1 July 2010
Revised manuscript received 8 November 2010
Manuscript accepted 18 November 2010

Printed in USA